Proceedings of ISINN-30, JINR, E3-2024-42, Dubna, 2024, p.40 – 46

Angular Correlation Analysis in the Neutrons Capture by ^{109}Ag Nucleus

V.L. Kuznetsov[1,2], L.V. Mitsyna[1], A.I. Oprea[1,3,*], C. Oprea[1,4], N.V. Rebrova[1], P.V. Sedyshev[1]

[1]*Frank Laboratory of Neutron Physics, Joint Institute for Nuclear Research, Dubna*
[2]*Laboratory of Neutron Research, INR RAS, Troitsk, Russia*
[3]*Technical College "Alexandru Roman", Alesd, Bihor county, Romania*
[4]*National College "Emanuil Gojdu" Oradea, Bihor county, Romania*

**alex.i.oprea@yandex.ru*

Angular distribution and forward-backward effect in slow neutron capture process by ^{109}Ag nucleus were investigated in the frame of Flambaum-Sushkov formalism and two-level approximation. The expression of the angular distribution in ^{109}Ag(n,γ)^{110}Ag process contains Legendre Polynomial of second order, leading to an anisotropy of differential cross sections and a decreasing of Forward-Backward (FB) effect. In comparison with the asymmetry effects on other nuclei, FB coefficient varies very fast near P resonance, from ±0.21 maximal value to zero, for ^{109}Ag(n,γ)^{110}Ag reaction in less than 1 eV interval, due to the very small values of P neutron and gamma widths. This result will lead to a few percent and lower values of the experimental FB effect measured in a neutron energy interval near the P resonance. Using theoretical results, experimental FB coefficient was modeled taking into account target dimensions, attenuation of neutrons and gamma quanta in the target. Simulations have demonstrated that FB effect, in the neutron energy interval from 28 up to 35 eV is lower than 1%.

Keywords: slow neutrons, angular distributions, forward–backward asymmetry effect, widths

INTRODUCTION

Investigation of asymmetry and parity breaking effects in nuclear reactions with slow and resonant neutrons are traditionally investigated at FLNP. First proofs of existence of spatial parity violations effects were obtained in the slow neutrons capture process by Cadmium nuclei. Latter, with the development of experimental techniques and progress of theoretical approaches, new results of parity violation effects were obtained in capture process on Lanthanum, in other reactions like (n,p), (n,α) or fission [1–3]. Asymmetry and parity breaking effects are investigated more efficiently with the help of corresponding coefficients because they represents in fact the relative ratio of the angular distributions terms describing the effects and those that are not including the effects [3–5].

ELEMENTS OF THEORY

Forward-backward effect (FB) in the capture process of unpolarized slow and resonant neutrons by ^{109}Ag nucleus in the frame of resonant – resonant approach in the two levels approximation was investigated. Relation of definition of FB effect is:

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

where W is the angular correlation and θ is the polar angle.

Angular correlation in capture process of slow unpolarized neutron reactions has the form:

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

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.

The case of un-polarized neutrons is the most simple. Expression of angular correlations taking into account polarized neutrons can be found in [4], Geometry of the experiment with polar and azimuth angles (θ,φ) respectively are represented in [6]. If α coefficient is not zero, then it gives FB effect. The β parameter is responsible for the anisotropy in angular distribution. Expression of angular distribution is obtained with the help of reaction amplitudes corresponding to the type of interactions (n,γ), (n,p), (n,α), (n,f) etc. For ^{109}Ag(n,γ)^{110}Ag with un-polarized s and p neutrons, in the presence of two compound nucleus resonance there are only two S and P amplitudes, respectively. These amplitudes are parity conserving and their expressions are described in [5,6]. Differential cross section is proportional to the angular correlation and has the form:

$$W(\Omega) \sim \frac{d\sigma}{d\Omega} = |f|^2 = |f_1 + f_2|^2 = |f_1|^2 + |f_2|^2 + 2\,\mathrm{Re}\, f_1 f_2^*\,, \qquad (3)$$

where f_1, f_2 are the s and p neutrons capture amplitudes, Ω is the solid angle.
Applying relations (1–3) the FB effect is:

$$\alpha_{FB} = 2\,\mathrm{Re}\, f_1 f_2^* \cdot \left(|f_1|^2 + |f_2|^2\right)^{-1} \qquad (4)$$

From (4), FB effect can be interpreted as the interference of S and P amplitudes (waves). If the incident neutrons are polarized and more than 2 resonances are describing the compound nucleus states then the expressions (3) and (4) become more complexes [3–5].

RESULTS AND DISCUSSIONS

Cross sections, angular distribution and FB effect in the ^{109}Ag(n,γ)^{110}Ag reaction with slow and resonant neutrons were evaluated. Calculations were realized in the frame of mixing states of compound nucleus with the same spins and opposite parities and two levels approximation [4]. According to [4], parity violation and asymmetry effects can be observed in the presence of two S and P resonances, in the vicinity of P state [4]. Spin, parities, energies and widths are taken from [7]. In the calculations, spin and parities of S and P resonances with energies E_s = 30.6 eV and E_p= 32.7 eV are $J^{\mathrm{H}}_{s,p} = 1^{\pm}$, respectively. Expressions of differential cross section and FB effect are given in relations (5) and (6).

$$\frac{d\sigma}{d\Omega}(E_n,\theta) = \frac{g\lambda_n^2}{4}\left[\frac{\Gamma_n^S\Gamma_\gamma^S}{S[E_n]} + \frac{\Gamma_n^P\Gamma_\gamma^P}{P[E_n]}\right] + \frac{3\lambda_n^2}{80\sqrt{7}}\left[\frac{\Gamma_n^P\Gamma_\gamma^P}{P[E_n]}\left(4X_nY_n + \sqrt{2}Y_n^2\right)Y_n^2 P_2(\cos\theta)\right] +$$
$$+\frac{3\lambda_n^2}{10} cfb1(E_n)\left[\left(\frac{Y_n}{\sqrt{2}} - X_n\right)\left(\frac{X_\gamma}{\sqrt{3}} - Y\gamma\right)\right]P_1(\cos\theta), \qquad (5)$$

$$\alpha_{FB}(E_n)=\frac{\left(\frac{Y_n}{\sqrt{2}}-X_n\right)\left(\frac{X_\gamma}{\sqrt{3}}+Y_\gamma\right)cfb1(E_n)}{cf\,2(E_n)+cf\,3(E_n)\left(4X_nY_n+Y_n^2\right)Y_\gamma^2}\,, \tag{6}$$

where λ_n is the neutron wave length; g is the statistical factor; E_b is the neutron incident energy; $\Gamma_{n,\gamma}^{S,P}$ are the neutron and gamma widths in S and P sates respectively; $X_{n,\gamma}, Y_{n,\gamma}$ are the neutron and gamma reduced partial widths having the properties $X_n^2+Y_n^2=1; X_\gamma^2+Y_\gamma^2=1$.

Differential cross section (5) contains the isotropic term (not depending on polar angle), the term proportional to $P_1(\cos\theta)$ giving the FB effect and the anisotropic term proportional to $P_2(\cos\theta)$. Full description of the functions and parameters describing cross section and FB effect from (5) and (6) is given in [6].

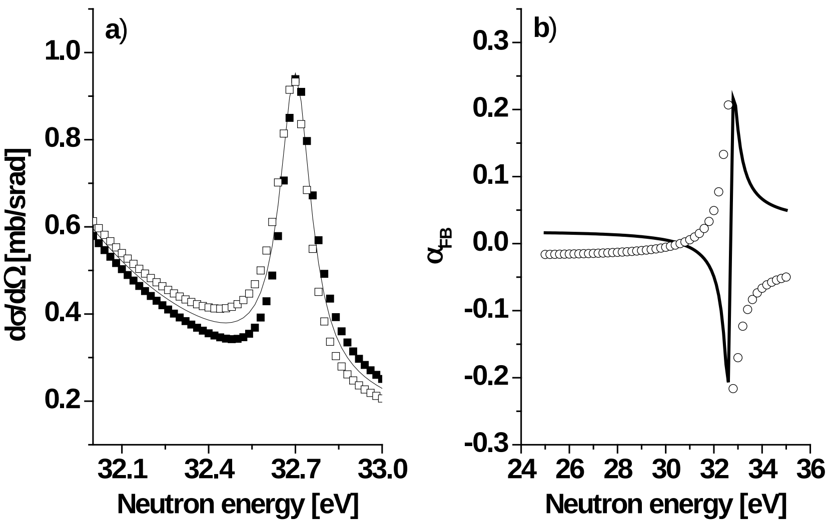

Fig. 1. Energy dependence of a) differential cross section near the p-resonance for 3 polar angles θ: straight line – $\theta = 90^0$; full square – $\theta = 54.73^0$; empty square – $\theta = (180 - 54.73)^0 = 125.27^0$; b) FB effect: full line – $X_n = X_\gamma = -Y_n = -Y_\gamma = 0.707$); empty circles – $X_n = X_\gamma = -Y_n = -Y_\gamma = -0.707$).

Differential cross section is represented in Fig.1a for three angles. From (5), at $\theta = 90^0$ the FB effect is zero. For $\theta = 54.73^0$ and 125.27^0 the Legendre Polynomial of second order is zero and the asymmetry in angular distribution is coming only from FB effect. Theoretical evaluations from Fig. 1a are useful in the analysis of experimental data.

In Fig. 1b the FB effect is represented for two sets of neutron and gamma partial reduced widths (X,Y). Maximum value of the FB effect is around 0.21 but is rapidly decreasing in a less than 1 eV energy interval. This fact can be understood easily also from Fig. 1a where the difference in the cross section in the forward and backward directions is very quickly decreasing. Theoretical results from Figs.1a and 1b were used in the simulation of FB effect experiment. From differential cross section (5), angular correlation $W(\Omega)$ was obtained by dividing to (n,γ) cross section. Then, integral over solid angle Ω of angular correlation $W(\Omega)$ is equal with 1. In this case polar and azimuth angles (θ,φ) can be generated by Direct Monte-Carlo method and they have the following expressions:

$$\theta = \pm ArcCos\left[\frac{-2+\beta}{2(\alpha+\beta)}\left(1 \pm \sqrt{\frac{(-2+\beta)^2}{4(\alpha+\beta)^2} \pm \frac{2+\alpha-4r}{\alpha+\beta}}\right)\right], \quad (7)$$

$$\varphi = 2\cdot\pi\cdot r^{'}; r, r' \in [0,1) - \text{random numbers.} \quad (8)$$

For a point-like target a simple calculation and simulation shows that modeled FB effect is a half of theoretical FB value. In the case of a target with finite dimensions it is necessary to consider neutrons and gamma neutron and gamma loss in the target. Photons and neutrons are attenuated according to the law:

$$N_\gamma = N_{0\gamma} Exp(-\mu x_\gamma) \quad \text{and} \quad N_n = N_{0n} Exp(-n\sigma_{tot} x_n), \quad (9)$$

where N_γ and N_n are the numbers of gammas and neutrons after passing in the target distances x_γ, x_n, respectively; x_γ and x_n are the path of photons and neutrons in the target; $N_{0\gamma}$ and N_{0n} are the initial numbers of gammas and neutrons; μ is the gammas linear attenuation coefficient; n is the atoms density in the target; σ_{tot} is the neutron total cross section.

Using (9) and Direct Monte-Carlo Method, position of photons and neutrons are generated according the formulas:

$$p_\gamma(r,\mu) = -\mu^{-1}\ln(1-r) \quad \text{and} \quad x_n(n,\sigma_{tot},r') = -(n,\sigma_{tot})^{-1}\ln r', \quad (10)$$

where $r, r' \in [0,1) -$ random numbers.

For a target with 2 mm thickness, at the neutrons energy E_n =32.6 eV, where theoretical effect is 0.21, at 10^5 events, the simulated FB coefficient is 0.133. Gammas loss in the target is about 10%. For the same neutron energy and events, for 5 mm thickness, simulated effect is 0.128. Loss of photons is about 17%. In both cases neutrons attenuation is neglected.

Results of theoretical and simulated FB effect are shown in Figs.2a and 2b for 10^5 and 10^6 generated events. Target thickness is 2 mm, gamma attenuation is considered and neutrons one is neglected. Neutrons energy interval is between 28 and 35 eV. The corresponding averaged FB effect is α_{FB}^{theor} = 0.0183. For 10^5 and 10^6 generated events simulated FB coefficients are α_{FB}^{sim} = 0.0149±0.0083 and α_{FB}^{sim} = 0.0135±0.0027, respectively. First, a large difference between theoretical and averaged effect can be observed. This aspect is due to the fact that FB coefficient decreases very fast from maximum value to zero in about 1 eV neutron energy interval. Outside of this 1 eV interval, the effect is zero and large errors can be observed especially for 10^5 events (Fig. 2a). In the region were the effect is close to the maximum, the errors are much smaller. Approximately 70 and 700 events were recorded in each energy bins 0.1 eV (from Fig.2a) and 0.01 eV (Fig.2b), respectively. These aspects also explain the large errors per bin observed in Fig. 2a and their visible reduction in Fig. 2b The absolute errors 0.0083 and 0.0027 are mean absolute errors over the incident energy range from 28 to 35 eV. Until now the attenuation of the neutrons in the target was not considered. Computer simulation of neutrons attenuation on a target of 2 mm thickness for neutrons with energies from 28 to 35 eV is represented in Fig. 3.

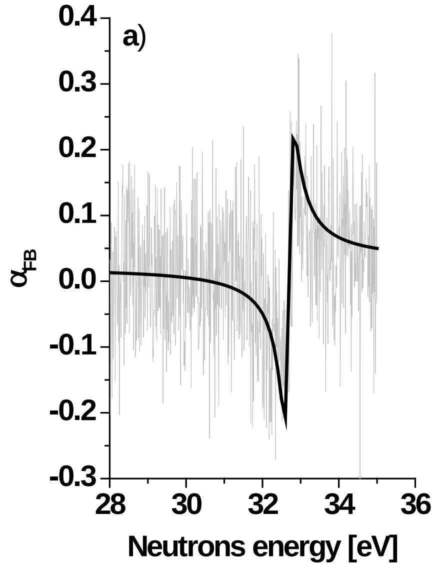

Fig. 2. Comparison between theoretical and modeled FB effect without taking into account of neutrons attenuation. Number of events: a) 10^5; b) 10^6.

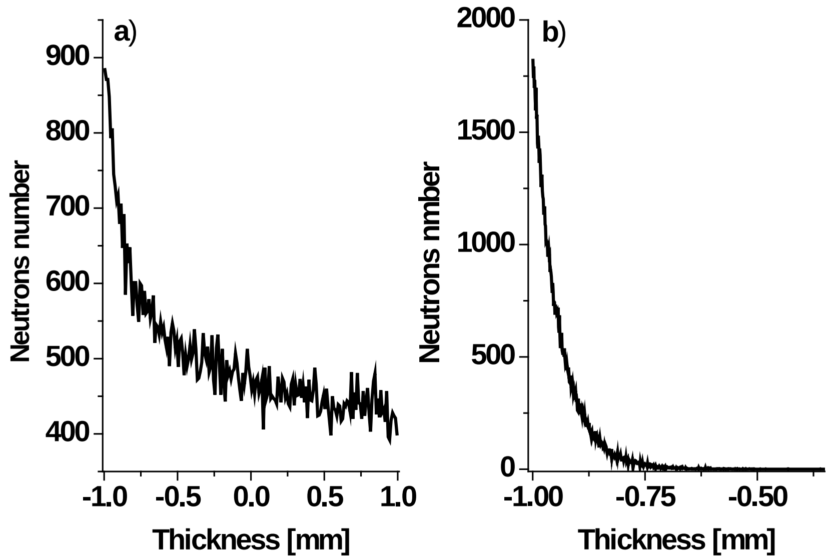

Fig. 3. Incident neutrons attenuation in the target (2 mm thickness). Neutrons energies were taken a) in the intervals from 28 to 35 eV; b) at E_n = 30.6 eV.

Results from Fig. 3 were obtained for 10^5 generated events using relation (9). In Fig. 3a neutrons energy is varying from 28 to 35 eV, the theoretical FB effect is 0.0183 and the incident flux is decreasing more than 4 times. In Fig. 3b, the neutrons energy is 30.6 eV and theoretical FB effect is also 0.0183. Incident flux is decreasing very fast and in 0.25 mm all neutrons are scattered due to the large value of the cross section. For neutrons energy E_n= 32.6 eV, the FB effect has the maximum value 0.21, but the cross section is very small and practically the neutrons which give the maximum effect are distributed almost uniformly in the target. Simulated data from Figs. 3a and 3b are of interest in the designing of a target with optimal dimensions. Taking into account conclusions and results from the last paragraph, FB effect is modeled considering the decreasing of neutrons flux. Results are presented in Figs. 4a and 4b for neutrons with energies from 28 to 35 eV. Number of simulated events is 10^5 in Fig. 4a and 10^6 in Fig. 4b. For 10^5 simulated events the errors are large due to the gamma and neutrons attenuation in the target. If the generated events are increased to 10^6, the errors are decreasing. Averaged theoretical and simulated FB effects between 28 and 35 eV are α_{FB}^{theor} = 0.0183, α_{FB}^{sim} = 0.00556±0.00446, respectively, in Fig. 4a and α_{FB}^{sim} = 0.00694±0.0022 in Fig. 4b. These results show that the neutrons attenuation decrease also the measured FB effect by more than three times and suggests the need to increase the measurement time and take into account the corrections due to gamma and neutron attenuation related to the target thickness.

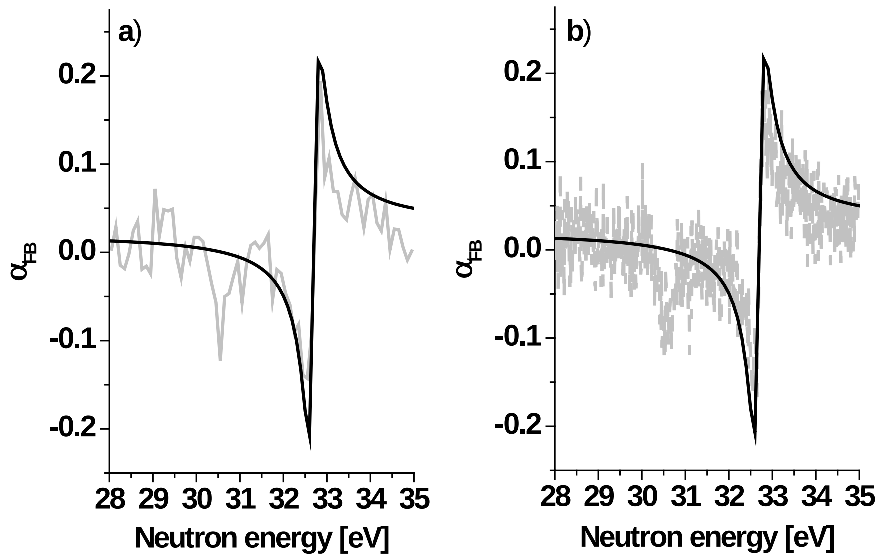

Fig. 4. Comparison between theoretical and modeled FB effect considering neutrons attenuation. Events: a) 10^5; b) 10^6.

CONCLUSIONS

Asymmetry FB effect in slow neutron capture process by ^{109}Ag nucleus was investigated. The theoretical coefficient FB was obtained in the resonant-resonant approach using two-level approximation. Simulation of the effect was carried out using cross sections, angular correlations and FB coefficient applying Direct Monte Carlo Method. Dimensions of the target, gamma and neutron attenuation in the target and other parameters were also considered. It was established that the target dimensions, gamma and neutron attenuations decrease the magnitude of FB value. The maximum value of the FB effect is about 0.21 near the P resonance but it rapidly decreases to zero in the range less than 1 eV. For these reasons it is necessary to look for the effect in a small energy range in the vicinity of the maximum FB effect for a suitable target thickness. Investigation of FB and of other asymmetry and parity-breaking effects provides the possibility to demonstrate the existence of a non-leptonic weak interaction between nucleons by extracting the corresponding matrix element. The present results are of interest in the preparation of measurements of asymmetry and parity breaking effects at the IREN neutron source at FLNP JINR, Dubna.

REFERENCES

1. Yu. G. Abov, P. A. Krupchitsky and Yu. A. Oratovsky, Phys. Lett., **12**, 1, 25 (1964). https://doi.org/10.1016/0031-9163(64)91162-X
2. G.E. Mitchell, J.D. Bowman, S.I. Penttila and E.I. Sharapov, Physics Reports, **354**, 3, 157 (2001). https://doi.org/10.1016/S0370-1573(01)00016-3
3. V. E. Bunakov, Physics of Elementary Particles and Atomic Nuclei, **26**, 2, 285 (1995). http://www1.jinr.ru/Archive/Pepan/1995-v26/v-26-2/pdf_obzory/v26p2_1.pdf
4. V. V. Flambaum and G. F. Gribakin, Prog. Part. Nucl. Phys., **35**, 423 (1995). https://doi.org/10.1016/0146-6410(95)00045-K
5. V. E. Bunakov and L. B. Pikelner, Progr. Part. Nucl. Phys., **39**, 337 (1997). https://doi.org/10.1016/S0146-6410(97)00046-X
6. A.I. Oprea, C. Oprea and V.L. Kuznetsov, Proceedings of the 29th International Seminar on Interaction of Neutrons with Nuclei (ISINN29), 198 (2023). http://isinn.jinr.ru/proceedings/isinn-29/pdf/Oprea2.pdf
7. S.F. Mughabghab, Atlas of Neutron Resonances: Resonance Properties and Thermal Cross Sections, **2**, Amsterdam-Oxford-Cambridge, Elsevier Science (2018).