Parity Violation Effects in Capture Process of Slow Neutrons on Lead Nucleus

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Abstract. In the capture process of slow neutrons by ^{204}Pb nucleus, asymmetry of emitted gamma quanta was evaluated. Using theoretical and experimental data on scattering and capture process of slow neutrons new information about weak matrix element and negative resonance were extracted.

INTRODUCTION

The measured parity breaking effects, in neutrons scattering were the following: spin rotation per unit length of emitted neutrons for initially transversal polarized neutrons ($d\Phi/dz$) and polarization of emitted neutrons of initially longitudinal polarized neutrons (P) [1]. Preliminary results on capture process are published in [2]. Lead nucleus has a few isotopes but only the isotope ^{204}Pb is responsible for parity breaking effects [3]. Relations of definitions of PV effects together with their theoretical expression can be found in [4, 5].

In the capture and scattering process of slow and cold neutrons on Lead nucleus were observed some unexpected large experimental spatial parity violation (PV) effects in comparison with theoretical evaluations. The differences between theoretical and experimental data were explained by the presence of new, unknown negative P-resonance near neutron threshold [3].

In the present work experimental data and theoretical evaluation of neutrons scattering and capture processes of PV effects on ^{204}Pb were analyzed. Possible existence of a negative resonance was confirmed. Matrix element of weak non leptonic interaction was also extracted.

THEORETICAL BACKGROUND

Parity breaking effects were calculated in the frame of the "resonance-resonance" model. According to this approach, PV and asymmetry effects can be observed in the presence of compound nucleus resonances with the same spins and different parities. Parity breaking effects, coming from weak non leptonic interaction between nucleons, in nuclear reactions are going in the presence of strong interaction which is parity conserving. As it is expected that weak interaction is 2–4 order of magnitude lower than strong nuclear interaction and therefore PV effects have very small values (10^{-7}–10^{-4}) which are difficult to measure in experiment. Using nuclear reaction induced by slow neutrons with formation of compound nucleus in the presence of resonance, PV effects are amplified and they can reach even tens of percents values. A comprehensive description of parity breaking effects and their amplification mechanisms can be found in [6, 7].

In the capture process of slow neutrons by ^{204}Pb nucleus, the asymmetry of emitted gamma quanta A_γ, is defined as [3, 4]:

$$A_\nu = \frac{\sigma_{n\gamma}^{+} - \sigma_{n\gamma}^{-}}{\sigma_{n\gamma}^{+} + \sigma_{n\gamma}^{-}}, \tag{1}$$

where: $\sigma_{n\gamma}^{+}, \sigma_{n\gamma}^{-}$ are neutron capture cross sections with initial longitudinal polarized neutrons with spins parallel (+) and anti-parallel (-) with the direction of incident neutrons.

Cross sections are evaluated based on the amplitude capture process described in [6,7]. The amplitudes of neutrons capture reaction involving spatial parity breaking process (f_{PV}^{SP}, f_{PV}^{PS}) have the following expression [4, 6, 7]:

$$f_{PV}^{SP}(E_n) \sim W_{SP} \frac{\sqrt{\Gamma_n^S \Gamma_\gamma^P}}{\left[(E - E_S) + i\frac{\Gamma_S}{2}\right]\left[(E - E_P) + i\frac{\Gamma_P}{2}\right]} Exp\left(\varphi_n^S - \varphi_\gamma^P\right), \tag{2}$$

$$f_{PV}^{PS}(E_n) \sim W_{SP} \frac{\sqrt{\Gamma_n^P \Gamma_\gamma^S}}{\left[(E - E_S) + i\frac{\Gamma_S}{2}\right]\left[(E - E_P) + i\frac{\Gamma_P}{2}\right]} Exp\left(\varphi_\lambda^S - \varphi_n^P\right), \tag{3}$$

where W_{SP} is weak non leptonic matrix element. $W_{SP} \sim 10^{-4}$–10^{-2} eV<<1; $E_{S,P}$ is energy of S and P resonances, respectively; Γ_n^S, Γ_n^P are neutron widths corresponding to S and P states of compound nucleus; $\Gamma_\gamma^S, \Gamma_\gamma^P$ are gamma widths in the S and P states; Γ_S, Γ_P are total widths for S and P states, respectively ($\Gamma_S = \Gamma_n^S + \Gamma_\gamma^S + \Gamma_p^S + \Gamma_\alpha^S + ...$, $\Gamma_P = \Gamma_n^P + \Gamma_\gamma^P + \Gamma_p^P + \Gamma_\alpha^P + ...$); φ_n^S, φ_n^P are S and P neutrons phases; $\varphi_\gamma^S, \varphi_\gamma^P$ are S and P gamma phases.

Relation (2) represents the capture of neutrons with orbital momentum l=0 (s-neutron), followed by formation of a compound nucleus in S states. Further, due to weak interactions between nucleons in compound nucleus a gamma quantum is emitted from a P state of compound nucleus. Expression (3) describes the process when neutrons with orbital momentum l=1 (p-neutron) are captured, a compound nucleus in a P state is formed, followed by emission of gamma quanta corresponding to an S state of compound nucleus due to the weak interactions between nucleons.

In comparison with expressions (2) and (3), the amplitudes describing nuclear strong interaction, which are parity conserving (f_{PC}^{S}, f_{PC}^{S}) are shown below, [4, 6, 7].

$$f_{PC}^{S} \sim \frac{\sqrt{\Gamma_n^S \Gamma_\gamma^S}}{(E - E_S) + i\frac{\Gamma_S}{2}}, \quad f_{PC}^{P} \sim \frac{\sqrt{\Gamma_n^P \Gamma_\gamma^P}}{(E - E_P) + i\frac{\Gamma_P}{2}} \tag{4}$$

Relations (4) describes the nuclear process which is parity conserving (PC). In the capture process of an s-neutron (or p-neutron), an S (or P) compound nucleus is formed, followed by gamma emission corresponding to S (or P) states of compound nucleus.

For a better understanding of PV and PC phenomena, in the amplitudes from (2–4) expressions, sums of Clebsch-Gordan were not shown. From (2–4) formulas it is obvious that parity breaking and asymmetry effects are coming from the interference of amplitudes described above. Furthermore, theoretical evaluations on other nuclei and reactions like (n,p), (n,n), (n,α) have demonstrated that asymmetry and PV effects can be observed near P resonances. Also, in the resonances, where the cross sections have maximal values the effects are equal with zero. Between resonances, where the cross sections have small values, the effects can reach maximal values. From these, can be concluded that the measurements of PV effects which are acting in the background of nuclear forces, represents a very difficult and accurate task [2], [4–8].

RESULTS AND DISCUSSIONS

Asymmetry of emitted gamma quanta in $^{204}Pb(n,\gamma)^{205}Pb$ capture reaction from slow and cold neutrons up to 500 eV was evaluated in accordance with relation (1). Cross section, for parallel and anti-parallel spin orientation of incident neutrons relative to their initial direction was calculated applying Flambaum-Sushkov approach [4–8]. Were analyzed also the influence of first 10 resonance of ^{205}Pb compound nucleus and it was concluded that for incident cold and slow neutrons contribution to the PV effects are coming only from the first 2 resonances, an S and P resonance respectively. Energy, spin and parity of S and P states of compound nucleus are respectively: $E_S = -2980$ eV, $J^{\Pi} = (1/2)^{+}$ and $E_S = 450$ eV, $J^{\Pi} = (1/2)^{-}$ [9]. Taking into account all above, using the two levels approximation in the frame of the formalism of the mixing states of the compound nucleus with the same spins and opposite parities, asymmetry of emitted gamma quanta (A_γ) has the form:

$$A_\gamma = \frac{2}{\sqrt{3}} W_{SP} ƛ_n^2 \Gamma_S^n \sqrt{\Gamma_S^\gamma \Gamma_P^\gamma}\, c_{PNC}(E_n) / ([S][P]) / \left(\sigma_S^\gamma(E_n) + \sigma_P^\gamma(E_n)\right), \tag{5}$$

$$c_{PNC}(E_n) = (E_n - E_P) Cos[\Delta\varphi(E_n)] - \frac{\Gamma_P}{2} Sin[\Delta\varphi(E_n)], \tag{5.1}$$

$$[S] = (E - E_S)^2 + \frac{\Gamma_S^2}{4},\ \ [P] = (E - E_P)^2 + \frac{\Gamma_P^2}{4}, \tag{5.2}$$

$$\sigma_S^\gamma(E_n) = g_S \pi ƛ_n^2 \Gamma_n^S \Gamma_\gamma^S [S]^{-1},\ \ \sigma_P^\gamma(E_n) = g_P \pi ƛ_n^2 \Gamma_n^P \Gamma_\gamma^P [P]^{-1}, \tag{5.3}$$

$$g_S = (2J_S + 1)[(2I+1)(2s+1)]^{-1},\ \ g_P = (2J_P + 1)[(2I+1)(2s+1)]^{-1}, \tag{5.4}$$

where: $ƛ_n$ is reduced neutrons wave length; $J_S = J_P = 1/2$ are spins of compound nucleus in S and P states, respectively; $I = 0$ is spin of target nucleus; $s = 1/2$ is neutron spin.

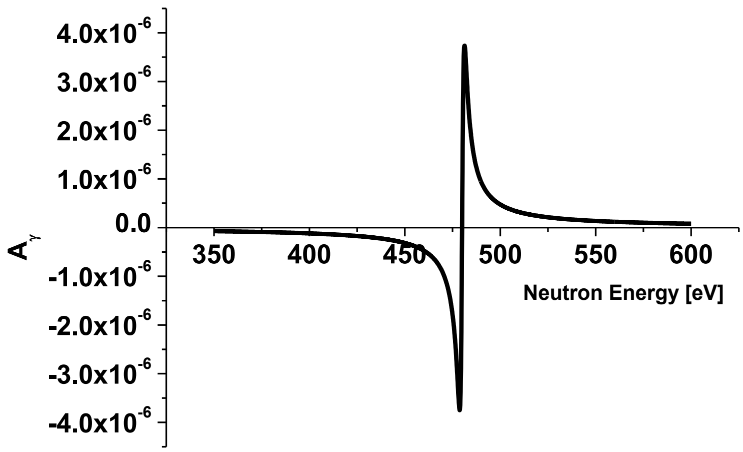

Fig. 1. Energy dependence of A_γ

Neutrons energy dependence of the asymmetry of emitted gamma quanta is represented in Fig. 1.

In the vicinity of P-resonance (E_P = 480 eV), A_γ has maximal value and is decreasing quickly faraway from resonance. In the resonance $A_\gamma(E_n = E_P = 480\ \text{eV}) = 0$.

In reference [5] parity breaking effects like polarization of emitted neutrons (P) and neutrons spin rotation (dΦ/dz) in the scattering of cold and slow neutrons were analyzed. Using neutrons resonance parameters from [9] a serious difference between experimental data [1] and theoretical evaluations [5] was observed. Results are shown below.

$$\frac{d\Phi}{dz}^{theor}\left(E_n = 3.27\cdot 10^{-3} eV\right) = \pm 2.41\cdot 10^{-8} rad/cm -> \\ \frac{d\Phi}{dz}^{\exp}\left(E_n = 3.27\cdot 10^{-3} eV\right) = \left(2.47 \pm 0.23\right)\cdot 10^{-4} rad/cm \tag{6}$$

$$P^{theor}\left(E_n = 1.767\cdot 10^{-3} eV\right) = \pm 1.41\cdot 10^{-8} -> P^{\exp}\left(E_n = 1.76\cdot 10^{-3} eV\right) = \left(0.7 \pm 0.8\right)\cdot 10^{-6} \tag{7}$$

Due to undetermined phases sign, the $\pm$ sign appears in the expression of theoretical evaluation. The high difference between theoretical and experimental data, in resonant-resonant approach, was explained by the presence of a negative P-resonance near the threshold. Based on qualitative analysis of only polarization data (P), the energy of new P-resonance was suggested to be, E_P = –16 eV [3]. It was clear that new data are necessary to be included because in reference [3] the value of weak matrix element W_{SP} was supposed to be of order of 10^{-4} eV.

In [5] the authors added theoretical and experimental data of neutrons spin rotation (see (6) and (7)) and for the first time the energy of P-resonance and the value of weak matrix element were extracted. The obtained results are the following:

$$E_P = -18\,\text{eV}, \qquad W_{SP} = 2.79\cdot 10^{-3}\,\text{eV} \tag{8}$$

Results from (8) are obtained by neglecting capture channel in the case P-resonance. In reference [2] gamma asymmetry (A_γ) was measured and cannot by higher than a certain value as shown below:

$$A_\lambda^{\exp}\left(3.27\cdot 10^{-3}\right) = 5\cdot 10^{-7} \tag{9}$$

From here, result that capture data are necessary to be added. Therefore, using expression (5) together with existing measurement (9), scattering theoretical and experimental data of (P) and (dΦ/dz) (see (6), (7)), weak matrix element W_{SP}, energy of P-resonance E_P and gamma width Γ_γ^P were extracted and their values are the following:

$$E_P = -23\,\text{eV},\ W_{SP} = 3.40\cdot 10^{-3}\,\text{eV},\ \Gamma_\gamma^P = 4.73\cdot 10^{-6}\,\text{eV} \tag{10}$$

Considering scattering and capture theoretical evaluations and existing experimental data the hypothesis of the existence of a P-negative resonance near the threshold is once again confirmed. The effect of the presence of the new P-negative resonance is very difficult to observe in the cross section due to the very small value of gamma width (Γ_γ^P) (see (10)).

CONCLUSIONS

Capture and scattering PV process of slow and cold neutrons on ^{204}Pb nucleus were analyzed. Theoretical data of PV process were evaluated in the frame of the model of the mixing states of compound nucleus with the same spin and opposite parities and two levels approximation. From calculated PV effects and existing experimental data the existence of a P-negative resonance near the threshold is confirmed. The values of P-resonance energy, weak matrix element and gamma width were also extracted. Due to the very low values of PV effects their measurements are very difficult and presented data have large absolute errors. For the improvement of future results are necessary new experimental data in a wide energy range which can be obtained at high intensity neutrons sources.

The present work represents a proposal for new PV effects measurements both at basic facilities of FLNP JINR in Dubna and of neutron centers abroad.

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