MAIN RESULTS ON NUCLEAR PHYSICS OBTAINED AT IHEPNF NSC KIPT DURING THE LAST DECADE

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The main experimental results on nuclear physics obtained at INEPT KIPT during the last decade have been observed.

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INTRODUCTION

One of the primary sources of information on properties of atomic nuclei are nuclear reactions with different bombarding particles. These reactions allow one to study spectroscopic characteristics of some nuclear levels (spins, parity, matrix element of radiative transitions etc.) and statistical properties of levels at higher excitation energies as well as other regularities of nuclear structure. It is obvious, that when using different bombarding particles, from all the diversity of nuclear properties the most distinguishing are only certain of them. Therefore, using in the study of nuclei a wide set of particles (from gamma-quanta to heavy ions) one can obtain a more complete image of atomic nuclear structure. Proceeding from this at NSC KIPT the research on nuclear physics was conducted traditionally on beams of electrons, gamma-quantum, protons and more heavy ions. So, it was possible to study the structures of nuclei from hydrogen to uranium. The results of investigations of earlier years were published in different journals, monographies, reviews, e.g. [1-3] and reported at many conferences.

The investigations performed during last 8-10 years are, in main, a continuation of earlier developed basic lines. They are directed to obtaining a more detailed and accurate information and to more thorough analysis of this information. For example, the studies on interactions between polarized gamma-quanta and nuclei ^{12}C have shown that from all the possible mechanisms the main one is the mechanism of quasi-linear interaction between gamma-qunta and an alpha-cluster of the nucleus ^{12}C when the residual nucleus ^{8}Be is formed in excited states. The studies on photofission of ^{232}Th nuclei on beams of polarized gamma-quanta have shown that at low photon energies the fission process is determined by the dipole excitation. When investigating the resonance-like structures observed in reactions of radioactive capture of protons by nuclei it is shown that due to triplet pairing existing between an odd neutron and a proton being on one and the same orbit, there is an appreciable displacement of the centre of gravity in the magnetic dipole resonance for even-even and odd-odd nuclei. When studying the gamma-decay of isobaric-analogue states in light nuclei it was shown that M1-transitions from the analogue to antianalogue states are significantly slowed as compared to the one-particle estimation. Application of the method of averaged resonances in reactions of radiation proton capture has made it possible to establich that the radiation force function in nuclei of the pf-shell is determined by the spread width of E1-resonance with taking into account the temperature of a nucleus in a final state. The study of heavy ion-atomic nuclear interactions allowed one to obtain new information on mechanisms of complete and uncomplete nuclear fusion of an incident particle with a target nucleus.

Below the main results obtained at IPHENP during last 8-10 years of activity are given in the text in the following sections.

Σ-ASSYMETRY IN THE REACTION ^{12}C(γ,α^{8}Be)

Now one accumulated a great volume of experimental studies on mechanisms of reactions of nuclei ^{12}C and ^{16}O photofission with α-particle yield [4-7]

$$\gamma+{}^{12}C\to 3\alpha, \quad (1)$$

$$\gamma+{}^{16}O\to 4\alpha. \quad (2)$$

The interest shown for these reactions was conditioned by some causes related with examination of the alpha-cluster nuclear structure and suppositions on the quasi-alpha-particle interaction mechanism. In many experimental works it is shown that the mechanism of these reactions, as a rule, is determined by two-particle channels of photofission of nuclei ^{12}C and ^{16}O:

$$\gamma+{}^{12}C\to\alpha+{}^{8}Be^*, \quad (3)$$

$$\gamma+{}^{16}O\to\alpha+{}^{12}C^*, \quad (4)$$

In this case the residual nucleus ^{8}Be in reaction (3) is formed in exited state with a complete moment and a parity $J^\pi=2^+$. However, the experimental results do not exclude a probability of forming the residual nucleus ^{8}Be in a ground state with $J^\pi=0^+$. Besides, as is shown in [8], realization of the residual nucleus ^{8}Be in an exited state with $J^\pi=4^+$ is possible if one takes into account the classical cluster structure of nucleus ^{12}C, i.e. the distinction in the oscillator function parameters describing the state of nucleon associations. The experimental data, we have obtained earlier on ^{8}Be excitation energy in reaction (3) do not exclude a possibility of forming this nucleus in a state with $J^\pi=4^+$[9]. Our preliminary data on the Σ-asymmetry show that this value is significantly less than unity [10].

This paper is aimed to the experimental study on distributions over all possible kinematic variables for α-particles in final state of reactions (1) and (2), as well as on the energy dependence of the Σ-asymmetry of the yield in reaction (2) on the beams of bremsstrahlung and linearly polarized γ-quanta from the linear electron accelerator LUE-2000. The experiment on the study of reactions (1) and (2) has been carried out in two stages. In the 1st stage we used photoemulsions of BYa-2 type irradiated with a beam of γ-quanta of a 300 MeV maximum energy from LUE-2000. In the 2nd stage we used a beam of linearly polarized γ-quanta obtained from LUE-2000.

The overall estimation of a maximally possible total contribution from background reactions has shown that it does not exceed 15 %. The results of the experiment are shown in Fig. 1.

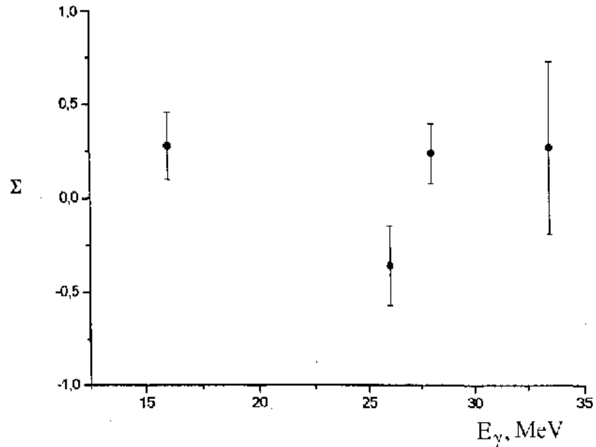


Fig. 1. *Σ-assymetry in the reaction* $^{12}C(\gamma,\alpha^8Be)$

As is seen from the figure at low-energy γ-quanta the Σ-assymetry value is considerably less than unity that indicates on the formation of a residual nucleus ^{8}Be in excited states. So, the results obtained evidence that the main mechanism of the reaction under study is the mechanism of quasi-linear interaction of γ-quanta with a alpha-cluster of ^{12}C when the residual nucleus ^{8}Be is formed in excited states. This conclusion confirms the result we have obtained earlier for the model-independent analysis of angular α-particle distributions in this reaction. The results have shown also that the residual nucleus ^{8}Be is formed in excited states with a complete moment and parity $J^\pi = 2^+ 4^+$ [11].

NUCLEAR RESPONSE FUNCTION MOMENTS

Response functions (RF) are the extending of the form-factor notion for all the energies ω transferred to a nucleus. These functions express the response of a nucleus to the effect of a polarized virtual photon on it. Transversal $R_T(q,\omega)$ and longitudinal $R_L(q,\omega)$ RF correspond to transversally and longitudinally polarized virtual photon.

Response function moments (RFM) are particular important for comparison of the theory with the experimental data. Because the calculations using the least model approach, which are the sum rules (SR), describe RF only in the moments representation. The relation of RF with a twice differential cross-section $d^2\sigma$ and k^{th} moment of RF $S_{T/L}^{(k)}(q)$ is described as:

$$d^2\sigma \cong \sigma_M (G(q^2))^2 \{R_L(q,\omega)+[0.5+tg(\theta/2)]R_T(q,\omega)\}, \quad (5)$$

where σ_M is the Mott cross-section, $G(q)$ is the proton electric form-factor, θ is the electron scattering angle, q is the 3−momentum transferred to the nucleus;

$$S_{T/L}^{(k)}(q) = \int_0^\infty R_{T/L}(q,\omega)\omega^k d\omega . \quad (6)$$

The experiments on measuring RF are very complex. Therefore, there are only a small number of nuclei (about 11) for which modern R-data are obtained.

With undoubted usefulness of these data they possess also some shortcomings:

a number of problems can be solved experimentally only for q<1.5 fm^{-1} while all the rest measurements, excluding ^{3}H, ^{3}He and ^{12}C cases, were conducted for $q \geq$ 1.5 fm^{-1}. With this q, the electroproduction contribution into the R_T-function excludes possibility to determine S_T-moments;

an accuracy of measurements with high ω restricts the number of determined S_L-moments by the value k=0.

To extend the investigations into the range of $q\sim$ 1 fm^{-1} we have carried out the measurements on ^{2}H, ^{4}He, ^{6}Li and ^{7}Li nuclei [1/] at the accelerator LUE-300. By now the measurement data processing has given the values $S_T^{(0)}(^4He)$ [13] and ratio $S_T^{(0)}(^7Li) / S_T^{(0)}(^6Li)$ [14], and $S_T^{(k)}(^2H)$, $S_L^{(k)}(^2H)$ for k = −1, 0, 1 [15]. Analysis of these data leads to the following conclusions.

Comparison of SR for ^{4}He [16] with obtained $S_T^{(0)}(^4He)$ at q = 0.75-1.5 fm^{-1} has shown that the contribution of meson exchange currents into $S_T^{(0)}$ is (4±7)% (i.e. does not exceed 11%), whereas the similar investigation [17] at q=1.5 − 2.5 fm^{-1} estimated this contribution as 15...20%.

The measurement of the ratio $S_T^{(0)}(^7Li) / S_T^{(0)}(^6Li)$ within accuracy of 2% allow to reveal for the first time a difference in correlation functions of isotopes. The question on a maximum number for finitely valued RFM concerns to the main problems of SR [18]. Our investigation of the asymptotic for ω of experimental RF of nucleus ^{2}H [19] resulted in a maximum k=1. The obtained parameters of RF extrapolation function decrease the known uncertainty in experimental RFM that has a special importance for the moments with k=1. According to [18], all these results of ^{2}H RF research are related to RF of other nuclei too. The moment with k=1 depends on nucleon-nucleon forces inside the nucleus and therefore it is interesting to compare the calculations of this moment with experimental data. Our $S_L^{(1)}$-data on ^{2}H [15], [20] permitted to extract [21] and [22] from some theoretical works as not being in contradiction with the experimental ones. Here let us note, that the calculation of the $S_L^{(0)}$ -moment of ^{2}H [22] deviates by three standard errors from the experimental value of [15].

In our investigations of the Coulomb nuclear energy [23,24] we used the equality

$$S_L^{(0)}(q) = Z\,(G(q^2))^2, \text{ at } q>2\ Фm^{-1} . \quad (7)$$

Such notion about the $S_L^{(0)}$-moment was corresponding to the accuracy of measurements before 80th years. The further experiments (see [25]) have shown the lower values of $S_L^{(0)}(q)$ and thus the disturbance of

1/ For measurements on ^{2}H and ^{4}He we have constructed gas targets GM-1 and GM-2 exceeding the foreign analogs [12] by some basic characteristics.

equality (7) (MIT-effect). Though these new $S_L^{(0)}$-data have changed very slightly the numerical results of [23,24], nevertheless they required to reconsider our notions about the structure of a nucleus and, in particular, about its Coulomb energy. The most convincing explanation of the MIT-effect is an idea about modification on nuclear nucleons (see, for example, [18]) as a result of which their radius increases, and the square of a nuclear proton form-factor satisfies equality (7). Note, that according to this approach the radius and respectively, the form-factor of a modified proton should be dependent on the properties of a nucleus in which it is located. A search for the relation between experimental values of $S_L^{(0)}$-moments and charge-and- matter density distributions in nuclei has led us to the hypothesis about a stepwise modifications of a part of nuclear nucleons [26]. According to this hypothesis the nucleon modification occurs when the density of the matter surrounding exceeds 0.142±0.005 Fm^{-3} and the properties of the modified nucleon are similar in all the nuclei. Thus, the modified nucleons take place only in the central region of nuclei and their relative number depends on the atomic number of this nucleus. The hypothesis under consideration puts in correspondence all the known $S_L^{(0)}$-data and leads to some conclusions, among them: affirmation about the significant increasing of the proton radius by modification (~40%); about possibility to investigate the charge distribution in the modified proton by measurements the dependence of the moment $S_L^{(0)}$ on q on heavy nuclei.

Basing on calculations of the hypothesis proposed we have found the expression for the contribution of proton modification into the Coulomb nuclear energy according to which this contribution is from 0.04 MeV for ^4He to 9 MeV for ^{208}Pb [27].

Σ-ASYMMETRY AND CROSS_SECTION IN (1^-,0)-, (1^-,1) - CHANNELS OF ^{232}Th PHOTOFISSION

Investigations of angular distributions of fission fragments give important information on the properties of barriers of heavy nuclear fission and on quantum numbers of low-lying excited states.

At low photon energies the fission is determined mainly by the electric dipole (E1) and significantly weaker quadrupole (E2) excitation. The fragment angular distributions are described by the formula

$$W(\theta) = a + b \sin^2\theta + c \sin^2 2\theta. \quad (8)$$

The coefficients a,b,c are determined by the contributions of 5 fission channels with quantum numbers (J^π,K)=(1^-, 0), (1^-,1), (2^+,0), (2^+,1), (2^+,2), where J,π are the spin and the parity of excited state, K is the projection J into the nuclear symmetry axis. Since from the fitting of equation (8) one obtains three values of a,b,c, then for the analysis one uses three fission channels (1^-,0), (1^-,1), (2^+,0), neglecting the contributions of (2^+,1), (2^+,2) channels. At present for nuclear photo fission the linearly polarized photons are coming into use [29,30]. In these experiments for ^{232}Th nucleus one obtained a new independent value i.e. the Σ–asymmetry characterizing the analyzing power of a photonuclear reaction. The Σ–asymmetry can not be expressed in terms of the coefficients a,b,c and via the cross-sections of three fission channels [29,31]. At the angle θ=π/2 the expression of the Σ- asymmetry has a simple form:

$$\Sigma(\pi/2) = b/(a + b), \quad (9)$$

$$\Sigma(\pi/2)=[2\sigma(1^-,0)-\sigma(1^-,1)]/[2\sigma(1^-,0)+\sigma(1^-,1)]. \quad (10)$$

In this case the coefficient c and the cross-section σ (2^+,0) do not influence on the Σ-asymmetry [29,32]. Using expression (9) we have obtained the values of Σ-asymmetry for ^{232}Th nucleus from the experimental values of the coefficients a, b and their ratio b/a in the energy range up to 20 MeV. For the photon energy up to E_γ =10 MeV we processed the data of [33], and for E_γ> 10 MeV-the results of all the photonuclear experiments. All these experiments were carried out with the bremsstrahlung photon spectra. The Σ–asymmetry values obtained are shown in Fig. 2. It is seen that the value of Σ–asymmetry is close to unity at 5.65 MeV and decreases smoothly with energy increasing up to 20 MeV. Despite of the fact that the data obtained with different spectrum forms of photons (bremsstrahlung photons, virtual photons on the electron and positron beams, coherent part of photon spectrum when channeling the electrons in the silicon crystal) they are in good agreement between themselves. Such a agreement indicates that in the ^{232}Th nucleus for the Σ–asymmetry the dipole approximation is good fulfilled and the contributions of (2^+,1)-and (2^+,2) channels of quadrupole fission do not reveal within accuracy of experimental errors.

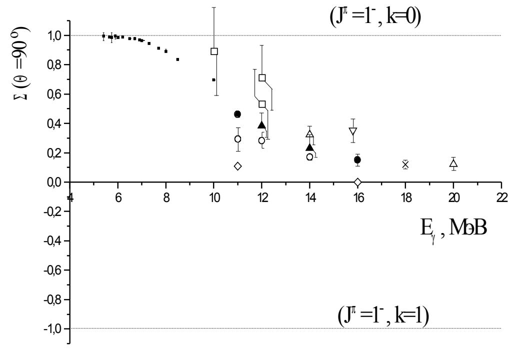


Fig. 2. *Σ–asymmetry of ^{232}Th fission is obtained in the present paper from the data of different works:- [33], black triangle – [34],* O *– [35], □ – [36], □ – [37]-bremsstrahlung photons, ◊-electrons, virtual photons [38], •-positrons, virtual photons [38], -bremsstrahlung polarized photons [29], ×-polarized photons in the process of electron channeling in the silicon crystal [30]*

Equation (10) shows that for (1^-,0)-channel the Σ-asymmetry equals to (+1), and for the (1^-,1)-channel it equals to (-1). The lines in Fig. 2 are indicating these values. The obtained values of the Σ-asymmetry are positive, i.e. generally they are determined by the (1^-,0) fission channel. Up to the energy 6.5 MeV only the (1^-,0) channel reveals (Σ-asymmetry equals to +1), and above 6.5 MeV the contribution of the (1^-,1) channel decreasing the significance of Σ-asymmetry becomes apparent. From this it follows that the energy of 6.5 MeV is a threshold of ^{232}Th photofission reaction through the (1^-,1) channel.

a)

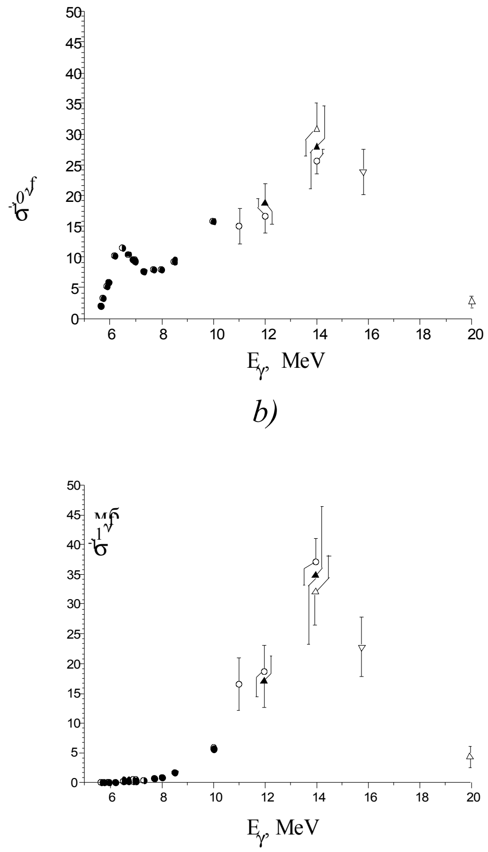


Fig. 3. *Fission cross-sections* $\sigma_{\gamma,f}^{1^-,0}$ *(a) and* $\sigma_{\gamma,f}^{1^-,1}$ *(b) of* ^{232}Th *nuclei by bremsstrahlung photons are obtained in the present paper from the data of some works:* ·*–[33], black triangle–[34],* **o***–[35],* **∇***–[36],* **Δ** *–[370]*

The energetic behavior of fission cross-sections for three main channels can be obtained by analyzing the angular distributions of fission fragments. The coefficients a,b,c are related with the cross-sections σ(J$^\pi$,K) by the following way [29]:

$$a=3\sigma(1^-,1)/2,$$

$$b=3\sigma(1^-,0)/4-3\sigma(1^-,1)/4, \qquad (11)$$

$$c=15\sigma(2^+,0)/16.$$

Using these equations and experimental data for the coefficients a,b,c [33-37], we have obtained the cross sections σ(J$^\pi$,K) for three fission channels. The cross section σ(2$^+$,0) was obtained for the energies up to 10 MeV and it was much less then dipole cross sections. There is not data for the coefficient c above 10 MeV. The cross sections in the dipole fission channels σ(1$^-$,0), σ(1$^-$,1) are given in Fig. 3. The figure shows that the both dipole cross sections give the peaks at 14 MeV. Such peak position is in agreement with the data on electron scattering [39]. An essential distinction is observed near the fission threshold where the cross section σ(1$^-$,0) has a sharply standing out peak at the energy of 6.5 MeV. The information on the cross section σ(J$^\pi$,K) is available only for ^{238}U and it has been obtained in the experiment with target photons [40] from the fission threshold up to 8.9 MeV. Our data for the nuclei ^{232}Th are qualitatively coincident with the data of [40] and can be used for checking different theoretical models.

M1- RESONANCE IN ODD NUCLEI OF THE SD-SHELL

When studying [41,42] the γ-decay in resonance-like structures observed in the reaction of radiation proton capture by the nuclei ^{21}Ne, ^{25}Mg, ^{29}Si, ^{34}S, we revealed a new phenomenon related to the existence of triplet pairing between an odd neutron and a proton being located on one and the same orbit. It manifests in that the position of the center of gravity (CG) of the magnetic dipole resonance (MDR) for odd-odd 4N+np nuclei is situated 3 MeV below by the excitation energy than in even-even 4N-nuclei. In the above mentioned papers one proposed a model to explain this phenomenon. According to this model the odd nuclei of the sd-shell could be divided into two groups, depending on the state in which the odd particle stays in the $d_{5/2}$– or $d_{3/2}$ subshell. To date the numerous experimental spectroscopic information is accumulated about the resonance states of the nuclei ^{27}Al, ^{31}P, ^{35}Cl, ^{37}Cl with the help of the reaction of radiation proton capture by the nuclei ^{26}Mg, ^{30}Si, ^{34}S, ^{36}S, respectively [43,47]. However, in the energy range where one observes resonance-like structures (RLS) in this reaction [48,49], the experimental information is insufficient to identify with assurance MDR. Therefore, we conducted a series of measurements concerning the identification and determination of the center of mass position, the fine structure and the total MDR force in the nuclei ^{27}Al, ^{31}P, ^{35}Cl, ^{37}Cl. The functions of excitation of the reactions of ^{26}Mg, ^{30}Si, ^{34}S, ^{36}S(p,γ), ^{27}Al, ^{31}P, ^{35}Cl, ^{37}Cl, being necessary for determining the forces of resonances ($S=(2J+1)\Gamma_p\Gamma_\gamma/\Gamma$), were measured in the range of accelerated proton energies E_p=1.8-3 MeV for ^{27}Al and ^{37}Cl, E_p=1-2,7 MeV for ^{31}P, E_p=1,2-3 MeV for ^{35}Cl [8,9]. The measurements were performed at the NSC KIPT accelerator ESU-4. To measure the yield of γ-quanta with E_γ>2,6 MeV we applied the ∅150x100 mm NaJ(Tl) detector placed at a distance of 5 cm from the target at an angle of 55° relatively to the proton beam direction for excluding the dependence of γ-quanta on the angle. The resonance forces were determined from the comparison between the area under the resonance curve and that one under the calibrating resonance. For ^{27}Al this is the resonance at E_p=1966 keV, for ^{31}P-the resonance at E_p=1880 keV, for ^{35}Cl-the resonance at E_p=1212 keV, for ^{37}Cl-resonance at E_p=1887 keV, the forces of which are well known [43]. As a result of measurements in odd nuclei we revealed RLS similar to those, which were observed for even nuclei we have investigated earlier [41,42]. In all the previous cases RLS have had a complicated structure, i.e. they were composed of the states belonging both to the M1-resonance of the ground state and to the M1-resonance "constructed" on the excited states. And only in a single case (^{34}Cl) CG of RLS was determined by the states of the M1-resonance on the excited state. The final conclusion on the nature of RLS observed can be made after determining all the quantum characteristics of resonance states composing these RLS and after studying their γ-decay. For this purpose we measured the spectra and angular distributions of γ-quanta being formed during the decay of the most intense resonances composing these RLS. To measure the γ-spectra we used a Ge(Li)-detector with 60 cm^3 volume and 4 keV resolution for Eγ =1332 keV. The detector was placed at a distance of 7 cm from the target. The target was situated in the rotation center at an angle 49^O to the proton beam direction. The measurements were conducted at angles 0°, 60°, 30 °, 90°, 45°. The correction taking into account the final detector dimensions were selected from the literature data. As a monitor we used a scintillation detector with ∅150x100 mm NaI(Tl) crystal. This detector was applied also for measurement of the excitation function. The measurement results, as coefficients of expansion by Legendre polynomials (a_k), and results of angular distributions of γ-quanta formed during the decay of resonances composing RLS under consideration are given in [48,49]. The parity value is assigned to resonance states basing on comparison of a probability for electromagnetic transitions having different multipolarity with recommended upper limits (RUL) of the given quantities [50]. The probability of the γ_0 transition B(M1) being considered was calculated from the expression

$$B(M1)\uparrow=86,6b_0S(eV)/((2J_0+1)E^3_{\gamma 0}\ (MeV)),$$

where b_0 is the branching coefficient for the ground state, J_0 is the spin of the ground state, $E_{\gamma 0}$ is the energy of γ-transition to the ground state.

The distributions of probabilities for magnetic dipole γ-transitions obtained allow one to conclude that resonances composing RLS belong to states of the M1-resonance on ground as well as on excited states of nuclei ^{27}Al, ^{31}P, ^{37}Cl. MDRCG($E_{cg} = \Sigma_k E_k B_k(M1)/\ \Sigma_k B_k(M1)$) on ground states of nuclei ^{31}P, ^{35}Cl, ^{37}Cl (Fig. 4) is equal to 8.5±0.3 MeV, 9.1±0.1 MeV, 10.5±0.2 MeV, respectively, and is situated in the region expected for odd nuclei with an occupated $d_{5/2}$-subshell. This experimental fact evidences in favour of that in MDR formation in nuclei ^{31}P, ^{35}Cl, ^{37}Cl the nn(pp)-pair from the $d_{5/2}$-subshell takes part, therefore the position of MDR CG in these nuclei is influenced by the value of nn (pp)-pairing in this subshell.

MDR CG in nuclei ^{25}Mg [43], ^{27}Al equals to 5.8± 0.2 MeV and 6.1±0.2 MeV, respectively, and is situated in the excitation energy range expected for the nuclei with a unoccupied $d_{5/2}$-subshell. The total force of MDR ($S^{M1}_{EW}= \Sigma_k E_k B_k(M1)$) in nuclei ^{31}P, ^{35}Cl, ^{37}Cl equals to 10.2 MeV μ_N^2, 2.5 MeV μ_N^2, 12.8 MeV μ_N^2, respectively, and is compared to that in 4N+2n and 4N+np nuclei [42] that obviously also confirms the conclusion about the fact that in formation of the M1-resonance in odd nuclei with an occupied $d_{5/2}$- subshell the valence nn(pp)-pair takes part.

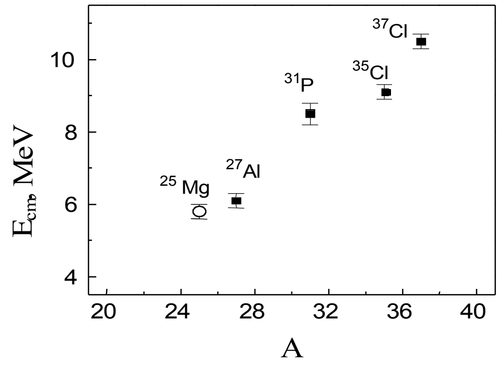


Fig. 4. Position of the center of mass of the M1-resonance for odd nuclei of the sd-shell. ○ – literature data [45], ▪ – our data.

L-FORBIDDEN M1-TRANSITION WITH Δ T=1 IN ODD NUCLEI d2s- SHELL

Over a long period of time it was supposed that the main mode of the γ-decay of isobaric-analogous states (AS) in light nuclei is the M1-transition onto the anti-analogous state (AAS). However, later in a number of precision experiment it was established that in some nuclei the M-1 transitions AS→AAS are much slowed down as compared to the single-particle evaluation [51]. To explain these facts it was necessary to introduce into the model representation a new degree of nuclear freedom, i.e. the states such as a core polarization. The detailed calculations performed in the framework of a shell model with surface δ-forces [52] have shown that the absolute probability of AS γ-decay in odd nuclei with $21 \leq A \leq 41$ is divided among M1-transitions into AAS and the states such as a core polarization. This conclusion was sufficient to interprete the radiation widths of AS decay well-known at that time in this range of nuclei [53]. Meanwhile, in experiments of latter years one found the isovector γ-transitions which have not been represented in the theoretical approach proposed in [52]. First of all, they are l-forbidden transitions like $T_> = T_0+1/2 \rightarrow T_< = T_0-1/2$. There was not systematic calculations explaining the mechanism of *l*- forbidding removing even in a simple model and, probably, namely in virtue of the imaginary theoretical unfoundedness, one did not give a proper consideration to them.

Proceeding from the foregoing, in this paper one made an attempt to establish, by the way of experimental data analysis, the empirical regularities for the *l*-forbideen M1-transitions observed during the AS decay in odd nuclei of the 1*d*2*s*-shell. It is reasonable to expect that there are should exist certain regularities and that their reveal would help, at least, to systematize the knowledge on these M-1-transitions and by this to determine the further outlooks for the study of this problem in light nuclei. The evident interest in these γ-transitions is caused by the fundamentality of the problem i.e. clarifying the role of charge dependence of nuclear forces in the mechanism of isospin level mixing in nuclei.

A peculiarity of the range of nuclei under consideration is the presence in it both spherical and deformed nuclei. This fact complicates significantly the problem of identification of pure single-particle *l*-forbidden M1-transitions with ΔT=1. In this connection it is necessary to identify the configurations using the data on the intensities of state occupations measured in reactions with transfer of one nucleon and data from the experiences on nucleon scattering on nuclei. As an indirect way one can use the values of mixing by multipolarities δ ($E2/M1$). However, the experimental data about these parameters are extremely fragmentar and this does not allow evaluating the contribution of collective components into the structure of isobaric-analogous resonance states. Basing on available data it can be note that, as one would expect, the additions of a $E2$-component in *l*-forbidden M1-transitions are insignificant.

Information about the total radiation decay widths of Γ_γ- analogous resonances is obtained from the data on the cross-sections of the corresponding (pγ)-, (nγ) and (γ ,γ)-reactions ([54,43] and its references). For qualitative determining the degree of delay of *l*-forbidden M1-transitions as compared to single-particle estimations, we used the factors of forbidding the standard formulation of which has the form $F_M=B(M1)^{theor}/B(M1)^{ýêñï}$. Estimation of the $B(M1)_{teor}$ value was performed by the Moshkovsky formulas [55]. Analysis of the accumulated experimental material makes it possible to formulate some general conclusions.

1. It is established that *l*-forbidden M1-transitions with isospin change by unity are observed over all the range of odd nuclei $21 \le A \le 41$. Their intensity in a number of cases is comparable by the order of magnitude with the intensity of permitted single-particle M1-transitions AS →AAS.

2. It is found that the forbidding factors F_M are minimum (~10) for γ-transitions being observed mainly during decay of the analogous resonances in nuclei close to the equilibre deformation region A~25. The maximum of values F_M >500 is related with γ-transitions $s_{1/2} \Leftrightarrow d_{3/2}$ in the nuclei ^{35}Cl, which is almost spherical. While in the upper part of the 1*d*2*s*-shell the $s_{1/2} \Leftrightarrow d_{3/2}$ transitions are characterized by a significant decrease of forbidding factors (up to ~10), one observes the tendency of F_M growth with increasing the energy of γ-transition in one and the same AS.

3. The *l*-forbidden M1-transitions in nuclei having the neutron number close to the magic number N =20 are not identified. At the same time in nuclei with Z=20 the F_M values are changing in a wide interval: $F_M \approx 10 \div 100$. However, it should be noted that this conclusion is preliminary because of the lack of data and requires further experimental evidence.

4. A marked correlation between values of F_M and values of C^2S AS spectroscopic factors was not observed. It allows one to assume that *l*-forbidden $M1$-transitions $T_> \to T_<$ occurs due to the adding of other configurations to the initial and final states of a radiating particle. The fact that these transitions are observed in the immediate vicinity of occupied shells allows us to conclude that collective effects should not play a significant role in *l*-forbidding removing. However, *l*-forbidding weakening in the range of nuclei A~25 is evidently related to the increasing role of collective effects.

APPLICATION OF THE METHOD OF AVERAGED RESONANCES (MAR) IN REACTIONS OF LOW ENERGY PROTON CAPTURE BY NUCLEI ^{46}Ti, ^{60,61,62,64}Ni, ^{56,58}Fe, ^{68}Zn, ^{71}Ga and ^{72}Ge

Appearance of the ARM in NSC KIPT as a research direction in the nuclear spectroscopy is related to works [56, 57] in which, for the first time, one proposed to use a statistical model (SM) for analysis of the experimental data from the proton capture reaction measured under conditions of statistical averaging for nuclei with A>40 and Ep<5 MeV. The success of applying ARM was provided with large γ-yields of the reaction in the case of using half-thick targets. Analyses were conducted in the framework of SM which solved its inherent problems using optical model (OM), fermi-gas and evaporation models. Difficulties of using the statistical model were connected, in main, with the choice of optical potential parameters (being well-known for higher energies) and lack of the data on the radiative strength functions.

The work has been carried out in four stages: developing of the analysis method for γγ-correlations, differential cross sections and angular distributions of γ-rays arising during the decay of the final states, occupied with non-observed cascade γ-transitions; studying the mechanisms of capture reactions; studying the value and energy dependence of RSF in the resonance region of nuclear excitation energy.

The present paper was aimed to the study of the RSF in nuclei of the pf-shell in the excitation energy range of 5-13 MeV. Now, the information on RSF for these energies (corresponding to transitions from the resonance excitation energies region) is insufficient. The method of RSF obtaining that we have proposed earlier is based on data of partial cross sections (PS) of the proton capture reaction. It is a model-dependent one, but it permits to obtain the necessary information, as we use the well-substantiated SM and ARM, in which the realization of conditions for nuclei of the pf-shell is easy to implement.

Creation of the coincidence spectrometer and the pair γ-spectrometer on the base of high-effective sodium and Ge-Li detectors makes it possible to single out the primary γ-transitions from high-excited nuclear states and thereby to solve the tasks to be achieved.

In this latest stage of the work we measured PS of (p,γ) -reactions on nuclei ^{46}Ti, ^{60,62,64,66} Ni, ^{56,58} Fe, ^{68}Zn, ^{71}Ga and ^{72}Ge at proton energies of 1.0-3.2 MeV. The cross-sections are described within the framework of SM with a standard set of OM parameters and level density. Here RSF was considered as unknown “varying” functions.

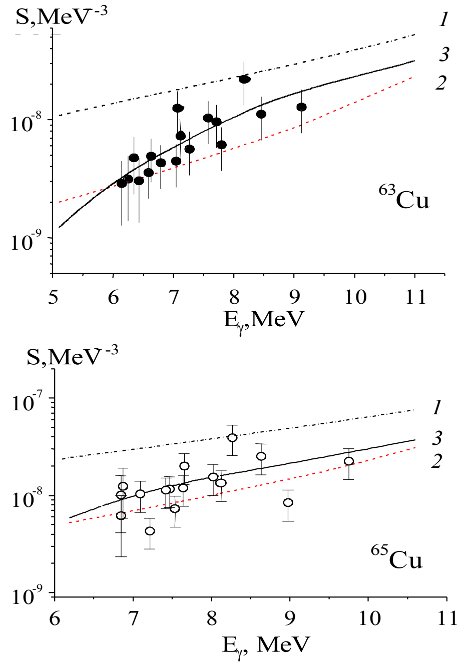


Fig. 5. *Experimental and calculation values of RSF of primary γ-transitions in ^{63,65}Cu:•-RSF the energy E_p=2.84 MeV for ^{63}Cu, o-RSF at E_p=2.30 MeV for ^{65}Cu; Lorenz dependence of RSF (Brink-Axel model- curve 1; statistical approach with taking into account the temperature (Fermi-liquid model)- curve 2; the same with taking into account the shell nuclear structure - curve 3*

As a result of PS analysis we determined the strength functions in nuclei ^{45}Sc, ^{61,62,63,65}Cu, ^{57,59}Co, ^{67,69}Ga, ^{71}Ge, ^{73}As [58-64], Fig. 5. It was shown that defined RSF couldn't be described by the Lorenz curves being parametrized via the photoabsorption reaction cross-sections. RSF analysis was performed in the framework of a phenomenologic approach developed in the articles by Yu. Kadmensky, V. Sirotkin, V. Plujko [65-68]. At present the approach is adopted as a basic method for evaluation of data on strength functions at IAEA. Upon this the mass dependence of RSF can be revealed only by studying a great number of nuclei.

Analysis has shown that RSF can not be considered as S_γ dependent only on the γ-quantum energy, and take the form $S(E_\gamma,T_f)$, where T_f is the temperature of a nucleus in the final state. The RSF relation with properties of nuclei in the final states contradicts to the Brink hypothesis. It leads to its new formulation i.e. the E1-resonance can be constructed on any excited nuclear state with taking into account its excitation energy, and RSF in the region of binding energy will be determined by the spread E1-resonance width with taking into account the temperature of a nucleus in the final state. As a consequence, when γ-quantum energy goes to zero, RSF should go to the nonzero limit unlike the Lorentz dependence.

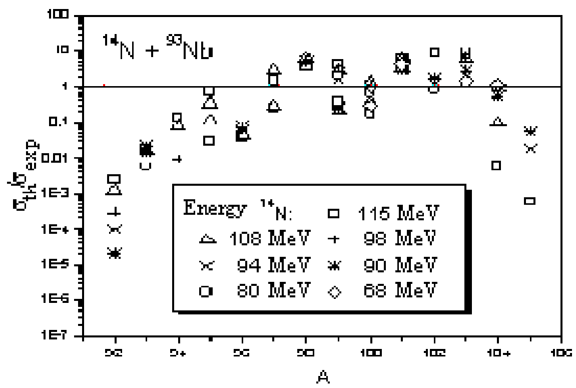
Conclusions on such behaviour of RSF below the E1-resonance are confirmed in the articles by R. Chrien (USA), Yu.P. Popov (Dubna), V.V. Plyujko (Kiev) for ^{144}Nd, ^{157}Gd and others.

Being guided by the theory preconditions we can say that the primary γ-transitions into final states of nuclei are determined by the collective movement mode, i.e. the E1-transitions from the resonance energy region can be considered as giant dipole excitations. And RSF's related with them determine the emission of heated nuclei and depend on the temperature of nuclei in the final states. The factor taking into account the difference between RSF in a cold nucleus and RSF in a heated nucleus is interpreted as a mean number of the 1p-1h excited states in the heated system placed in the external magnetic field.

NUCLEAR RECTIONS WITH HEAVY IONS

The mechanisms of heavy ion-nucleus interactions have been studied by measuring and analysis of excitation functions of the reactions induced by ^{14}N and ^{20}Ne in ^{93}Nb, charge and mass distributions of products and mean recoil ranges. Experiments were performed at the heavy ion linear accelerator of NSC KIPT. Thin metallic niobium foils with thicknesses of (0.5…4.0) mg∗cm^2 were irradiated by 8.5 MeV/A heavy ion beams. The aluminum foils-absorbers were put before the targets for decreasing incident ion energies. Al foil-catcher was placed behind the investigated target in close geometry to collect the recoil nuclei. The foil stack was installed in an insulated Faraday cup into which the ion beam was falling. The induced activities of the irradiated targets were measured by Ge(Li)-detector of 50 cm^3 volume and 3.5 keV resolution for 1332.5 keV γ-line and with the analyzer AM-02Ф1 connected with the computer PC/AT-386. The accumulated γ-spectra was treated by ACTIV-code [69]. Nuclei-products were identified by the energies, relative intensities of followed γ-transitions and half-lives [70]. The activities of Nb-foils and Al-catchers were measured separately for determination of escape fraction of the radioactive nuclei and calculation of the experimental recoil ranges.

a)



b)

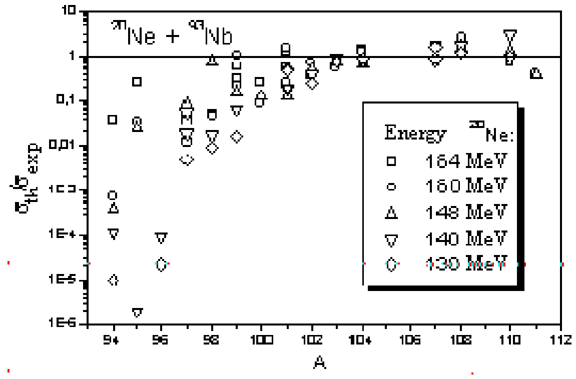


Fig. 6. *Ratio of theoretical cross sections to experimental ones vs residual nuclei mass number in interactions $^{14}N+{}^{93}Nb$ (a) and $^{20}Ne+{}^{93}Nb$ (b) for different energies of incident ions*

The excitation functions of ^{14}N induced reactions resulting in formation of more than 20 final nuclei in the mass number range from the nucleus-target to the compound nucleus (^{107}Cd) were measured at the incident energies (5.0...8.5) Mev/A. Approximately the same quantity of nuclei was observed in the interaction ^{20}Ne+^{93}Nb (compound nucleus ^{113}Sb). The experimental cross-sections of studied reactions are in reasonable agreement with scarce data published at some incident energies by other authors [71,72]. To analyze the experimental excitation functions of heavy ion reactions the theoretical calculations of the cross-sections have been carried out within the framework of statistical model of nuclear reactions using ALICE code [73]. The agreement between the experimental excitation functions of the reactions producing compound-like nuclei (close to ^{107}Cd for the interaction ^{14}N+^{93}Nb and ^{113}Sb for the interaction ^{20}Ne+^{93}Nb) and theoretical ones may be considered as satisfactory. However, as the mass number of a nucleus-product decreases the disagreement increases and reaches a maximum value for the target-like residual nuclei such as ^{96}Tc, ^{95}Tc, ^{94}Tc, ^{93m}Mo, ^{92m}Nb, ^{90}Nb (Fig. 6). It can be caused by a significant contribution of reaction mechanisms differing from the process of formation and subsequent decay of the compound nucleus: quasi-elastic scattering, few-nucleon transfer reactions, reactions of incomplete fusion of the incident ion with the nucleus-target.

Short experimental recoil ranges of ^{96}Tc, ^{95}Tc and ^{94}Tc nuclei (in comparison with the heavier nuclei such as ^{100}Pd, ^{101}Pd, ^{100}Rh, ^{101}Rh et al.) are in agreement with the theoretical values calculated for the process of fusion of α-fragment of incident ^{14}N ion with the target nucleus and formation of the intermediate ^{97*}Tc nucleus which evaporates 1,2 and 3 neutrons respectively.

The residual ^{93m}Mo, excitation cross-section of which exceeds the complete fusion model prediction on 2 orders of magnitude, can be formed in a similar process after emission of a nucleon combination p3n by intermediate ^{97*}Tc. The values of ^{90}Nb and ^{92m}Nb residual recoil ranges more correspond to the process of quasi-elastic scattering. The calculations of incomplete fusion reaction cross sections in the sum rule model [74], we have performed, do not exhaust the high yields of isotopes of technetium, niobium and ^{93m}Mo. Probably more direct processes also give a significant contribution to the production cross-sections of the mentioned above isotopes.

NUCLEON CORRELATIONS IN REACTIONS OF THE A(γ,pn)(A-2) TYPE ON NUCLEI OF THE P-SHELL

Photonuclear reactions serve as one of instruments for investigations of nucleon correlations in nuclei, since the energy and pulse introduced into the nucleus with a photon at the giant resonance can be absorbed only by the correlated nucleon pair.

In the presented paper given are the results of investigations of photo processes on the γ-quantum bremsstrahlung beam before the meson production threshold by the method of a diffusion chamber in the magnetic field.

Due to the high informativity the track method is preferable for study of the multiparticle reactions because it permits to investigate the correlations effects without risk of distortions caused by the choice of the experiment geometry. At present only with this method one can measure by model-independent manner a total cross-section of multiparticle photodisintegration.

The following reactions were studied:

$$\gamma + {}^{12}C \to p + n + {}^{10}B, \quad (12)$$

$$\gamma + {}^{12}C \to p + n + \alpha + {}^{6}Li, \quad (13)$$

$$\gamma + {}^{14}N \to\to p + n + {}^{12}C, \quad (14)$$

$$\gamma + {}^{16}O \to p + n + {}^{14}N. \quad (15)$$

Reactions (12), (14), (15) were chosen to clear up the A-dependence of nuclear reactions. Reaction (13) was considered as a probabilistic process with the escape of one nucleon from the s-shell. The energy of γ-quantum was determined basing on the conservation law and in the supposition that the final nuclei are formed in a ground state. The details of the method of reaction distinguishing and obtaining the kinematic particle parameters were described earlier [75-78].

TOTAL CROSS-SECTION

The dependence of total reaction cross-sections on the γ-quanta energy was measured. The integral cross-section of the reaction ^{12}C(γ,pn)^{10}B is equal to 25±0.8 MeV mb that does not contradict to data by other authors [79].

The maximum of the cross-section of the reaction ^{12}C(γ,pn)α^{6}Li seems to be less distinctive and at higher energies too than the cross section of reaction (12). The integral cross-section equals to 11,8±0.8 MeV mb. The agreement between the cross-section of ^{14}N(γ,pn)^{12}C reaction and the measurement results by Komar [80] is observed. The integral cross-section of the reaction ^{16}O(γ,pn)^{14}N equals to 152.1±2.7 MeV·mb. The results of calculations on cross-section of reaction (15), in the supposition that the main contribution into the matrix element is obtained from exchange meson currents [81], describes satisfactorily the energy dependence of the total cross-section. The calculation [82] performed with taking into account the nucleon exchange by one or several mesons displays satisfactorily the energy dependence of a total cross-sections with a correlation parameter β=0.8 fm^{-1}. Beginning from 40 MeV the cross-sections of reactions (12-15) have a similar energy behavior that confirms the model of γ-absorption by the correlated nucleon pair.

THE REGION OF THE QUASI-DEUTRON MODEL APPLICATION

The track method is effective for investigation of the following angular and energy correlation effects being characteristic for the quasi-deuteron model. Nucleons escape from the nucleus almost in opposite sides that follows from the differential cross-sections depending on the angle of nucleon flying away. Nucleon pairs take away the most part of energy. The part of kinetic energy being taken away by the pn-pair appreciably differs from the statistical one. The residual nucleus is a spectator, therefore the angular distributions of residual nuclei at energies higher than 50 MeV for different nuclei are equal and practically isotropic.

In a wide energy range the reaction cross-sections are proportional to the cross-section of deuteron photodisintegration. The proportionality has taking place at energies higher than 40 MeV. So, the traditional Levinger model describes behavior of the cross-section at energies above the region of the giant resonance.

At energies behind the giant resonance the angular distributions of protons and neutrons in the system of inertion center are symmetrical relatively to 90^{O}. The maxima of both distributions are displaced into the front half-sphere. The forms of angular distributions of protons and neutrons are coinciding that was observed in other reactions too.

PULSE DISTRIBUTION OF NUCLEON PAIRS

The pulse of pn-pair in the quasi-deuteron model and in the absence of interaction in the final state (IFS) should not be dependent on the photon energy since it is the intranuclear characteristic [83]. In Fig. 7 shown are the results of the presented experiment. The experimental data obtained for reaction (15) are in agreement with the results of [84].

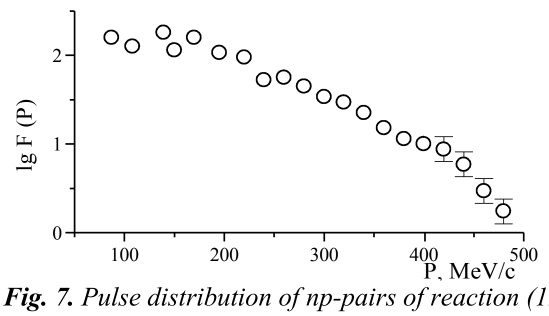


Fig. 7. *Pulse distribution of np-pairs of reaction (12)*

The experiment has demonstrated that the position of the maximum of pulse pn-pairs distribution and distribution width are in a strong dependence on the γ-quantum energy. This effect evidences on a significant IFS influence on the form of pulse distribution curve in the range of energies close to the giant resonance.

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