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Forward-Backward Asymmetry Effect in Slow Neutrons Capture by Silver Nucleus

P.V. Sedyshev[1], A.I. Oprea[1], C. Oprea[2], V.L. Kuznetsov[1,3]

[1]*Frank Laboratory for Neutron Physics (FLNP), Joint Institute for Nuclear Research (JINR), 141980 Dubna, 6 Joliot Curie str., Moscow Region, Russian Federation*

[2]*County Center for Education, 11 Mihai Eminescu str., 410019, Oradea, Bihor County, Romania*

[3]*Laboratory of Neutron Research, INR RAS, Troitsk*

Forward-backward asymmetry effect in the capture process of slow neutrons on Silver nucleus was investigated. Cross sections, angular distributions, and forward-backward effect were obtained in the frame of the mixing states of compound nucleus with the same spin and opposite parities formalism. Simulated gamma spectra, taking into account different type of target and gamma loss, were also evaluated. Using modeled gamma spectra, the influence of target properties (composition, target thickness) on the investigated effect were analyzed. Forward-backward effect together with other asymmetry and parity breaking effects allow to extract new information on neutrons and gamma reduced partial widths and matrix element of weak non-leptonic interaction.

INTRODUCTION

Asymmetry and spatial parity and time breaking effects, in slow neutrons induced processes traditionally were investigated for a long time in FLNP JINR Dubna [1,2]. Furthermore, first experimentally proof of the existence of spatial parity violation effect in slow neutrons capture reaction by Cadmium nuclei was realized in 1964 also at FLNP [3]. In the beginning, the search of symmetry breaking effects was oriented on the capture of slow and resonance neutrons by heavy nuclei. With the improvements of experimental technique and theoretical progresses, the investigations were extended to light and medium nuclei and to other nuclear reactions like (n,p), (n,α), neutrons induced fission etc. [4,5].

Symmetry breaking effects were revealed experimentally by mean of asymmetry coefficients which can be obtained using angular correlations. Parity non-conservation in nuclear reaction phenomena were explained by the existence of non-leptonic weak interaction between nucleons in nuclear systems "incident particle + target" [6]. In consequence, dealing with weak interaction, symmetry breaking effects have very low values of order of 10^{-9}–10^{-7}.

In the case of slow neutrons induced reaction, nuclear process is going with formation of an intermediate compound nucleus in the presence of resonances. Theoretically it was demonstrated that compound nucleus resonances enable amplification mechanisms (kinematic, dynamic, structural) of asymmetry and parity breaking effects increasing the corresponding coefficients up to 10^{-1} [7,8].

The search of asymmetry and parity breaking effects in nuclear reaction is of great importance because allow to extract the matrix element of weak interaction and demonstrates the universality of weak forces [9].

In the present work, in the frame of so-called resonance-resonance approach and two-level approximations, forward-backward asymmetry effect, obtained in capture process of slow and resonant neutrons by ^{109}Ag nuclei was analyzed.

ELEMENTS OF THEORY

Relation of definition of forward–backward asymmetry coefficient (effect) is:

$$\alpha_{FB} = \frac{W(\theta=0) - W(\theta=\pi)}{W(\theta=0) + W(\theta=\pi)}, \tag{1}$$

where W is the angular correlation; θ is the polar angle

Angular correlation in the case of capture process of un-polarized neutrons by nuclei has the expression:

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

where α, β are coefficients; $\vec{n}_n, \vec{n}_\gamma$ are the unit vectors of direction of incident neutrons and emitted gamma quanta respectively.

Geometry of the experiment and for the evaluations is represented in Fig. 1.

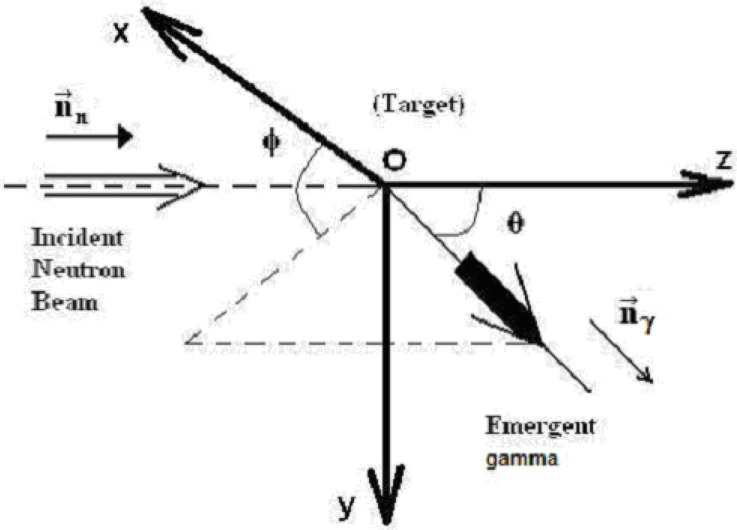

Fig. 1. Geometry of capture experiment for the calculations.

Angular correlation is proportional to differential cross section according to the following relations:

$$W(\Omega) \sim \frac{d\sigma}{d\Omega} = |f|^2 = \sum_i |f_i|^2 + \sum_{i\neq j} \mathrm{Re}\, f_i^* f_j, \tag{3}$$

where $d\sigma/d\Omega$ is differential cross section; Ω is solid angle; f_i are amplitudes of (n,γ) reaction.

In the case of slow neutrons capture process, with formation of compound nucleus, described by resonance, reaction amplitude f are described in the formalism of the mixed states of compound nucleus with the same spin and opposite parities [7,8]. According to this formalism, asymmetry and parity breaking effects can be evidenced in the vicinity of pair of resonances with the same spin and opposite parities. Considering a number of isolated, well defined resonances of compound nucleus, reaction amplitudes can be written for each state [2,7,8]. Furthermore, compound nucleus resonances are enhancing the asymmetry and parity violation effects through amplification mechanisms mentioned above [2,7,8].

In (n,γ) process for incident neutrons with orbital momentum l_n = 0,1 compound nucleus resonance (S and P resonance respectively) are formed. Then, reaction amplitudes have the form:

$$f_1 = -\frac{1}{2k} C(I, I_z, a, a_n; J_S, J_{Sz}) C(I', I_z', a_\gamma, a_{\gamma z}; J_S, J_{Sz}) \cdot \frac{T_S^n T_S^{\gamma *}}{(E - E_S) + i\frac{\Gamma_S}{2}} Exp(-i\varphi_0), \tag{4}$$

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

$$C(L, \nu_\gamma, a_\gamma, a_{\gamma z}; j_\gamma, j_z) \frac{T_P^n(j_n) T_P^*(j_\gamma)}{(E - E_P) + i\frac{\Gamma_P}{2}} \cdot Y_{1\nu_n}^*(\vec{n}_n) Y_{1\nu_{\gamma p}}(\vec{n}_\gamma) Exp(-i\varphi_1), \tag{5}$$

where C are the Clebsch-Gordan coefficients depending on quantum numbers; $J, J', J_z, J_z', I, I_z, I', I_z'$ are the spins of compound (S and P), target, residual nuclei respectively with their projections (z); $a_n, a_{bz}, a_\gamma, a_{\gamma z}$ are the spins of neutrons and gamma quanta and their projections; L is total orbital momentum; $T_{S,P}^{n,\gamma}$ are the reduced amplitudes in S and P states respectively for neutrons and gamma quanta; ϕ_1, ϕ_2 are phases in S and P states respectively.

Amplitudes f_1, f_2 describe the following nuclear process: capture of neutrons with orbital momentum l_n = 0, 1 (s and p neutrons) and formation of S and P resonance of compound nucleus respectively, followed by emission of gamma quanta. These amplitudes are describing strong nuclear interaction which is parity conserving and they are not including weak non-leptonic interaction.

Applying relations (1–3) in the case of (n,γ) reaction induced by slow, resonance un-polarized neutrons, with formation of a compound nucleus described by a pair of S and P resonances (expressions (3), (4)), differential cross section, angular correlation and forward-backward effect (coefficient) are obtained. In terms of amplitudes f_1, f_2 forward-backward effect is:

$$\alpha_{FB} = \frac{2\,\mathrm{Re}\, f_1 f_2^*}{|f_1|^2 + |f_2|^2}. \tag{6}$$

The relation (6) suggests that forward-backward effect, in the frame of resonant-resonant formalism [2,7,8] can be interpreted as result of interference in compound nucleus of resonances with the same spin and opposite parities.

RESULTS AND DISCUSSIONS

Capture process of slow and resonant neutrons by ^{109}Ag nucleus was investigated, Compound nucleus, ^{110}Ag is characterized by a pair of S and P resonances with the following energies, spins and parities ($E_{S,P}, J^{\pm}_{S,P}$): $E_S = 30.6(\mathrm{eV}); J_S = 1^+$ and $E_P = 32.7(\mathrm{eV}); J_S = 1^-$ [10]. Silver is a heavy nucleus, and for neutrons with energies of tens of eV's compound nucleus has a large number of resonances. In order to evidence forward-backward asymmetry effect, as first step, it is enough to consider only the mentioned resonances because they have the same spin and opposite parities, the condition necessary to observe asymmetry and parity violation effects.

First, expression of differential cross section was obtained (7), after that, angular distribution and finally, the forward-backward effect according to relations (1–6).

$$\frac{d\sigma}{d\Omega}(E_n,\theta)=\frac{g\lambda_n^2}{4}\left[\frac{\Gamma_n^S\Gamma_\gamma^S}{S[E_n]}+\frac{\Gamma_n^P\Gamma_\gamma^P}{P[E_n]}\right]+\frac{3\lambda_n^2}{80\sqrt{7}}\left[\frac{\Gamma_n^P\Gamma_\gamma^P}{P[E_n]}\left(4X_nY_n+\sqrt{2}Y_n^2\right)Y_n^2P_2(\cos\theta)\right]+ \tag{7}$$
$$+\frac{3\lambda_n^2}{10}cfb1(E_n)\left[\left(\frac{Y_n}{\sqrt{2}}-X_n\right)\left(\frac{X_\gamma}{\sqrt{3}}-Y\gamma\right)\right],$$

where the functions are:

$$cfb1(E_n)=\frac{\left(2\Gamma_n^S\Gamma_\gamma^S\Gamma_n^P\Gamma_\gamma^P\right)^{1/2}}{P[E_n]S[E_n]}\left\{\left[(E_n-E_S)(E_n-E_P)+\frac{\Gamma_S\Gamma_P}{4}\right]\cos\phi-\left[(E_n-E_S)\frac{\Gamma_P}{2}-(E_n-E_P)\frac{\Gamma_S}{2}\right]\sin\phi\right\}, \tag{7.1}$$

$$S[E_n]=(E_n-E_S)^2+\frac{\Gamma_S^2}{4};P[E_n]=(E_n-E_P)^2+\frac{\Gamma_P^2}{4};\Gamma_{S,P}=\Gamma_n^{S,P}+\Gamma_\gamma^{S,P}+\Gamma_p^{S,P}+\Gamma_\alpha^{S,P}+\ldots \tag{7.2}$$

Forward-backward asymmetry effect is:

$$\alpha_{FB}(E_n)=\frac{\left(\frac{Y_n}{\sqrt{2}}-X_n\right)\left(\frac{X_\gamma}{\sqrt{3}}+Y_\gamma\right)cfb1(E_n)}{cf\,2(E_n)+cf\,3(E_n)\left(4X_nY_n+Y_n^2\right)Y_\gamma^2} \tag{8}$$

with functions:

$$cfb1(E_n)=\frac{\left(2\Gamma_n^S\Gamma_\gamma^S\Gamma_n^P\Gamma_\gamma^P\right)^{1/2}}{P[E_n]S[E_n]}\left\{\left[(E_n-E_S)(E_n-E_P)+\frac{\Gamma_S\Gamma_P}{4}\right]\cos\phi-\left[(E_n-E_S)\frac{\Gamma_P}{2}-(E_n-E_P)\frac{\Gamma_S}{2}\right]\sin\phi\right\}, \tag{8.1}$$

$$cf\,2(E_n)=\frac{\Gamma_n^S\Gamma_\gamma^S}{S[E_n]}+\frac{\Gamma_n^P\Gamma_\gamma^P}{P[E_n]};cf\,3(E_n)=\frac{1}{5\sqrt{7}}\cdot\frac{\Gamma_n^P\Gamma_\gamma^P}{P[E_n]}, \tag{8.2}$$

partial reduced widths and properties:

$$X_n=\pm\sqrt{\frac{\Gamma_n^S\left(\frac{1}{2}\right)}{\Gamma_n^S}};Y_n=\pm\sqrt{\frac{\Gamma_n^P\left(\frac{3}{2}\right)}{\Gamma_n^P}};X_\gamma=\pm\sqrt{\frac{\Gamma_\gamma^S(l_\gamma)}{\Gamma_\gamma^S}};Y_n=\pm\sqrt{\frac{\Gamma_\gamma^P(l_\gamma)}{\Gamma_\gamma^P}}, \tag{8.3}$$
$$X_n^2+Y_n^2=1;X_\gamma^2+Y_\gamma^2=1$$

and phases:

$$\varphi=\varphi_{neutron}=ArcTan\left(\frac{R}{\lambda_n}\right). \tag{8.4}$$

Using expressions (7–8) angular correlation was obtained. For the simulation of forward-backward asymmetry coefficient, angular distribution of polar angle θ was evaluated by Direct Monte-Carlo method. Expression of generated polar angle is:

$$\theta = \pm ArcCos\left[\frac{-2+\beta}{2(\alpha+\beta)}\left(1 \pm \sqrt{\frac{(-2+\beta)^2}{4(\alpha+\beta)^2} \pm \frac{2+\alpha-4r}{\alpha+\beta}}\right)\right], \tag{9}$$

where α, β are coefficients from relation (2).

Because spatial parity is conserving, azimuth angle has an uniform distribution and is generated with the formulae:

$$\varphi = 2 \cdot \pi \cdot r', \tag{10}$$

here r, $r' \in [0,1]$ are random numbers.

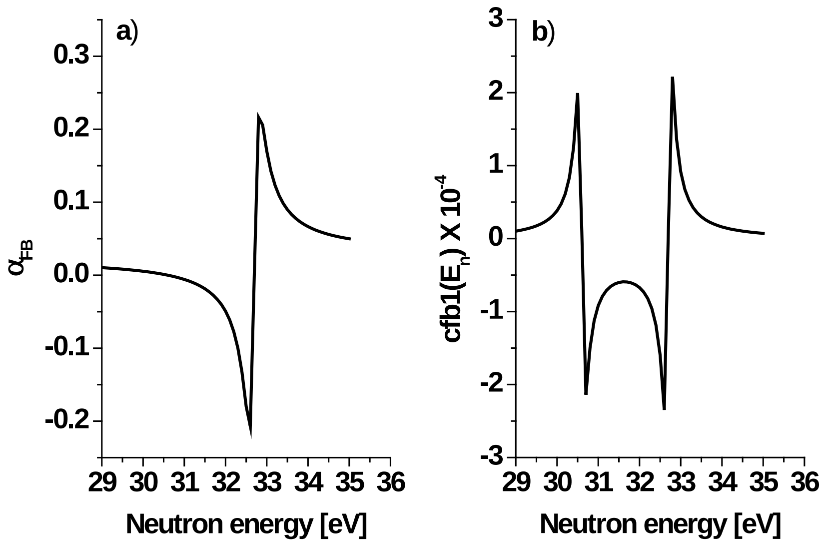

Fig. 1. a) Forward-backward neutrons energy dependence. b) Neutrons energy dependence of $cfb1(E_n)$ function (8.1).

In Fig. 1.a forward-backward effect is represented in the two levels approximation. The shape of the dependence is that prescribed by theory. In previous work of the authors analogue shape dependences were obtained in the analysis of ^{35}Cl(n,p)^{35}S reaction with slow and resonance neutrons [4,11]. Maximum value of forward-backward effect is around 0.2 between S and P resonances and is decreasing fast, moving away from resonances.

In Fig. 1.b neutrons energy dependence of $cfb1(E_n)$ is represented, This function, $cfb1(E_n)$, has the largest influence in the shape and quantitative dependence of forward-backward asymmetry coefficient. Resonance positions can be well observed in the figure.

Forward-backward effect was further computer modeled considering a finite target and attenuation of gamma quanta in the target. Attenuation law of gamma quanta is:

$$N = N_0 \cdot Exp(-\mu \cdot x), \tag{11}$$

where μ is attenuation coefficient; x is the distance covered by gamma quanta.

Applying relations (9–10) for the generation of polar and azimuth angles respectively, considering relations (1–8), a target of 2 cm thickness, μ = 0.4 cm^{-1} attenuation coefficient for silver and incident neutrons energy up to 40 eV, simulated forward-backward effect is:

$$\alpha_{BN}^{SIM} \cong 0.1. \tag{12}$$

The result (12) was obtained for 10^5 events, and about 35% of generated gammas of which are lost in the target. Due to the thickness of the target the effect is decreasing by approximately 2 times. Similar results have been obtained by authors in the analysis of asymmetry and spatial parity violating effects on (*n*,*p*) reaction with slow and resonance neutrons on ^{35}Cl and ^{14}N nuclei [4,11].

CONCLUSIONS

Capture process of slow and resonant neutrons by ^{109}Ag nucleus was investigated. Cross, section, differential cross section, angular correlations and forward-backward effect were evaluated in the frame of resonant-resonant formalism and two-level approximation. Forward-backward effect was also simulated, using theoretical results of angular correlation, expression of forward-backward effect and Direct Monte-Carlo method for generation of polar and azimuth angles respectively. Forward-backward energy evaluated dependence is in concordance with similar investigations of authors. For silver, modeled forward-backward effect is exactly half of theoretical effect for point-like target and about two times smaller for target with finite dimensions.

The results obtained in this work can be considered preliminary. It is necessary to investigate the influence of other resonance of ^{109}Ag because this nucleus has a lot of resonances close one to another. The formalism of the calculation of angular distribution must be improved by an averaging method for a large number of close resonances.

It is necessary in the future to investigate theoretically and experimentally other asymmetry and parity breaking effects on slow and resonant neutrons capture process by silver isotopes.

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