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**ISINN-16**

**XVI International Seminar  
on Interaction of Neutrons with Nuclei**



**Neutron Spectroscopy,  
Nuclear Structure,  
Related Topics**

**Dubna, 2008**

**Abstracts**

Dubna  
2008

Joint Institute for Nuclear Research

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**NEUTRON SPECTROSCOPY,  
NUCLEAR STRUCTURE,  
RELATED TOPICS**

*XVI International Seminar  
on Interaction of Neutrons with Nuclei*

Dubna, June 11–14, 2008

*Abstracts of the Seminar*

Объединенный институт  
ядерных исследований  
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8. Calviani M. Fission cross section measurements of actinides at CERN n TOF facility.
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32. Kadmensky S.G., Titova L.V. Fission dynamics and correlation effects in fragments angular distributions for fission induced by thermal neutrons and low-energy gamma-quanta

33. Kadmensky S.G., Titova L.V. The structure of transitional fission states for nuclear fission induced by linearly polarized gamma-quanta
34. Lyuboshitz V.V. and Lyuboshitz V.L. Low-energy scattering of a polarized neutron on a polarized proton"

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40. Kamanin D.V. Experimental evidences of clustering in thermal fission of  $^{235}\text{U}$ .
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43. Pyatkov Yu.V., Different modes of collinear multibody decay of  $\text{Pu}^*$  isotopes
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49. Sukhovej A.M., Khitrov V.A. Main parameters of the gamma-decay process and the property of nucleus  $^{174}\text{Yb}$  from the radiative capture of slow neutrons.
50. Sukhovej A.M., Khitrov V.A. Distribution of parameters of the primary gamma-transition intensities following resonance neutron capture and some properties of the  $^{157,159}\text{Gd}$  compound nuclei.

51. Sukhovej A.M., Khitrov V.A. Possibilities for determining the reliable compound states cascade gamma-decay parameters and main errors of applied methods of experiment:  $^{96}\text{Mo}$  as an example.
52. Tyukavkin A. MEASURING OF THE FRAGMENTS NUCLEAR CHARGES AT THE MINI-FOBOS SPECTROMETER.
53. Kim G.N., Khandaker M. U., Kim K., Lee M. W., Kim K. S., Cho Y.S., and Lee Y.O., Production cross section of residual radionuclides by proton-induced reactions on  $^{nat}\text{Cd}$  and  $^{nat}\text{Fe}$
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56. Badita C.-R., Low background gamma-ray spectrometry on environmental samples at GammaSpec laboratory of IFIN-HH.

## THE DEVELOPMENT OF SEGMENTED HIGH RESOLUTION FAST NEUTRON SPECTROMETER

J. N. Abdurashitov<sup>a</sup>, V. N. Gavrin<sup>a</sup>, V. L. Matushko<sup>a</sup>,  
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### Abstract

We present the development of a spectrometer based on full energy absorption using liquid scintillator doped with enriched  $^6\text{Li}$ . Of specific interest, the spectrometer is expected to have good pulse height resolution, estimated to lie in the range (10–15)% for 14 MeV neutrons. It should be sensitive to fluence rates from  $10^{-4} \text{ cm}^{-2} \text{ s}^{-1}$  to  $10^2 \text{ cm}^{-2} \text{ s}^{-1}$  above a threshold of 500 keV in an uncorrelated  $\gamma$ -background of up to  $10^2 \text{ s}^{-1}$  ( $E_\gamma > 100 \text{ keV}$ ). The detector's efficiency is determined by the volume of the scintillator ( $\sim 1.2 \text{ l}$ ) and is estimated to be (0.2–0.5)% for 3 MeV neutrons. The good pulse height resolution is achieved by compensation of the non-linear light-yield of the scintillator due to the use of optically separated segments, which collect scintillations from each recoil proton separately. We have constructed a pilot version of the detector using undoped liquid scintillator, and we demonstrate here the response of the detector to neutrons from a Pu- $\alpha$ -Be source, whose energies range up to 10 MeV and the response of the detector to 14.1 MeV neutrons from a D-T source also. Initial testing indicates a low threshold ( $\approx 600 \text{ keV}$ ) and good spectral response after requiring a multiplicity of three segments. Such a spectrometer has applications for low-background experiments in fundamental physics research, characterizations of neutron fluence in space, and the health physics community.

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## LEVEL DENSITIES AND THERMAL PROPERTIES OF $^{56,57}\text{Fe}$

E. Algin<sup>1</sup>, U. Agvaanluvsan<sup>2</sup>, Y. Alhassid<sup>3</sup>, M. Guttormsen<sup>4</sup>, G.E. Mitchell<sup>5</sup>, J. Reksad<sup>4</sup>, A. Schiller<sup>6</sup>, S. Siem<sup>4</sup>, A. Voinov<sup>6</sup>

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Nuclear level densities for  $^{56,57}\text{Fe}$  have been extracted from the primary  $\gamma$ -ray spectra using ( $^3\text{He}, ^3\text{He}'\gamma$ ) and ( $^3\text{He}, \alpha\gamma$ ) reactions. Nuclear thermodynamic properties for  $^{56}\text{Fe}$  and  $^{57}\text{Fe}$  are investigated using the experimental level densities. These properties include entropy  $S$ , Helmholtz free energy  $F$ , caloric curves (i.e., the energy-temperature  $E$ - $T$  relation), chemical potential  $\mu$ , and heat capacity  $C_v$ . Experimental heat capacities are compared with Shell Model Monte Carlo calculations.

## STATUS OF THE UCN SOURCE PROJECT AT FRM-II REACTOR

Altarev I., Frei A., Gutsmedl E., Paul S., Schreckenbach K., Stoepler R.

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*Abstract:* A superior solid deuterium source of ultra-cold neutrons is under development at the new Munich reactor FRM-II. Being started in 1999, the project had been slowed down for several years owing to funding delay. Since 2007 it is fully funded. Though the basic concept of the source and its expected performance remains, it is considerably revised in details. Its location changed from radial SR4 to tangential SR6 beam tube. A UCN converter is now combined with solid hydrogen pre-moderator. Neutron guide is significantly enlarged in cross-section and length. The area available for placing experiments with UCN is also increased. We present a status report of the project.

SYMMETRIES AND SPIN-ANGULAR CORRELATIONS  
IN NEUTRON INDUCED REACTIONS:  
ELASTIC, RADIATIVE AND FISSION CHANNELS

Barabanov A.L.

Kurchatov Institute, Moscow 123182, Russia

Spin-angular correlations in neutron induced reactions arise due to interference of partial waves (carriers of definite angular momenta) and are sensitive to any mechanisms influencing these waves. Therefore from the beginning of 1950th years spin-angular correlations are actively used as a tool of studying of those terms in Hamiltonians of strong, weak and electromagnetic interactions which depend on angular momenta (spins). In particular, forces breaking fundamental symmetries, P parity and T invariance, are of this type.

However, each of reactions, (n, n), (n, gamma) and (n, f), initiated by neutrons, has special features. The purpose of the report is to present the current situation with measurement of different spin-angular correlations in neutron reactions and to discuss their importance.

The report is devoted mainly to the interaction of slow neutrons with medium and heavy nuclei. It is well known that P violating effects in neutron resonances are strongly enhanced due to dynamic, kinematic and resonance mechanisms. The same should be true for T violation. Thus the possibilities of testing T invariance in neutron elastic channel without false effects are emphasized.

Investigations of P even and P odd spin-angular correlations in elastic and inelastic (radiative and fission) channels arising due to interference of s- and p-waves could allow us to determine p1/2- and p3/2-amplitudes of neutron p-wave resonances. It is also a way to study both s- and p-wave contributions from negative resonances and fix positions and widths of these resonances.

Special attention is given to fission reaction where exit channels are related to transition states with definite spin J, parity and projection K of spin J on the deformation axis (K is also the total helicity of fission fragments). The use of multilevel method of describing spin-angular correlations of "forth-backward" and "left-right" types in neutron induced fission enables to separate (JK) fission channels and determine their weights. The contributions K=0 are of special interest due to their relation to symmetries of nuclear form at the fission barrier.

T odd triple correlation in ternary fission is also considered. It is shown that spin-orbit mechanism could generate both TRI and ROT effects.

THE ROTATION OF THE FISSIONING COMPOUND NUCLEUS IN  
REACTIONS INDUCED BY POLARIZED NEUTRONS

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The drawbacks and advantages are discussed of the classical approach [1,2] to the rotation of the fissioning nucleus which appears after the absorption of the polarized low-energy neutrons. It is shown that the vector  $\vec{R}$  which is named in [1,2] "the angular moment of the nuclear collective rotation" and is connected with the values J of the nuclear spin and its projection K on the symmetry axis of the deformed nucleus by the expression

$$R = \hbar \sqrt{J(J+1) - K^2} \quad (1)$$

contradicts both classical and quantum mechanics. It is also shown that the well-known expression for the polarization vector  $\vec{P}(J)$  of the compound-nucleus which appears after the absorption of the neutron with polarization  $\vec{p}_n$  by the unpolarized target with spin I

$$\vec{P}(J) = \begin{cases} \frac{J+1}{3J} \vec{p}_n & \text{for } J = I + 1/2, \\ -\frac{1}{3} \vec{p}_n & \text{for } J = I - 1/2, \end{cases} \quad (2)$$

does not take into account the specificity of fission for the compound nucleus with the axially symmetrical deformation and the fixed quantum numbers K.

The correct quantum approach with the spin density matrix of [3] allows to define the polarization vector  $\vec{P}_K(J)$  of the fissioning deformed nucleus with fixed quantum numbers J and K

$$\vec{P}_K(J) = \frac{\langle \vec{J}(K) \rangle}{J} = \frac{g_{KJJ}}{2J} \vec{p}_n \quad (3)$$

$$g_{KJJ} = \frac{J(J+1) - I(I+1) + 3/4}{J} \cdot \frac{J(J+1) - K^2}{(J+1)}$$

The ensemble-averaged vector  $\langle \vec{J}(K) \rangle$  is a classical vector directed perpendicularly to the system's symmetry axis which can be used for the definition of the systems rotation velocity. Because of its classical nature it does not obey the uncertainty relation "angular momentum—angle of rotation" and allows therefore to define the rotation angle of the fissioning system with high precision (as it was done in [1,2]). However, this expression does not take into account the resonance interference and is strictly valid only for the isolated resonance.

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During the nonadiabatic deformational motion of axially symmetrical fissile nucleus in precession region because of dipole-dipole Coulomb interaction of fission prefragments the simultaneous excitation of E1-giant isovector dipole resonances in mentioned prefragments on condition, that spin  $J$  and its projection  $K$  onto symmetry axis of fissile nucleus conserve, can take place. These resonances are characterized by life times less than  $10^{-21}$  s, and decays with emission of precession E1  $\gamma$ -quanta with energies  $E_{\gamma} \approx 15$  MeV. Angular distribution of precession  $\gamma$ -quanta in the case of nonpolarized fissile nucleus is defined as  $A_0 = a \sin^2 \theta$ , where  $a$  is constant,  $\theta$  is angle between the direction of  $\gamma$ -quanta flight and  $z$  axis, which direction is chosen in direction of the flight of light fission fragment. This distribution has maximum at  $\theta=90^\circ$ , reduce to zero at  $\theta=0^\circ$  and distinguish from practically isotropic angular distribution of evaporational  $\gamma$ -quanta  $A_{ev}$  ( $A_{ev} \gg a$ ).

For the experimental observation of precession  $\gamma$ -quanta T-odd correlations in angular distributions of  $\gamma$ -quanta, emitted in fission induced by thermal polarized neutrons, can be investigated, since these correlations are observed for precession  $\gamma$ -quanta, but are absent for evaporational  $\gamma$ -quanta. T-odd correlations appear because of Coriolis interaction of spin  $J$  of polarized fissile nucleus and total spin  $j$  of emitted  $\gamma$ -quanta. Using methods, developed in paper [1,2] for the description of T-odd correlations in angular distributions of  $\alpha$ -particles, emitted by fissile nucleus in ternary fission, it can be shown, that in angular distribution of precession  $\gamma$ -quanta, in addition to term  $A_0(\theta)$ , the term  $A_T(\theta, \varphi)$  appears. The term  $A_T(\theta, \varphi)$  is defined by only T-odd ROT-correlation and has structure  $A_T(\theta, \varphi) = b |\mathbf{p}| \sin 2\theta \cos \varphi$ , where  $b$  is constant,  $\mathbf{p}$  is polarization vector of thermal neutron, which defines the direction of  $\gamma$  axis. Since the  $\gamma$ -quanta motion is free, coefficient  $b$  has non-zero values only with taking into account the interference of different neutron resonances of fissile nucleus. Since detectors of  $\gamma$ -quanta don't separate precession and evaporational  $\gamma$ -quanta, the coefficient of asymmetry  $D(\theta)$  will be defined by relation  $A_T(\theta, \varphi)$  and  $A_{ev}$  at  $\varphi=0$  and will be expressed by formula  $D(\theta) = (b/A_{ev}) \sin 2\theta$ , which takes zero values at  $\theta=0^\circ$  and  $90^\circ$  and has maximum at  $\theta=45^\circ$ . The angular dependence of coefficient  $D(\theta)$  is close to dependence of analogous coefficient, obtained experimentally [3].

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## Fission cross section measurements of actinides at CERN n\_TOF facility

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Sensitivity studies for advanced nuclear systems such as fast Gen-IV reactors, extended burnup LWR cores, and ADS shows that actinide data are crucial for assessing critical integral parameters of these systems, such as the multiplication factor. The data are particularly important for transmutation or incineration scenarios. The incineration process relies on neutron induced fission of trans-uranium isotopes, in particular of <sup>237</sup>Np, <sup>241,243</sup>Am and <sup>245</sup>Cm. A large effort is therefore being devoted to the accurate determination of fission cross-sections for these isotopes.

In recent years, attention has been focused also on the Th-U fuel cycle, due to the abundance of <sup>232</sup>Th in the earth crust, the proliferation resistance of the fuel cycle, and to the possibility of breeding in a thermal spectrum. In the past, nuclear data for isotopes involved in the Th-U cycle did not receive the same attention as the isotopes of the U-Pu cycle. In the IAEA list of first priority isotopes, the fissile <sup>233</sup>U is one of the most important requests.

With these motivations, the n\_TOF Collaboration has performed measurements of the neutron induced fission cross sections of <sup>233</sup>U, <sup>241,243</sup>Am, <sup>245</sup>Cm, and of the fission standards <sup>235,238</sup>U. Two sealed Fission Ionization Chambers were used as fission fragment detectors. Since some of the isotopes are characterized by an activity that reaches hundreds of MBq, the innovative features of the n\_TOF beam, i.e. the high instantaneous flux and low repetition rate, has been crucial for collecting high accuracy fission data on these isotopes.

The results of the analysis of <sup>235</sup>U, <sup>233</sup>U up to  $\sim 100$  MeV, and the preliminary results for <sup>245</sup>Cm, <sup>241</sup>Am and <sup>243</sup>Am from thermal energies up to 2 MeV will be presented. The present data will allow to improve the accuracy of the cross-section databases, to extend the Resolved Resonance Region (RRR) above the present limits, and to obtain resonance parameters in energy intervals, where only evaluated

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cross section or old and discrepant data are currently available. An accurate assessment of uncertainties of the experimental data will be presented, together with a preliminary analysis of the resonances in the RRR region of  $^{233}\text{U}$  and of  $^{245}\text{Cm}$  by means of the R-matrix code SAMMY.

Additionally, new results on the  $^{238}\text{U}/^{235}\text{U}$  fission cross-section ratio up to 300 MeV will be shown.

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## ON THE COINCIDENCE MEASUREMENT IN THE YAGUAR NN-EXPERIMENT

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### Abstract

An hypothesized improvement in the signal-to-noise ratio in the YAGUAR nn-scattering experiment is to measure coincidences between the main detector, located below the scattering volume, and a second detector placed above the scattering volume. Here we investigate the relative size of the coincidence count rate to the main detector count rate. We present an analytical estimate and results of Monte Carlo modeling which use the modified code PZSIM developed and used previously [1] to calculate the detector counts and neutron spectra after nn-scattering. Results suggest a coincidence efficiency relative to the standard one-detector geometry of  $10^{-5}$  to  $10^{-6}$  depending on the detector options. The reason for such a small effect is the conservation of energy and momentum in the interaction between two particles of equal mass (only relatively rare head-on collisions are relevant) in addition to the very dispersed detector arrival times for the neutrons, which have a wide range of energies.

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TRACE ELEMENT ATMOSPHERIC POLLUTION IN THE BALKANS  
STUDIED BY THE MOSS TECHNIQUE, ENAA AND AAS

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In 1995, 2000, and 2005/2006 JINR contributed to the international programme «Atmospheric Heavy Metal Deposition in Europe: - Estimations Based on Moss Analysis» with the results obtained in collaborative studies with a number of countries including several Balkan countries: **Bulgaria, Romania, Northern Serbia and Bosnia, Macedonia, Croatia,** and the European part of **Turkey** (Thrace Region). A combination of instrumental ENAA at the IBR-2 reactor in JINR, Dubna, and AAS in relevant counterpart laboratories provides data for concentrations of about 40 chemical elements (**Al, As, Au, Ba, Br, Ca, Cd, Ce, Cl, Co, Cr, Cs, Cu, Dy, Eu, Fe, Hf, Hg, I, In, La, Lu, Mg, Mn, Na, Nd, Ni, Pb, Rb, Sb, Sc, Se, Sm, Ta, Tb, Ti, Th, V, W, Yb, Zn**) that substantially exceeds the requested number of elements (marked as bold) by the European Atlas of Heavy Metal Atmospheric Deposition edited under the auspices of the United Nations Economic Commission for Europe (UNECE). The above trace elements are not all strictly relevant as air pollutants, but most of them can be used as air-mass tracers. Multivariate statistical analysis applied to the data sets obtained has revealed the origin of pollutants and the character of pollution sources within the sampled area, as well as those sources affecting this area through long-range atmospheric transport. Maps of elemental distributions created by modern GIS technology (geographical information system) are presented.

DETAILED STUDY OF THE EFFECTS FOLLOWING FROM ROTATION  
OF THE SCISSIONING NUCLEI IN TERNARY FISSION OF  $^{235}\text{U}$   
BY COLD POLARISED NEUTRONS (“ROT” AND “TRI” EFFECTS)

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In experiments with  $^{233}\text{U}$  and  $^{235}\text{U}$  as the targets in a beam of cold polarized neutrons it was observed that the angular distribution of ternary particles (TP) relative to the momentum of the light fragment (LF), being roughly Gaussian, exhibits a slight variation at the relative level  $\sim 10^{-3}$  upon flipping the neutron spin ( $\sigma$ ) relative to the plane formed by LF and TP momentums ( $\sigma, \mathbf{p}_{\text{LF}}$ ) [1,2]. It was proposed to distinguish between two types of change of the TP angular distribution when flipping  $\sigma$ . One type is “SCALING” where with spin flip the shape and the position of the angular distribution remains unchanged, but the total probability for TPs to move towards one or the other hemisphere of the ( $\sigma, \mathbf{p}_{\text{LF}}$ )-plane becomes asymmetric. We call this the TRI effect. The second type of change is “SHIFT” when with spin flip the angular distribution is shifted in angular position without changing the total probability. This is called the ROT effect. As follows from the experiments, in  $^{235}\text{U}(n,f)$  the TRI effect is dominant, while in  $^{235}\text{U}(n,f)$  the ROT effect gives rise to a pronounced angular dependence of the asymmetry in LF-TP counts rate on the angle between LF and TP.

The ROT effect is traced to a collective rotation of the partially polarized fissioning nucleus around its polarization direction during the ejection phase of TPs, and the hypothesis was corroborated by trajectory calculations [2]. One can suppose that the TRI effect could be due to the rotation affecting other degrees of freedom in the nucleus before rupture.

In the talk the results of a recent experiment [3] on TRI and ROT effects in  $^{235}\text{U}(n,f)$  ternary fission are presented and discussed. In this experiment both effects could be clearly separated by the precise measurement of the asymmetry in LF-TP count rates as a function of angle (LF, TP) upon flipping neutron spin

The characteristic parameters of both effects – angle of ROT-shift and TRI-coefficient – were obtained as a function of TP energy, FF mass and sum of FF kinetic energies. The average values of the ROT-shift and TRI-coefficient were found to be:  $0.22(1)^\circ$  and  $+0.0017(2)$ . Our semi-classical model of the ROT effect [2] can be further verified by comparing the new detailed experimental data with results of trajectory calculations. For the TRI asymmetries, however, we have no model with quantitative predictions. It is still a challenge for interpretation though theory has had first successes discussing both effects on a common footing. But again quantitative results are not yet available [4].

Obviously, the ROT and TRI effects depend on many parameters of the fission process – such as the overlap of resonances, the collective characteristics of transition states, the structure of scission configurations, the dynamics, etc. Since both effects are closely related to the fission mechanism, their study is thought to be a valuable contribution to our understanding of the fission process.

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**Measurements of Neutron Transmissions and Cross Sections on the TOF spectrometers of Moscow Meson Factory**

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**Abstract** On 50 m. flight path of a pulsed neutron source RADEX of Moscow Meson Factory (MMF) INR RAN was carried measurements of neutron transmissions and cross sections by means the setup REPS. which consists the 8-sectional liquid and neutron ( $n, \gamma$ )-detector of volume 40 l ( $L=49.3$  m) and the neutron detector with  $^3\text{He}$  counters ( $L=51.5$  m) of high efficiency  $\epsilon(E_{th.})=95$  %. Time-of-flying spectra were measured for the thin metal disk samples-radiators Cr,  $^{148}\text{Sm}$ ,  $^{238}\text{U}$ , with diameter of 80 mm by means of this setup REPS. The parameters of the pulsed neutron source of MMF were the proton current of linear accelerator  $I_p = 11$  mA, the proton energy  $E_p=209$  MeV, the proton pulse repetition rate of  $f = 50$  Hz, the proton pulse duration of  $\tau = 1-5$  mks. The setup REPS has the thick boron and lead shielding from the neutrons and  $\gamma$ -rays background, which scattered in room of detectors. The low background and the high energy resolution of spectrometer resolved to determinate the new resonances. Recently, the analogous transmissions, the group total and capture cross-sections for Cr,  $^{148}\text{Sm}$ ,  $^{238}\text{U}$  Mn, Ta, W were obtained from the measured time-of-flying spectra on 18 m flight path of a pulsed neutron source with Rb target of the radiochemistry complex MMF by means  $^3\text{He}$  counter SNM-18. These values were obtained by GRUCON code on the basis of the estimated data libraries also.

**WDXRS OF MINOR AND TRACE ELEMENT CONTENTS IN SOILS OF THE KHAMAR-DABAN MOUNTAIN RANGE**

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The Baikal Paper-and-Pulp Complex (BPPC) is a key source of industrial air emissions on the southern shore of the Baikal Lake to the north-east of the city of Baikalsk. Indirect retrospective assessment of the regional pollution level is achievable through a survey focused on environment objects that accumulate both major, minor, and trace elements present in industrial air emissions. Topsoil is a more appropriate subject for such surveys.

As research subjects were used topsoil samples taken on the Khamar-Daban mounts to the north-east of BPPC at a height of about 1200 - 1500 m above sea level in two areas located 11 (Area 1) and 84 km (Area 2) away, respectively.

Mass fractions of 21 chemical elements (As, Ba, Br, Co, Cr, Cu, Fe, Mn, Mo, Nb, Ni, Pb, Rb, Sr, Th, Ti, V, U, Y, Zn, and Zr) were measured by instrumental wave-dispersive X-ray spectrometry (WDXRS) using ARF-6 Analyzer (Ag- and Mo-tube) and SPM-25 Quantometer (Rh-tube). Measurements of 100s duration were carried out twice. The  $K_{\alpha 1}$ -lines were used to register intensities of characteristic X-ray of Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, As, Br, Rb, Sr, Y, Zr, Nb, Mo, Ba and  $L_{\beta 1}$ -lines - Pb, Th, and U. The sample matrix effect was account by noncoherent scattered  $K_{\alpha}$ -line of the X-ray tube.

A considerable remoteness of Area 2 from BPPC allows to assuming it as a checkpoint in BPPC air emission impact assessment. The collation of average mass fraction values in topsoil on the Khamar-Daban mount slopes and tops in Areas 1 and 2 made for all investigated chemical elements did not reveal any statistically valid differences. The comparison of the obtained results with literature data makes it possible to conclude that average mass fractions of all elements in the Khamar-Daban topsoil are within the range of levels characteristic of non-polluted soils on the territories of former USSR, CIS and across the world.

## THE ESTIMATION OF SCISSION NEUTRON PARAMETERS FROM N-F AND N-N ANGULAR CORRELATIONS IN $^{235}\text{U}(n_{th},f)$ REACTION

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With the aim to investigate the process of neutron emission two experiments on studying of neutron-fragment and neutron-neutron angular correlations in  $^{235}\text{U}(n_{th},f)$  reaction were carried out in PNPI recently [1,2].

The neutron spectra for different angles as well as the angular dependences of neutron-fragment and neutron-neutron coincidence rates from these experiments were compared with the results of calculations based on Monte-Carlo method. In process of calculation it was assumed that the major part of fission neutrons evaporates from fully accelerated fragments but a fraction of total number of fission neutrons can be emitted isotropically in the laboratory system. This part of neutrons can appear just near to the rupture point (so-called scission neutrons). The number of neutrons evaporated by each fragment was chosen randomly by two-dimensional Gaussian distribution:  $(\bar{\nu}_L, \sigma_{\nu_L}^2, \bar{\nu}_H, \sigma_{\nu_H}^2, \text{cov}(\nu_L, \nu_H))$ . The temperature parameters of neutron spectra for light and heavy fragments and the ratio  $\bar{\nu}_L/\bar{\nu}_H$  were determined by using experimental data of neutron spectra at  $0^\circ$  and  $180^\circ$  in laboratory system. We took into account the presence of angular anisotropy of neutron emission from fission fragments in their centre-of-mass systems [3].

The experimental results of n-n angular dependence were integrated over all neutron energy values but correspond with six different energy thresholds in the range 425÷2030 keV. This allowed us to get some information not only about the contribution of additional component but also concerning its energy distribution.

From the comparison of experimental data connected to both n-f and n-n angular distributions simultaneously with the results of Monte-Carlo calculations it was concluded that about 7% of total number of neutrons in  $^{235}\text{U}(n_{th},f)$  reaction are emitted isotropically and probably can be attributed to "scission neutrons" arising just at rupture moment. The form of this component corresponds to Weisskopf distribution with temperature parameter  $T \approx 1$  MeV.

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## THE $^{235}\text{U}(n,f)$ PROMPT FISSION NEUTRON SPECTRUM

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The prompt fission neutron spectrum  $N(E)$  plays an important role in various nuclear technologies, both in energy and non-energy applications. From a more fundamental point of view, an accurate knowledge of  $N(E)$  can shed some light on the nuclear fission process itself.

At IRMM we have measured the neutron spectrum at an incident neutron energy of about 0.5 MeV. This was done on request of the OECD, Nuclear Energy Agency's (NEA) Working Party of International Nuclear Data Evaluation Co-operations (WPEC), based on a recommendation of its subgroup 9. This subgroup came to the conclusion that the present database of the neutron spectrum for  $^{235}\text{U}(n,f)$  at thermal incident neutron energy is insufficient and needs improvement. Modelling of this spectrum with the present Los Alamos (LA) model is not possible. First measurements at 0.5 MeV incident neutron energy have been performed, since at this energy the LA-model can perfectly describe the experimental results of Johansson and Holmquist [1]. The results achieved so far do not reproduce the measurements of Ref. [1], but are in agreement with several other literature values. Also the measurements are neither in agreement with the Los Alamos model, nor with the mean neutron energy coming from integral experiments and benchmark investigations. The present experiment is the only one utilizing several neutron detectors at different angles. Having performed three different runs, so far the conclusion is that the results at 90 degree coincide in all runs despite differences in the experimental conditions. The data at e.g. 120 degree differ between the runs. The physical reason for this behaviour is not understood at present.

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# FISSION FRAGMENT MASS DEPENDENT PROMPT NEUTRON EMISSION INVESTIGATION FOR RESONANCE NEUTRON INDUCED FISSION OF $^{235}\text{U}$ AND FOR $^{252}\text{Cf}(\text{SF})$

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The resonance neutron induced fission of  $^{235}\text{U}$  and  $^{239}\text{Pu}$  was investigated intensively for decades because of the great importance of these actinide nuclei for nuclear energy production at one hand and for the understanding of the fundamental aspects of nuclear fission process at the other hand. Experimental investigations of the prompt neutron distribution for resonance neutron induced fission carried out in the early 1970-ties of both uranium and plutonium revealed small fluctuations of the prompt neutron multiplicity between resonances [1, 2]. The nature of these fluctuations is still not entirely understood a fact that stimulated further more elaborated investigations. In the 1980-ties at IRMM fission fragment (FF) mass fluctuations were first observed in resonance neutron induced fission of  $^{235}\text{U}$  [3] and in the late 1990-ties similar fluctuations were reported in Refs. [4,5] for  $^{235}\text{U}$  and  $^{239}\text{Pu}$ . The fluctuations of the average number of prompt fission neutrons was correlated with fluctuations of the fission fragment average TKE value. Here we report about simultaneous measurements of the FF TKE and prompt neutron emission yields.

The experimental setup consisting of 8 large volume (4 litre of NE213 liquid scintillator) neutron detectors from the DEMON collaboration and a double Frisch-grid ionisation chamber was used in the measurements of  $^{235}\text{U}(n_{\text{res}}, f)$  and  $^{252}\text{Cf}(\text{sf})$ . The data acquisition electronics based on standard CAMAC modules provided the means for multi-parameter measurements including the digitization of correlated fission fragments pulses, resonance neutron time-of-flight (TOF), prompt neutron TOF and prompt neutron/gamma pulse shape discrimination parameters. The data acquisition software was a modified version of the program used in the measurements reported in Ref. [4] to record list-mode data. Prompt neutron multiplicity data for the  $^{235}\text{U}(n_{\text{res}}, f)$  reaction were evaluated using the  $^{252}\text{Cf}(\text{sf})$  reaction data, taken in identical measurement conditions (with the resonance neutron beam on). Preliminary results of the data analysis will be presented as well as a new data acquisition system based on full event digitization.

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# FISSION DYNAMICS AND CORRELATION EFFECTS IN FRAGMENTS' ANGULAR DISTRIBUTIONS FOR FISSION INDUCED BY THERMAL NEUTRONS AND LOW-ENERGY GAMMA-QUANTA

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Low-energy fission of nuclei-actinides is described [1] using presentation about conservation of axially symmetry of fissile nucleus shape during fission process. Therefore only Coriolis interaction can be the source of conservation-braking for projection  $K$  of spin  $J$  of fissile nucleus onto its symmetry axis. Because of dynamical enhancement mechanism [2], this interaction for thermalized states of nucleus, corresponding to sufficiently high temperatures of nucleus, uniformly mixes states with different  $K$ , that take place in neutron resonance states of the first well of deformational potential of nucleus. At the same time, in the framework of quantum fission theory [3] it can be demonstrated that influence of Coriolis interaction on all stages of fissile nucleus evolution, connected with transition through internal fission barrier, with deformational motion of nucleus in second well of deformational potential, where thermalization of the nucleus is possible, but the temperatures must have low values, and, finally, with transition through external barrier and descent from the barrier to the scission point, where nucleus decays onto fission fragments, is negligibly small. It follows that in the second well fissile nucleus doesn't forget  $K$  values, selected by internal fission barrier, so  $K$ -distribution after rupture of nucleus, which forms fragments' angular distribution, is defined by combined influence of transitional fission states of fissile nucleus on internal and external fission barriers.

The joint analysis of fragments' angular distributions of low-energy photofission of nuclei-targets  $^{234}\text{U}$ ,  $^{236}\text{U}$  и  $^{240}\text{Pu}$ , P-odd and P-even correlations in fragments' angular distributions for fission of nuclei-targets  $^{233}\text{U}$ ,  $^{235}\text{U}$  and  $^{239}\text{Pu}$  by thermal polarized neutrons and angular distributions of fragments for fission of aligned in strong magnetic fields nuclei-targets  $^{233}\text{U}$ ,  $^{235}\text{U}$  by thermal nonpolarized neutrons. It is shown that for mentioned nuclei internal fission barriers correspond to their shapes with zero value of octopole deformation parameter  $\beta_3$  and are higher than external barriers, which connected with big values of  $\beta_3$  and correspond to pear-like shape of fissile nucleus. Obtained results allow consequently describe low-energy fission of investigated nuclei in reactions  $(\gamma, f)$  and  $(n, f)$  and overcome difficulties in mentioned description, which are pointed out in paper [1].

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THE STRUCTURE OF TRANSITIONAL FISSION STATES FOR NUCLEAR FISSION INDUCED BY LINEARLY POLARIZED GAMMA-QUANTA

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In the framework of quantum fission theory [1] the investigation of fragments' angular distributions for fission of nuclei-actinides by linearly E1 and E2 photons with degree of polarization  $p$ , which is defined as [2,3]:

$$W(\theta, \varphi) / W(\pi/2, \pi/4) = (a + b \sin^2 \theta + c \sin^2 2\theta) + p \cos 2\varphi (d \sin^2 \theta - 4c \sin^4 \theta), \quad (1)$$

where coefficients  $a, b, c, d$  [2] depend on the total cross-section of photo-creation of compound nucleus  $\sigma_{\gamma}^J$ , relation  $\Gamma(JK)/\Gamma$  of partial fission width  $\Gamma(JK)$  for transitional fission state  $(J,K)$  to the total width  $\Gamma$  of compound nucleus decay was carried out. Using experimental values of coefficients  $a, b, c$  for fragments' angular distributions of nuclei  $^{234,236,238}\text{U}$ ,  $^{240}\text{Pu}$ ,  $^{232}\text{Th}$  by non-polarized photons with energies  $E_{\gamma}=4-26$  MeV coefficients  $d$  was calculated on the base of presentation [1] about the main role of transitional fission states with  $(J,K) = (1,0), (1,1), (2,0)$ , taking into account deviations of fragments' angular distributions from O. Bohr's formula.

The analysis of energy dependences of relations  $b/a, 4c/d, d/b, c/b$  shown, that the contribution of polarization term in formula (1) at first increase with energy  $E_{\gamma}$  rise from  $E_{\gamma}=4$  MeV, reaching maximum at energies, which are the most optimal for polarization effects observation; 5.45–5.7 MeV for  $^{240}\text{Pu}$ , 5.6–6 MeV for  $^{234}\text{U}$ , 5–6 MeV for  $^{236}\text{U}$ , 4.9–5.5 MeV for  $^{238}\text{U}$ , where  $d/b=2-7$ . Contribution of polarization term in fragments' angular distribution (1) with further increase of energy  $E_{\gamma}$  decrease, and at  $E_{\gamma} \geq 20$  MeV fragments' angular distribution (1) becomes close to isotropic ( $d=b, b/a \ll 1, c/a \approx 0$ ), that is confirmed by results of papers, discussed in [4], where  $b/a=0.05$  at  $E_{\gamma}=26$  MeV for  $^{238}\text{U}$  and  $E_{\gamma}=18$  MeV for  $^{236}\text{U}$  and  $b/a=0.1$  at  $E_{\gamma}=20$  MeV for  $^{232}\text{Th}$ . The analysis of experimental data of fragments' angular distributions for fission of  $^{232}\text{Th}$  by linearly polarized photons [3] at energy  $E_{\gamma}=10$  MeV, when  $c \approx 0$ , shown, that fragments' angular distributions  $W(\theta, 0), W(\theta, \pi)$  and  $W(\pi/2, \varphi)$  for the case, when the electric field strength  $E$  is directed along  $y$  axis, are in accordance with each other and lead to the experimental value  $d=0.48 \pm 0.08$ , which coincides with the value of the coefficient  $d=0.54 \pm 0.01$ , obtained from analysis of fragments' angular distribution for non-polarized photons.

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Experimental evidences of clustering in thermal fission of  $^{235}\text{U}$

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In our previous publications [1-3] we have reported a new ternary decay channel linked with magic constituents from  $^{252}\text{Cf}$  (sf). It has been named "collinear cluster tripartition" (CCT) because the decay products fly apart almost collinearly. The masses of two reaction products were measured by the TOF-E (time-of-flight vs energy) method which allows one to study the multi-body decays by means of the "missing mass" criteria. In order to distinguish the CCT event from the binary fission one we applied different gating such as selection by the neutron multiplicity [4], velocity, linear momentum and their combinations. Due to such procedure we succeeded to reveal some different, at least ternary, decay modes manifested themselves via pronounced structures in the mass-mass distributions of the detected fragments. The yields of the modes observed were found in the range of  $10^{-5} - 4 \cdot 10^{-3}$  per binary fission.

The results mentioned above were confirmed in our recent experiment dedicated to  $^{235}\text{U}(n_{th}, f)$  reaction. It was performed at the beam of IBR-2 neutron pulsed reactor installed in the Frank Laboratory of JINR using double-armed TOF-E spectrometer of fission fragments (FF) mini-FOBOS. For the first time we were able to measure the FF nuclear charges thus increasing substantially the identification reliability of the CCT events. One of the modes revealed seems to correspond to the following decay scenario. At some stage of elongation the initial nucleus clusterizes into a nuclear system of two magic constituents. Its rupture is ruled out due to energy conservation reason. Namely, the expected total kinetic energy would exceed the reaction energy release  $Q$ . The further elongation is achieved thanks to the subsequent clusterization of the light magic constituent leading to formation of the lighter, also magic, fragment and a light charged particle. The spectrum of their charges is shown in fig.1. The most populated states observed are presented below.

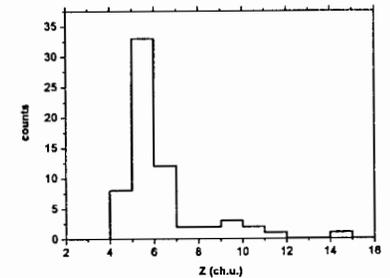


Fig. 1. Spectrum of the nuclear charge of the lightest fragments detected.



The lower limit of the yield of the ternary decay mode discussed is about  $3 \cdot 10^{-5}$ /binary fission. It is more than two orders of magnitude higher of the carbon yield in conventional ternary fission.

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# Production Cross Section of Residual Radionuclides by Proton-induced Reactions on $^{nat}\text{Cd}$ and $^{nat}\text{Fe}$

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## Abstract

Cyclotron produced radionuclides (both the  $\gamma$  and  $\beta^+$  emitter) find wide applications in various practical fields. Excitation functions play a crucial role leading to the production of radionuclides as an alternative production route by cyclotron. Based on the well measured excitation functions, one can easily calculate the optimum production condition.

We have measured the excitation functions of  $^{nat}\text{Cd}(p,x)$  processes and  $^{nat}\text{Fe}(p, xn)$  processes by using the stacked foil activation technique combined with high resolution high purity germanium (HPGe) gamma-ray spectrometry. Stacks of natural Cd foils of 50  $\mu\text{m}$  thickness and 99.97% purity were bombarded with proton beams. The Cd (or Fe) foils were interleaved with 99.6% purity, 50  $\mu\text{m}$  thick natural Cu foils and 200  $\mu\text{m}$  thick (99.99%) natural Al foils so that known cross sections for the  $^{nat}\text{Cu}(p, x)^{62,65}\text{Zn}$  and  $^{27}\text{Al}(p,x)^{22,24}\text{Na}$  reactions could be used as beam monitoring purposes. Following irradiation, the residual radionuclides were measured through off-line method. The present measured cross sections of the produced radionuclides were compared with the available literature data, theoretical data from the model calculations by TALYS and ALICE-IPPE codes, and found overall good agreement among them. Integral yields were also deduced using the measured cross sections of the respective radionuclides.

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## STATUS OF THE EXPERIMENTS ON RADIATIVE BRANCH OF DECAY

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## Annotation

The report is dedicated to the investigation of the neutron radiative decay. The theoretical spectrum of radiative gamma quanta, calculated within the framework of the standard electroweak interaction model, is discussed. On the basis of a comparison drawn between neutron and muon decays, it is demonstrated that the study of radiative branches of elementary particle decay occupies a central place in the fundamental problem of searching for deviations from the standard electroweak model. Particular attention is paid to analyzing the results of the experiments conducted at ILL in 2002 [1] and at the second and third cycles at the FRMII reactor of the Technical University of Munchen [2] in 2005.

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## THE SYSTEMATIC STUDY OF (n,p) CROSS SECTIONS FOR 18 AND 20 MeV

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Investigation of charged particle emission reactions induced by fast neutrons is important for nuclear reaction mechanism study and nuclear reactor technology. On the other hand, it is often necessary in practice to evaluate the neutron cross sections of the nuclides, for which no experimental data are available. In connection with this, we carried out the systematical analysis of known (n,p) and (n, $\alpha$ ) cross sections and observed so-called isotopic effect in the wide energy interval of  $E_n=6-16$  MeV [1].

Also, to explain this effect some formulae based on the statistical model [2], exciton model [3] and PWBA [4] were deduced.

In this paper, from the view point of our systematic analysis the known experimental (n,p) cross sections for  $E_n=18$  and 20 MeV are analyzed.

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## NEUTRON INDUCED ACTIVITY IN LOW-BACKGROUND GAMMA SPECTROSCOPY SYSTEMS

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Cosmic rays induced neutrons can produce measurable activity in carefully selected materials used for construction of low-background gamma spectroscopy systems. In order to improve shielding of low-background counting systems, flux of neutrons inside the shield and level of induced activity should be measured.

Several gamma lines emitted after neutron capture as well as after inelastic scattering in Ge and couple different surrounding shielding materials were detected and analyzed in different conditions. Two HPGe detectors were located in two different passive shields: pre WW II iron and commercial low-background lead. Significantly lower presence of neutrons is observed in iron shielded detector than in detector shielded by lead, as can be expected. But introducing the massive (3 inch thick) NaI Compton suppression system in iron shield produced measurable activity obtained by neutron capture and inelastic scattering at sodium and iodine nuclei. Time variation of well known 846.8 keV gamma line emitted after  $^{56}\text{Fe}(n,n')^{56}\text{Fe}$  reaction is followed during two separated time intervals (one year each). Relative intensities of other gamma lines emitted in de-excitation of  $^{56}\text{Fe}$  are compared with available data gathered in neutron inelastic scattering reactions on  $^{56}\text{Fe}$ . Different materials were packed in Marineli geometry with the purpose of measurement gamma lines produced by interaction of relatively abundant neutrons present in environment of lead shielded detector.

## LOW-ENERGY SCATTERING OF A POLARIZED NEUTRON ON A POLARIZED PROTON

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The spin structure of the amplitude of *s*-wave elastic scattering of a slow neutron on a free proton is considered. The formula for effective cross-section of scattering of a slow polarized neutron on the polarized proton target is obtained, and it is shown that, in the effective cross-section, the amplitudes of triplet ( total spin  $S = 1$  ) and singlet ( total spin  $S = 0$  ) scattering are summed up incoherently. In doing so, the maximum value of integral cross-section  $\sigma_{max} \approx 35.6$  barn corresponds to the antiparallel orientations of spins of the totally polarized neutron and proton (  $P_1 P_2 = -1$ , where  $P_1$  and  $P_2$  are the polarization vectors ), whereas the minimal magnitude of cross-section  $\sigma_{min} \approx 3.6$  barn is observed in the case of parallel orientation of spins (  $P_1 P_2 = +1$  ).

The low-energy scattering of polarized neutrons is also analyzed. Taking into account the identity effect, the *s*-wave scattering of neutrons is possible only in the singlet state. According to the isotopic invariance, one could expect that the amplitude of *s*-wave scattering of two neutrons must coincide, with the precision of (1 ÷ 3) %, with the singlet amplitude of neutron scattering on the proton. Nevertheless, in fact the scattering lengths take the values  $a^{(np)} = -f^{(np)}(0) = -23.6$  fm and  $a^{(nn)} = -f^{(nn)}(0) = -17.1$  fm; so, we have  $|a^{(np)}/a^{(nn)}| \approx 1.38$ . However, the concept of "isotopic invariance" is applicable rather to the interaction potential than to the scattering amplitude. Analysis shows that, if the modulus of amplitude is large as compared with the range of force action, the magnitude of scattering amplitude becomes very sensitive to the parameters of potential. Within the model of spherical rectangular well, the change of depth or width of the well by several per cent leads to the substantial change of scattering length.

## IS IT POSSIBLE TO STUDY PT-NONINVARIANT EFFECTS WITH NO COINCIDENCE SCHEME USING THERMAL NEUTRON SOURCE?

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In the process of development of the methods proposed in the paper [1] a new line of attack in search for PT-noninvariant effects in neutron induced  $\gamma$ -transitions is proposed. The scheme is based on combination of a powerful thermal neutron source and relatively simple <sup>4</sup>He cryogenic facility. The neutron source serves as a generator of excited nuclei in a target. The function of the refrigerator is to create an alignment of nuclei in the target. According to the proposition contained in [2] a five-vector correlation  $A_{pt} = (\vec{J}\vec{E})(\vec{k}_\gamma[\vec{J} \times \vec{E}])$ , where  $\vec{J}$  is the direction of alignment and  $\vec{E}$  – the linear polarization of  $\gamma$ -quantum, is an object of measurements.

A main advantage of the scheme is a possibility to use extremely high-flux neutron sources. Due to the domination of S-wave capture amplitude there is no need to know the direction of linear momentum of a captured neutron, thus shaped neutron beam is not required. Evidently the cryogenic and magnetic elements of the set must be tolerant to arduous conditions of neutron radiation working beyond the human control during a long time of an experiment. The set should be neutron transparent therefore ZrNb alloys look optimal materials. The discussed requirement rules out the possibility to use <sup>3</sup>He as a cooling agent. That is why one should limit himself by ordinary pumping <sup>4</sup>He facility with the temperature limitation slightly lower 1 K. Because of that a list of magnetic substances which can be aligned at such temperatures is very short. In fact rare-earth metals Tb, Dy, Ho, and, maybe, very specific composites containing these elements are applicable only. What about a material of magnets, requirements on external magnetic field are not rigorous because one of the discussed ferromagnetic targets is necessary anyway. For example permanent magnet made from thin BaNd wire may be used. Complex-shaped detector array is necessary to get rid of spurious effects.

Principal point of the approach is to choose optimal i. e. manifesting maximal P-odd effect target isotope among presented above. Filtering of  $\gamma$ -spectrum may be used for increasing the effect. If these operations would result in finding of an example in which integral P-odd effect is about  $10^{-4}$  then efficiency of the discussed scheme in search for PT-nonconservation would turn out to be competitive to the efficiency of measurements of permanent electric dipole moments of elementary particles and atoms.

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## STUDY OF PT-NONINVARIANT EFFECTS WITH RADIOACTIVE SOURCES

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Various schemes of measurement of PT-invariance nonconservation effects in  $\gamma$ -transitions induced by decay of radioactive isotopes decay are discussed. The transitions convenient for such studies are analyzed. The scheme based on the measurement of linear polarization of  $\gamma$ -radiation of an aligned sample proposed in [1] looks optimal for such measurements in the most cases. The alignment is created by a magnetic field at low temperatures or turns out to be determined by registration of preceding (subsequent) particle of a cascade. In the latter case to measure the PT-noninvariant correlation  $A_{pt} = (\vec{k}_1 \vec{\epsilon})(\vec{k}_\gamma [\vec{k}_1 \times \vec{\epsilon}])$ , where  $\vec{k}_1, \vec{k}_\gamma$  - linear momenta of an attendant particle and  $\gamma$ -quantum, coincidence scheme is used. The counting rate in this scheme is lower than in the cryogenic, based on the correlation  $A_{pt} = (\vec{J} \vec{\epsilon})(\vec{k}_\gamma [\vec{J} \times \vec{\epsilon}])$  where  $\vec{J}$  - the vector of alignment of a sample in a refrigerator, one. Nevertheless it allows one to work with short-living (up to 1 h.) sources and elements inconvenient for cryogenic orientation; it is more simple and labor-saving.

A wide range of radioactive isotopes are considered. The efficiency of an example is determined by the (measured or estimated) value of the P-odd effect in a certain  $\gamma$ -transition, peculiarities of spectrum of a source and possibilities of isotope production. The examples:  $^{161}\text{Dy} (25.7 \text{ keV}) \rightarrow ^{161}\text{Dy} (\text{g.s.})$ ,  $^{57}\text{Fe} (14.4 \text{ keV}) \rightarrow ^{57}\text{Fe} (\text{g.s.})$ ,  $^{178}\text{Hf} (1147.4 \text{ keV}) \rightarrow ^{178}\text{Hf} (632.2 \text{ keV})$ ,  $^{240}\text{Pu} (1030.5 \text{ keV}) \rightarrow ^{240}\text{Pu} (141.7 \text{ keV})$  and  $^{184}\text{W} (1185.0 \text{ keV}) \rightarrow ^{184}\text{W} (364.1 \text{ keV})$  look promising in the both discussed schemes. In the cascade following the last transition it is interesting to study triple PT-noninvariant correlation  $A_{pt} = (\vec{k}_{\gamma_1} \vec{k}_{\gamma_2})(\vec{k}_{\gamma_1} [\vec{k}_{\gamma_2} \times \vec{k}_{\gamma_3}])$ . The transitions:  $^{180\text{m}}\text{Hf} (1141.5 \text{ keV}) \rightarrow ^{180}\text{Hf} (640.9 \text{ keV})$ ,  $^{183}\text{W} (309.5 \text{ keV}) \rightarrow ^{183}\text{W} (207.0 \text{ keV})$ ,  $^{152}\text{Eu} (89.8 \text{ keV}) \rightarrow ^{152}\text{Eu} (\text{g.s.})$ , and the  $\alpha\gamma$ -cascade  $^{225}\text{Ac} \rightarrow ^{221}\text{Fr} (99.6 \text{ keV}) \rightarrow ^{221}\text{Fr} (\text{g.s.})$  are promising for coincidence scheme. The cryogenic scheme is useful for investigation of  $\gamma$ -radiation:  $^{237}\text{Np} (86.5 \text{ keV}) \rightarrow ^{237}\text{Np} (\text{g.s.})$ ,  $^{119}\text{Sn} (23.6 \text{ keV}) \rightarrow ^{119}\text{Sn} (\text{g.s.})$  etc.

I. Szymanski Z. Nucl. Phys. 1968. V. A113. P. 385.

## Cross section evaluation using the statistical approach on the (n, $\alpha$ ) on $^{64}\text{Zn}$ in MeV region neutron incident energy

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**Abstract.** The cross section evaluation of the (n, $\alpha$ ) reaction for heavy and medium nuclei is interesting for applicative and for fundamental researches respective. For incident neutron energy range of order of some MeV the reaction mechanism for many neutron reaction is not well established. In this work will be evaluated the cross section of  $^{64}\text{Zn}(n,\alpha)$  reaction using the statistical model of nuclear reaction and the results will be compared with experimental data.

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**Abstract.** Using the theoretical evaluations of the asymmetry effects in the (n,p) reaction on  $^{14}\text{N}$  and  $^{35}\text{Cl}$  presented in the previous sessions of ISINN we realize a computer experiment of the measurement of the asymmetry effects. The influence of the experiment setup parameters (like the neutron energy flux, the thickness of the target and others) on the measured coefficients will be analyzed and the results are compared with existent experimental data.

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The most interesting and important problems of low energy fission dynamics are associated with the properties of the transition states of fissioning systems in the vicinity of the external barrier top -- distribution of the energy accumulated during the system's descent from the fission barrier, rupture mechanism of strongly deformed nucleus and the initial characteristics of the reaction products at rupture. Unfortunately, sufficiently justified solutions of all these problems are absent up to now. The discovery of the new effects of angular asymmetry of LCP emission in ternary fission of some heavy nuclei induced by the cold polarized neutrons /1, 2/ have opened the new opportunities to attack all these problems once more. Angular distributions of the light charged particles in ternary fission can be expressed as:

$$W(\Omega) \sim 1 + D_{\text{TRI}} \sigma_n [\mathbf{P}_f \times \mathbf{P}_{\text{LCP}}] + D_{\text{ROT}} \sigma_n [\mathbf{P}_f \times \mathbf{P}_{\text{LCP}}] \cdot (\mathbf{P}_f \cdot \mathbf{P}_{\text{LCP}}), \quad (1)$$

where  $\sigma_n$ ,  $\mathbf{P}_f$ , and  $\mathbf{P}_{\text{LCP}}$  are unit vectors pointing in directions of the neutron longitudinal polarization and linear moments of fission fragments and LCP respectively.  $D_{\text{TRI}}$  and  $D_{\text{ROT}}$  are the asymmetry coefficients of LCP emission, which depend on the transition states characteristics and on the relationship between fission fragments' and LCP velocities near the rupture point. The second term in the formula (1) represents the probability of LCP emission with respect to the plane which contains the vectors  $\sigma_n$  and  $\mathbf{P}_f$ . The third one describes the shift of LCP angular distribution as a result of the fissioning system rotation around the polarization direction. The main problems and challenges for the theory consist in disentangling of these two effects and explaining the drastic difference of their ratios in ternary fission of  $^{233,235}\text{U}$  isotopes having very similar fission characteristics. One might guess that such a difference is connected with different properties of transition states in these isotopes. On the other hand the first quantum analysis of TRI and ROT effects in ternary fission /3/ led to the conclusion that this difference may be explained by the phase difference of the nearby s-resonances in those isotopes. As the trajectory calculations had demonstrated /4/, the shift of LCP angular distributions observed in experiments strongly depends on the mixture of transition states with  $J = (I \pm 1/2)$  having different values and opposite signs of polarization, and on the relationship between the initial velocities of fission fragments and LCP. With further increase of experimental accuracy of the both effects measurements for different fissioning systems and with refinements of the experimental data treatment, we also hope to check the degree of validity of the well known and much used hypothesis of K-value conservation in low energy fission.

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## COMPILATION OF NEUTRON RESONANCE PARAMETERS NRF-3

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This report is a continuation of the previous one where the initial stage of the production of new neutron resonance parameters compilation was reported [1]. Now the largest part of recent data is prepared for publication as vol I/24 in LB Springer. V.Pronyaev (Obninsk) and F.Gunsing (Saclay) are participating in the Introduction to the book. The great number of resonance parameters comes from measurements at CERN-nTOF and RPI-linac as well as data on  $^{129}\text{I}$ ,  $^{61}\text{Ni}$  resonances from GELINA and  $^{147}\text{Sm}$  resonance spin values from DANCE. Only data not included in NRF-2 [2] (LB vol.I/16C, 2004) and in BNL-325 (2006) are presented in the book. The NRF-3 contents will be discussed.

The NRF-3 file was considered in [1] as a part of the total file of nuclear excitations from different reactions including data from reactions with charged particles (vol.I/19A) and low-lying excitations. Recently published compilation of bound levels of all nuclei (LB vol.I/19BC, file CRF) [3] and file of nuclear binding energies (MDF) are used together with MRF-3 in the analysis of "the stabilizing effect of nuclear shells". The observed presence of a system of stable intervals in neutron resonances and in low-lying levels is considered as a continuation of the tuning effect in particle masses [4-6]. There is a coincidence of electromagnetic mass splitting of the nucleon, the pion and the electron with the certain members of the observed systems of stable nuclear intervals. This could be interpreted as a manifestation of "the tuning effect in nuclear data" originated from the influence of nucleon structure [5]. The parameters of the mean-field description of nuclear masses (a nearly constant mass defect of about 8 MeV per nucleon) and parameters in calculations of the residual nucleon interaction are compatible with "tuning effect in nuclear data".

Performed analysis of CRF-data for heavy nuclei permitted two conclusion:

- 1) Reported in the literature grouping effect in excitations of Po isotopes at  $E^* = 680$  keV and of Hq isotopes at  $E^* = 425$  keV corresponds to the stability of the residual nucleon interactions in nuclei around lead. In the  $^{208}\text{Bi}$  spacing distribution shows the same system of stable intervals.
- 2) There exist grouping effects in excitations of isotopes of Tb and Pt. The study of tuning effects in the combined file of nuclear data will be presented.

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## DIPOLE SHIFT OF NEUTRON SCATTERING RESONANCES

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Coulomb interaction creates neutron electric dipole moments at the scattering of slow neutrons by nuclei. A value of the induced neutron electric dipole moment is proportionate to electric polarizability of the neutron and maybe about  $10^{-3} \text{ e} \cdot \text{fm}$  for lead isotopes. The interaction of the neutron electric dipole moment with Coulomb field of nucleus shifts energies and widths of resonance states at the scattering of slow neutrons by nuclei. Estimation of the energy shift using Coulomb Born approximation results in  $\sim 2$  keV for lead.

A neutron-nucleus scattering can be used for measurement of the energy shifts of the resonances and electric polarizability of the neutron.

# DISTRIBUTION OF PARAMETERS OF THE PRIMARY GAMMA-TRANSITION INTENSITIES FOLLOWING RESONANCE NEUTRON CAPTURE AND SOME PROPERTIES OF THE $^{157,159}\text{Gd}$ COMPOUND NUCLEI

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The re-analysis of the published experimental data on the primary transition intensities following neutron capture in different groups of neutron resonances in  $^{156,158}\text{Gd}$  has been performed. In the narrow excitation energy intervals, there are determined the most probable values of:

the summed intensities of the E1 and M1 primary gamma-transitions;

the numbers of the excited by them levels of both parities;

the ratios  $k(M1)/k(E1)$  of radiative strength functions;

the dispersions of the random intensity deviations from the mean value and

the averaged intensity ratios for the primary transitions to the levels with  $J=5/2$  relatively to analogous data for  $J=1/2$  and  $3/2$  (for capture of the 24 keV neutrons).

All the data on level density and radiative strength functions determined in this way confirm the presence of clearly expressed step-like structure in level density below 3 MeV and general trend in change in strength functions as changing the primary gamma-transition energy. The change in distribution dispersions and especially in the ratio  $k(M1)/k(E1)$  for different excitation energies point to considerable change in structures of these nuclei  $E_{ex} > 1.5-2.0$  MeV. As in neighboring isotopes  $^{156,158}\text{Gd}$ , the shape in energy dependence  $k(M1)+k(E1)$  noticeably differs as changing mass of nuclear mass. This can result from dependence of gamma-decay process on the neutron resonance structure and/or levels excited by gamma-transitions.

# MAIN PARAMETERS OF THE GAMMA-DECAY PROCESS AND THE PROPERTY OF NUCLEUS $^{174}\text{Yb}$ FROM THE RADIATIVE CAPTURE OF SLOW NEUTRONS

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Independent analysis of the published data on the intensities of primary gamma-quanta from the capture of neutrons with the energy  $\approx 2$  keV in the nucleus  $^{173}\text{Yb}$  was performed. The distribution of these random intensities relative to the average value is approximated in different primary gamma-transitions energy bins. The extrapolation of the obtained distributions to the zero threshold of the registration of the primary gamma-transition intensity made it possible to obtain independently of other experimental methods the expected number of both parities levels for the spins  $J=1-4$  and the entire possible sum of the partial widths of dipole electrical and magnetic gamma-transitions to the levels with the excitation energy to  $\approx 4$  MeV.

Thus determined level densities and sum of radiation strength functions confirm the characteristic properties of analogous parameters, extracted from the intensities of the two-step cascades of the thermal neutron radiative capture for the nuclei from the mass region  $40 \leq A \leq 200$ . Also this makes it possible to estimate sign and value of these parameters' systematic errors, caused by the very strong dependence of the radiation strength functions of cascade gamma-transitions on the structure of the excited levels, at least, lower than a half of the neutron-binding energy.

The comparison with the modern level density model predictions shows that the nucleus  $^{174}\text{Yb}$  is in superfluid state in main part of excitation levels at least lower than  $\approx 3.5-4$  MeV.

## LEVEL DENSITY AND RADIATIVE STRENGTH FUNCTION OF THE $^{237}\text{U}$ NUCLEUS FROM THE $(\bar{n}, \gamma)$ REACTION

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The independent analysis of the published data on the intensities of the primary gamma-quanta following resonance neutron capture in  $^{236}\text{U}$  has been performed. Distribution of these intensities about the mean value was approximated in different energy intervals of the primary gamma-transitions and neutrons. Extrapolation of the obtained functions to the zero registration threshold of the primary gamma-transition allowed us to estimate (independently on the other experimental methods) expected level number of both parities for spin values  $J=1/2$  и  $3/2$  and sum of radiative widths for both electric and magnetic dipole gamma-transitions to levels with excitation energy up to  $\approx 2.3$  MeV.

Level densities and sums of radiative strength functions determined in this way confirm characteristic behavior of analogous data derived from intensities of the two-step cascades following thermal neutron radiative capture in nuclei from the mass-region  $40 \leq A \leq 200$ . Besides, this permits one to estimate sign and magnitude of systematic uncertainties for their model predicted values, at least, below a half of the neutron binding energy. Comparison with the model notions of level density testifies to super-fluidity phase of this nucleus for the main part of excited levels, at least, below 2.3 MeV.

## STATUS AND PROBLEMS OF EXPERIMENTAL STUDY OF EXCITED NUCLEUS SUPERFLUIDITY

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Modern nuclear models assume a coexistence of normal and superfluid phases of nuclei, as a minimum, up to the excitation energy of neutron resonances. Experiment, accordingly, has to reveal important details of interconnection of these phases. First of all, this concerns to large-scale details. An effective method to study this problem is an investigation of neutron radiative capture. The most relevant characteristics of the abovementioned interconnection are the energy dependence of excited level density in given spin window  $\rho^J(E)$  and the radiative strength function (*RSF*) of primary gamma-transitions from a compound-state to the low lying states. The values  $\rho^J(E)$  and *RSF* have to be extracted from respective experimental data with maximal reliability and minimal systematic uncertainties. To reach this goal it is necessary in data analysis to depart from the obsolete simplified models of *RSF* and from the standard approaches for  $\rho^J(E)$ . The two-step  $(n, 2\gamma)$ -reaction and in general various multi-step reactions provide favorable possibilities for such type of investigations.

In paper [1,2] on the basis of practically modelless approach there was obtained the phenomenological information on *RSF* of primary gamma-transitions and  $\rho^J(E)$  for wide range of nuclei  $40 \leq A \leq 200$ . Very important fact established in this study was a discovery of step-like behavior of  $\rho^J(E)$  below an excitation energy  $E \leq 0.5B_n$ . Beside that it was revealed a presence of highly excited levels having vibrational nature in range of normal many quasi-particle excited levels.

In this paper it was made an attempt to expand the approach derived in [1,2] for analysis of  $(\bar{n}, \gamma)$ -reaction measured for actinide nuclei with keV neutrons. The obtained results give some evidence for similarity of general behavior of  $\rho^J(E)$  and *RSF* in this region of nuclei with the same obtained in [1, 2].

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POSSIBILITIES FOR DETERMINING THE RELIABLE COMPOUND STATES CASCADE GAMMA-DECAY PARAMETERS AND MAIN ERRORS OF APPLIED METHODS OF EXPERIMENT ANALYSIS:  $^{96}\text{Mo}$  AS AN EXAMPLE

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Authors [1] have performed re-analysis of their experimental data and changed a portion of results presented by them earlier. The necessity and volume of the performed re-analysis, as it was expected, is caused by incorrect subtraction of Compton background from each experimental gamma-spectrum and erroneous normalization of all the spectra to the same decay number.

Unfortunately, the authors have not performed quantitative analysis of systematical errors and, mainly, their transfer coefficients to the determined parameters.

1. Necessity and probability of effective search for error transfer of the total gamma-spectra to the primary transition spectra was demonstrated in [2]. Identical analysis for gamma-decay of the  $^{96}\text{Mo}$  excited levels shows, for example, that the "unexpected enhancements in the radiative strength functions (RSF) of low energy gamma-ray..." is an inevitable consequence of presence of quite ordinary uncertainties in normalization of the total gamma-spectra. For instance, linear increase in their areas due to error of normalization in limits 0 to 10% in energy intervals of decaying levels from 9 MeV to the ground state leads to double overestimate in intensity of the primary gamma-transition spectrum at the 1 MeV primary transition energy for the nucleus excitation energy of 9 MeV. Approximately the same overestimation is regularly observed and for  $^{96}\text{Mo}$  lower excitation energy. This error quickly increases at lower energy of primary transitions, but its sign and value change at higher energy. And transfer coefficients of these errors onto the determined level densities and radiative strength functions undoubtedly and strongly exceed analogous values of analysis of two-step cascades due to difference in functional dependencies.

2. There are no doubts in inevitable discrepancy between gamma-spectra following depopulation of levels of the same energy, but excited or by primary gamma-transitions from higher-lying levels or due to nucleon product emission of nuclear reaction. Corresponding errors and coefficients of their transfer onto the values of level density and radiative strength functions must be determined numerically for the worst cases.

3. The desired parameters are to be determined with the help of the verified programs of multidimensional fitting with obligatory regularization of degenerated (in case of [1] data) matrix and by maximal varying initial values of level density and strength functions.

4. Obtaining of reliable data requires one to account the strongest violation of the Axel-Brink hypothesis for gamma-transitions to the levels with different ratio between vibrational and quasiparticle components. This is regularly and easily revealed experimentally as considerable increase in cascade population of levels in region of step-like

structure (nuclear excitation energy 3-5 MeV and, possibly, more) when two-step cascades are investigated.

Analysis [3] showed principle discrepancy between experimental form of the two-step cascade intensity in  $^{57}\text{Fe}$ , for example, and that calculated with the use of the data of the ( $^3\text{He}, ^3\text{He}'\gamma$ ) reaction. This was performed with accounting for all the requirements of mathematical analysis and statistics.

5. The main sources of errors of data treatment on the two-step cascade intensities have been analyzed in [2] and detailed in [3].

So, one can conclude that the method for extraction of level density and radiative strength functions from the total gamma-spectra is characterized by considerably larger systematical errors than the method for analysis of the data from two-step reactions.

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**THE MISSING POINTS IN CALCULATIONS OF  
ELECTROMAGNETIC TRANSITIONS BY USING THE  
CODE PHINT: AN EXAMPLE ON DOUBLY EVEN  
PALLADIUM NUCLEI**

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The logic of the program codes PHINT is based on the mathematical and physical statements describing interacting boson model (IBM) which is one of the model of nuclear structure physics. But the big problem is again how the best values of the parameters can be inputted during the run of such codes. So, it is required to modify the codes and add some loops into the programs to get best-fitted values of the parameters. Moreover, there exist Many B(E2) and B(M1) values that are still not known so far and they will be stated. But the big problem is the way how to obtain the best-fitted parameters to calculate the best-fitted values of energies, B(E2) and B(M1). Even the parameters can hardly be approximated to obtain energies and B(E2) values, but it is very difficult to approximate the parameters to obtain B(M1) values. The mixed symmetry states are related to M1 values and in the world; the mixed symmetry (MS) states are also the area of interest for many nuclear physicists today. There are many things to be done in this area and this new subject is especially interesting for the nuclei existing around the transitional region having many interesting features such as high-spin isomers, backbending phenomena, even-odd energy staggering of quasi- $\gamma$  bands caused by a soft triaxial deformation, and features recently referred to as "chiral bands". These nuclei belong to a typical transitional region between spherical and deformed shapes. The even-even nuclei in this region seem to be soft with regard to the  $\gamma$  deformation with an almost maximum effective triaxiality of  $\gamma \sim 30^\circ$ . After obtaining the best-fitted values of B(E2) and B(M1), E2/M1 multipole mixing ratios will be easily calculated by using the reduced E2/M1 mixing ratio equation. Also it will be turned out that the IBA and some other potential, such as Bohr-Mottelson Hamiltonian with Davidson potential, are fairly reliable models for the calculation of spectra in the entire set of such nuclei. Using the best fitted values of parameters in the IBM Hamiltonian, we have calculated energy levels, B(E2) values and multipole mixing ratios  $\delta(E2/M1)$  for a number of transitions in <sup>102,104,106,108,110,112</sup>Pd nuclei. The results were compared with the previous experimental and theoretical data and it is observed that they are in good agreement. Many B(E2) and  $\delta(E2/M1)$  values that are still not known so far are stated and the set of parameters used in these calculations is the best approximation that has been carried out so far. So, By using PHINT, it has turned out that the interacting boson approximation (IBA) is fairly reliable for the calculation of spectra in the entire set of even even nuclei.

NEUTRON LIFETIME DEPENDENCE ON DECAY ASYMMETRY

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Abstract

Neutron decay in magnetic field is considered. The decay events are divided into two different (asymmetrical) flows of decay – with different signs of electron momentum projection onto neutron spin. Determination of the decay constants separately on the different flows (amounts) leads to two different values of the main constants corresponding to the different mean decay fluxes. To determine the full decay flux it is necessary to take into account the weights of the two flows (up and down the spin), in which the full flow of decay events is distributed. Appreciation of the asymmetry leads to the difference of the weighted average value for the full decay constant from its arithmetic average of two main decay constants (single event fluxes). In terms of neutron lifetime this effect is expressed in the difference of the weighted average value  $\tau_w$  of lifetime from the arithmetic average value  $\tau'_0$ . It is shown that this difference is described by the expression  $\tau_w = \tau'_0 \cdot \frac{1 - \Delta^2}{1 + \Delta^2}$ ,  $\Delta^2 = A \cdot \frac{\bar{v}_e}{c}$ , where  $\frac{\bar{v}_e}{c}$  - the mean electron velocity at the decay moment in units of the light velocity,  $A$  – angle correlation coefficient of electron emission in respect to neutron spin direction. The correspondence of this expression to the known experimental results is demonstrated. The mentioned relation can be used for an independent determination of  $A$ -coefficient.

## MEASUREMENTS OF ANGULAR AND ENERGY DISTRIBUTIONS OF PROMPT NEUTRON EMISSION FROM THERMAL INDUCED FISSION

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The experimental setup and methodology of the measurements of the angular and energy distributions of prompt fission neutron is described. The neutrons were detected by means of two scintillation detectors, while the fission fragments were detected by multi-wire parallel-plate detectors in conjunction with the time-of-flight technique. To separate events corresponding to neutrons and  $\gamma$ -quanta, a double discrimination was applied: by the pulse shape and the time-of-flight. In the course of experimental data processing, a few corrections were introduced accounting for neutron detector background, angular resolution of fragment detectors and neutron registration efficiency.

The energy spectra and angular distributions of fission neutrons have been measured for thermal neutron-induced fission of  $^{235}\text{U}$ . A comparison of the measured angular distribution of the  $^{235}\text{U}(n_{th}, f)$  fission neutrons with a theoretical distribution, calculated using the model of isotropic emission of neutrons from fully accelerated fragments, shows that in the integral spectra a difference in the neutron yield does not exceed 5%, while a maximal effect is  $\sim 10\%$  at the angles near  $90^\circ$ .

## Measurement of the Total Neutron Cross-Sections and Resonance Parameters of Natural Molybdenum and Niobium

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### Abstract

The neutron total cross-sections of niobium were measured in the neutron energy region from thermal to 200eV by using the time-of-flight method at the Pohang Neutron Facility, which consists of an electron linear accelerator, a water-cooled tantalum target with a water moderator, and a 12-m long time-of-flight path. A  $^6\text{Li-ZnS(Ag)}$  scintillator with a diameter of 12.5 cm and a thickness of 1.6 cm was used as a neutron detector, and a high purity natural niobium metallic disc with a diameter of 8.0 cm and a thickness of 3 mm thickness was used for the neutron transmission measurement. The notch filters composed of Co, In, Cd were used to estimate the background level and calculate the length of neutron flight path. In order to reduce the gamma-ray background from Bremsstrahlung and from neutron capture, we employed a neutron-gamma separation system based on their different pulse shapes. The present measurement was compared with the existing experimental and the evaluated data. The resonance parameters of  $^{98}\text{Mo}$  and  $^{93}\text{Nb}$  sample were obtained from the transmission ratio by using the SAMMY code, which utilizes both Doppler and resolution broadening effects and Bayes' generalized least squares technique.

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## STUDY OF NEUTRON EMISSION IN HIGH-ENERGY REACTIONS WITH LEAD NUCLEI

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This investigation is dedicated to study of neutron production in high-energy reactions. Time-of-flight data on neutron spectra in reactions with lead nuclei induced by high-energy protons, He and C are analyzed in framework of Moving Source Model. The MSM includes main processes with the neutron emission during decay of excited target-like nuclei, and it perfectly describes the experimental results. The energy and projectile dependences of the model parameters and neutron multiplicity are analyzed. Contributions of the different modes of disintegration and de-excitation to the neutron yield are discussed.

## NEUTRON ACTIVATION ANALYSIS OF TRACE ELEMENT CONTENTS IN THE CROWNS OF HUMAN PERMANENT TEETH

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Teeth have been suggested as dose monitors for the exposure of human body to elements concentrated in calcified tissues. In accordance with it, teeth are used in occupational medicine and environmental health studies. Moreover, a chemical element analysis of human teeth are often used in paleoanthropology for dietary and environment reconstruction in the assessment of the social and economic status of human groups. It is developed because for efficient application of teeth analysis in all the above-mentioned directions, it is necessary to know the normal levels and age-related changes of teeth trace elements on a large scale. The effect of age on trace element contents in intact crowns of permanent teeth of 24 relatively healthy 16-55 years old men was investigated. Contents or upper level of means of 31 trace elements: Ag, As, Au, Ba, Br, Cd, Ce, Co, Cr, Cs, Eu, Fe, Gd, Hf, Hg, La, Lu, Nd, Rb, Sb, Sc, Se, Sm, Sr, Ta, Tb, Th, U, Yb, Zn, and Zr in crowns of permanent teeth were determined by instrumental neutron activation analysis using long-lived radionuclides. Mean values ( $M \pm S.E.M.$ ) for mass fraction of Co, Eu, Fe, Hg, Sb, Sr, and Zn (mg/kg on dry weight basis) were:  $0.0030 \pm 0.0012$ ,  $0.00081 \pm 0.00023$ ,  $4.7 \pm 1.1$ ,  $0.00053 \pm 0.00020$ ,  $0.022 \pm 0.007$ ,  $198 \pm 40$ , and  $136 \pm 11$  respectively. The upper level of means of Ag, As, Au, Ba, Br, Cd, Ce, Cr, Cs, Gd, Hf, La, Lu, Nd, Rb, Sc, Se, Sm, Ta, Tb, Th, U, Yb, and Zr (mg/kg on dry weight basis) was lower than 0.02, 0.1, 0.01, 100, 10, 2, 0.02, 0.3, 0.02, 0.1, 0.03, 0.05, 0.003, 0.1, 0.6, 0.0009, 0.04, 0.01, 0.007, 0.01, 0.05, 0.07, 0.03, and 0.2 respectively. The statistically significant changes of Co, Eu, Fe, Hg, Sb, Sr, and Zn content in crowns of permanent teeth with age was not found.

## ROLE OF NUCLEAR ANALYTICAL METHODS IN THE ENVIRONMENTAL HEALTH ELEMENTOLOGY

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Study of changes in the content of chemical elements in an organism at all levels of its organization in response to changes of environmental conditions and detection of the role of chemical elements in the etiology and pathogenesis of different diseases is one of the subjects of new scientific discipline – Medical Elementology. It is possible to call this part of Medical Elementology as the Environmental Health Elementology.

The basic information unit in environmental health elementology is the quantitatively expressed content of a chemical element in a studied biological object. However only in the last decades of the 20<sup>th</sup> century there appeared really quantitative and metrologically sound (quality assured) methods for analysis of chemical elements in biological objects which allowed us to start studying the content of a large number of chemical elements in the human organism, practically at all levels of its organization. Among these methods, it is necessary first to mention (using internationally accepted abbreviations) spectral methods such as AAS, ICP-OES and nuclear and related methods - ICP-MS, NAA, XRF, PIXE, PIGE, SRXRF. Their combination in an instrumental variant (without preliminary concentration or separation) allows the determination of up to 60 or more chemical elements present in biological samples.

Application of nuclear-physical methods not only expands the number of chemical elements accessible to estimation, but also opens additional unique opportunities of studying biological objects. These methods do not demand destruction and utilization of a sample. They also avoid the possibility of additional introduction of chemical elements into the sample or losses of chemical elements during the sample preparation. This property makes nuclear-physical methods among the most reliable and gives them the referent status. Besides that, as the sample remains intact, nuclear-physical methods can be successfully combined with other analytical methods.

The absolute prerogative of nuclear-physical methods is the possibility of measuring the content of some chemical elements in the human organism *in vivo*. Current developments in INAA and XRF already allow the content of elements such as H, C, N, O, Na, P, Cl, K, Ca, Zn, Sr, Cd, I, Pb to be determined *in vivo*, either in the whole body, or in certain organs and tissues. There are theoretical and technological preconditions for significant expansion of *in vivo* methods in the near future.

In the study developed method and device for *in vivo* EDXRF measurement of Pb, Sr and some other chemical element contents in human teeth will be presented.

## NUCLEAR INTERACTION DYNAMICS IN <sup>56</sup>Fe(α,xn) REACTION

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Neutron spectra and angular distributions in <sup>56</sup>Fe(α,xn) reaction have been measured at α-particle energies of 12, 16, 18, 27, 45 MeV. The measurements were performed by time-of-flight fast neutron spectrometers on the pulsed accelerators. The analysis of the measured data have been carried out in the framework of equilibrium, preequilibrium and direct nuclear reaction mechanisms. The calculations are done using the exact formalism of the statistical theory as given by Hauser-Feshbach with the nuclear level densities of Ni isotopes, excited in this reaction, determined on the basis of new experimental data on the low-lying levels, the s-wave neutron resonance spacing and neutron evaporation spectra. The contributions of equilibrium, preequilibrium and direct mechanisms of neutron emission has been studied in a wide energy range of α-particles.

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## Nuclear level densities and spin distributions

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Nuclear level densities contain the essential information on nuclei at higher excitation energies, especially when individual levels cannot be resolved anymore. The exponential increase of the level density can be described by the Back-Shifted Fermi Gas formula (BSFG) with the two free parameters  $a$  and  $E_1$  or by the Constant Temperature formula (CT) with the parameters  $T$  and  $E_0$ . These two free parameters can be determined for each nucleus by a fit to the known individual levels in a given energy and spin range at low excitation energies and by the neutron resonance density at the neutron binding energy. Additionally a formula for the spin distribution has to be assumed. We have done this for 310 nuclei between  $^{19}\text{F}$  and  $^{251}\text{Cf}$ . For most of them the neutron resonance density was known.

Our result is that the level density parameters of the 310 nuclei can be well reproduced using very simple formulas containing only  $A$ ,  $P_a$ ,  $S'$  and  $dS/dA$ :

$$a = A^{0.90} (0.1848 + 0.00828 S'), \quad E_1 = p_1 \pm 0.5 P_a + p_2 dS/dA,$$

$$T = A^{-2/3} / (0.0571 + 0.00193 S'), \quad E_0 = q_1 \pm 0.5 P_a + q_2 dS/dA,$$

(values in MeV or  $\text{MeV}^{-1}$ ).

$A$  is the nuclear mass number,  $P_a$  the deuteron pairing energy,  $S'$  the shell correction and  $dS/dA$  its derivative. The fitted values  $p_i$  and  $q_i$  are different for even-even, even-odd, odd-even and odd-odd nuclei.

These new simple formulas use only values which can be calculated from well known ground state mass tables. They can be applied to calculate level density parameters of nuclei where experimental values are not available.

In a recent investigation we studied the spin distribution in the 310 low-energy nuclear level schemes, because the experimental information is rather scarce. The distribution is usually assumed to follow the formula  $f(J) = \exp(-J^2 / 2\sigma^2) - \exp(-(J+1)^2 / 2\sigma^2)$  with the spin cut-off parameter  $\sigma$ , which corresponds roughly to the maximum of the spin distribution. The theory predicts that  $\sigma$  increases with the moment of inertia, with the nuclear mass and with the nuclear temperature. But the various parameters for these dependencies are not well known. We fitted  $\sigma^2$  to the experimental spin distributions in these 310 level schemes including more than 8000 levels with their spins. The surprising result is that  $\sigma^2$  depends only weakly on  $A$  and that  $\sigma^2$  is nearly independent of  $a$ ,  $T$  and the deformation:

$$\sigma^2 = 2.42(30) A^{0.29(3)}.$$

The parameters vary weakly if even-even, odd and odd-odd nuclei are fitted separately. There is also a strong even-odd spin staggering in even-even nuclei. The energy dependence of  $\sigma^2$  was not investigated, because mainly data below 2 – 3 MeV were available which do not allow to find this dependency.

Details of our studies can be found in:

T. von Egidy, D. Bucurescu, Phys.Rev.C72,044311(2005); Phys.Rev.C72,067304(2005); Phys.Rev.C73,049901(E)(2006).

## LOW BACKGROUND GAMMA-RAY SPECTROMETRY AT GAMMASPEC LABORATORY OF IFIN-HH

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The activity field of the GammaSpec laboratory in IFIN-HH consists in interdisciplinary researches based on: (a) high resolution low-background gamma-ray spectrometry to determine man-made and natural origin radionuclides; (b) Instrumental Neutron Activation Analysis (INAA) to determine major, minor, and trace elements by neutron irradiation at the TRIGA reactor of the Institute of Nuclear Researches in Pitesti (about 100 km far from Bucharest-Magurele). Our laboratory has obtained the accreditation from the National Commission for Nuclear Activities Control in Romania (CNCAN), in accordance with Romanian nuclear legislation and quality norms, and International Standardization Organization (ISO) regulations (ISO/IEC 17025-2005 standard). The main samples investigated by gamma-ray spectrometry originated from the environment (soil, sediment, vegetation, water), VVR-S reactor decommissioning (dust deposition, building materials, metallic objects), and nuclear activities at the Radioisotope Production Laboratory (CPR) of our institute (waste water and sludge, air dust collected on filter). Besides that, we investigated various types of rocks (phosphate, zircon, thorium and uranium ores, salt), phosphogypsum (fertilizer industry by-product) and building materials containing phosphogypsum. The gamma spectrometric system is based on an HPGe EG&G Ortec detector (2.1 keV FWHM at 1332.5 keV of  $^{60}\text{Co}$ , and 30 % relative efficiency). The detector shield (lead thickness of 10 cm, coated with Cu foil) permits to obtain a count rate of 1.77 cps for the natural background spectrum. Activity concentrations of naturally occurring radionuclides ( $^{40}\text{K}$ ,  $^7\text{Be}$ ,  $^{235}\text{U}$ ,  $^{238}\text{U}$ -decay series, and  $^{232}\text{Th}$ -decay series), as well as man-made radionuclides (mainly  $^{137}\text{Cs}$ ,  $^{241}\text{Am}$ , and  $^{60}\text{Co}$ ), were measured in the natural origin samples. The radionuclides detection limits for various types of samples are presented in this paper, together with the laboratory results obtained in the frame of IAEA-CU-2004-03 world wide open proficiency test on determination of gamma-emitting radionuclides in spinach ( $^{137}\text{Cs}$  and  $^{40}\text{K}$ ), spiked soil and spiked water samples ( $^{241}\text{Am}$ ,  $^{60}\text{Co}$ ,  $^{109}\text{Cd}$ ,  $^{134}\text{Cs}$ ,  $^{137}\text{Cs}$ ,  $^{54}\text{Mn}$ ,  $^{65}\text{Zn}$ ,  $^{210}\text{Pb}$ ). As an example, the following radionuclide detection limits (in Bq/L) were found for water sample measured in Marinelly geometry (volume 1 L): 0.38 ( $^{241}\text{Am}$ ); 0.092 ( $^{137}\text{Cs}$ ); 0.090 ( $^{60}\text{Co}$ ); 0.69 ( $^7\text{Be}$ ); 0.91 ( $^{40}\text{K}$ ); 0.27 ( $^{228}\text{Ac}$ ); 0.85 ( $^{234}\text{Th}$ ); 0.21 ( $^{214}\text{Pb}$ ); 0.17 ( $^{214}\text{Bi}$ ).

INSTRUMENTAL NEUTRON ACTIVATION ANALYSIS:  
INTERLABORATORY COMPARISON BASED ON SHORT-LIVED ISOTOPES

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The phosphate fertilizer industry is responsible for the negative impact on the environment and human health, giving rise to an increase in incidence rate for fluorosis, respiratory and other diseases. The overall objective of the joint project between IFIN-HH in Magurele (Romania) and JINR in Dubna (Russia) is the investigation by nuclear and nuclear-related techniques of the environmental pollution with toxic elements due to the industrial production of phosphate fertilizers. The target point of the project is TURNU fertilizer plant in Romania. Instrumental Neutron Activation Analysis (INAA) was employed in IFIN-HH for medium- and long-lived isotopes and in JINR Dubna for short-lived isotopes in soil and vegetables collected in the vicinity of the fertilizer plant and control area. The neutron irradiation was carried out at the TRIGA reactor in Pitesti and at the IBR-2 reactor in Dubna, respectively. In addition, Proton Induced X-Ray Emission (PIXE) at the Van de Graaf accelerator of IFIN-HH was applied to some of the samples. To examine the possibilities for further trilateral collaborative studies the interlaboratory comparison was undertaken. The results on soil, potato and carrot samples obtained by INAA at FLNP JINR (Russia) and BNC (Hungary) based on short-lived isotopes, as well as in IFIN-HH (Romania) based on medium- and long-lived isotopes are reported. The following elements were investigated: Al, Br, Ca, Cl, Cu, Dy, In, K, Mg, Mn, Na, Sr, and Ti. Among them, K, Na and Br (medium half-life), as well as Ca and Sr (long half-life) were also determined by INAA in IFIN-HH. The potentialities of applying complementary analytical techniques are discussed.

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Acceleration Matter Effect in Neutron Optics: First Observation and  
Investigation  
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As that was recognized recently after the wave of any nature passed through the spatially restricted medium volume which is moving with linear acceleration, the wave frequency and correspondent energy change. This Accelerating Matter Effect (AME) is universal and seems was not been detected till recently. Using of UCN allowed us to demonstrate it in neutron experiment.

The results of the experiments for the observation of the AME in a neutron optics will be

reported. The theoretical size of this effect is  $\Delta E \approx wd \frac{1-n}{n}$ , where d is the slab thickness,

n the refraction index and w the slab acceleration [1,2]. In our experiments [3,4] we measured very precisely the energies of UCN after their transmission through a silicon slab, which oscillated harmonically along and towards the neutron motion. A technique based on quantum properties of Neutron Interference Filters (NIF) was used. The experiments were carried out with ultracold neutrons and the maximum value of the energy transform was equal to  $\pm (2 \div 6) \times 10^{-10}$  eV. Results testify that the effect is really exists and correspond to theoretical predictions with accuracy better than 10%. Some future possibilities for the investigation of the ACE will be also discussed.

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