Asymmetry and Spatial Symmetry Breaking Effects Modeling in (n,p) Reactions

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Abstract. Asymmetry and spatial parity breaking effects in nuclear reaction induced by slow and resonant neutrons on ^{35}Cl nucleus followed by protons emission were analyzed. Effects were obtained applying Flambaum-Sushkov formalism using two-levels approximation. In the computer simulation, different types of target and neutrons incident flux were considered. Obtained results are compared with existing experimental data. Differences between theoretical evaluation, computer modeling and experimental data are explained considering contributions of other open channels.

INTRODUCTION

After the discovery of parity non-conservation phenomena (PNC) of neutrons, protons it was supposed universal characteristic of weak interaction [1]. Later, theoretically was evidenced the non-leptonic characteristic of weak forces which can be observed in the interactions between nucleons [2]. The constant of weak non-leptonic interactions is of order of 10^{-7} in comparison with nuclear strong interactions which is parity conserving (PC). Weak non-leptonic interaction is acting together with nuclear force and therefore is very difficult to measure it in the experiments. First experimental proof of the existence of weak non-leptonic interaction between nucleons was evidenced at FLNP, in the measurement of the asymmetry of emitted gamma quanta in capture process of slow neutrons by ^{113}Cd nuclei. The nonzero value of measured asymmetry was interpreted as effect of weak interaction between nucleons [3]. Analogue phenomena in other neutrons reactions on light medium and heavy nuclei (including fission), were observed at FLNP basic facilities [4,5]. Parity breaking effects observed in slow neutrons processes were very well explained by in the frame of the model of the mixing states of compound nucleus with the same spins and opposite parities [6,7].

Authors had analyzed, using the resonance-resonance approach, asymmetry and spatial parity breaking effects in $^{35}Cl(n,p)^{35}S$ reaction with slow and resonance neutrons. Forward-backward (FB), left-right PC effects, together with PNC one were obtained and compared with experimental data. From experimental data and theoretical evaluations of asymmetry coefficients, weak matrix element was extracted [8,9].

In the present work a mathematical modeling of FB asymmetry coefficient measurement, in the $^{35}Cl(n,p)^{35}S$ reaction was realized. The asymmetry coefficient was obtained using resonant-resonant approach, considering an incident neutrons flux on a target with a given thickness. Results are analyzed and compared with measurements obtained at FLNP basic facility.

THEORY AND FORMULAS

In the resonant-resonant formalism it is supposed that asymmetry and parity violation (PV) effects are manifesting in the presence of resonance of compound nucleus with the same spins and opposite parities. In addition resonances enhance the effects mainly due to amplification mechanisms (cinematic, dynamic and structural) [6,7]. In *(n,p)* reaction induced by neutrons with orbital momentum l=0, 1 (*s, p* neutrons) compound nucleus in the *S* and *P* states can be formed. Amplitudes of (n,p) process corresponding to parity PC interaction are [6,7]:

$$f_{np}^{S(P)}\left(E_n\right) \sim \sqrt{\Gamma_n^{S(P)}\Gamma_p^{S(P)}}\left[\left(E-E_{S(P)}\right)+0.5\cdot i\cdot\Gamma_{S(P)}\right]^{-1} Exp\left(\Delta\varphi_{np}^{S}\right) \ , \qquad (1)$$

where E_n is neutron energy; $\Gamma_n^S, \Gamma_p^S, \Gamma_n^P, \Gamma_p^P =$ neutron and proton widths corresponding to S and P states of compound nucleus, respectively; $\Gamma_{S,P} = \Gamma_n^{S,P} + \Gamma_p^{S,P} + \Gamma_\gamma^{S,P} + \Gamma_\alpha^{S,P} + ... =$ total widths in S and P states as sum of neutron, proton, gamma, alpha and other particles widths in the given channel; $E_{S,P} =$ energy of S and P resonances; $\Delta\varphi_{np}^{S,P} = \varphi_n^{S,P} - \varphi_p^{S,P} =$ difference of neutron and proton phases in S and P states.

Amplitudes form (1) represents the capture of an *s*-neutron (*p*-neutron) with formation of an *S*-resonance (*P*-resonance) of compound nucleus followed by emission of protons with orbital momentum necessary for parity conservation. If the weak interaction between nucleons are considered then the corresponding amplitudes can be written as [6,7]:

$$f_{np}^{SP(PS)}\left(E_n\right) \sim W_{PNC}\sqrt{\Gamma_n^{S(P)}\Gamma_p^{P(S)}}\left\{\left[\left(E-E_S\right)+0.5\cdot i\cdot\Gamma_S\right]\left[\left(E-E_P\right)+0.5\cdot i\cdot\Gamma_P\right]\right\}^{-1} Exp\left(\varphi_n^S - \varphi_p^P\right), \qquad (2)$$

where $W_{PNC} =$ weak matrix element; $W_{PNC} << W_{PC}$; $W_{PC} =$ matrix element of nuclear interaction.

Relations (2) describe the capture of an *s*-neutron (*p*-neutron) with formation of compound nucleus in *S* state (*P*-state). Due to the weak non-leptonic interaction between nucleons in the intermediate state, compound nucleus is changing the spatial parity going from *S*-state (*P*-state) to *P*-state (*S*-state) followed by protons emission. In formulas (1), (2) sum over Clebsh-Gordan coefficients and spherical functions are omitted for a better understanding of the processes. Detailed calculations can be found in [6–9]. If the (n,p) reactions is going with formation of a compound nucleus characterized only by *S* and *P* resonances with participation of weak interaction then total amplitude is:

$$f_{np} = f_{np}^S + f_{np}^P + f_{np}^{SP} + f_{np}^{PS} \ . \qquad (3)$$

Differential cross section, angular correlation and cross section are calculated as following:

$$\left[d\sigma/d\Omega\right]\left(E_n,\theta,\phi\right) = \left|f\right|^2 \sim W\left(\theta,\phi\right), \sigma\left(E_n\right) = \int\left[d\sigma/d\Omega\right]\left(E_n,\theta,\phi\right)d\Omega\,,$$
$$\int_{(\Omega)} W(\theta,\phi)\sin(\theta)d\theta d\phi = 1, \qquad (4)$$

where $W(\theta,\phi) =$ angular correlation; $\theta, \phi =$ polar and azimuth angles.

Using angular correlations, asymmetry and PV effects can be obtained. Forward-backward effect is defined as:

$$\alpha_{FB}\left(E_n\right) = \left(W\left(\theta=0\right) - W\left(\theta=\pi\right)\right)\cdot\left(W\left(\theta=0\right) + W\left(\theta=\pi\right)\right)^{-1}. \qquad (5)$$

RESULTS AND DISCUSSIONS

The ^{35}Cl nucleus, in fundamental state has the spin and parity $J^{\Pi} = (3/2)^{+}$. In $^{35}Cl(n,p)^{35}S$ reaction induced by *s* and *p* neutrons with energies up to 1000 eV, ^{36}Cl compound nucleus is formed which can be characterized by *S* and *P* resonance with following energies, spins and parity: $E_S = -180eV, E_P = 398eV$, $J_S = 2^{+}, J_P = 2^{-}$. Residual nucleus ^{35}S is in fundamental state with the following spin and parity, $J^{\Pi} = (3/2)^{+}$. Neutrons resonance parameters of ^{36}Cl compound nucleus are taken from [10]. For incident neutrons energy interval up to 1000 eV the influence of other resonances can be neglected. If the incident neutrons are unpolarized then the PNC components of the amplitudes are zero, therefore the amplitude of *(n,p)* process is:

$$f_{np} = f_{np}^{S} + f_{np}^{P}. \tag{6}$$

Using relations (4), angular correlations can be written as:

$$W(E_n,\theta) = \left(\left| f_{np}^{S} \right|^2 + \left| f_{np}^{P} \right|^2 + 2\,\mathrm{Re}\, f_{np}^{S} f_{np}^{P*} \right) \left[\sigma_{np}(E_n) \right]^{-1} = \left[1 + \alpha(E_n)\cos(\theta) + \beta(E_n)\cos^2(\theta) \right] [4\pi]^{-1}. \tag{7}$$

Applying (5) the FB asymmetry effect is:

$$\alpha_{FB}(E_n) = \left. \frac{2\,\mathrm{Re}\, f_{np}^{S} f_{np}^{P*}}{\left| f_{np}^{S} \right|^2 + \left| f_{np}^{P} \right|^2} \right|_{\theta=0} = \pm \frac{\sqrt{\Gamma_n^S \Gamma_p^S \Gamma_n^P \Gamma_p^P}}{\Gamma_n^S \Gamma_p^P [P] + \Gamma_n^P \Gamma_p^P [S] (1 \pm 0.7 X_n Y_n X_p Y_p)} u_{FB}(E_n)(X_n - Y_n)(X_p - Y_p), \tag{8}$$

$$u_{FB}(E_n) = \left[(E - E_S)(E - E_P) + 0.25 \Gamma_S \Gamma_P \right] \cos(\Delta\varphi) - \left[0.5 (E - E_S) \Gamma_P - 0.5 (E - E_P) \Gamma_S \right] \sin(\Delta\varphi), \tag{8.1}$$

$$[S] = (E - E_S)^2 + 0.25 \cdot \Gamma_S^2, \quad [P] = (E - E_P)^2 + 0.25 \cdot \Gamma_P^2, \tag{8.2}$$

$$X_n^2 + Y_n^2 = 1, \quad X_p^2 + Y_p^2 = 1, \tag{8.3}$$

where X_n, Y_n, X_p, Y_p are reduced partial neutron and proton widths; k is wave number; Z, Z' are charge of target and residual nuclei respectively; *e* is elementary charge; *h* is Planck constant.

Also, α and β coefficients from (7) were evaluated and they have the following form:

$$\alpha = \pm \sqrt{\Gamma_n^S \Gamma_p^S \Gamma_n^P \Gamma_p^P} \left[\Gamma_n^S \Gamma_p^S [P] + \Gamma_n^P \Gamma_p^P [S] \right]^{-1} u_{FB}(E_n)(X_n - Y_n)(X_p - Y_p), \tag{9}$$

$$\beta = \mp 0.35 X_n X_p Y_n Y_p \Gamma_P^n \Gamma_P^p [S] \left(\Gamma_n^S \Gamma_p^S [P] + \Gamma_n^P \Gamma_p^P [S] \right)^{-1}. \tag{10}$$

From relation (8) FB effect can be interpreted as the result of interference between *S* and *P* states of compound nucleus. This confirms the main assumptions of the formalism of mixing states of compound nucleus with the same spins and opposite parities that asymmetry and PV effects can be observed in the presence of at least a pair of S and P resonances. The "±" sign in relations (8), (9), (10) appears due to the determination of phases sign cannot. Further, if α is positive then β will be negative, and vice-versa. Coefficient β is important in the investigation of differential cross section anisotropy. It is easy to observe that if β=0 then $\alpha_{FB} = \alpha$. Coefficients α and β determine completely the angular correlation which allows to generate polar and azimuth angles necessary in the computer modeling of FB measurement. Polar angle θ can be determined by direct Monte Carlo method [11] applying the relations:

$$\int_0^{\theta c<\pi} W(\theta)\sin(\theta)d\theta = r < 1 \Rightarrow \theta = \pm ArcCos\left[\frac{-2+\beta}{2(\alpha+\beta)}\left(1\pm\sqrt{\frac{(-2+\beta)^2}{4(\alpha+\beta)^2}\pm\frac{2+\alpha-4r}{\alpha+\beta}}\right)\right], \tag{11}$$

$$\varphi = 2\pi r, r \in [0,1), \tag{12}$$

where r is random number.

If β=0 then the generator for polar angle θ is simplifying and takes the form:

$$\theta c = ArcCos\left\{\left(\sqrt{1+2\alpha_{FB}+\alpha_{FB}^2-4\alpha_{FB}r}-1\right)\left(\alpha_{FB}\right)^{-1}\right\}. \tag{13}$$

Experimental FB coefficient differs from theoretical definition and can be written as:

$$\alpha_{FB}^{\exp} = \left(N_F - N_B\right)\cdot\left(N_F + N_B\right)^{-1}, \tag{14}$$

where N_F, N_B = number of protons in the forward and backward directions.

In the experiment, forward direction means all protons emitted from the target in the solid angle $0 \leq \theta < \pi/2, \varphi \in [0,2\pi]$ and correspondingly backward directions represents the solid angle $\pi/2 \leq \theta < \pi, \varphi \in [0,2\pi]$. For a point target, forward (F) and backward (B) events, are:

$$N_F = \int_0^{\pi/2} \Phi_n(E_n)W(\theta,\varphi)\sin(\theta)d\theta d\varphi, \quad N_B = \int_{\pi/2}^{\pi} \Phi_n(E_n)W(\theta,\varphi)\sin(\theta)d\theta d\varphi, \tag{15}$$

where $\Phi_n(E_n)$= flux of incident neutrons.

Applying (15), FB asymmetry coefficient is:

$$\alpha_{FB}^{\exp} = (\alpha/2)\cdot\left[3(1+\cos\theta_{\max})\right]\cdot\left(3+\beta+\beta\cdot\cos\theta_{\max}+\beta\cdot\cos^2\theta_{\max}\right)^{-1} \text{ or if } \beta=0, \alpha_{FB}^{\exp} = \alpha_{FB}/2, \tag{16}$$

where $\theta_{\max}$ = maximal angle of protons emerging from the target.

Due to the geometry and thickness of the target polar angle in expression (15) is lower than $\pi/2$. Passing through the target protons lose their energy and maximal path depends on initial protons energy material type. Stopping power data are taken from [12]. Cross section of $^{35}Cl(n,p)^{35}S$ process is represented in Fig. 1a). Theoretical evaluation describes well existing experimental data. Results from Fig. 1a) are calculated using the expression [9]:

$$\sigma_{np}(E_n) = g\pi\lambda\!\!\!^{-}{}_n^2\left(\Gamma_S^n\Gamma_S^p/[S]+\Gamma_P^n\Gamma_P^p/[P]\right), \tag{17}$$

where $\lambda\!\!\!^{-}{}_n$ = neutron wave number; $g = (2J+1)/[(2I+1)(2s+1)]$ = statistical factor; J, I, s = spin of compound nucleus, target nucleus and neutron, respectively.

Fig. 1 shows the dependence on incident neutrons energy up to 1000 eV of α, β coefficients according to relations (8), (9), (10).

In the $^{35}Cl(n,p)^{35}S$ reaction with neutrons energy up to 1000 eV cross section is well described by compound nucleus mechanism and the main contribution is given by the first 2 resonances (*S* and *P*). Influence of higher resonance interferences and interferences can be neglected [9]. Comparing Figs. 1a) and 1b) result that when FB effect has high values, cross section is very low and vice versa. This is an important feature not only for FB effect but also for other PV and asymmetry coefficients. From Fig. 1b), in the given energy interval results, the influence of β on FB effect is not so large. As is expected α and β have opposite sign. For resonance energy, E_p=398 eV, $\alpha_{FB} = 0$ but $\beta \cong 0.08$. This fact is of interest in the measurement of differential cross section in the resonance. Coefficient β reduces with few percent α_{FB} coefficient. In the evaluations, neutron resonance parameters, phases for neutron and proton widths are taken from [10].

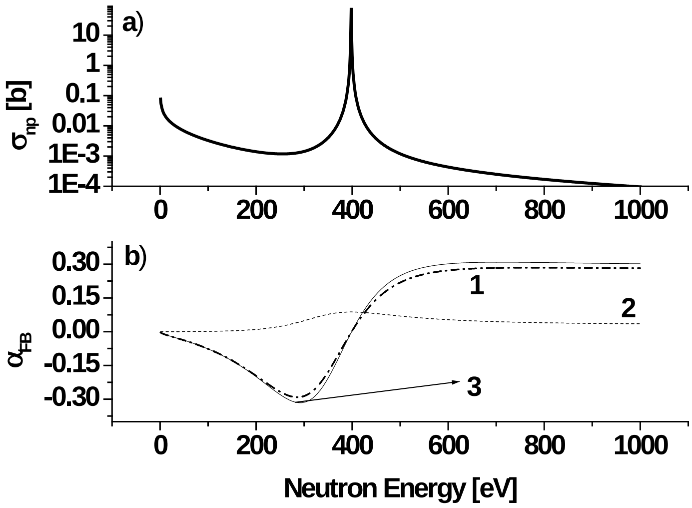

Figure 1. Neutron energy dependences of cross section and angular correlation coefficients (7). a) $^{35}Cl(n,p)^{35}S$ cross section b) Coefficients. 1 – α_{FB} (8); 2 – β (10); 3 – α (9).

Results obtained above will be applied in the mathematical modeling of experimental evaluation of FB coefficient. A constant flux of incident neutrons interact with a rectangular *NaCl* target with different thickness and dimensions were tested (see Fig. 1). In the target a $^{35}Cl(n,p)^{35}S$ process takes place. Part of emitted protons with initial energy $E_p \cong Q_{np} = 0.62$ MeV by losing their energy can get out from the target. If the maximum protons path is larger than thickness than the FB effect can be observed [8]. Polar and azimuth angle were generated using (11) and (12). Angular distribution coefficients, α and β, were calculated applying relations (9) and (10). Reduced neutrons and protons widths have the following values: $X_n = X_p = -Y_n = -Y_p = 1/\sqrt{2}$. Spectra of emitted protons in forward and backward directions are simulated. Further N_F, N_B were determined and simulated α_{FB}^{sim} are calculate. Forward and backward protons spectra obtained in the mathematical modeling are shown in Fig. 2.

Protons spectra from Fig. 2 were obtained for a target with a square like transversal surface with 1 cm side length. Incident neutrons energy was chose from 150 up to 260 eV. In this energy interval it is expected to have a large FB effect and advantageous experimental conditions [8]. For target with 0.25 mg/cm^2 thickness about 15% of protons are not getting out from the target. If thickness is 5 mg/cm^2 than almost 15% of protons are getting out from the target. Table 1 with FB effect results with simulated FB coefficient are shown in Table 1.

For a point target, ratio between measured (or modeled) and theoretical effect is equal with 2 (see relation (16)). If the target is rectangular then with the increasing of the thickness the ratio of simulated and averaged FB coefficient is decreasing. Thickness is an important parameter and must be chosen in an optimal way in order to not lose the FB effect and to have necessary statistics in the measurements.

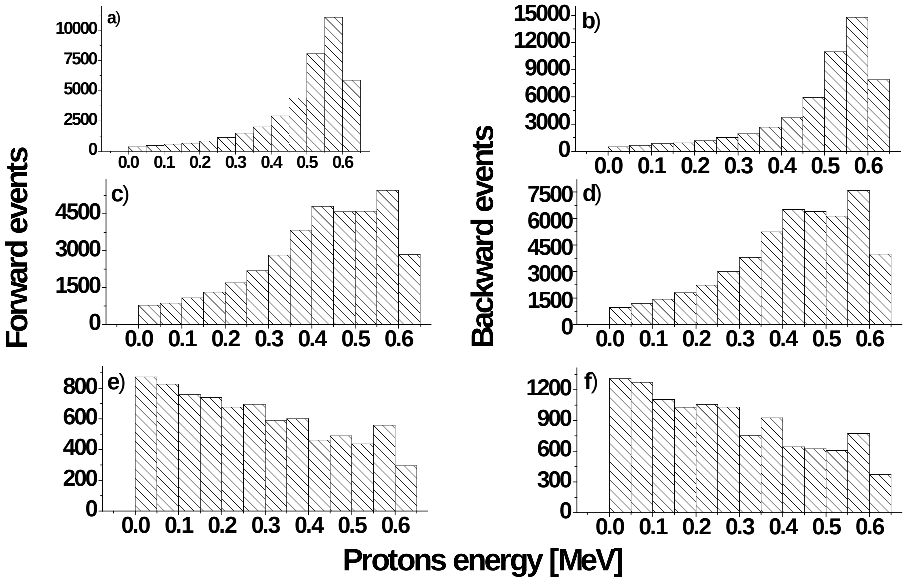

Figure 2. Forward, backward protons spectra for different target thickness. Generated events – 100 000. Target thickness: a) and b) – 0.25 mg/cm^2; c) and d) – 0.5 mg/cm^2; e) and f) – 5 mg/cm^2.

Table 1. Simulated FB effect for different thickness. Flux of incident neutrons is constant with energy from 150 up to 260 eV. *g* = target thickness

g [mg/cm^2]	α_{FB}^{sim}	$\overline{\alpha_{FB}}$	$\overline{\alpha_{FB}}/\alpha_{FB}^{sim}$
0.25	-0.146	-0.274	1.92
0.5	-0.155	-0.274	1.77
5	-0.179	-0.274	1.53

Averaged FB asymmetry coefficient for neutrons with energy from 150 up to 260 eV was calculated using the following formula:

$$\overline{\alpha_{FB}} = \left(E_{\max} - E_{\min}\right)^{-1} \int_{E\min}^{E\max} \alpha_{FB}\left(E_n\right) dE_n, E_n \in \left[E_{\min}, E_{\max}\right]; E_{\min} = 150eV; E_{\max} = 260eV \,. \tag{18}$$

For the same neutrons energy interval is $\alpha_{FB}^{\exp} = 0.23 \pm 0.05$ [8] which is higher than results obtained from simulation. This fact can be explained in many ways. First reason could be that the measurements are difficult because they are affected by high background and the effect has maximum value where the cross section is very low. A second and uninvestigated reason can come from the fact that in $^{35}Cl(n,p)^{35}S$ reaction alpha channel is also open. Energy of emitted alpha particles is about 0.94 MeV and close to the value protons energy. It is of interest therefore to investigated FB effect in the case of (*n,α*) reaction on ^{35}Cl. Another aspect which can affect measured proton spectra and must be analyzed in the future is related to the heating of the target due to the interaction with neutrons and energy loss of charged particles.

Theoretical and experimental investigations of FB effect in $^{35}Cl(n,p)^{35}S$ reaction with slow and resonance neutrons is very important because correlated with other effects allow us to extract the matrix element of weak non-leptonic interaction between neutrons [9].

CONCLUSIONS

Forward-backward effect in $^{35}Cl(n,p)^{35}S$ nuclear reaction with neutrons up to 1000 eV was investigated. In the frame of the model of the mixing state of the compound nucleus with the same spin and opposite parities cross section, angular correlation and FB effect were calculated. Results were used in the mathematical modeling of FB effect on a target with finite dimensions. Using angular correlation, distribution of polar and azimuth angles were obtained. For different experimental condition (target thickness, area of transversal surface, flux and energy of incident neutrons etc.) protons spectra and FB asymmetry coefficient were simulated. Modeled FB effect is lower than existing experimental data. Were evidenced few reasons that could explain the difference between real measurement and mathematical modeling which represents a subject for future investigations.

The results of present studies represent a proposal for asymmetry and PV effects for slow and resonant neutrons induced reaction followed by charged particles emission at FLNP basic facilities.

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