

**IX International Symposium
on Exotic Nuclei**

I-69

**Petrozavodsk, Russia
September 10–15, 2018**

**PEโตรZAVODSK
2018
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**IX INTERNATIONAL SYMPOSIUM
ON EXOTIC NUCLEI
(EXON 2018)**

Petrozavodsk, Russia, September 10–15, 2018

Book of Abstracts

Organized by

JINR, Dubna
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DECAY SPECTROSCOPY OF THE HEAVIEST NUCLEAR SPECIES AND PERSPECTIVES AT S3

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The synthesis of new elements has reached up to $Z = 118$ with IUPAC recently assigning the naming rights for the elements 113, 115, 117 and 118 to groups at the FLNR and at RIKEN [1–4]. Nuclei beyond fermium-rutherfordium owe their existence solely to quantum mechanics effects what makes them an ideal laboratory to study the strong nuclear interaction by in-beam methods as well as decay spectroscopy after separation [5].

While in-beam spectroscopy gives access to nuclear structure at higher spins like e.g. rotational bands [6], decay spectroscopy after separation of these deformed nuclei in the region $Z=100-112$ and $N=152-162$ provides direct links to the next heavier spherical closed shell nuclei, by investigating single particle levels [7]. Particularly interesting features are meta-stable states due to nuclear deformation, so-called K isomers, can be used to trace the spherical superheavy nuclei (SHN) and to locate the island of stability [8].

High intensity accelerators, efficient in-flight separators and spectrometers, and highly efficient detectors with fast electronics are the essential ingredients for the success of the field. The new SPIRAL2 facility and, in particular, the separator-spectrometer setup S3 [9] presently under construction at the accelerator laboratory GANIL in Caen, France, will offer great perspectives for the field [8]. An overview of the recent achievements and future perspectives for the field of SHN research will be given.

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SUPERHEAVY ELEMENT CHEMISTRY AT FLNR

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The discovery of superheavy elements (SHE) with atomic numbers 113-118, as well as new relatively long-lived isotopes of elements 104-112 [1] predetermined the development of a new direction in modern radiochemistry - the chemistry with single SHE atoms. The main tasks are chemical identification of new SHE and the revealing of the influence of relativistic effects on the chemical properties. Experimental data on the chemical identification of ^{288}Mc on its decay product ^{268}Db and the results of pioneering experiments on the chemistry of elements Cn, Nh and Fl are reviewed.

Further development of these studies is associated with the launch of the world's first Super Heavy Element Factory at FLNR [2] based on the new accelerator DC-280 (with the intensity of accelerated heavy ion beams an order of magnitude greater than that reached today) and a new gas-filled separator for radiochemical research. The realization of this project will not only expand the chemical investigations, but also significantly improve the statistical reliability of obtained results.

1. Yu Ts Oganessian, S N Dmitriev, "Synthesis and study of properties of superheavy atoms. Factory of superheavy elements", *RUSS CHEM REV*, 2016, 85 (9), 901–916, DOI: [10.1070/RCR4607](https://doi.org/10.1070/RCR4607)
2. Sergey Dmitriev, Mikhail Itkis and Yuri Oganessian, Status and perspectives of the Dubna superheavy element factory // Proceedings of the Nobel Symposium NS 160, EPJ Web of Conferences **131** (2016) 08001.

RIKEN RI BEAM FACTORY STRIKES BACK

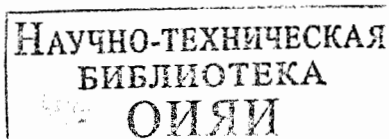
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In EXON-2016 we presented a talk "RIKEN RI Beam Factory, New Hope" describing a new supplemental fund to upgrade RILAC which created Nihonium. This upgrade imposed us the two years down time in the SHE research.

Our accelerator group, however, developed a bright idea to convert 30-year old RIKEN Ring Cyclotron to the discovery machine for 119 and 120 the element, which fills up the down time and even more importantly enables us to perform the parallel operation in searching new elements.

Recent update in RIKEN RI Beam Factory is reported both in the SHE search and RI beam experiments.



PRESENT STATUS AND PERSPECTIVES OF SHE RESEARCHES AT RIKEN

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THE iTHEMBA LABS SAIF PROJECT AND OTHER FACILITY DEVELOPMENTS

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The iThemba Laboratory for Accelerator Based Sciences has been operating a K=200 Separated Sector Cyclotron for nuclear physics research, isotope production and hadron therapy since about 1986. The conflicting demands of these diverse application place severe restrictions on research capacity and on the possibility to respond to future demands.

To increase the beam time for research and isotope production, the establishment of a new facility, the South African Isotope Facility (SAIF) has been proposed. The new facility will consist of two parts:

1. The Accelerator Centre for Exotic Isotopes (ACE Isotopes) will be a dedicated facility for radioisotope production. A commercial high-current 70 MeV H-cyclotron for this purpose will free the SSC and allow an increase in beam time for nuclear physics and related research.
2. The Accelerator Centre for Exotic Beams (ACE Beams) will be a radioactive ion beam (RIB) facility for nuclear physics research. The SSC will be used as a driver for an isotope separation on-line (ISOL) facility. A 66 MeV proton beam of up to 50 μ A will be delivered by the SSC for producing radioactive beams from a target ion source. The first stage of this project will be a low-energy radioactive ion beam (LERIB) project without post acceleration. The second stage will be the post acceleration of the radioactive beams with a linear accelerator to energies of between 4 and 5 MeV per nucleon.

Some of the required funding has been secured for LERIB and its construction is already in progress.

Other facility developments that will be presented include:

- [1] A comprehensive upgrade of gamma detection facilities. The GAMKA project, a collaboration between iThemba LABS and 4 Universities led by the University of the Western Cape, obtained funding for Ge and LaBr₃ detectors that will expand the AFRODITE array to a maximum of 18 clovers, complete the ALBA array of 23 large volume LaBr₃ detectors for high energy gamma rays, and allow for various innovative combinations of LaBr₃ and Ge detectors (the GAMKA array). An important application would be in high resolution particle-gamma coincidence experiments with the K600 magnetic spectrometer.
- [2] A fast timing array of 8 small LaBr₃ detectors, to be used with AFRODITE/GAMKA for lifetime measurements.
- [3] An upgrade of the iThemba LABS mono-energetic neutron beam facility.
- [4] The development and implementation of a tape station aimed at future use with the LERIB low energy radioactive beam facility.

EXOTIC NUCLIDES AT THE REACTOR PIK: PITRAP PROJECT

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Investigation of neutron-rich exotic heavy nuclides is important for both nuclear physics and nuclear astrophysics. On the part of nuclear physics, they can help to understand the position of the boundary of neutron stability, that is, the existence of nuclides as such. For astrophysics, they are interesting because a huge number of them are directly involved in the explosive processes occurring in the universe. These processes can be studied if the properties of these nuclides are known.

The PIC reactor [1], which is under commissioning in Gatchina [2], by virtue of its capacity can be a very productive source of these exotic nuclides, including still unknown ones. The first main stage of their studies can be a measurement of masses (total binding energies). These values, representing the fundamental characteristics of any system, are paramount to describe astrophysical processes.

Synergy of such studies will appear when the ion trap system as a mass spectrometer is used. It has proven itself not only as the most accurate, but also very sensitive device [3].

The idea behind the PITRAP project is just to combine the high production of exotic nuclides provided by a powerful reactor with the single atom sensitivity of the Penning trap-system studying these nuclides.

Fission products are formed in the uranium target located in the reactor through channel near the core. The hot target connected with the ion source of the mass separator is chosen from various opportunities. Mass separator is located behind biological protection wall. The separated ion beam is directed to the ion track leading to the ion trap by means of deflecting devices.

The analysis showed that with the intensity of the neutron beam about $10^{14}/\text{cm}^2/\text{s}$ at the site of the target and the mass of uranium about several grams, it is possible to obtain a high flux of the resulting fission nuclides, which will far exceed the yields of nuclides in the planned projects on particle accelerators (FRIB, FAIR, SPIRAL, etc.).

The project PITRAP as a whole is discussed; the developed scheme of the ion channel and two Penning traps using the latest methods of ion manipulation and detection is presented [4].

In the trap, the ions are held in a microscopic volume by a strong high-uniform magnetic field (7 T, provided by the superconductive magnet) and weak electrostatic fields of a special configuration. The intrinsic cyclotron frequency of the ion in the trap, which can be measured very precisely, is directly related to the nuclide mass. The proposed trap system PITRAP is designed to measure the masses of nuclides with a relative precision of 10^{-9} .

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STUDY OF EXOTIC NUCLEI IN THE FLEROV LABORATORY OF NUCLEAR REACTIONS AT JOINT INSTITUTE FOR NUCLEAR RESEARCH

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One of the fundamental problems of nuclear physics is defining the limits of nuclear stability. It requires advanced studies of nuclei at the boarder of stability and far beyond it both on the proton and neutron driplines. In such regions, the nuclear systems exist in short lived resonant states. The most effective way to study such systems is the use of radioactive ion beams (RIB).

This experimental technique has been realized in most of leading facilities in the world, GSI (Germany), RIKEN (Japan), NSCL (USA), Ganil (France), CERN (Switzerland), etc. It is also used in the Flerov Laboratory of Nuclear Reactions (FLNR) at Joint Institute for Nuclear Research (Dubna, Russia) with the ACCULINNA and ACCULINNA-2 fragment separators operating at intermediate (6-60 MeV/nucleon) energies [1]. This is the region where a wide spectrum of direct reactions (transfer, exchange, charge-exchange reactions and etc) are available for studies.

The present report observes methods of the exotic nuclei study developed in FLNR, in particular, methods of theoretical analysis of the experimental data on spectroscopic and correlation data, and its application for the SDM studies. The developed methodology is based on the comprehensive study of correlations among the fragments emitted in the decays of the nuclear-unstable systems which are populated in direct reactions induced by RIBs at intermediate (20-60 A MeV) energies. Fragment separator Acculinna-2 has been built, approved by PAC (Programme Advisory Committee) and commissioned in the G.N. Flerov Laboratory of Nuclear reaction (JINR, Dubna) in 2017. It has been tested with the ^{15}N beam at the energy 49.7 MeV/nucleon. The secondary beams ^6He and ^{12}Be produced in the beryllium target have been obtained with purities and intensities predicted by the code Lise++ [3,4]. Here we list the most meaningful and challenging experiments on the light drip-line nucleus studies at Acculinna, which should be clarified at Acculinna-2: (i) the search for the minor 2p-decay branch of the first excited state of ^{17}Ne , the $\Gamma_{2p}/\Gamma_\gamma$ width ratio; (ii) study of breakdown of the shell closure in the doubly magic ^{10}He in the $^3\text{H}(^8\text{He},p)^{10}\text{He}$ reaction; (iii) study of the β -delayed proton emission in ^{26}P and ^{27}S , which offers insight into the structure of the initial and the final states of these exotic nuclei. Among the first-day experiments is study of the low-energy resonance states of ^7H anticipated for the $4n$ - decay.

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ACCELERATOR FACILITIES OF FLNR. STATUS AND PLANS OF DEVELOPMENT

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Throughout of FLNR history, the work in the Laboratory deals with accelerator facilities. Today three cyclotrons are working in Flerov Laboratory. These facilities worked more than 15 000 hours in 2017. These were experiments on the synthesis of superheavy elements, investigations of the exotic nucleus and experiments in other direction as well as application works, like SEE testing of electron components for Russian Federal Space Agency (Roscosmos) and others. The new cyclotron DC-280 is being created in FLNR. It will be the basic facilities of the Super Heavy Elements Factory. Construction of the Factory is at the final stage. All DC-280 systems have been tested. The getting of the first beam of accelerated ions is planned in the end of September. Modernization of two main cyclotrons is planned in the near future. The modernization of the U-400M cyclotron is going to start in the next year. The accelerator will get optimized main magnet system, the new vacuum pumping system and new diagnostic elements. The project of the new experimental hall is being developed. We are planning to create about 1000 m² of experimental area for placing the new experimental setups for working with ion beams of the U-400 cyclotron. The modernization of the accelerator is planned too. It gets: the new main magnet system, it will be more energy effectively and will allow smooth variation of ion energies; the new RF system will provide 5 RF harmonics for ion acceleration. Increasing of the full intensity of accelerated ions beam is planned too. Moreover, creation of new accelerator for applied research is planned. It will be DC-130 cyclotron with two main energies of accelerated ions: 2 and 4.5 MeV/n. Its magnet system will be based on the magnet of former U-200 cyclotron.

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Modernization of the U-400 Axial Injection System,
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RADIOACTIVE ION BEAMS FOR THE FISSION STUDY OF THE HEAVIEST NEUTRON-RICH NUCLEI

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Initial set of radioactive ion beams (RIBs) was produced by the Acculinn-2 fragment separator which started operating in 2017 at the primary beam line of the U400M cyclotron. Obtained results prove the high efficiency RIB separation envisaged in the project of this facility entering into the composition of the DRIBs-3 complex developed in FLNR, JINR. Upgrade made in 2019 for U400M will raise the energy and intensity the primary-beams delivered by this cyclotron. As a result, production rates exceeding a level of $10^8 - 10^{10} \text{ c}^{-1}$ will be available at the exit point of Acculinn-2 for many radioactive nuclei.

Specific interest for the discussed problem makes the series of RIBs, ^{10}Be , $^{14,16}\text{C}$, $^{17,19}\text{N}$, ^{20}O , $^{21,23}\text{F}$, ^{24}Ne , ^{28}Mg , involving nuclei with lifetimes longer than 0.5 s. After passing these nuclei through the stages of a gas catcher and ECR charge breeder the obtained multiply charged ions will be injected for acceleration into the U400R cyclotron working in tandem with U400M. In 2020 the presently well working U400 cyclotron will be reconstructed (hence the R adding) to give high-quality heavy-ion beams with variable energy.

So, RIBs listed above will be available from the DRIBs-3 complex. Tuning smoothly their energy in a range of 4 – 6 MeV/nucleon one can observe events where the neutron-rich clusters, such as $^{5,7}\text{H}$, $^{6,8}\text{He}$, ^9Li , ^{12}Be , are transferred to the heavy target nuclei. Taking sequentially the targets of ^{244}Pu , ^{248}Cm , $^{250,251}\text{Cf}$, and ^{254}Es and providing precise detection for the emitted beam-like products (^4He , ^8Be , ^{12}C , ^{16}O) one may be able to detect the fission process of heavy reaction products with $94 < Z < 104$ and $155 < N < 164$ formed in excited states with low ($\approx 10 - 15 \text{ MeV}$) excitation energies and small ($\approx 10 \text{ h}$) spins.

BEYOND-NEUTRON-THRESHOLD SPECTROSCOPY PROGRAM AT ALTO WITH TETRA, MONSTER AND PARIS SPECTROMETERS

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There has been recently growing evidence [1,2], from β -delayed gamma and neutron spectroscopy measurements on neutron-rich nuclei, seemingly pointing towards the existence of specific regions of the daughter nucleus excitation spectrum that clearly concentrate larger fractions of the β -strength. These regions significantly overlap with regions where highly collective excitation modes (typically E1) of the nucleus are expected to lie, raising again the question of the nature of unbound states populated by high- Q_β radioactivity.

We have recently launched an experimental program at ALTO to investigate the structure of the neutron-threshold region. This endeavor was further encouraged by two remarkable serendipities. The first one concerns the unexpected observation of “ultra”-high-energy γ -rays (8-9 MeV) [3] in the β -delayed emission products of ^{83}Ga ($Z=31$; $N=52$; $T_{1/2}=312$ ms ; $Q_\beta=11.7$ MeV) sources collected at the BEDO station [4]. The second one concerns β -delayed neutron-emission probability (P_n) measurements of the $^{82,83,84}\text{Ga}$ ($N=51,52,53$) precursors [5] using the neutron counter TETRA [6] : quite unexpectedly, after a steep increase of the P_n values from $N=51$ to 52, the P_n falls down again at $N=53$ by a factor ~ 2 .

These results will be presented and discussed. It will be shown that they clearly point towards the existence of structures in the threshold region of the daughter-nucleus excitation spectrum, governing the decay properties in the ^{78}Ni region. Some of these structures might be related to the hypothetical emergence of a neutron skin beyond $N=50$. Current scenarios in several nuclear applications and astrophysics [7] can be substantially affected. In particular, the relative importance of first-forbidden transition in the ^{78}Ni region may have long been overestimated.

Perspectives for further investigation of these questions at ALTO using the PARIS, TETRA and MONSTER (γ and neutron) spectrometers will be presented.

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LATEST UPDATE ON THE SOUTH AFRICAN UNDERGROUND LABORATORY (SAUL) PROJECT AND OTHER DEVELOPMENTS

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This presentation will report on measures being undertaken to advance the case for the establishment of a deep underground facility to complement those in the Northern Hemisphere to study – among others – solar and cosmic neutrino detection experiments and searches for rare beta decays. Having a Southern Hemisphere analogue of the DAMA/LIBRA experiment would provide a major control on systematic such as seasonal fluctuations which would be 6 months out of phase with those in the Northern Hemisphere – and would be valuable in the study of possible annual modulation effects in certain radioactive decays, with good shielding. These would be important in seeing whether these effects are indications of new physics. If radioactive decay rates did show an annual modulation, they could also be an additional potential background for dark matter searches that look for annual modulation effects. This paper will report on the latest developments and progress to date; and further elucidate on general developments in latest other new projects being planned in South Africa.

PRODUCTION OF NEUTRON-RICH NUCLEI BY MULTINUCLEON TRANSFER REACTIONS AT KISS PROJECT

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Properties of neutron-rich nuclei around the neutron closed shell $N = 126$ are important to investigate the r-process in the astrophysical nucleosynthesis, because the waiting point nuclei on $N = 126$ are considered as progenitors of the peak at the mass number of 195 in the solar r-abundance distribution. Intense theoretical [1] and experimental [2] efforts have been currently invested in the possibility of using multi-nucleon transfer (MNT) reactions to produce those nuclei.

We are now developing KEK Isotope Separation System (KISS) at RIKEN RIBF facility to produce and separate those neutron-rich nuclei and measure their nuclear properties such as lifetimes and masses [3, 4]. The MNT reaction between a ^{136}Xe beam and a ^{198}Pt target is considered to be one of the best candidate reactions for efficient production of the nuclei of interest. The experimental study performed at GANIL to investigate its relevance for producing neutron-rich nuclei close to $N = 126$ demonstrated the promising potential of the proposed MNT production mechanism [5, 6]. KISS consists of an argon gas cell based laser ion source and an isotope separation on-line system to extract single species of neutron-rich isotopes around $N = 126$ produced by those MNT reactions.

In this presentation, we will report the recent experimental results for nuclear production and spectroscopic studies at KISS and its future plan.

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TWO-NEUTRON HALO STATE OF ^{15}B AROUND 3.48 MEV BY A THREE-BODY MODEL *

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We investigate low-lying bound states of the neutron-rich nucleus ^{15}B by assuming it is a three-body system made of an inert core ^{13}B and two valence neutrons. Although discovered more than fifty years ago, it is fair to say that the spectrum of ^{15}B has not been thoroughly understood yet. Experimentally, ^{15}B has been studied using the in-beam γ -spectroscopy technique and multi-nucleon transfer reaction. Two bound excited states at $E_x = 1.327, 2.734$ MeV are observed in the γ -ray spectrum, and five excited states at $E_x = 3.48(6), 4.90(6), 5.95(8), 7.63(8), 10.25(8)$ MeV in the $^{13}\text{C}(^{14}\text{C}, ^{12}\text{N})^{15}\text{B}$ reaction, but spins/parities of these states have not been determined experimentally yet. Theoretically, properties of the excited state at $E_x = 3.48(6)$ MeV are less clear, and different models predict different energies and spin/parity assignments. In this talk, we would like to help clarify the properties of the excited state at 3.48(6) MeV, which is just beneath the two-neutron disintegration threshold and is probably a three-body bound state. Thanks to the large hierarchy between the neutron separation energies of ^{13}B , ^{14}B , and ^{15}B , it is plausible that ^{15}B could be studied by a three-body model. The three-body wave functions are obtained using the Faddeev formalism. Besides the ground state $3/2_1^-$, a second $3/2_2^-$ state is discovered at around 3.61 MeV, which might be identified with the excited state observed at 3.48(6) MeV. The spatial distributions of the two valence neutrons in the $3/2_1^-$ and $3/2_2^-$ states are given in Fig. 1. It is found that the $3/2_2^-$ state is a two-neutron halo state with a large matter radius $r_m \approx 4.770$ fm.

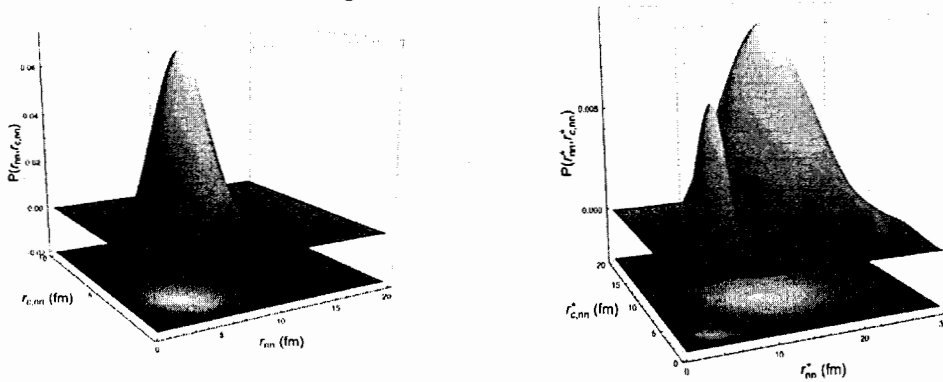


Figure 1: Spatial distribution of two valence neutrons in the $3/2_1^-$ (Fig. (a)) and $3/2_2^-$ states (Fig. (b)) of ^{15}B in the three-body model.

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CLUSTERS IN LIGHT STABLE AND EXOTIC NUCLEI

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Knowledge on physics of nuclear molecules has increased considerably and nuclear clustering remains one of the most fruitful domains of both nuclear physics and nuclear astrophysics, facing some of the greatest challenges and opportunities in the years ahead [1-4]. For instance, since the pioneering discovery of molecular resonances in the $^{12}\text{C}+^{12}\text{C}$ reaction [5] more than half a century ago a great deal of research work has been undertaken in alpha clustering [2-4].

Of particular interest is the relationship between superdeformation (SD) and nuclear molecules, since nuclear shapes with major-to-minor axis ratios of 2:1 have the typical ellipsoidal elongation (with quadrupole deformation parameter $\beta_2 \approx 0.6$) for light nuclei [6-9]. Furthermore, the structure of possible octupole- unstable 3:1 nuclear shapes (with $\beta_2 \approx 1.0$) - hyperdeformation (HD) - for actinide nuclei has also been widely discussed in terms of clustering phenomena. Various approaches of the superdeformed and hyper-deformed bands associated with quasimolecular resonant structures are highlighted in the present contribution.

Highly deformed shapes and SD rotational bands have been recently discovered in several such $N = Z$ nuclei, in particular, ^{36}Ar using γ -ray spectroscopy techniques [6-9]. Extremely deformed rotational bands in ^{36}Ar are observed as quasimolecular bands in both $^{12}\text{C}+^{24}\text{Mg}$ and $^{16}\text{O}+^{20}\text{Ne}$ reactions, and their related ternary clusterizations are also predicted theoretically [6-9].

The search for "exotic" shapes and Bose-Einstein alpha condensates in light $N=Z$ alpha-conjugate nuclei is investigated [2-4]. The evolution of clustering from stability to the drip-lines is examined and clustering aspects are discussed for light exotic nuclei with large neutron excess: the detailed investigation of neutron-rich Oxygen isotopes with their complete spectroscopy [1,6-9] is proposed as a typical

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p-n CORRELATION MEASUREMENTS FROM REACTION ${}^2\text{H}({}^9\text{Li},\text{p}){}^{10}\text{Li}$ USING RIB FROM FRAGMENT SEPARATOR ACCULINNA-2

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A significant part of experiments dedicated to the investigation of the structure of light exotic nuclei is based on the detection of charged particles - nuclear interaction products. The experimental difficulty of detection of neutrons from reactions is caused by comparatively low (in comparison with charged particles) detection efficiency of neutron detectors.

However neutron measurements can considerably enrich nuclear physics with information on nuclear structure especially near the neutron drip line, where neutron decay is the dominant process.

The fragment separator ACCULINNA-2 was commissioned at FLNR, JINR in 2017. One of the first experiments was measurements of ${}^2\text{H}({}^9\text{Li},\text{p}){}^{10}\text{Li}$ reaction. Radioactive ion beam of ${}^9\text{Li}$ with an average energy of 25 MeV/A was used to bombard Cd_2 target. The aim of the work was to investigate the prospects of charged particle - neutron correlation measurements as a tool to study the structure of light nuclei near neutron drip line. In the report preliminary results of p-n correlation measurements are presented.

SEARCH FOR STATES WITH HALO IN ^{12}B AND ^{12}N

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On base of ANC analysis of the new obtained experimental data neutron halo was confirmed for the 2^- , 1.67 MeV and 1^- , 2.62 MeV states in ^{12}B . An unexpected result was received for the 3^- , 3.39 MeV state, which is unbound and is 19 keV above the decay threshold $^{12}\text{B} \rightarrow ^{11}\text{B} + n$. Its halo radius was found to be increased and equal to ~ 6.5 fm. This result can be considered as an evidence of the neutron halo in this ^{12}B state. If this state is truly neutron halo, this observation would indicate to the first halo excited state with a nonzero orbital momentum of the last neutron.

Another interesting question is possible existence of states with halo in other members of the isobaric triplet ^{12}B - ^{12}C - ^{12}N . We can expect the formation of a proton halo in the 2^- , 1.19 MeV and 1^- , 1.80 MeV states of ^{12}N nuclei. To check this prediction MDM analysis of existing ($^3\text{He}, t$) experimental data was done.

IDENTIFICATION OF DILUTE CLUSTER STATES IN ^{11}B , ^{12}C , ^{13}C

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A review of recent experiments including those performed by our collaboration is given. The main accent is done to unique information which is extracted from the measurements of the inelastic scattering cross-sections using the Modified diffraction model (MDM). The enhancement of the radii of some highly excited cluster states of ^{12}C , ^{11}B and ^{13}C was definitely observed. The radii values are in general 20-30% larger than those of the corresponding ground states but much less than those predicted by the model of alpha particle condensation. This result was independently confirmed by another method used by our group – nuclear rainbow method (NRM). A rotational band based on the 0^+_2 (Hoyle) state in ^{12}C is identified. The radius of the second member of the band 2^+_2 ($E^* = 9.8$ or 9.6 MeV) occurred to be similar to that of the Hoyle state (~ 3.0 fm). A new 4^+ state was identified at $E^*=13.75$ MeV. Radius for this state was determined using MDM and was also increased. The radii of the 8.86 MeV, $1/2^-$ state in ^{13}C and 8.56 MeV, $3/2^-$ state in ^{11}B occurred to be close to that of the Hoyle and these states can be considered as analogues of the latter. Moreover, existence of rotational band, based on 8.56 MeV, $3/2^-$ state in ^{11}B , was confirmed and for all members of the band increased radii were observed. Comparison of the data with the predictions of such theoretical models as alpha condensation (AC) and antisymmetrized molecular dynamics (AMD) has been done. Though some of the predictions of AC (e.g., the probability of the $L=0$ component of alpha clusters in the Hoyle state) are close to the experiment most of the data disagree with them and one may speak only about rudimentary manifestation of the condensate effects.

Another question arises if analogues of the Hoyle state can be in other 4N systems. There are many predictions that some 0^+ states in ^{16}O have enlarged radii and can be considered as analogues of the Hoyle state. We applied MDM to data on inelastic scattering of $\alpha+^{16}\text{O}$, $E(\alpha)=386$ MeV with excitation of 0^+_3 - 0^+_6 . We didn't observe any enhancement of radii of these states.

TOTAL REACTION CROSS SECTIONS OF NEUTRON-RICH LIGHT NUCLEI MEASURED BY THE COMBAS FRAGMENT-SEPARATOR

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Preliminary results of measurements of the total reaction cross sections σ_R for weakly bound ^4He , ^6He , ^8He , ^7Li , ^8Li , ^9Li , ^{11}Li , ^7Be , ^9Be , ^{10}Be , ^{11}Be , ^{12}Be , ^8B , ^{10}B , ^{11}B and ^{12}B nuclei at energy range (10-45) A MeV with ^{28}Si and ^{181}Ta target are presented. The secondary beams of light nuclei were produced by bombardment of the ^{15}N (50 A MeV) primary beam on Be target and separated by COMBAS fragment-separator. In dispersive focal plane a horizontal slit defined the momentum acceptance as 1% and a wedge degrader of 600 μm Al was installed. The B_p of the second section of the fragment-separator was adjusted for measurements in energy range (10-45) A MeV. The strong absorption model reproduces the A-dependence of σ_R , but not the detailed structure. We are comparing our experimental data with Glauber multiple scattering theory and preliminary results are obtained.

COLLECTIVE MOTION IN STABLE AND UNSTABLE NUCLEI WITHIN NUCLEAR DENSITY FUNCTIONAL THEORY

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Nuclear density functional theory (DFT) is a powerful microscopic framework to describe the ground state of the nuclei from light to heavy mass region. Its time-dependent extension allows us to describe collective excited states including low-energy collective states and giant resonances. Recent theoretical development on the finite-amplitude method which is an iterative technique to solve the time-dependent DFT in the small-amplitude approximation enables us to perform efficient calculations for the various kinds of excitation modes. I will recapitulate the theoretical framework and discuss the collective pairing excitation in and around the ground state.

Pairing correlation introduces spontaneous gauge symmetry breaking, and it generates the Nambu-Goldstone mode (pairing rotation) in superconducting nuclei. Experimentally pairing rotation can be visible in the systematic of the binding energies of even-even nuclei. I will show a systematic investigation of the pairing rotational moment of inertia from stable to unstable nuclei and discuss the pairing property in connection with the pairing energy density functional within the nuclear DFT.

TOTAL REACTION CROSS SECTION AND BREAKUP REACTION OF WEAKLY BOUND CLUSTER LIGHT NUCLEI AT 22 TO 34 MeV/u

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Total reaction cross-section measurement and breakup of weakly bound cluster nuclei around mass $A \sim (6 \div 12)$ produced from U400M accelerator and COMBAS fragment-separator at intermediate energies $(22 \div 34)$ MeV/u has been studied experimentally. Secondary beam using unstable light nuclei ${}^6, {}^8\text{He}$, ${}^8\text{Li}$, ${}^{7,9,10}\text{Be}$ and ${}^{8,11,12}\text{B}$ impinged on a Si-CsI(Tl) telescope. The telescope served as target, degrader of beam energy and detecting system for the reactions.

The momentum distribution of ${}^{3,4}\text{He}$, ${}^6\text{Li}$ and ${}^7\text{Be}$ resulting from the breakup of ${}^6\text{Li}$, ${}^7\text{Be}$ and ${}^8\text{B}$ has also been determined. Furthermore, the large cross sections for the He breakup channels support for the supposed cluster structure of ${}^6\text{Li}$ and ${}^7\text{Be}$. In the final analysis, the large value of one proton removal cross section for ${}^8\text{B}$ was obtained which contributes an evidence to illustrate the halo structure of this nucleus.

EVIDENCE OF ENHANCED 3α RADIUS PROBED BY HADRONIC REACTIONS

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In light nuclear systems, it is well known that cluster structures appear in excited states. One of characteristic properties in the cluster structures is a prominent extension of the nuclear radius. Typical examples are the Hoyle 0_2^+ state and its rotational excited state, 2_2^+ , in ^{12}C , which are considered to have the developed 3α cluster structure [1, 2]. The matter radii of these 3α states are expected to be enhanced by about 60 % in comparison to the radius of the ground state but the direct measurement of the radius of the 3α state is completely impossible.

In the present study, we focus on the 3α rotational state, 2_2^+ , and demonstrate that the evidence of the enhanced radius in the 2_2^+ state can be clearly identified in the differential cross section of the $\alpha + ^{12}\text{C}$ inelastic scattering. We perform the microscopic coupled-channel (MCC) calculation for the $\alpha + ^{12}\text{C}$ inelastic scattering [3, 4]. In the MCC calculation, the $\alpha - ^{12}\text{C}$ nuclear interactions are derived by the folding procedure. Here we employ the microscopic ^{12}C transition density, which are prepared by the 3α RGM [1] and the DDM3Y effective nucleon-nucleon interaction [5]. As for the internal excitations of ^{12}C , the collective (2_1^+ and 3_1^-) and cluster states (0_2^+ , 0_3^+ and 2_2^+) are included. The differential cross sections for the elastic and inelastic scattering are calculated at the incident energy of $E/A = 96.5$ MeV, and the computational results are compared to the experimental data measured by Itoh *et al.* at Tohoku University, Japan [6].

The MCC calculations for the α scatterings nicely reproduce the differential cross sections of the various exit channels. In particular, our calculation reproduces the differential cross section of the excited state at $E_x = 10$ MeV, which is considered as a mixture of 0_3^+ and 2_2^+ components. From the comparison of the cross sections of the 2_1^+ state and that of the 2_2^+ state, we have found that the latter cross section is prominently shrunk in comparison to the former one. This shrinkage structure can be attributed to the enhanced matter radius in the 2_2^+ state.

Furthermore, we have evaluated the spatial size to product the final state from the respective partial cross sections, which are the partial wave decomposition of the angle-integrated differential cross section. From the partial wave analysis, we have speculated the matter radius of the $^{12}\text{C}(2_2^+)$ state and found about 1 fm enhancement in comparison to the ground state of ^{12}C .

In the present report, we will extend our analysis to other hadronic reaction, such as $^{13}\text{C}(K^-, \pi^-)^{13}_\Lambda\text{C}$, and the probe of the enhanced radius of $3\alpha + \Lambda$ will be discussed.

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STUDY OF CLUSTER STRUCTURE OF $^{8,9,10}\text{Be}$ IN $d\text{-}^9\text{Be}$ INTERACTION

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Energy spectra of protons, deuterons, tritons and alpha-particles emitted from reactions induced by deuterons on ^9Be -target were measured. Experiment was performed using 15 MeV deuteron beam of U-120 cyclotron at Skobeltsyn Institute of Nuclear Physics. The self-supporting Be target with thickness of 0.9 mg/cm^2 was prepared from a 99% pure thin foil of beryllium. To measure the scattered charged fragments a telescope consisting of three Si detectors with thicknesses of 24, 415 and $315 \mu\text{m}$ was used. Particle identification was performed based on the $\Delta E\text{-}E_1$ and $E_1\text{-}E_2$ loki. The Si-telescope was rotated, which allowed to obtain data from $\theta_{\text{lab}} = 30^\circ$ to $\theta_{\text{lab}} = 160^\circ$ in steps of 10° . Some measurements were made also with the registration of neutrons from the decay of excited states. In this case, the neutrons were detected by hydrogen-containing scintillators, and the neutron energy was determined by the time-of-flight method.

The angular distributions of the cross sections for the ground and several excited states of $^{8,9,10}\text{Be}$ are obtained both in the inclusive (with registration of a single charged particle) and in the exclusive experiment (with the registration of an additional neutron).

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TOWARDS THE LIMITS OF NUCLEAR STRUCTURE ALONG THE PROTON-UNBOUND ARGON AND CHLORINE ISOTOPES

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In order to understand of the limits of nuclear structure existence, one can take a closer look at the nuclear systems located far beyond the driplines. The recent investigations of the argon and chlorine isotopes located by two and three mass units beyond the proton drip line will be reviewed. These isotopes were detected by measuring the trajectories of their decay-in-flight products by the means of tracking technique with micro-strip detectors [1]. The experiment has been performed at the FRS fragment separator in GSI, Germany in 2012. The data have been obtained as a by-product of the main objective, ³⁰Ar [2]. The emission of proton (1p) or two-proton (2p) was detected in double or triple correlations with residual heavy ion (HI), i.e. HI+p and HI+p+p, respectively. This technique allowed for the first-time observation of the ³⁰Cl and ²⁸Cl isotopes by measuring their 1p-separation energies S_p of -0.48(2) and -1.60(8) MeV, respectively. The first-time observed excited states of ³¹Ar demonstrated a very high level of isobaric symmetry with respect to its mirror ³¹Al, which allowed to derive the 2p-separation energy S_{2p} of 6(34) keV for the ³¹Ar ground state. The state in ²⁹Ar with $S_{2p} = -5.50(18)$ MeV was also observed for the first time.

In particular, the Monte-Carlo simulations performed in order to interpret and precisely identify the 1p and 2p decay energies, as well as the spectroscopy of the previously-unobserved ²⁹Ar, ^{28,30}Cl isotopes will be presented in detail.

On the basis of the obtained data, the limits of nuclear structure existence are predicted for ²⁶Ar and ²⁵Cl in the respective isotopic chains [3].

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NEW NUCLEAR STRUCTURE DATA BEYOND ^{132}Sn

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Exotic nuclei beyond the ^{132}Sn double shell-closure are influenced by both the Sn superfluity and the evolving collectivity only few nucleons away. Toward even more neutron-rich nuclei, especially at intermediate mass number, interplay between single-particle and collective particle-hole excitations compete. In some cases with the extreme addition of neutrons also other effects as the formation of neutron skin, stabilization as sub-shell gaps or orbital crossings may be expected.

The knowledge of nuclear ingredients is especially interesting beyond ^{132}Sn and little is known on how the excitation modes develop with the addition of both protons and neutrons and for example systematic prompt and decay studies can be a very sensitive probe.

Recently, we have approached this region of nuclei in several such measurements following fission as ^{238}U on ^9Be , n-induced fission on ^{241}Pu and ^{235}U . Consistent data analysis allows to access various spins and excitation energies and provide new input to theory. Examples from these studies on several nuclei in the $A\sim 140$ region will be presented together with the possible interpretation of the new data.

NEW INSIGHT INTO THE CLUSTER STRUCTURE OF ${}^9\text{Be}$ BY REACTIONS WITH DEUTERON BEAM

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Due to the Borromean structure, a special attention has been focused on the ${}^9\text{Be}$ nucleus, the breakup of which can occur directly into two alpha particles and a neutron or via one of two unstable intermediate nuclei such as ${}^8\text{Be}$ or ${}^5\text{He}$ [1, 2]. Scattering of a projectile, such as ${}^1\text{H}$ or ${}^3\text{He}$, on a target is a standard tool to study the structure of nucleus. The experiments were performed using ${}^2\text{H}$ ion beams at 19.5 MeV, 25 MeV and 35 MeV energies delivering by the accelerator facilities at INP (Rez, Czech Republic), IPNO (Orsay, France) and Department of Physics, University of Jyväskylä, Jyväskylä (Finland), respectively. Particle identification was performed based on the energy-loss measurements of ΔE and residual energy E_r , i.e., by the so-called ΔE -E method.

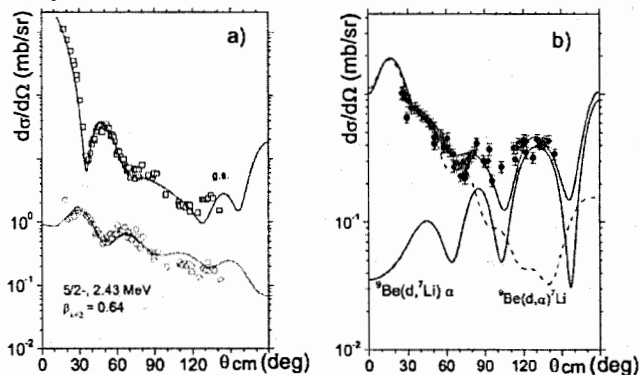


Fig.1 a) Experimental angular distribution for elastic ($\square$) and inelastic scattering($\circ$) of 19.5 MeV deuterons from ${}^9\text{Be}$ target compared with the calculations. The curves are the results of the optical-model and the coupled-channel calculations.

b) Experimental angular distribution ($\bullet$) for ${}^4\text{He}+{}^7\text{Li}$ reaction channel.

The angular distributions of the ${}^9\text{Be}(d,d){}^9\text{Be}$, ${}^9\text{Be}(d,p){}^{10}\text{Be}$, ${}^9\text{Be}(d,t){}^8\text{Be}$, ${}^9\text{Be}(d,{}^3\text{He}){}^8\text{Li}$, and ${}^9\text{Be}(d,{}^4\text{He}){}^7\text{Li}$ reaction channels were measured and described within the framework of the optical model, the coupled-channel approach and the distorted-wave Born approximation (Fig.1). The experiments were designed to study the breakup of ${}^9\text{Be}$ in an attempt to determine the contribution of the ${}^8\text{Be}+n$ and ${}^5\text{He}+\alpha$ channels in the inclusive measurements. We found that the ratio about 2.7:1 may be assigned to the contributions of these two configurations, respectively. The determined value justifies that the ${}^5\text{He}+\alpha$ breakup channel plays an important role. To clarify how the cluster structure reflects to nuclear reaction mechanism, a special attention was paid to the ${}^4\text{He}+{}^7\text{Li}$ reaction channel, which can proceed through two different mechanisms: either transfer of d (dashed line in Fig.1b) or transfer of ${}^5\text{He}$ (solid line in Fig.1b) from the target to the projectile. Their coherent sum shown as the black curve is in good agreement with the experimental points. It is important to note that for the correct description of the data, it is necessary to set the sufficiently large values of the spectroscopic factors for the systems ${}^9\text{Be}=\alpha+{}^5\text{He}$ ($S=1.2$) and ${}^7\text{Li}=d+{}^5\text{He}$ ($S=1.0$). In addition, to describe the structure of the angular distributions it is also necessary to assume a 30% admixture of the d-state in the structure of ${}^7\text{Li}$. The analysis shows that the contribution of the compound nucleus mechanism is negligible. In the ${}^4\text{He}+{}^7\text{Li}$ channel (see Fig.1b), the deuteron transfer provides only a small contribution at backward direction, whereas a relatively large contribution of ${}^5\text{He}$ transfer was found in agreement with the result [3,4]. This demonstrates that the specific structure of the ${}^9\text{Be}$ nucleus as a weakly bound system of two alpha particles and a neutron strongly favors the five-nucleon transfer compared to the deuteron transfer. Our finding confirms conclusions [3,4] suggested a significant contribution of five-nucleon transfer (in ${}^5\text{He}$ configuration) to the ${}^4\text{He}+{}^7\text{Li}$ channel.

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QUARK MODEL OF NUCLEAR STRUCTURE: FROM STABLE NUCLEI TO NUCLEAR DRIP LINE

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Starting with the quark model of nucleon structure in which valence quarks are strongly correlated within a nucleon, light nuclei are constructed by assuming the similar correlations between the quarks of neighboring nucleons [1]. Binding of nucleons in stable nuclei are provided by quark loops which result in three and four nucleon correlations. The quark loop that can be identified with three nucleon force results in a "pairing" effect. And namely quark loops leading to four-nucleon correlations are responsible for the binding energy enhancement in even-even nuclei which are formed by virtual alpha-clusters. Moreover, the quark loops are responsible for formation of exotic (borromean) nuclei [3]. These loops corresponding triangular nucleon configurations ${}^3\text{H}$ and ${}^3\text{He}$ are building blocks of both stable and borromean nuclei. In borromean nuclei possessing maximal deformation, these configurations are weakly bound because of specific orientation of quark loops formed by a core nucleon and two halo nucleons. The model predicts the maximally possible neutron excess in helium isotopes is 4, i.e. the last helium bound state is ${}^8\text{He}$, and a bound state of ${}^{10}\text{He}$ does not exist [4].

Application of the model to larger collections of nucleons reveals the emergence of the facecentered cubic (FCC) symmetry at a nuclear level where nucleons are arranged in alternating spin-isospin layers. The FCC model of nuclear structure, which is isomorphic to the shell model and, moreover, composes the features of the liquid drop and cluster models. For medium and heavy nuclei the arrangement of nucleons is modified by Coulomb repulsion of protons. This effect together with quark/nucleon correlations leads to deviation from the shell model expectations. The model predicts the boundary of the maximal numbers of proton and neutron excess, i.e. proton and neutron drip lines.

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COULOMB SHIFT IN TWO-CENTER CLUSTER SYSTEMS

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The so-called α cluster structure appears in the excited states of light nuclear system, and the structures have been extensively investigated in the $N = Z$ system along the stability line [1]. Furthermore, the α cluster structures are extensively discussed in neutron excess ($N > Z$) systems [1]. In neutron excess systems, the valence neutrons play the glue-like roles among the cluster cores, and the various chemical-bonding structures are generated. We can see the typical example of such the chemical-bonding structures in the Be isotopes, in which excess neutrons form the covalent orbit around the two center cores of ${}^8\text{Be} = \alpha + \alpha$ [2].

In the present report, we focus on the mirror systems, which is obtained by replacing neutrons to protons in neutron excess system, and demonstrate that the Coulomb shift of the mirror systems is a new probe to catch the sign of the clustering phenomena. Here we discuss the Coulomb shift of the mirror systems, such as ${}^{18}\text{O} = \alpha + {}^{14}\text{C}$ and ${}^{18}\text{Ne} = \alpha + {}^{14}\text{O}$.

The interaction potential of α and the residual nucleus is derived from the double folding (DF) model with the effective nucleon-nucleon interaction of the density-dependent Michigan 3-range Yukawa [3]. The validity of the DF potential is checked by applying it to the $\alpha + {}^{14}\text{C}$ elastic scattering. The scattering calculation with the DF potential and the phenomenological absorptive potentials nicely reproduces the the observed differential cross sections.

The energy level of these mirror systems are calculated from the orthogonality condition model (OCM), in which the functional space allowed by the Pauli's exclusion principle is exactly constructed [4]. In the present OCM calculation, the Pauli allowed states are constructed by the mathematical technique about the $\text{SU}(3)$ group theory. The OCM calculation predicts the formation of the 0^+ resonance above the α threshold. In the ${}^{18}\text{O}$ calculation, the 0^+ resonance nicely corresponds to the $0^+ 4$ state in its energy and width, which has been assigned in the recent experiment [5], although there is no experimental information on the 0^+ resonances in ${}^{18}\text{Ne}$.

We have evaluated the energy difference of the 0^+ states between ${}^{18}\text{O}$ and ${}^{18}\text{Ne}$, which arises from the difference of the Coulomb interaction. The theoretical calculation predicts that the Coulomb shift for the excited 0^+ state is about half the ground Coulomb shift, and this reduction of the Coulomb shift is induced by the development of the α clustering. Therefore, the present result strongly suggests that the Coulomb shift is new probe to identify the cluster degrees of freedom. In this report, we will discuss the relation of the reduction of the Coulomb shift and the development of the cluster degrees of freedom in detail.

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SHAPE COEXISTENCE IN ^{31}Mg REVEALED BY β - γ AND β -n- γ SPECTROSCOPY WITH SPIN-POLARIZED ^{31}Na

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In neutron-rich nuclei with the neutron number close to the magic number $N = 20$, namely in nuclei located in or near the “island of inversion”, shape change of the ground states from spherical to deformed shape has been investigated as a function of the neutron number for many years by a variety of experimental and theoretical studies. Recently, the theoretical calculation of the AMD+GCM frame work [1] predicted not only the ground-state deformation but also shape coexistence in a low excitation energy region in the neutron-rich Mg isotopes. Later the shell model calculation pointed out the important role of competition between the mean field, which favors spherical shape, and the nuclear correlations, which cause deformation [2]. Very recently, the large-scale shell model calculation showed configuration mixings of spherical $0p0h$ and deformed $n\pi h$ configurations to a large extent [3]. Thus, it is expected that various types of structure coexist in a narrow excitation energy region in such nuclei. However, up to now, the detailed experimental information, such as spins and parities of the excited states, transition probabilities, is not available in the most of island-of-inversion nuclei. It has been difficult to discuss the nuclear structure in detail.

In the present work, we studied the detailed level structure of neutron-rich nucleus ^{31}Mg ($N=19$) by the β - γ and β -n- γ spectroscopy of *spin-polarized* ^{31}Na [4] at TRIUMF where highly polarized radioactive beams are provided. The most powerful tool is the spatially asymmetric β -decay to firmly assign the spin-parity of the excited states of ^{31}Mg : the spins and parities of 8 levels, including 3 neutron-unbound levels, were determined and very detailed β -decay, γ -transition, and neutron-emission probabilities were obtained. Such information enabled us to compare the experimental properties and theoretical predictions of the AMD+GCM [1] and of the shell model [3] on a level-by-level basis. It was found that the levels in ^{31}Mg are categorized into four types of largely deformed rotational bands, states with spherical natures, and a state with a significantly mixed configuration. These facts show clear evidence for the shape coexistence in ^{31}Mg . It is interesting to note that the above-mentioned mixed-configuration state shows collective nature through the β -decay intensity and at the same time single-particle nature through the neutron spectroscopic factor.

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PROTON ELASTIC SCATTERING FROM ${}^6\text{He}$ AT 200 A MeV MEASURED WITH POLARIZED PROTON TARGET FOR RI-BEAM EXPERIMENTS

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Spin-dependent interactions play essential roles in nuclear structure and reactions. One of the best-known manifestation of them is the spin asymmetry in nucleon elastic scattering, which is a direct evidence of the existence of strong spin-orbit interaction in the world of atomic nuclei. Since the spin-orbit interaction is expected to work in the surface region, it is natural to expect that such interaction could be strongly modified by the characteristic surface structure of neutron-skin or -halo nuclei [1]. This work aims at investigating the spin-orbit interaction between proton and neutron-rich ${}^6\text{He}$ by measuring differential cross sections and vector analyzing powers in the elastic scattering.

At RIKEN RIBF, we measured the proton elastic scattering from ${}^6\text{He}$ at 200 A MeV utilizing a spin-polarized proton target specially developed for the RI-beam experiments. A novel technique of dynamic nuclear polarization is adopted for the target, which enables high proton polarization of about 20% in a relaxed condition of low magnetic field (~ 100 mT) and at high temperature (~ 100 K) [2]. Recoil protons were detected at both left and right sides of the beam line with ESPRI Recoil Proton Spectrometers composed of a plastic scintillator, an MWDC, and NaI(Tl) scintillators. Magnetic rigidity of the scattered particles was analyzed by the SAMURAI spectrometer for event selection.

Differential cross sections have been obtained in the highest momentum transfer region ($1.7\text{--}2.7\text{ fm}^{-1}$) among the existing measurements, which serve as probe for the density distribution especially sensitive to its core part [3]. The data are well described by using a relativistic impulse approximation model assuming point-proton distribution that reproduces the known value of the charge radius and point-neutron distribution whose core-partradius is close to that of point-proton distribution. In addition to the analysis of differential cross sections, preliminary results of the vector analyzing powers will also be presented.

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STUDY OF GROUND STATES OF ${}^{7,9,11}\text{Li}$ NUCLEI AND DYNAMICS OF EXTERNAL NEUTRONS IN REACTIONS ${}^{7,9,11}\text{Li} + {}^{28}\text{Si}$

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The probability densities for the ground states of ${}^6\text{He}$, ${}^6\text{Li}$ nuclei were calculated in Refs. [1, 2] by Feynman's continual integrals method in imaginary (Euclidean) time. The present work is devoted to studying light nuclei ${}^{7,9,11}\text{Li}$ using the same approach. For example, the probability density for the ${}^{11}\text{Li}$ nucleus is shown in Figure 1a. The dynamical approach based on numeric solution of the time-dependent Schrödinger equation [3 – 5] was applied to the description of adiabatic and diabatic rearrangement of neutrons in reactions ${}^{7,9,11}\text{Li} + {}^{28}\text{Si}$ (see Figure 1b,c) and to the calculation of total reaction cross sections [4, 5].

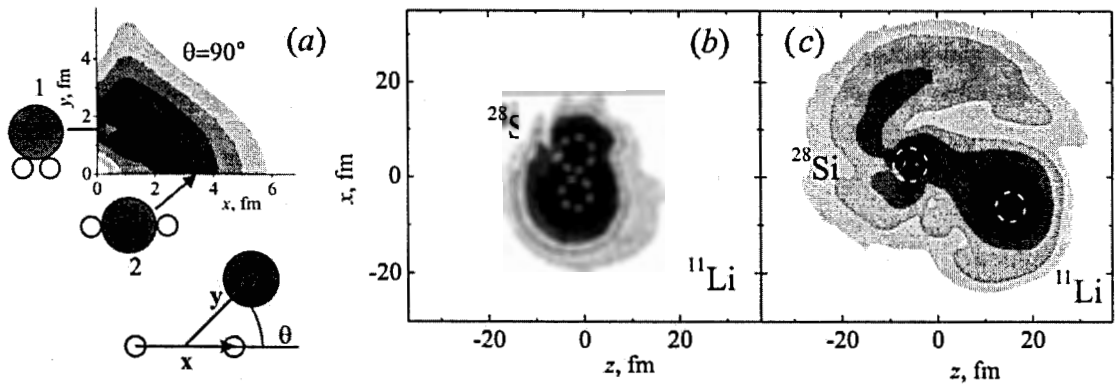


Figure 1. (a) The probability density for the ${}^{11}\text{Li}$ nucleus (configuration ${}^9\text{Li} + n + n$) and the vectors in the Jacobi coordinates; neutrons and ${}^9\text{Li}$ -core are denoted as small empty circles and large filled circles, respectively. The most probable configurations are ${}^9\text{Li} + \text{di-neutron}$ (1) and the cigar configuration (2). (b, c) An example of the time evolution of the probability density for the external neutrons of ${}^{11}\text{Li}$ nucleus in the collision with ${}^{28}\text{Si}$ for $E_{cm} = 100$ MeV and impact parameter $b = 8$ fm. The radii of circumferences equal the effective radii of nuclei. The course of time corresponds to the panel locations (b, c).

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DESCRIPTION OF THE TETRANEUTRON RESONANCE

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A low-lying resonance in the system of four neutrons (tetraneutron) was recently first observed by Kisamori et al. [1]. To the best of our knowledge, a theoretical description of this resonance was presented only in our paper [2] where we used the JISP16 NN interaction and a recently proposed Single-State HORSE formalism [3] extended to the case of democratic decays which is able to extract resonance energies and widths from the results of the No-Core Shell Model (NCSM) calculations.

A further development of the Single-State HORSE formalism together with new tetraneutron results obtained with various models of inter-nucleon interactions in extended NCSM model spaces will be presented.

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EXPERIMENTAL STUDIES OF TOTAL REACTION CROSS SECTION ENERGY DEPENDENCE FOR ${}^{6,8}\text{He} + {}^{28}\text{Si}$ AND ${}^{9,11}\text{Li} + {}^{28}\text{Si}$ REACTIONS

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The energy dependence of total reaction cross sections $\sigma_R(E)$ have been measured for ${}^{6,8}\text{He} + {}^{28}\text{Si}$ and ${}^{9,11}\text{Li} + {}^{28}\text{Si}$ reactions by direct and model-independent method. The transmission method based on a registration of prompt n- γ radiation by 4 π -technique as well as a registration of energy losses in the target (ΔE Si-detector) was used.

The experiments were performed at Flerov Laboratory of Nuclear Reactions Joint Institute for Nuclear Research (FLNR JINR) Dubna.

Secondary beam particles ${}^{6,8}\text{He}$ and ${}^{9,11}\text{Li}$ (produced by ${}^{15}\text{N}$ primary beam with ${}^9\text{Be}$ target) were separated and transported by ACCULINNA fragment-separator to thin Si target positioned in n- γ shielded experimental cave at FLNR JINR. The measured data $\sigma_R(E)$ have been compared with published one. It was observed the unusual wide enhancement of $\sigma_R(E)$ values for ${}^{9,11}\text{Li} + \text{Si}$ reaction in the energy range $\sim 10\text{--}30$ A MeV in comparable with ${}^{6,7}\text{Li} + \text{Si}$ reactions. Calculated cross section values performed by a model in a frame of microscopic approach based on the numeric solution of the time-dependent Schrödinger equation are in agreement with the experimental data.

The work was supported by the Russian Science Foundation (RSF), research project 17-12-01170.

THE LOW-LYING STATES OF ${}^9\text{Be}$ FROM ${}^9\text{Be} + \alpha$ SCATTERING AT 30 AND 90 MeV

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The differential cross-sections of the ${}^9\text{Be}(\alpha, \alpha){}^9\text{Be}'$ scattering ($E_{\text{lab}}(\alpha) = 90$ MeV) with excitation of ${}^9\text{Be}$ states 2.43 MeV, 2.78 MeV, 4.7 MeV, 5.59 MeV and 7.94 MeV were obtained. The aim of this experiment was to determine the spin parities of excited states which form predicted third rotational banding the ${}^9\text{Be}$ nucleus (2.78 MeV, 5.59 MeV, 7.94 MeV). We also used the data previously obtained in the experiment on the ${}^9\text{Be}(\alpha, \alpha){}^9\text{Be}'$ scattering ($E_{\text{lab}}(\alpha) = 30$ MeV) [1].

In [2] following values of spin-parities for excited states are accepted: 2.78 MeV ($1/2^-$), 4.7 MeV ($3/2^+$), 5.59 MeV ($3/2^-$) and 7.94 MeV ($5/2^-$). But in [3] for the ${}^9\text{Be}$ excited states were proposed new values of spin-parities $J^\pi=3/2^-, 1/2^-, 5/2^-$ and $3/2^-$, respectively. The ${}^9\text{Be}$ values differ from the generally accepted ones and should be checked.

Analysis of our experimental data has shown that for the 2.78 MeV and 7.94 MeV states the spin-parity values shouldn't be changed. For the 4.7 MeV and 5.59 MeV states, we could not give an exact answer, we rebooth necessity of the spin-parities change.

In [4] the new excited state 3.82 MeV in the ${}^9\text{Be}$ was found with an assumed spin-parity $J^\pi=3/2^-$. It gives an opportunity to suppose that the 3.82 MeV state can be the second member of the predicted third rotational band and can replace 5.59 MeV state.

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STUDIES OF ^{22}C AND $^{50,52}\text{Ca}$ AT SAMURAI

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for SAMURAI collaboration

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The matter radius of the two-neutron halo nucleus ^{22}C and the electric dipole response of the neutron-rich Ca isotopes were studied by using SAMURAI spectrometer at RIBF.

The ^{22}C nucleus has drawn attention due to its possible enhanced halo structure, as suggested by the huge reaction cross section on a proton target [1]. The estimated root-mean-squared radius of 5.4 ± 0.9 fm is much larger than known halo nuclei such as ^{11}Li . Due to the large uncertainty in the root-mean-squared radius of the previous measurement, it has been difficult to draw definite picture of the ^{22}C structure through the comparison with theoretical predictions. To obtain more precise data for root-mean-squared radius of ^{22}C , the reaction cross section of ^{22}C on the carbon target was measured at 235 MeV/nucleon

The pygmy dipole resonance (PDR) is the low-energy electric dipole mode located at 6~10 MeV. While PDR has been observed many neutron-rich nuclei, the PDR structure is not yet known. The recent theoretical work showed that the PDR strengths are enhanced at $^{48-54}\text{Ca}$ [2], and it is due to the occupation of low angular-momentum orbit by the valence neutrons. In addition, the strong correlation between the PDR strength and the neutron skin thickness for ^{52}Ca and ^{54}Ca [3]. To investigate the evolution of PDR in neutron-rich Ca isotopes experimentally, the relativistic Coulomb excitation of $^{50,52}\text{Ca}$ was performed.

The experiments were performed using the SAMURAI spectrometer at RIBF. The incoming beams were impinged on Pb and/or C targets. The outgoing charged particles and neutrons were measured by SAMURAI spectrometer and neutron detectors, respectively. The neutron detectors were the combination of NEBULA and the NeuLAND demonstrator. For $^{50,52}\text{Ca}$ measurement, the de-excitation γ -ray from the reaction residue was measured by the new γ -ray detector CATANA.

In this talk, we will report on the ^{22}C matter radius and the dipole response of $^{50,52}\text{Ca}$ close to the one-neutron separation energy.

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FUNDAMENTAL SYMMETRY TESTS USING ATOMIC NUCLEI: THE ROLE OF NUCLEAR STRUCTURE

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The plethora of accessible atomic nuclei provide excellent opportunities to test assumed symmetries of the standard model. However, in order to achieve these goals for a majority of the cases it is essential that

- a) The experimental measurements are of high (sub-percent or better) precision and
- b) The effects of nuclear structure are well understood.

In this talk I will highlight some recent experimental work led by the University of the Western Cape in this exciting sub-field of nuclear physics. I shall mainly focus on a few specific cases, where the effects of nuclear structure play a critical role in performing highly sensitive and stringent tests of the currently accepted structure of electroweak interactions.

CLUSTERING AND EMERGENT COLLECTIVITY IN MULTIDIMENSIONAL POTENTIAL ENERGY SURFACE CALCULATIONS

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Over the last three decades both the quantity and quality of the experimental data on the properties of nuclear-decay modes have increased tremendously [1]. Theoretical models must be able to treat the multiple nuclear shapes seen in new decay modes with changing intrinsic structures of a primordial clusters formed from the nucleons present in a fissile nucleus. Clustering and nuclear collective states play important role in determining nuclear potential energy surfaces (PES's), fission barriers and landscape [2]. For the first time multi-dimensional calculations of PES's were presented in [3] by Pashkevich. New features of the PES structure emerging in seven-dimension deformation space have been compared there to the few-dimensional PES, the distinction have been explained in catastrophe theory terms. Possibility of the emergent collectivity and clustering influenced by nuclear deformation was studied in [4]. The dynamics of the fission process is described as the evolution of collective degrees of freedom of the system such as the main fission elongation value and the mass-asymmetry mode. In this work PES's are calculated by the macroscopic-microscopic method using realistic nuclear potential with constant thickness of the surface layer for strongly deformed nuclear shapes in high-dimensional deformation space. Complex multimodal structure of the heavy nuclei fission potential energy surfaces represents effect of a large-amplitude collective motion of the nucleons and their self-organization. By the asymmetry value used as a constraint we study stability of the emergent collective states of cluster structures that can play a role in nuclear dynamics and, in particular, in the dynamics of fission [5]. Strong influence of clustering on the multimodal structure formation has been demonstrated by the use of the state space of high-dimensionality.

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THEORETICAL STUDY OF HALO NUCLEUS OF ^{11}Be

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The aim of work is theoretical study of Coulomb breakup of halo nuclei in non stationary quantum approach. Exotic nuclei are the subject of intensive experimental research. Coulomb break up are relevant for interpretation and planning of experiments in radioactive beams. These investigations have opened new prospects in studying the structure of nucleus and have found applications in other areas of physics, including nuclear astrophysics.

The halo is one of the most intensively studied objects in modern low-nucleus physics. The mean radii of certain nucleons orbits may be larger than nuclear interaction range. A characteristic feature of halo nuclei physics is correlations between the mechanism of nuclear reaction and structure [1].

The breakup is one of the important tools for studying halo properties. In these reactions, the information from dissociation of projectile into fragments could be used to conclude about the properties of halo part of wave function. With a good approximation, the breakup could be regarded as a transition from the bound state of two (three) particles to the continuum, due to the changing Coulomb field [2].

Among the halo nuclei, the ^{11}Be nucleus is of particular importance, since the relative simplicity of its structure allows more accurate theoretical studies. In fact, the bound states of the ^{11}Be nucleus can be described quite well as a ^{10}Be nucleus and a weakly bound neutron. With a good approximation, the decay can be regarded as a transition from a two-particle bound state to a continuum due to a changing Coulomb field in the process of collision of nuclei with a target [3].

The energy of ground and first exotic states of ^{11}Be were calculated by using the potential of Woods-Saxon form with taking into account the spin-orbital interaction as in [2,3]. In addition, the root-mean-square (rms) radius of the ground state of ^{11}Be nucleus was calculated numerically. The rms radius of the core is one of the most fundamental and important of its characteristics.

This work is the initial stage of work on the investigation of the breakup of halo nuclei in the quantum-mechanical approach. A detailed investigation is planned to research the effect of the external field on the breakup of the halo nucleus, using the numerical method for solving the nonstationary Schrodinger equation.

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BETA-DECAY STUDIES OF EXTREMELY PROTON-RICH NUCLEI FROM Mg TO S

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Extremely proton-rich nuclei $^{20,21}\text{Mg}$, ^{22}Al , $^{22,23}\text{Si}$, ^{26}P and $^{27,28,29}\text{S}$ have been produced by fragmentations of ^{28}Si and ^{32}S primary beams impinged on a ^9Be target at the HIRFL-RIBLL1 of the Institute of Modern Physics, Lanzhou, China. Beta-decay studies have been performed using silicon arrays [1] and clover-type HPGe detectors and brand new results have been obtained:

1: ^{20}Mg [2], a new proton group was observed and the corresponding excited state in ^{20}Na was proposed;

2: ^{22}Si [3], a charged-particle group at 5600 (70) keV in the decay-energy spectrum was identified experimentally as β -delayed two-proton emission from the isobaric analog state of ^{22}Al .

The ground-state mass of ^{22}Si was obtained in the experiment for the first time. Two-proton separation energy for ^{22}Si is deduced to be -108 (125) keV, which indicates that it is a very marginal candidate for two-proton ground-state emission. Moreover, a large mirror asymmetry for the first 1^+ excited state of ^{22}Si was observed in comparison with the mirror nucleus ^{22}O .

3: ^{27}S and other nuclei, the experimental data are being analyzed and more interesting decays of these nuclei will be investigated in future. For example, proton and gamma emissions from the excited state (1120 keV, $3/2^+$) of ^{27}P were observed at the same time in the beta decay of ^{27}S in our measurements, which can be used to calculate the astrophysical reaction rate for the $^{26}\text{Si}(p,\gamma)^{27}\text{P}$ reaction and study the nucleosynthesis of ^{26}Al in the Milky Way.

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TOPOLOGICAL TYPOLOGY OF NUCLEI

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With the experimental discovery of spatially isolated multiclusters in nuclei [1-3], nuclear physics and its main section - the physics of the structure of the nucleus - acquires a new impulse and a new content that differs sharply from the historical neutron-proton model of Ivanenko-Heisenberg. The generally accepted hypothetical homogeneity of the radial distribution of nuclear matter in our days is fragmented into a whole series of new topological typifications. In this paper, we propose a new classification of nuclear geometry for seven types of the topological structure of the atomic nucleus, which are experimentally justified with varying degrees of uniqueness and reliability.

The topological type I (spherical nuclei - *spheroids*), naturally corresponds to even-even double magic nuclei and nuclei with filled Heptert-Mayer shells. For example, the *spheroids*: ${}^4_2\text{He}_2$, ${}^{14}_6\text{O}_8$.

Topological types II and III (elongated and flattened - *spheroids* or ellipsoids of rotation) seem to fill the bulk of the isotope matrix in the Z-N coordinates along "Valley of Stability". For example, *prolate spheroids*: ${}^{18}\text{Ne}$, ${}^{22}\text{Ne}$; *oblate spheroids*: ${}^{12}\text{C}$, ${}^{26}\text{Si}$.

The topological type IV (the *toroid* is a nucleus with zero nuclear density in the center) has been historically searched for a long time, but it has not yet been experimentally reliably established. The first candidates for this form of the nucleus, calculated theoretically, are sulfur isotopes. For example, *toroids*: ${}^{32}\text{S}$, ${}^{34}\text{S}$.

The topological type Y (*saturnoid* (our term) is a nucleus with an increased nuclear density in the center) has not yet been experimentally established. For example, *saturnoids*: ${}^{70}\text{Ge}$, ${}^{72}\text{Ge}$, ${}^{74}\text{Ge}$, ${}^{76}\text{Ge}$, ${}^{78}\text{Se}$, ${}^{80}\text{Se}$, ${}^{82}\text{Se}$, ${}^{84}\text{Se}$. It should be noted historically the first predictions of Migdal A. B. on the realism of nuclear superdensity in the form of a π -condensate. The most natural confirmation of this effect was proposed to consider the superdensity of the nucleon and helium-4 (α -particle), which are 5-7 times higher than the "normal" nuclear density ($\rho_0 = 0,147 \text{ Fm}^{-3}$).

The topological type of VI *simplexes* are strongly clustered nuclei with masses of intra nuclear clusters of nuclear matter from 1 to 4: ${}^9\text{Be}$, ${}^{11}\text{B}$, ${}^{12}\text{C}$, ${}^{13}\text{C}$, ${}^{14}\text{C}$, ${}^{24}\text{Mg}$. These are recently experimentally discovered nuclei with a pronounced multi-cluster structure on α -particle beams.

Topological type VII *planetoid* - nucleus with a well-distinguished core and in a remote orbit that has valence nucleons. These are discoveries on beams of heavy ions of exotic nuclei with a planetary structure: ${}^6\text{He}$, ${}^6\text{Be}$, ${}^{10}\text{Be}$, ${}^{10}\text{C}$, ${}^{11}\text{Li}$, ${}^{12}\text{Be}$, ${}^{20}\text{C}$, ${}^{22}\text{C}$, ${}^{24}\text{C}$.

Thus, the newest discoveries of new forms in radial distributions of nuclear density pose essentially new requirements for conducting beam research on the structure of the nucleus. This is the increased angular accuracy of the spectrometers, a reduced pitch in the angle for increasing the accuracy of the angular distributions of the differential cross sections, and a minimal statistical error for the detection of thin angular fluctuations of the cross sections, which carry information about exotic nuclei and their clusters.

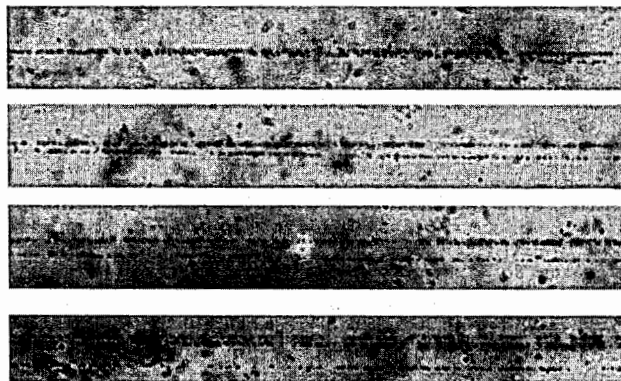
CLUSTER STRUCTURE OF LIGHT RELATIVISTIC NUCLEI

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Events of dissociation of relativistic nuclei in nuclear track emulsion (NTE) allow a holistic investigation of "cold" ensembles of lightest nuclei. So far, with regard to fine structure dissociation of relativistic nuclei, the NTE technique remains the only means providing unique completeness of such observations at the best angular resolution and as well as a sufficient statistical provision. Moreover, full-bodied studies of light nuclear structure require reconstruction of relativistic decays of the unstable ^8Be and ^9B nuclei. Feasibility of such studies in electronic experiments is not visible at all. The cluster structure of light nuclei and the role of the unstable ^8Be and ^9B nuclei in them is studied in the BECQUEREL project (<http://becquerel.jinr.ru/>) on the basis of NTE layers longitudinally exposed at the JINR Nuclotron to relativistic Be, B, C and N nuclei, including radioactive isotopes [1]. Recent advances are highlighted [2-4]. On the practical side series of experiments with newly reproduced samples NTE has confirmed prospects of NTE in low and high energy nuclear studies [5].

Recently it is suggested to search in relativistic ^{12}C dissociation for α -particle triples in the second excited state $0+2$ of the ^{12}C nucleus (the Hoyle state). The started study of the Hoyle-state (HS) in dissociation is setting new limit of NTE use. Being performed in contrast to relativistic energy of 3α -ensembles and minimum possible energy stored by them such observations would clearly demonstrated HS as a full-fledged and sufficiently longlived nuclear-molecular object. Probably, not only single but also pair- and even triple-wise combinations of α -particles that are close to ^8Be might be observed to reflecting the HS structure in less distorted way. It can be expected that ^8Be and HS will become reference points to search for more complex states of dilute nuclear matter in dissociation of heavier relativistic nuclei. The current experiment task is to search for several hundreds of 3α -events in NTE pellicles and measure the angles of α -particles in the relevant ranges with a resolution allowing reconstructing decays of the unstable ^8Be nucleus and HS (example in Fig.). HS events are observed in dissociation $^{12}\text{C} \rightarrow 3\alpha$ at 4.5 A GeV/c and 1 A GeV/c ^{12}C nuclei with a contribution preliminary estimated to be of the order of 10%. Thus, the first data on relativistic HS are encouraging.



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5. P. I. Zarubin "Recent application of nuclear track emulsion technique" Phys. Atom. Nucl. 80, 1126(2017); DOI: 10.1134/S1063778816130093. Fig. Sequential shots of coherent dissociation $^{12}\text{C} \rightarrow 3\alpha$ at about 1 A GeV/c (from top to bottom); when moving from the vertex three He fragments can be distinguished. Values of the invariant mass of the α -pairs are 57, 60 and 270 keV. Invariant mass of the α -triple is 230 keV while its total transverse momentum 111 MeV/c.

STUDY OF ${}^6\text{He}$ - d REACTION AS A FIRST EXPERIMENT AT ACCULINNA-2 SEPARATOR

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ACCULINNA-2 is a newly assembled fragment separator at Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, Russia. As a first experiment, ${}^6\text{He}$ -d elastic and inelastic scattering in inverse kinematics have been measured at 25 MeV/nucleon energy with beam intensity $I=10^5$ pps. This is the first time this reaction has been measured. Angular distributions for elastic and inelastic scattering have been obtained for a range of 25 - 130 CM degrees. Preliminary data analysis of elastic scattering in terms of optical model and cross section for one-neutron transfer in reaction ${}^6\text{He}(d,t){}^5\text{He}$ will be presented.

MICROSCOPIC ANALYSIS OF THE $^{12,14}\text{Be}$ ELASTIC SCATTERING ON ^{12}C AND PROTONS

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The hybrid model of microscopic optical potential (OP) [1–3] is utilized for analysis of the elastic scattering of $^{12,14}\text{Be}$ on ^{12}C at 57 MeV/nucleon and on the proton target at 0.6 GeV/nucleon. The microscopic OP consists of the double folding real part and the imaginary part which is constructed within the high energy approximation theory. OP depends on the nuclear density distributions of the $^{12,14}\text{Be}$ nuclei and thus the microscopic models of them [4,5] are tested in our study. The differential and reaction cross sections are calculated with and without accounting for contributions of inelastic channels with a help of the computer code DWUCK4 [6]. The momentum distributions of the halo nucleons in the stripping and breakup reactions have been also calculated.

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ROLE OF CONSTANT VALUE OF SURFACE DIFFUSENESS ON PREDICTION OF ALPHA DECAY HALF-LIVES OF SUPERHEAVY NUCLEI

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We have tested the effect of using different constant values of surface diffuseness parameter on the alpha decay half-lives and transmission coefficients of some predicted superheavy nuclei using the WKB approximation. The deformed nuclear Woods-Saxon potential, deformed Coulomb potential and centrifugal potential have been used in calculations. We have tested the possible range of variation of diffuseness parameter which was chosen to be $0.1 \leq a \leq 0.9$ (fm). Significant dependency of the results on the choice of this parameter was observed.

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DYNAMICAL APPROACH FOR SYNTHESIS OF SUPERHEAVY ELEMENTS

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More than 50 years ago, the existence of the Island of Stability in the nuclear chart surrounding the doubly magic superheavy nucleus containing 114 protons and 184 neutrons was predicted [1]. It is well known that the stability and the decay properties of superheavy nuclei strongly depends on the shell structure. However, it was pointed out that this shell structure also dramatically affects the fusion process, especially the cold fusion reaction [2]. To synthesis of new superheavy elements $Z \geq 119$, we try to clarify the mechanism of whole the dynamical process and take advantage of the shell structure in fusion process.

According to the macroscopic-microscopic model, the single-particle level diagram for the reaction $^{70}\text{Zn} + ^{208}\text{Pb} \rightarrow ^{278}\text{Cn}$ was calculated by P. Moller et al [2], and it showed that the magic-fragment gap combination $28+82=110$ remains far inside the touching point. The original fragment cluster or shell structure is presented during most of the fusion process. In this case, the kinetic energy in the entrance channel is not dissipated into internal energy, and finally the fusion is enhanced. Moreover, in the cold fusion reaction, due to the shell effect, there are so-called cold fusion valley, which leads to fusion. It is expected that the nuclear friction would be small along the valley, too [3]. To describe such aspects, the dynamical studies with a microscopic dissipation model should be required.

Here, we employ the Langevin equation with the microscopic transport coefficients, friction and mass tensors, which are calculated by linear response theory [4,5,6]. The microscopic friction tensor depends on the nuclear temperature, and the magnitude of the microscopic friction tensor is smaller than the macroscopic one at the low temperature [4,5,6]. We try to investigate the effects of the microscopic transport coefficients along the cold fusion valley.

We calculate the fusion cross section in the reaction $^{70}\text{Zn} + ^{208}\text{Pb} \rightarrow ^{278}\text{Cn}$ at the low excitation energy. We obtain that the fusion cross section is enhanced one order of magnitude at the excitation energy $E^* = 10\text{-}15$ MeV, comparison with the case using the macroscopic transport coefficients. It is clearly shown the shell effects in the fusion process. In the talk, we would like to discuss the dissipative mechanism during the fusion process precisely.

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PREDICTIONS OF FISSION FRAGMENT MASS DISTRIBUTIONS FOR SUPER-HEAVY ELEMENTS

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The total deformation energy at the moment of neck rupture, for the heaviest nuclei for which spontaneous fission has been detected ($^{279-281}\text{Ds}$, ^{281}Rg and $^{282-284}\text{Cn}$) [1,2] is calculated using the Strutinsky's prescription.

The nuclear shapes just before scission are described in terms of Gassinian ovals defined for the fixed value of elongation parameter $\alpha=0.98$ and generalized by the inclusion of four additional shape parameters: α_1 , α_3 , α_4 , and α_6 . Supposing that the probability of each point in the deformation space is given by Boltzmann factor, the distribution of the fission-fragment masses is estimated. The octupole deformation α_3 at scission is found to play a decisive role in determining the main feature of the mass distribution: symmetric or asymmetric. Only the inclusion of α_3 leads to an asymmetric division [3].

In this situation, the scission configuration has one almost spherical fragment with $A_L \approx 136$ and one extremely deformed (neck shaped) complementary fragment. After rupture of the first neck (with smallest radius), the light spherical fragment is separated from the rest. The question is: will the heavy deformed fragment undergo a second fission or will it recover a more or less compact shape? In other words: is the fission of SHE binary or sequential-ternary? To give an answer, we study the potential energy surface of this complementary fragment in order to find its saddles and valleys. The position on this map of its shape at the scission of the SHE gives a hint about its post scission evolution. Such a study has been carried out for the scission on congruences of ^{284}Cn , ^{296}Fl and ^{312}Og .

Finally, detailed calculations are performed in the unexplored region of super-heavy nuclei: the even-even Fl ($Z=114$), Lv ($Z=116$), Og ($Z=118$) and ($Z=126$) isotopes. For these nuclei, the most probable mass of the light fragment has an almost constant value (≈ 136) like in the case of the most probable mass of the heavy fragment in the actinide region. It is the neutron shell at 82 that makes this light fragment stable over such a large series of elements. Naturally, for very neutron-deficient isotopes, the mass division becomes symmetric when $N = 2 \times 82$. In this way, the fission process of super-heavy nuclei smoothly joins the heavy-actinide systematics (from Fm to Sg) where the neutron-rich isotopes show a symmetric mass division.

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NUCLEAR LEVEL DENSITY OF SUPERHEAVY NUCLEI USING TEMPERATURE-DEPENDENT LEVEL DENSITY PARAMETER

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The influence of using a temperature-dependent level density parameter and pairing energy term on the back-shifted Fermi gas (BSFG) model of nuclear level density of some superheavy nuclei has been investigated. The Lestone formula and temperature dependent liquid drop model relations were used for temperature-dependent level density parameter. By using the statistical mechanical definition of temperature and its relation to the state density the thermal properties of some super heavy nuclei have been obtained.

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SPECTROSCOPY OF TRANSFERMIUM NUCLEI USING THE GABRIELA SETUP AT THE FOCAL PLANE OF THE “SHELS” RECOIL SEPARATOR, FLNR, DUBNA

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The heaviest elements provide a unique laboratory to study nuclear structure and nuclear dynamics under the influence of large Coulomb forces and large mass (A). The stability of nuclei beyond the spherical “doubly-magic” ^{208}Pb ($Z = 82$, $N = 126$) decreases rapidly until the transfermium region ($Z > 100$) where a lowering of the level density of single-particle states for nuclei in the neighbourhood of the deformed doubly-magic ^{270}Hs reverses this trend locally [1]. However, the position of the spherical doubly-magic nucleus beyond ^{208}Pb remains uncertain with calculations predicting $Z = 114$, 120 , or 126 for the next magic proton shell, and $N = 172$ or 184 for neutrons [2]. It is therefore crucial to determine the relative excitation energies of single-particle states in the transfermium region [3] to reduce the extrapolation required in predicting the position of this “island of stability” for the very heaviest nuclei [4]. Moreover, the deformed isotopes in the Fm-Sg ($Z=100-106$) region sample most of the nucleonic orbits which are involved in the stabilisation of the predicted spherical super-heavy elements. In addition, their less-neutron-deficient representatives (some of which are barely known or not even charted) are members of the alpha decay chains of the newly synthesized $Z=115-118$ elements. Hence, the systematic study of the structure and decay properties of deformed transfermium elements is essential, and probably for many years, the only available way to reach an understanding of the structure at the upper end of the nuclear chart.

At the FLNR experiments to perform detailed spectroscopy of transfermium nuclei are carried out using GABRIELA [5] at the focal plane of SHELS [6]. Recent results will be presented: the excited states in ^{251}Fm following the alpha decay of ^{255}No [7], K-isomer decay in ^{255}Rf , ^{256}Rf and ^{257}Rf , excited states in ^{253}No populated via the alpha decay of ^{257}Rf , and the observation of pxn evaporation channels following the population of $^{259}\text{Db}^*$ [8]. Planned improvements and future experiments will also be discussed.

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INVESTIGATION OF THE PROPERTIES OF SHORT-LIVED SF ISOTOPES OF TRANSFERMIUM ELEMENTS

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In the last years we carried out several experiments aimed to investigate properties of short-lived SF isotopes. The neutron-deficient isotopes of nobelium were produced in fusion-evaporation reactions using the $^{206,208}\text{Pb}$ target and an intense ^{48}Ca -beam. Fusion-evaporation residues were separated by the SHELS separator (FLNR, Dubna) and implanted into a large-area double-sided silicon 48x48 strip detector surrounded by ^3He -based neutron counters. The half-life and decay branching ratio for $^{252,254}\text{No}$ is measured. The average number of neutrons per spontaneous fission of ^{254}No is determined for the first time.

THEORETICAL STUDIES ON ENERGY DISSIPATION IN HEAVY-ION FUSION REACTIONS AND ITS APPLICATION TO SYNTHESIS OF ELEMENT 120

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Energy dissipation is systematically studied based on time-dependent density functional theory (TDDFT). For the mathematically rigorous derivation of the TDDFT, see [1]. For fusion and quasi fission events [2-3], we propose a new method of deriving the dissipation effect from the TDDFT dynamics. Following a preceding work [4] the dissipation is extracted as the friction coefficient [5-6] in a rather exact manner, and the correlation between the friction and the fission is examined [7]. Consequently a method for microscopically providing a component of friction tensor coefficient for the Langevin calculations is proposed: TDDFT + Langevin hybrid method. In this way, quantum effects such as the shell effect are introduced to the Langevin calculations without any fitting parameters. The obtained method is applied to predict the possibility of synthesizing the element 120.

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STRUCTURE OF SUPERHEAVY NUCLEI

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In nuclear theory the mean field concept plays the role of the basic approach for several more specific advanced theories. These theories can be built upon introducing the single particle mean field basis. Therefore it is very important for the whole field of nuclear structure to examine the consequences of the underlying mean field.

The structure of nuclei which have not been investigated yet or whose investigations have just started is interesting because we do not exclude manifestation of the features which have not been observed in the well investigated regions of the nuclide chart. In the present talk the results obtained basing on the several existing variants of the nuclear mean field for nuclei with $Z > 100$ are considered:

- Low-lying two-quasiparticle and collective vibrational excitations of the even-even nuclei.
- Excitation spectra of the odd-proton and odd-neutron nuclei.
- Quasiparticle structure of the superheavy nuclei along the alpha-decay chain of $^{288}115$.
- The neutron number dependence of the energies of the gamma-vibrational states in nuclei with $Z > 100$ which indicates on manifestation of the pseudospin symmetry.

ROLE OF DEFORMATION AND ORIENTATION OF TARGET NUCLEUS ON THE COULOMB BARRIER PARAMETERS

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The shapes of colliding nuclei offer an essential tool to investigate the fusion and consequent patterns of heavy ion induced reactions. The production and decay cross-sections of heavy/superheavy nuclei are controlled mainly by the Coulomb barrier parameters (height (V_b) and radius (R_b)) which are sensitive to nuclear deformations and orientations [1]. Therefore, the knowledge of the interaction potential at respective deformations and orientations of interacting nuclei is important in describing these parameters. In the present work, we have studied the effect of deformation (quadrupole β_2 and hexadecapole β_4) and orientation degrees of freedom on the distribution of Coulomb barrier parameters by considering spherical+deformed (^{48}Ca +actinide target) systems such as $^{237}\text{Np}+^{48}\text{Ca}\rightarrow^{285}113^*$ [2], $^{243}\text{Am}+^{48}\text{Ca}\rightarrow^{291}115^*$ [3], and $^{249}\text{Bk}+^{48}\text{Ca}\rightarrow^{297}117^*$ [4] using quantum mechanical fragmentation theory (QMFT) [5].

We have estimated the compact and elongated configurations of the interacting nuclei that lead to the hot and cold fusion, respectively. In present calculations, projectile angle (θ_p) is kept fixed as ^{48}Ca is a spherical nucleus and corresponding potential is assumed to be isotropic in angle, hence the angle of target nucleus is varied. It is observed from the calculations that the variation of target angle (θ_T) changes the barrier parameters significantly. For the reactions under consideration, the Coulomb barrier radius (R_b), decreases while going from oblate to prolate shapes. For fixed value of hexadecapole deformations, the quadrupole deformations produce rapid variation in R_b . This variation of R_b with β_2 is linear for $\theta_T \geq 70^\circ$ and it will be of further interest to explore the behavior of barrier characteristics over wide angular spread.

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A SEARCH FOR ALTERNATIVE WAYS FOR PRODUCING OF NEW NEUTRON RICH HEAVY AND SUPERHEAVY NUCLEI

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The understanding of fission and quasifission processes in the reactions with heavy ions is needed for tracing paths aimed at reaching the island of stability situated near $Z = 114-126$ and $N = 184$. One of the possible path-ways to obtain new isotopes of superheavy elements with $Z = 118-126$ is the reactions of actinide targets with Ti, Cr, Fe, Ni, Kr and Gd ions. The quasifission process is strongly connected with the properties of reaction entrance channel. At the transition to heavier ions the contribution of quasifission and multinucleon transfer reactions increases while the formation probability of compound nucleus decreases.

The study of the mass-energy distributions of binary fragments formed in the reactions with ^{48}Ca ions [1], ^{238}U target [2], $^{52}\text{Cr}+^{232}\text{Th}$, ^{248}Cm and $^{84}\text{Kr}+^{198}\text{Pt}$ at energies around the Coulomb barrier will be presented. The estimated fusion probability for the reactions Ca, Ti, Cr and Ni ions with actinide nuclei shows that it depends exponentially on the mean fissility parameter of the system. For the reactions with actinide nuclei leading to the formation of superheavy elements the fusion probabilities are of several orders of magnitude higher than in the case of cold fusion reactions.

Recently it was proposed to use multinucleon transfer reactions, particular, inverse quasifission as a promising pathway to produce new neutron-rich isotopes of heavy and superheavy nuclei that cannot be obtained in complete fusion reactions. The role of double magic lead shell on the formation of the inverse QF fragments in the reactions $^{156,160}\text{Gd}+^{186}\text{W}$ [3] have been investigated. The enhanced yield of products with masses 200-215 u was observed for the both reactions at the Coulomb barrier energy.

The orientation effect caused by the strong deformation of colliding nuclei also plays an important role in the formation of the reaction fragments. It has found that that the formation cross section of Pb-like fragments with mass around 208u at energy above the barrier for side-to-side collisions is about 50 times higher than in the case of measurements at near the Coulomb barrier energy, while the reaction cross section increases only 2.6 times. The enhancement found in the yield of products with masses heavier than the target mass confirms that low-energy multinucleon transfer reactions may be used for producing new neutron-rich isotopes and for the synthesis of new superheavy elements.

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EVALUATION FOR POSSIBILITY OF SYNTHESIZING NEW SUPERHEAVY ELEMENT

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The synthesis of superheavy elements are including touching probability (first stage), formation probability (second stage) and survival probability (third stage).

An accurate prediction is important to synthesis new nuclei and superheavy elements. To calculate these probabilities, coupled channel model [1,2] is used in first stage, Langevin equation which is a dynamical model [3,4] in second stage and Statistical model [5] is used for last stage.

There are many uncertain parameters in each probability, here we are more focused on uncertain parameter of the survival probability in last stage. In survival probability, there are some uncertain parameters such as fission barrier height parameter ∂B_f , friction parameter γ and level density parameter a_f/a_n . In the super heavy element region, it is not decided which values to be used [6,7]. As the parameters change, the calculation results are change too. Based on this calculation, the pattern of the changes in each element are uniform.

As the fission barrier height parameter ∂B_f increase, the fission process become hard and the fusion process will become easier. The increase of the survival probability causes the increase of the evaporation residue cross section. From these parameter factors, we need to adjust the value of these parameters to get the best (reasonable) value of the parameters. There are also many possible systems for the element that has not been discovered yet. These calculations will give the experiment team some guides to discover the new heavy compound nucleus region.

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ACHIEVEMENTS AND CHALLENGES IN THEORETICAL PREDICTIONS OF CHEMICAL PROPERTIES OF SUPERHEAVY ELEMENTS

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Recent years have been marked by a number of achievements in the area of chemical studies of properties of superheavy elements (SHEs). Thus, interesting gas-phase chromatography experiments were conducted on volatility of Cn, Nh and Fl, as adsorbed on gold surfaces [1-3]. The first attempt of chemical characterization of Nh has also been announced using a similar approach [4]. There is presently a search for new gas-solid systems that would allow for more selective separation procedures and techniques [5,6]. Also, some preparations for further chemical studies on carbonyls of Sg, Bh and Mt are in progress [5]. All these experiments and preparations are aimed at observation of interesting and often unusual behaviour of SHEs, that is influenced by increasingly important relativistic effects on their electron shells.

Theoretical chemistry of the heaviest elements has also been advancing due to further development of relativistic computational codes. Presently, accurate 2-component relativistic methods having advantages over expensive 4-component ones are available for calculations on the heaviest element systems. Based on them solid-state codes are presently on the way to be applied to solid state properties and adsorption phenomena of the heavy elements. As a result, adsorption properties of SHEs, and of their homologs, have been accurately predicted using these advanced periodic codes [7-9].

In the presentation, recent developments in the relativistic quantum-chemical methods and their application to SHE systems are overviewed. An accent is put on predictions of adsorption behaviour of Cn, Fl and Nh and of their compounds on gold and hydroxylated SiO₂ surfaces. Future prospects, both from the methodical point of view, as well as from the point of view of applications to interesting chemical systems of the heaviest elements, are discussed.

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SYSTEMATIC CALCULATIONS ON ALPHA-DECAY HALF-LIVES OF HEAVY AND SUPERHEAVY NUCLEI

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Alpha clustering and alpha decay are important for ground state properties of many nuclei [1-9]. Alpha decay is a powerful way to identify new nuclides and new elements in heavy and superheavy region [1-3]. The different methods to calculate α -decay half-lives and branching ratios to various daughter states are discussed. Emphasis is placed on the microscopic models of the coupled channel calculations on α -decay half-lives and branching ratios of heavy nuclei [3-9]. Systematic calculations on the half-lives and branching ratios are carried out by the density-dependent cluster model and by multi-channel cluster model and good agreement with available data is reached. This is the systematic calculation on α -decay half-lives of heavy and superheavy nuclei.

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THE FIRST IONIZATION POTENTIALS OF HEAVY ACTINIDES, Fm ($Z = 100$), Md ($Z = 101$), No ($Z = 102$), AND Lr ($Z = 103$)

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In heavy element region, especially in the seventh row of the periodic table, strong relativistic effects influence the electronic structure even affecting ground-state configurations [1]. The first ionization potential (IP_1), a measure of the energy required to remove one valence electron from a neutral atom, gives information on the valence electronic structure. IP_1 values of heavy actinides beyond einsteinium (Es, $Z = 99$), however, have not been determined experimentally so far due to the difficulty in obtaining these elements produced in nuclear reactions on scales of one atom at a time.

Recently, we conducted measurements of IP_1 values of the heavy actinide elements, lawrencium (Lr, $Z = 103$), nobelium (No, $Z = 102$), mendelevium (Md, $Z = 101$) and fermium (Fm, $Z = 100$) by using a novel method based on a surface ionization process. In a surface ionization process, it has been well known that an ionization efficiency depends on a temperature and a work function of the ionizing surface, and IP_1 of the atom.

The experiments were performed using the ISOL (Isotope Separator On-Line) system at the JAEA tandem accelerator facility. The surface ion-source coupled to a He/CdI₂ gas-jet transport system was installed in the ISOL for a surface ionization of the short-lived heavy actinide isotopes, ^{256}Lr ($T_{1/2} = 27$ s), ^{257}No ($T_{1/2} = 24.5$ s), ^{251}Md ($T_{1/2} = 4.27$ min), and ^{249}Fm ($T_{1/2} = 2.6$ min), which were produced in the $^{249}\text{Cf} + ^{11}\text{B}$, $^{248}\text{Cm} + ^{13}\text{C}$, $^{243}\text{Am} + ^{12}\text{C}$, and $^{243}\text{Am} + ^{11}\text{B}$ reactions, respectively. The surface-ionized and mass-separated ions of the actinide isotopes were collected and measured to determine their ionization efficiencies.

We successfully determined the IP_1 values of the heavy actinides based on the IP_1 dependence of ionization efficiencies. The measured IP_1 value, 4.96 ± 0.08 eV, of Lr is in excellent agreement with the value of 4.963(15) eV predicted by state-of-the-art relativistic calculations [2]. This result strongly suggests that the ground state electronic configuration of the Lr atom is $[\text{Rn}] 5f^{14}7s^27p_{1/2}$ as a result of strong relativistic effects, although that of its lanthanide homologue Lu is $[\text{Xe}] 4f^{14}6s^25d$. Moreover, the IP_1 of Lr is distinctly low among actinide elements.

On the other hand, in contrast to Lr, our experimental results clearly showed that No has the highest IP_1 among them due to its full-filled 5f and 7s orbitals; the IP_1 value increased with an atomic number up to No and decreased dramatically at Lr, indicating the similar trend with that of heavy lanthanide elements [3].

In the presentation, details of the experiments and the results, and further experiments performed at JAEA-ISOL will be given.

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FISSION TIMESCALE OF SUPERHEAVY ELEMENT $Z = 120$

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Nuclear fission is a fundamental decay mode for very heavy atomic nuclei. The formation and survival of superheavy elements is strongly governed by the associated reaction dynamics and, in particular, the fission probability. Traditionally, the nuclear techniques (pre-scission neutrons, charged particles, and γ -ray multiplicities) indicate that the fission process is fast enough with an upper bound in average fission time: $\langle \tau_f \rangle \leq 10^{-19} \text{ s}$ [1]. On the other hand, the atomic techniques (crystal blocking and K X-ray method), lead to scission time scales much longer with a lower bound in $\langle \tau_f \rangle > 10^{-18} \text{ s}$. Recently, the atomic clocks [2] are used to explore the survival of super-heavy element with $Z = 120$.

In the present work, an explicit simulation of large amplitude collective dynamics [3, 4] with particle evaporation is performed to extricate the enduring ambiguities between the atomic and nuclear techniques measurements. The deformation and energy dependent shell-correction is incorporated in ' α ' using the modified Ignatyuk prescription. Simulation is performed for an ensemble of 10^6 Langevin trajectories to generate the results for a single macro-state. Each of these trajectories is allowed a maximum dynamical time of 10^{-15} s in steps of $3 \times 10^{-25} \text{ s}$. For each fission event, we record the average n -evaporation time τ_n , the time τ_{nl} when the last n is evaporated, and the scission time τ_f .

The concept of neutron clock fails at lower excitation energies where the fission process is much slower in agreement with atomic clocks. Moreover, in the present calculation, the $Z = 120$ nucleus is found to survive more than 10^{-18} s at very low excitation energy.

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STUDY OF NEUTRON-DEFICIENT NUCLEI IN THE $^{239,240}\text{Pu}+^{48}\text{Ca}$ REACTIONS

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Three new decay chains of ^{285}Fl were observed in the $3n$ -evaporation channel of the $^{240}\text{Pu} + ^{48}\text{Ca}$ reaction. The irradiation was performed at the Dubna Gas Filled Recoil Separator (DGFRS) and using 250-MeV ^{48}Ca beam accelerated at the U400 cyclotron of the Flerov Laboratory of Nuclear Reactions, JINR during December 2016 and January-February 2017. The decay properties of the observed nuclei are mostly in agreement with a chain identified at the BGS in the $^{242}\text{Pu}(^{48}\text{Ca},5n)$ reaction and three chain previously observed at the DGFRS in the same $^{240}\text{Pu}(^{48}\text{Ca},3n)$ reaction at lower energy of 245 MeV. The lifetime of ^{269}Sg observed in one chain exceeds that derived from other five decays by a factor of 33, which might indicate the observation of transitions through different levels in ^{285}Fl and descendants. The cross section of the reaction was measured to be $0.58^{+0.60}_{-0.33}$ pb, which is lower by a factor of 4-5 than the value measured at 245-MeV ^{48}Ca and is in agreement with expectations for the $3n$ -evaporation channel. The assignment of SF events observed during the irradiation is presented and discussed.

PREPARATORY EXPERIMENTS FOR THE CHEMICAL INVESTIGATION OF NIHONIUM MONOHYDROXIDE

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The chemistry of niobium (Nh, $Z = 113$) was targeted for the very first time using gas-phase thermo chromatography in a behind-the-target approach [1]. The therein observed chemical species was rendered rather volatile, showing a weak interaction with inert surfaces and an enhanced reactivity toward gold surfaces. To further clarify the chemical speciation of the niobium species, these studies were pursued under more inert conditions behind the Dubna Gas-Filled Recoil Separator (DGFRS)[2]. However, out of an expected number of five niobium-related events, none was observed. It was concluded that due to the application of exclusively inert conditions (i.e., highly purified argon carrier gas as well as Teflon surfaces between the production site and the detector), Nh was preserved in its elemental state, showing a higher-than-expected adsorption interaction on Teflon [2,3]. This in turn suggested that indeed NhOH was the most likely species observed in the first attempts [1].

These studies have been continued, aiming in a next step at an unambiguous identification of nihonium monohydroxide (NhOH). A new experiment was developed and tested behind the Separator for Heavy Element Spectroscopy (SHELS) [4] with the lighter homolog of the superheavyelement, i.e., thallium (Tl, $Z = 81$). The results of these investigations as well as the prospects for a next chemistry experiment with nihonium will be presented

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EXPERIMENTAL STUDY OF THE $^{249-251}\text{Cf}+^{48}\text{Ca}$ REACTIONS: TOWARD THE MAGIC NEUTRON NUMBER $N=184$

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Recently several complete-fusion reactions have been studied at the DGFRS setup (FLNR, JINR) with an aim of exploring the boundaries of the "Island of Stability" of the superheavy elements (nuclei around $Z=114-126$ and $N=184$). During the $^{249-251}\text{Cf}+^{48}\text{Ca}$ run with mixed Cf target (50.7% of ^{249}Cf , 12.9% of ^{250}Cf , and 36.4% of ^{251}Cf) just one decay chain was detected at the 252-MeV beam energy which was attributed to the previously observed ^{294}Og isotope, the product of the $^{249}\text{Cf}(^{48}\text{Ca}, 3n)^{294}\text{Og}$ reaction; the corresponding reaction cross section was measured. For the $^{251}\text{Cf}(^{48}\text{Ca}, 3-4n)^{295,296}\text{Og}$ reactions no Og decays were detected during this run. Future possibilities of synthesizing new nuclides in the region of SHEs, as well as of more neutron-rich isotopes of nuclei with $Z=116, 117$ and of neutron-deficient nuclides with higher Z (119 and 120), are discussed.

CLUSTERIZATION AND CRYSTALLIZATION OF COMPLEX NUCLEI

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The review gives the main aspects of the fundamentally new nuclear physics. A new paradigm of nuclear phenomena is substantiated. In it, the composition and structure of complex nuclei are re-examined in a new way, nuclear forces and nuclear interactions are re-introduced in a new way. In addition, the mechanisms of nuclear reactions are considered in a new way and a new topology of nuclear space is proposed.

Theoretical and experimental facts about the clustering of nuclei are discussed and experimental proofs of their real existence are considered. A method for measuring and identifying each type of cluster in one experiment and in one mass spectrum is described.

The sum of the experimental facts in favor of the solid model of the nucleus and the ordering of its structure into a quasi crystalline lattice is generalized. Systematics of the geometric parameters of the nuclei - radii, surface diffusion and shape deformation is given throughout the "Valley of Stability". It is shown that super dense nuclei whose density significantly exceed the mean (normal) density $n_0 = 0,147 \text{ fm}^{-3}$ exist. These are nuclei from ^4He to ^{32}S , while the maximum density (super density) is demonstrated by the ^4He nucleus (α -particle). This suggests two "bricks" of nuclear composition - nucleons and α -particles, and the densest spherical packing's in a binary nuclear system: in fact, the ratio of their radii is theoretically equal to 0.4142. And the ratio of the radii of nucleons and α -particles is exactly equal to $\frac{r_p}{r_\alpha} = \frac{0.7 \text{ fm}}{1.68 \text{ fm}} = 0.417$. And if we follow this theory, then the "Island of stability", we propose to search not at $Z = 114$, but at $Z = 128$.

Facts and generalizations are presented in favor of constructing a new nuclear theory in the basis of the topology of a curvilinear non-Euclidean space. Inside the nucleus volume and in the near-nuclear space, this is a Riemannian space with a geodesic in the form of an ellipse with positive curvature $\kappa > 0$. The closed Riemannian space in the micro world of nuclei is the area inside the "Valley of Stability". On the edges of this valley the Riemannian space opens into a flat Euclidean space with zero curvature $\kappa = 0$. Outside the nucleus, the Riemannian space at the Fermi boundary is rectified. Then the zero curvature undergoes a discontinuity and goes over into the Lobachevski space with negative curvature $\kappa < 0$, and the corresponding instability of the nuclear structure, which serves as the fundamental cause of radioactivity.

NON-MONOTONIC MOLECULAR POTENTIAL FOR $\alpha + {}^{12}\text{C}$ ELASTIC SCATTERING

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An important characteristic feature of the experimental elastic scattering data of α -particles from light nuclei at incident energies up to about 50 MeV is the unusual enhancement of cross-section at large angles, which is commonly known as the anomaly in large angle scattering (ALAS). The traditional Woods-Saxon optical model potential has been found inadequate in describing ALAS in the α -particle elastic scattering. This work reports the analyses of the experimental angular distributions of $\alpha + {}^{12}\text{C}$ elastic scattering in terms of the non-monotonic molecular (NMM) potential which has its root in the energy-density functional theory of Brueckner, Coon and Dabrowski (BCD) [Brueckner *et al.*, *Phys. Rev.* 168 (1968) 1184]. The EDF calculations have been carried out using the available density distribution of α -particles to generate the microscopic non-monotonic α - ${}^{12}\text{C}$ potential. As the raw EDF-generated potentials have been found inadequate to describe the experimental $\alpha + {}^{12}\text{C}$ elastic scattering data, empirical NMM potentials have been employed to fit the data from 18 to 60 MeV incident energies. Two sets of real NMM potentials have been found through the analysis, which are termed as set-1 and set-2 potentials. The closeness of the fits to the data using set-1 with unshifted repulsive core ($D_1 = 0$) and set-2 with shifted repulsive core ($D_1 \neq 0$) suggests that the effect of the potential shape in the central region of the target nucleus is not that significant in determining the angular distribution of cross-sections at low incident energies and the scattering is dominated by the nuclear potential at the nuclear surface. The potentials, found in this study, have volume integrals for the real part $J_R/(4A) = 113.36 \text{ MeV}\cdot\text{fm}^3$ with $D_1 \neq 0$, and $J_R/(4A) = 105.13 \text{ MeV}\cdot\text{fm}^3$ with $D_1 = 0$. The volume integrals with magnitudes in this range are normally expected for non-monotonic molecular potentials. The energy dependence of the imaginary volume integral $J_I/(4A)$ has also been studied.

HIGH SPIN γ -RAY SPECTROSCOPY OF HEAVY, OCTUPOLE DEFORMED Ac AND Fr NUCLEI PRODUCED IN FUSION-EVAPORATION REACTIONS WITH THE INTENSE A~90 RADIOACTIVE BEAMS

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The most intensive radioactive beams available at the future facilities as for example SPES at LNL, having masses around $A=90$, may reach intensities exceeding 10^{10} particles per second, what corresponds to the minimum current required for γ -spectroscopy experiments using fusion-evaporation reactions. At energies of about 400 MeV, when colliding with a thin ^{130}Te target such neutron rich $^{90-94}\text{Rb}$ projectiles will induce fusion-evaporation reactions leading to the octupole deformed isotopes of actinium (n evaporation channels) and francium (α n evaporation channels). The expected cross section for fusion-evaporation reaction is of the order of 100 mb, although it will be accompanied by the dominant fusion-fission process.

The nuclei of interest have been investigated so far only through reactions of fusion of light neutron-rich beams of oxygen and carbon with lead or bismuth targets. Use of the above mentioned more symmetric reactions will increase significantly the range of the angular momentum available in the residual nuclei and may shed new light onto the evolution of the known in this region alternative parity bands, towards the fission limit at higher spins. Analysis of quasi-continuum, combined with the discrete γ -spectroscopy, will allow to obtain a comprehensive picture of the evolution of shapes and collectivity in the actinides.

It is considered to use efficient γ -ray spectrometers as AGATA and PARIS, combined with the Recoil Filter Detector (RFD) which measures the velocity vector of evaporation residues. The RFD will be used to suppress the background γ -rays from the fission reactions and to perform event by event Doppler correction, as the recoil velocity may exceed 4% of the light speed. Moreover, application of RFD will enable lifetime measurements based on intensity analysis of γ -transitions emitted promptly inside the target.

A successful measurement of this type will open a perspective of using RIB investigations of exotic nuclei populated in fusion-evaporation reactions at high spins.

BETA DECAY PROBABILITY OF A PROTON ON A CLASSICAL RUTHERFORD TRAJECTORY

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At a previous edition of the EXON Conferences it was shown that in the strong field of a high Z nucleus, the acquired potential energy of proton moving in this field makes the energy balance necessary for its beta decay positive for a very short time interval. On the other side, the increase of the Q value for the decay significantly diminishes the lifetime (proportional to Q^{-5}). On that occasion, a rough evaluation for the decay probability along the trajectory was done. This time, the evaluation is quite precise for the movement on a classical Rutherford trajectory and integrated over the range of relevant impact parameters. Surprisingly, this evaluation is not very far from the first one. Though the value obtained is very small (as expected otherwise for a weak interaction process), it still can be tried experimentally, as different irradiation segments can be combined.

Even more interesting from the experimental point of view is the using of the intense, high energy gamma source of ELI-NP to create the required conditions.

If successful, this can be the first experimental approach to reproduce in the laboratory the original nucleosynthesis reaction in the Sun in which two protons fuse to give deuterium, neutrino and positron.

BETA-DECAY AND DELAYED MULTI-NEUTRON EMISSION IN VERY NEUTRON-RICH ISOTOPES

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Performance is analyzed of self-consistent models of nuclear beta decay which are based on the different energy-density functional. Considered are the continuum quasiparticle random phase approximation DF+CQRPA [1], interacting shell-model [2], relativistic QRPA [3] and Finite Amplitude Method [4]. These frameworks include the allowed Gamow–Teller and first-forbidden beta decays. The recent “beyond the QRPA” models [5,6] are also critically analyzed. The beta-decay energy release, half-lives and delayed multi- neutron emission branching obtained in these models are compared for the “reference” Ni and Sn and Au isotopic chains near the major neutron shells-closures at $N=50, 82, 126$. Also the K, Ca, Sc isotopes near the new neutron sub-shells at $N=32, 34$ are discussed. An emphasis is made on the share of the first-forbidden decays in the total rates, as well as on consistency of the results with available experimental decay schemes. A special attention is payed to possible constraints imposed on the strength of quasiparticle-phonon coupling by the beta decay properties.

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EXPLORING COLLECTIVITY IN ^{167}Lu VIA LIFETIME MEASUREMENTS

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Neutron deficient Lu nuclei with mass $A \sim 165$ present normal deformed prolate shape [1] near ground state but assume strongly deformed triaxial shapes (TSD) [2] with or without wobbling character [3] at high spins ($I \geq 25 \hbar$). For Lu nuclei with $A > 167$, highly deformation driving $1/2^-$ [541] orbital forms the yrast band. These nuclei are observed as most rigid among all Lu isotopes with respect to changes in triaxiality. Interestingly, beyond ^{167}Lu [4], no other higher mass Lu nuclei has shown any TSD band or wobbling band at high excitation. This further complicates the issue of the origin of triaxiality. Experimentally, information about triaxiality in the nucleus can be obtained either by observing decoupled bands and evaluating their signature splitting [5, 6] or by measuring the quadrupole moment of the band as done in ^{165}Lu [5]. However, the signature splitting can be due to K-mixing [5, 7] in axially deformed nuclei also. In the present work, the quadrupole moment (Q_t) of the yrast band in ^{167}Lu is measured with RDM lifetime measurement technique. To draw conclusion about triaxiality, the Q_t values have been compared with values extracted using equilibrium (β_2, γ) parameters obtained from the TRS calculations.

The experiment was done with the 15 UD Pelletron accelerator facility available at the Inter University Accelerator Center (IUAC), New Delhi. High spin states in ^{167}Lu were populated via $^{159}\text{Tb}(^{12}\text{C}, ^4\text{n})$ reaction at a beam energy of $E_{\text{lab}} = 74 \text{ MeV}$. The target was a self-supporting ^{159}Tb foil of thickness $\sim 1.2 \text{ mg/cm}^2$ and stopper, a thick self-supporting gold foil of thickness $\sim 8 \text{ mg/cm}^2$. In the experiment, the data was taken from 10- 2000 μm in 15 unequal steps. The de-excited γ -rays, were detected with the Gamma Detector Array (GDA) setup available at IUAC. The data was recorded in the singles mode with the condition that at least two BGO crystals should fire ($M \geq 2$) in coincidence with one HPGe detector.

The results of the measurement are very encouraging. The almost constant nature of extracted $B(E2)$ values reflects the stability of deformed structure of ^{167}Lu in the yrast configuration. Theoretical Q_t values extracted using (β_2, γ) values obtained through total routhian surfaces (TRS) calculations, agree at low spins but tend to differ from experimental Q_t values at higher spins suggesting a small involvement of triaxiality in ^{167}Lu . The detailed analysis of the results will be discussed during the presentation.

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EMISSION OF HIGH ENERGY PARTICLES IN HEAVY ION COLLISIONS IN HYDRODYNAMIC APPROACH

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To describe the collisions of heavy ions and to find the equation of state of a nuclear matter, it is natural to choose the hydrodynamic approach (see, for example, [1]). The dynamics of heavy ion collisions involves the use of a non-equilibrium equation of state [2, 3, 4] taking into account the effects of nuclear viscosity. This allowed describing energy spectra of protons, pions, and fragments for the collisions of different nuclei at the medium-energy range [3, 4, 5, 6]. However, "high-energy tails" of proton spectra obtained in [7], as it turned out, are not reproduced near the kinematic limit of the spectrum when the cross section decreases by 5 orders of magnitude. They turn out more hardened when we use a grand canonical ensemble for the distribution function of emitted protons. In this paper, we succeeded to introduce an amendment with account of the micro canonical distribution in the high-energy part of the spectrum to reproduce experimental data [7] in reaction $^{16}\text{O} + ^{27}\text{Al} \rightarrow p + X$ at the ^{16}O ion energy of 207 and 310 MeV at the angle of 30° without breaking the agreement with other data.

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UNUSUAL STRUCTURES IN ^{163}Gd , STRUCTURE OF ^{163}Tb ; CONFIRMATION OF HIGH NEUTRON YIELDS FOR Ba-Mo SF OF ^{252}Cf , FUTURE PLANS

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The level structures of ^{163}Gd , and ^{163}Tb have been investigated via β -decay of ^{163}Eu with LeRIBSS, low energy radioactive ion beam spectroscopy station, at ORNL. A UCx target was bombarded with ≈ 50 MeV protons to induce fission. The detector station to study the beta decay of mass separated ^{163}Eu had four Clover HPGe detectors for γ -rays and two plastic scintillators for β detection. Gamma rays belonging to $^{163,165}\text{Gd}$ and ^{163}Tb were identified by mass selection and γ - γ - β and γ - γ coincidences. The 71 new γ transitions observed in ^{163}Gd yielded unusual level structures with several high energy levels having transitions near 50 keV and transitions up to 2 MeV depopulating the same levels. Such structures have not been seen before and call for further experiments and theoretical work. Eleven new γ -rays were observed in ^{163}Tb .

The neutron multiplicity yields of Ba – Mo, Ce – Zr and Nd – Sr have been studied with improved precision by using γ - γ - γ - γ as well as γ - γ - γ data and the latest level structures of these nuclei. The results clearly confirm that the Ba – Mo yield data have a hot fission mode where 8, 9, and 10 neutron evaporation channels are observed which are not in the other channels. This mode can indicate ^{144}Ba is likely hyper deformed at scission to give rise to such high neutron multiplications.

A new experiment is being planned to do fission fragment- γ - γ coincidence studies to investigate details of the fission process and to study new more neutron-rich nuclei.

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STRUCTURE OF β -DECAY STRENGTH FUNCTION $S_\beta(E)$ AND WIGNER SPIN-ISOSPIN SU(4) SYMMETRY

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The strength function $S_\beta(E)$ governs [1] the nuclear energy distribution of elementary charge-exchange excitations and their combinations like proton particle (πp)-neutron hole (νh) coupled into a spin-parity I^π : $[\pi p \otimes \nu h]_I^\pi$ and neutron particle (νp)-proton hole (πh) coupled into a spin-parity I^π : $[\nu p \otimes \pi h]_I^\pi$. The strength function of Fermi-type β -transitions takes into account excitations $[\pi p \otimes \nu h]_0^+$ or $[\nu p \otimes \pi h]_0^+$. Since isospin is a quite good quantum number, the strength of the Fermi-type transitions is concentrated in the region of the isobar-analogue resonance (IAR). The strength function for β -transitions of the Gamow-Teller (GT) type describes excitations $[\pi p \otimes \nu h]_1^+$ or $[\nu p \otimes \pi h]_1^+$. Residual interaction can cause collectivization of these configurations and occurrence of resonances in $S_\beta(E)$. In heavy and middle nuclei, because of repulsive character of the spin-isospin residual interaction [1], the energy of GT resonance is larger than the energy of IAR ($E_{GT} > E_{IAR}$). One of the consequence of the Wigner spin-isospin SU(4) symmetry is $E_{GT} = E_{IAR}$. SU(4) symmetry-restoration [2] effect induced by the residual interaction, which displaces the GT towards the IAR with [1] increasing $(N-Z)/A$. In tango halo [3] nucleus ${}^6\text{Li}$ (g.s.) for low energy GT phonon (GT strength $B(\text{GT}) \approx 5g_A^2/4\pi$ ($\Sigma(\text{Ikeda sum rule}) = 6g_A^2/4\pi$) we have $E_{GT} < E_{IAR}$, $E_{GT} - E_{IAR} = -3562.88$ keV, and $(N-Z)/A = 0.33$ for ${}^6\text{He}$ (${}^6\text{He}$ g.s. is the parent state). Such situation may be connected with contribution of the attractive [4] component of residual interaction in this nucleus. It will be very interesting to find a region of atomic nuclei, where the $E_{GT} \approx E_{IAR}$ and spin-isospin SU(4) symmetry determine the nuclear properties (SU(4) region). From simple estimation (Fig.1) value $Z/N \approx 0.6$ corresponds to the SU(4) region. Different manifestations of the SU(4) symmetry are discussed.

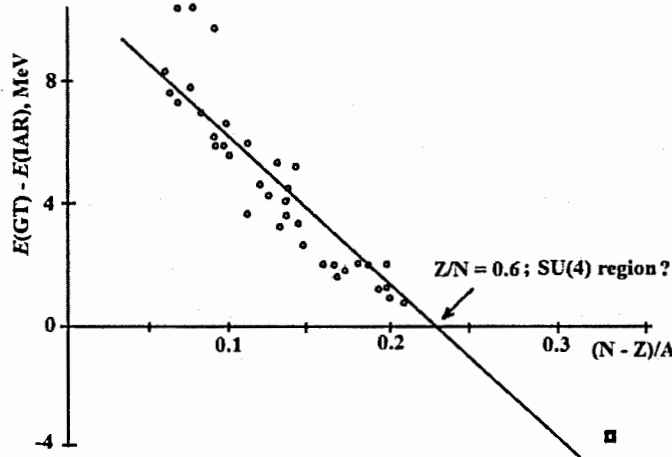


Fig.1. Difference of the $E_{GT} - E_{IAR}$ energies (circles) as a function of the neutron excess [1]. Datum for ${}^6\text{He}$ β^- - decay was added (square).

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INVESTIGATION OF INTERACTION OF DEUTERONS WITH ^{13}C NUCLEI

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The success of the diffraction mechanism with strong absorption in explaining the elastic and inelastic scattering of alpha-particles stimulated a new interest in the mechanism of both elastic and inelastic scattering of deuterons on light nuclei. Since the structure of the alpha particle is strongly coupled, while the deuteron is weakly bound, the question remains whether diffraction with strong absorption in the scattering of deuterons plays an equally important role, especially in the case of light nuclei.

In recent years, the scattering of deuterons by the nuclei of carbon isotopes was investigated at intermediate energies from 4 to 17 MeV. Analysis of the $^{12}\text{C}(d,d)^{12}\text{C}$ reaction data in the energy range 9-14 MeV [1,2] with a simple potential, established the applicability of the optical model for light nuclei. Literature data on the elastic scattering of deuterons on ^{13}C nuclei are not so many, there are several works where the energy of deuterons is in the region of 13.7-17 MeV [3,4].

This work is devoted to the experimental and theoretical investigation of elastic and inelastic processes of scattering of deuterons with ^{13}C nuclei by measuring the differential cross sections of these processes and their further analysis.

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STUDY OF THE EFFECT OF POSITIVE Q -VALUE NEUTRON TRANSFERS ON NEAR-BARRIER FUSION OF HEAVY IONS

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Tunnelling and coupling are two critical aspects in heavy-ion nuclear reactions at near-Coulomb barrier energies. In near-barrier fusion reactions with heavy-ions, the coupling effect of the positive Q -value neutron transfers (PQNT) is still a complicated and unsolved problem. For studying this effect, the fusion excitation functions of some typical systems were measured by using an electrostatic deflector setup at CIAE. In this presentation, the recent experimental results measured at CIAE will be reviewed, with special emphasis on the effect of the positive Q -value neutron stripping channels, and some discussions for this effect will be given also.

Additionally, considering the current inconsistent experimental data and theoretical analysis, the concept of residual enhancement that mainly aims for reducing the additional uncertainties was proposed to extract a reliable quantitative PQNT effect. More details will be given in this presentation.

ADDITIONAL ARGUMENTS IN FAVOR OF TRUE QUATERNARY FISSION OF LOW EXCITED ACTINIDES

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In our previous publications [1,2] we discussed possible physical scenario standing behind rectangular-like structures in the fission fragments mass-correlation distributions from ^{252}Cf (sf) and ^{235}U (n_{th} , f). The rectangle is bounded by the known magic nuclei such as ^{68}Ni , ^{84}Se and others. The fission events aggregated in the rectangle show extremely low total kinetic energies. Previously only decay mode with two Ni clusters in the exit channel was discussed. A more complete analysis will be presented which gives additional arguments in favor of true quaternary fission of ^{252}Cf and $^{236}\text{U}^*$ nuclei.

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REACTIONS WITH EXOTIC NUCLEI AT ENERGIES AROUND THE COULOMB BARRIER

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Recent experimental research on the reactions with exotic nuclei at energies around the Coulomb barrier will be presented in the symposium, including the following two topics:

1) Optical model potentials (OMPs) of exotic nuclear systems. Due to the limitation of intensity and quality of radioactive ion beam (RIB), it is rather difficult to extract the OMPs of exotic nuclear systems by the elastic scattering. For this reason, a transfer reaction method was proposed and applied to extract the OMPs of ${}^6\text{He}+{}^{12}\text{C}$, ${}^{64}\text{Zn}$, ${}^{209}\text{Bi}$ systems via ${}^{11}\text{B}$, ${}^{63}\text{Cu}$, ${}^{208}\text{Pb}({}^7\text{Li}, {}^6\text{He})$ reactions. The complete picture of threshold anomaly behavior has been obtained in the ${}^6\text{He}+{}^{209}\text{Bi}$ system for the first time [1]. Results show that the dispersion relation is not applicable for the exotic nuclear systems. Possible reasons are discussed; however, further study is strongly required to discover the underlying physics.

2) Reaction mechanism of weakly-bound nuclear systems. An important task is to understand the breakup effects as well as its mechanism. To this end, a complete-kinematics measurement method was developed and applied in the ${}^{17}\text{F}+{}^{58}\text{Ni}$, ${}^{208}\text{Pb}$ experiment. The processes of elastic scattering, breakup/transfer, and fusion evaporation have been identified successfully. Preliminary results of ${}^{17}\text{F}+{}^{58}\text{Ni}$ show that the fusion is suppressed at above-barrier energies due to the loss of incident flux while enhanced at below-barrier energies due to couplings to the continuum states. Detailed theoretical analyses are still in progress.

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SPECTROSCOPY OF $^{63,65,67}\text{Mn}$: STRONG COUPLING IN THE $N=40$ ISLAND OF INVERSION AND IMPROVED CONSTRAINTS FOR URCA COOLING IN THE ACCRETED NEUTRON STAR CRUST

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Excited states in $^{63,65,67}\text{Mn}$ were studied via in-beam γ -ray spectroscopy following knockout reactions from ^{68}Fe . Similar level schemes, consisting of the $11/2^-$, $9/2^-$, $7/2^-$ and $5/2^-$ gs level sequence, connected by $I \rightarrow (I-1)$ transitions, were established, the first time for $^{65,67}\text{Mn}$. Their level structures show features consistent with strongly-coupled rotational bands with $K = 5/2$. State-of-the-art shell-model calculations with the modified LNPS effective interaction reproduce the observed levels remarkably well and suggest the dominance of 4-particle-4-hole neutron configurations for all the states. The data on the low-lying excited states of odd-mass $^{53-67}\text{Mn}$ provide a textbook example of nuclear structure evolution from weak coupling through decoupling to strong coupling along a single isotopic chain on the n-rich side of the β stability line. The results show an enhancement of Urca neutrino cooling in the accreted neutron star crust associated with $A = 63$ nuclei and rule-out significant cooling from $A = 65, 67$. This improves constraints that can be made on past surface nuclear burning on accreting neutron stars with observed quiescent cooling light curves.

SHORT-RANGE (PAIRING) VERSUS LONG-RANGE (COLLECTIVE) CORRELATIONS IN TWO-NEUTRON TRANSFER REACTIONS INDUCED BY ^{18}O

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It is shown that the pairing correlation is very important for the elastic two-neutron transfer reactions, for reaction induced by 84 MeV ^{18}O on several targets with low collectivity in its ground state (spherical), proceeding through the one-step process. For the transition to lower excited states, the one-step process also dominated, for the final nuclei having low collectivity. On the contrary, if the collectivity of these states is considerable, the two-neutron transfer reaction is dominated by a two-step process through an intermediate partition.

ISOBARIC RESONANCES IN CHARGE-EXCHANGE REACTIONS

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The isobaric charge-exchange resonant states are connected with the charged branch of excitations and corresponds to excited states of isobaric nuclei $A(N-\Delta Q, Z+\Delta Q)$ with charge $\Delta Q = \pm 1$. They manifested in the corresponding charge-exchange reactions, for example (ν, e) , (p, n) , (n, p) , $(^3\text{He}, t)$, $(t, ^3\text{He})$, $(^6\text{Li}, ^6\text{He})$ etc., or in β -transitions of nuclei and β -delayed processes. These resonant states are collective isobaric excitations and they are of the most interest. The theoretical investigation of these collective states began with the first calculations of the giant Gamow-Teller resonance (GTR) [1] and other collective states [2], long time before their experimental studies in the charge-exchange reactions with $\Delta Q = +1$ [3, 4]. Below the GTR is lying the isobaric analog resonance (AR), and even lower, the so-called, pigmy resonances (PR) [5], which are important in the charge-exchange reactions [6, 7] and β -delayed process [8].

The energies and matrix elements of the excited resonant states that determine the structure of the charge-exchange strength function $S(E)$ were calculated both in the self-consistent theory of finite Fermi-systems (TFFS), and in its approximate model version. The energy differences between the GTR and AR $-\Delta E_{G-A}$ were calculated and it is shown that the value of ΔE_{G-A} tends to zero in heavier nuclei, demonstrating the restoration of Wigner SU(4)-symmetry [9]. Using the same method the energies of GTR and pigmy resonances for nine tin isotopes were calculated [5]. Comparison of the calculations with the experimental data on the energies of charge-exchange resonances gives the standard deviation $\delta E < 0.50$ MeV, which is comparable with experimental errors. A comparison of the calculated and experimental strength functions $S(E)$ also shows their similarity both in energies and in matrix elements. The influence of charge-exchange resonances on the process of neutrino capture by nuclei is also investigated [7] and it is shown that taking these resonances into account is of fundamental importance. For example, not taking into account only the GTR, the cross section of the back beta-decay reaction in ^{71}Ga , ^{74}Ge , ^{98}Mo and ^{127}I is reduced by 25% and more at the neutrino energies 5 MeV and more [7]. Pigmy resonances also have a significant influence on the neutrino capturing cross section. These effects were not taken into account in previous calculations, for example in [10].

Further investigation of the resonant structure of the strength functions $S(E)$ will allow us to analyze the data of the charge-exchange reactions and β -delayed processes. So the appearance of PR in the energy window of the emission of β -delayed neutrons (DN) leads to a sharp increase in the probability of this DN process [8]. Similarly for the β -delayed fission process [11].

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MEASUREMENT OF MASS-GATED NEUTRON MULTIPLICITY FOR $^{192,202}\text{Po}$ NUCLEI USING NAND FACILITY

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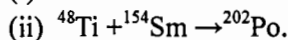
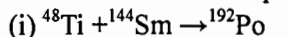
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The prevalent reaction mechanism for nuclear reactions induced between heavy ions is not only fusion-fission (FF), but a fast, out of equilibrium process called quasi-fission (QF) [1]. For understanding the reaction mechanism of heavy ion induced FF reactions, our aim is to measure neutron multiplicity and mass-energy correlation three systems:



For the system $^{18}\text{O} + ^{192}\text{Os} \rightarrow ^{210}\text{Po}$, experimental data exists for neutron multiplicity, evaporation residue (ER) cross-section and fission excitation function [2]. The chosen systems span the neutron deficient ^{192}Po (N=108) to neutron rich ^{210}Po (N=126) nuclei. For systems with heavier projectile, sizable contribution from QF process is expected. Also, ^{144}Sm is nearly spherical ($\beta=0.088$) and ^{154}Sm is deformed ($\beta=0.27$) nuclei. We planned to do consistent analysis of Po (N=108 to 126) nuclei to study the role of shell effects in fission dynamics. With this motivation, we have measured pre-scission neutron multiplicities the extracted mass-distribution from two compound nuclei, namely $^{192,202}\text{Po}$ populated by $^{48}\text{Ti} + ^{144,154}\text{Sm}$ systems at 260 and 230 MeV of laboratory energy using National Array of Neutron Detectors (NAND) facility at IUAC, New Delhi. This experiment was performed using 15 UD Pelletron + LINAC facility. Fission fragments were detected by a pair of multi-wire proportional counters (MWPCs) (6.4" $\times$ 4.4") kept at fission fragment folding angle of $\pm 60^\circ$. Two silicon PIPS detectors were also placed inside the chamber at $\pm 13.5^\circ$ w.r.t to beam direction for beam monitoring purpose. The neutrons emitted were detected by an array of 100 organic liquid scintillators (BC501A) [3]. The pre- and post-scission components of neutron multiplicities are obtained from the measured neutron energy spectra by using a multiple source least-square fitting procedure, using the Watt expression [4]. Further, statistical model calculations were performed for these systems using Bohr Wheeler as well as Kramer's formalism [5]. The disagreement of the statistical model results with the experimental values even at higher value of dissipation strength (β) may points towards the presence of QF and fast-fission.

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ORIGIN OF DRAMATIC CHANGE OF FISSION MODE IN FERMIUM ISOTOPES INVESTIGATED USING LANGEVIN EQUATION

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Understanding of the nuclear fission process is a great interest on development of nuclear physics and industry. Owing to the complex nature of the fission process, many phenomena have not yet been elucidated, even though almost 80 years have passed since its discovery [1,2]. One of the biggest challenges is to clarify the dramatic change of fission fragment mass distributions (FFMDs) in fermium (atomic number $Z=100$) region. In contrast to the mass asymmetric fission for typical actinide nuclides, a sharp mass-symmetric FFMD emerges in neutron-rich heavy actinides [3] following the addition of just one extra neutron, e.g. from mass asymmetric fission of ^{257}Fm to sharp-symmetric fission of ^{258}Fm . Long-standing challenges to elucidate this isotope dependence of fermium are to unveil different pathways on the potential energy surface leading to different scission configurations and to explain the mechanism causing such a sudden change of fission path.

In this work, we performed theoretical calculation to challenge the unsolved problem of fermium fissions using a fluctuation dissipation model (Langevin calculation) [4-11]. The key role feature of this semi-classical stochastic model is that the dynamics of fission process with each time evolution generated in an event-by-event basis, by tracking trajectories of a system moving on the potential energy surface.

We studied the fission of even-even fermium nuclides $^{250-260}\text{Fm}$ at low excitation energy using Langevin equations of three-dimensional nuclear shape-parameterization. The calculated results fission fragment mass and total kinetic energy distributions show a dramatic change from asymmetric shape for the lighter fermium isotopes to sharp symmetric shape for the heavier isotopes [11].

We have theoretically demonstrated this dramatic change of fermium fissions for the first time. And we discovered that the sudden change of the fission mode between lighter and heavier fermium isotopes is strongly regulated by the structure of the second fission barrier height and the dynamical motion of the nucleus.

Our finding contains an important message for super-heavy element research and astrophysical nucleosynthesis.

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HEAVY-ION REACTION AND FISSION STUDIES AT JAEA TANDEM ACCELERATOR FACILITY

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This talk will discuss the heavy-ion reaction and fission studies at the JAEA tandem accelerator facility. Heavy-ion fusion reactions have been studied to understand the mechanism for the synthesis of super-heavy elements, where effects of static deformation of the target nucleus ^{238}U were investigated in the reactions using various projectile nuclei [1-3].

Recently, we are promoting a program of fission/reaction studies in multi-nucleon transfer reactions [4]. This approach allows us to investigate fission of neutron-rich nuclei, which cannot be populated by particle capture reactions. From the measurement of fission fragment mass distributions (FFMDs) for various nuclides and their evolution with initial excitation energy, role of multi-chance fission on FFMD was investigated [5]. The obtained data set was used to improve the Langevin model to describe low-energy fission [6], which derives a clear explanation of the transition from the mass-asymmetric fission to the sharp symmetric fission observed in fermium isotopes.

In addition to FFMDs, prompt neutrons have been measured in correlation with fission fragments for the fission and reaction studies.

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LIGHT CLUSTERS IN SUPERNOVA MATTER

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Equation of state (EoS) - is the important component of supernova modeling. In first theoretical models of Supernovae the very simple equation of states were used: the matter was considered as the ideal gas of neutron, protons, alpha-particles and ^{56}Fe , with taking into account electron-positron pairs birth and black-body radiation [1]. Later this approach was modified – instead of one definite nucleus (Fe), the “effective” nucleus is considered, which represent all chemical composition. Parameters of this nucleus (mass number A, atomic number Z, etc.) are defined from the minimization of full system energy. This approach became very popular, starting from EoS by Lattimer and Swesty [2] and applied widely in astrophysics up to now. Since that a lot of different equations of state there were proposed, but all of them in the region of light nuclei considered only alpha-particles.

The most advanced equation of state, taking into account the light nuclei, was developed on the basis of quantum statistical model [3]. It was also shown that besides alpha-particles, deuterons, tritons and neutron-rich helium isotopes are strongly abundant under conditions, typical for supernova matter [4]. Together with light neutron-rich nuclei for astrophysical applications light neutron clusters [7], which can change the abundance of other light nuclei and properties EoS as a whole, can be important either.

In the paper the importance of light clusters consideration under EoS computation for supernova matter [5,6] was investigated. The calculations of isotope composition for thermo dynamical conditions in collapsing matter of stellar core were done. In these calculations besides already known and considered light clusters, dineutrons and tetra neutrons as well as ^4H , were taking into account first. As it was turned out their part in matter under subnuclear density may be significant. On the basis of calculations have been done for the wide range of dineutron and tetra neutron binding energy values it was shown that light neutron clusters also should be included in the equation of state together with already included light charged clusters (like neutron-rich helium and hydrogen isotopes). Calculation results were verified during forecast comparison of three different equation of states [8, 6 and cited there in], in which different nuclear input was used. The consequences of EoS composition expansion for the supernova explosions are discussed.

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FISSION FRAGMENT DISTRIBUTION AND THE R-PROCESS

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The first registration of neutron stars merger process and simultaneous registration of the r-elements [1] have confirmed theoretical predictions that the main scenario of the r-process nucleosynthesis should be connected with the jets appeared during neutron stars merger in close binaries but not the supernova explosion [2].

As it was shown for the first time in numerical calculations of the r-process nucleosynthesis [3] in neutron star merger scenario, fission in such a scenario of the main r-process leads to formation of heavy r-elements from the second peak at abundance curve till uranium and thorium and results in arbitrary the same abundance of heavy elements for all different mergers of neutron stars where the quasi-equilibrium between 2nd and 3^d peaks exists.

In the present report we discuss the influence of fission mass distribution model on the final abundance of heavy elements in the jet matter, ejected during neutron star merger [1]. Different models of exotic nuclei fission fragment distribution [4] were applied to the r-process, calculated for the one of the scenario of neutron star mergers [5], where the significant influence of fission fragment distribution model applied on the abundance of heavy nuclei was shown. The family of different fission distribution models and their application to the r-process models were considered with the aim to understand of the main reason leading to different abundances when the different fission fragments distribution models were used. It was shown that fission fragment distribution model, when fission cycling number $n_c = \ln(\sum Y_i^0 / \sum Y_i^f) > 1$, does not influent on the r-process results significantly. And when $n_c < 1$ the final heavy nuclei abundance depend on the fission fragment distribution model. We considered either the influence of possible strengthening of true ternary fission on the final distribution of heavy nuclei formed in the r-process [6].

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PROBLEM OF THE 2p-CAPTURE IN ASTROPHYSICS

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Proton capture reactions play an important role in a nucleosynthesis process, especially in explosive nucleosynthesis as in X-ray burst [1]. The X-ray binary system (Red Giant – Neutron Star) is characterized by a repeated sudden increase of X-ray emission, which is a consequence of a thermonuclear explosion in the atmosphere of an accreting neutron star. At high temperature and density conditions, the freshly accreted hydrogen and helium ignite. But the slow CNO cycles can be broken out, and the rapid proton capture (rp) process, which is a sequence of proton captures and β^+ decays and responds for the production of proton-rich isotopes up to mass 100 region, is initiated. The trigger conditions for the burst depend on the efficiency of the breakout reactions from the hot CNO cycle [2].

The breakout reactions are still under discussion. At the beginning, only α -capture reactions on the waiting-points nuclei of the CNO cycles ($^{15}\text{O}(\alpha,\gamma)^{19}\text{Ne}$ and $^{18}\text{Ne}(\alpha,p)^{21}\text{Na}$) have been taken into account [2-4]. However, at present, the alternative two-proton capture reactions ($^{15}\text{O}(2p,)^{17}\text{Ne}$ and $^{18}\text{Ne}(2p,)^{20}\text{Mg}$) are also considered [5, 6]. In theoretical predictions, the direct three-particle capture process enhances the reaction rate by a few orders of magnitude [6] compared with a sequential [5].

Almost all of the nuclear reactions relevant to solar energy generation are nonresonant and charged-particle induced. For such reactions it is helpful to remove much of the rapid energy dependence associated with the Coulomb barrier, by evaluating the probability of s-wave scattering off a point charge. The nuclear physics (including effects of finite nuclear size, higher partial waves, antisymmetrization, and any atomic screening effects not otherwise explicitly treated) is then isolated in the S-factor, defined by the Sommerfeld parameter. Since the S-factor is slowly varying, one can extrapolate $S(E)$ more reliably from the range of energies spanned by data to the lower energies characterizing the Gamow peak.

In present work we have found the energy dependence of the astrophysical factor for the 2p-capture. The analysis is performed in the model of PWIA type [7] based on the Green function method and hyperspherical harmonics method.

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MANIFESTATIONS OF PEAR-SHAPED CLUSTERS IN COLLINEAR CLUSTER TRI-PARTITION OF ^{252}Cf

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The bulk of our experiments of recent years were dedicated to study of new multibody at least ternary decay channel of low excited heavy nuclei [1, 2]. Due to specific features of the effect, it was called collinear cluster tri-partition (CCT). Now we have an entire collection of different CCT manifestations, observed through the linear structures in the mass correlation distributions of the decay products. Some of the structures look like the strait lines satisfying the condition $M_1 + M_2 = \text{const}$, where M_1 and M_2 are the fission fragments (FFs) detected in coincidence, while their total mass is less than the mass of the fissioning nucleus. The energies and nucleon compositions of the FFs involved let us to suppose that a preformation of the heavy pear-shaped clusters in the body of the mother system give rise to the structures under analysis. The clusters are the deformed nuclei with magic number of neutrons around $N = 134$ [3].

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COLLISIONS OF STATICALLY DEFORMED NUCLEI WITHIN A DYNAMICAL MODEL BASED ON LANGEVIN EQUATIONS

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The multinucleon transfer processes in collisions of heavy ions is a promising way to produce the neutron-enriched nuclei hardly reachable by other methods (like fusion or fragmentation reactions). Synthesis and properties of these exotic nuclei are of particular interest for understanding the astrophysical r-process.

The multidimensional dynamical approach based on Langevin equations is a powerful tool for theoretical analysis of processes taking place in collisions of heavy ions. A rather well description of collisions of heavy nuclei that spherical in the ground states was achieved in [1] within this approach.

The collisions with nuclei that deformed in their ground states are analyzed in the present work. In this case the orientation of deformed colliding nuclei was taken into consideration in the dynamical calculations that based on the developed model. Initial mutual orientation of colliding nuclei influences the distributions of reaction products at near-barrier energies. These orientation effects are continuously disappeared with increasing the collision energy. Particularly, they have to be taken into account in calculation of possibility to produce neutron-enriched isotopes of heavy and super heavy elements in collisions of actinides.

The different distributions of fragments calculated for the $^{160}\text{Gd} + ^{186}\text{W}$, $^{154}\text{Sm} + ^{154}\text{Sm}$, $^{238}\text{U} + ^{238}\text{U}/^{248}\text{Cm}$ reactions are in agreement with the available experimental data.

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STUDY OF NUCLEON TRANSFER IN REACTIONS $^3\text{He} + ^{197}\text{Au}, ^{194}\text{Pt}, ^{45}\text{Sc}, ^{59}\text{Co}$ WITHIN TIME-DEPENDENT APPROACH

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Theoretical description of the experimental data on the formation of various isotopes in reactions $^3\text{He} + ^{197}\text{Au}$, $^3\text{He} + ^{194}\text{Pt}$ [1], $^3\text{He} + ^{45}\text{Sc}$ [2], and $^3\text{He} + ^{59}\text{Co}$ [3] requires taking into account neutron and proton transfer channels, as well as fusion-evaporation channels. To calculate the probabilities of nucleon transfer as well as transfer cross sections the time-dependent Schrödinger equation (TDSE) [4–6] has been solved numerically. Fusion-evaporation was taken into account using the statistical model code of the NRV web knowledge base [7]. Results of calculations are in agreement with experimental data. An example of the evolution of probability density for the proton of ^3He nucleus in the collision with ^{45}Sc at $E_{\text{cm}} = 10$ MeV and impact parameter $b = 5$ fm is shown in Figure 1.

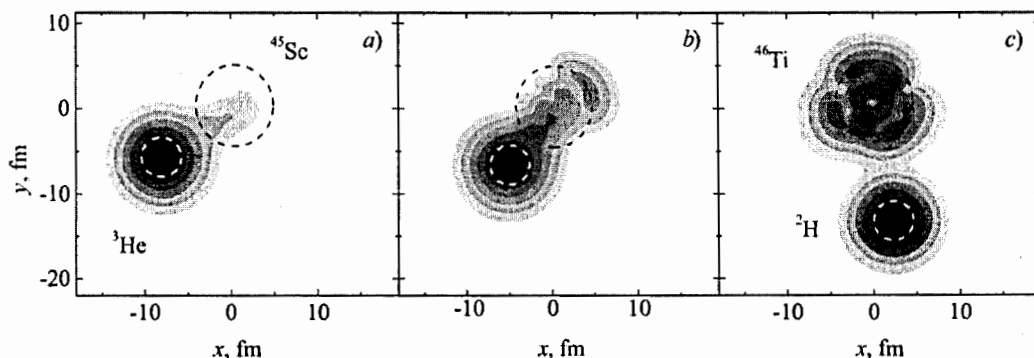


Figure 1. An example of the time evolution of the probability density for the proton of ^3He nucleus in the collision with ^{45}Sc at $E_{\text{cm}} = 10$ MeV and impact parameter $b = 5$ fm. The radii of circumferences equal the effective radii of nuclei. The course of time corresponds to the panel locations (a, b, c)

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TWO-PHONON STRUCTURES OF BETA-DECAY RATES

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The β -decay properties are very important for understanding the nuclear structure evolution at extreme N/Z ratios, for analysis of radioactive ion-beam experiments, and modelling of the astrophysical r -process. For this reason, the β -decay properties of r -process “waiting-point nuclei” ^{129}Ag , ^{130}Cd , and ^{131}In provides valuable information, with important tests of theoretical calculations. One of the successful tools for nuclear structure studies is the quasiparticle random phase approximation (QRPA) with the self-consistent mean-field derived from the Skyrme interaction. The framework allows to relate the properties of the ground states and excited states through the same energy density functional. On the other hand, it would be desirable to overcome the discrepancies between the theoretical predictions low-energy 1^+ spectrum using the one-phonon QRPA wave functions of the daughter nucleus and the measurements [1]. We have generalized the approach to the coupling between one- and two-phonon terms in the 1^+ wave functions and the tensor force effects on the β -decay rates of neutron-rich nuclei [2]. The β -delayed multi-neutron emission probabilities helps to reconstruct the Gamow-Teller strength distribution and it can be extracted using the ^3He long-counter TETRA [3]. We applied the influence of the phonon-phonon coupling on the multi-neutron emission probabilities [4]. The even-even Cd isotopes near the r -process paths at $N=82$ was studied. In the talk we will conclude that the present approach makes it possible to perform the new microscopic analysis of the properties of the 1^+ states of the daughter nuclei $^{126,128,130}\text{In}$. The model is extended by enlarging the variational space for the 1^+ states with the inclusion of the two-phonon configurations constructed from the 3^+ phonons. We find that the first 1^+ state has the dominant two-phonon configuration composed of the 3^+ phonon and such contribution leads to the noticeable $B(E2; 1^+_1 \rightarrow 3^+_1)$ value. For β -delayed neutron measurements the neutron detection efficiency can be obtained from the comparison of gated γ -spectra [5].

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R-PROCESS NUCLEI NEAR $N=126$ AND STABILITY BEYOND DRIP-LINE IN THE RELATIVISTIC HARTREE-BOGOLIUBOV THEORY

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More than half of nuclei heavier than Fe are synthesized in r -process nucleosynthesis. Extremely neutron-rich nuclei far away from the stability line are produced in environments of high neutron densities and high temperatures. The corresponding r -process path passes through the magic numbers $N = 50, 82$ and 126 . The synthesis of nuclei around these magic numbers is manifested in peaks around $A \sim 80, 130$ and 190 , respectively, in the r -process nuclear abundances.

We have investigated nuclei above $N = 126$ relevant to the third-peak in r -process nuclear abundances within the framework of Deformed Relativistic Hartree-Bogoliubov theory. Three different Lagrangian models, viz, nonlinear scalar and vector coupling model [1] (NL-SV1), nonlinear scalar coupling model NL3, and a recent Lagrangian model without nonlinearities [2] SVI-2 have been employed. Ground-state properties of nuclei with $Z = 58 - 72$ in the highly neutron-rich region beyond $N = 126$ until the neutron drip line have been calculated. It is observed that properties of nuclei in the extreme region of the neutron drip line obtained with the Lagrangian model SVI-2 without nonlinearities are in better agreement with predictions of macroscopic-microscopic (MM) models such as Finite-Range Droplet Model (FRDM-12) and Hartree-Fock-Bogoliubov mass formula (HFB-24) than with the existing nonlinear Lagrangian models NL-SV1 and NL3. The model NL3 shows the largest deviations from the MM models. Thus, SVI-2 may be better suited for nuclei in the extreme regions.

It is shown that in approaching the r -process path above $N = 126$, nuclei in several isotopic chains ($Z > 60$) exhibit enhanced stability with all the Lagrangian models studied. This shifts the expected drip line significantly farther into the neutron-rich region. A large number of nuclides near the r -process path are shown to exhibit a coexistence of prolate and oblate shapes in the ground state with large deformations. Many of these states are also found to be nearly degenerate. This is expected to have an effect on the half-life decay of r -process nuclei and hence on nuclear abundances. The enhanced stability is also expected to have a significant influence on the r -process nucleosynthesis.

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EXOTIC ONE AND TWO PROTON RADIOACTIVITY

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Nuclei close to the proton drip line enter into the stability region by emitting either β^+ or positron or by emitting a proton. Two-proton (2-p) radioactivity occurs when one-proton (1-p) emission is energetically forbidden and it happens in proton-oversaturated light nuclei. In this work, we have proposed a new simple l -dependent formula to calculate the half-life period of 1-p emitters. Further, using Cluster-core model (CCM) and Quantum Mechanical Fragmentation Theory (QMFT), we have studied the 2-p emitters, which would give indications on where to look for such exotic nuclei.

Model dependent and independent formulae for the systematic studies of α -decay, cluster decay as well as proton decay were proposed by many as in Ref. [1,2]. They vary among themselves mainly on the number of parameters and the data set used for fitting. Taking clue from all these studies, a model independent and l -dependent four parameter formula has been proposed by us [3] for the estimation of half-lives for the 1-p transition from ground state and isomeric states of 44 proton emitters, based on the idea that, the angular momentum l associated with the transitions linearly varies as a function of the inverse square root of the Q -values.

$$\log T_{1/2} = ((a * l) + b)\xi + ((c * l) + d)$$

Here $a = 0.0322$, $b = 0.8204$, $c = -0.1527$, $d = -26.4801$ and $\xi = \frac{Z_1^{0.8}}{\sqrt{Q}}$.

The proposed formula may serve as a handy tool for planning new experiments. In the case of 2-p emitters, by using CCM, we have calculated the potential energy surfaces (PES) of all experimentally proved and theoretically proposed nuclei. To strengthen the PES results, we have calculated the preformation probability (P_0) of 2-p clusters within QMFT.

The l -dependent four parameter formula for 1-p emitters obtained as a result of fitting the charge number of the daughter and Q -value is compared with the experimentally known proton emitters and with the available theoretical values and are found to be in good agreement. The fragmentation potential energy calculations of 2-p emitters reveal a strong preference of 2-p cluster +core combination with minimum potential energy. The P_0 calculation results substantiate with the PES calculations and are in good agreement with the experimentally proved and theoretically proposed 2-p emitters.

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A NEW EXPLANATION OF HEAVY IONS SUB-BARRIER FUSION ENHANCEMENT PHENOMENON

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We have suggested an alternative view on heavy ions sub-barrier fusion enhancement. It has been very often observed, that heavy ion fusion cross-sections for isotopes of the same elements thus having almost the same barriers differ dramatically. This effect is known as the sub-barrier fusion enhancement. In order to explain these phenomena corrections to the barrier penetration are hitherto introduced, which are based on intrinsic properties of individual nuclei. Therefore, any generalization of the experimental data is hardly possible. We like to show that the sub-barrier fusion is rather of compound nucleus nature and its likelihood is determined mainly by nuclei general properties. Detail nuclear structure of fusing nuclei seems to be of minor importance for the fusion cross-section at energies deeply under the barrier. A simple energy scaling makes enhancement completely removed or greatly reduced, what supports idea of enhancement origin as a statistical rather than a dynamical one. Dedicated fusion experimental data for colliding systems of various 2-neutrons transfer Q -values have been analysed within the frame of the discussed approach as well as data for fusion of light projectiles, strongly and weakly bound, on heavy targets. Limitations of a proposed approach as well as some straightforward physical and methodological implications will be discussed.

OBSERVATION OF *U* AND *Cf* FISSION IN NUCLEAR TRACK EMULSION

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Application of the nuclear track emulsion technique (NTE) [1-2] in radioactivity and nuclear fission studies is discussed. It is suggested to use a HSP-100 automated microscope for searching for a collinear cluster tri-partition of heavy nuclei implanted in NTE. Calibrations of α -particles and ion ranges in a novel NTE are carried out. Surface exposures of NTE samples to a Cf-252 source were carried out (example in Fig). Planar events containing fragments and long-range α -particles as well as fragment triples only were studied. Use of the image recognition program "ImageJ" for obtaining characteristics of individual events and for events from the large scan area is presented. First photos of NTE that was soaked with chemical compound enriched uranium are shown. Search of ternary fission of U-235 produced by thermal neutrons are on progress now.



Fig. Examples of observed ternary fission events of Cf-252 in NTE.

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THE BETA-DECAY OF ^{28}S

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The β -decay property of the proton-rich nucleus ^{28}S ($T_z=-2$), produced through projectile fragmentation of a primary beam ^{32}S on a ^9Be target, has been studied at the HIRFL - RIBLL1 of the Institute of Modern Physics, Lanzhou, China.

The energies of the β -delayed protons were measured using silicon arrays [1]. The spectra of β -delayed γ -decays and p- γ emissions were obtained for the first time using double-sided silicon strip detectors and clover-type HPGe detectors.

The decay scheme of ^{28}S based on the present experimental data will be established and compared with both the mirror decay scheme and the shell-model calculations.

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HIGHLIGHTS OF THE DAY-ONE EXPERIMENTAL PROGRAM AT THE GAMMA-BEAM SYSTEM OF ELI-NP*

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The emerging experimental program with brilliant gamma beams at the Extreme Light Infrastructure – Nuclear Physics facility (ELI-NP), which is under construction in Magurele, Romania will be presented with emphasis on the prepared day-one experiments. Experiments at ELI-NP will cover nuclear resonance fluorescence (NRF) measurements, studies of large-amplitude motions in nuclei, photo fission and photonuclear reactions of astrophysics interest, and measurements of photonuclear reaction cross sections. The physics cases of the flagship experiments at ELI-NP will be discussed, as well as the performance of the related instruments, which are under construction, for their realization.

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SEPARATION EFFICIENCY MEASUREMENT OF THE MASS SEPARATOR MASHA FOR SHORT-LIVED Hg AND Rn ISOTOPES

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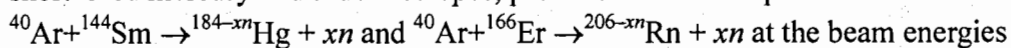
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The mass spectrometer MASHA was developed in FLNR JINR to measure masses of superheavy elements and investigate their characteristics by using ISOL-method.

The separation efficiency of MASHA spectrometer was determined in this work for short lived mercury and radon isotopes, produced in the complete fusion reactions



$E_{\text{lab}} = 5 \div 7 \text{ MeV/n.}$

Two experiments were carried out for this purpose. In the first one, the absolute cross sections of evaporation residues (radon and mercury isotopes) were obtained with use of moving absorber technique. The beam interruption method was applied. During the accumulation time (beam is on) five thin aluminium foils of absorber array were placed one under another so the reaction products were stopped there. After that the absorber array moved and extended on its full length 15 cm that each absorber foil was placed opposite to silicon detector on the measurement time (beam is off). Then the alpha decays of synthesized isotopes were detected. As a result the method allowed reliable identification of reaction products on their α -decay energies and decay times.

In the second experiment the radon and mercury isotopes, synthesized in the same reactions, passed through the hot catcher, ECR ion source and magneto-optic system of MASHA spectrometer and were detected by multi-strip detector in the focal plane of spectrometer. As hot catcher we used polygraphene sheet. The separation efficiency was determined from the yields of radon and mercury isotopes detected in the focal plane of the mass spectrometer and the absolute values of xn -channel cross sections. The dependence of separation efficiency on the time of heating was investigated. The experiment showed the good potential of using poly graphene sheet at ^{40}Ar beam intensity up to 0,5 μA .

EXPERIMENTAL FOUNDATIONS OF NUCLEAR PHYSICS IN NON-EUCLIDEAN SPACES

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An attempt is made to present a number of experimental data obtained at the accelerator, in the spirit of a new nuclear paradigm, which we called "Riemannian nuclear physics". Within the framework of the new paradigm, the deletion of the notion of "wave function" and there is no requirement to solve the equation of motion in the form of the Schrödinger equation. That is, under the pressure of all the new experimental facts we have to state that on the basis of only quantum mechanical views, it is impossible to describe the world of nuclei, and, consequently, the entire microcosm. Such a return to the deterministic Newtonian paradigm and the Hamiltonian equations of motion is associated with the accumulated contradictions of the quantum-mechanical paradigm with experimental data. In the present paper, a system of proofs of the necessity of turning to non-Euclidean geometry for atoms, nuclei and elementary particles is consistently cited. The basis representations of the new Riemannian nuclear physics were first presented by us in [1, 2].

In the Riemannian space [3], the radius of curvature κ of the m-plane of an elliptic space is $\kappa = \frac{1}{R^2}$, where R – root-mean-square radius of the nucleus. The stratification of a Riemannian space is considered as an alternative to the quantization of the nuclear and near-nuclear orbits of clusters and nucleons, respectively. Such stratification allows us to divide the Riemannian space into even and odd spheres with the corresponding radii.

The aim of the paper is to consider the geometry of the nucleus under the assumption of its curvature and stratification as an alternative to quantum mechanics. Such an approach could remove a number of contradictions, for example, the absence of electron emissions when they move along closed orbits in an atom or valence nucleons in the nucleus. In the Riemannian space of a geodesic, that is, a straight line permitting such a nonradiative motion, the ellipse is just that. The stratification of the m-sphere, in our opinion, is similar to shells and therefore explains the quantum nature of nuclear levels. Thus, the discrete quantum nature of nuclear parameters can be obtained without going beyond classical physics.

It would seem that the problem remains in de Broglie waves. However, this problem is solved in a natural way due to the Riemannian nature of the nuclear and near-nuclear space: incident beams of accelerated particles or neutrons bend their trajectories in curvilinear space like classical optical lenses with subsequent interference. In this interpretation, the concept of dualism of waves and particles for the microcosm is superfluous.

Apparently, it makes sense, in the framework of the Riemannian paradigm, to identify nuclear-spectroscopic levels with near-nuclear spatial closed (elliptical) layers. This will allow calculating their curvature by normalizing to the first layer tangential to the core surface. Drawing an analogy with the notation in nuclear spectroscopy, the spatial layers are also denoted as s-, p-, d-, f-, g-, h-layers.

In our work in the measured angular distributions of elastically scattered alpha particles with an energy of 10 MeV / nucleon, using the parametrized phase analysis method, the areas of nuclear space are identified: with positive curvature $\kappa > 0$ (Riemannian space), with zero curvature $\kappa = 0$ (Euclidean space) and with negative curvature $\kappa < 0$ (Lobachevsky space). On this basis, a hypothesis, that the fundamental cause of nuclear radioactivity is a transitional spatial layer from positive to negative curvature, has been advanced.

1. Yushkov A.V., Dyachkov V.V., Zaripova Y.A. New regularities in nuclear physics and microcosm structures // XXI International Scientific and Practical Conference "Relevant issues of Innovation Development in the New Millennium", 2015. – Monthly scientific journal. – №9(20). – P. 35-40.
2. Dyachkov V.V., Zaripova Y.A., Yushkov A.V. Cluster structure of nuclei and new spatial regularities // KazNU Bulletin. Physics series. – №2(57). – 2016. – P. 88-97.
3. Rosenfeld B.A. Non-Euclidean spaces. – M.: Nauka, 1969. – 548 p.

ROLE OF PENNING-TRAP MASS SPECTROMETRY IN FUNDAMENTAL PHYSICS

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With the recent progress in a development of high-precision Penning-trap mass spectrometry it has become possible to perform very accurate measurements of the masses of nuclides (from very short-lived to stable ones) and of the Q-values of various nuclear processes.

Almost each big RIB facility has a running high-precision Penning-trap mass spectrometer: LEBIT at NSCL and Canadian Penning trap at ANL in the USA, TITAN at TRIUMF in Canada, TRIGATRAP at Mainz research reactor and SHIPTRAP at GSI in Germany, ISOLTRAP at CERN in Switzerland and JYFLTRAP at JYU in Finland.

Their mutual complementarily enables experimental access to a large variety of nuclides throughout the nuclear chart: from light nuclides to superheavies, from neutron-rich nuclides to nuclides situated along the proton drip-line. These Penning-trap mass spectrometers, which are operated online, are designed to measure masses of short-lived nuclides with uncertainties down to 10^{-8} .

Another class of Penning-trap mass spectrometers, which in fact comprises only FSU-trap (USA) and PENTATRAP (Germany), is employed for mass-ratio measurements on very long-lived nuclides with relative uncertainties of about 10^{-11} . Such ultra-precise mass-ratio measurements are required for, e.g., experiments on the determination of the neutrino mass.

In this contribution I will first give a very brief overview of the existing Penning-traps and their measurement program. Then, I will focus on the past and present activity of our group as well as our future plans at SHIPTRAP and PENTATRAP.

IGISOL: RECENT RESULTS AND DEVELOPMENTS

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In this contribution I will give a short overview of the IGISOL facility [1] and show results of some recent measurements and discuss on-going development work.

Significant fraction of the experiments use or utilize JYFLTRAP Penning trap setup, which is capable of high-precision mass measurements and is also extensively used for high-precision ion beam purification for decay spectroscopy studies.

In the atomic mass measurement side, we have made measurements related to nuclear astrophysics, nuclear structure physics and neutrino studies and I will show some recent results from these measurements.

JYFLTRAP has been also used to purify samples of neutron rich nuclei for decay spectroscopy studies.

Other experiments include ^{20}F β -decay study, where a very weak second-forbidden, non-unique, ground-state-to-ground-state decay branch was discovered [2].

On the development side, an atom trap for $^{135}\text{m-Cs}$ is being setup by the University College London group with an ultimate goal to produce a coherent gamma ray source.

Another project, MORA, lead by P. Delahaye from GANIL, France, has recently been started to determine the time-reversal sensitive triple D correlation parameter from ^{23}Mg decay.

JYFLTRAP side upgrades include MR-TOF and PI-ICR mass measurement technique [3]. The latter has already been extensively used in mass measurements and the detection technique also allows mass resolving power in excess of 10^6 to be reached.

[1] I.D. Moore, P. Dendoveed and J. Ärje, *Hyperfine Interact* 223 (2014) 17.

[2] O. Kirsebom et al., *arXiv:1805.08149v1* (2018).

[3] S. Eliseev et al., *Appl. Phys. B* 114 (2014) 107.

PRODUCTION OF NEW ISOTOPES AND SEARCH FOR NEUTRON DRIP LINE WITH THE BigRIPS SEPARATOR AT RIKEN RI BEAM FACTORY

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Since the commissioning of the BigRIPS in-flight separator [1] at the RIKEN RI Beam Factory [2] in 2007, extensive searches of new isotopes have been conducted to explore the uncharted territory of nuclear chart. A total of 132 new isotopes have been produced and identified using the in-flight fission of a ^{238}U beam at 345 MeV/nucleon and the projectile fragmentations of ^{124}Xe and ^{78}Kr beams at the same energies.

Recently, particle-bound isotopes along the neutron drip line have been searched for fluorine and neon isotopes using the projectile fragmentation of a ^{48}Ca beam at 345 MeV/nucleon. The experimental results show that existence of particle-stable states of $^{32,33}\text{F}$ and $^{35,36}\text{Ne}$ have been excluded with high confidence levels. It is thus found that the neutron drip line is located at ^{31}F and ^{34}Ne for F and Ne isotopes, respectively.

In the talk, the results of new-isotope-search experiments will be summed up and the future plane will be briefly presented. The results of search for the neutron drip line for fluorine and neon isotopes will be also presented.

[1] T. Kubo, Nucl. Instrum. Methods Phys. Res., Sect. B **204**, 97 (2003).

[2] Y. Yano, Nucl. Instrum. Methods Phys. Res., Sect. B **261**, 1009 (2007).

FUSION TRIGGERED LIQUID-PHASE TRANSMUTATOR MONITORED AND CONTROLLED REAL-TIME BY CAN LASER

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An innovative scheme to generate energetic neutrons (or other particles) for the purpose of transmutation of long-lived radioactive waste into short-lived radioactive or stable nuclides and their real-time monitoring is presented. Our methods include the triggering of the transmutation by the use of a Field Reversed Configuration (FRC) deuterium/tritium (or other fusing elements) plasma and either deuterium and/or tritium beams with a typical energy range of 10-50 keV to generate the energetic neutrons. The beam can drive collective modes thus generating high-energy tail in the plasma (by the wake field driving process). The transmutator consists of a transparent solution of the carrier salt FLiBe, MA (Minor Actinides) and FP (Fission Products) surrounding the FRC machine in a radially varying density arrangement in order to multiply, manage, and control the number of neutrons by fission and other nuclear processes. This liquid phase transmutator concept allows to use the real-time monitoring of the FP and MA concentration and thus control of the system's operation by high fluency lasers (CAN – Coherent Amplification Network laser) and laser-driven gamma sources (laser back-scattering Compton gamma-rays). Laser monitoring is based on spectroscopy whereas the gamma beam relies on the Nuclear Resonance Fluorescence. Gamma spectroscopy is also investigated. Furthermore, the real-time chemical separation and removal of FP's is possible in-situ. The energy generated by the transmutation is converted into electricity. The safety is provided both by passive and active measures: passive measure is a frozen plug on the bottom of the transmutator which thaws in the event of run-away; active measure includes the real-time monitoring and feedback controls.

SILICON FOUR-SEGMENT CHARGED PARTICLE DETECTORS

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Silicon four-segment charged particle detectors KDP-1K have been developed to be used in experiments carried out at FLNR JINR for the detection of nuclear reaction products. The detectors were made of n-type Si using the ion implantation technology with thermal surface passivation. The input aperture of the detector is 54.1×54.1 mm. The active area of each segment is 25.0×25.0 mm with a $50 \mu\text{m}$ gap between the segments. To reduce surface leakage currents, a system of common guard rings was used in the design of the detecting structures. The thickness of the detectors of the delivered batch was $622 \pm 5 \mu\text{m}$. Spectrometric and electrical characteristics of the detectors have been measured. All measurements were carried out at room temperature 22 ± 2 °C. Typical leakage currents of the segment at a full depletion bias voltage of 130V were equal to 6-12nA ($1-2 \text{ nA/cm}^2$). The spectrometric characteristics of each quadrant of the detectors were measured using an alpha radiation ^{239}Pu source (OSAI set) at the over-depletion bias voltage of 150 V at $1 \mu\text{s}$ shaping time constant using standard spectrometric electronics. Typical values of the energy resolution were 24-26 keV FWHM and 49-54 keV FWHM under irradiation from the pn junction and ohmic side contact, respectively. The energy equivalent of the detector noise was 7-8 keV FWHM. The higher values of the detector energy resolution, when irradiated from the side of the ohmic contact, are mainly due to the greater thickness of the contact layers on the reverse side of the detector and the associated with it spread in the energy loss. The work was based on the previous experience obtained in the late 1980s when creating and developing silicon microstrip detectors [1] at the Riga Research Institute of Radioisotope Instrumentation (RNIIRP) in conjunction with IHEP, and in general reflects the interest of JSC IPTP to this area, namely, development and manufacturing of silicon pad, strip and microstrip radiation detectors for high energy physics experiments.

- [1] I.P.Barkov, I.M.Gazizov, L.L.Kurchaninov, V.V.Rykalin, A.I. Saraykin, V.A.Stankevich "Construction and investigation of silicon microstrip detector characteristics", preprint, Institute of High Energy Physics (Serpukhov), IHEP 90-76, Protvino, 1990.

THE STATUS OF NEW FRAGMENT SEPARATOR ACCULINNA-2 AND THE FIRST DAY EXPERIMENTS

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The new fragment separator ACCULINNA-2 was newly installed in FLNR JINR at the end of 2016. The separator is destined to add considerably to the studies of drip line nuclei performed with the use of variety of direct reactions known to be distinctive to the 15 ÷ 50 MeV/nucleon exotic secondary radioactive ion beams (RIBs). The capacity of this set-up to grant the projected high transmission and purification level have been confirmed experimentally for a number of RIBs in last two years. The intensities obtained for the secondary beams of ^{14}B , ^{12}Be , $^{9,11}\text{Li}$, $^{6,8}\text{He}$ in the fragmentation reaction ^{15}N (49.7 MeV/nucleon) + Be (2mm) are in average 15 times higher in comparison to the ones produced at its forerunner ACCULINNA separator. The ACCULINNA-2 setup will become a backbone facility at the FLNR for the research in the field of light exotic nuclei in the vicinity of the nuclear drip lines.

This report shows the status of the project, describes a RIB quality of ^6He , ^9Li , ^{10}Be obtained for recently carried out experiment and provides an overview of the developing detection, monitoring and control subsystems.

NEW FRONT AND BACK-END ELECTRONICS FOR THE UPGRADED GABRIELA DETECTION SYSTEM

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At the FLNR experiments to perform detailed nuclear structure studies of transfermium nuclei are carried out using the GABRIELA [1] set-up. Following the modernisation of the VASSILISSA separator (SHELS) [2] the GABRIELA detection system has also been upgraded. Not only has the detection hardware been upgraded, but, we are in the process of choosing new front-end electronics for the silicon detectors and implementing a fully digital DAQ using state of the art digitisers from National Instruments [3]. These developments will improve both the timing resolution (allowing shorter lived isomeric states to be studied) and the energy resolution (improving the signal-to-background ratio allowing weaker channels to be observed). The characteristics of the upgraded detection system will be presented along with results from the electronics tests. In particular the ability to discriminate 'escape' alpha particles from internal conversion electrons in the "tunnel" and to discriminate the recoils of interest from light charged particles that punch through the implantation DSSD will be presented. It will also allow us to detect fast pile-up events in the implantation DSSD and perform time of flight measurements between the MKP and the DSSD when only one emissive foil is used (which is crucial to a successful experimental programme using asymmetric reactions such as $^{22}\text{Ne}+^{238}\text{U}$ and $^{18}\text{O}+^{242,4}\text{Pu}$)

[1] K. Hauschild, et al., Nucl. Instr. Methods Phys. Res. Sect. A560 388 (2006)

[2] A.G. Popeko et al., Nucl. Instr. Methods Phys. Res. Sect. B376 140 (2016)

[3] NI-PXIe 5170 and NI-PXIe 5170

INFORMATION PROVIDING OF FUNDAMENTAL RESEARCH

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It is well known, that in the XXI century development of society more and more depends on knowledge storage. It is enough to say that contemporary economy is characterized as "knowledge-based economy".

Fundamental science achievements are a knowledge generator, that's why under the conditions of an extremely rise of new information mass the providing processes of scientific groups with effective means for receipt and processing information are getting special meaning.

So far definite methods and technologies of various aspects data accumulation, their classification, logical and semantic analysis are formed to choose substantial information and suitable forms of its receipt.

Among the main trends of an information service it is necessary to mark up the principles "Big Data" and "Cloud Computing" as well. Scientific association uses such the services in the "grid-system" variant as well.

We'll give an example of one from a number of specialized service complexes, that is used by tens of scientific organizations.

The complex bases on the following main proposals:

- the assignment of a remote access for data bases Thomson Reuters (Web of Science), Scopus, Elsevier, Sci Val Funding, materials of American Physical Society, American Mathematical Society, etc.;
- the use of the information analytical system (IAS), that is an instrument for automatization of processes of collection and analysis of structured and non-structured information from various sources (the Internet, file system, above mentioned data bases, etc.).

The active search of data regime (on-line), persistent monitoring of above named sources and the Internet as well in the automatic mode are realized in the system.

According to the users' opinions the complex has demonstrated the good results during the operating in different subject trends.

A NEW SCATTERING CHAMBER FOR CONDUCTING PRECISION EXPERIMENTS ON THE HEAVY-ION REACTION CROSS SECTIONS AT THE ACCELERATOR DC-60 (ASTANA) AT LOW ENERGIES

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Within the framework of the long-term program of cooperation between JINR, ENU and Institute of Nuclear Physics (INP), joint experiments connected with the peculiarities of the interaction of lithium nuclei (${}^{6-9,11}\text{Li}$) at energies near the Coulomb barrier will be conducted on the U-400M cyclotron of G.N. Flerov Nuclear Reaction Laboratory (FLNR JINR) and on the DC-60 accelerator (Astana) of the INP. To obtain new experimental information on the properties of weakly bound (cluster and exotic) lithium nuclei (the entire chain of lithium isotopes) and their manifestation in interaction with other nuclei, the features of the angular distributions of elastic and inelastic scattering cross sections, the energy dependences of the total reaction cross sections $\sigma_R(E)$ and cross sections of individual dominant reaction channels; the corresponding reaction mechanisms in the previously unexplored region of energy will be studied. Experiments in Astana (Kazakhstan) are supposed to be carried out at the DC-60 using a new scattering chamber and corresponding detector systems and nuclear electronics, which was manufactured at the FLNR JINR. The new dispersion chamber for the DC-60 is a completely new modern installation, which includes a new electronic system for collecting and processing experimental information FASTER.

Control experiments using the new camera are going to be conducted on ${}^{10}\text{B}$ beam on the DC-60.

MAVR FACILITY AT FLNR JINR

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A project of the high-resolution magnetic analyzer MAVR is proposed. The analyzer will comprise new magnetic optical and detecting systems for separation and identification of reaction products in a wide range of masses (5–150) and charges (1–60). The magnetic optical system consists of the MSP-144 magnet and a doublet of quadrupole lenses. This will allow the solid angle of the spectrometer to be increased by an order of magnitude up to 30 msr. The magnetic analyzer will have a high momentum resolution (10^{-4}) and high focal-plane dispersion (1.9 m). It will allow products of nuclear reactions at energies up to 30 MeV/nucleon to be detected with the charge resolution $\sim 1/60$. Implementation of the project is divided into two stages: conversion of the magnetic analyzer proper and construction of the nuclear reaction products identification system. The MULTI detecting system is being developed for the MAVR magnetic analyzer to allow detection of nuclear reaction products and their identification by charge Q , atomic number Z , and mass A with a high absolute accuracy. The identification will be performed by measuring the energy loss (ΔE), time of flight (TOF), and total kinetic energy (TKE) of reaction products. The particle trajectories in the analyzer will also be determined using the drift chamber developed jointly with GANIL. The MAVR analyzer will operate in both primary beams of heavy ions and beams of radioactive nuclei produced by the U400 - U400M acceleration complex. It will also be used for measuring energy spectra of nuclear reaction products and as an energy monochromator.

DEMONSTRATION OF MASS MEASUREMENT USING RARE-RI RING

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Nuclear mass is one of the basic probes to obtain information about the nuclear structure, stability of the nuclei, shape, and interactions. Also, nuclear masses are important for understanding the synthesis of heavy elements via the r-process.

In order to measure masses of most neutron-rich nuclei relevant for r-process nucleosynthesis, an isochronous storage ring named Rare-RI Ring was constructed at the RI Beam Factory of RIKEN. The Rare-RI Ring is based on the isochronous mass spectrometry technique to achieve mass measurement with a precision of 10^{-6} in less than 1-ms measurement time. A demonstration of mass measurement of ^{79}As , ^{77}Ga , ^{76}Zn , and ^{75}Cu , whose masses are well known have been performed using a reference particle of ^{78}Ge . In this contribution, the result of the demonstration of mass measurement will be discussed.

CONTROL AND DATA ACQUISITION SYSTEMS OF THE MASHA SETUP

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The mass separator of super heavy elements also known as MASHA setup from the automation systems point of view is described. The setup uses ISOL (Isotope Separation On-Line) method and represents the modular online mass spectrometer where masses of new elements from helium up to mass $A=450$ are measured directly in the course of their synthesis with accelerated heavy-ion beams. During the last years the control, the data acquisition and the beam diagnostics systems were modified. The modernization was in changing the platforms to the modern one from the CAMAC to the NI PXI and from the Smart-BOX to the Wago PLC and the NI CompactRIO. The new systems were integrated and tested on the beam experiments with heavy ions at the U-400M cyclotron. The future experimental program of the MASHA setup for study of the physical and chemical properties of superheavy elements at the SHE factory is discussed.

FEATURES OF THE SOLID-STATE ISOL METHOD FOR FUSION EVAPORATION REACTIONS INDUCED BY HEAVY IONS

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A solid-state ISOL system, installed in the mass spectrometer MASHA, is presented. The system is intended for separation of reaction products of complete fusion reactions induced by heavy ion beams. A polygraphene foil is used as a hot absorber of reaction products. Both total separation efficiencies and separation times of short-lived mercury and radon isotopes were measured. The measurements were performed at heavy ion beam intensities of up to 0,5 μA . It was observed a gradual decreasing of the total separation efficiencies due to modification of the hot absorber inner structure.

A new design of the hot catcher, on basis of a thin sheet composed of carbon nanotubes and graphene, is proposed. Test experiments showed good prospective possibilities of using such materials for the reactions under investigation.

In case of ^{283}Cn production a modified separation system consisting of the ECR source and a hot catcher, is also considered. This isotope will be produced in the reaction $^{48}\text{Ca}+^{242}\text{Pu}$ as a decay product of nuclei ^{289}Fl . The whole system will be heated up to 300°C in order to increase its separation efficiency. Besides, the inner surface of vacuum pipelines and chambers will be covered with special chemical inert glass-enamel coating.

AN ALTERNATIVE METHOD OF MEASURING EXCITATION FUNCTION OF RESONANCE REACTIONS WITH NEUTRON EMISSION

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In the present work an effective method of measuring excitation function of resonance reactions with neutron emission is proposed. The method involves performing experiments in inverse kinematics using thick gaseous targets. The target is assumed to be an extended chamber filled with gas (helium or hydrogen), which also serves as a moderator for heavy ion beam. Start signal for time measurement is triggered by cyclotron radiofrequency system. Neutrons from reaction are detected with scintillation detectors based on the stilbene crystals. This method has its advantage over conventional one, when there is a necessity to use radioactive isotope beams or when measurement at 180 degree angle needs to be done. Test experiment was performed on the basis of DC-60 cyclotron in Astana (Kazakhstan). The excitation function of resonance reaction $^{13}\text{C}(\text{a},\text{n})^{16}\text{O}$ in excitation energy range of 8.2-8.5 MeV was measured. The obtained results were compared with the data of recognized works previously measured in conventional method.

"MULTI" SET-UP FOR TOTAL REACTION CROSS-SECTION MEASUREMENTS

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The detector setup "MULTI" is a 4π γ -spectrometer designed for spectroscopy of nuclear reactions with the exotic nuclei. Charged reaction products are identified by the multilayer dE telescope with an active target. Total reaction cross section is evaluated from relative decrease of the beam intensity in the telescope elements (fig.1) together with identification of reaction products. Prompt gammas from nuclear reactions are detected by 4π γ -spectrometer for enhanced identification of the correct events in the target. It is necessary to achieve the same registration efficiency for various reaction channels with different multiplicities of emitted gamma radiation. The spectrometer is continuously developed for achieving better detection parameters. Previous upgrade raised detection efficiency. Actual aim is to enhance gamma identification with precise, high-resolution gamma detectors for spectroscopy of prompt gamma. Parameters of the setup with CdZnTe and CeBr₃ detectors in various geometries (fig.2) are investigated with Monte Carlo method in Geant4.

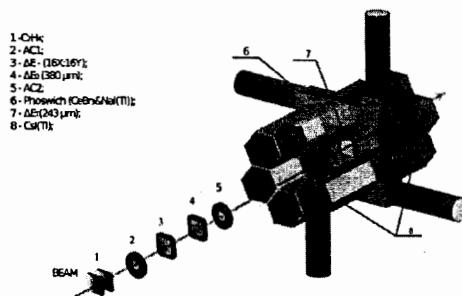


Fig.1: Upgraded MULTI scheme.

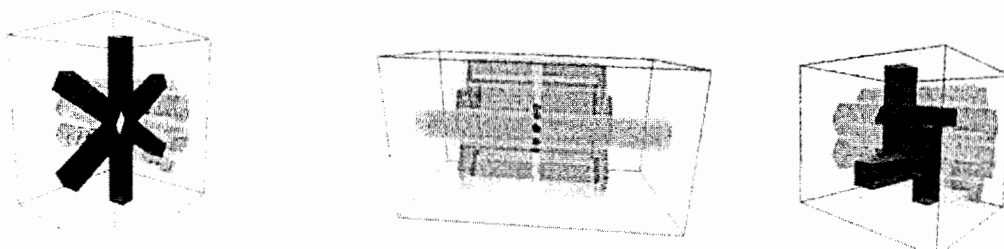


Fig. 2: Geometries investigated in Geant4.

VME BASED DATA ACQUISITION SYSTEMS

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The data acquisition systems (DAQs) should meet requirements of the modern nuclear physics experiments including investigations with radioactive ion beams. We want to show on two examples how this can be implemented in DAQs based on VME standard. First example is the DAQ [1] developed together with GSI experts for the new in-flight fragment separator ACCULINNA-2 [2], which have possibility to work with several crates in VME, CAMAC and other standards. The main advantage of this system is that it allows the remote DAQ (event collector) to be located at the distances up to 100 meters far from the main event builder. The mode of operation of this DAQ is configurable depending on running experiments. As second example, VME based DAQ with USB controller [3] will be reported as well. It is effective for applied physics and for experiments with limited numerical parameters (several hundred).

[1] R.S. Slepnev *et al.* // Instrum. Exp. Tech. 2012. V. 55. I.6.P. 645.

[2] <http://aculina.jinr.ru/acc-2.php>

[3] <http://www.wiener-d.com/sc/modules/vme--modules/vm-usb.html>

MANIFESTATION OF CLUSTER DEGREES OF FREEDOM IN FISSION FRAGMENTS AT CROSSING OF METAL FOILS

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In our previous publications [1–3] we discussed new original effect appeared at crossing of the metal foils by fission fragments (FFs). We have observed significant mass deficit in the total mass M_s of the FFs detected in coincidence with the ions knocked out from the foil. In the series of recent, more detailed experiments we have compared the mass of the FF before (M_{tt}) and after (M_{te}) it passes the foil event by event. In the light of the obtained results, a FF from conventional binary fission is supposed to be born in the shape isomer state which looks like a di-nuclear system consisting of the a magic core and lighter cluster. Comparison of the correlation mass distributions M_{tt} - M_{te} for different metal foils is presented aimed at testing possible models of the effect.

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2. Yu.V. Pyatkov et al., International Symposium on Exotic Nuclei "EXON-2014", Kalaninograd, Russia, 08–13 September 2014. Conference proceedings, Editors: Yu. E. Penionzhkevich, and Yu. G. Sobolev. Published by World Scientific Publishing Co. Pte. Ltd., 2015. p. 383.
3. Yu. V. Pyatkov et al., Int. Symposium on Exotic Nuclei "EXON-2016", Kazan, Russia, 04-10 September 2016. Conference proceedings, Editors: Yu. E. Penionzhkevich, and Yu. G. Sobolev. Published by World Scientific Publishing Co. Pte. Ltd., 2017. p. 284

DISCOVERY OF ^{60}Ca

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The discovery of the important neutron-rich nucleus $^{60}\text{Ca}_{40}$ and seven others near the limits of nuclear stability is reported from the fragmentation of a 345 MeV/u ^{70}Zn projectile beam on ^9Be targets at the RIKEN RI Beam Factory.

The produced fragments were analyzed and unambiguously identified using the BigRIPS two-stage in-flight separator. The eight new neutron-rich nuclei discovered during 100 hours of beam-on-target, ^{47}P , ^{49}S , ^{52}Cl , ^{54}Ar , ^{57}K , $^{59,60}\text{Ca}$, and ^{62}Sc , are the most neutron-rich isotopes of the respective elements.

In addition, one event consistent with ^{59}K was registered.

The results are compared with the drip lines predicted by a variety of mass models and it is found that the models in best agreement with the observed limits of existence in the explored region tend to predict the even-mass Ca isotopes to be bound out to at least ^{70}Ca .

PRODUCTION AND STUDY OF NEUTRON RICH HEAVY NUCLEI, GALS SETUP

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A new setup, based on stopping nuclei in the gas cell and subsequent resonance laser ionization and separation by magnetic field is under stage of realization at Flerov Laboratory JINR. This setup is devoted to synthesis and study of new neutron rich heavy nuclei formed in low energy multi-nucleon transfer reactions.

The heavy neutron rich nuclei are very important for nuclear physics investigations, for the understanding of astrophysical nucleosynthesis and r-process. In this region is located the closed neutron shell $N=126$ which is the last so-called “waiting point”. Study of the structural properties of nuclei along the neutron shell $N=126$ could also contribute to the present discussion of the quenching of shell gaps in nuclei with large neutron excess.

A creation and launch of this facility will open a new field of research in low-energy heavy-ion physics, and new horizons in the study of unexplored “north-east” area of the nuclear map. It could be helpful also for finding a new way for production of heavy and superheavy nuclei.

The current status of this setup will be discussed.

EXPERIENCE OF REACTION STUDIES AT ACCULINNA AND PROSPECTIVE RESEARCH AT ACCULINNA-2

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The present report shows the status and scientific program of the project of new fragment separator ACCULINNA-2 which has been built, approved by Programme Advisory Committee and commissioned in FLNR JINR in 2017.

The ACCULINNA-2 setup will become one of the main experimental facilities of FLNR for research in the field of light exotic nuclei in the vicinity of the nuclear drip lines.

Recent first results related to study of nuclei far from stability obtained at the ACCULINNA-2 facility will be presented. A short and middle-term scientific program of ACCULINNA-2 will be put in the perspective of the present and futures research program of FLNR.

PROJECT OF PRIORITY EXPERIMENTS AT SHE FACTORY

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At present, the region of known superheavy nuclei (SHN) with $Z \leq 118$ and their α -decay descendants forms a relatively narrow “ridge” in the nuclear landscape. In order to more fully understand the role of shell stabilization in this region, it is essential to considerably extend the area of synthesized SHN which require a significant increase in the overall sensitivity of experiment.

A new experimental complex, the SHE Factory at FLNR, including a high-current cyclotron DC280 and a gas-filled separator DGFRS-2, is planned to be commissioned by the end of 2018. The project of priority experiments which are planned to be performed for testing the capabilities of DGFRS-2 coupled with DC280 will be presented. These include experiments on the production of $Z=90-104$ isotopes in ^{48}Ca - and ^{50}Ti -induced reactions. In the next stage, study of the $^{243}\text{Am}+^{48}\text{Ca}$ reaction is planned to be carried out for measurement of yields of Mc isotopes with large statistics at different beam energies. The production of elements Cn and Fl in the $^{242}\text{Pu}+^{48}\text{Ca}$ reaction with use of the chemistry setup placed behind DGFRS-2 and investigation of their chemical properties is discussed as well. The first research experiments, including synthesis of new elements 119 and 120 in the reactions of ^{249}Bk and $^{249-251}\text{Cf}$ with ^{50}Ti , will be also considered.

"PARIS" GAMMA CALORIMETER – STATUS OF THE PROJECT AND FIRST EXPERIMENTAL RESULTS

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on behalf of the PARIS collaboration

One of the goals of radioactive ion beam facilities, which are being under development in Europe (SPIRAL2, SPES, HIE-ISOLDE or GSI-FAIR) is the production of very exotic nuclei, study of which is very often at the detection limit. This requires the use and, in the most cases, construction of novel, extremely efficient experimental detection systems. One of such systems is the gamma calorimeter PARIS - Photon Array for Studies with Radioactive Ion and Stable Beams. The PARIS project has been initiated in the context of SPIRAL2 facility, but is planned to be used in another radioactive (and stable) ion beam facilities in the world. It is a large array of phoswich detectors expected to measure γ rays over a wide range of energy from few hundred keV to 40 MeV. It is envisaged to serve the dual purpose of a high-energy ray spectrometer (or calorimeter) and a spin-spectrometer, capable of determining the multiplicity of low energy (100 keV to few MeV) discrete γ rays associated with a specific reaction. Upon completion PARIS is envisaged to be an array of 216 phoswich detectors. The front section of each of the phoswich detectors is a cubic (2"×2"×2") LaBr₃ or CeBr₃ scintillator optically coupled to a (2"×2"×6") long rectangular bar of NaI(Tl). Each of these detectors is to be read by a single photomultiplier tube (PMT) of 2" diameter that would allow close packing of such detectors. It is planned to combine 9 phoswich detectors in a square (3×3) close packed geometry forming a single cluster [1-3]. The project is to be executed in a phased manner with the completion of one cluster in the first phase (PARIS prototype) and four clusters by the end of the second phase (PARIS demonstrator). This phase is just accomplished. The third phase will see the completion of 12 clusters. In its final configuration, commissioned by the end of the fourth phase, PARIS is envisaged to have clusters covering 4π solid angle around the target. A variety of experiments in nuclear structure and reaction dynamics are foreseen to be pursued with PARIS using both stable and radioactive ion beams. The first experiments, in which PARIS detectors were used, were already performed at IPN Orsay, GANIL and in IFJ PAN Krakow.

In the talk the main idea of PARIS gamma calorimeter will be described, as well as information about PARIS status and performance. Also, the very first physical results, validating the PARIS concept, will be shown. In addition, the future plans will be presented.

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[2] M. Zieblinski *et al. Acta Phys. Pol B*, 44:651, 2013;

[3] C. Gosh *et al., Journal of Instrumentation* 11 (2015).

GALILEO GAMMA-RAY SPECTROMETER

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Nuclear structure research is evolving towards extreme regions of spin and excitation energies and neutron-proton ratio. Gamma-ray spectroscopy, as the main tool to investigate the structure of nuclei, has to respond to the increasing experimental difficulties. The GALILEO gamma-ray spectrometer has been constructed at the Legnaro National Laboratory of INFN (LNL-INFN) with the aim to be an advanced device in the field of nuclear structure studies with in-beam γ -ray spectroscopy methods. Such studies take advantage of reactions induced by the stable beams delivered by the Tandem-ALPI-PIAVE accelerator complex and by the radioactive beams which will be provided by the SPES facility in the near future [1]. The GALILEO Phase-1 consists of a 2π high-resolution γ -ray array using 25 GASP High Purity Germanium Detectors (HPGe) [2]: with 5 detectors placed at 152° , 5 at 129° , 5 at 119° and the last ten detectors at 90° with respect to the beam direction. The geometry of the array was designed to maximize the photo-peak efficiency under typical in-beam medium-high γ -ray multiplicity conditions, achieving a value of about 3% for 1.3 MeV gamma-ray. The Ge detectors are surrounded by anti-Compton shields in order to reach, for the whole array, a peak-to-total ratio of about 50%. A wide set of ancillary devices has been developed/installed to enhance the sensitivity of Galileo to nuclei produced at low cross-sections: light-charged particle detector EUCLIDES [3], Neutron Wall array [4], SPIDER heavy ion detector [5], plunger device, TRACE position-sensitive Si detector [6].

The research which is undergoing at GALILEO are aimed at many aspects of nuclear structure: i) the study of $N=Z$ nuclei that provides the most relevant information about the properties of the neutron-proton pairing interaction and its evolution with the spin and excitation energy; ii) the study of isospin symmetry as a tool to understand fundamental questions such as the charge-symmetry and charge-independence of the nuclear two-body interaction; iii) study of nuclear shapes, etc.

In the presentation it will be discussed the outfit of the first experimental campaigns using reactions with stable beams and targets performed at GALILEO coupled to one or more its ancillary devices and the future perspective using beams of radioactive isotopes provided by SPES.

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- [5] M. Rocchini, K. Hadyńska-Klęk, A. Nannini et al., Phys.Scr. 92, 074001 (2017)
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RESPONSE OF TETRA LONG NEUTRON COUNTER TO MONO ENERGETIC PHOTO-NEUTRONS

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Nowadays much effort is devoted to understand the role of neutron excess and its influence on the nuclear structure, specifically, in the vicinities of closed neutron shells. In contrast to nuclear the shell structure along the beta-stability line, which has been studied theoretically and experimentally quite well, the yet unknown shell structure in drip-line nuclei is currently of great interest. Therefore, the recent studies of international collaboration JINR-IN2P3 are aimed at systematic investigation of the gross-properties of beta-decay as well as nuclear structure studies of neutron-rich photo-fission fragments produced at ALTO ISOL facility, Ref. [1, 2].

One of the work-horse of such investigations is the neutron detector TETRA: 4π high effective setup which consists of 80 ^3He counters complimented by $4\pi\beta$ plastic scintillator and a High Purity Germanium Detector as is described in Ref. [3].

The efficiency of detection of a single neutron measured with a ^{252}Cf source was 52(2)% which agreed well with the MCNP simulations [4]. One of the drawbacks of such ^3He detectors systems is that due to the moderation process the information of the initial neutron energy is not conserved. Simulation of TETRA response to a mono energetic isotropic neutron source revealed a flatness up to 1 MeV followed gradually decrease towards 10 MeV. Therefore, to measure Pxn values one has to assume a certain beta-delayed neutron energy spectrum which increases the systematic errors to obtained values. Thus, even partial information on initial neutron energy will be extremely useful to impact the precision of our measurements.

Indeed, *East and Walton* [5] have shown that for a ^3He counter it is still possible to exploit the energy dependence of the thermalization process to partially recover the neutron energy information, namely the average energy of the neutron spectrum E_n . Consequently, to characterize the energy response function of TETRA under real experimental conditions we used a set of monoenergetic neutrons (of known energy) to placed at the geometrical center of detector. In fact, these sources, widely used in the 1960s until the mid-1970s, have sadly been forgotten, mainly because of the technical difficulties in production and implementing them. The basic principle of photo source neutrons is to expose heavy water or beryllium to an intense gamma flux. In a photo-dissociation reaction a group of neutrons having a maximum energy $E_n - S_n$ is obtained. The gamma source is chosen so that in its radioactive decay only one gamma line is predominantly populated and has an energy higher than the neutron emission threshold (S_n) of Be ($S_n = 1.67$ MeV) and ^2H ($S_n = 2.22$ MeV). Six sources of this type have been recommended as a standard ones [6], covering the neutron spectrum from 25 keV to ~ 900 keV (exactly the neutron emission energy regime beta-expected delay in the fission products studied at ALTO).

In the presentation it is discussed the response of TETRA to mono energetic photo-neutron sources pre-reproduced at the TANDEM accelerator of IPN Orsay.

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