Angular Correlation Analysis in the Neutrons Capture Process 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, Russian Federation
[2] Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russian Federation
[3] Technical College "Alexandru Roman", Alesd, Bihor county, Romania
[1] National College "Emanuil Gojdu" Oradea, Bihor county, Romania

.

ABSTRACT

Angular distributions in the $^{109}Ag(n,\gamma)^{110}Ag$ reaction were evaluated in the framework of Flambaum-Sushkov's approach and the two-levels approximation. The angular correlation is a pondered sum of Legendre polynomial with coefficients that depend on the energy of the incident neutrons, the partial reduced widths of the incident neutrons, and the emergent gamma. These coefficients are of interest in the evaluation of asymmetry and parity-breaking effects in neutrons induced processes.

Several computer simulations have been done to evaluate the impact of experimental conditions on the angular distribution coefficients and asymmetry effects. The computer evaluation took into consideration the target's dimensions, the attenuation of neutrons and gamma rays, the flux of incident neutrons, and other parameters. Additionally, the analytical expression of the polar angle was obtained by the Direct Monte-Carlo method. Computer analyses have shown that more than 10% of the gamma quanta are lost in the target for a thickness of 1 mm and a transverse area of 1 cm^2. In the case of a 10% forward-backward asymmetry coefficient, edge effects can be neglected. For asymmetry and parity breaking effects, gamma attenuation, edge effects and target dimensions become significant at values below 0.1.

For neutrons at around 30 eV in the $^{109}Ag(n,\gamma)^{110}Ag$ process, where the forward-backward effect is approximately 0.2, the coefficient corresponding to the second-order Legendre polynomial is approximately 0.05. Absolute errors of the forward-backward effect and second order Polynomial Legendre coefficient were also derived under various experiment settings and cross-section experimental precisions.

The results of the simulations are helpful for future measurements of the angular distribution and related asymmetry and parity violation effects, that will be carried out at the neutrons source IREN, the FLNP JINR Dubna's basic facility.

STRUCTURE OF THE PRESENTATION

INTRODUCTION

ASIMMETRY AND PARITY VIOLATONS EFFECTS (SPATIAL AND TIME) ARE TRADITIONALY INVESTIGATED, THEORETICAL AND EXPERIMENTAL, AT FLNP JINR DUBNA

IN 1964 AT FLNP JINR DUBNA FOR THE FIRST TIME WAS EVIDENCED THE EXISTENCE OF SPATIAL PARITY NON CONSERVATION EFFECT (PNC) IN THE CAPTURE OF SLOW POLARIZED NEUTRONS BY CADMIUM NUCLEI (YU. G. ABOV AND COLLABORATORS)

LATER PNC EFFECTS IN THE CAPTURE OF POLARIZED THERMAL NEUTRONS WERE OBSERVED ON LANTHANUM NUCLEI (L.B. PIELNER, V.P. ALFIMENKOV AND OTHER VENERABLE SENIOR SCIENTISTS OF FLNP JINR DUBNA)

PROGRESS IN THEORETICAL INVESTIGATIONS AND EXPERIMENTAL TECHNIQUES ALLOWED TO EVIDENCE PARITY BREAKING EFFECTS IN SLOW AND RESONANCE NEUTRON INDUCED FISSION AND NUCLEAR REACTIONS WITH EMISSION OF CHARGED PARTICLES (PROTONS AND ALPHAS)

ELEMENTS OF THEORY. FORWARD – BACKWARD EFFECT

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

FORWARD – BACKWARD COEFFICIENT
RELATION OF DEFINITION

$$\alpha_{FB}(\theta) = \frac{W(\theta)-W(\pi-\theta)}{W(\theta)+W(\pi-\theta)}$$

FORWARD – BACKWARD COEFFICIENT
GENERAL RELATION OF DEFINITION ARE VERY USEFUL IN THE ANALYSIS OF EXPERIMENTAL AND THEORETICAL DATA

ANGULAR CORRELATION – W(θ)

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

FB EFFECT – UN POLARIZED NEUTRONS

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

RELATION BETWEEN ANGULAR CORRELATION AND DIFF. CROSS-SECTION

AMPLITUDES OF REACTIONS (*f_i*) ARE DEFINED BY THE TYPE OF INTERACTIONS (DIRECT, COMPOUND, PRE-EQUILIBRIUM), PARITY CONSERVING, PARITY BREAKING ETC

ELEMENTS OF THEORY. FORWARD – BACKWARD EFFECT

ASYMMETRY AND PARITY BREAKING EFFECTS WERE DESCRIBED IN THE FRAME OF FLAMBAUM-SUHKOV "RESONANCE-RESONANCE" FORMALISM

THIS FORMALISM PREDICTS THAT ASYMMETRY AND PARITY NON CONSERVATION EFFECTS CAN BE OBSERVED IN THE PRESENCE OF PAIRS OF RESONANCE WITH THE SAME SPINS AND OPPOSITE PARITIES

FORWARD – BACKWARD EFFECT (FB) WILL BE EVALUATED IN THE CASE OF SLOW s, p, NEUTRONS PROCESSES WITH FORMATON OF COMPOUND NUCLEUS.

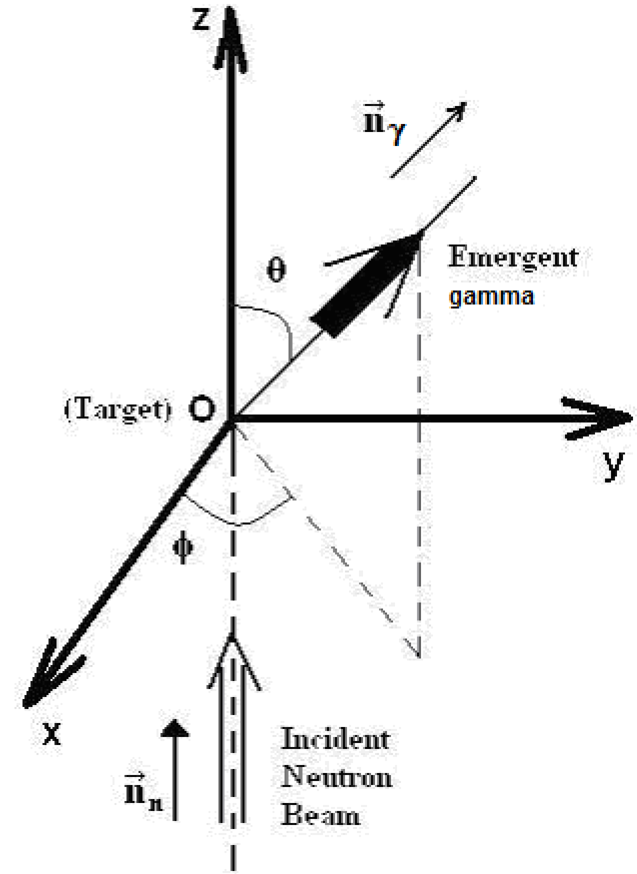
FORWARD BACKWARD EFFECT IS PARITY CONSERVING

ANGULAR DISTRIBUTIONS, CROSS SECTONS AND FB EFFECT CAN BE DESCRIBED BY TWO AMPLITUDES f_1 and f_2

THESE AMPLITUDES REPRESENTS THE CAPTURE OF THE s AND p NEUTRONS FOLLOWED BY EMISSIONS OF GAMMA QUANTA OR CHARGED PARTICES IN THE EMERGENT CHANNELS

ELEMENTS OF THEORY. AMPLITUDES

Geometry of the Experiment



Amplitudes of Reaction

S PROCESS

$$f_1 = -\frac{1}{2k} C^{J_S,J_{Sz}}_{I,I_z,a,a_n} C^{J_S,J_{Sz}}_{I',I'_z,a_f,a_{fz}} \cdot \frac{T_S^n T_S^{f*}}{(E-E_S)+i\frac{\Gamma_S}{2}} Exp(-i\varphi_0)$$

$$f_2 = -\frac{2\pi}{k} \sum_{\substack{j_n,j_{nz},\nu_n \\ j_f,j_{fz},\nu_f}} C^{J_P,J_{Pz}}_{I,I_z,j_n,j_{nz}} C^{j_n,j_{nz}}_{l_n,\nu_n,a,a_n} C^{J_P,J_{Pz}}_{I',I'_z,j_f,j_{fz}} C^{j_f,j_{fz}}_{l_f,\nu_f,a_f,a_{fz}} \cdot$$

$$\cdot \frac{T_P^n(j_n) T_P^{f*}(j_f)}{(E-E_P)+i\frac{\Gamma_P}{2}} \cdot Y^*_{l_n\nu_n}(\vec{n}_n) Y_{l_f\nu_f}(\vec{n}_f) Exp(-i\varphi_1)$$

P PROCESS

BOTH S AND P PROCESSES ARE CONSERVNG SPATIAL PARITY

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

ANGULAR CORRELATION

ELEMENTS OF THEORY. CROSS SECTIONS

S WAVE CONTRIBUTION

$$\left|f_1\right|^2 = \frac{g_S}{4k^2}\frac{\Gamma_S^n \Gamma_S^f}{(E-E_S)^2 + \frac{\Gamma_S^2}{4}}; g_{S,P} = \frac{\left(2J_{S,P}+1\right)}{\left(2I+1\right)\left(2s_n+1\right)}$$

P WAVE CONTRIBUTION

$$\left|f_2\right|^2 = \frac{4\pi^2}{k^2} \sum_{\substack{j_n, j_{nz}, \nu_n \\ j_f, j_{fz}, \nu_f}} C^{J_P, J_{Pz}}_{I, I_z, j_n, j_{nz}} C^{j_n, j_{nz}}_{l_n, \nu_n, a, a_n} C^{J_P, J_{Pz}}_{I', I'_z, j_f, j_{fz}} C^{j_f, j_{fz}}_{l_f, \nu_f, a_f, a_{fz}} \cdot T_P^n(j_n) T_P^{f*}(j_f) Y^*_{l_n \nu_n}(\vec{n}_n) Y_{l_f \nu_f}(\vec{n}_f) \times$$

$$\times \sum_{\substack{j'_n, j'_{nz}, \nu'_n \\ j'_f, j'_{fz}, \nu'_f}} C^{J_P, J_{Pz}}_{I, I_z, j'_n, j'_{nz}} C^{j'_n, j'_{nz}}_{l_n, \nu_n, a, a_n} C^{J_P, J_{Pz}}_{I', I'_z, j'_f, j'_{fz}} C^{j'_f, j'_{fz}}_{l_f, \nu_f, a_f, a_{fz}} \cdot T_P^n(j'_n) T_P^{f*}(j'_f) Y^*_{l_n \nu_n}(\vec{n}_n) Y_{l_f \nu_f}(\vec{n}_f) \times$$

$$\times \frac{\Gamma_P^n(j_n)\Gamma_P^{f*}(j_f)}{(E-E_P)^2 + \frac{\Gamma_P^2}{4}} = \frac{g_P}{4k^2} \cdot \frac{\Gamma_P^n \Gamma_P^f}{\left(E-E_P\right)^2 + \frac{\Gamma_P^2}{4}} + \sum_{L=even=0.2.4....} a_L\left(E, X, Y\right) P_L\left(\cos\theta\right)$$

S - P INTERFERENCE TERM – GIVING FB EFFECT

$$2\,\mathrm{Re}\, f_1 f_2^* = -\frac{2\pi}{k^2}\mathrm{Re}\left[\sum_{\substack{j_n, j_{nz}, \nu_n \\ j_f, j_{fz}, \nu_f}} C^{J_S, J_{Sz}}_{I, I_z, a, a_n} C^{J_S, J_{Sz}}_{I', I'_z, a_f, a_{fz}} C^{J_P, J_{Pz}}_{I, I_z, j_n, j_{nz}} C^{j_n, j_{nz}}_{l_n, l_{nz}, a, a_n} C^{J_S, J_{Pz}}_{I', I'_z, j_f, j_{fz}} C^{j_P, j_{Pz}}_{l_f, l_{fz}, s_f, s_{fn}} \cdot \frac{T_S^n T_S^{f*} T_P^{n*}(j_n) T_P^f(j_f)}{\left[(E - E_S) + i\frac{\Gamma_S}{2}\right]\left[(E - E_P) - i\frac{\Gamma_P}{2}\right]} \times Y_{l_n \nu_n}\left(\vec{n}_n\right) Y_{l_f l_{fz}}\left(\vec{n}_f\right) Exp(-i\Delta\varphi)\right]$$

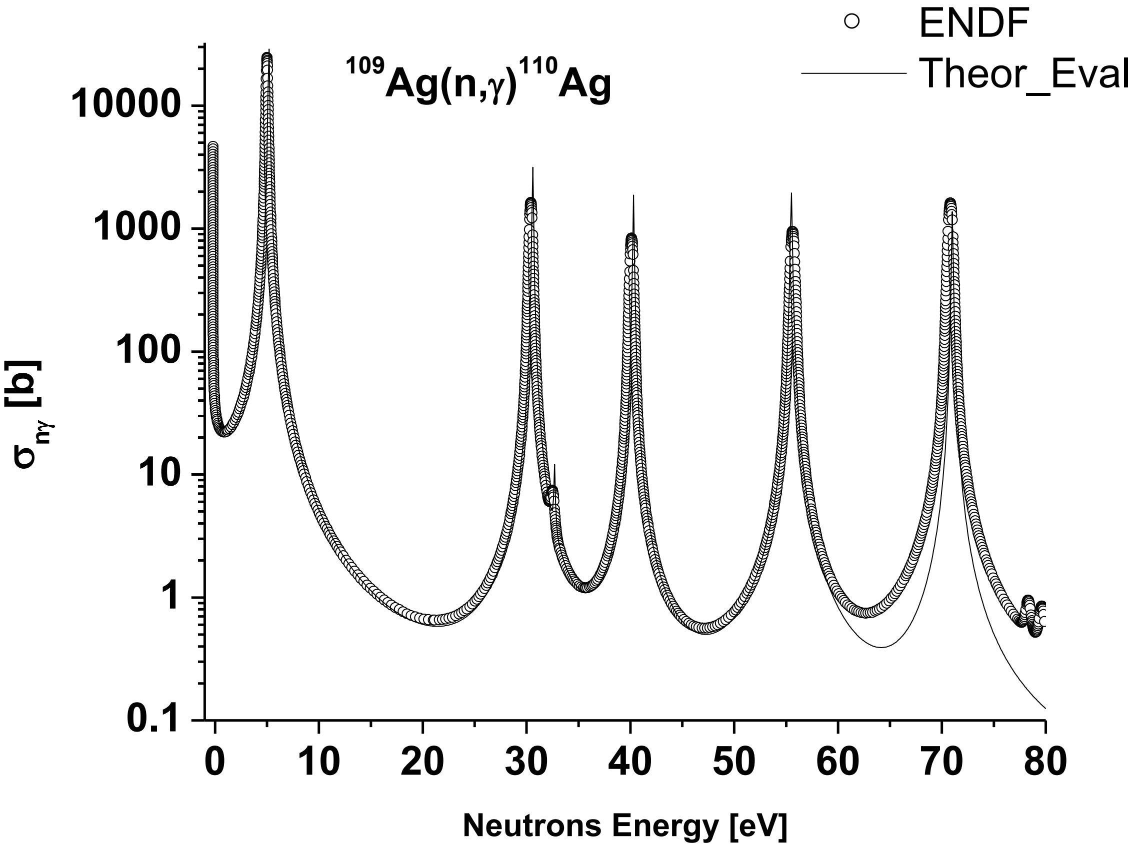
$$2\,\mathrm{Re}\, f_1 f_2^* = \sum_{L = odd = 1,3,\ldots} b_L(E, X, Y) P_L(\cos\theta)$$

$$P_L = Legendre\_Polynomials$$

$$X, Y = \mathrm{Re}duced\_partial\_widths$$

$$\theta = Polar\_angle$$

RESULTS. CAPTURE CROSS SECTION



6 S RESONANCES
1 P RESONANCE

THERMAL NEUTRONS ENERGY E_n = 0.0253 eV

$$\sigma_{n\gamma}^{Exp}\left(E_n = 0.0253eV\right) = 90.49b$$

$$\sigma_{n\gamma}^{Theor}\left(E_n = 0.0253eV\right) = 88.66b$$

CONTRIBUTON OF HIGHER RESONANCES IN THE CROSS SECTIONS CAN BE NEGLECTED

$$\sigma_{n\gamma}^{Exp}\left(E_n\right) = \sum_S \frac{g_S \pi}{k^2} \frac{\Gamma_n^S \Gamma_\gamma^S}{\left(E_n - E_S\right)^2 + \frac{\Gamma_S^2}{4}} + \sum_P \frac{g_P \pi}{k^2} \frac{\Gamma_n^P \Gamma_\gamma^P}{\left(E_n - E_P\right)^2 + \frac{\Gamma_{P\backslash}^2}{4}}$$

RESULTS. FORWARD – BACKWARD EFFECT

^{109}Ag Nucleus – 2 Levels (S and P)

Type	Spin	Parity	Energy
S	1	+	30.6 eV
P	1	-	32.7 eV

OBS. ^{109}Ag – a large number of resonance

DIFFERENTIAL CROSS-SECTION

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

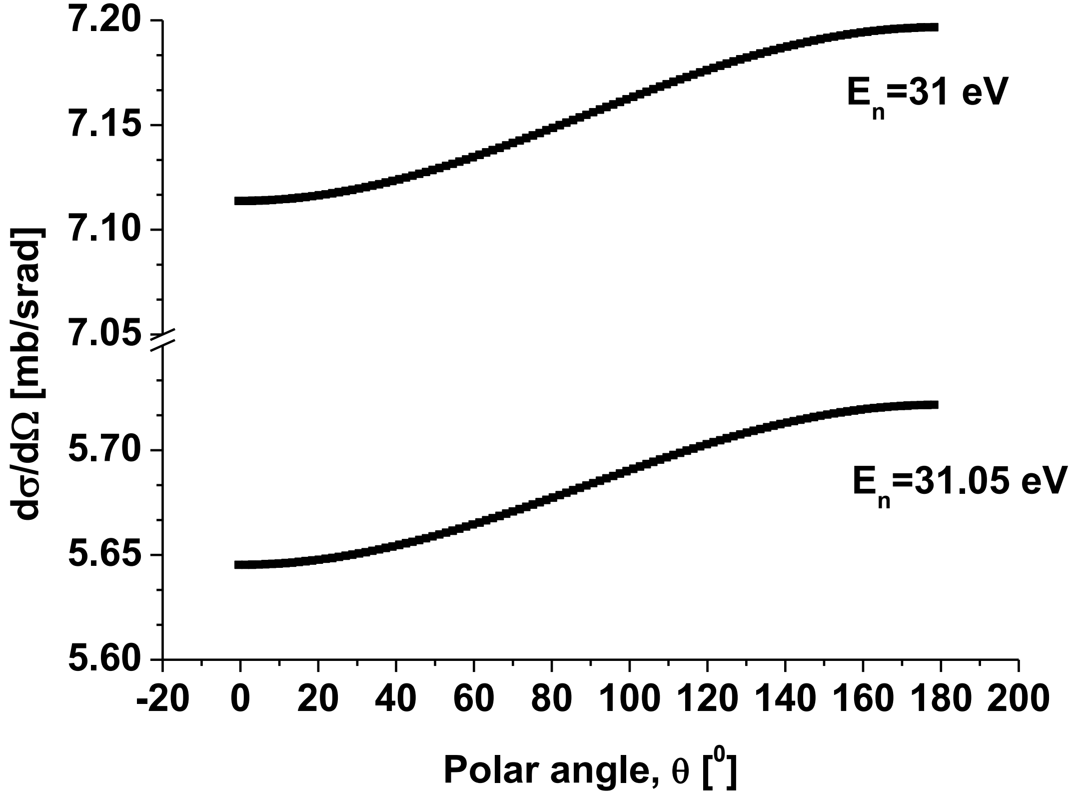
$$+\frac{3\lambda_n^2}{10}cfb1(E_n)\left[\left(\frac{Y_n}{\sqrt{2}}-X_n\right)\left(\frac{X_\gamma}{\sqrt{3}}-Y\gamma\right)\right]P_1(\cos\theta)$$

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

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

$$\Gamma_{S,P}=\Gamma_n^{S,P}+\Gamma_\gamma^{S,P}+\Gamma_p^{S,P}+\Gamma_\alpha^{S,P}+\ldots$$

RESULTS. DIFFERENTIAL CROSS SECTION



DIFFERENTIAL CROSS SECTION CALCULATED NEAR THE ENERGIES WHERE FB EFFECT HAS MAXIMUM VALUE

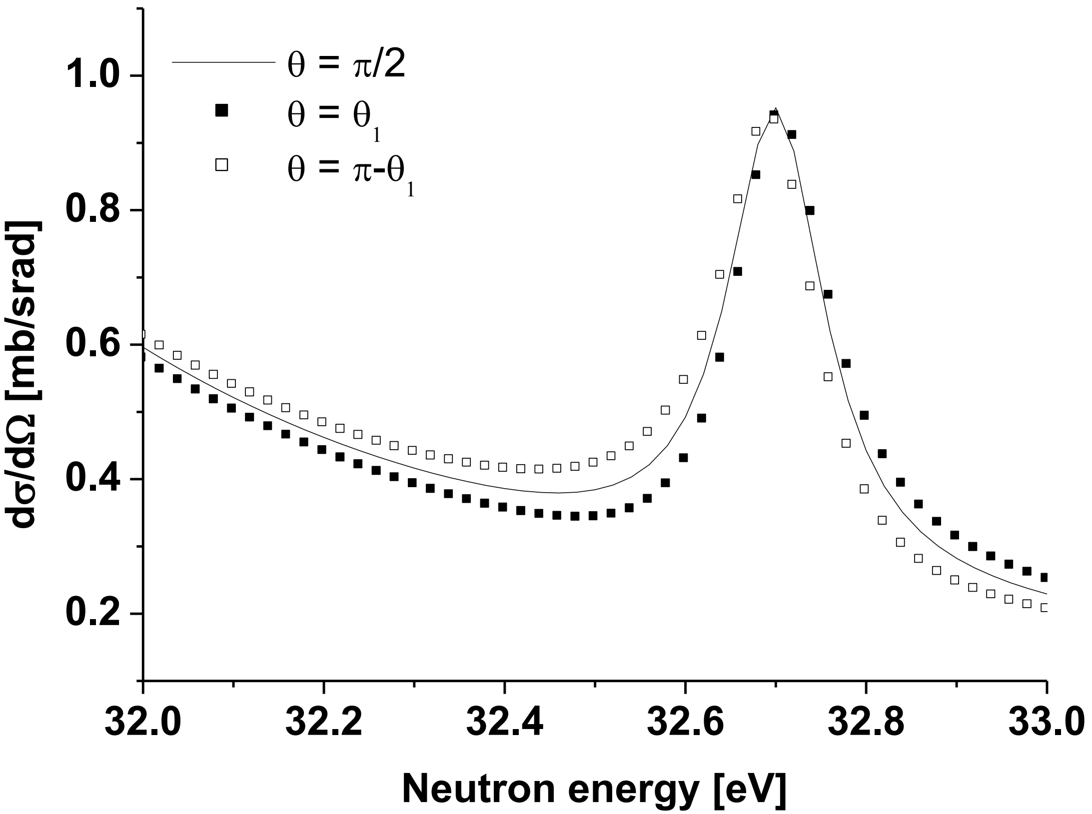
THEORETICAL CALCULATIONS
HAVE INDICATED THE POSSIBLE EXISTENCE OF THE TERM INCLUDING POLYNOMIAL LEGENDRE OF SECOND ORDER

- THE TERM INCLUDING THE LEGENDRE POLYNOMIAL OF SECOND ORDER GIVES ANIZOTROPY IN THE ANGULAR DISTRIBUTION
- THIS TERM DECREASES THE FB EFFECT

IN THE CASE OF SILVER HIS CONTRIBUTION IS VERY LOW MORE THAN TEN TIMES LOWER THAN THE FB TERM

RESULTS. DIFFERENTIAL CROSS SECTION

Differential cross section near the P resonance
E_P = 32.7 eV



Line
$\theta = \pi/2$ – Line – FB effect is zero

Full Square
$\theta = \theta_1$ = 0.955317 rad = 54.73^0
Legendre Polynomial 2nd order is Zero
FB effect is not zero

Empty Sqare
$\theta = \pi - \theta_1$ = 0.955317 rad = 54.73^0
Legendre Polynomial 2nd order is zero
FB effect is not zero

RESULTS. FORWARD – BACKWARD EFFECT

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

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

$$cfb1(E_n)=\frac{\left(2\Gamma_n^S\Gamma_\gamma^S\Gamma_n^P\Gamma_\gamma^P\right)^{1/2}}{P[E_n]S[E_n]}$$

$$\left\{\begin{aligned}&\left[(E_n-E_S)(E_n-E_P)+\frac{\Gamma_S\Gamma_P}{4}\right]\cos\phi-\\&-\left[(E_n-E_S)\frac{\Gamma_P}{2}-(E_n-E_P)\frac{\Gamma_S}{2}\right]\sin\phi\end{aligned}\right\}$$

PARTIAL REDUCED WIDTHS

$$X_n^2+Y_n^2=1;X_\gamma^2+Y_\gamma^2=1$$

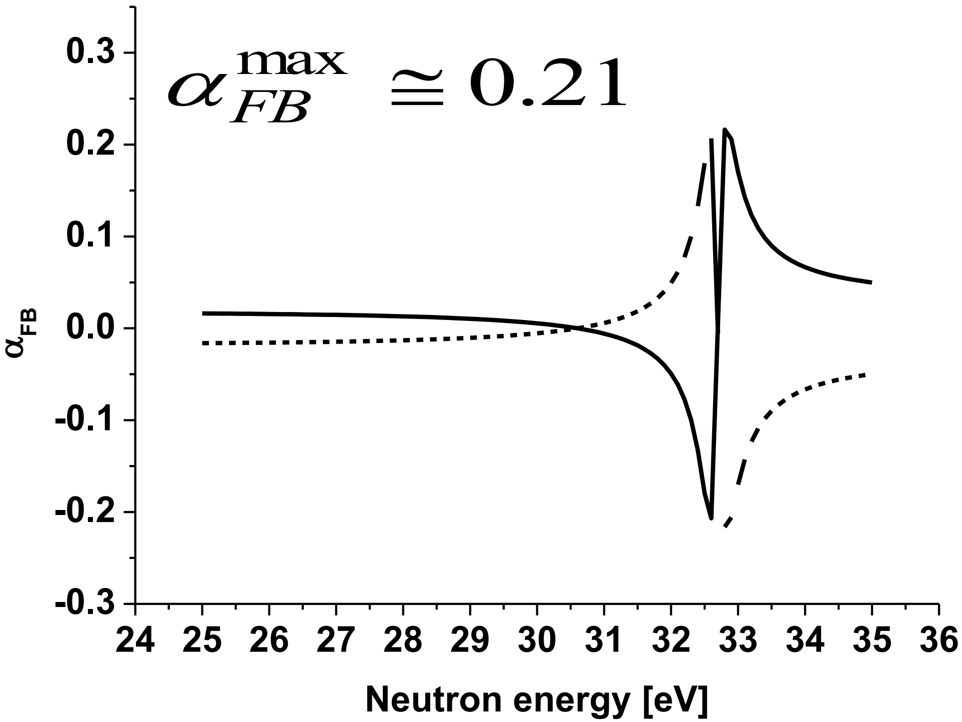
$$X_n=\pm\sqrt{\frac{\Gamma_n^S\left(\frac{1}{2}\right)}{\Gamma_n^S}};Y_n=\pm\sqrt{\frac{\Gamma_n^P\left(\frac{3}{2}\right)}{\Gamma_n^P}}$$

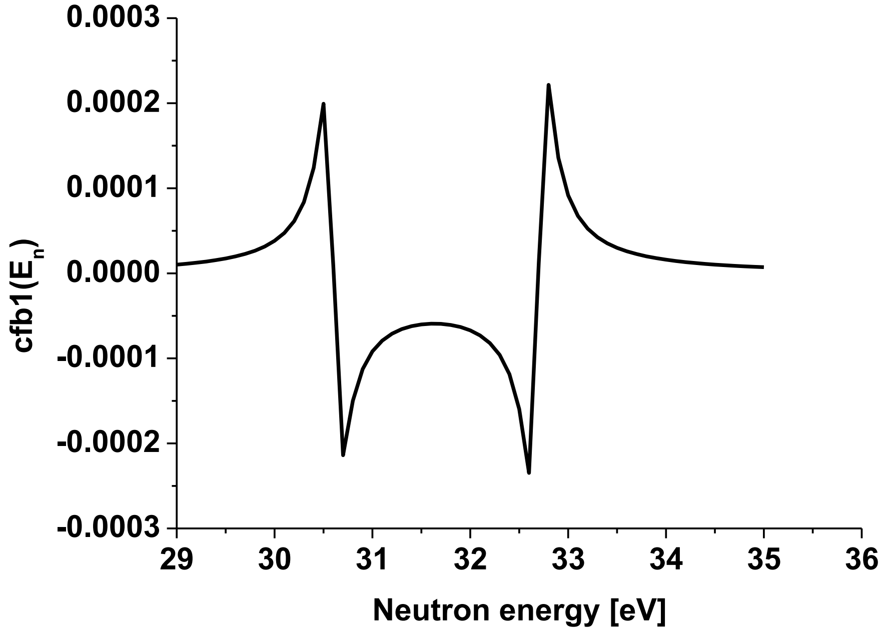
$$X_\gamma=\pm\sqrt{\frac{\Gamma_\gamma^S(l_\gamma)}{\Gamma_\gamma^S}};Y_n=\pm\sqrt{\frac{\Gamma_\gamma^P(l_\gamma)}{\Gamma_\gamma^P}}$$

PHASES

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

RESULTS. FORWARD – BACKWARD EFFECT





FULL LINE

$$X_n = +\frac{1}{\sqrt{2}}; Y_n = -\frac{1}{\sqrt{2}}; X_\gamma = +\frac{1}{\sqrt{2}}; Y_\gamma = -\frac{1}{\sqrt{2}}$$

POINT – SEGMENT LINE

$$X_n = -\frac{1}{\sqrt{2}}; Y_n = +\frac{1}{\sqrt{2}}; X_\gamma = -\frac{1}{\sqrt{2}}; Y_\gamma = +\frac{1}{\sqrt{2}}$$

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

RESULTS. FORWARD – BACKWARD EFFECT. COMPUTER SIMULATION

ATTENUATION OF GAMMA QUANTA IN THE TARGET

$$N = N_0 \cdot Exp(-\mu \cdot x)$$

$$\mu = 0.4cm^{-1} - Ag$$

GENERATION OF THE PATH OF GAMMA

$$p(r,\mu) = -\frac{\ln(1-r)}{\mu}$$

$$r = Random; 0 \le r < 1$$

GENERATION OF AZIMUTH ANGLE

$$\varphi = 2 \cdot \pi \cdot r'$$

$$r, r' \in [0,1) - random\_numbers$$

GENERATION OF POLAR ANGLE

$$\frac{d\sigma}{d\Omega} \sim W(\Omega) = 1 + \alpha'_{FB}\cos(\theta) + \beta\cos^2(\theta) = 1 + \alpha'_{FB}\,\vec{n}_n \cdot \vec{n}_p + \beta(\vec{n}_n \cdot \vec{n}_p)^2$$

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

$$r = Random; 0 \le r < 1$$

RESULTS. FORWARD – BACKWARD EFFECT. COMPUTER SIMULATION

$$d = 2mm - target\_thickness$$

$$E_n = 32.6 eV$$

$$\alpha_{FB} = 0.21$$

$$N_0 = 100000 events$$

$$N_F = 56458; N_B = 43452; (Lost + Emergent)$$

$$Lost\_in\_the\_Target$$

$$N_{Lost} = 9744; N_{Lost}^F = 5332; N_{Lost}^B = 4412$$

$$\alpha_{FB}^{SIM} \cong 0.129 - Without\_lost$$

$$\alpha_{FB}^{SIM} \cong 0.133 - With\_lost$$

$$d = 5mm - target\_thickness$$

$$N_0 = 100000 events$$

$$N_F = 56235; N_B = 43765; (Lost + Emergent)$$

$$Lost\_in\_the\_Target$$

$$N_{Lost} = 17037; N_{Lost}^F = 9440; N_{Lost}^B = 7597$$

$$\alpha_{FB}^{SIM} \cong 0.125 - Without\_lost$$

$$\alpha_{FB}^{SIM} \cong 0.128 - With\_lost$$

$$Point\_like\_Target$$

$$\alpha_{FB}^{sim} = \frac{\alpha_{FB}^{theor}}{2}$$

CONCLUSIONS

INVESTIGATED PROCESS $^{109}Ag(n,g)^{110}Ag$ – WITH SLOW NEUTRONS
- FORWARD – BACKWARD EFFECT WAS OBTAINED APPLYING FLAMBAUM – SUSHKOV RESONANT – RESONANT FORMALISM
- ANGULAR DISTRIBUTION WAS EVALUATED
- OTHER AUXILIARY FUNCTIONS WERE ALSO EVALUATED
- SIMULATED FB-EFFECT WAS EVALUATED FOR POINT-LIKE TARGET AND FOR TARGET WITH FINITE DIMENSIONS CONSIDERING THE ATTENUATION OF GAMMA QUANTA

PRESENT RESULTS - IMPORTANCE
- PREPARATION OF FB AND OTHER EFFECTS MEASUREMENTS AT FLNP

INVESTIGATION OF ASYMMETRY AND SIMETRY BREAING COEFFICIENTS IMPORTANCE
- REACTION MECHANISM
- NEW DATA ON REDUCED PARTIAL WIDTHS -> ATOMIC NUCLEUS STRUCTURE
- ALLOW TO EXTRACT FROM EXPERIMENTAL AND THEORETICAL DATA OF ASIMMETRY AND PARITY VIOLATION EFFECTS MATRIX ELEMENT OF WEAK NON LEPTONIC INTERACTIONS

CONCLUSIONS

PLANS FOR FUTURE

- THE INFLUENCE OF OTHER RESONANCES TO THE FB EFFECT

- EVALUATION OF OTHER ASYMMETRY AND PARITY NON CONSERVING EFFECTS -> NECESSARY TO EXTRACT NON-LEPTONIC WEAK MATRIX ELEMENT

- BACKGROUND EVALUATON

THANK YOU VERY MUCH FOR YOUR ATTENTION :)