Romanian Reports in Physics, Vol. 63, No. 2, P. 357–375, 2011

ASYMMETRY EFFECTS IN (n,p) REACTIONS ON ^{35}Cl AND ^{14}N NUCLEI*

A.I., OPREA[1], C. OPREA[1], YU.M. GLEDENOV[1], P.V. SEDYSHEV[1], C. PIRVUTOIU[2], D. VLADOIU[2]

[1] Frank Laboratory for Neutron Physics, Joint Institute for Nuclear Research (FLNP-JINR), 141980 Dubna, Russian Federation
[2] Faculty of Physics, Bucharest University, Romania

Received January 20, 2010

Abstract. The asymmetry effects in (n,p) reactions on ^{35}Cl and ^{14}N nuclei using the model of the mixing states of the compound nucleus with the same spin and opposites parities were obtained. Firstly the two levels approximation for both reaction was used and later an evaluation of the influence of the other resonance was done. The studied asymmetry effects are the forward - backward, left - right and parity non-conservation. The theoretical results are compared with experimental data obtained at the basic facilities of the Frank Laboratory for Neutron Physics using a double grid ionization chamber.

Key words: angular correlations, asymmetry effects, parity violation.

1. INTRODUCTION

The asymmetry effects are an efficient tool for investigation of various phenomena in atomic and nuclear physics. In this paper we have obtained the asymmetry effects in the ^{35}Cl(n,p)^{35}S and ^{14}N(n,p)^{14}C reactions with thermal and resonance neutrons. The investigated effects are the forward – backward, left – right and parity non conservation. Each mentioned effect mathematically can be described by corresponding asymmetry coefficient and respectively they are the forward – backward, left – right and parity non conservation coefficients. For the incident neutron energy interval (up to some keV for ^{35}Cl(n,p)^{35}S reaction and to 1 MeV for ^{14}N(n,p)^{14}C reaction) it is supposed that the (n,p) reaction is going by formation of a compound nucleus and this compound nucleus is described by defined quantum numbers and properties like spin, parity resonance energies, mass and others. An important step in the evaluation of the asymmetry effects is to

* Paper presented at the Annual Scientific Session of Faculty of Physics, University of Bucharest, June 5, 2009, Bucharest – Măgurele, Romania.

obtain the differential cross section or the angular correlation. The cross section, differential cross section (or the angular correlation) and the asymmetry coefficients are obtained using the formalism of the mixing of the states of the compound nucleus with the same spin and opposite parities. With the help of asymmetry coefficients it is possible in principle to extract the matrix element of the weak non leptonic interaction manifested between nucleons and this will be very well illustrated in the present paper in the case of ^{35}Cl(n,p)^{35}S reaction in the two levels approximation.

2. ELEMENTS OF THE FORMALISM OF THE MIXING STATES OF THE COMPOUND NUCLEUS WITH THE SAME SPIN AND OPPOSITE PARITIES

For the evaluation of the asymmetry effects in the (n,p) reactions will be used the formalism of the mixing states of the compound nucleus with the same spin and opposite parities. This formalism was developed for fission and (n,γ) reactions with thermal and resonance neutrons for medium heavy nuclei. The main purpose of this approach is to describe the parity violation (PV) effects existing in the nuclear reactions due to the weak non leptonic interaction between nucleons [1, 2, 3]. The PV effects between nucleons are very low in intensity and are of order of 10^{-7} in comparison of nuclear interaction between the same nucleons. This weak interaction acts in the background of the strong nuclear interaction and for this reason is very difficult to separate them in the experiment. Qualitatively the PV effects in the nuclear reaction can be explained by the complex nature of the nuclear potential. It is supposed that the nuclear potential has a part responsible to PV phenomena much lower than the phenomena corresponding to the strong nuclear interaction. A very attractive and comprehensive presentation about the weak interaction between nucleons, the nature and the form of the potentials describing this interaction can be found on [4].

Experimental proof of the PV effects in nuclear reactions was evidenced first by Abov and co – workers in the early 1964 at the Laboratory for Neutron Physics of Joint Institute for Nuclear Research – Dubna, Russia (former USSR). In the ^{113}Cd(n,γ)^{114}Cd reaction it was observed an asymmetry of the emitted gamma quanta in the capture of the polarized transversal thermal neutrons and they explained this effect by the existence of the weak non leptonic interaction between nucleons acting in the compound nucleus formed in the reaction [5]. The Abov experiment gave a great impulse in theoretical and experimental researches of the PV phenomena in nuclear reactions. After, were investigated not only (n,γ) reactions for other nuclei but were searched PV effects on other types of reaction like (n,n), (n,p), (n,α), for various nuclei starting with heaviest and ending with lighter. An excellent review of the experimental results on PV searching in nuclear reactions can be found in [6].

Based on the hypothesis of the universality of the weak interaction emitted by Feynmann and Gell Mann [7] were developed many theoretical approaches for the explanation of the experimental results of the PV effects. One of the developed approaches is the mixing states of the compound nucleus with the same spin and opposites parities, applicable formalism to the nuclear reactions induced by thermal and resonance neutrons. In this approach it is supposed that the nuclear reaction is going by formation of a compound nucleus. The compound nucleus can be described by some states (resonance) and is characterized by definite quantum numbers like spin, parities, mass, resonance energies, time of life and other properties. An important condition to have asymmetry effects is the existence of the states of the compound nucleus with the same spin and opposite parities. Also the presence of the compound nucleus assures the amplification of the asymmetry effects at least by one of three main mechanisms. These mechanisms are: cinematic, dynamic and structural [1, 2, 3]. For the description of the reaction induced by neutrons are proposed some amplitudes of reactions (including the amplitudes describing PV effects) supposing that the resonance of the compound nucleus are well separated. We will not write the amplitudes for (n,γ) because there are already written in [1, 2, 3]. With minor changes these amplitudes can be applied for (n,p) reactions.

2.1. THE AMPLITUDES OF THE (n,p) REACTION

We start now with the study of the (n,p) reaction with formation of compound nucleus described by two states, an *S* state with positive spatial parity and a *P* state with negative spatial parity. For the sake of simplicity and for evidencing of the one of the main idea of the paper (extraction of the weak matrix element from experimental asymmetry coefficients) in the beginning we neglect the influence of other resonance and use the so called two level approximation very well fulfilled for the $^{35}Cl(n,p)^{35}S$ reaction up 1 keV neutron incident energy. First time, the amplitudes for the (n,p) reaction with thermal and resonance neutrons and emitted proton, both with orbital momentum equal to 0 or 1, were written in [8].

$$f_1 = -\frac{1}{2k} C(I, I_z, a, a_n; J_S, J_{Sz}) C(I', I'_z, a, a_p; J_S, J_{Sz}) \cdot \\ \cdot \frac{T_S^n T_S^{p*}}{(E - E_S) + \mathrm{i}\frac{\Gamma_S}{2}} \mathrm{Exp}(-\mathrm{i}\varphi_0). \tag{1}$$

The amplitude from (1) describes the capture of the neutron with orbital momentum l_n=0 by the target nucleus followed by formation of the compound nucleus with positive parity or *S* state of the compound nucleus (the Breit – Wigner term) and emission of a proton with orbital momentum l_p=0. It is easy to see that this amplitude conserves the spatial parity.

As is already had been underlined, for the existence of asymmetry effects it is necessary the presence of the resonance of the compound nucleus with negative parity (P state of the compound nucleus). In this case we have the amplitude:

$$f_2 = -\frac{2\pi}{k} \sum_{\substack{j_n, j_{nz}, \nu_n \\ j_p, j_{pz}, \nu_p}} C(I, I_z, j_n, j_{nz}; J_P, J_{Pz}) C(1, \nu_n, \frac{1}{2}, a_n; j_n, j_{nz}) \cdot$$

$$\cdot C(I', I'_z, j_p, j_{pz}; J_P, J_{Pz}) C(1, \nu_p, \frac{1}{2}, a_p; j_p, j_{pz}) \frac{T_P^n(j_n) T_P^{p*}(j_p)}{(E - E_P) + \mathrm{i}\frac{\Gamma_P}{2}} \cdot \tag{2}$$

$$\cdot Y^*_{1\nu_n}(\vec{n}_n) Y_{1\nu_p}(\vec{n}_p) \mathrm{Exp}(-\mathrm{i}\varphi_1).$$

The relation (2) shows us the capture of a neutron with l_n=1 by the target nucleus with the formation of a compound nucleus in a P state followed by the emission of a proton with the same orbital momentum, l_p=1, as the incident neutron. This amplitude, like f_1, conserves also the spatial parity

$$f_3 = -\frac{\sqrt{\pi}}{k} W_{SP} \sum_{j_p, j_{pz}, \nu_p} C(I, I_z, \frac{1}{2}, a_n; J_S, J_{Sz}) C(I', I'_z, j_p, j_{pz}; J_P, J_{Pz})$$

$$C(1, \nu_p, \frac{1}{2}, a_p; j_p, j_{pz}) \frac{T_S^n T_P^{p*}(j_p)}{(E - E_P + \mathrm{i}\frac{\Gamma_P}{2})(E - E_S + \mathrm{i}\frac{\Gamma_S}{2})} Y_{1\nu_p}(\vec{n}_p) \mathrm{Exp}(-\mathrm{i}\varphi_1). \tag{3}$$

This amplitude includes the PV effect (see the weak matrix element W_{SP}). The target nucleus captures the incident neutron with orbital momentum l_n=0 and the compound nucleus in an S state is formed. In the compound nucleus due to the weak interaction between nucleons the compound nucleus changes the parity and passes in the P state. After, the compound nucleus in P state emitts a proton with orbital momentum l_p=1.

$$f_4 = -\frac{\sqrt{\pi}}{k} W_{SP} \sum_{j_n, j_{nz}, \nu_n} C(I', I'_z, \frac{1}{2}, a_p; J_S, J_{Sz}) C(I, I_z, j_n, j_{nz}; J_P, J_{Pz}) \cdot$$

$$\cdot C(1, \nu_n, \frac{1}{2}, a_n; j_n, j_{nz}) \frac{T_S^{p*} T_P^n(j_n)}{(E - E_P + i\frac{\Gamma_P}{2})(E - E_S + i\frac{\Gamma_S}{2})} Y^*_{1\nu_n}(\vec{n}_n) \mathrm{Exp}(-\mathrm{i}\varphi_0). \tag{4}$$

This amplitude also violates the spatial parity. The incident neutron with l_n=1 interacts with the target nucleus with formation of the compound nucleus in a P state. Under the influence of the weak interaction between nucleons the compound nucleus changes his parity and is passing in a S state emitting after a proton with orbital momentum l_p=0.

In the references [1, 2, 3] can be found the amplitudes of (n,γ) reaction for the cases when the incident neutrons and outgoing protons have orbital momentum higher than *1* but due to the fact that in mentioned reaction will be involved only neutrons and protons with orbital momentum $l_{n,p}$=0,1 we limit the amplitudes only to these cases. These four amplitudes describe the (n,p) reaction if the resonance of the compound nucleus are distinct and this can be write as [3]:

$$\begin{aligned} &kR << 1 \\ &\left|E_S - E_P\right| >> \Gamma. \end{aligned} \tag{5}$$

In the formulas (1), (2), (3), (4), (5) were used the following notations:

C( )= the Clebsch-Gordan coefficients

$I, I', I_z, I'_z =$ spin and his projection of the target and residual nucleus

$J_S, J_P, J_{Sz}, J_{Pz} =$ spin and his projection of the compound nucleus in the *S* and *P* states

$E_S, E_P =$ energies of the *S* and *P* resonance states of the compound nucleus

$\Gamma_S, \Gamma_P =$ total widths of the *S* and *P* states of the compound nucleus

$j_n, j_p =$ total orbital momentum of the neutron and proton

$\vec{j} = \vec{l} + \vec{s}$, *l, s* = orbital momentum and spin of the neutron and protons

$\nu_n, \nu_p =$ the projection of the orbital momentum of the neutron and proton

$a_n, a_p =$ the spin projection of the neutron and proton

Y= spherical function

$\varphi_0, \varphi_1 =$ phases corresponding to the orbital momentum *l*=0,1

$$\begin{matrix} T_S^n = \eta_S^n \sqrt{\Gamma_S^n} = \mathrm{Exp}(i\xi_S^n)\sqrt{\Gamma_S^n}, T_S^p = \eta_S^p \sqrt{\Gamma_S^p} = \mathrm{Exp}(i\xi_S^p)\sqrt{\Gamma_S^p} \\ T_P^n = \eta_P^n \sqrt{\Gamma_P^n} = \mathrm{Exp}(i\xi_P^n)\sqrt{\Gamma_P^n}, T_P^p = \eta_P^p \sqrt{\Gamma_P^p} = \mathrm{Exp}(i\xi_P^p)\sqrt{\Gamma_P^p} \end{matrix} =$$ reduced amplitudes corresponding to the *S* and *P* states of the compound nucleus

$\Gamma_S^n, \Gamma_S^p, \Gamma_P^n, \Gamma_P^p =$ neutrons and protons widths corresponding to the *S* and *P* states of the compound nucleus

$\xi_S^n, \xi_P^n, \xi_S^p, \xi_P^p =$ neutrons and protons phases corresponding to the *S* and *P* states of the compound nucleus

$W_{SP} = i < S | H_W | P >=$ weak matrix element

$H_W =$ Hamiltonian of the weak interaction

k = neutron reduced wave number, *R* = channel radius.

2.2. ANGULAR CORRELATIONS AND ASYMMETRY COEFFICIENTS. GENERAL FORMULAS

Using the amplitudes of (n,p) reactions defined in the precedent paragraph we write the total amplitude for investigated case:

$$f = f_1 + f_2 + f_3 + f_4. \tag{6}$$

The angular correlation $W(\Omega)$ and differential cross section are:

$$W(\Omega) \sim \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = |f|^2 = |f_1 + f_2 + f_3 + f_4|^2 \tag{7}$$

In the simple case of the incident un polarized neutrons the contribution of the PV terms (f_3 and f_4) are zero and we have for the cross section and angular correlation the following expressions:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = |f_1|^2 + |f_2|^2 + 2\,\mathrm{Re}\, f_1 f_2^*, \tag{8}$$

$$W(\theta) = 1 + \alpha(\vec{n}_n \cdot \vec{n}_p) + \beta(\vec{n}_n \cdot \vec{n}_p)^2 = 1 + \alpha\cos\theta + \beta\cos^2\theta, \tag{9}$$

where $n_{n,p}$ = the unitary vector of the neutron respective proton, θ = the polar angle between the unitary vectors.

Now we can define the forward-backward (FB) coefficient as:

$$\alpha_{FB} = \frac{W(\theta=0) - W(\theta=\pi)}{W(\theta=0) + W(\theta=\pi)}. \tag{10}$$

Using (7) and (8) the FB coefficient is:

$$\alpha_{FB} = \left.\frac{2\,\mathrm{Re}\, f_1 f_2^*}{|f_1|^2 + |f_2|^2}\right|_{\theta=0}. \tag{11}$$

From relation (11) the FB effect can be interpreted as the result of the interference of the amplitudes f_1 and f_2 conserving the spatial parity. For every reaction it is necessary to see the value of the β coefficient because it will influence the value of the FB and other effects. In the studied (n,p) reaction on ^{35}Cl β can be neglected up to 1 keV but it is necessary also to take him into account in the case of the contribution of a few resonance. For the second (n,p) reaction on ^{14}N the β coefficient is zero. This coefficient is important in the experimental measurement of the differential cross section, especially in the resonance where usually the asymmetry effects are zero.

In the case of transversal polarized neutrons it is possible to evidence another asymmetry effect and this will be the left-right (LR) effect. After not so complicated calculations differential cross section and the angular correlation have the form:

$$\frac{d\sigma}{d\Omega} = |f_1|^2 + |f_2|^2 + 2\,\mathrm{Re}\, f_1 f_2^* + 2\,\mathrm{Im}\, f_1 f_2^*, \tag{12}$$

$$\begin{aligned} W(\Omega) &= 1 + \alpha\cos\theta + \beta\cos^2\theta + \alpha'_{LR}\sin\theta\sin\phi = \\ &= 1 + \alpha\, \vec{n}_n \cdot \vec{n}_p + \beta(\vec{n}_n \cdot \vec{n}_p)^2 + \alpha'_{LR}\, \vec{\sigma}\cdot(\vec{n}_n \times \vec{n}_p). \end{aligned} \tag{13}$$

In the expression (12) and (13) the both effects give their contribution. If we want to evaluate only one of the effect, for example the LR, as is suggested in [1, 2, 3, 8] it is possible in experiment to choose a setup where the FB effect will be zero. In this case the expressions (12) and (13) will take a simpler form.

$$\frac{d\sigma}{d\Omega} = |f_1|^2 + |f_2|^2 + 2\,\mathrm{Im}\, f_1 f_2^* \tag{14}$$

$$W(\Omega) = 1 + \alpha_{LR}\sin\theta\sin\phi = 1 + \alpha_{LR}\, \vec{\sigma}\cdot(\vec{n}_n \times \vec{n}_p)\,. \tag{15}$$

If the incident neutrons are polarized the amplitudes f_3 and f_4, responsible for PV effects are neglected because $f_3, f_4 << f_1, f_2$ [8]. Now the relation of definition of the LR coefficient is:

$$\alpha_{LR} = \frac{W\left(\theta = \frac{\pi}{2}, \phi = \frac{3\pi}{2}\right) - W\left(\theta = \frac{\pi}{2}, \phi = \frac{\pi}{2}\right)}{W\left(\theta = \frac{\pi}{2}, \phi = \frac{3\pi}{2}\right) + W\left(\theta = \frac{\pi}{2}, \phi = \frac{\pi}{2}\right)}, \tag{16}$$

where: $\phi =$ the azimuth angle, $\times =$ the vector product, $\sigma =$ the spin vector of incident neutron.

Expressions (14), (15) and the definition relation of the LR effect, after some simple transformation give us a new formula for the LR coefficient:

$$\alpha_{LR} = \left.\frac{2\,\mathrm{Im}\, f_1 f_2^*}{|f_1|^2 + |f_2|^2}\right|_{\theta=\frac{\pi}{2},\phi=\frac{\pi}{2}}. \tag{17}$$

The LR effect, like the FB effect, is a result of the interference of the f_1 and f_2 amplitudes conserving the spatial parity. Until now we neglected the contribution to the differential cross section or to the angular correlation of the PV amplitudes. Applying the same procedure like for the FB and LR effects we write the cross section and the angular correlation with the contribution of the PV amplitudes f_3 and f_4.

$$\frac{d\sigma}{d\Omega} = |f_1|^2 + |f_2|^2 + |f_3|^2 + |f_4|^2 + 2\,\mathrm{Re}\, f_1 f_3^* + 2\,\mathrm{Re}\, f_2 f_4^*, \tag{18}$$

$$W(\Omega) = 1 + \alpha_{PNC} \sin\theta \cos\phi = 1 + \alpha_{PNC} \vec{\sigma} \cdot \vec{n}_p \,. \tag{19}$$

For the expressions (18) and (19) it supposed that the experimental setup is chosen in such a way that the other effects, FB and LR, are zero.

Now we introduce the definition of the parity non conservation (PNC) coefficient:

$$\alpha_{PNC} = \frac{W(\theta = \frac{\pi}{2}, \phi = 0) - W(\theta = \frac{\pi}{2}, \phi = \pi)}{W(\theta = \frac{\pi}{2}, \phi = 0) + W(\theta = \frac{\pi}{2}, \phi = \pi)} \,. \tag{20}$$

Using (18), (19) in the definition relation for PNC effect we obtain:

$$\alpha_{PNC} = \left. \frac{2 \operatorname{Re} f_1 f_3^* + 2 \operatorname{Re} f_2 f_4^*}{|f_1|^2 + |f_2|^2 + |f_3|^2 + |f_4|^2} \right|_{\theta = \frac{\pi}{2}, \phi = 0} \,. \tag{21}$$

From (21) the PNC effect can be interpreted like the result of the interference of f_1, f_3 and f_2 and f_4 amplitude. It is obvious that for every reaction is necessary to evaluate the contribution of each pair of amplitude. The weak matrix element is of order of 10^{-2} eV or lower and in many evaluation the contribution of the amplitudes f_3, f_4 is neglected in the denominator of relation (21) because the square modules of these amplitude have a very small value in comparison with others terms of the mentioned expression.

Asymmetry effects and the corresponding asymmetry coefficients are more than these presented in this work [9, 10]. We limit our presentation to FB, LR and PNC effects due to the fact that other asymmetry effects are lower than these three mentioned in the (n,p) reaction investigated and because our experimental setup does not allow us to evidence other effects. The FB and LR effects, like result of the interference between amplitudes conserving the spatial parity, can reach 30–40% or higher, but PNC effects usually is of order of 10^{-3}–10^{-4}, in rare case being of order of 10^{-2} and in some exceptional cases 10^{-1} [11].

3. THE ^{35}Cl(n,p)^{35}S REACTION. THE TWO LEVELS APPROXIMATION

After the discovering of the PV effects in (n,γ) reaction on heavy nuclei were investigated other nuclei and reactions. Due to their simplicity were searched PV effects on light nuclei in (n,p), (n,α), (n,t) (t = tritium) reactions. Therefore were effectuated measurements on light nuclei like ^{3}He, ^{6}Li, ^{10}B to find new proofs of the existence of PV effects [12]. The upper limit of the PV effects on these nuclei was less than 10^{-4} with 90% of confidence. The obtained results, in the frame of the model of the mixing states of the compound nucleus with the same spin and opposite parities, easy can be explained. If we work with light nuclei first it is necessary to find at least two levels with the same spin and opposite parities. Even these levels exist, they are to far one from other to fulfill the condition of cinematic amplification. The experience shows that in the case of light nuclei the amplification mechanisms are not working. One of the first nuclei suitable for searching PV effects, not only in (n,p) reaction, is ^{35}Cl nucleus. This nucleus is very cheap and is easy to realize targets of ^{35}Cl for experiments because often is used NaCl. The ^{35}Cl nucleus has distinct and well separated resonance on a wide neutron energy interval. Average distance between energy levels is of order of 10 keV but for thermal neutrons there are two close levels (levels 1, 2 from Table 1) with the same spin and opposite parities. The next level (level 3 from Table 1) is higher than 4 keV and for this reason the two levels approximation is available for neutrons incident energy up to 1 keV. The ^{35}Cl nucleus has a very good ratio between proton widths in *S* and *P* states and this will lead to the amplification of the asymmetry effects [13]

$$\sqrt{\Gamma_S^p \cdot \left(\Gamma_P^p\right)^{-1}} \cong 5.4 . \tag{22}$$

In the ^{35}Cl(n,γ) reaction was observed an asymmetry due to circular polarization of the emitted gamma quanta in the integral spectra at the capture of un polarized incident thermal neutrons [14]. The asymmetry was interpreted as a result of PV phenomena and the weak matrix element between the first two states from Table 1 extracted from this reaction is about 10 times higher than the evaluation from [15]. For this reason a comparison with the weak matrix element extracted from the ^{35}Cl(n,p)^{35}S reaction between the same states would be of great interest.

Table 1

Resonance energy for ^{36}Cl compound nucleus

№	Resonance energy (eV)	Spin and parity
1	$E_{S1} = -180$	$J_{S1}^{\Pi} = 2^{+}$
2	$E_{P1} = 398$	$J_{P1}^{\Pi} = 2^{-}$
3	$E_{P2} = 4249$	$J_{P2}^{\Pi} = 1^{-}$
4	$E_{P3} = 5496$	$J_{P3}^{\Pi} = 1^{-}$
5	$E_{S2} = 14802$	$J_{S2}^{\Pi} = 2^{+}$

The presence of the all three amplification mechanisms of the asymmetry effects and the value of the weak matrix element indicates the ^{35}Cl nucleus suitable for PV effects searching.

3.1. ASYMMETRY COEFFICIENTS IN THE TWO LEVELS APPROXIMATION

In this paragraph will be calculated the asymmetry coefficients in the two levels approximation and they are: the FB, LR and PNC coefficients. In the evaluation will use the first two level from Table 1. These levels have the same spin with the value 2, with energies E_S = –180 eV and E_P = 398 eV respectively and opposite parities. Also will be used the general formulas (8) – (21) from the part 2 of the present paper. The neutron resonance parameters, averaged proton, alpha and gamma widths are taken from [16, 17].

After some long but not difficult calculation the FB coefficient has the form:

$$\alpha_{FB} = \pm \frac{\sqrt{\Gamma_S^n \Gamma_S^p \Gamma_P^n \Gamma_P^p}}{\Gamma_S^n \Gamma_S^p [P] + \Gamma_P^n \Gamma_P^p [S]} u_{FB}(E)(X_n - Y_n)(X_p - Y_p), \tag{23}$$

where the terms included in (23) are:

$$[S] = (E - E_S)^2 + \frac{\Gamma_S^2}{4}, \quad [P] = (E - E_P)^2 + \frac{\Gamma_P^2}{4},$$

$$u_{FB}(E) = \left[(E - E_S)(E - E_P) + \frac{\Gamma_S \Gamma_P}{4} \right] \cos(\Delta\varphi) - \\ - \left[(E - E_S)\frac{\Gamma_P}{2} - (E - E_P)\frac{\Gamma_S}{2} \right] \sin(\Delta\varphi).$$

$$X_n = \frac{T_P^n\left(j_n = \frac{1}{2}\right)}{\sqrt{\Gamma_P^n}}, \quad Y_n = \frac{T_P^n\left(j_n = \frac{3}{2}\right)}{\sqrt{\Gamma_P^n}} \text{ – reduced neutron widths,}$$

$$X_p = \frac{T_P^p(j_p = \frac{1}{2})}{\sqrt{\Gamma_P^p}}, \quad Y_p = \frac{T_P^p(j_p = \frac{3}{2})}{\sqrt{\Gamma_P^p}} \text{ – reduced proton widths.}$$

Reduced widths have the property: $X_n^2 + Y_n^2 = 1$, $X_p^2 + Y_p^2 = 1$,

$\Delta\varphi = \Delta\varphi_{neutron} + \Delta\varphi_{coul}$ – neutron and Coulomb phases,

$$\Delta\varphi_{neutron} = kR, \quad \Delta\varphi_{coul} = \frac{ZZ'e^2}{\frac{h}{2\pi} v_p},$$

where: Z, Z' = charge of the emitted particle (Z = 1 for proton in our case) and of the residual nucleus, e = the elementary charge, h= Planck constant, v_p= proton velocity. The reduced neutron and proton widths are unknown parameters and they can be obtained from experiment or by a theoretical model of interaction in the compound nucleus.

Following the same procedure the LR coefficient has the form:

$$\alpha_{LR} = \pm \frac{\sqrt{\Gamma_S^n \Gamma_S^p \Gamma_P^n \Gamma_P^p}}{\Gamma_S^n \Gamma_S^p [P] + \Gamma_P^n \Gamma_P^p [S]} u_{LR}(E) \left(X_n + \frac{Y_n}{2} \right) \left(X_p - Y_p \right) \tag{24}$$

$$u_{LR}(E) = \left[(E - E_S)(E - E_P) + \frac{\Gamma_S \Gamma_P}{4} \right] \sin(\Delta\varphi) - \left[(E - E_S)\frac{\Gamma_P}{2} - (E - E_P)\frac{\Gamma_S}{2} \right] \cos(\Delta\varphi)$$

The PNC coefficient is:

$$\alpha_{PNC} = \pm W_{SP} \frac{\sqrt{\Gamma_S^n \Gamma_S^p \Gamma_P^n \Gamma_P^p}}{\Gamma_S^n \Gamma_S^p [P] + \Gamma_P^n \Gamma_P^p [S]} \left(\frac{u_1(E)}{4} \sqrt{\frac{\Gamma_S^n}{\Gamma_P^n}} - Y_n^2 \frac{u_2(E)}{4\sqrt{2}} \sqrt{\frac{\Gamma_P^n}{\Gamma_S^n}} \right) \left(X_p - Y_p \right), \tag{25}$$

where the functions u_1 and u_2 are:

$$u_1(E) = (E - E_S)\cos(\Delta\varphi) - \frac{\Gamma_S}{2}\sin(\Delta\varphi), \; u_2(E) = (E - E_P)\cos(\Delta\varphi) - \frac{\Gamma_P}{2}\sin(\Delta\varphi).$$

The ± sign before the asymmetry coefficients appears due to the X, Y unknown parameters because they can have value between –1 and +1.

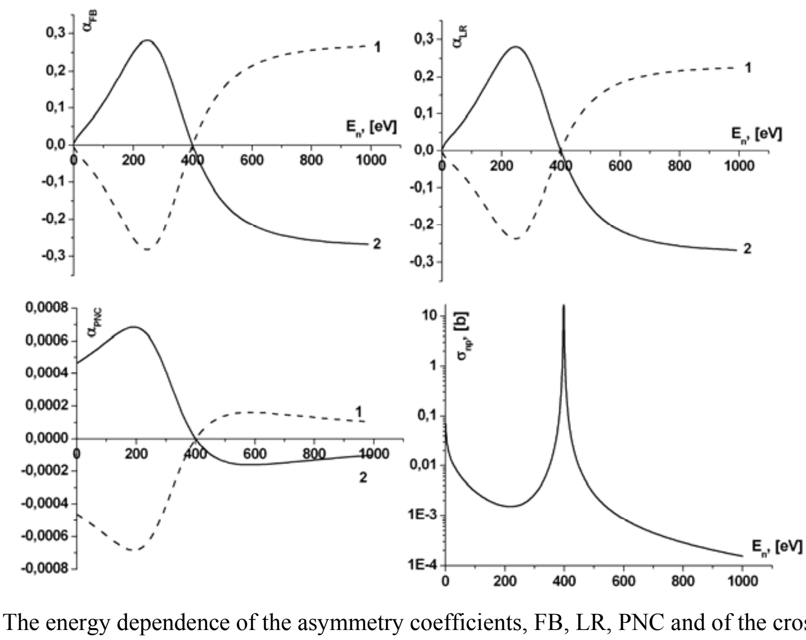

Fig. 1 – The energy dependence of the asymmetry coefficients, FB, LR, PNC and of the cross section, in the two levels approximation: 1 – ($X_n = X_p = -Y_n = -Y_p = 0.707$); 2 – ($X_n = X_p = -Y_n = -Y_p = -0.707$); $W_{SP} = 0.06$ eV.

In Fig. 1 are represented the theoretical evaluations of the asymmetry coefficients in accordance with relations (23), (24), (25). There are a small number of published experimental measured effects. One of the most important causes of the small number of experimental points is the low value of the (n,p) reaction cross section, especially for the neutron energy where the effects have high values. In the case of the ^{35}Cl(n,p) from Fig. 1 we see that the effects have maximum values in the interval 200–300 eV. In this energy interval the cross section is of order of mb or lower [18]. In 1988 at the reactor from Institute for Nuclear Researches, Leningrad USSR were measured the LR and PNC effects for thermal polarized neutrons and the values are: $\alpha_{LR} = -(2.4 \pm 0.43) \cdot 10^{-4}$, $\alpha_{PNC} = -(1.51 \pm 0.34) \cdot 10^{-4}$ [19]. In 1998 at the IBR30 reactor from FLNP – JINR Dubna was measured the FB effects with un polarized neutrons with energy about 260 eV, $\alpha_{FB} = (23 \pm 2.3) \cdot 10^{-2}$ [18]. Experimental values are in good agreement with theoretical evaluation.

3.2. THE WEAK MATRIX ELEMENT

The weak matrix element, W_{SP} appears in the f_3, f_4 amplitudes and has a very small value. In principal, in the cross section and differential cross section, if the incident neutrons are polarized, will have terms proportional with the square of the weak matrix element. Experimentally to evidence such terms and further, to extract the matrix element is a quite difficult task. For this reason we use asymmetry coefficients because the PNC effect is proportional to the weak matrix element. Another way to extract the weak matrix element could be a theoretical one but the used our approach does not allow us such a way. The formalism of the mixing states of the compound nucleus with the same spin and opposite parities does not describes the phenomena from the compound nucleus. The weak matrix element can be extracted from experimental FB, LR and PNC effects [11]. We write now the effects in a compacted form. The LR, and PNC coefficients are considered in thermal point where $\Gamma_S^n >> \Gamma_P^n$ and the u_2 function in PNC effect can be neglected. Will be used experimental value indicated above, in the thermal point, $E_n^{th} = 0.0253$ eV, for LR and PNC, and $E_b^{\max} = 260$ eV for FB effect.

$$\begin{aligned}
&\alpha_{FB}^{\max} = (X_n - Y_n)(X_p - Y_p) f_{FB}(E_n^{\max}), \\
&\alpha_{LR}^{th} = (X_n + \frac{Y_n}{2})(X_p - Y_p) f_{LR}(E_n^{th}), \\
&\alpha_{PNC}^{th} = W_{SP}(X_p - Y_p) f_{PNC}(E_n^{th}), \\
&X_n^2 + Y_n^2 = 1, \quad X_p^2 + Y_p^2 = 1.
\end{aligned} \tag{26}$$

From this system of five equations the weak matrix element is:

$$W_{SP} = \frac{3\dfrac{\alpha_{PNC}^{thx}(E_{th})}{f_{PNC}(E_{th})}\left(\dfrac{\alpha_{LR}^{th}(E_{th})}{f_{LR}(E_{th})}\right)^{-1}}{\sqrt{8-4\dfrac{\alpha_{FB}^{\max}(E_{\max})}{f_{FB}(E_{\max})}\left(\dfrac{\alpha_{LR}^{th}(E_{th})}{f_{LR}(E_{th})}\right)^{-1}+5\left(\dfrac{\alpha_{FB}^{\max}(E_{\max})}{f_{FB}(E_{\max})}\left(\dfrac{\alpha_{LR}^{th}(E_{th})}{f_{LR}(E_{th})}\right)^{-1}\right)^{2}}}. \quad (27)$$

The weak matrix element extracted from experimental values of FB, LR, PNC effects using formula (27) is $W_{SP} = (0.057 \pm 0.0012)$ [19] in agreement with theoretical evaluation from [15].

4. CASE OF ^{14}N(n,p)^{14}C REACTION

The ^{14}N nucleus was chosen because, like the ^{35}Cl is easy to find him, cheap for target preparation and ^{15}N has also two levels with the same spin and opposite parities. Nevertheless the situation is not so good like in the ^{35}Cl nucleus. The levels are enough far and situated in the hundred keV energy region of incident neutrons, they are quite large, all these leading to small values of the asymmetry effects including the PNC effect (see Fig. 2). The ^{14}N nucleus is light and the neutron, proton, gamma experimental widths from different resonance parameters atlases are not so well measured. With the increasing of the incident neutron energy, in the MeV's region, the model of the mixing states of the compound nucleus with the same spin and opposite parities is not so accurate already.

Table 2

Resonance energy for ^{15}N compound nucleus

№	Resonance energy (keV)	Spin and parity
1	$E_{P1} = 492.6$	$J_{P1}^{\pi} = (1/2)^{-}$
2	$E_{S1} = 639$	$J_{S1}^{\pi} = (1/2)^{+}$
3	$E_{S3} = 997$	$J_{S3}^{\pi} = (3/2)^{+}$
4	$E_{S4} = 1116$	$J_{S4}^{\pi} = (3/2)^{+}$
5	$E_{S2} = 837$	$J_{S2}^{\pi} = (1/2)^{+}$

The pairs of resonance creating asymmetry effects are the first two states from Table 2. Applying the same procedure as for ^{35}Cl(n,p)^{35}S reaction we have obtained the asymmetry effects. We write them in a compacted form, taking into account only the first two resonance:

$$
\begin{aligned}
&\alpha_{FB} = -\left(X_n + 2\sqrt{2}Y_n\right) X_p f_{FB}(E_n),\\
&\alpha_{LR} = \left(-X_n + 2\sqrt{2}Y_n\right) X_P f_{LR}(E_n),\\
&\alpha_{PNC} = W_{SP} X_p \left(c_1\left(E_n\right)\sqrt{0.25\Gamma^n_{S_1}\cdot\left(\Gamma^n_P\right)^{-1}} + c_2\left(E_n\right)Y_n^2\sqrt{\Gamma^n_P\cdot\left(\Gamma^n_{S1}\right)^{-1}}\right) f_{PNC}(E_n),\\
&X_n^2 + Y_n^2 = 1, \quad \left|X_p\right| \le 1.
\end{aligned}
\tag{28}
$$

There are only a few experimental data on asymmetry effects and one of these is: $\alpha_{LR} = -\left(0.66 \pm 0.18\right)\cdot 10^{-4}$ [19] for thermal neutrons. In the same reference the PNC coefficient was practically zero. In 2006, at FLNP–JINR Dubna was obtained a preliminary (unpublished) result for the FB effect about 0.4. These experimental results are not enough to determine if the two levels approximation is working, in spite of the fact that the theoretical evaluation of the LR and PNC effects is good agreement with existent experimental data. Furthermore the evaluation of the (n,p) cross section describes well the region of the first two resonance but is not in agree with thermal point $\sigma^{th}_{np} = 1.8\,\mathrm{b}$ [16]. This suggests that is necessary to introduce other resonance, at least to describe the cross section.

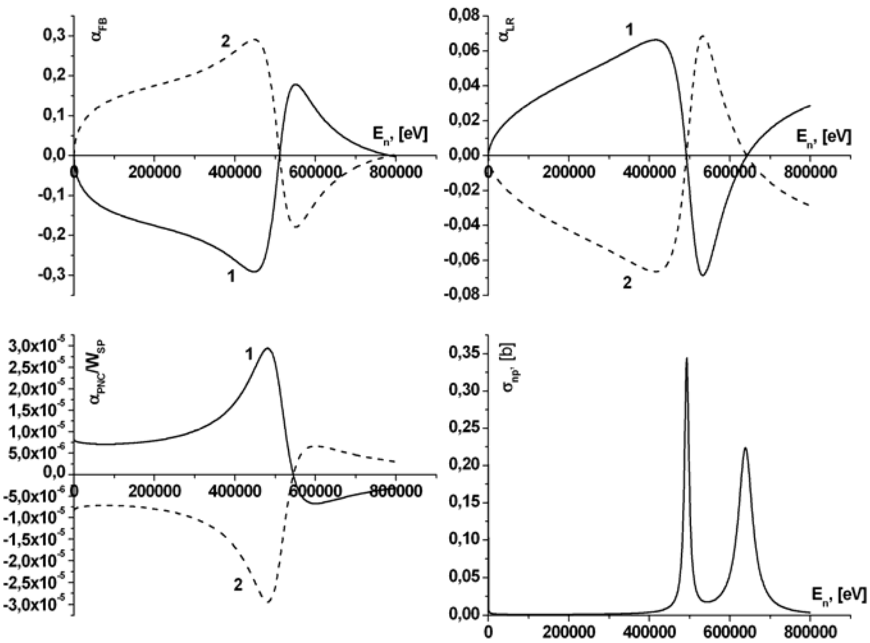

Fig. 2 – The energy dependence of the asymmetry coefficients, FB, LR, PNC and of the cross section, in the two levels approximation: 1 – ($X_n = X_p = Y_n = 0.707$); 2 – ($X_n = X_p = -Y_n = -0.707$). The weak matrix element is unknown and we divided the PNC effect to the weak matrix element.

5. THE INFLUENCE OF THE OTHER RESONANCE TO THE ASYMMETRY EFFECTS

The two levels approximation is working well in some energy interval like is the case of the (n,p) reaction on ^{35}Cl for the incident neutron energy up to 1 keV. If the incident energy increases it is expected that the resonance from this range to influence the experimental and theoretical evaluation. Already we noted this to the (n,p) reaction on ^{14}N nucleus where two resonance cannot describe well the cross section in the thermal point and far from the pair of resonance. To evaluate the contribution of other resonance to the asymmetry effects in the (n,p) reactions in ^{35}Cl and ^{14}N nuclei we will take into account the resonance from the Table 1 and Table 2. The resonance from the tables were selected having in mind possible new experiments at facilities which offer incident neutrons in these energy interval with enough intensity. For the evaluation will be used the same formalism. Like in the two levels approximation the starting point is the (n,p) reaction amplitude. This amplitude is:

$$f = \sum_{i-1}^{n} f_{Si}^{PC} + \sum_{j=1}^{m} f_{Pj}^{PC} + \sum_{i \neq j}^{l} f_{SiPj}^{PNC}. \tag{29}$$

This amplitude contains summation after all S and P states of the compound nucleus and another sum of PNC amplitudes on the pair of states with the same spin and opposite parities. In the evaluation were taken into account only S and P states of the compound nucleus (see Tables 1, 2). Following the same procedure we'll calculate the cross sections, the angular correlation and using the relations of definition of the asymmetry effects we have obtained the following expressions for the FB, LR and PNC coefficients:

$$\alpha_{FB} = \left. \frac{2\,\mathrm{Re} \sum\limits_{i \neq j} f_{Si}^{PC} f_{Pj}^{PC}}{\sum\limits_{i-1}^{n} \left| f_{Si}^{PC} \right|^2 + \sum\limits_{j=1}^{m} \left| f_{Pj}^{PC} \right|^2 + \sum\limits_{i \neq j} 2\,\mathrm{Re}\, f_{Si}^{PC} f_{Sj}^{PC*} + \sum\limits_{i \neq j} 2\,\mathrm{Re}\, f_{Pi}^{PC} f_{Pj}^{PC*}} \right|_{\theta=0}, \tag{30}$$

$$\alpha_{LR} = \left. \frac{2\,\mathrm{Im} \sum\limits_{i \neq j} f_{Si}^{PC} f_{Pj}^{PC}}{\sum\limits_{i-1}^{n} \left| f_{Si}^{PC} \right|^2 + \sum\limits_{j=1}^{m} \left| f_{Pj}^{PC} \right|^2 + \sum\limits_{i \neq j} 2\,\mathrm{Re}\, f_{Si}^{PC} f_{Sj}^{PC*} + \sum\limits_{i \neq j} 2\,\mathrm{Re}\, f_{Pi}^{PC} f_{Pj}^{PC*}} \right|_{\theta=\frac{\pi}{2}, \phi=\frac{\pi}{2}} \tag{31}$$

$$\alpha_{PNC} = \left. \frac{2\operatorname{Re}\sum_{i\neq j} f_{Si}^{PC} f_{SiPj}^{PNC*} + 2\operatorname{Re}\sum_{i\neq j} f_{Pj}^{PC} f_{PjSi}^{PNC*}}{\sum_{i-1}^{n}\left|f_{Si}^{PC}\right|^2 + \sum_{j=1}^{m}\left|f_{Pj}^{PC}\right|^2 + \sum_{i\neq j} 2\operatorname{Re} f_{Si}^{PC} f_{Sj}^{PC*} + \sum_{i\neq j} 2\operatorname{Re} f_{Pi}^{PC} f_{Pj}^{PC*}} \right|_{\theta=\frac{\pi}{2},\phi=0}, \quad (32)$$

Detailed expressions of the terms from (30), (31), (32) relations are in [20]. We see new terms of interference type between resonance with the same spin and parities. If these terms are not zero then they give their contribution in the cross section and will change the behavior of the asymmetry effects. In the FB and LR coefficients we neglected the PV amplitude supposing they are much smaller than the amplitudes conserving the parities. For the evaluation of the contribution of the all resonance we realized special computer programs able to give cross sections, angular correlations, interference terms, and FB, LR, PNC coefficients.

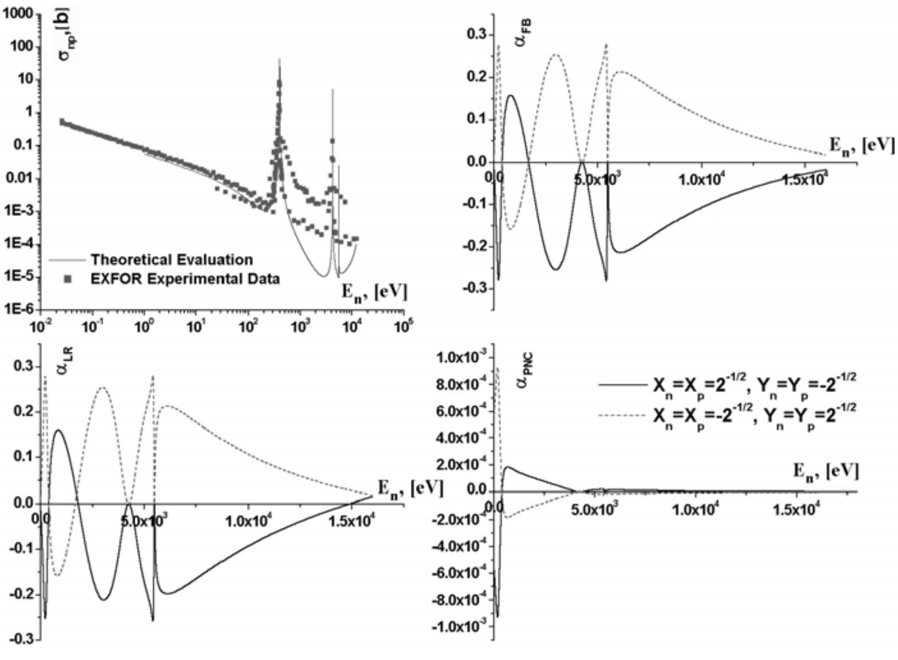

Fig. 3 – The cross section, FB, LR, PNC effects with the contribution of the resonance from Table 1 for ^{35}Cl(n,p)^{35}S reaction.

In Fig. 3 the theoretical cross section is compared with experimental values from EXFOR data base and there is a good agreement from thermal point until 1 keV. Further our evaluation is much lower than the experimental points between resonance but the resonance are described well and the shape of the dependence remains. These can be explained as results of parameterization of the neutron, proton and gamma widths. Another reason could be the influence of the other open channels as with the increasing of incident neutron energy their reciprocal influence can grow.

The asymmetry effects have more complex form and this is a result of the contribution of all resonance. From Table 1 we can see more pairs ($1^+ - 1^-$, $2^+ - 2^-$) of resonance that in principle can contribute to the asymmetry effects. The interference between states with the same spin and parity can also "modulate" the asymmetry effects. An important result from Fig. 3 and evaluations is that the states 3, 4, 5 from Table 1 do not influence practically the range where the two levels approximation is working. This fact is due to the well separated states of the compound nucleus.

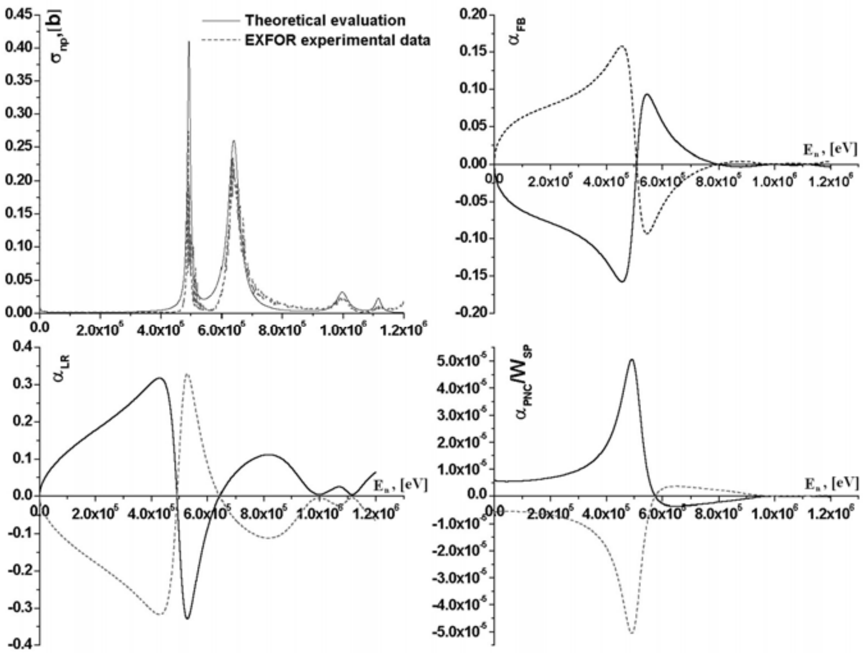

Fig. 4 – The cross section, FB, LR, PNC effects with the contribution of the resonance from Table 2 for $^{14}N(n,p)^{14}C$ reaction.

With the resonance from Table 2 the cross section in the (n,p) reaction on ^{14}N nucleus describes well the experimental data starting with the thermal point. Between resonance are some difference and this can be explained by parameterization of the neutron and other widths. With the increasing of the neutron energy other reaction channel can influence the (n,p) channel. Also because ^{14}N is a light nucleus with the increasing of the neutron energy other reaction mechanism (like direct) may become significant. The asymmetry effects are given by the interference between pairs of resonance with the same spin and opposite parities. The interference between states with the same spin and parities can also changes the behavior of the effects. The PNC effect like was expected is much lower than in the case of ^{35}Cl and practically zero for a wide energy interval.

6. DISCUSSIONS

In this paper were analyzed the asymmetry effects, FB, LR, PNC, ^{35}Cl(n,p)^{35}S and ^{14}N(n,p)^{14}C reactions in the frame of the model of the mixing states of the compound nucleus with the same spin and opposite parities in the two levels approximation and with the contribution of more than two resonance. For the first reaction in the two levels approximation was extracted the weak matrix element from the experimental asymmetry effects. This is an important result because demonstrates the existence of the weak non leptonic interaction between nucleons. For the ^{14}N nucleus the two levels approximation is not so suitable and it is necessary to take into account other resonance. Due to the lack of the experimental data for asymmetry effects, the weak matrix element could not be obtained. The PNC effect measured for thermal point is very small, practically zero, indicating also a small value of the weak matrix element. There is of interest in future to determine if the PNC coefficient is zero of has a very small different by zero value because such a value confirms the existence of the PNC effects in nuclear reaction.

The small number of experimental data for both reactions is due to the difficulties of the measurement of the (n,p) cross section. As it is possible to see from the figures of this paper where the asymmetry effects have the maximum of their value where the cross section is very small usually less than 1 mb. For this reason to obtain experimental energetic dependence of the asymmetry effects would be of a great interest in order to obtain from them new data on *X, Y* unknown parameters and if it is possible the weak matrix elements.

Acknowledgments. This work was supported by the Grant of Plenipotentiary Representative of Romanian Government to JINR Dubna for 2007 and 2008.

REFERENCES

1. V. V. Flambaum, O.P. Sushkov, Nucl. Phys., **A412**, 3 (1984).
2. V. V. Flambaum, O.P. Sushkov, Uspekhi Fizicheskih Nauk (in Russian), **136**, 1 (1982).
3. V. V. Flambaum, G. F. Gribakin, Prog. Part. Nucl. Phys., **35**, 423 (1995).
4. N. Tanner, Phys. Rev., **107**, 1203 (1957).
5. Yu. G. Abov, P. A. Krupchitsky, Yu. A. Oratovsky, Phys. Lett., **12**, *1*, 25 (1964).
6. C. M. Frankle, S. J. Seestrom, Yu. P. Popov, E. I. Sharapov, N. R. Robertson, Physics of Particles and Nuclei, **24**, 4, 939 (1993).

7. R. P. Feynmann, M. Gell-Mann, Phys. Rev., **109**, 193 (1957).
8. G. Rigol, Preprint P4-85-70 (in Russian), Joint Institute for Nuclear Research (JINR), Dubna, 1985.
9. L.C. Biedenharn, M.E. Rose, Reviews of Modern Physics, **25**, 1 (1953).
10. D. A. Varshalovich, A. N. Moskalev, V. K. Khersonsky, *Quantum Theory of Angular Momentum*, Nauka, Leningrad, 1965.
11. S. V. Zenkin, N. A. Titov, Preprint П – 0367 (in Russian), Institute for Nuclear Research of USSR Academy of Science, Moscow, 1984.
12. D. F. Zaretsky, V. K. Sirotkin, Yadernaya Fizika (in Russian), **32**, 1026 (1980).
13. Yu. P. Popov, F. L. Shapiro, Journal of Experimental and Theoretical Physics (in Russian), **40**, *6*, 1610 (1961).
14. V. A. Vesna, E. A. Kolomensky, V. M. Lobashev, V. A. Nazarenko, A. M. Pirozhkov, L. M. Smotritsky, Yu. V. Sobolev, N. A. Titov, Pisma JETF (in Russian), **36**, *5*, 169 (1982).
15. M. Avenier, G. Bagieu, H. Benkoula, Nucl. Phys., **A436**, 83 (1985).
16. S. F Mughabghab, M. Divadeenam, N. E Holden, *Neutron Cross Sections*, NY Academic Press, **1** (1981).
17. *** *Radiatsionyi zahvat neytronov – Spravochnik*, EnegoAtomIzdat, Moskva, 1986.
18. Yu. M Gledenov, R Machrafi, A. I Oprea, V. I. Salatski, P. V. Sedyshev, P. I. Szalanski, V. A. Vesna, I. S. Okunev, Nucl. Phys., **A654,** 943 1999.
19. A. Antonov, V. A. Vesna, Yu. M. Gledenov, T. S. Zvarova, V. M. Lobashev, I. S. Okunev, Yu. P. Popov, Kh. Rigol, L. M. Smotritskii, E. V. Shulgina, Sov. J. Nucl. Phys. **48**, 2 (1988).
20. A. I. Oprea, C. Oprea, Yu. M. Gledenov, P. V. Sedyshev, P. J. Szalanski, Proceedings on the Thirteenth International Seminar on Interaction of Neutron with Nuclei (ISINN-13), 25-28 May 2005, E3-2006-7, Dubna, 2006.