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INTERNATIONAL SYMPOSIUM ON EXOTIC NUCLEI
8-13 September 2014, Kaliningrad, Russia



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**VII INTERNATIONAL SYMPOSIUM
ON EXOTIC NUCLEI
(EXON 2014)**

Kaliningrad, Russia, September 8–13, 2014

Book of Abstracts

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CHALLENGES IN NUCLEAR PHYSICS: NOW AND IN NEAREST FUTURE

Walter Greiner

FIAS, Frankfurt-am-Main

My talk will be focused on several most exciting problems of present-day nuclear physics.

First of all I shall overview the state of affairs in production and study properties of **super-heavy elements** (stability of these nuclei with increasing of proton number Z , methods of their production, nearest experiments and further progress, search of SHE in cosmic rays, etc.).

Then I shall discuss the problems of **neutron rich nuclei** (their astrophysical significance, possible reaction mechanisms for the production of heavy neutron rich nuclei, studying neutron rich nuclei with closed neutron shells including those located at the neutron drip line and beyond it).

The next subject of my talk will be **strange nuclei and antimatter**. Extension of the nuclear map into the two additional directions would broaden significantly our comprehension of the nuclear matter.

I shall discuss also the fundamental problem of vacuum decay (spontaneous formation of electron-positron pairs) in **super-strong electric fields** appearing in collisions of very heavy (U-like) nuclei. This problem attracts recently new and great interest owing to our deeper understanding of the process and new experimental possibilities.

APPLICATION OF MICROSCOPIC OPTICAL POTENTIAL MODEL TO ANALYZE THE $^{10,11}\text{Be}$ ELASTIC SCATTERING ON PROTONS AND NUCLEI

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The known density distributions of $^{10,11}\text{Be}$ obtained within the generator coordinates model (GCM) and quantum Monte Carlo model (QMC) we implemented for calculations of microscopic optical potential (OP) and elastic cross sections of the $^{10,11}\text{Be}$ scattering from proton and ^{12}C targets. The real part of OP was obtained using double folding model, and imaginary part of OP was estimated within the model developed basing on the high energy approximation. Depths of the potential were fitted to the experimental data taking into account the known dependence of their volume integrals on energy. These OPs could be used in the further calculations of reaction cross sections where these nuclei take part.

FUSION, BREAKUP AND SCATTERING OF LIGHT UNSTABLE NUCLEI

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We will discuss systematic results reached in the investigation of reaction mechanisms and scattering of light unstable weakly bound nuclei, at near barrier energies, and its effects on fusion and total reaction cross sections. Particularly, we show that the fusion of proton and neutron halo nuclei are suppressed by dynamic breakup effects at energies above the Coulomb barrier and enhanced at sub-barrier energies. We also discuss the shortcomings in the available methods to "reduce" cross sections of different systems, when one wants to compare total reaction cross sections in the same graphic. These shortcomings are not present when one wants to do similar "reduction procedure" with fusion cross sections.

Finally, we show that the energy dependence of the optical potential obtained in the elastic scattering of these light unstable nuclei corresponds to the so-called Breakup Threshold Anomaly (BTA).

B-19954

NUCLEAR STATES WITH ABNORMALLY LARGE SIZES

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Clusterization of nucleons leads to the appearance of nuclear structures significantly differing from the predictions of standard models of nuclei.

During the last decay two excited states of light nuclei attracted a special interest: the Hoyle state (0^+ , $E^* = 7.65$ MeV) in ^{12}C and the $\frac{1}{2}^+$, $E^* = 1.68$ MeV level of ^9Be .

Besides the exceptional role of these states in nucleosynthesis this interest was dictated by the non-ability of most of modern nuclear theories to predict their main properties. The methods of measuring the radii of nuclei in their short-lived states developed recently allowed finding the effect of size isomerism, that is, significant enhancement of nuclear radii in the mentioned states relatively those in the ground ones.

As the result, the observation of rudimentary signatures of the alpha particles condensation and of a neutron halo in the $\frac{1}{2}^+$, $E^* = 1.68$ MeV state of ^9Be took place. These both states are heads of rotational bands whose higher members are characterized by enhanced sizes as well. These data allowed performing a critical reconsideration of many settled ideas about the structure both of the nuclei mentioned above and some of their neighbors (^{11}B , ^{13}C) which also demonstrated the existence of size isomers.

EXOTIC NUCLEI AND MATTER IN A CHIRALLY EFFECTIVE APPROACH

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In this presentation a relativistic approach to describe nuclear and in general hadronic matter is introduced and discussed.

Here, not only the nuclear forces but also the masses of the nucleons are generated through meson fields. Within this framework it is possible to calculate properties of finite nuclei at a level of accuracy similar to dedicated relativistic nuclear structure models. Due to the more general approach, a wider range of properties of hadronic states can be investigated.

A number of results, including neutron-rich nuclei and hyper nuclei towards the drip line will be presented. Going beyond matter around saturation density the consequences of this approach for extremely dense and isospin asymmetric systems like neutron stars will be studied.

COMPLETE AND INCOMPLETE FUSION PROCESSES IN ^{11}B -INDUCED REACTION ON ^{197}Au TARGET AT ENERGIES ABOVE THE COULOMB BARRIER

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Experimental results, measured in $^{11}\text{B}+^{197}\text{Au}$ interaction at energies of ≈ 255 -137 MeV by using of the induced activity are presented. The irradiation was made on the ^{11}B -beam of energy 24 MeV/nucleon, obtained from U-400M cyclotron (JINR, Dubna). The targets along with Al-foils in a form of stack were placed normal to beam direction. The activities accumulated in targets were recorded using HPGe detectors. The radionuclides produced in large range of masses, including masses close to the target and fission like fragments, have been allowed to analyse the contribution of the different reaction channels. The presence of such isotopes as Tl, Au, Hg, Pt serves as an indication of the possible contribution of the processes followed to relatively lower excitation energy than in the total fusion. A number of measured nuclei has been used for the presentation of the fission like fragment mass-yield for two limiting energies 255 MeV and 137 MeV. The obtained fission cross sections were achieved the essential exceeding in comparison with those for α -particle at the same energy range [1]. The results expected from calculations using code PACE4 were shown an excess approximately 40% over experimental data for both energies. This comparison can point to the suppression of the complete fusion process in this energy range $\sim 40\%$. The similar quantitative estimation of the suppression probability on the fusion process at energies above Coulomb barrier was obtained in a number of other works for reactions induced weakly bound and α -composed projectiles [2,3]. On the other hand the suppression of the complete fusion process is appeared by the presence of a number of the products close to the target produced obviously via incomplete fusion. The subsequent analysis of experimental data can give the more exactly estimation for the suppression or survival of the fusion process at high energy reactions.

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SUB-BARRIER FUSION: DOES REARRANGEMENT OF NEUTRONS PLAY A ROLE?

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Study of the fusion reactions at near-barrier energies has a long history. There was a great progress in understanding of the role of coupling of the relative motion with collective degrees of freedom such as rotations of statically deformed nuclei and vibrations of nuclear surfaces. The sub-barrier fusion enhancement due to the excitation of collective states is well understood and can be properly described within the quantum channel-coupled [1,2,3] or equivalently within empirical channel-coupled (ECC) [4,3] calculations. Extra enhancement of the sub-barrier fusion was found for some systems having positive Q -values of the neutron transfer (the $^{40}\text{Ca} + ^{90,96}\text{Zr}$ case [5], for example) and attributed to the additional coupling with the neutron rearrangement channels. The strong effect of the neutron rearrangement was predicted [6] and then confirmed experimentally [7,8] for the fusion of weakly bound nuclei such as ^6He as compared with fusion of ^4He .

The neutron rearrangement was quite consistently incorporated into the ECC approach using semiclassical approximation for the transfer probability [6] (note, that it is rather difficult to include the neutron rearrangement channels to the quantum channel-coupled approach). The ECC model with neutron rearrangement has already been successfully used to reproduce and predict cross sections for the sub-barrier fusion reactions of stable nuclei [6,9,10].

However the understanding of the influence of the neutron rearrangement on the sub-barrier fusion is not yet completely clear. For example, recent experimental studies reveal that in such systems as $^{60}\text{Ni} + ^{100}\text{Mo}$ [11], $^{58}\text{Ni} + ^{130}\text{Te}$ [12] no sub-barrier fusion enhancement is observed even in the presence of positive and rather large Q -values for neutron rearrangement. These results show that there are another factors (beyond large positive Q -values) influencing the enhancement of the sub-barrier fusion due to neutron rearrangement.

This work is aimed at the clarification of the mechanism of the neutron rearrangement in the fusion reactions. Both "positive" and "negative" (with and without effect of neutron rearrangement) experimental observations are explained. Sufficient conditions determining the role of neutron rearrangement channels in the sub-barrier fusion are formulated. Finally, we propose several combinations of colliding nuclei with large effect of neutron rearrangement to be studied experimentally.

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PROBING NEUTRON-SKIN THICKNESS OF UNSTABLE NUCLEI WITH TOTAL REACTION CROSS SECTIONS

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We report on our recent analysis of the total reaction cross sections, σ_R , of unstable nuclei and discuss their sensitivity to the neutron-skin thickness,

$$\delta = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle} \quad [1].$$

A study of the neutron-skin thickness has attracted much interest. The knowledge of the skin thickness gives more insight into the properties of neutron-rich nuclei and neutron stars, and the equation of state of asymmetric nuclear matter. Since the neutron distribution is difficult to probe, measurements of the skin thickness are still not as precise as those of the proton radius. Here we discuss the possibility of determining the skin thickness using σ_R . The σ_R is easily and accurately measured as long as they are produced sufficiently. The recent radioactive ion beam facilities allow us to measure precise σ_R for neutron-rich Ne and Mg isotopes [2,3].

The σ_R is calculated with the Glauber model using projectile densities obtained with the Skyrme-Hartree-Fock method on the three-dimensional coordinate space. We cover 91 nuclei of O, Ne, Mg, Si, S, Ca, and Ni isotopes. Defining a reaction radius,

$$a_R = \sqrt{\sigma_R/\pi}$$

to characterize the nuclear size and target (proton or ^{12}C) dependence. We see the ^{12}C target probes the matter radius, and the proton target has some sensitivity to the skin-thickness. Based on the systematic analysis of the a_R (σ_R), we find an empirical formula for expressing a_R with the point matter radius and the skin thickness, and two practical ways of determining the skin thickness are proposed:

1. Measure a_R at different energies on the proton target
2. Measure a_R for the different targets

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TOTAL REACTION CROSS-SECTION for the ${}^6\text{He}+{}^9\text{Be}$ SYSTEM

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This work consists of the study of the ${}^6\text{He}+{}^9\text{Be}$ collision at two energies $E_{\text{lab}}=16.2$ MeV and 21.3 MeV. The measurements was performed at the 8 MV Pelletron accelerator of the Physics Institute of the University of Sao Paulo, Brazil, using the RIBRAS facility [1]. The RIBRAS system consists of two superconducting solenoids used to select and focus the ${}^6\text{He}$ secondary beam, that was produced by the ${}^9\text{Be}({}^7\text{Li}, {}^6\text{He})$ reaction with a ${}^7\text{Li}$ primary beam of 300 nA. The detection system consisted of four ΔE -E silicon telescopes, with 20 microns and 1000 microns thickness respectively, which allow to separate the ${}^6\text{He}$ particles from the ${}^7\text{Li}$ beam contaminant and light particles. The elastic scattering angular distributions have been analysed in the context of several theoretical models, using the computer code FRESCO [2]. The total reaction cross section have been obtained

and are compared in a systematics of the total reaction cross sections of systems involving stable weakly bound and tightly bound projectiles on ${}^9\text{Be}$ target. An analysis of the enhancements observed in the total reaction cross section induced by ${}^6\text{He}$ on light, medium mass and heavy targets is presented.

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TOTAL REACTION CROSS SECTION EXCITATION FUNCTION FOR ${}^6\text{He}$, ${}^8,{}^9\text{Li}$ PARTICLES WITH ${}^{181}\text{Ta}$, ${}^{59}\text{Co}$, ${}^{28}\text{Si}$, ${}^9\text{Be}$ NUCLEI

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Total reaction cross section excitation function $\sigma_R(E)$ was measured for ${}^6\text{He}$, ${}^8\text{Li}$ and ${}^9\text{Li}$ secondary beams on ${}^{181}\text{Ta}$, ${}^{59}\text{Co}$, ${}^{28}\text{Si}$ and ${}^9\text{Be}$ targets in a wide energy range using a direct and model-independent method. This experimental method is based on a 4 Π -technique applied in event-by event mode [1,2]. A high efficiency (4 Π -geometry) CsI(Tl) γ -spectrometer was used for the detection of reaction products (prompt γ -quanta and neutrons) occurring at each impact of a beam particle on the target. The energies of ${}^6\text{He}$, ${}^8\text{Li}$ and ${}^9\text{Li}$ particles have been changed in a wide energy range $E_{\text{beam}} \sim [5\text{A MeV} \div 30\text{A MeV}]$. Secondary beams have been provided by ACCULINNA facility [3] of FLNR JINR. This is a single achromatic stage fragment separator accomplished by TOF transport line (the TOF base is 8 m long) for particle-by-particle identification. The ACCULINNA was initially tuned to deliver a mixed beam of ${}^6\text{He}$ and ${}^8\text{Li}$ particles with roughly equal relative intensities. The measuring was done with all series of targets and then the energy of ${}^6\text{He}$ and ${}^8\text{Li}$ was changed. In this way we could collect experimental data for different targets in the same conditions. Measured $\sigma_R(E)$ data for ${}^6\text{He} + {}^{\text{nat}}\text{Si}$ reaction was compared with $\sigma_R(E)$ [4] measured by the transfer technique [5]. This comparison gave as an additional stability control of the 4 Π -technique.

The measured $\sigma_R(E)$ data for the above mentioned reactions are compared with a different theoretical predictions.

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EXCITED STATES OF HELIUM ISOTOPES ${}^{6,7}\text{He}$

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The excited states of heavy helium isotope ${}^{6,7}\text{He}$ were studied in stopped pion absorption on ${}^{10,11}\text{B}$ nuclei. The measurements were carried out at low energy pion channel of LANL with two-arm multilayer semiconductor spectrometer [1].

In three reaction channels ${}^{11}\text{B}(\pi^-, dt){}^6\text{He}$, ${}^{10}\text{B}(\pi^-, pt){}^6\text{He}$ and ${}^{10}\text{B}(\pi^-, dd){}^6\text{He}$ ${}^{10}\text{B}(\pi^-, pt)X$ the ${}^6\text{He}$ state with $E_x \approx 3.5(3)$ MeV and $\Gamma \approx 3.1(4)$ MeV has been first observed. At high excitation new levels of ${}^6\text{He}$ have been found with $E_x \approx 9.3(2)$ MeV, $\Gamma \approx 1.0(4)$ MeV, $E_x = 22(1)$ MeV, $\Gamma = 2.7(1.4)$ MeV and $E_x = 27.0(8)$ MeV, $\Gamma = 2.5(1.1)$ MeV in the ${}^{10}\text{B}(\pi^-, pt)X$ channel.

Excitation spectrum of ${}^7\text{He}$ has been studied in three reaction channels ${}^{11}\text{B}(\pi^-, pt){}^7\text{He}$, ${}^{11}\text{B}(\pi^-, dd){}^7\text{He}$ and ${}^{10}\text{B}(\pi^-, pd){}^7\text{He}$. The first time in one experiment it was observed three low-lying narrow ($\Gamma < 0.5$ MeV) states with $E_x = 3.1(1)$, $4.9(2)$ and $6.7(2)$ MeV. At high excitation new levels have been found with $E_x \approx 19.8(3)$ MeV, $\Gamma \approx 1.5(3)$ MeV and $E_x = 24.8(4)$ MeV, $\Gamma = 4.6(7)$ MeV.

In the experimental data an abnormally low level of ${}^7\text{He}$ at $E_x \sim 1$ MeV was not found.

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MEASUREMENTS OF THE TOTAL REACTION CROSS SECTIONS FOR ${}^{6,8}\text{He}$, ${}^{8,9}\text{Li}$ AND ${}^8\text{B}$ NUCLEI ON ${}^{27}\text{Al}$, ${}^{181}\text{Ta}$ AND ${}^{208}\text{Pb}$

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Preliminary results of measurements of the total reaction cross sections (σ_r) for weakly-bound ${}^{6,8}\text{He}$, ${}^{8,9}\text{Li}$ and ${}^8\text{B}$ nuclei with energies of (15-33) A MeV on ${}^{27}\text{Al}$, ${}^{181}\text{Ta}$ and ${}^{208}\text{Pb}$ targets are presented. A secondary beams of ${}^{6,8}\text{He}$, ${}^{8,9}\text{Li}$ and ${}^8\text{B}$ were produced by bombardment of the ${}^{11}\text{B}$ (33 A MeV) primary beam on a Be (89 mg/cm²) target and separated by COMBAS fragment-separator [1]. In dispersive focal plane (F₁), a horizontal slit defined the momentum acceptance as 1%, and a wedge degrader of 200- μm Al was installed. The $B\rho$ of a second section of fragment-separator (after F₁) was adjusted for measurements in energy range 15-33 A MeV. The position of secondary beams at the reaction targets (${}^{27}\text{Al}$, ${}^{181}\text{Ta}$ and ${}^{208}\text{Pb}$) was determined by parallel-plate avalanche counters and diaphragm (ϕ 15 mm). Time-of-flight (TOF) between RF cyclotron and ΔE (100 μm) detector (before the reaction target) was determined. After the reaction targets, the scattered particles were detected by two Si ΔE detectors 300- μm (32 X-stripes, 64x64 mm²) and 1000- μm (32 Y-stripes, 64x64 mm²) and E-detector from scintillation CsI/Tl wall (64x64 mm²), which consisted from nine CsI/Tl granules (each granule 8 x 18 mm² surface and thickness 20 mm). Analysis measured $\sigma_r(b)$ for weakly-bound ${}^{6,8}\text{He}$, ${}^{8,9}\text{Li}$ neutron halo nuclei and ${}^8\text{B}$ proton halo nucleus on ${}^{27}\text{Al}$, ${}^{181}\text{Ta}$ and ${}^{208}\text{Pb}$ targets is in a progress.

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ANALYSIS OF INTERACTION CROSS-SECTIONS OF IONS ${}^6\text{He}$, ${}^8,9\text{Li}$ WITH NUCLEI $A = 9 - 181$ AT LOW ENERGIES

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Reactions with weakly bound nuclei have many unique characteristics, some of which have been actively discussed in recent publications [1]. The analysis of experimental interaction cross-sections using modern phenomenological and semi-microscopic models is highly relevant for obtaining new information regarding structural characteristics of nuclear matter.

Within the framework of the optical model an analysis of new experimental data on reactions total cross-sections of light, weakly bound nuclei ${}^6\text{He}$, ${}^8,9\text{Li}$ with stable nuclei ${}^9\text{Be}$, ${}^{28}\text{Si}$, ${}^{59}\text{Co}$, ${}^{181}\text{Ta}$ at (12 – 21) A MeV energies has been performed by us.

The energy dependence of reactions total cross-sections (${}^6\text{He}+{}^9\text{Be}$) in the energy range $E = (1.37 - 25)$ A MeV was studied in detail. For this reaction, as a result of joint analysis of experimental data (angular distributions [2] of elastic scattering and reactions total cross-sections), optimal parameters of the optical potential and radial characteristics of the investigated nuclei were found.

The data from the work [3] was taken as starting parameters for the optical potential. Using them it was possible to obtain good correlation of the theoretical and experimental differential cross-sections of elastic scattering and total cross-sections.

From the analysis (based on the semi-microscopic folding model) of experimental interaction cross-sections of ions ${}^6\text{He}$, ${}^8,9\text{Li}$ with stable nuclei the radial characteristics of the investigated nuclei were extracted.

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NEW VISION FOR OLD PHYSICS OF ALPHA CLUSTERS IN NUCLEI

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Recent development of theoretical approaches resulted in unified calculation of the shell model and the alpha cluster structures in atomic nuclei. These developments are the most evident in the progress of *ab initio* calculations [1-3] as well as in more traditional model approaches [4-6].

Simultaneously new experimental findings are stimulated by extensive astrophysical interest and by new possibilities provided by rare beams [7-10].

I will review these general trends and consider some specific examples. A first detailed recent results (experiments and calculations) will also be presented for $N \neq Z$ nuclei.

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FEW-BODY MODELS OF LIGHT NUCLEI

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Experiments indicate cluster structure in many light nuclei. In these cases the many-body dynamics of nuclear structure may be well approximated by few-body cluster models that often suggest conceptually simple approaches explaining successfully many features of light nuclei. Few-body cluster models are frequently used for a description of the nuclear structure of weakly bound nuclei. They have attractive features supplying in the most transparent way the asymptotic behavior and continuum properties of weakly bound systems. Such models assume a separation in the internal cluster (core) degrees of freedom and the relative motion of few-body constituents. Such separation is only an approximation. Still in many circumstances the core cannot be considered as inert system and additional degrees of freedom connected to excited core states have to be taken into account. For fixed total angular momentum a coupling with excited core states having different spins involves additional partial waves into the consideration. This allows to account for some emergent core degrees of freedom and get a more realistic description of nuclear properties. It is an analog to increasing the number of shells within the framework of shell-model approaches.

In this work the properties of the bound states and low-lying resonances in ¹¹Be and ¹²Be nuclei have been explored within the few-body cluster models with core excitations included.

THE MICROSCOPIC ANALYSIS OF THE NEUTRON TRANSFER AND FUSION REACTIONS WITH NUCLEI ${}^6\text{He}$ AND ${}^8\text{He}$

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Coupled channels equations with neutron transitions between two-center states proposed in work [1] and the time-dependent Schrödinger equation with the paired interaction were solved for reactions ${}^6,8\text{He}+{}^{197}\text{Au}$ and ${}^6,8\text{He}+{}^{209}\text{Bi}$. Results of coupled channels calculations with the proximity potential for the formation of the ${}^{198}\text{Au}$ isotope cross section and for fusion cross section agree satisfactorily with the experimental data [2-5] near the barrier $V_B \approx 20$ MeV (Fig. 1). The cross section of the transition $1p_{3/2}({}^6\text{He}) \rightarrow 3d_{5/2}({}^{198}\text{Au})$ has the maximum below the barrier. This reason gives qualitative explanation of the presence of the maximum of the ${}^{198}\text{Au}$ isotope formation cross section near the barrier. The enhancement of the fusion cross section in the reaction ${}^6\text{He}+{}^{197}\text{Au}$ in comparison with the reaction ${}^4\text{He}+{}^{197}\text{Au}$ is explained by the decreasing of the two-center energy level $1p_{3/2}({}^6\text{He})$ near the barrier.

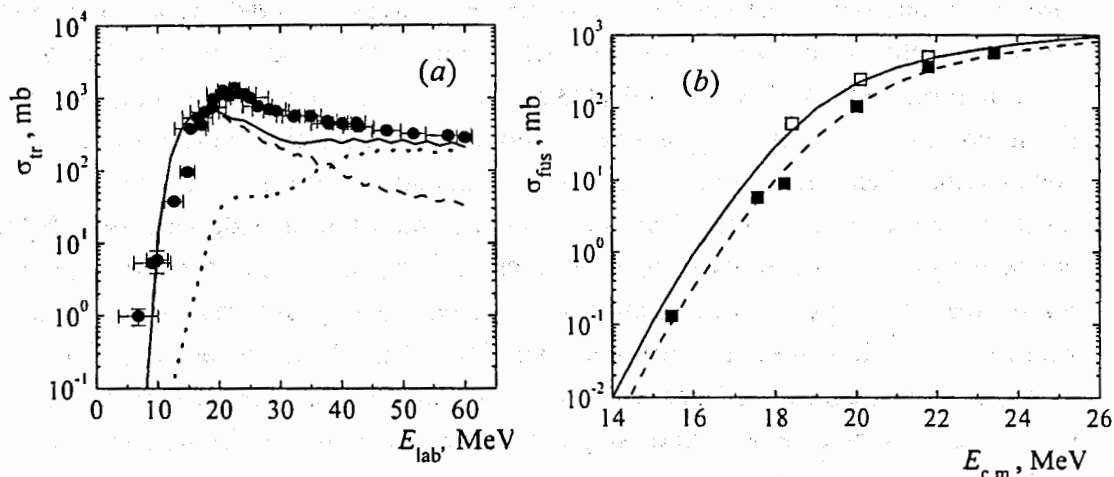


Fig. 1. (a) The energy dependence of the cross section for the formation of the ${}^{198}\text{Au}$ isotope in the ${}^6\text{He}+{}^{197}\text{Au}$ reaction. Filled circles represent the experimental data from [2]; the solid line the calculation for the transfer of one neutron, the dashed line the calculation for the transition $1p_{3/2}({}^6\text{He}) \rightarrow 3d_{5/2}({}^{198}\text{Au})$; the dotted line the calculation for the transition $1p_{3/2}({}^6\text{He}) \rightarrow 1j_{15/2}({}^{198}\text{Au})$; (b) Measured (symbols) and calculated (lines) fusion cross section as a function of center-of-mass energy $E_{c.m.}$ for ${}^4\text{He}+{}^{197}\text{Au}$ (filled squares and the dashed line) and ${}^6\text{He}+{}^{197}\text{Au}$ (empty squares and the solid line) reactions [3, 4, 5].

This work was partially supported by the Russian Foundation for Basic Research (RFBR), research project No 13-07-00714-a.

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PAIRED AND QUASISTATIONARY WAVE FUNCTIONS FOR HALO NUCLEI AND DECAYS

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Wave functions of paired valence $1p_{3/2}$ neutrons of halo nuclei ${}^6\text{He}$, ${}^8\text{He}$ were calculated by the iterative solving of the Schrödinger equation. The axial self-consistent potential $V_{\text{pair}}(\mathbf{r}) = C\rho_{n,l,j,m_j}(\mathbf{r})\delta_{m_j,-m'_j}$ proportionate to the probability density ρ_{n,l,j,m_j} of the state with the defined value of the total angular momentum projection m_j was used as a model of the pairing interaction [1]. These functions were used as initial conditions for the time-dependent Schrödinger equation solving [2, 3] for reactions ${}^{6,8}\text{He}+{}^{197}\text{Au}$ and ${}^{6,8}\text{He}+{}^{209}\text{Bi}$. The difference method of the computation of energies and wave functions of quasi-stationary states of neutrons in nuclei ${}^5\text{He}$, ${}^7\text{He}$ and protons, alpha-particles (Fig. 1), [4] and heavy clusters in heavy nuclei is offered. This method based on the join of the solution with the small probability flow through the barrier and the solution without such flow. In the model with the surface cluster area (Fig. 1) the probability of the formation of alpha-particles in even-even isotopes of uranium is determined.

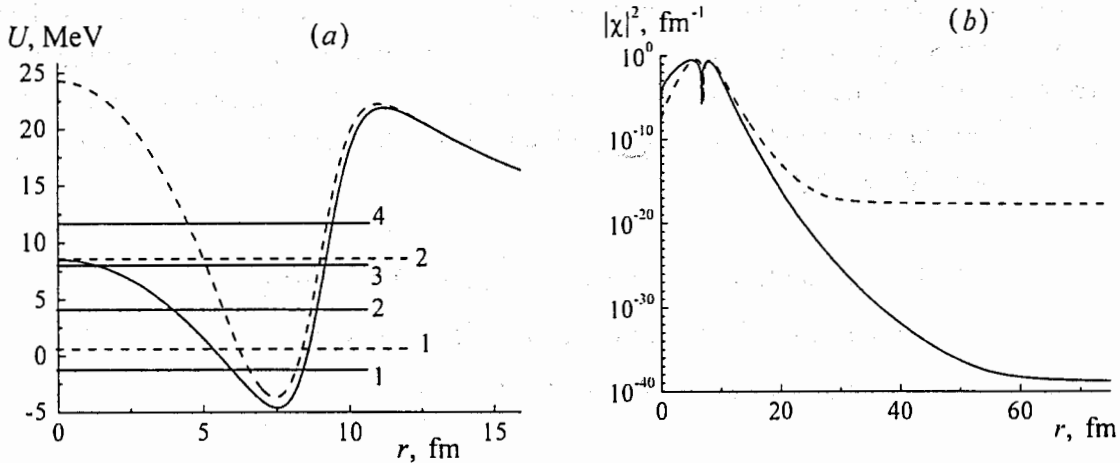


Fig. 1. Potential energies, levels of energy with numbers 1 – 4 (a) and the radial probability density $|\chi(r)|^2$ for the second quasi-stationary level (b) of an alpha-particle in nuclei ${}^{238}\text{U}$ (full curves) and ${}^{224}\text{U}$ (dashed curves) in the model with the surface cluster area for an orbital angular momentum $L=0$.

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FIRST EXPERIMENTS AT THE FRAGMENT-SEPARATOR ACCULINNA-2: HYDROGEN-7

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Hydrogen-7 represents one of the most intriguing puzzles in modern nuclear physics. This system has the largest proton-neutron asymmetry possible in nuclei (the other realistic nuclear system with such a large N/Z ratio is ^{12}He which is not expected to form a narrow resonance). Its decay pattern is expected to be the extremely exotic 5-body $t+4n$ channel with simultaneous emission of 4 neutrons [1]. For sufficiently low decay energies (so far not excluded by the experimental data) a radioactivity-scale lifetime can be expected for this decay channel [2,3]. We propose to search for the ^7H g.s. using the quasifree $(\alpha, 2\alpha)$ knockout reaction from ^{11}Li , as the ^{11}Li WF has a spatially extended halo, and the halo part of ^{11}Li WF has an important $[s^2]$ component which can lead to a better overlap with the $[s^2p^2]$ part of the ^7H WF after a knockout reaction. In the quasi-free scattering $^4\text{He}(^{11}\text{Li}, 2\alpha)^7\text{H}$ reaction an α -particle is knocked out from ^{11}Li by the alpha target nucleus and the detection of these two α -particles is sufficient to extract the missing mass of ^7H . The use of telescopes composed of a set of micro-strip Si detectors provides a reconstruction of the vertex position inside the target with an accuracy of about ± 100 μm . This accuracy also allows a very thick target which is only limited by the energy loss of the outgoing α -particles.

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INTERNAL STRUCTURES OF ${}^9,{}^{10}\text{Be}$ AND ${}^{10}\text{B}$ IN SCATTERING OF ${}^4\text{He}$ FROM ${}^9\text{Be}$

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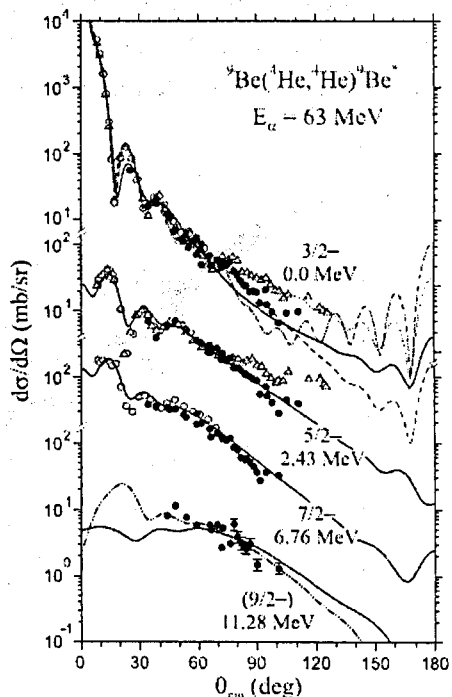
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Angular distributions of the differential cross sections for the ${}^9\text{Be}(\alpha, \alpha){}^9\text{Be}^*$, ${}^9\text{Be}({}^4\text{He}, {}^3\text{He}){}^{10}\text{Be}$ and ${}^9\text{Be}({}^4\text{He}, t){}^{10}\text{B}$ reactions were measured [1]. The observed states are most likely populated in one-step direct transfer reactions. Experimental angular distributions for ground and a few low lying states were described within the optical model and distorted-wave Born approximation frameworks. Fig. 1 shows measured differential cross sections for the elastic and inelastic scattering (symbols) together with the results of theoretical calculations (curves) performed within optical model and coupled channel approaches [2].

Spectroscopic factors for the ground and excited states of ${}^{10}\text{B}$ and ${}^{10}\text{Be}$ were deduced and compared with [3]. The values $9/2^-$ were assigned to the spin and parity of the 11.28 MeV state in ${}^9\text{Be}$. However, it doesn't allow to give unambiguous preference to one of the possible configurations $\alpha+\alpha+n$ or $\alpha+{}^5\text{He}$. In order to improve the agreement between the Theoretical prediction and the experimental data, related to this $9/2^-$ state, an additional hexadecapole term β_4 in the definition of the ${}^9\text{Be}$ radius had to be introduced. With respect to ${}^{10}\text{Be}$, it was found that in order to describe the data one needs a much smaller radius of the real part of the optical potential for the exit channel ($r_V = 0.95$ fm) in comparison to the radius in the entrance channel ($r_V = 1.40$ fm). This could be interpreted as evidence for the compactness of the ${}^{10}\text{Be}$ nucleus.



The comparison of the differential cross sections for the isobaric analog states of ${}^{10}\text{Be}$ and ${}^{10}\text{B}$ was done. The structure of ${}^{10}\text{Be}$, ${}^{10}\text{B}$ and ${}^{10}\text{C}$ nuclei was usually considered as two α -clusters in the presence of two extra nucleons. One may see that the ${}^{10}\text{B}$ ground state could be treated as a three cluster configuration ${}^{10}\text{B} = \alpha+d+\alpha$, where the pairing of proton and neutron results in formation of a deuteron cluster inside ${}^{10}\text{B}$. In the case of the 1.74 MeV excited state, it might be considered as a state where the deuteron cluster becomes unbound. Thus, it becomes a four-body configuration ${}^{10}\text{B}(0+, 1.74 \text{ MeV}) = \alpha+p+n+\alpha$, i.e. two α -clusters with an uncorrelated proton and neutron pair.

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STUDY OF CLUSTER STRUCTURE OF LIGHT NUCLEI BY PROTON QUASIFREE SCATTERING AT LOW ENERGIES

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Availability of radioactive nuclear beams led to the discovery of unusual structure at the periphery of the nucleus – a neutron or a proton halo. However, even for the most studied ${}^6\text{He}$ halo nucleus the structure of its halo (dineutron or cigar-like configuration) is not completely determined.

In this work, we consider a possibility to study the structure of halo nuclei (${}^6\text{He}$, ${}^8\text{He}$) using the reaction of quasifree scattering (QFS) of proton by the clusters composing these nuclei. As clusters of ${}^6\text{He}$ and ${}^8\text{He}$ we considered ${}^6\text{He}$, ${}^4\text{He}$, n and 2n . To determine the kinematical regions allowed for proton kinematical calculations were performed for reactions ${}^{6,8}\text{He}+p \rightarrow p+C+S$, where C and S are clusters constituting the halo nucleus: cluster C is involved in proton QFS, and cluster S is a spectator. By definition, the spectator does not undergo scattering and continues moving with the same total momentum as that which it had in the incident halo nucleus.

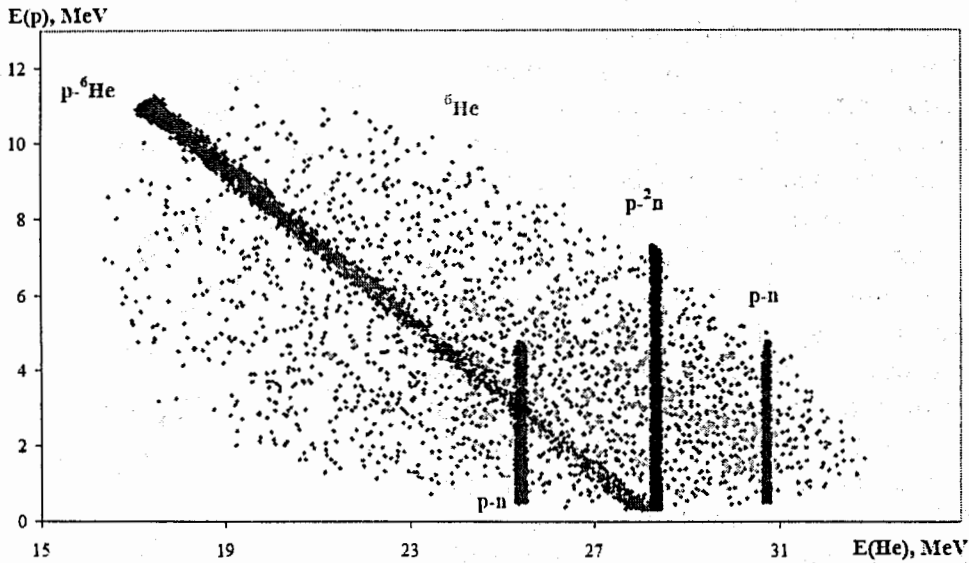


Fig.1. Two-dimensional plot $E_{\text{He}}-E_p$ for proton QFS by clusters of ${}^8\text{He}$ (or ${}^6\text{He}$). $E_{8\text{He}}=40$ MeV. Grey dots represent calculation for ${}^8\text{He}+p \rightarrow {}^6\text{He}+p+n+n$ breakup reaction.

The simulation results for proton QFS by ${}^6\text{He}$, n and 2n clusters of ${}^8\text{He}$ are presented in Fig. 1 as a two-dimensional plot $E_{\text{He}}-E_p$. One can see that events of quasi-free proton scattering by different clusters occupy different regions in the two-dimensional Dalitz plot. Thus we can hope that experimental study of proton quasi-free scattering by constituents of halo nuclei allow one to determine their cluster structure.

EXPOSURES OF NUCLEAR TRACK EMULSION TO LIGHT RADIOACTIVE NUCLEI, NEUTRONS AND HEAVY IONS

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Nuclear track emulsion (NTE) stays to be a versatile and inexpensive technique for forefront researches. In JINR samples of reproduced NTE have been exposed to 1.2 A GeV ^{11}C nuclei, 7 A ^8He nuclei, thermal and fast neutrons and 1.2 A MeV Kr and Xe ions. NTE has retained its position as a means for studying a nuclear clustering via relativistic fragmentation [1]. The Nuclotron allows one to expose NTE to light radioactive nuclei. Data on coherent dissociation of the nuclei ^{11}C in NTE are discussed.

Using the ACCULINNA separator ^8He nuclei were implanted into NTE which allowed to observe a drift of ^8He atoms and to derive the distribution over decay energy $Q_{2\alpha}$ [2]. The established "tail" of large values $Q_{2\alpha}$ could allow one to examine a structure of the state $^8\text{Be}_{2+}$. Correlations of α -particles $^{12}\text{C} \rightarrow 3\alpha$ are studied in NTE exposed to 14.1 MeV neutrons of the apparatus DVIN [3]. Energy distributions $Q_{2\alpha}$ and $Q_{3\alpha}$ indicate on superposition of the ^8Be 0^+ and 2^+ states in the ^{12}C ground state at that $^8\text{Be}_{2+}$ is dominating. NTE enriched with boron is exposed to thermal neutrons at the reactor IBR-2 allow one to extend range calibration for the ^7Li nucleus using events $n_{\text{th}} + ^{10}\text{B} \rightarrow ^7\text{Li} + (\gamma) + \alpha$. Angular and energy correlations of the reaction products are studied.

There is a prospect of an NTE application in physics of a ternary fission. It is necessary to perform range calibrations and to estimate of angular resolution for an available variety of heavy ions. NTE samples without light protection paper are exposed to ions $^{86}\text{Kr}^{+17}$ and $^{132}\text{Xe}^{+26}$ at the cyclotron IC-100. Ranges of Kr and Xe ions correspond to the primary energy value. Scatterings of ions degraded in NTE to 300 A keV with a visible recoil nucleus are measured. Progress of analysis of NTE exposure to a ^{252}Cf source will be presented. Number of events analyzed in these pilot studies is a small part of available statistics. NTE provides a basis for the application of automated microscopy and image recognition software, allowing one to rely on unprecedented statistics. Thus, a synergy of classical nuclear technique and modern technology can be achieved. The report is illustrated by macrophotographs of the discussed events.

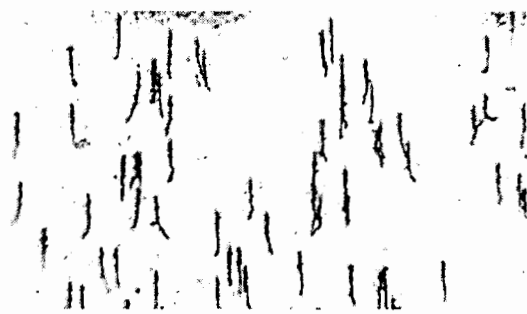


Fig. Macroscopic photograph of NTE exposed to 1.2 A MeV Xe ions.

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FUSION REACTIONS INDUCED BY $^{4,6,8}\text{He}$ ON HEAVY TARGETS

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Fusion cross sections induced by $^{4,6,8}\text{He}$ were studied using different reactions [$^4\text{He}+^{209}\text{Bi}$, $^4\text{He}+^{208}\text{Pb}$, $^4\text{He}+^{197}\text{Au}$], ($^6\text{He}+^{209}\text{Bi}$, $^6\text{He}+^{206}\text{Pb}$, $^6\text{He}+^{197}\text{Au}$) and ($^8\text{He}+^{209}\text{Bi}$, $^8\text{He}+^{204}\text{Pb}$, $^8\text{He}+^{197}\text{Au}$). The reactions [$^4\text{He}+^{208}\text{Pb}$, $^6\text{He}+^{206}\text{Pb}$, $^8\text{He}+^{204}\text{Pb}$] give the same compound nucleus ^{212}Po . Theoretical calculations were done using the Code PACE4 with [the radius parameter $r_0=1.3$ fm, the depth of the real nuclear well $v_0=67$ MeV, the depth of the imaginary nuclear well $w_0=9.5$ MeV, IMAG(I) imaginary well is potential volume and the maximum angular momentum $l_{\text{max}}=30$]. The quantum mechanical transmission probability for one dimensional barrier was used instead of the classical solution to describe the experimental data. Good agreement between theoretical calculations and experimental results are obtained. Our studying shown that evaporation cross sections induced by $^{6,8}\text{He}$ did not effect by targets or compound nuclei and any change in the evaporation cross sections result from the behavior of the weakly bound nuclei $^{6,8}\text{He}$.

Keywords—Fusion reaction, Evaporation channels, Cross sections

MAIN PHYSICAL PROPERTIES OF AN EXOTIC QUASIPARTICLES

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The principal parameters (charge, mass, time of life, conditions of generation and observation) of an exotic quasiparticles had been determined and nuclear processes involved its participation are considered. Our first observations [1,2] showed, that before generation of an exotic quasi particles the used laser system must operate some times in pulse-periodic mode (eliminated metallic targets must be "incandesced"). Now it was repeatedly character caterpillar tracks very similar to that [3], but only an exotic quasiparticles took of from not vacuum chamber. It was shown itself directly in air from target with different time delays: from few minutes to one year after stopping influence of laser beam, when laser-activated target was arranged near on Kodak x-ray film in special protected envelope (or near ILFORD-3200 film in special chamber). The theoretical explanation of the time delay effect of an exotic quasiparticles generation is represented in present report.

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THE TWIN EXOTIC QUASIPARTICLES

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The X-ray images produced by RFR-4 [1] demonstrate us not only discrete trajectory of moving and radiative quasiparticles but also traces of double particles [2]. It is distinctly viewed in CR39-detector [2]. The behavior of such twin particles are different from behavior of magnetic monopoles (or "monopolinos"). If last of them are "very nuclear active" [3] the twin particles are more "quiet".

Now we can propose that it may be dyons. By using F. Wilczek's remarks on dyons [4] and knowing only its typical image size $r_0 \approx 10 \mu\text{m}$ we can estimate the mass of dyons $\approx 10^{-34} \text{ g}$ [2], when $q = e$ (it is easy to show that case when magnetic g and electric q charges are equals to each other is not realistic), and then $g \approx (137/4)e$, i.e. in twice less then possible minimal magnetic Dirac's monopole charge. So dyon can be constructed from two pieces with total magnetic charge $g = g_d$ - minimal magnetic charge of Dirac's monopole. But dyons of course could not being single possible candidate for explanation of our doublet particles observations. In addition, for example, we could proposed, that they can be neutral Higgs particles H^0 which have doublet structure [5] or two positive and negative Higgs bosons [6] but only with extra small masses. Because of, if we have such slight magnetic charges (with mass $\approx 2 \cdot 10^{-35} \text{ g}$, [2]) we must have very slight Higgs bosons too.

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HOW DOES THE NEUTRON REARRANGEMENT WITH POSITIVE Q-VALUES INFLUENCE THE SUB-BARRIER FUSION OF LIGHT WEAKLY BOUND NUCLEI

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Considerable interest is devoted to study of fusion reactions involving light weakly bound nuclei. In these reactions an increase of the fusion cross section at energies below the Coulomb barrier is observed. The processes of the rearrangement of valence neutrons with positive Q-values (that leads to a gain in the kinetic energy of the colliding nuclei) may substantially increase the sub-barrier fusion cross section. It should be noted that deep sub-barrier fusion cross section of ${}^6\text{He}$ with ${}^{206}\text{Pb}$ was predicted [1] to be several orders of magnitude larger as compared with fusion of ${}^4\text{He}+{}^{208}\text{Pb}$ which was fully confirmed later in experiments [2, 3, 4]. Deep sub-barrier fusion of light nuclei (including exotic ones) may be important also for astrophysical nucleosynthesis [5].

Theoretical analysis of the role of weakly bound neutrons in the process of sub-barrier fusion is very complicated, because it requires a simultaneous account for the break-up, neutron transfer and total fusion channels within one model. Note, that at sub-barrier energies the possible effect of the break-up channels is rather small as compared to the one caused by the neutron rearrangement. In addition, coupling to surface vibrations and rotation of heavy target is less important for fusion of light nuclei because of their small size. However just the rearrangement of nucleons at approaching stage may lead to significant sub-barrier fusion enhancement owing to large positive Q-values.

In this work an empirical coupling channel model (ECC model) [1, 6] is used for analysis of the sub-barrier fusion reactions with account for neutron rearrangement. The aim of this work is to study the mechanism of the neutron rearrangement in the fusion reactions with light weakly bound nuclei. The reactions with neutron rich as well as proton rich light nuclei are considered.

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MOMENTUM DISTRIBUTIONS IN STRIPPING REACTIONS OF HALO NUCLEI ON LIGHT TARGET

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Analytical methods of calculation were used repeatedly within the diffractive theory of reactions induced by weakly bound nuclei (see e.g. [1-4]). Particularly, the nucleon stripping reaction induced by the halo nucleus on the light target was considered in [3]. The approximate expression for the differential cross section for this reaction was obtained in the limiting case when the effective radius of the target is much less than the decay length of the halo wave function.

In the present work an improved version of the small target approximation is proposed for the nucleon stripping reaction of the halo nucleus, consisting of the core and nucleon. Black disk model for description of the constituent-target interactions and Yukawa's wave function for the nucleon-core system are used. Simple analytical expressions are obtained for the differential cross section and longitudinal momentum distribution of core fragments, the appropriate corrections being proportional to the target radius to halo size ratio squared. It follows from numerical calculations made for light target nuclei that accuracy of the approximate expressions increases significantly when these corrections are taken into account.

The small target approximation shown to be applied also to the differential (in longitudinal nucleon momentum) cross section for core stripping reaction of the halo nucleus. In this case a general relationship of the diffractive theory between the cross sections for both stripping reactions must be used additionally.

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EVIDENCE FOR THE STATES WITH ABNORMALLY LARGE RADII IN ^{13}C

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In ^{13}C spectrum there exist different structures: shell model levels, clusters states, neutron halo state. In this paper we analyzed the available data on the inelastic scattering of deuterons, ^3He -ions and alpha-particles at the incident energies 10 – 12 MeV/u and ~ 100 MeV/u leading to the excited states of ^{13}C with the aim to determine the radii of such states within the framework of MDM (Modified diffraction model) [1]. Additionally we measured the differential cross-sections of the elastic and inelastic $^{13}\text{C} + \alpha$ scattering at $E(\alpha) = 65$ MeV to get high-quality data at low energy region where MDM is most adequate.

Excited states $\frac{1}{2}^-$ (8.86MeV, 11.08MeV), lying near the threshold $^{13}\text{C} \rightarrow ^9\text{Be} + \alpha$ and supposed to be candidates for the Hoyle state (the second 0^+ state in ^{12}C , at $E_x = 7.65\text{MeV}$) analogs, have abnormally large radii. Their radii are by a factor 1.2 larger than the ^{13}C radius in its ground state and are close to the radius of the Hoyle state ($\langle R \rangle = 2.89 \pm 0.04$ fm [1]). General agreement with the theoretical predictions [2, 3, 4] was observed.

The 3.09 MeV ($\frac{1}{2}^+$) state is predicted to have a neutron halo. Its radius determined by MDM is $R_{\text{rms}} = 3.01 \pm 0.08$ fm. An estimate made from the position of the Airy minimum gives $R_{\text{rms}} = 3.0$ fm. A neutron halo radius of this state was obtained [5] from the analysis of the $^{12}\text{C}(d,p)^{13}\text{C}$ reaction at $E_d = 25$ MeV. It can be used for evaluating the corresponding RMS which occurred to be $R_{\text{rms}} = 2.68 \pm 0.26$ fm. Thus, all three independent methods gave similar results increasing the reliability both of the halo existence in the 3.09 MeV state and the models used for radii determination.

The 9.90 MeV ($3/2^-$) state is strongly excited in the α -transfer reactions and by some predictions is a possible head of a rotational band. The preliminary analysis shows that the predicted radius enhancement [6] probably does not take place.

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NEW ROTATIONAL BAND IN ^{11}B

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There are predictions [1, 2] based on the model of antisymmetrized molecular dynamics (AMD) and alpha-condensate models that the state in ^{11}B $\frac{1}{2}^-$, $E^* = 8.56$ MeV has the mean-square radius RMS, which is much larger than the radius of the ground state. Moreover, there are predictions [3, 4] about the existing the rotational band based on the 8.56 MeV ($3/2^-$) state.

For verification of these predictions two experiments on $^{11}\text{B} + \alpha$ scattering were performed at $E_\alpha = 65$ MeV (Jyväskylä, Finland) and 40 MeV (last data were partly published in [5]). The radii values were determined using Modified Diffraction Model [6].

The value of the 8.56 MeV state radius was determined to be $\langle R \rangle = 2.68 \pm 0.15$ fm, which is 0.4 fm larger than the radius of the ground state what is in agreement with previous data [7] and AMD calculations [1]. This value is close to the radius of the Hoyle state in ^{12}C indicating to the similarity of their structures.

We got preliminary results for the differential cross-section of the inelastic scattering leading to 10.34 MeV ($5/2^-$), 11.6 MeV ($7/2^-$) and 13.1 MeV ($9/2^-$) states. These states are predicted [3, 4] to be members of the rotational band based on the 8.56 MeV ($3/2^-$) state. The behavior of the angular distributions of the inelastic scattering confirms this suggestion. Thus we got evidence that the rotational band under discussion and the band based on the Hoyle state demonstrate some common features.

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DECAY MECHANISM OF LIGHT MASS NUCLEI AND RELATED DEFORMATION EFFECTS

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In low energy regime, the decay study of light mass nuclei is of considerable importance as it offers a wide range of possibilities for exploring structural properties of constituent nuclei and related nuclear processes. With an aim to address the dynamics involved in asymmetric heavy ion reactions $^{12}\text{C}+^{28}\text{Si}$ and $^{11}\text{B}+^{28}\text{Si}$ leading to light mass $^{40}\text{Ca}^*$ and $^{39}\text{K}^*$ nuclei, the collective clusterization approach is applied to study the decay cross-sections in reference to experimental data of [1]. In framework of the dynamical cluster decay model DCM [2], the fragment mass identification corresponding to given charge spectra and role of quadrupole (β_2) deformation on the decaying fragments has been investigated. For both the nuclei the cross-sections for $Z=3,4,5$ have been fitted using only parameter of the model, neck-length parameter ΔR . For, $^{40}\text{Ca}^*$ system with spherical approach, favorable isotopes for $Z=3$ are $A_2=5,6,7$, for $Z=4$ is $A_2=8$ while for $Z=5$ the masses $A_2=9,10$ are prominent. However, for the β_2 -deformed fragmentation, $A_2=4,5,6,7$ contribute corresponding to $Z=3$ while rest remain identical. On the contrary for $^{39}\text{K}^*$ nucleus, $A_2=6,7$ for $Z=3$, $A_2=8,9$ for $Z=4$ and $A_2=10,11$ for $Z=5$ are most prominent isotopes independent of choice of fragmentation. From Fig.1 it is evident that fragments with masses $A_2=5$ and 12 for $^{40}\text{Ca}^*$ and $A_2=4$ and 11 for $^{39}\text{K}^*$ nucleus have relatively higher potential for β_2 approach. This suggests that although, the projectile and target involved are deformed, the deformations are effective only for few decaying fragments for both the even and odd mass nuclei. In conclusion, using collective clusterization approach the favorable fragment masses constituting towards the decay of doubly magic $^{40}\text{Ca}^*$ and neighboring $^{39}\text{K}^*$ nucleus have been identified for the spherical and β_2 -deformed approach. No significant role of deformations has been observed on the decaying fragments. It is relevant to mention that entrance channel play no role in the decay of $^{39}\text{K}^*$ nucleus for spherical fragmentation. However, it would be of further interest to address entrance channel effects via β_2 -deformed and hexadecapole (β_2 - β_4) deformed approach.

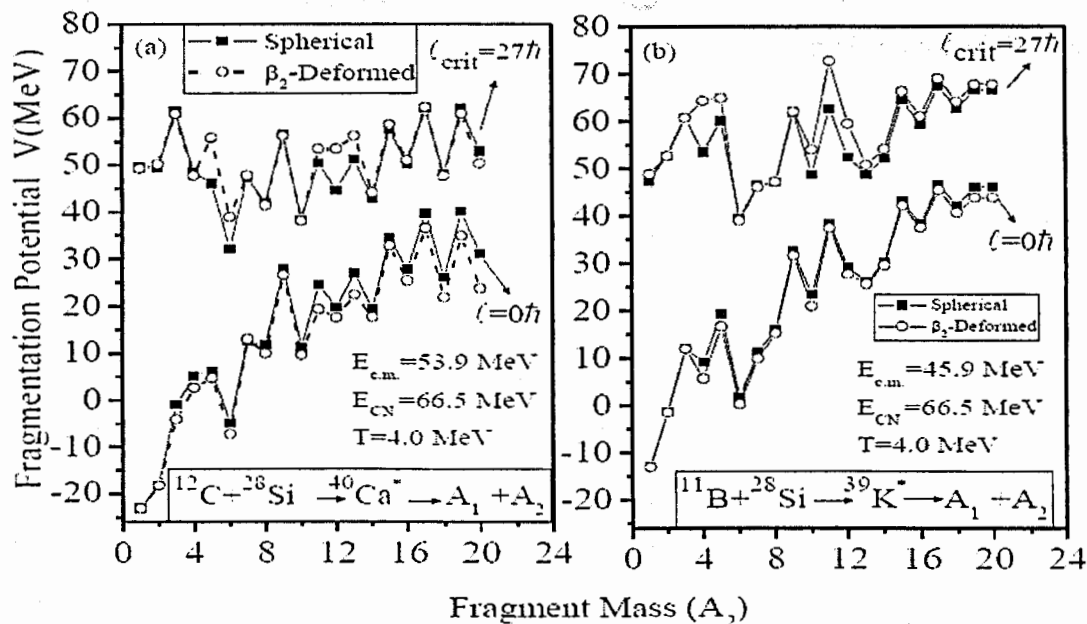


Fig.1 Fragmentation potential plotted to study the role of deformations for the decay of $^{40}\text{Ca}^*$ and $^{39}\text{K}^*$ systems formed at $E_{\text{CN}}=66.5 \text{ MeV}$.

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STUDY OF THE RESONANCE IN THE $\alpha+^{13}\text{C}$ INTERACTION AT LOW ENERGIES

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The study of the resonance reaction $^{13}\text{C}(\alpha,\alpha)^{13}\text{C}$ using Thick Target Inverse Kinematics (TTIK) method was performed at Heavy Ion Cyclotron Complex DC-60 in Astana, Kazakhstan. 22.8 MeV beam of ^{13}C ions were used to take $\alpha+^{13}\text{C}$ data in the region of 1.5-3.6 MeV in center of mass frame. New low energy experimental results important for astrophysics were obtained. This new data structure will be further analyzed by R-matrix approach. The time of flight method using the cyclotron radio frequency signal and the signal from the Si detectors was utilized to perform particle identification process at particular energy region. The method provides good resolution for TTIK for a range of cases of the interaction of heavy ions with helium or hydrogen.

NUCLEI AT THE END OF NUCLEAR MAP

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One of the fundamental outcomes of the nuclear shell model is the prediction of the "stability islands" in the domain of the hypothetical superheavy elements. The enhanced stability has been expected for the deformed nuclei near $Z=108$ and $N=162$, yet much stronger effect has been predicted for heavier spherical nuclei close to the shells $Z=114$ and $N=184$, next to the doubly-magic nucleus ^{208}Pb ($Z=82$, $N=126$).

The talk is devoted to the experimental verification of these predictions – the synthesis and study of both the decay and chemical properties of the superheavy elements.

For the synthesis of the heavy nuclei fusion reactions of the nuclei of ^{208}Pb , ^{209}Bi with the projectiles of ^{50}Ti , ^{54}Cr , ^{70}Zn (cold fusion) have been used, which allowed to investigate decay properties of the nuclides with $Z=104-113$ and $N=151-165$ in the region of the deformed shells $Z=108$ and $N=162$. The synthesis of even heavier and more neutron-rich nuclei has been carried out in the fusion reactions of $^{233,238}\text{U}$, ^{237}Np , $^{242,244}\text{Pu}$, $^{245,248}\text{Cm}$, ^{249}Bk and ^{249}Cf with the ^{48}Ca projectiles (hot fusion), that made it possible to study decay of the 48 neutron-rich nuclides with $Z=104-118$ and $N=161-177$.

The decay properties of the new isotopes present direct experimental evidence of the existence of the Island of stability in the region very heavy (superheavy) nuclei that considerably expand the Periodical Table of the chemical elements.

Further progress of SHE research is related to the studies of nuclear and atomic structure of super heavy elements, fission modes of the neutron-rich nuclides with $Z \geq 104$, as well as the synthesis of the new elements and isotopes in close proximity to the magic numbers protons and neutrons. It is directly associated with new facility – the Factory of SHE- based on new high-current heavy ion accelerator, new setups and more sophisticated detectors. New experimental potentialities will be presented also.

In the talk are used the results obtained in FLNR (Dubna, Russia) in collaboration with LLNL, (Livermore, USA), ORNL (Oak-Ridge, USA), PSI (Villigen, Switzerland) and Vanderbilt University (Nashville, USA) as well as in GSI (Darmstadt, Germany) and RIKEN (Tokyo, Japan).

SEARCH FOR ISOTOPES OF ELEMENT 120 ON THE ISLAND OF SHN

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The existence of the island of Super-Heavy Nuclei (SHN) was experimentally proven at FLNR Dubna in recent years. Decay modes and half-lives of the isotopes produced so far are in accord with most of the predictions of the theoretical models. In addition, the systematics of measured cross-sections can be understood only on the basis of relatively high fission barriers as predicted for nuclei in and around the island of SHN. However, due to experimental constraints (availability of targets, long measuring times at cross-section levels of picobarn and below), the extension of the island in proton and neutron numbers and also the location of the center of highest stability could not yet be explored. Various theoretical models predict proton numbers 114, 120, or 126 and neutron numbers 172 and 184 as closed nucleon shells. Except for the neutron number 172 which can be excluded as a shell closure resulting in increased stability, the existing experimental data are not sufficient for determining the strength of the shells obtained in the calculations. A key role in answering some of the open questions plays the synthesis of isotopes of element 120. In this contribution we will report on experiments aiming to synthesize element 120 at the velocity filter SHIP. The experiments were performed at GSI in collaboration with colleagues from FLNR Dubna, LLNL Livermore, ORNL Oak-Ridge, UT Knoxville, RIKEN Wako-shi, JAEA Ibaraki, JGU Mainz, Comenius University Bratislava, University of Jyväskylä, and University of Warsaw. A publication of the most recent results of experiments performed at SHIP is in preparation, and preliminary results will be presented.

POTENTIAL AND FUTURE OF CHEMICAL INVESTIGATIONS OF SUPERHEAVY ELEMENTS

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The power of chemical techniques to identify an element and thus its atomic number is undisputable. On the other hand, chemical properties are increasingly influenced by the nuclear charge representing the atomic number. These so-called relativistic effects scaling with Z^2 [1] complicate severely this identification especially for the super heavy elements (SHE). Therefore, analytical techniques are developed at the frontiers of nuclear chemistry and radiochemistry, which are able to chemically separate SHE, identify their chemical state, determine properties of these chemical states, and unambiguously detect the single atoms. Such developments require careful long-term preparations using tracers of more abundant elements which reveal chemical properties similar to the SHE. As a first guess, these are the homologues in the corresponding groups of the periodic table. Otherwise, predictions of deviations of chemical properties from the periodic rules have to go hand in hand with the design of the most sensitive experiments. Finally, chemical properties of SHE can be experimentally derived and benchmark not only modern theoretical predictions based on quantum chemical formalisms but also the chemical trends established by the periodic table.

This presentation is focused on gas phase chemical techniques proven to be the most efficient ones for solving these demanding tasks (see for review [2,3]). Here, some selected more recent developments in this field are presented with special focus on their challenges, advantages, disadvantages, and their future potential. Some new gas phase chemical methods are introduced promising access to the sub-second time domain, thus, enabling the chemical investigation of the heaviest SHE known so far.

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SECONDARY RELATIVISTIC EFFECTS IN SUPERHEAVY ELEMENT CHEMISTRY

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Synthesis and chemical identification of new superheavy elements (SHEs) is of top interest during the last decade. Since the thermochromatography on gold has been proved to be a unique method of chemical detection of heaviest elements, main attention was paid to the description of the SHEs – gold interactions. Adsorption energies of SHEs on gold surface were estimated using the cluster model. Its reliability was improved by monitoring charge distributions in the vicinity of the adsorption site and taking into account the effects of relaxation of the cluster compatible with its embedding into the crystal. In some cases the results differ significantly from those of previous theoretical studies. For instance, the new estimates of element 113 and element 120 on gold adsorption energies (1.0-1.2 eV and 2.5-2.7 eV respectively) are recommended. Further development of the SHE “chemical” identification techniques may benefit from having a broader view of their chemical properties. We performed systematical relativistic calculations of molecular structures and energetics of presumably stable binary compounds of SHEs with the most common light elements. These calculations were performed within the two-component shape-consistent small-core pseudopotential model and employed the non-collinear version of relativistic density functional theory to treat electronic correlations. We focus on the properties of roentgenium (E111), copernicium (E112), element 113 and flerovium (E114) which are expected to display particularly strong relativistic contraction and stabilization of the valence s or $p_{1/2}$ subshells. Secondary relativistic effects (delocalization and destabilization of the subvalence d subshell) lead to substantial changes in superheavy elements chemistry. The obtained results along with the similar data for the homologues of SHEs were visualized through the “chemical graphs” which reflect the main trends in changing basic gas-phase chemical properties of the elements in the given group of the Periodic table and demonstrate the specificity of SHEs. The changes in chemical properties in passing from Au to Rg and Hg to Cn are not so regular and uniform, presumably due to the interplay of the s -subshell contraction and destabilization of the $d_{5/2}$ subshell.

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SHELL STRUCTURE IN HEAVY NUCLEI *

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Over the past decade or so, advances in detection technology have lowered the observational limit for studies of heavy and superheavy nuclei. In particular, exploitation of variations of the recoil-decay tagging technique have enabled a great deal of new data to be obtained in nuclei in the so-called "transfermium" region [1]. In-beam spectroscopic studies can now be carried out at the level of 10 nb and up to $Z=104$ [2,3].

The transfermium nuclei have proton number Z around 100 and neutron number N around 152, and are quadrupole deformed. Use of coincident α - γ spectroscopy, in beam spectroscopy of rotational bands, and studies of high- K states has led to a consistent picture of the single-particle structure of nuclei in this region. In turn, this consistent picture from experimental data can be used to confront modern approaches of theoretical nuclear structure physics. An interesting case is the poor reproduction of the deformed shell gaps at $Z=100$ and $N=152$ in modern self-consistent approaches based on Skyrme energy-density functionals or relativistic mean field. Attempts to improve the theoretical description of these nuclei are under way [4]. An overview of the most recent experimental and theoretical studies of heavy nuclei will be given.

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EFFECT OF NUCLEAR SHELL STRUCTURE ON HEAVY-ION FUSION REACTIONS FOR COMPOUND NUCLEI WITH $Z \geq 80$

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A major thrust in contemporary heavy-ion physics has been the search for a doubly magic spherical nucleus beyond $^{208}_{82}\text{Pb}$. Existence of such a nucleus beyond the macroscopic limit is dependent solely upon microscopic stabilization through shell effects. Different theoretical predictions for the double-shell closure beyond Pb have been made and, particularly, the proton shells with $Z = 114, 120, 122, 124, 126$ have been predicted. The heaviest nucleus synthesized so far is $^{294}_{118}$. Although these discoveries declare mankind's arrival on the *island of stability*, nothing conclusive can be said about the exact location of the doubly magic spherical superheavy nucleus yet. The formation cross sections of superheavy nuclei are so small (< 1 pb) that it is practically impossible to undertake systematic investigations of the reaction mechanism with the prevailing limits of experimental sensitivity. However, one can study the reaction mechanism near the heaviest doubly magic spherical nucleus available in nature, $^{208}_{82}\text{Pb}$. Knowledge acquired from studying these two shells in the ^{208}Pb nucleus might then be extrapolated to the next heavier proton and neutron shell closures.

The effect of the nuclear shell structure on the heavy-ion fusion reaction was investigated in the reactions $^{40}\text{Ar} + ^{144}\text{Sm}$ and $^{40}\text{Ar} + ^{166}\text{Er}$. Evaporation residues from these fusion reactions were measured near Coulomb barrier region using a mass separator "MASHA". The evaporation residue cross sections were compared with theoretical calculations using a couple channel code. It was found that these cross sections correlate strongly with the nuclear structure of colliding nuclei. This correlation is explained in terms of the coupling of relative motion to internal degrees of freedom of the colliding nuclei. It is associated with specific details of the colliding partners such as deformation, vibration, and nucleon transfers or related to the gross features of nuclear matter such as neck formation between the two colliding nuclei.

The work was supported by the Russian Fond for Fundamental Research, grant № 13-02-12089 ofi m.

DEGENERATION OF GAMOW-TELLER AND ANALOG RESONANCES IN HEAVY NUCLEI AND WIGNER SU(4)-SYMMETRY RESTORATION

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Giant Gamow-Teller (GTR) and analog (AR) resonances are collective excitations, which are observed in 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. (see more in [1]). Energies of GTR – E_{GTR} and AR – E_{AR} are measured with accuracy 0.2 – 0.5 MeV. The energies and other characteristics of these resonances were calculated for many times, and the first of them were carried out more than 40 years ago [2] in the framework of the theory of finite Fermi systems (TFFS) [3].

This paper presents the results of the calculations for the energy difference $\Delta_{\text{G-A}} = E_{\text{GTR}} - E_{\text{AR}}$ obtained from the semiclassical solutions of the TFFS equations for the nuclear effective field. It is shown that $\Delta_{\text{G-A}}$ values decreases in heavy nuclei, and even for ^{208}Pb it is 0.5 MeV. While the average discrepancy between the calculations and experimental data for 33 nuclei is 0.30 MeV. Even greater accuracy (less than 0.15 MeV) is obtained for the energy of the E_{AR} using a two-parameter approximation for the difference between the Coulomb energies $\Delta E_{\text{Coulomb}}$ of neighboring isobars nuclei. We analyzed the experimental data for more than 400 nuclei with $A = 3 - 244$. Deformation of heavy nuclei is taken into account phenomenologically as well as in the work [4] with parameters β_2 and β_4 taken from [5]. It was found that with increasing mass number A energy $\Delta_{\text{G-A}}$ goes to zero, i.e. GTR and AR degenerate and SU(4) symmetry is restored, as was predicted earlier [6].

The calculations were performed with the refined constants of local spin-isospin ($\bar{\sigma}\bar{\tau}$) and isospin-isospin ($\bar{\tau}\bar{\tau}$) interaction of quasiparticles – g'_0 and f'_0 accordingly. In this paper, by comparing of the calculated energy difference between the GTR and located below the "pygmy" resonance with the experimental data [7] for nine Sb isotopes, the value $g'_0 = 1.22 \pm 0.04$ was obtained.

We also studied the convergence of GTR and AR resonances energies in heavy nuclei with $Z \geq 100$, located on the line of beta-stability. The $\Delta_{\text{G-A}}$ energies are calculated for the heavy and superheavy nuclei up to the values of the mass number $A = 300$. It is shown that the deformation in the region of heavy nuclei significantly affects on the position of GTR and AR. Particularly strong influence of the deformation is on the energy difference $\Delta_{\text{G-A}}$ and the magnitude of this effect can be up to 0.30 MeV. It was also noted that in the region of superheavy nuclei GTR and AR degeneration depends on the values of g'_0 and f'_0 constants used in the calculations, but more precisely it depends on their attitude f'_0 / g'_0 .

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HEAVY AND SUPERHEAVY ELEMENTS PRODUCTION IN HIGH INTENSIVE NEUTRON FLUXES OF EXPLOSIVE PROCESS

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The understanding of heavy elements formation process in nature is based on a progress in nuclear physics and astrophysical scenario as well. Observation of abundances for elements give us the final results of different nucleosynthesis processes in different objects during billions of years. That is why additional experimental information can give us a very important knowledge of nucleosynthesis details. This information can be received from the analysis of nucleosynthesis in explosions [1] and simulation of such processes as well.

Simulation of heavy and superheavy elements formation in impulse nucleosynthesis is based on the model developed in 1985–1990 years [2, 3]. The adiabatic expansion of the matter under conditions of the pulse nucleosynthesis [4] was considered for the model. The mathematical description was also extended for binary starting target-isotopes – the adiabatic binary model (ABM); in the model the Losing factor (which summed the loss of isotope concentration at the end of isobaric chain) also had been included [5]. In astrophysics the superheavy elements (SHE) formation occurs in the r-process nucleosynthesis [6]. The discussed model allows to test the theoretical predictions used in astrophysical calculations with support of experimental results and basing on the model calculations of heavy and superheavy elements production in high fluxes of neutrons.

Duration of the discussed explosive processes is defined by their scale: $t \leq 10$ s for astrophysical events and $t < 10^{-6}$ s for nuclear explosion. The possibility of SHE production in astrophysical explosive processes is strongly depends on the parameters of processes and their duration, which can be short in order to rich the island of long-lived nuclei in SHE region. In the impulse nucleosynthesis in explosive star and the similar prompt process in nuclear explosions we have a problem of nuclear data in the region of very neutron-rich heavy and superheavy nuclei and their stability to the beta-delayed and spontaneous fission processes. The calculated data on $T_{1/2}$ and beta-delayed neutron emission probabilities for the neutron-rich nuclei are also important. The problems mentioned above and different opportunities of heavy and superheavy nuclei production in high neutron flux of thermonuclear explosions are discussed. The results of our calculations are compared with the experimental data taken from the USA thermonuclear explosions (Par, Barbel, Mike).

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STUDIES ON CHEMICAL AND NUCLEAR PROPERTIES OF THE HEAVIEST ELEMENTS AT JAEA

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Studies on exotic nuclear and chemical properties of the heaviest elements with atomic numbers $Z > 100$ are being performed using the JAEA tandem accelerator. Investigation of the chemical properties of the heaviest elements offers unique opportunities to obtain information about trends in the periodic table of the elements at the limits of nuclear stability, and to assess the influence of relativistic effects on chemical properties. Typical chemical experiments on the heaviest elements and recent successful achievement on the measurement of an ionization potential of the heaviest actinide with ISOL (Isotope Separator On-Line) will be described. Nuclear structure and fission of heavy nuclei are also extensively studied at JAEA. In this presentation, recently obtained α - γ spectroscopic results on No nuclides (element 102) as well as fission characteristics of actinides will be introduced. An outlook of future studies on the heaviest elements at JAEA will be briefly discussed.

ADVANCED THEORETICAL STUDIES FOR CHEMICAL IDENTIFICATION AND PREDICTION OF CHEMICAL BEHAVIOUR OF THE HEAVIEST ELEMENTS

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A number of interesting and important experiments on the chemistry of the heaviest elements such as 112 (Cn) and 114 (Fl) have recently been conducted.^{1,2} Some new ones, e.g., for the gas-phase chemistry of element 113 are in view.³ Their aim is to find out whether the new elements behave similarly to or differently from the lighter homologs in the chemical groups due to the strong relativistic effects on their electron shells.^{4,5}

All those investigations have been accompanied by extensive theoretical studies⁵, that helped to plan those expensive and sophisticated experiments with single atoms, as well as to interpret their outcome. Most of the theoretical predictions for chemically interesting systems were done with the use of the Density Functional Theory (DFT) methods.⁶ Thus, adsorption behaviour of Cn and Fl on gold was predicted by performing DFT adsorbed atom (ad-atom) - gold cluster calculations.⁷ Those methods were criticized by some workers,⁸ who claimed that they underestimate van der Waals interaction in systems like Cn and Fl. Accordingly, the sequence in the adsorption between Cn and Fl (Cn < Fl) might have been opposite to the predicted one.

To waive this allegation, we have recently repeated the calculations with the use of the Dirac-Fock Coupled-Cluster (CC) method,⁹ that takes into account weak interactions and therefore gives more accurate values of binding energies. The new results confirm the older ones. This means that the used DFT methods can accurately describe the interactions including the weak ones. Thus, the sequence in the adsorption of these elements on gold is Cn < Fl, as was originally predicted.⁷

Moreover, we perform now calculations of adsorption of the heaviest elements on various surfaces using periodic codes. This new approach is more grounded, as the surface is represented by a surface of a bulk of substance, but not by an atomic cluster. Moreover, the exchange-correlation potentials used in the new approach take into account van der Waals effects at the highest level of theory. Investigations for elements such as Tl and 113 are in progress. Predictions for even heavier elements are also discussed.

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PRODUCTION AND STUDY OF NEUTRON-RICH ISOTOPES NEAR THE NEUTRON $N=152$ SHELL CLOSURE

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The mass-separator "MASHA" can measure with a high precision the mass of any nucleus from helium up to $A=450$. Fission fragments, alpha-particles and beta-particles are detected in the focal plane with a high efficiency. These unique properties of the mass-separator MASHA open great perspectives for the investigation of neutron rich nuclei produced in multinucleon transfer reactions. Mainly nuclei near the neutron $N = 126$ and $N = 152$ shell closures are of great interest. These regions of nuclei are not enough good investigated yet and their research can have direct relation to the synthesis of superheavy elements. As is known the island of stability close to the super heavy elements in the region $Z=112-118$ exists due to the shell effects in nuclei. More detailed investigation of these shell effects can greatly help at synthesizing the next super heavy elements.

The position-sensitive quantum counting hybrid pixel detectors of the MEDIPIX type satisfy the requirements. They provide a high spatial resolution and a single-quantum detection. Further, connecting these detectors with the integrated readout interface FITPix developed by the Prague group one can have a compact and portable radiation camera which operates as an active nuclear emulsion for heavy charged particles and fission fragments, alpha-particles, electrons (positrons), as well as X-rays in a wide and linear dynamic range with the on-line tracking visualization.

Heavy neutron rich radon isotopes were produced in multinucleon transfer reaction $^{48}\text{Ca} + ^{232}\text{Th}$. Radon isotopes with given masses were detected using two detectors: a multi-strip detector of the well-type (made in CANBERRA) and a position-sensitive quantum counting hybrid pixel detector of the MEDIPIX type. The radon isotopes implanted into the detectors then emit alpha- and beta-particles until reaching the long lived isotopes. The position of the radon isotopes, the tracks, the time and energy of beta-particles were measured and analyzed. A new software for the particle recognition and data analysis of experimental results was developed and used. It was shown that MASHA+MEDIPIX setup is a powerful instrument for investigation of neutron-rich isotopes far from stability limits.

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DISAPPEARANCE OF $Z = 120$ & 126 MAGICITY AND HYPER DEFORMATIONS IN SUPERHEAVY NUCLEI

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Significant stride has been made in discovering superheavy nuclei until $Z=118$ [1]. Feasibility of synthesis of superheavies beyond and including $Z=120$ would depend upon as to how shell effects would behave at this proton number. It is also not known as to what would be the influence of the presumed magicity of $Z=126$? The conventional wisdom has it that $Z=120$ and especially $Z=126$ are predicted to be magic numbers for extreme superheavy nuclei.

We have undertaken a study of structure of superheavy nuclei in the region of $Z=120$ to $Z=126$ within the framework of the deformed relativistic Hartree-Bogoliubov (DRHB) approach. Nuclei in this region entail a large density of states and are thus susceptible to a coupling to the continuum especially those which are close to being proton unbound. The DRHB approach takes into account the coupling to the continuum. This makes it suitable for nuclei in the end of the periodic table. Additionally, the pairing in this approach is included within the Bogoliubov quasi-particle scheme, which takes into account the shell gaps at the Fermi surface appropriately. We use the successful Lagrangian model NL-SV1 [2] based upon the vector self-coupling of ω -meson for this exploration.

It is shown that the perceived shell gaps at $Z=120$ and $Z=126$ diminish significantly, thus making these proton numbers as non-magic. This is especially the case for the presumed magic number $Z=126$. It is also shown that due to very large Coulomb force, nuclei emerge with elongated shapes with hyper deformations of $\beta_2 \sim 0.70-0.80$. The deformation energy contributes several MeV to total binding energy, which lends additional stability to the nuclei in and around $Z=126$. Consequences on the formation of superheavy nuclei in this region will be discussed.

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RECENT EXPERIMENT ON SYNTHESIZING FLEROVIUM ISOTOPES IN THE REACTION $^{239}\text{Pu} + ^{48}\text{Ca}$

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In 2013-2014 we carried out the experiment aimed at the synthesis of neutron-deficient isotopes of flerovium in the reaction $^{239}\text{Pu}(^{48}\text{Ca}, 2-4n)^{287-x}\text{Fl}$. At ^{48}Ca energy of 245 MeV ($E^*=35.4-40.1$ MeV), we accumulated the total beam dose of 1.3×10^{19} . According to theoretical calculations based on macroscopic-microscopic fission barriers of the nuclei, the cross section of the reactions with evaporation of 2 or 3 neutrons was expected to be about 4 pb. However, we could detect only a single decay event that could originate from spontaneous fission of ^{284}Fl with a lifetime of about 0.5 ms. The observed cross section (0.3 pb) appeared to be an order of magnitude lower than the predicted value, while the cross sections of the evaporation channels in the reactions with heavier target isotopes ^{242}Pu and ^{244}Pu amounted 7-13 pb. Such a drastic decrease of the cross section can point to a considerable lowering of the stability of superheavy nuclei when moving away from the $N=184$ shell, that is caused by a more substantial decrease of nuclear fission barriers than it is predicted by theory.

EFFICIENCY OF *AB INITIO* APPROACHES TO STUDY CHEMISTRY OF SUPERHEAVY ELEMENTS

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Reliability and efficiency of modern *ab initio* methods of relativistic electronic structure calculations is discussed in context of their application to studying the physical-chemical properties of superheavy elements (SHE) and their compounds with the accuracy demanded by the "chemical" experiments on the SHEs from "island of stability", which are on the agenda. Such experiments took place for the elements of 7th period and suggested for the beginning of 8th period in some future. The discussion is important in connection with a variety of approaches used nowadays to predict the chemical and adsorption properties of SHEs when accounting for a very small statistics and very high cost of such experiments. The evaluation of the reliability of one or another theoretical prediction is important to minimize the cost of the measurements and interpret them correctly.

First of all attention is paid to applicability of modern versions of relativistic pseudopotentials (RPP) compared to the four-component approaches. The most elaborated four-component models *formally* should provide the best accessible computational accuracy, however, they are much more expensive than the RPP methods. In turn, modern RPP formulations provide such a high precision that they, in fact, almost do not contribute to the overall error of the calculation, which is, actually, limited by the accuracy of correlation treatment for the systems under consideration. Another problem is the reliability of the popular exchange-correlation functionals within the density functional theory (DFT) that is only applicable to study SHE compounds with ~10 or more atoms. All the known functionals were calibrated in studies of systems with relatively light atoms; their accuracy in application even to common heavy element compounds is doubtful. However, for SHEs the influence of relativistic effect dramatically increases, that leads to higher uncertainties of the DFT calculation. So, some more sophisticated schemes should be applied in general for SHEs because the number of experimental data for them (which can be used for calibration) is negligible. We briefly present the most efficient "wavefunction theory" correlation methods, such as many-body perturbation and coupled-cluster theories, which can help to calibrate the DFT functionals in absence of the experimental data.

The results of calculations of compounds of Cn (eka-Hg), Fl (eka-Pb) and element 120 (eka-Ra) are discussed, which examine the role of electron correlations and relativistic (spin-orbit) effects. The importance of the careful optimization of atomic bases is underlined. It is demonstrated that *ab initio* RPP calculations with a high level of accounting for the electron correlation, being most efficient when applied to small (few-atomic) systems, can be utilized to calibrate the exchange-correlation functionals for the subsequent DFT calculations of complex polyatomic systems with SHEs, though, often on the limit of their possibilities. It is demonstrated that the DFT with popular approximate exchange-correlation functionals fails to properly describe the interactions of Cn with gold, presumably because of absence of dispersion-type terms, whereas, in most other cases this theory provides quite satisfactory results. In turn, applying the "wavefunction correlation corrections" to the DFT study the adsorption energy of Cn on gold can be dramatically improved. Such a correction is also useful for the element 113 though its value is not so high here.

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SYNTHESIS OF SUPERHEAVY NUCLEI WITH $Z=112-118$

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Review of discovery and investigation of the "Island of stability" of superheavy nuclei at the separator DGFRS (FLNR, JINR) in the reactions of ^{48}Ca with target nuclei ^{238}U - ^{249}Cf will be presented. The synthesis of the heaviest nuclei, their decay properties, and methods of identification are discussed. The results are compared with data obtained at the separators SHIP and TASCA (GSI, Darmstadt) and BGS (LBNL, Berkeley). The role of shell effects in the stability of superheavy nuclei is demonstrated by comparison of the experimental data and results of theoretical calculations. The recent experiments aimed at the investigation of the region of neutron-deficient nuclei produced in ^{48}Ca -induced reactions with lighter plutonium isotopes are described. Future experiments at DGFRS on the study of superheavy nuclei will be considered.

EXPERIMENTS ON THE SYNTHESIS OF THE SUPERHEAVY NUCLEI $Z=117$ IN THE COMPLETE-FUSION $^{48}\text{Ca}(^{249}\text{Bk}, xn)^{297-X}117$ REACTION

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The reaction of ^{249}Bk with ^{48}Ca has been investigated with an aim of synthesizing and studying of the decay of isotopes of the new element 117. The experiments were performed at five projectile energies (in two runs, in 2009-2010 [1] and 2012 [2]) and with a total beam dose of ^{48}Ca ions of about 9×10^{19} . The experiments with $^{249}\text{Bk} + ^{48}\text{Ca}$ reaction yielded data on α -decay characteristics and excitation functions of the produced nuclei that establishes these to be $^{293,294}117$ – the products of the $4n$ - and $3n$ -evaporation channels, respectively. Totally, we have observed 20 decay chains of the $Z=117$ nuclides. The cross sections for the production of $^{294}117$ and $^{293}117$ were measured to be 1.1 pb for the $3n$ and 2.4 pb for the $4n$ reaction channel [3]. The new $^{289}115$ events, populated by α decay of $^{293}117$, demonstrate the same decay properties as those observed for $^{289}115$ produced in the $^{243}\text{Am}(^{48}\text{Ca}, 2n)$ reaction thus providing cross-bombardment evidence [3]. In addition, a single decay of $^{294}118$ was observed from the reaction with ^{249}Cf – a result of the in-growth of ^{249}Cf in the ^{249}Bk target. The observed decay chain of $^{294}118$ is in good agreement with decay properties obtained during 2002-2005 in the reaction $^{249}\text{Cf}(^{48}\text{Ca}, 3n)^{294}118$ [4]. The energies and half-lives of the odd- Z isotopes observed in the 117 decay chains together with the results obtained for lower- Z superheavy nuclei demonstrate enhanced stability with increasing neutron number towards the predicted new magic number $N=184$.

The experiments are carried out in the Flerov Laboratory of Nuclear Reactions, Joint Institute for Nuclear Research, using the heavy-ion cyclotron U400.

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SUPERHEAVY ELEMENT CHEMISTRY BY RELATIVISTIC DENSITY FUNCTIONAL THEORY ELECTRONIC STRUCTURE MODELING

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Two-component density functional theory in its non-collinear formulation combined with the accurate relativistic electronic structure model defined by shape-consistent small-core pseudopotentials (RDFT/PP) provides a robust basis of efficient computational schemes for predicting energetic and structural properties of complex polyatomic systems including superheavy elements (SHEs). The equal-footing treatment of Coulomb interactions, scalar and spin-dependent relativistic effects is essential for attaining optimal accuracy/cost ratio for the studies of molecules and clusters as well as supramolecular systems. The elimination of core shells from the explicit treatment and smoothing of valence/subvalence spinors in the vicinity of atomic nuclei justifies the use of conventional non-relativistic approximants for the exchange-correlation functional. The restrictions of the use of the RDFT/PP scheme with simple generalized-gradient and hybrid functionals are briefly discussed. Because of the exceptional role of thermochromatography in the experiments on the "chemical" identification of SHEs with atomic numbers $Z \geq 112$, we focus on the description of the adsorption of single SHE atoms on the surfaces of solids through cluster modeling of adsorption complexes. The reliability of this approach is improved by monitoring charge distributions in the vicinity of the adsorption site and taking into account the effects of relaxation of the cluster compatible with its embedding into the crystal. In some cases our results differ significantly from those of previous theoretical studies. New estimates of desorption energies of the E113 and E120 atoms from gold surface (1.0-1.2 eV and 2.5-2.7 eV respectively) are recommended. The RDFT/PP is applied to evaluate the adsorption properties of E113 and other 13 group elements on quartz. The results of systematical comparative studies on chemical bonding in simple molecules of binary compounds of SHEs and their nearest homologs with most common light elements, obtained at the RDFT/PP level and visualized through the "chemical graphs", provide the understanding of the general chemistry of SHEs which at present cannot be derived from the experimental data. These results are used to discuss the main trends in changing chemical properties of the elements in the given group of the periodic table and demonstrate the specificity of SHEs.

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POSSIBILITY OF SYNTHESIZING A SUPERHEAVY NUCLEUS AT THE CENTER OF ISLAND OF STABILITY

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The search for new elements is a long-standing important subject in nuclear physics. Since 1966, according to macroscopic-microscopic calculations [1], a magic island of stability surrounding the doubly magic superheavy nucleus containing 114 protons and 184 neutrons has been predicted. During the last thirty years, making use of various developments in experimental techniques, research for the synthesis of superheavy elements has progressed significantly and approaching to the island step by step. In cold fusion reactions with Pb and Bi targets [2,3], the heaviest element with $Z=113$ was reported by RIKEN [4]. Another possibility is to use actinide nuclei as targets, and is called hot fusion reactions. Using the hot fusion reactions, production of new superheavy elements with $Z=114, 115, 116, 117$ and 118 has been reported by Flerov Laboratory of Nuclear Reactions (FLNR) [5]. Recently, other laboratories performed experiments by the hot fusion reaction and obtained results which were consistent with those by FLNR [6].

For superheavy elements of around $Z=114$ and $N=184$, practical combinations of a target and projectile, such as $^{48}\text{Ca}+^{244}\text{Pu}$, have been used by the FLNR group [5]. In this case, the neutron number in the compound nucleus is less than $N=184$. Actually, if we plan to synthesize the doubly magic superheavy nucleus $^{298}114_{184}$, we must fabricate more neutron-rich compound nuclei because of the neutron emissions from excited compound nuclei. Since combinations of stable nuclei do not provide such neutron-rich nuclei, the reaction mechanism for nuclei with $Z=114, N>184$ has rarely been investigated until now. However, because of the characteristic properties of these nuclei, we find an unexpected reaction mechanism for enhancing the evaporation residue cross section. We report this mechanism.

Using the dynamical model [7], we discuss the possibility of synthesizing new superheavy elements. The neutron number of the compound nuclei which were produced so far is insufficient to reach the Island of Stability. In order to synthesize the double magic superheavy nucleus such as ^{298}Fl , we must generate more neutron-rich compound nuclei (for example ^{304}Fl) because of the neutron emissions from excited compound nuclei. Such neutron-rich compound nucleus has advantages to achieve a high survival probability in comparison with ^{292}Fl and ^{298}Fl . During the fusion-fission process, we take account of the neutron emission with Langevin calculation, and estimate the possibility of the production of such neutron rich compound nuclei.

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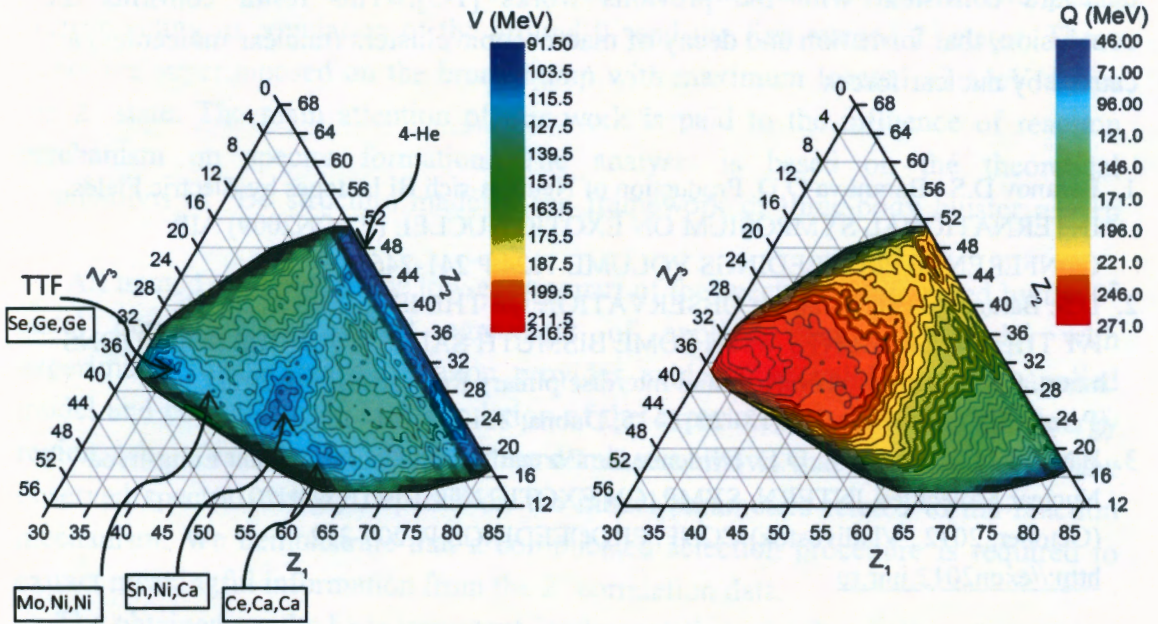
TRUE TERNARY FISSION MODES OF ^{252}Cf

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In a ternary fission process a radioactive nucleus breaks into three fragments. Though the emission of three fragments of about equal masses is energetically favorable as predicted within the liquid drop picture, the experimental evidence of which is not yet unambiguously confirmed. However, recently, using the missing mass approach a new kind of radioactive fission decay, the so called collinear cluster tri-partition (CCT) for $^{252}\text{Cf}(sf)$ and $^{235}\text{U}(n, fff)$, has been reported [1].

Theoretical studies of ternary fission require complete minimization of the potential energy for the mass and charge asymmetry involved. Recently a three cluster model (TCM) has been proposed for the studies of ternary fission [2]. In TCM we imply a condition on the mass numbers of the fission fragments such as $A_1 \geq A_2 \geq A_3$ in order to avoid repetition of combinations. The potential energies of the thus identified favorable combinations are plotted in the Fig.1 (a) and their corresponding Q-values are plotted in Fig. 1(b). The PES can be computed for three different arrangements of the fragments. Fig. 1(a) corresponds to an arrangement in which the heaviest (A_1) and the lightest (A_3) fragments are kept at the end.



PES results indicate different favorable ternary breakups as labelled. ^4He accompanied ternary breakup remains the most favorable split which is also supported by a larger Q-value around (Sn,Pd,He). Apart from this, PES reveals three distinct regions where the potential energy is minimum as labelled. Of which, the deepest minimum corresponds to (Sn,Ni,Ca). However, a very larger Q value and minimum in PES is seen for the true ternary splitting (Se,Ge,Ge). The PES and Q value systematics clearly indicate the possibility of heavy charged particle accompanied fission as well as clearly indicates true ternary fission mode.

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GENERATION OF BISMUTH ISOTOPES IN $\text{Bi}_2(\text{SO}_4)_3$ SOLUTION AFTER ELECTROSTATIC FIELD EXPOSURE

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Experimental data on the isotopes generation in experiments with bismuth salts presented repeatedly [1-3]. The disadvantage of these data is relatively small statistics and low resolution for the energy spectra of alpha particles. The situation changed after the acquisition of alpha spectrometer SEA-13P, which was manufactured in "ASPECT" Ltd. Si detector area increased 10 times compared to previously used detectors. Standard device was supplemented with electron detector on a plastic scintillator, allowing confidently identify decays of bismuth 212. New device allowed to measure the energy of alpha particles with 1% accuracy. The new data are consistent with the previous works [1-3]. This result confirms the conclusion, that formation and decay of macroscopic clusters (nuclear molecules) are caused by nuclear forces.

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TRUE THREE-BODY DECAYS OF THE 2^+ STATES: ^6Be EXAMPLE

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The ^6Be nucleus was populated with sufficient efficiency in the excitation energy range up to 16 MeV and full angular range in the center-of-mass frame of the $^1\text{H}(^6\text{Li}, ^6\text{Be})n$ charge-exchange reaction. The invariant spectrum shows two peaks corresponding to population of the ground 0^+ and the first excited 2^+ states. These peaks are superimposed on the broad bump with maximum located ~ 3 MeV above the 2^+ state. The main attention of our work is paid to the influence of reaction mechanism on spectra formation. The analysis is based on the theoretical calculations of ^6Be structure made in the framework of three-body cluster $\alpha+p+p$ model.

All treated variables in the low-energy part of the spectrum (dominated by the 0^+ state) demonstrate excellent agreement of applied theoretical model with experimental data. This observation provides evidence of validity of the applied model and correctness of MC simulation of the experiment. Analysis of the energy region, where the ^6Be first excited state dominates, shows that the formation of the observed spectra strongly depends on the model parameters related to the reaction mechanism. We demonstrate that a complicated selection procedure is required to extract meaningful information from the 2^+ correlation data.

The obtained results have important implementations for the studies of the three-body decays of excited states in general. The results of the theoretical model which provided the perfect description of the correlation data for the 0^+ ground state of ^6Be is now found to be in a full agreement with the correlation data for the 2^+ state. Complete kinematics measurements with high statistics presents a proper tool to analyze complicated spectra formed by the broad overlapping resonances. We have suggested an adequate approach to analysis of correlation experiments and we assume that obtained results have important implementations for the studies of the few-body decays in general.

ASTROPHYSICAL ASPECTS OF ${}^4\text{He}(2n,\gamma){}^6\text{He}$ RADIATIVE CAPTURE REACTION

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Two neutrons radiative capture by ${}^4\text{He}$ nucleus has been investigated in several papers early [1-3]. However conclusions obtained by different authors are in contradiction. One of the unclarified question concerns the role of the ${}^4\text{He}(2n,\gamma){}^6\text{He}$ reaction in astrophysical processes where it may be considered as a bridge reaction through the $A = 5$ mass gap similar to the triple- α reaction leading to the ${}^{12}\text{C}$ formation during stellar evolution.

In this work we analyze two-nucleon radiative capture within the potential model by the example of two reactions, namely ${}^4\text{He}(d,\gamma){}^6\text{Li}$ and ${}^4\text{He}(2n,\gamma){}^6\text{He}$ ones. In both cases the final state is treated within a three-cluster approximation using realistic wave function [4]. The deuteron capture reaction has been extensively studied and the vast experimental data are available. This reaction is used here in order to demonstrate the applicability of the model and to define its limitations. In order to determine the main mechanism of the ${}^4\text{He}(2n,\gamma){}^6\text{He}$ reaction the different conditions in the entrance channel are considered. Two neutrons are treated either as a bound system (di-neutron) or as free particles. Reaction is considered as a two-step process passing through the intermediate ${}^5\text{He}$ state, or as a simultaneous two-neutron capture. Reaction rates are calculated within the assumptions given above.

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A NON-EQUILIBRIUM EQUATION OF STATE IN HEAVY-ION COLLISIONS AT INTERMEDIATE ENERGIES

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In the development of the approach in [1] for the description of heavy-ion collisions, we proposed to use the method of moments for solving the kinetic equation, which gives, for the first moments with weights $1, \vec{p}, p^2$, equations of the hydrodynamic type, allowing us to find the distribution function of the nucleons, $f(\vec{r}, \vec{p}, t)$ (where $\vec{r}$ is the spatial coordinate, $\vec{p}$ is the momentum, and t is the time). At the same time, we used a non-equilibrium equation of state to describe the hydrodynamic evolution of a system of the «hot spot» type, according to which $f(\vec{r}, \vec{p}, t)$ is associated with an equilibrium component, $f_0(\vec{r}, \vec{p}, t)$, and a non-equilibrium component $f_1(\vec{r}, \vec{p}, t)$:

$$f(\vec{r}, \vec{p}, t) = f_1 \cdot q + f_0 \cdot (1 - q),$$

where q is the relaxation factor. Here, $f_1(\vec{r}, \vec{p}, t)$ is given in the form of a Fermi-ellipsoid in the momentum space, which is a convenient parameterization of the excitations in the Fermi-liquid theory, and $f_0(\vec{r}, \vec{p}, t)$ is given as the equilibrium Fermi-sphere. In this approach, the account of the non-equilibrium component has led to a successful description of the heavy-ion collision dynamics, in particular to the description of the energy spectra of protons emitted at various angles [1-4].

In the present paper we develop a method for the calculation of the factor q by taking the moment from a kinetic equation with weight $p_x^2 - (p_y^2 + p_z^2)/2$ that determines the degree of anisotropy of the distribution function, $f(\vec{r}, \vec{p}, t)$. We found that $q = 1$ on the shock wave during the compression stage in the energy range ~10–100 MeV/nucleon and that q decreases with increasing energy, which results in an increase of the isotropy of the function $f(\vec{r}, \vec{p}, t)$ at higher intermediate energies, in accordance with experimental data on the proton spectra.

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TWO-PROTON DECAY OF THE FIRST EXCITED STATE OF ^{17}Ne

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It is generally accepted that the study of nuclei near the drip line led to the discovery of new properties of nuclear matter. Nucleus ^{17}Ne located on the border of proton stability is of interest for several reasons. The ground state is one of the most promising candidates for two proton halo structure. A special interest attracts the first excited state ($J^\pi=3/2^-$) with an energy of 1.288 MeV which is only 344 keV above two-proton decay $^{17}\text{Ne} \rightarrow ^{15}\text{O}+2p$ threshold, and one proton decay channel is energetically forbidden. In other words, this state is a candidate for a true two-proton radioactivity, if this decay branch can compete with the γ -decay to the ground state of ^{17}Ne . In addition, the decay mode of the first excited state of ^{17}Ne is of great interest from the point of view of astrophysics. The possibility of bridging the waiting point of the rp process by the two proton radiative capture reaction $^{15}\text{O}(2p,\gamma)^{17}\text{Ne}$ is discussed in [1]. In Ref. [2], an upper limit of $\Gamma_{2p}/\Gamma_\gamma < 0.0077$ was determined by direct observation of the two-proton decay branch of the first excited state of ^{17}Ne . One should note that this value is at least three orders of magnitude higher than the theoretical expectations [3].

The main purpose of the experiment presented here was the search for the two-proton decay branch of the first excited state of ^{17}Ne populated in $^1\text{H}(^{18}\text{Ne},d)^{17}\text{Ne}$ reaction. The experiment was performed using the radioactive ^{18}Ne beam with energy 38 MeV/n provided by the ACCULINNA fragment separator in FLNR JINR (Dubna). The purity of ^{18}Ne secondary beam achieved 17% with ^{16}O as the dominant contamination. The available beam intensity was up to 2×10^5 pps. The experiment was done in two steps. In the first run we used thin gaseous cryogenic hydrogen target to have energy resolution sufficient to resolve the low-laying excited states of ^{17}Ne in the missing mass spectrum of the deuterons from the $^1\text{H}(^{18}\text{Ne},d)$ reaction. Deuterons were detected by a detector telescope consisting of annular position sensitive silicon detectors which spanned laboratory angles $5\text{-}15^\circ$ in forward hemisphere. From the data of the first run we estimated differential cross section for population of the ground and first excited states of ^{17}Ne . In the second run, which was made with a thick liquid hydrogen target, we have measured deuterons in coincidences with protons from the ^{17}Ne decay. The protons were detected by a square $6 \times 6 \text{ cm}^2$ telescope placed 30 cm downstream of the target on the beam axis. The telescope consisted of two 1 mm thick position sensitive silicon detectors backed by a wall made of (4×4) CsI(Tl) detectors with PMT readout. A 1.4 mm aluminum filter was install in front of the square telescope to stop the ions from beam cocktail, whereas the protons from the ^{17}Ne decay deposited only a small part of their energy in this filter. As a result, no events which could be attributed to the two-proton decay branch of the first excited state of ^{17}Ne was found. An upper limit of branching ratio $\Gamma_{2p}/\Gamma_\gamma$ was set at a level of $\sim 10^{-4}$ pushing down the previous limit by about two orders of magnitude and corresponding to the upper limit of the model predictions. The analysis of the experimental data also demonstrates good prospects of the chosen way for coming to a final solution of this problem.

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NEW LEVELS IN $^{149,150,151,152,153}\text{Pr}$ BY COMBINING HIGH STATISTICS γ DATA AND MASS/Z GATED SPECTRA

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The mass assignments of the previously reported levels in $^{151,152,153}\text{Pr}$ (1,2) have recently been called into question (3). The levels in $^{151,153}\text{Pr}$ reported previously (1) were assigned to $^{152,154}\text{Pr}$, respectively, in (3) and the levels in ^{152}Pr (2) were assigned to $^{151,153}\text{Pr}$ (3). In this paper we combine high statistics γ - γ and γ - γ - γ data obtained in the spontaneous fission of ^{252}Cf with Gammasphere with isotopically identified fission fragments (A and Z) gated γ - γ data obtained in the $^{238}\text{U}+^9\text{Be}$ induced fission data (4). The experiment with ^{252}Cf was carried out at the Lawrence Berkeley National Laboratory. Transfer and fusion were used to induce fission with a ^{238}U beam bombarding a ^9Be target at GANIL. Over 400 fragments were detected and identified by both mass and Z in the VAMOS ++ spectrometer. The coincident γ -rays were detected by the EXOGAM array.

From the ^{252}Cf data 6 new levels and one new band in ^{149}Pr and 11 new levels in two new bands in ^{150}Pr were obtained. Mass and Z gated γ and γ - γ coincident data from GANIL were analyzed for $^{151,152,153}\text{Pr}$. These data were used to identify the strongest transitions in each of these isotopes. The multiple γ coincidence data were used to extend the levels to high spins. The results for these three isotopes are as follows: In ^{151}Pr the previous levels (1) are confirmed and in addition the two bands reported in ^{152}Pr are now definitely established in ^{151}Pr too. In ^{152}Pr three new bands with 25 previously unreported transitions are established. One band is built on a known 4.1 μs isomer. The previous levels assigned to ^{153}Pr (2) are confirmed except for the highest state in one of the two bands. Also the neutron yields as a function of the Y partners confirm these assignments. The power of combining two such data sets will be discussed and a proposed plan for a new mass gated γ - γ experiment with spontaneous fission sources at GANIL will be described. Finally, a new band structure in ^{100}Y containing 10 new transitions will be presented. These levels are very similar to those in $N=61$ ^{102}Nb .

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THE GAMMA QUANTA PROBE IN THE FUSION-FISSION DYNAMICS IN THE REACTION $^{34}\text{S} + ^{186}\text{W}$ NEAR THE INTERACTION BARRIER

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The reaction $^{34}\text{S} + ^{186}\text{W}$ at $E_{\text{lab}}(^{34}\text{S}) = 160$ MeV, was investigated with the aim of making a complete description of the fusion-fission process. Gamma rays in coincidence with binary reaction fragments using the high efficiency gamma-ray spectrometer ORGAM at the TANDEM Accelerator facility of I.P.N., Orsay, and the time-of-flight spectrometer for fission fragments CORSET of the Flerov Laboratory of Nuclear Reactions (FLNR), Dubna were measured. The coupling of the ORGAM and CORSET setups offers the unique opportunity of extracting details for characterizing the fusion-fission process and gives very important information regarding new ways for production of neutron-rich heavy and superheavy nuclei.

Characteristics as γ -ray energy and angular distribution, provided by ORGAM spectrometer, were measured in coincidence with fission-like products of the above mentioned reaction, registered by CORSET set-up which was used for measuring mass and mass-angle correlation. Corrections regarding fission fragments energy losses in the target and foils of the detectors, as well as Doppler shift for the gamma ray energies were performed. By using discrete gamma lines the charge distribution of the fragments was identified and compared with theoretical predictions.

Details regarding the experimental setup, methods of processing the acquisitioned data and preliminary results regarding mass and charge distribution of the fission fragments will be presented.

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NEW DIRECTIONS IN STUDY OF TERNARY DECAYS

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Our program of studying of ternary decays of heavy nuclei dedicated basically to the collinear cluster tri-partition process [1] discovered by us earlier is extended due to the theoretical predictions presented in [2] and our own experimental findings. In the frame of a three-centre phenomenological model developed by the authors [2] new minimum of a short-lived molecular state is revealed in the deformation energy at a separation distance very close to the touching point of the constituents of ternary chain-like configuration. The half-life of the quasi-molecular state which could be formed in ^{12}C accompanied fission of ^{252}Cf is roughly estimated to be the order of 1 ms. We have planned to verify this prediction experimentally using COMETA-R spectrometer installed at the IBR-2 reactor. The experiment is in progress and first results obtained will be reported.

The experiments in the second direction to be continued are aimed at investigating of new shape-isomeric states in fission fragments. One of the perspective goals consists in estimating of a typical life time of these states lying presumably in a microsecond range. We are planning to gain this goal using VEGA (V-E Guide based Assembly) setup to be installed at the IBR-2 reactor. Project details will be discussed.

At last very short lived fission isomers forming in a sequential fission process are under discussion. Experimental indications of such decay channel were obtained recently at COMETA-R spectrometer.

Thus, studies of rare ternary decays let us find new perspective field for investigation namely searching for unknown manifestations of shape-isomer phenomenon.

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MICROSTRUCTURE MANIFESTATIONS IN NUCLEAR REACTIONS

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Many nuclear reactions are described in macroscopic approach that involves only potential and excitation energies, statistical equations and macroscopic parameters such as radius, level density, rotational energy, and so on. At the case of direct reactions, the initial and final states are known as definite quantum states, and the theory must account the matrix element of this quantum transition. That is hardly applicable when the continuum of microstates is populated on the stages of intermediate compound-nucleus, or even of the final product formation. However, this does not mean that the nucleon orbits filled in the target nucleus and the final-product quantum numbers must be completely neglected. The problem is formulated, how to find the manifestation of microstructure peculiarities in the experimental data on cross sections and yields of studied reactions. Inelastic neutron acceleration (INNA) process has been recently approved [1, 2] to have much higher cross section compared to the standard-theory predictions for the ^{177m}Lu and $^{178m2}\text{Hf}$ isomeric targets. This special reaction with thermal/cold neutrons involves the transition from isomeric to lower-lying level with energy release to the neutron kinetic energy (acceleration). Such a transition is normally accompanied with the transfer of a great orbital momentum to the accelerated neutron. Thus, the process probability is restricted due to low transmission coefficients $T_l \ll 1$ for $l \geq 3$. Experimental INNA cross sections exceed the predicted ones by an order of magnitude. The only explanation could be drawn that the intrinsic orbital-momentum distribution influences the neutron emission. The single-particle shell model predicts that in medium and heavy nuclei only about 30% of all neutrons sit at the orbits with the lowest moments $l = 0, 1, 2$. Their emission is regulated by normal T_l values but only for 30% of neutrons in the nucleus. Therefore, the integral emission rate is suppressed by a factor of about 0.3. The statistical neutron-emission width Γ_n must be respectively reduced. This must be manifested in experimentally-tested time scale of the compound-nucleus decay. Emission of neutrons from the orbits with $l = 3 - 5$ and greater is hindered by the centrifugal barrier, but could happen after the orbital moments exchange with the re-arrangement of orbits – the dynamical process inside the nucleus. A minor addition into the total emission rate is yet expected. Moreover, both direct neutron emission and past re-arrangement could not provide a great orbital momentum release being useless for explanation of the enhanced INNA probability. The new mechanism must be introduced for virtual penetration of a neutron pair through the centrifugal barrier. The pair possesses zero angular momentum in sum and could virtually penetrate to the external space. Remind that the energy conservation hinders a real penetration of the pair. But in virtual process, the pair could split: one of neutrons is ejected with a great orbital momentum and the second one returns back to its initial bound orbit. The INNA probability arises strongly while total emission rate is changed only slightly.

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RARE MECHANISMS OF STOPPED PIONS ABSORPTION BY $^{10,11}\text{B}$ NUCLEI

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Study of the rare mechanisms of stopped pions absorption was provided due to the correlation measurements results of $^{10}\text{B}(\pi^-, dt)X$ and $^{11}\text{B}(\pi^-, tt)X$ reactions. The experiment was carried out at low energy pion channel of LANL with two-arm multilayer semiconductor spectrometer of charged particles [1].

The analysis of two-dimensional distributions (Dalitz' diagram) allowed to identify following reaction channels:

- 1) Quasi-particle pion absorption on the intra-nuclear cluster of $^{5(6)}\text{Li}$
 $\pi^- + ^{5(6)}\text{Li} \rightarrow d(t) + t$, where the residual ^5He system is a "spectator";
thus, indications of the existence of the rare cluster structure in $^{10(11)}\text{B}$ nuclei were found: ($^5\text{He} + ^{5(6)}\text{Li}$);
- 2) Two-particle channels $\pi^- + ^{10(11)}\text{B} \rightarrow d(t) + ^8\text{Li}^*$ and $\pi^- + ^{10}\text{B} \rightarrow t + ^7\text{Li}^*$ with the following $^{7,8}\text{Li}^*$ decay;

In the Missing Mass spectrum of two-particle channels $\pi^- + ^{10(11)}\text{B} \rightarrow d(t) + ^8\text{Li}^*$ and $\pi^- + ^{10}\text{B} \rightarrow t + ^7\text{Li}^*$ the highly excited states of $^{7,8}\text{Li}$ were found. These states break up with the triton emission: $^{7(8)}\text{Li}^* \rightarrow t + ^{4(5)}\text{He}$. The levels of $^8\text{Li}^*$ isotope with the resonance parameters (E_x, Γ): ($8.7 \pm 0.2, 1.9 \pm 0.4$) MeV and ($10.1 \pm 0.3, 4.0 \pm 1.3$) MeV were observed for the first time.

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CALCULATED SCISSION-NEUTRON PROPERTIES IN AGREEMENT WITH EXPERIMENTAL DATA ON PROMPT NEUTRONS

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The main properties of the neutrons released during the neck rupture and emitted immediately thereafter are calculated for ^{236}U in the frame of the dynamical scission model [1, 2]. These properties are: the angular distribution with respect to the fission axis (calculated on spheres of radii $R=30$ fm and 40 fm at time $T=4\times 10^{-21}$ sec), the distribution of the average energies of neutrons emitted from each state (calculated for durations of the neck rupture $\Delta T = 1$ and 2×10^{-22} sec) and the total neutron multiplicity (calculated for two values of the minimum neck-radius, 1.6 fm and 1.9 fm). They are compared with measurements of prompt fission neutrons during ^{235}U (n_{th} , f). The experimental trends are well reproduced, i.e., the focusing of the neutrons along the fission axis, the preference of emission from the light fragment, the range, slope and average value of the neutron energy spectrum and the average total neutron multiplicity. One can therefore not exclude that prompt fission neutrons and scission neutrons are one and the same.

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INVESTIGATION OF $^{70,72,74}\text{Ni}$ FROM β DECAY OF $^{70,72,74}\text{Co}$

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N. Blasi², S. Ceruti^{1,2}, F. C. L. Crespi^{1,2}, M.-C. Delattre¹⁶, Zs. Dombradi⁵, A. Gottardo⁷,
I. Kuti⁵, K. Matsui⁹, B. Melon¹⁷, D. Mengoni¹⁸, T. Miyazaki⁹, V. Modamio-Hoybjør⁷,
S. Momiyama⁹, D. Napoli⁷, R. Orlandi¹⁹, H. Sakurai^{3,9}, R. Taniuchi⁹, J. Taprogge^{20,21},
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The characterization of nuclear models in regions far from the valley of stability is strongly conditioned by the experimental access to nuclear properties in exotic nuclei. One of the main unanswered questions of modern nuclear physics is whether the traditional magic numbers of protons and neutrons, such as they are known near stability, are maintained at extreme values of isospin, or whether new magic numbers emerge as a result of the unbalanced neutron-to-proton ratio. The nuclear region around ^{78}Ni , with 28 protons and 50 neutrons, has attracted great attraction for this purpose. This work aims at studying the even-even $^{70,72,74}\text{Ni}$ nuclei from β -delayed γ - spectroscopy of the $^{70,72,74}\text{Co}$ progenitors to test the strength of state-of-the-art shell-model calculations in the vicinity of the doubly-magic ^{78}Ni core.

With this aim, neutron-rich $^{70,72,74}\text{Co}$ nuclei were produced at the Radioactive-Isotope Beam Factory (RIBF) facility at RIKEN, as part of the EURICA campaign [1,2]. Nuclei in the isotopic chains of Cu, Ni, Co and Fe were produced in the in-flight fission of a 345 AMeV ^{238}U stable beam impinging on a 3 mm Be target. The reaction residues were identified using the large-acceptance magnetic spectrometer BIGRIPS [3], and were sent to a β -decay station consisting of the WAS3ABi active stopper [1] and the EURICA γ spectrometer [2]. An array of 18 LaBr₃ scintillation detectors was also mounted around the WAS3ABi active stopper in order to allow for fast-timing measurements. The unprecedented high intensities of the primary beam, 10 pA, enabled the collection of high statistics for the nuclei of interest. The β -delayed γ -spectroscopic study, still ongoing, is providing a large amount of new information in these nuclei, including the measurement of half lives for some of the states, such as the 6^+ , $\nu=2$ level in ^{72}Ni . These new results will allow to probe the strength of the seniority scheme near ^{78}Ni . The status of the data analysis will be discussed.

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TRUE TERNARY FISSION: MULTIPLE COLLINEAR FISSION MODES REVEALED FROM POTENTIAL ENERGY SURFACES AND EXPERIMENTS

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The observation of the collinear cluster decay in $^{252}\text{Cf}(\text{sf}, \text{fff})$, with three cluster fragments of different masses (e.g. ^{132}Sn , $^{52-48}\text{Ca}$, $^{68-72}\text{Ni}$), the collinear cluster tripartition, (CCT), has been observed by the FOBOS-group at the FLNR(Dubna) [1], with a similar decay mode in the reaction $^{235}\text{U}(\text{n}_{\text{th}}, \text{fff})$. This kind of *collinear* ternary fission of heavy nuclei into three heavy fragments has been predicted many times in theoretical work during the last decades [2]. In the present note we discuss the different collinear ternary fission (FFF) modes in $^{252}\text{Cf}(\text{sf}, \text{fff})$. The possible fission channels are predicted from potential-energy (PES) calculations, e.g. Fig.1. These PES's show pronounced minima for collinear ternary CCT- and FFF-decays, in both systems $^{252}\text{Cf}(\text{sf})$ (and $^{235}\text{U}(\text{n}_{\text{th}}, \text{f})$). The PES suggests the existence of several ternary fission modes to be observed simultaneously in the experiment. Setting particular gates during the analysis of the experimental data, we are able to extract for example the yield for FFF-decays by using conditions on the velocities. Such a symmetric decay into three nuclei of almost equal size (e.g. $Z=98 \rightarrow Z_i=32, 34, 32$) is observed with a probability of 4.0×10^{-6} /(binary fission). The Q-value for the FFF-decay in $^{252}\text{Cf}(\text{sf}, \text{FFF})$ is $Q_{\text{FFF}} = 268.3$ MeV, it is the largest. The FFF-decays have very similar dynamical features as the CCT-fission decays, however, the central fragment has very small kinetic energy and is mostly stopped in the source backing. Other possible CCT-decays, for e.g. $^{252}\text{Cf}(\text{sf}, \text{fff})$, have been identified with $Z_1, Z_2, Z_3 = (40, 40, 18)$, or $(42, 42, 14)$.

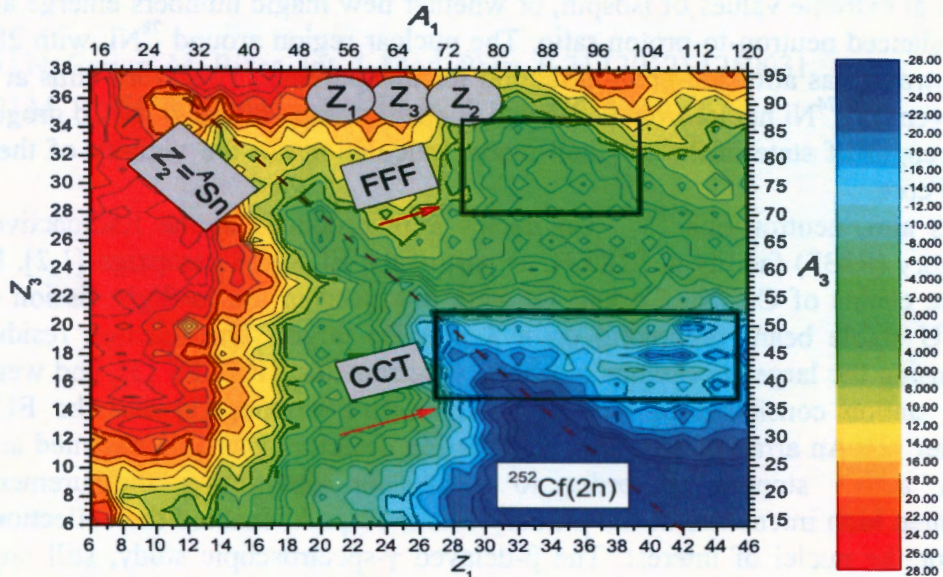


Fig. 1. The landscape of the potential energy surface (PES) for the ternary decay characterized by two of the three fragments, by Z_3 and Z_1 , for $^{252}\text{Cf}(\text{sf})$. The fragments with charges Z_2 for the CCT-decays are tin-isotopes labeled according to the inserts.

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TWO-PROTON AND TWO-NEUTRON RADIOACTIVITY MEASURED IN-FLIGHT BY TRACKING TECHNIQUE

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Extremely proton-rich nuclei with odd or even atomic numbers were predicted by V. Goldansky in 1960 to decay through one- or two-proton radioactivity, respectively. Two-proton (2p) radioactivity, a spontaneous decay of an atomic nucleus by emission of two protons, is one of the most recently discovered nuclear disintegration mode. It has first been reported for ^{45}Fe in 2002 with a half-life of about 4 ms, which is 1000 times longer than the quasi-classical estimate of a “di-proton” (or ^2He) cluster emission. Further observations of 2p radioactivity in ^{19}Mg , ^{54}Zn , ^{48}Ni , $^{94\text{m}}\text{Ag}$ have confirmed unexpectedly large half-lives of 2p precursors thus indicating a regular existence of long-lived nuclei beyond the proton drip line. The various experimental methods used to produce, identify and detect new nuclear species via their 2p decay will be reviewed. In particular, a novel tracking technique to study 2p decays in flight will be described in detail, and new data on the previously unknown 2p-decay precursor ^{30}Ar will be presented. The up-to-date theoretical understanding of specific observables accessible in the 2p decay measurements will be discussed with an emphasis on 2p-precursor's nuclear structure.

Neutron radioactivity, a spontaneous break-up of elements by emission of one or more neutrons, will be presented. Theoretical predictions of this still unobserved phenomenon, the recent experimental activity and plans within the FAIR project in Darmstadt will be reviewed. In particular, the case of two-neutron decay of ^{26}O will be considered in detail. Prospective candidates for observation of neutron radioactivity and the related experimental methods and neutron detectors will be discussed.

RECENT RESULTS FROM COLLINEAR LASER SPECTROSCOPY AT ISOLDE-CERN

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Collinear laser spectroscopy at ISOLDE-CERN has entered a new era with the installation of a cooler-buncher on the HRS mass separator, allowing low-background bunched-beam collinear laser spectroscopy experiments on beams of a few 1000 ions/s [1,2,3,4]. A further increase in sensitivity with nearly two orders of magnitude has been achieved in the new experimental beam line for collinear resonance ionization spectroscopy (CRIS), where ultra-low background conditions are combined with a very high detection efficiency [5] now allowing experiments on beams of less than 100 ions/s. Furthermore, the installation of a UHV-compatible windmill system at the end of the CRIS beam line has allowed alpha-decay studies on ultra-pure samples of isomeric beams [6].

In this presentation recent results from both experimental set-ups will be presented, including studies on isotopes of K, Ca, Mn and Fr.

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- [5] K.T. Flanagan et al., Physical Review Letters 111, 212501 (2013).
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STUDY OF SHAPE ISOMERIC STATES IN FISSION FRAGMENTS

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In our previous publications devoted to the collinear cluster tri-partition of the low excited nuclei [1-3] we have discussed the role of scattering medium in the registration of the CCT products. Briefly, even if initially two CCT partners fly in the same direction perfectly collinearly they get some angular divergence after passing the scattering medium on the flight pass due to the multiple scattering. Thanks to such effect they can be registered independently in the "stop" mosaic detector. Actually even thin backing of the radioactive source provides the observable effect.

In order to increase it additional absorber (Ti foil) was introduced just after the source at the distance of approximately 1 mm. We observe essential mass deficit in the total mass of the fission fragments detected in coincidence with Ti ions knocked out from the foil (fig. 1). For the sake of convenience, the FFs from such events are labeled as M_1 , M_2 and M_3 in an order of decreasing masses in the ternary event. The total mass of the two heavier fragments M_1+M_2 is plotted vs. the mass of the lighter fragment M_3 .

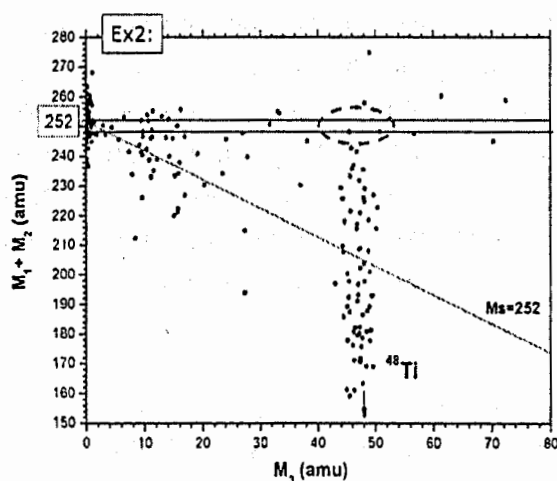


Fig. 1. FF mass distribution from $^{252}\text{Cf}(sf)$ for ternary events detected in the opposite mosaics of PIN diodes. Ti foil 2.2 μm thick was used as the additional absorber.

It could be expected if the scattered fragment looks like a di-nuclear system destroying due to inelastic scattering on the Ti nucleus. A mean flight time between the Cf source and the foil does not exceed 0.1 ns. It can be regarded as a low limit for the life time of the di-nuclear system (shape-isomer).

It should be stressed that the conventional elastic Rutherford scattering (without missing mass of the fission fragment involved) is observed in peripheral collisions.

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3. D.V. Kamanin, Yu. V. Pyatkov, "Clusters in Nuclei - Vol.3" ed. by C. Beck, Lecture Notes in Physics 875, pp. 183-246 (2013)

COMPLEX CONFIGURATION EFFECTS ON β -DECAY RATES

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One of the successful tools for nuclear structure studies is the quasiparticle random phase approximation (QRPA) with the self-consistent mean-field derived by making use of the Skyrme interaction. Many charge-exchange versions of it were developed during the last decade. Their common feature is that they allow 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 extend the description beyond the QRPA scheme in order to include damping effects observed experimentally. Making use of separable residual interaction one can perform the spin-isospin excitation calculations in large configuration spaces since there is an opportunity to avoid matrices whose dimensions grow with the size of configuration space. For the same reasons, we develop the finite rank separable approximation for the Skyrme interactions [1,2] that enables one to perform the charge-exchange calculations in the large configuration space [3,4].

In this talk we briefly describe our method for the charge-exchange excitations and present our studies of the coupling between one- and two-phonon terms in the wave functions and the tensor force effects on properties of Gamow-Teller (GT) states. We observe a redistribution of the GT strengths due to the tensor correlation influence on the 2p-2h fragmentation of GT states. The β -decay half-lives is decreased by these effects [5]. As an application we present the evolution of the β -decay scheme of the neutron-rich Ni isotopes and N=50 isotones, in comparison to the doubly-magic nucleus ^{78}Ni that is also an important waiting point in the r-process.

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STUDY of $^{82,83}\text{Ga}$ PRODUCED at ALTO WITH NEUTRON DETECTOR TETRA

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According to available schemes the nuclei in the vicinity of $N=50$ shell undergo Gamow Taylor (allowed) decays. In contrast, for nuclei crossing the $N=50$ shell, the first Forbidden (FF) transitions are expected to give a noticeable contribution [1]. With new experimental data on β -decay properties of more neutron rich species already (or shortly) available at new facilities the relative contribution of the Gamma-Teller and FF decays can be understood more. Furthermore, for an r -process site, β -decay properties „waiting points" (nuclei on closed neutron shells) have significant effects on the r -process dynamics and the abundance distribution [3, 2].

One of the means to investigate nuclear structure is in β -decay. Since β -delayed neutron emission becomes significantly strong decaying channel for neutron-rich nuclei far from stability, usage of a proper neutron detector to reveal their properties is indispensable. To conduct the appropriate investigations, in the frame of collaboration JINR (Dubna) and IPN Orsay a new detection system consisting of 80 ^3He -filled counters (TETRA neutron detector [4]), 4π β detector and a HPGe in order to measure simultaneously β , γ and neutron activities was constructed [5]. The efficiency of single neutron registration is $\sim 60\%$ and is almost at up to $\sim 1\text{MeV}$ neutron energy range. We present the new measurements at TETRA | neutron emission probability (P_n) and half-life of $^{82,83}\text{Ga}$ obtained with the laser ionization at ISOL facility ALTO. Our measurements reproduced well the $P_n(^{82}\text{Ga})$ known from literature before whereas $P_n(^{83}\text{Ga})$ was found to be of much difference. Interestingly, on one hand, that the discrepancy of experimental data obtained by different groups for ^{83}Ga is high and has to be understood. On the other, from a comparison of the available data sets for neutron rich Ga isotope to existing QRPA calculations performed in the allowed approximation (GT) and taking into account FF decays we draw a conclusion that more theoretical efforts are also required. Furthermore, it is highlighted the strong necessity of the detection system created for spectroscopy studies of neutron rich nuclei. Thus, thanks to measured β -neutron gated γ spectra, in which all the γ transitions irrelevant β -n branch are completely suppressed, we were able to study the structure of $^{81,82}\text{Ge}$ via β -n decay of Ga.

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STUDY OF THE N=50 SHELL GAP EVOLUTION TOWARDS ^{78}Ni AT ALTO: INVESTIGATING THE Z=32 “SINGULARITY”

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The evolution of neutron shell closure from N=40 to 50 is now suspected to originate from the same three-body force mechanism at play in the oxygen and calcium chains. And the region is thought to be an ideal playground for testing the most recent improvements achieved in an effort for deriving many-body effective forces. To accompany this effort, progress in the experimental knowledge in the neighborhood of ^{78}Ni is mandatory e.g. information on the single particle sequences and their evolution, evaluation of the collectivity etc.

Though the evolution of the N=50 shell effect towards ^{78}Ni has made the object of many experimental investigations during the past decade, the data has given rise to some debate. It appears from the analysis of the measured ΔS_{2n} that the N=50 shell gap decreases starting from Z=38 (Sr) towards Z=32 (Ge) but this decrease stops at Z=32 and the gap increases again from Z=32 (Ge) to Z=30 (Zn) pointing towards a “Z=32 singularity”.

We will present recent results obtained at the Orsay e-driven ISOL facility ALTO from β -delayed γ -spectroscopy and neutron emission probability measurements. A thorough exploitation of the neutron-rich Ga beams up to mass 84, produced at ALTO, both from surface and laser ionization within the ISOL technique, has been achieved. Studies extend now also to β -delayed neutron emission probability measurements thanks to the newly commissioned ^3He 4π neutron counter TETRA [1].

The accumulated results (of which some have been published recently in [2] and [3]) allow pointing toward the microscopic origin of the Z=32 “singularity” and its connection with fast collectivity development just next to ^{78}Ni .

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CAN WE OBSERVE A "STIMULATED" PROTON BETA DECAY?

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An experiment is proposed aiming to observe a "stimulated" proton beta decay. The "missing mass" for the decay is suggested to be taken from the potential energy that a proton acquires on a part of a Rutherford trajectory, in the vicinity of a highly charged nucleus. The mechanism does not involve nuclear (strong) forces.

PRODUCTION OF EXOTIC NUCLEI IN LOW-ENERGY MULTI-NUCLEON TRANSFER REACTIONS

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A possibility for the production of exotic (mostly neutron rich) nuclei in low-energy multinucleon transfer reactions will be discussed in the talk. Due to the bending of the stability line toward the neutron axis, in fusion reactions of stable nuclei one may produce only short-living proton rich isotopes of heavy elements. For elements with $Z > 100$ only neutron deficient isotopes (located to the left of the stability line) have been synthesized so far. That is the main reason for the impossibility to reach the center of the "island of stability" ($Z \sim 110 \div 120$ and $N \sim 184$) in fusion reactions with stable projectiles. Multi-nucleon transfer processes at near barrier collisions of heavy (and very heavy, Ulike) ions seem to be most realistic reaction mechanism allowing one to produce new neutron enriched heavy nuclei located in the unexplored upper part of the nuclear map.

Our predictions for the production of new neutron rich heavy nuclei in multinucleon transfer reactions will be discussed (along with dynamics of such processes) and new (most promising) experiments will be proposed. A special attention will be paid to the "inverse" quasi-fission mechanism leading to formation of reaction fragments with masses lighter than projectile and heavier than target masses [1].

Low-energy multi-nucleon transfer reactions are shown to be very effective tool also for the production and spectroscopic study of light exotic nuclei. The corresponding cross sections are found to be 2 orders of magnitude larger as compared with high energy fragmentation reactions. Several optimal reactions for the production of extremely neutron rich isotopes of elements with $Z = 6 \div 14$ are proposed [2].

A new facility (based on selective laser ionization of reaction products) developed currently at the Flerov laboratory (JINR, Dubna) and aimed on the production and study of new neutron rich heavy nuclei produced in the multi-nucleon transfer reactions will be shortly reviewed [3].

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INFLUENCE OF NUCLEAR REACTION MECHANISMS ON POPULATION OF ISOMERIC STATES AND RATIOS

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Of particular interest is the investigation of reactions induced by weakly bound radioactive nuclear beams with unusual distribution of nucleons, strongly affecting the interaction of nuclei. This distribution can in turn affect the population of isomeric and ground states of fusion and transfer reaction products as compared to the population of nuclei formed in reactions with alpha particles and other stable nuclei.

The compound nuclei formation is a great theoretical and experimental challenge in case with weakly bound and halo nuclei. Weakly bound nucleons or entire clusters can be captured by the target nuclei in the sub-barrier energy region, like in reactions involving deuterons and the ^6Li and ^7Li nuclei. Nowadays reaction mechanism for stable nuclei leading to complete fusion is thoroughly studied, while complete and incomplete fusion reactions induced by weakly bound nuclei still remain a theoretical challenge.

The main objective of this investigation is to study mechanisms of nuclear reactions taking into account excitation functions for the formation of reaction products with light and heavy ions (in some cases, in ground and isomeric states). A comparison of measured isomeric ratios for the nuclei $^{195\text{m},197\text{m}}\text{Hg}$ ($7/2$), $^{196\text{m},198\text{m}}\text{Tl}$ (7^+) and $^{196\text{m},198\text{m}}\text{Au}$ (12^-) produced in reactions with beams of weakly bound nuclei d , ^3He , ^6He , ^6Li and alpha-particles, and other stable nuclei help identify the main factors which influence reaction mechanisms and isomeric ratios $\sigma_{\text{m}}/\sigma_{\text{g}}$ (i.e., input angular momentum, probability of population of high-spin states).

The behaviour of excitation functions and isomeric ratios for products of fusion reactions with neutron evaporation can be explained within the compound nucleus models of nuclear reactions (characterized by energy dependence). Compound nucleus reactions are usually characterized by a high isomeric ratio, which varies depending on the particle energy (due to the angular momentum and changes in excitation energy). The experimental values of $\sigma_{\text{m}}/\sigma_{\text{g}}$ obtained in various reactions through charged-particle emission shows a great difference in the behavior of excitation functions and isomeric ratios for fusion and direct reactions. Isomeric ratio is usually low in direct transfer reactions. Reactions with nucleon transfer on incident particles are characterized by low isomeric ratios essentially independent of energy. This behavior is mainly related to low-lying excited particle-hole states in the target nucleus.

PROJECTILE FRAGMENTATION AS A TOOL TO OBSERVE SHELL EFFECTS CLOSE TO THE NEUTRON DRIP-LINE

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Increased beam intensities at the NSCL, as well as advances in experimental techniques, using a two-stage separator, allowed to observe new nuclei along the neutron drip-line [1,2]. In a recent experiment, production cross sections for a large number of neutron-rich nuclei produced from the fragmentation of ^{76}Ge (130 MeV/u) and ^{82}Se (139 MeV/u) beams were measured [3,4], including 21 new isotopes of the elements $17 \leq Z \leq 26$. Enhanced cross sections of several new nuclei were compared to a simple thermal evaporation framework [2], and also have been well reproduced by the LISE⁺⁺ Abrasion-Ablation model [5] with masses derived from the full pf shell-model space with the GXPF1B5 effective interaction [6]. It seems that the systematic trends in the production cross sections demonstrate changes in the nuclear mass surface, that can be explained with a shell model that predicts a subshell closure at $N=34$ around $Z=20$.

In this contribution based on the theoretical pre-fragment analysis it will be discussed why projectile fragmentation is so sensitive to changes in the nuclear mass surface close to the neutron drip-line, and a new dBE production cross section systematics will be presented.

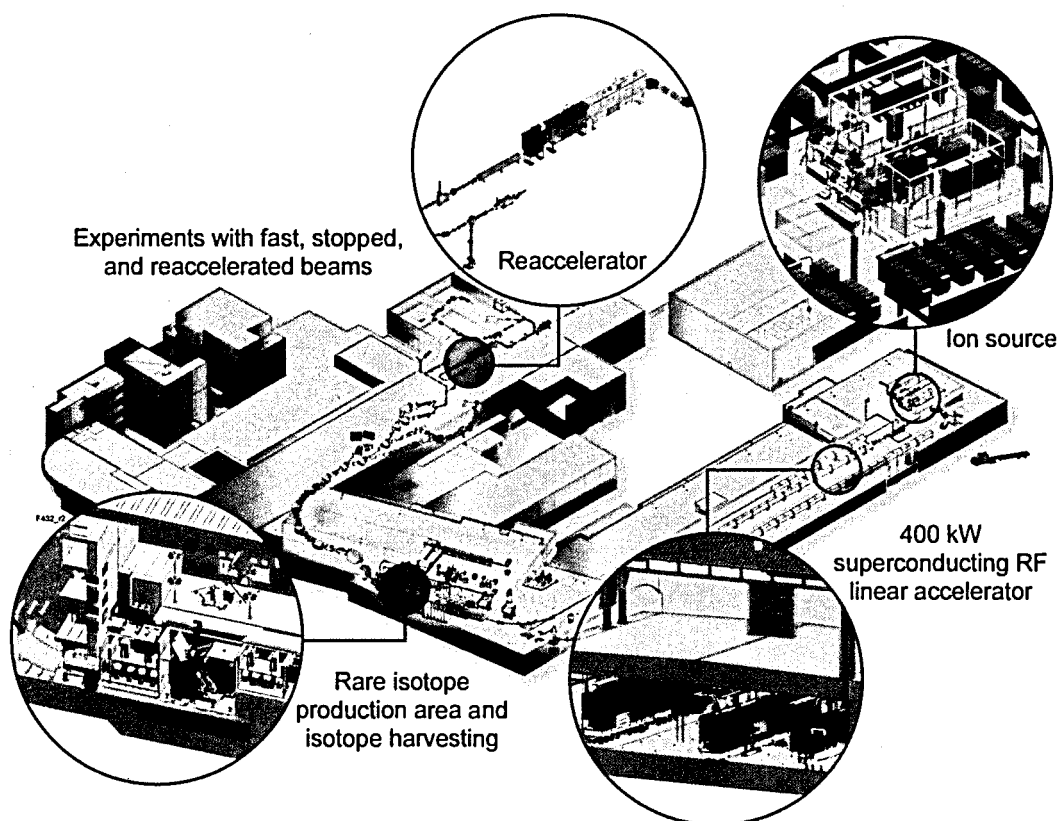
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FACILITY FOR RARE ISOTOPE BEAMS UNDER CONSTRUCTION

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FRIB, the US's "Facility for Rare Isotope Beams" at Michigan State University (MSU), will be based on a 400 kW, 200 MeV/u heavy ion linear accelerator. Once realized, FRIB will be a world-leading rare isotope beam facility, providing a wide variety of high-quality beams of unstable isotopes at unprecedented intensities, opening exciting research perspectives with fast, stopped, and reaccelerated beams. NSCL, the present premier rare isotope beam user facility in the US, enables pre-FRIB science and will eventually be integrated into FRIB. This talk will review new developments, present the FRIB facility and its science opportunities, and summarize the status of the project for which construction has started.



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PRESENT CAPABILITIES AND FUTURE PLANS OF THE TEXAS A&M CYCLOTRON INSTITUTE

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The Cyclotron Institute at Texas A&M operates a K150 cyclotron, a K500 superconducting cyclotron and associated advanced ECR sources. Together these provide a powerful arsenal of intermediate energy ion beams for both fundamental and applied research. Sophisticated state-of-the-art detectors and spectrometers enable research in nuclear structure, weak interactions, exotic nuclei, nuclear astrophysics, nuclear dynamics and thermodynamics, the nuclear equation of state atomic physics and nuclear science. Present capabilities and future plans of the Institute will be presented.

RIKEN RI BEAM FACTORY - HARVEST TIME

Hideto En'yo

RIKEN Nishina Center for Accelerator-Based Science

At RIKEN RI Beam Factory (RIBF), having all the experimental facilities in place, the uranium beam intensity recorded 25pnA in 2014. With use of this powerful beam many experiments are begin performed by variety of researchers from all over the world, producing a lot of new data which were just a dream in several years ago. Recent status of RIKEN RI Beam Factory (RIBF) is presented with future prospects in science and a future accelerator plan.

FLNR SHE FACTORY

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The study of nuclear physical and chemical properties of recently discovered superheavy elements (SHE, $Z = 112-118$) as well as synthesis of new elements ($Z > 118$) remain one of the most crucial tasks in modern science. Over the past decade, the unique results have been obtained that are of utmost importance both in nuclear physics and astrophysics (experimental evidence of the existence of islands of increased stability of SHE) as well as in chemistry (the influence of relativistic effects on the chemical properties of elements 112–114).

The new nuclides were synthesized in the fusion reactions between accelerated ^{48}Ca ions and nuclear targets ^{238}U , ^{237}Np , $^{242,244}\text{Pu}$, ^{243}Am , $^{245,248}\text{Cm}$, ^{249}Cf [1] and ^{249}Bk [2]. Their half-lives vary from 0.5 ms to 30 h depending on the proton and neutron numbers in the synthesized nuclei. The relatively long lifetimes of the new nuclides allowed the conduction of the first experiments devoted to their chemical identification and study of their properties. The identification of the decay chain of element 115, synthesized in the reaction $^{243}\text{Am}(^{48}\text{Ca}, 3n)$, was performed by the final decay product, i.e., the element 105 isotope (^{268}Db , $T_{1/2} = 29$ hr), which is a homologue of Ta and Nb [3]. The study of the chemical properties of elements 112, 114 and 113 produced in the reactions $^{242}\text{Pu}(^{48}\text{Ca}, 3n)^{287}114$ (α) $\rightarrow$ $^{283}112$; $^{244}\text{Pu}(^{48}\text{Ca}, 4n)^{288}114$ (α) $\rightarrow$ $^{284}112$, and $^{243}\text{Am}(^{48}\text{Ca}, 3n)^{288}115$ (α) $\rightarrow$ $^{284}113$ was performed in experiments, in which the volatility and adsorption on Au surface were studied [4-6].

Further development implies the construction of a first-ever SHE factory at JINR FLNR, which shall include the following:

- a new accelerator complex with the average-mass ion beam intensity 10-20 times higher than that of today;
- physical and chemical new-generation experimental set-ups (highly effective gas-filled recoil separator, gas catcher, etc.).

The work was carried out with the financial support from the Russian Foundation of Basic Research (project code # 13-03-12205-ofi-m).

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MARRIAGE OF LASER AND ACCELERATOR TECHNOLOGY: NUCLEAR PHYSICS WITH NEXT GENERATION OF HIGH POWER LASER AND BRILLIANT LOW ENERGY GAMMA BEAMS AT ELI-NP

S.Gales^{1,2} for the ELI-NP team

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The development of high power lasers and the combination of such novel devices with accelerator technology has enlarged the science reach of many research fields, in particular High energy, Nuclear and Astrophysics as well as societal applications in Material Science, Nuclear Energy and Medicine.

The European Strategic Forum for Research Infrastructures (ESFRI) has selected a proposal based on these new premises called "ELI" for Extreme Light Infrastructure. ELI will be built as a network of three complementary pillars at the frontier of laser technologies. The ELI-NP pillar (NP for Nuclear Physics) is under construction near Bucharest (Romania) and will develop a scientific program using two 10 PW class lasers and a Back Compton Scattering High Brilliance and Intense Low Energy Gamma Beam , a marriage of Laser and Accelerator technology at the frontier of knowledge. In the present paper, the technical description of the facility, the present status of the project as well as the science, applications and future perspectives will be discussed.

HIGH-RESOLUTION FRS AND SUPER-FRS EXPERIMENTS AT GSI-FAIR

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High-resolution spectrometer experiments with an incident ion beam characterized by a large phase space represent a great challenge for in-flight rare-isotope facilities. Projectile fragments and fission products separated in flight have an inevitable large angular and momentum spread due to their stochastic creation processes and the atomic interactions in the production target, degrader and detector materials. Solutions are to use dedicated ion-optical systems like energy-loss spectrometers and isochronous systems, or methods which reduce the incident phase space by cooling and energy bunching methods. Recent experiments with the fragment separator FRS have demonstrated the success of these efforts and will be reported in this contribution together with spectrometer experiments planned with the next generation facility Super-FRS.

NUCLEAR MOMENTS AND TRANSITION PROBABILITIES AT ALTO AND AT GANIL*

J. Ljungvall¹, G. Georgiev¹, I. Matea², D. Verney², and J. Wilson²

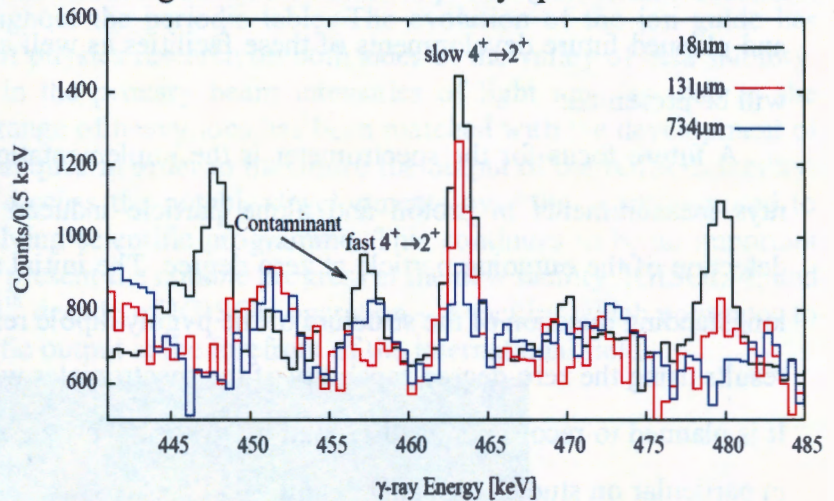
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During the last few years a collaboration between CSNSM and IPN Orsay has built and exploited a device called OUPS (Orsay Universal Plunger System). It has been designed to be used at the ALTO facility as well as at GANIL. So far several physics campaigns, aiming at lifetime- and g- factor measurements, have been performed. The results from the commissioning and the experiments performed up to now will be presented. Those include several physics subjects as e.g. shape coexistence, nuclear symmetries and shell structure from light masses and all the way up to neutron deficient osmium isotopes.

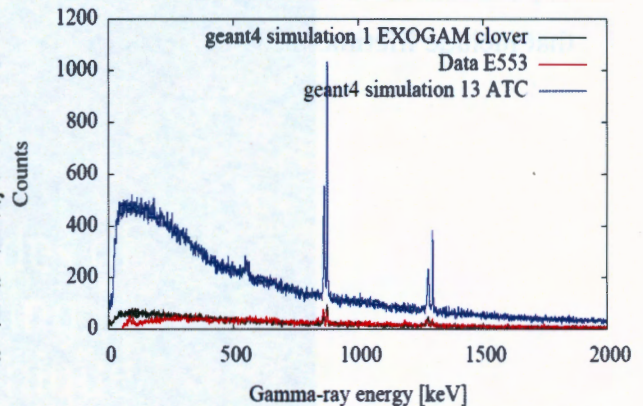


the Oups plunger



Few points of the upcoming AGATA campaign at GANIL, related to the realistic simulations of the experiments, will be touched upon. These include, but are not limited, to efficiency estimates and gamma-ray tracking. The importance of the realistic simulations for the detailed preparations of the experiments, the interpretation of the of “online” data and the validation of the approaches for the data analysis will be emphasized.

The necessary modifications of the OUPS plunger for the AGATA@Ganil campaign will be presented and few examples of typical experimental setups to be used for the AGATA@Ganil campaign will be mentioned. The latest news from the MINORCA setup, presently being installed at ALTO will be presented together with the main goals of the physics campaign which is envisaged.



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iTHEMBA LABS - AN OVERVIEW OF RESEARCH AND FUTURE DEVELOPMENTS

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The nuclear physics research programme at iThemba LABS, South Africa, utilize both light and heavy ion beams from a $k=200$ cyclotron. Experimental facilities include a k600 magnetic spectrometer and the AFRODITE γ -detector array. Recent and planned future developments of these facilities as well as selected recent results will be presented.

A future focus for the spectrometer is the implementation of coincident gamma rays measurements in proton and alpha particle induced inelastic reaction with detection of the outgoing particle at zero degree. The initial aim will be to study the longstanding question of the structure of the pygmy dipole resonance in nuclei. Other results using the zero degree capability of the spectrometer will also be presented.

It is planned to reconfigure and expand the AFRODITE γ -array. Some recent results, in particular on studies of nuclear chirality in the mass $A = 80, 110$, and 190 regions that include lifetime measurements will be present.

THE IGISOL TECHNIQUE – THREE DECADES OF DEVELOPMENTS

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The Ion Guide Isotope Separator On-Line (IGISOL) technique, conceived in the early 1980s as a novel variation to the helium-jet method, has been used to provide radioactive ion beams of short-lived exotic nuclei for fundamental nuclear structure research and applications for three decades. This direct on-line mass separation of primary recoil ions from nuclear reactions has achieved similar extraction efficiencies for both volatile and non-volatile elements throughout the periodic table. The evolution of the ion guide has been driven by the pursuit of physics research on both sides of the valley of beta stability. The gradual improvement in the primary beam intensities of light ions, as well as the increasing availability of a range of heavy ions has been matched with the development of novel ion manipulation techniques in order to maximize the output of the IGISOL facility. In this contribution, I will discuss the notable developments over the years, required to match the needs of the evolving scientific programme. This continues to be an important strategy and thus I will also present the notable progress at the new facility, IGISOL-4, and where our goals lie in the 4th decade of IGISOL operation – a facility which continues to produce high quality scientific output at the forefront of the international field.

Juha Äystö
Tommi Eronen
Ari Jokinen
Anu Kankainen
Iain D. Moore
Heikki Penttilä *Editors*

Three decades of
research using
IGISOL technique
at the University of
Jyväskylä

 Springer

SHE RESEARCH ON THE WAY TO NUSTAR AT FAIR

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The program for SHE research on the way to NUSTAR at FAIR includes reaction studies such as the systematic investigation of fusion-fission as well as deep inelastic transfer and quasi-fission as tools to explore new regions of SHE and possibilities for SHE synthesis. Of particular interest are nuclear molecules formed in central collisions at Coulomb Barrier energies as a new path to cold massive transfer¹). The goal is to extend the investigation of the nuclear structure of SHE specifically into the region of neutron rich isotopes beyond fermium and to explore possibilities to reach the island of spherical SHE.

In the second step we will develop a next generation in-flight separator for SHE research²). At present the most promising option is a compact velocity filter optimized for large acceptance combined with an ion-catcher-MRTOF system. Kinematic separation with a velocity filter allows selecting the type of reaction: complete fusion or deep inelastic transfer. The ion-catcher-MRTOF system will be used alternatively to the conventional silicon detectors. It allows fast separation at high rates and high mass resolution of the order of 10^{-5} sufficient for isobaric separation. The MRTOF system includes a separator stage, e.g. an RFQ, to select the mass range of interest, a prerequisite for sensitive measurements of transfer products³). It has been demonstrated in experiments with the FRS-ESR combination at GSI that mass measurements with high resolution allow isotope identification in A and Z⁴). The mass separated and A,Z identified products can be deposited on a silicon detector system for SHE spectroscopy.

Finally it is planned to develop a setup optimized for the use at the low energy buncher of the SuperFRS⁵) to investigate the influence of shell effects and isospin in target, projectile, and reaction products on the production cross section. We will also investigate the option to use the new in-flight separator system with cocktail beams of rare isotopes from the SuperFRS for the production and investigation of new isotopes. Such universal systems can be used at the planned ELI laser facility as well as high current accelerators for SHE production and investigation.

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LASER SPECTROSCOPY AT GSI AND FAIR – RECENT RESULTS AND PROSPECTS

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The GSI Helmholtz Centre at Darmstadt has been a place offering unique opportunities for the spectroscopy of highly charged ions (HCI) [1] and so will be the future FAIR facility. Moreover, the Super Fragment Recoil Separator (S-FRS) at FAIR will additionally provide short-lived isotopes that are not accessible at other places. The LASPEC collaboration is preparing a collinear laser spectroscopy setup to be installed behind the S-FRS [2,3].

I will present recent results from recent laser spectroscopy of hydrogen- and lithium-like $^{209}\text{Bi}^{80+,82+}$ at the ESR storage ring [1] as well as ongoing developments towards the spectroscopy of HCI in ion traps [4] and of short-lived isotopes at FAIR. The prospects and developments for LASPEC as well as for laser spectroscopy at the FAIR storage rings are discussed.

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PHYSICS WITH MINOS AT THE RIBF

Alexandre Obertelli

on behalf of the MINOS and SEASTAR collaborations.

MINOS is a new device composed of a thick hydrogen target and vertex tracker [1]. It has been conceived for in-beam spectroscopy of rare isotopes produced at fragmentation facilities. It is now hosted in the Spin-Isospin laboratory of the RIKEN Nishina Center. In the near future, MINOS in association with other detectors and spectrometers should contribute to exciting physics programs at the RIBF focusing on nuclei produced by hydrogen-induced secondary knockout reactions. The full detector and its electronics have been finalized and validated at the end of 2013.

A brief presentation of the MINOS detection system and main characteristics regarding (p,2p) reactions from in-beam validation at HIMAC will be present as well as the intended physics program at the RIBF. A report on the first SEASTAR campaign performed in spring 2014 will be made.

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EXPERIMENTS AT THE FRONTIERS OF NUCLEAR PHYSICS: THE EXPERIMENTAL PROGRAM OF THE NEW SUPER-FRS COLLABORATION

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The future FAIR facility will comprise the superconducting fragment separator (Super-FRS) as one of its main scientific instruments. This magnetic high-resolution spectrometer, coupled to the heavy-ion synchrotron complex SIS-18/SIS-100, will be the central device of the NuSTAR collaboration for research with exotic nuclei. Although the Super-FRS will be used for transmitting separated isotopes to downstream end stations at the exits of its three branches, it can also be used as a stand-alone experimental device with ancillary detectors. In this function, the Super-FRS is a powerful and versatile high-resolution spectrometer system for exotic nuclei over a large energy range up to 1,500 MeV/u. The various magnetic sections of the Super-FRS can be operated as dispersive, achromatic or dispersion-matched spectrometer units which are ideally suited to measure the momentum distributions of secondary reaction products with high resolution and precision. In this energy range and with this flexibility, the Super-FRS is a worldwide unique instrument and allows for a variety of novel experiments. Taking advantage of new stages and ion-optical modes, it also allows for a continuation and extension of preceding experiments at the existing FRS.

Among the planned experiments, there are the search for new isotopes, precise measurements of the production cross sections and kinematical properties, inclusive reaction and nuclear radii measurements, basic atomic collision studies, studies of hypernuclei, delta-resonances in exotic nuclei and the spectroscopy of atoms characterized by bound mesons or antiprotons. Rare decay modes like multiple-proton or neutron emission and the influence of the nuclear tensor force in the observation of high-momentum components of the nucleons are also addressed. The in-flight decay measurements of dripline nuclei in the picosecond range, pioneered at the FRS, will be extended with the proposed program. Fusion, transfer and deep-inelastic reaction mechanisms with the slowed-down and energy-compressed fragment beams are proposed for the high-resolution energy-buncher system at the Low-Energy Branch of the Super-FRS.

Examples will be given. A roadmap towards Super-FRS experiments at FAIR will be presented. Detector developments will be briefly discussed. Opportunities for new cooperations will be shown, and interested scientists will be invited to join these activities.

DEVELOPMENT OF NEUTRON DETECTORS FOR THE STUDIES ON THE ACCULINNA AND ACCULINNA-2 SETUPS

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The correlation studies is very effective tool in the researches of the neutron rich nuclei (for instance ^7H , ^{10}He [1, 2]). It is often necessary to register neutrons together with other decay products in order to obtain these correlations. There is a good example of such research – it is planned study of ^{10}Li on the ACCULINNA and ACCULINNA-2 setups [3, 4]. We want to make the experiments for study of ^{10}Li ground and excited states in $^9\text{Li}(d, p)^{10}\text{Li}$ and in $^{11}\text{Li}(p, d)^{10}\text{Li}$ reactions, where registration of neutron from the decay of ^{10}Li should improve energy resolution. It was shown recently [5], that neutron detector based on the stilbene crystal is good enough in comparison with other types of neutron detectors (DEMON, LAND, MONA). As a result, several R&D works [5, 6] with different design of the neutron detector based on the stilbene crystal were tested and reported.

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EXOTIC NUCLEI AND FISSION STUDIES AT LLNL

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The experimental nuclear physics group at LLNL is actively investigating exotic nuclei from light nuclei to super heavy elements in order to understand the interactions between nucleons in the nucleus. We use a variety of experimental probes to learn about the structure of the nucleus, the effects of altering the ratio of neutrons-to-protons in the nucleus, nuclear decay modes, and the limits of nuclear stability by studying neutron-rich and heavy isotopes. Nuclear spectroscopy of heavy and superheavy elements, as well as the synthesis and decay of superheavy elements, is probing the next region of doubly magic nuclei. Probing the nature of many-body and collective effects in the nucleus is critical to a fundamental understanding of fission. Recent experimental results on studies of exotic nuclei and fission measurements by scientists at LLNL will be presented.

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LAYOUT OF NEW EXPERIMENTS ON THE OBSERVATION OF SPONTANEOUS CREATION OF e^-/e^+ PAIRS IN SUPERCritical COULOMB FIELDS

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An especially interesting prediction of QED of strong fields [1] is the decay of neutral vacuum showing up as the spontaneous e^-e^+ pair creation in supercritical fields achieved in collisions of actinide nuclei [2,3]. Unfortunately, the predicted process has not yet been demonstrated unambiguously in experiments [1]. This happens largely because in the so far attainable experimental conditions fixed uranium targets were irradiated with uranium ions keeping electrons in the lower atomic orbits. One could rely only on the K-shell ionization occurring with a few-percent probability in such U+U collisions. The implementation of collisions of two bare nuclei eliminates this severe deficiency. Suggested here is to build a collider of co-moving beams of bare actinide nuclei supplied by relativistic beams obtained either from the SIS18 synchrotron (GSI-FAIR, Darmstadt) or from the booster ring of the future NICA complex (JINR, Dubna).

In the co-moving interaction scheme coasting beams are stored and cooled down stochastically in the two storage rings having one common section. (Some combination of stochastic and electron cooling might be a choice too). Energy $E_{lab} = 500A$ MeV set for the slower beam guarantees long life time of the U^{92+} ions. The faster beam energy is adjusted to match the desired collision energy E_{cm} . Choosing E_{cm} between 7.0 and 3.6A MeV one can span a range of closest-approach distance $R_{min} = 14 - 30$ fm in the U+U collisions. Assuming the use of 1.5-T dipole magnets, operating at room temperature, the two rings keeping the slower and faster beams will be about 60 and 75 meters in their circumferences.

A proper option is the $^{238}U + ^{235}U$ collision. Feasible longitudinal and transverse acceptances chosen for the storage rings will allow one to keep on the ring orbits and well recognize the nuclei coming out after the elastic U+U scattering in a range of $\theta_{cm} = 175^\circ - 130^\circ$. This approach will extend also to the ascertainment of the case when U^{92+} acquires an electron and becomes U^{91+} , as well as to the formation of products obtained in the nucleon or alpha-particle elastic transfers. Energy balance ascertainment within error bars of ± 500 keV might be real for such reactions. Accurate and detailed measurements of the e^+U^{91+} pair yields obtained for different precisely defined collision energies and scattering angles should be performed.

Similar measurements should be done also for positrons emitted in coincidence with the detected quasi-elastic transfer products. In reality a well attainable beam luminosity of up to $2 \times 10^{24} \text{ cm}^{-2} \cdot \text{s}^{-1}$ makes real the detection of positrons emitted in coincidence with the products of deep-inelastic collisions (DIC). Some data (see e.g. Ref. [5]) show that the DICs observed with a total cross section of 1 – 2 mb/sr at $E_{cm} = 1000 - 1500$ MeV originate from the decay of the di-nuclear U+U systems having lifetimes in a range of few times 10^{-21} s. Such time delay is considered to be long enough to display in the positron energy spectrum the spontaneous break-up of neutral vacuum [6].

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LATEST DEVELOPMENTS IN NUCLEAR, PARTICLE, AND ASTROPARTICLE PHYSICS AT JYFL

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Accelerator Laboratory at the Physics Department of the University of Jyväskylä has a long tradition in development, construction, and implementation of new instruments and detection techniques. This line of research has been recently extended from Nuclear- and Relativistic Heavy Ion collisions to Astroparticle and Neutrino Physics. In my presentation I shall review the latest developments and prove the highlights of the measurements conducted over the period since EXON 2012. Special emphasis will be given to the research conducted in collaboration with JINR Dubna, INR, Baksan and Khlopin Radium Institute.



Fig. 1. JYFL – Dubna – Naples – GSI collaboration taking a break during June 2013 experiment at the K130 cyclotron in Jyväskylä.

THE MULTICHANNEL TIME DISTRIBUTIONS SPECTROMETER IN REAL TIME

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For research and control of characteristics of radiation fluxes, radioactive sources in particular, for example, in paper [1], a spectrometer and methods of data measurement and processing based on the multichannel counter of time intervals of accident events appearance (impulses of particle detector) MC-2A (SPC "ASPECT") were created.

The spectrometer has four independent channels of registration of time intervals of impulses appearance and correspondent amplitude and spectrometric channels for control along the energy spectra of the operation stationarity of paths of each of the channels from the detector to the amplifier. The registration of alpha-radiation is carried out by the semiconductor detectors with energy resolution of 16-30 keV.

The detectors are installed in the same vacuum chamber as the source, and each of them registers a part of the radiation flux of the alpha-source within the respective solid angle. The counter allows registration of the moment of pulse time with the error up to $2,44 \times 10^{-7}$ seconds. Buffer memory has a FIFO structure in each channel with two independent ports, this makes it possible to record the time intervals to the hard drive of the computer without interrupting the measurement. The dead time of each channel with account for the recording cycle is 250 nanoseconds.

The control program MC-2A was developed for data acquisition and accumulation. Solid angles for source-detector are chosen from the conditions of average load in the channels of 20–40 seconds–1.

The accumulated at the hard drive arrays of successive time intervals of particles registration in each of the four channels are scanned off-line. The developed software allows getting time series of readings for any (more than 250 nanoseconds) specified time interval and correspondent arrays of time intervals between the events. This approach will make it possible not to lose the data on the time characteristics of radiation flux in contrast to [1, 2].

Using a spectrometer there have been taken measurements of oscillations of alpha-radiation ^{239}Pu flux intensity with a subsequent autocorrelative statistical analysis of the time series of readings.

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GAMMA-RAY SPECTROSCOPY OF EXOTIC NUCLEI WITH EURICA

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Gamma-ray spectroscopy following the β decay is an effective tool for probing low-lying yrast and non-yrast states, from which key information on nuclear structure, such as shape transitions/coexistence and single-particle orbits, can be obtained. For the study of rare isotopes, especially when the nucleus of interest lies at the boundaries of availability for spectroscopic studies, isomeric decays are likely to be a more useful means than β decays to populate excited levels. The combined β - γ and isomeric-decay measurements at the RI Beam Factory (RIBF) facility [1], which has the capability of providing the world's strongest RI beams, are at the forefront of exploration of exotic nuclei far from the stability line.

Research opportunities for decay spectroscopy at RIBF can be expanded in the EURICA (EUROBALL-RIKEN Cluster Array) project, which was realized in cooperation with the EUROBALL Owners Committee and the PreSpec Collaboration. The main body of EURICA consists of 12 Cluster-type HPGe detectors, surrounding a highly segmented silicon stopper system named WAS3ABi. In addition to the normal EURICA setup, 18 LaBr₃ detectors and plastic scintillators are installed for the fast-timing measurement of γ and β rays, respectively. The aim of the EURICA project is to pin down currently controversial subjects in nuclear physics and nuclear astrophysics, such as the evolution of shell structures that can lead to the appearance and/or disappearance of the *spherical* magic numbers, the effect of weak binding and pairing in largely diffused neutron densities, stable oblate, triaxial, and higher-order deformations at low excitation energy, decay properties of neutron-rich isotopes on the r-process path, and so on. A wide range of unstable nuclei on the Segre chart are within the scope of EURICA. In this presentation, the results of the EURICA experimental campaigns in 2012-2013 will be introduced, highlighting characteristic isomers in neutron-rich palladium and silver isotopes below the doubly-magic nucleus ¹³²Sn [2].

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PROSPECT OF ACCULINNA-2 FACILITY

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The ACCULINNA-2 project [1] at the U400M cyclotron in FLNR JINR is focused on the studies of nuclear properties far from stability valley and RIB-induced nuclear reactions in the lowest energy range (10÷50 MeV/nucleon) attainable for in-flight separators. The long-range program for experiments with RIBs and possible further development of this facility are discussed. This program is based on an existing experience of correlation measurements and a fruitful collaboration with foreign institutes [2]. In addition to the standard methods for RIB research, the specific equipment and instruments are foreseen to be used:

- unique cryogenic tritium [3] and ^3He targets and exotic solid-state targets of ^{10}Be , ^{14}C ;
- micro-strip silicon tracking detectors [4, 5] and radiation-hard silicon strip detectors [6];
- the NeuRad (Neutron Radioactivity) fine-resolution detector of neutrons [5];
- the GADAST (Gamma-ray Detectors Around Secondary Target) array [6];
- the OTPC detector (Optical Time Projection Chamber) [6].

The setup aims at the study of nuclear landscape beyond the proton and neutron drip-lines and intends to push this researches up to the limits of nuclear existence in the whole range of exotic nuclei with atomic numbers extending from $Z = 1$ to

$Z \approx 36$. The feasibility of the proposed program is confirmed by the recent works [4-9].

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RECENT PROGRESS IN EXOTIC NUCLEI STUDIES USING RESONANCE SCATTERING

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Resonance scattering combined with rare isotope beams and thick target inverse kinematics (TTIK) technique provides a powerful probe for structure of exotic nuclei. Many successful experiments have been performed and detailed spectroscopy information on exotic, mostly proton rich ([1,2] for example), but also a few neutron rich nuclei [3,4] have been extracted. The experimental efforts were mostly concentrated on measuring excitation functions for proton elastic scattering. More recently, clustering phenomena in exotic nuclei were studied using resonance elastic scattering of rare isotope beam ions on alpha-particles [5]. Also, successful attempts to measure excitation functions for proton inelastic scattering with rare isotope beams were made [6]. Recent results from resonance scattering experiment and development of new experimental approaches, such as application of active targets for resonance scattering measurements will be discussed.

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THE ALTO FACILITY AT IPN ORSAY

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The ALTO facility (Accélérateur Linéaire et Tandem d'Orsay) at Institut de Physique Nucléaire d'Orsay is in operation. The ALTO facility consists of two accelerators in the same area. A Tandem accelerator dedicated to stable (ions and cluster) beam physics and a linear electron accelerator dedicated to the production of radioactive beams.

The aim of the radioactive facility is to provide neutron rich isotope beams for both nuclear physics study (away from the valley of stability) and developments dedicated to next generation facilities such as SPIRAL2. The neutron rich isotopes are produced by photofission of ^{238}U induced by the 50 MeV electrons from the linear accelerator. The isotopes coming out of the fission target effuse towards an ion source to form a beam that is analyzed through the on line separator PARRNe. Additional experimental beam lines have been constructed.

First experimental results will be presented.

THE PROTON AND ELECTRON NON-STABILITY IN THE DARK MATTER MODELS

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In nuclear physics, still there is a question about the nature of the $SU(2)_I$ -isotopic and $U(1)_Y$ -hypercharge global symmetries in the description of the intrinsic properties of the proton and neutron, the main components of all nuclear matter. This question is closely related searches birth mechanism of these elements in the process of creation of the universe and, therefore, the mechanism of their instability. The latter is connected with the longstanding quest for experimental proton decays going preserving em-charge, and the neutron decay, which would have to go only if non-conservation in the reaction em-charge. In grand unified theories, adopting the hypothesis that the fundamental matter is presented in the form of quarks and electrons, attempts were made to solve these problems in part, but so far they have not led to success. proton decay scenarios grand unified theories is still not detected. In the author's article *Annales de la Fondation Louis de Broglie*, Volume 31, no 2-3, 2006. 227. "Majorana Neutrino and New Space-Time Geometry" - was proposed to solve the problem of stability of nuclear matter together with the problem of stability of the electron. In this approach, it was assumed the existence of fermionic matter different from Dirac fermions and, as a consequence of not having em-properties. In fact, this matter in their properties could resemble dark matter. These ideas formed the basis of our hypothesis that this is the pra-matter could be a source of light em-birth and, accordingly, the visible part of a universe filled by the Dirac matter. As a new spatio-temporal properties of this fermionic pra-matter should have new exotic spin properties that we will illustrate the example of several geometric models. We expect to discuss a number of phenomenological consequences of this approach, which also are touched and the stability issues of the nuclear and lepton matter.

ACTIVE TARGET – TIME PROJECTION CHAMBERS FOR REACTIONS INDUCED BY RARE ISOTOPE BEAMS: PHYSICS AND TECHNOLOGY

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Weakly bound nuclear systems can be considered to represent a good testing-ground of our understanding of non-perturbative quantum systems. These systems can be studied by reactions using rare isotope beams. Great progress in experimental sensitivity has been attained by increase in rare isotope beam intensities and by the development of new high efficiency detectors. It is now possible to study reactions leading to bound and unbound states in systems with very unbalanced neutron to proton ratios. Application of Active Target-Time Projection Chambers to this domain of physics will be illustrated by experiments performed with existing detectors. The NSCL has recently commissioned an Active Target-Time Projection Chamber (AT-TPC) to be used to study reactions induced by rare isotope beams at the National Superconducting Cyclotron Facility (NSCL) and at the future Facility for Rare Isotope Beams (FRIB). The AT-TPC counter gas acts as both a target and detector, allowing investigations of fusion, isobaric analog states, cluster structure of light nuclei and transfer reactions to be conducted without significant loss in resolution due to the thickness of the target. The high efficiency and low threshold of the AT-TPC allows investigations of fission barriers and giant resonances with fast fragmentation rare isotope beams. A large number of electronic channels (order of magnitude 10,000) and a high speed DAQ are needed. A short description of other detectors of this type under development will be given.

THE iTHEMBA LABS RADIOACTIVE BEAMS PROJECT

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iThemba LABS, based around the Separated Sector Cyclotron (SSC), is the premier nuclear particle accelerator laboratory in Africa and indeed in the Southern Hemisphere. Internationally, interest in nuclear physics is focusing on the study of the so-called 'terra incognita' – the unknown part of the table of nuclides – which includes the unstable 'neutron-rich' nuclei that cannot be produced using beams of stable atoms. This region holds the key to our understanding of nuclear forces and the origin of the elements of which the Universe is composed. Radioactive-ions are also of particular use in the development of advanced materials. Measurements of the decay of the probe ion give direct evidence on the site of the implanted ion, on the nature of the site, and on diffusion characteristics of the dopant ions. Neutron-rich nuclei can only be created and studied in the laboratory by using beams of artificially produced radioactive-ion beams from an accelerator such as a cyclotron.

iThemba LABS proposes a staged development of a rare-ion beam facility:

- 1. The first stage would see the addition of a high-current, 70-MeV cyclotron to iThemba LABS.**

This cyclotron would take over the production of radioisotopes, 24 hours a day, thus releasing the existing SSC to be dedicated to physics research – mainly pure and applied nuclear physics – and to neutron radiotherapy.

- 2. The second stage would see the production of radioactive-ion beams, bringing nuclear and materials research and training in South Africa to the international forefront.**

Since two H^- ion beams can be extracted simultaneously from the proposed new 70-MeV cyclotron, one of these will be used to produce radioactive ions via the Isotope-Separation-On-Line (ISOL) method. These ions will then be formed into a beam which can then be post-accelerated by the existing SSC for use in nuclear physics experiments.

LOW-ENERGY NUCLEAR SPECTROSCOPY IN A MICROSCOPIC MULTIPHONON APPROACH

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The low-lying spectra of heavy nuclei are investigated within the quasiparticle–phonon model. This microscopic approach goes beyond the quasiparticle random-phase approximation by treating a Hamiltonian of separable form in a microscopic multiphonon basis. It is therefore able to describe the anharmonic features of collective modes as well as the multiphonon states, whose experimental evidence is continuously growing. The method can be put in close correspondence with the proton–neutron interacting boson model.

By associating the microscopic isoscalar and isovector quadrupole phonons with proton–neutron symmetric and mixed-symmetry quadrupole bosons, respectively, the microscopic states can be classified, just as in the algebraic model, according to their phonon content and their symmetry. The method can be implemented numerically for systematic studies of spectroscopic properties throughout entire regions of vibrational nuclei including exotic ones.

Si DETECTORS FOR NUCLEAR PHYSICS EXPERIMENTS WITH EXOTIC BEAMS

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The experimental conditions at the present and future radioactive beam facilities at GSI/FAIR, MSU, RIKEN and JINR will provide unique opportunities for nuclear structure studies on nuclei far off stability, and will allow exploring new regions in the chart of nuclides of key importance for nuclear structure and nuclear astrophysics. In particular, using in-flight fragmentation technique provides possibility to study exotic nuclear with very short life-times. Using modern Si detectors allows measurements of position, time and energy loss with very high precision, hardly reachable having different type of detectors. These measurements can be performed by just one or separate detector systems, tuned for one particular measurement. It has been demonstrated that Si detectors can be used for measurements of heavy and light ions, for example, protons at the same time. Different environments – from air to ultra-high vacuum are possible. If needed, these detectors could stand relatively high radiation without substantial degradation of performance, matter of proper detector design.

All these aspects of using Si detectors will be discussed and results of different measurements presented.

TRANSACTINIDE CARBONYL COMPLEXES: A NEW CLASS OF COMPOUNDS IN SUPERHEAVY ELEMENT CHEMISTRY

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Many transition metals are known to form complexes with carbonyl ligands. Interestingly, in these complexes the metal atom has oxidation state zero. Furthermore, transition metal carbonyl complexes are known to be very volatile. Thus, carbonyl complexes are an extremely interesting class of compounds to be studied in the transactinides. As was shown recently, the transition metal carbonyl complexes of Mo(CO)₆, W(CO)₆, or Os(CO)₅ can easily be synthesized with good yield at ambient conditions by stopping fission products or recoil atoms of a fusion-evaporation reaction in a CO containing gas mixture [1]. Furthermore, by the introduction of the isoelectronic substituent N₂, even mixed nitrogen-carbonyl compounds were obtained [2]. In recent experiments performed at RIKEN, Sg(CO)₆, a first transactinide carbonyl complex was synthesized for the first time and its volatility was studied [3]. Future experiments will concentrate on the carbonyls of Bh, Hs, or even Mt, but also their thermal stability will be investigated.

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STUDY FOR FISSION USING MULTI-NUCLEON TRANSFER REACTION

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We present a recent development for the fission study using multi-nucleon transfer reaction at the JAEA tandem facility. Using multi-nucleon transfer reaction neutron-rich nuclei can be produced, which cannot be accessed by fusion-reaction, and several nuclei populated by different transfer channel can be studied in one experiment. Another feature of transfer reaction is that excitation energy of a compound nucleus can be populated continuously from the ground state up to several tens MeV, thus the excitation energy dependence of fission properties can be obtained.

We have carried out experiments in the reactions of $^{18}\text{O} + ^{238}\text{U}$ and $^{18}\text{O} + ^{232}\text{Th}$. Transfer channel and the excitation energy of compound nucleus was determined by using silicon ΔE -E detectors. Fission fragments are detected by position-sensitive multi-wire proportional counters. The fission chamber is surrounded by liquid neutron-detectors to detect neutrons accompanied by fission.

We obtained the fragment mass distributions from actinium to plutonium isotopes for 24 nuclei and their excitation energy dependence. Among them, nine nuclei were the first to obtain fragment mass distribution. Data for fission cross section as a surrogate for neutron-induced fission and prompt neutron-multiplicity per fission will be discussed.

MAGNETIC ANALYZER MAVR FOR STUDY OF EXOTIC WEAKLY BOUND NUCLEI

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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.

STUDY OF NEUTRON-UNBOUND STATES WITH MoNA-LISA

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The Modular Neutron Array (MoNA) in conjunction with the large-gap Sweeper magnet at the NSCL is an effective setup to explore neutron-unbound states. The recent addition of the Large-area multi-Institutional Scintillator Array (LISA) increased the efficiency and acceptance for the neutron detection.

Neutron-unbound nuclei beyond the dripline as well as neutron unbound excited states of bound nuclei have been populated using primarily proton removal reactions. The (d,p) reaction in inverse kinematics on a CD₂ target was used for the first time to measure ¹⁵Be. Results of other recent experiments including ¹⁰He, ¹⁰Li, and ^{12,13}Be, will be presented.

THE LASER ION SOURCE AT IPN-ALTO

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Resonant Ionization Laser Ion Sources (RILIS), based on the stepwise excitations of atomic transitions, offer an outstanding combination of excellent elemental selectivity and high ionization efficiency. It has become a powerful and versatile tool for generation of pure radioactive isotope beams at on-line mass separator facilities worldwide. Initiated in 2009, IPN-Orsay has installed RILIS in the Isotope Separators on-line (ISOL) system at the photon fission facility Alto, which aims to the measurements of the nuclear properties of exotic nuclei through $\beta\gamma$ and βn spectroscopy, among other techniques.

Rialto consists of two dye lasers pumped with a 532 nm 10 kHz Nd:YAG laser with the wavelength extension options with two frequency doublers and one tripler, and was successfully put into its first operation in 2011. Gallium isotopes were resonantly ionised and an enhancement factor of 15 was observed compared to surface ionisation. The β -decay of ^{84}Ga was studied in a first physics run. In 2013 and early 2014, zinc isotopes up to ^{80}Zn were resonantly ionised on-line with frequency tripling in the first step. An experiment of tin is planned in Oct 2014.

To provide the optimal laser ionization scheme and operational parameters for different elements during on-line radioactive beam deliveries, an off-line reference cell has been built to test the laser ionizations of different elements via different ionization schemes. The first commence of the off-line reference cell is expected starting in June 2014. The developments of tellurium and antimony are planned.

PROSPECTS FOR SEARCHING FOR NATURAL SHEs IN SOUTH AFRICA WITH ACCELERATOR MASS SPECTROMETRY

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Myth-making is an inherently human pastime while debunking myths often promotes humanity above superstition. Thus was alchemy debunked when Mendeleev was able to formulate the Periodic Table of Elements though at the time he had no knowledge of atomic structure.

When the nuclear atom and the quantum mechanical basis for its structure were uncovered, the possibility that “Super Heavy Elements” (SHEs) might exist in nature came into the minds of the scientific community. The ongoing monumental efforts to synthesize lighter isotopes at the “shores” of the predicted “island” of stable or quasi-stable elements are well-known, while the question remains – how and where should we focus our searches for SHEs in nature? One technique that has been applied is Accelerator Mass Spectrometry (AMS), though with no positive results reported thus far. Predictions from nuclear models as to the favoured atomic numbers for SHEs have led to searches in chemical homologues but relativistic effects for the outer electronic structure may be important which could therefore alter the chemical properties.

An AMS facility at the Gauteng site of the iThemba Laboratory for Accelerator Based Sciences (LABS) is currently undergoing its commissioning tests. The facility incorporates the fully-refurbished EN tandem accelerator transferred from the University of the Witwatersrand, a custom-built Low Energy Injection System (LEIS) and a High Energy Analysis System (HEAS) ordered from National Electrostatics Corporation (NEC). The AMS facility will be presented and prospects for searching for naturally-occurring SHEs will be discussed.

* *IAEA-supported Technical Expert*

OVERVIEW OF SEARCH FOR NEW ISOTOPES AND NEW ISOMERS AT RIKEN RI BEAM FACTORY

T. Kubo, N. Inabe, N. Fukuda, D. Kameda, H. Suzuki, H. Takeda, Y. Shimizu, D. S. Ahn, D. Murai, K. Kusaka, K. Yoshida, M. Ohtake, Y. Yanagisawa

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The BigRIPS in-flight separator [1] at the RIKEN RI Beam Factory (RIBF) [2], which became operational in March 2007, has been used to produce a variety of rare isotope (RI) beams by using in-flight fission as well as projectile fragmentation. Its major features are two-stage structure and large ion-optical acceptances. Excellent performance in particle identification is also the important feature. Efficient RI-beam production has been made possible by these features of the BigRIPS separator, allowing us to significantly expand the region of accessible exotic nuclei. Figure 1 schematically shows the present layout of the RIKEN RIBF.

In this talk, we will overview the search for new isotopes and new isomers which have been conducted from 2007 to 2014 at the BigRIPS separator using in-flight fission of $345 \text{ MeV/u } ^{238}\text{U}$ and projectile fragmentation of $345 \text{ MeV/u } ^{124}\text{Xe}$.

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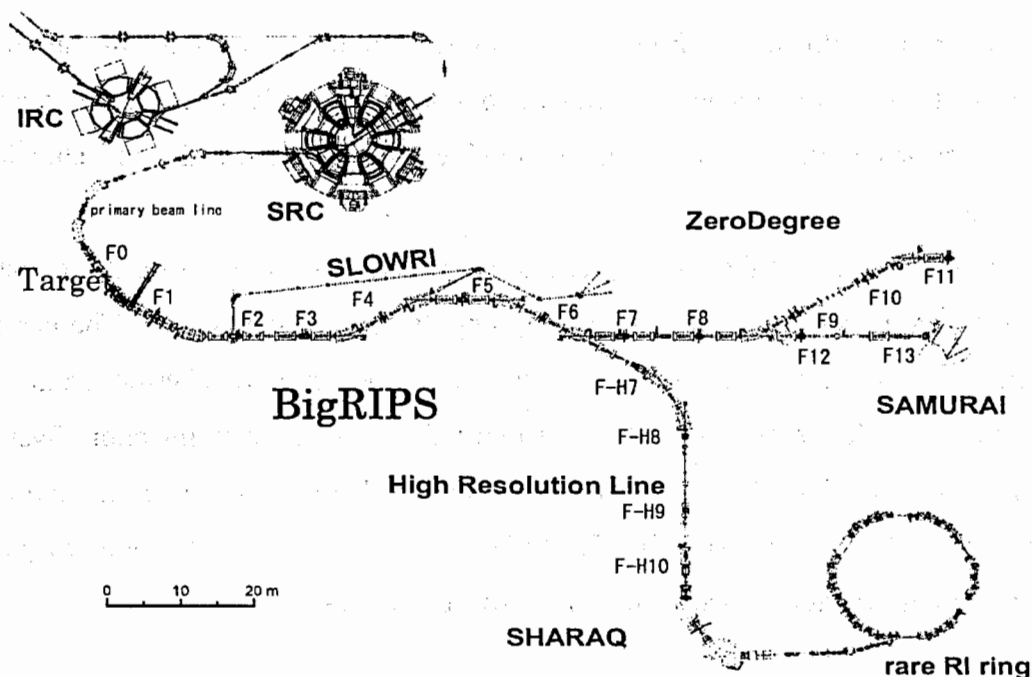


Fig. 1 Schematic layout of the RIKEN RI beam Factory (RIBF).

PRECISION MASS MEASUREMENTS OF SHORT-LIVED NUCLIDES AT STORAGE RING IN LANZHOU

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Nuclear mass is the fundamental property of a nucleus. The complex interplay of strong, weak and electromagnetic interactions in the nucleus contributes to the difference between its mass and the sum of the masses of its constituent nucleons. Precise and systematic measurements of nuclear masses not only provide information on nuclear structure, but also find their important applications in nuclear astrophysics. Recent commissioning of the Cooler Storage Ring at the Heavy Ion Research Facility in Lanzhou (HIRFL-CSR) has allowed us for direct mass measurements at the Institute of Modern Physics in Lanzhou (IMP), Chinese Academy of Sciences (CAS). In the past few years, a series of mass measurement experiments have been carried out using the CSRe-based isochronous mass spectrometry (IMS). Masses of short-lived nuclides of both neutron-rich and neutron-deficient have been measured up to a relative precision of 10^{-6} – 10^{-7} via fragmentation of the energetic beams of ^{58}Ni , ^{78}Kr , ^{86}Kr , and ^{112}Sn [1, 2, 3, 4, 5]. In this talk, the experiments and the results will be presented. The implications of our experimental results with respect to nuclear structures and stellar nucleosynthesis in the rp-process of x-ray bursts are discussed. Some disadvantages in the IMS method itself are pointed out and simulated, and further improvement using double ToF detectors are proposed.

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EXPERIMENTAL STUDY OF HEAVY ION INDUCED REACTIONS AT ENERGIES CLOSE TO THE COULOMB BARRIER

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Total Kinetic Energy (TKE) - Mass distributions of fission-like fragments for the reactions of heavy ions with various targets leading to the formation of heavy and superheavy compound systems at energies near the Coulomb barrier have been investigated. The measurements have been performed by the two time-of-light spectrometer CORSET.

The role of the shell effects, the influence of the entrance channel asymmetry and the deformations of colliding nuclei on the mechanism of the fusion-fission, quasifission and multinucleon transfer reactions are discussed. The influence of shell effects on the fragment yield in quasifission and multinucleon transfer reactions is considered [1].

The estimation of the available excitation energies of the formed fragments has been done from measured TKE by assuming that the excitation energy is divided between the two primary fragments according to their mass ratio. For TLF heavier than the target the excitation is about 30-50 MeV. Such excitation of these fragments gives a possibility to form nuclei which survive after emission of 3-5 neutrons.

The measured unexpected large yield of products with masses heavier than the target mass in damped collision confirms that low-energy multi-nucleon transfer reactions are a very promising path way for producing new neutron-rich isotopes. This result is particularly promising because such mechanism can be used for the synthesis of new superheavy elements [2].

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NUCLEAR AND APPLIED RESEARCH AT JYFL ACCELERATOR LABORATORY

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Accelerator Laboratory in the Department of Physics, University of Jyväskylä has three disciplines, basic research in nuclear physics, accelerator-based material science and accelerator based commercial services. Those areas are using primary ion beams from three accelerators; K130 heavy ion cyclotron, MCC30 light ion cyclotron and Pelletron accelerator, all of them equipped by in-house produced ion sources. In this presentation I will shortly introduce the present layout and basic instrumentation of the Accelerator Laboratory, including its research program in general.

Basic research has mainly concentrated on the research at ion Guide Isotope Separator On Line (IGISOL) and gas-filled recoil spectrometer (RITU). The highlight from a gas-filled recoil spectrometer RITU will be introduced and future prospects with a new vacuum mode separator MARA will be given.

The previous generation of IGISOL-facility, IGISOL 3 was shut down during the Summer 2010 and since then whole facility has been moved to the new building and re-commissioned. A wide research program of IGISOL facility will be introduced and research highlights will be presented with examples from IGISOL 3. The first results and future prospects of recently commissioned IGISOL-4 will be discussed.

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