Evaluation of parity violation effects for thermal neutrons scattering on ^{204}Pb nucleus

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Abstract. Isotopes of Lead are suitable for studies of parity violation effects in nuclear reactions. We have estimated the energetic dependences of some of these effects in the elastic scattering of thermal and resonance neutrons on ^{204}Pb. For this nucleus experimentally was found a great value than expected of the neutron spin rotation. The spin rotation of the transversal polarized neutron beam passing trough the matter was explained by the presence of the weak interaction but in the case of ^{204}Pb the measured unexpected value may indicate also, the presence of an unknown negative resonance of the compound nucleus ^{205}Pb.

Introduction

The presence of the weak interaction between nucleons in compound nucleus leads to the asymmetry effects in nuclear reactions. In the elastic scattering of neutrons some of these effects which can be measured in the experiment are [1]: the asymmetry of the emitted neutrons, the spin rotation of the transversal polarized neutrons beam and the longitudinal polarization of an initial unpolarized neutrons beam.

We used the approach very well described in [1] and applied the obtained formulas in the case of ^{204}Pb. First we used for our estimation of the mentioned parity violation effects the resonance parameters from [2] and after that the parameters for unknown negative *P* resonance proposed in [3] in order to explain the big unexpected value for spin rotation.

The natural Lead is a mixing of four isotopes with following masses and abundances *204 (1.43%), 206 (24.15%), 207 (22.4%)* and *208 (52.4%)*. The isotope ^{208}Pb is double magic and therefore all Lead isotopes have low levels densitie [3]. The analysis effectuated in [3] suggested that the main contribution to the spin rotation comes mainly from ^{204}Pb isotope. The experimental value for the spin rotation is of order of a few units of 10^{-6} [4, 5]. This value is of three order higher than the theoretical estimation [3].

In this work we evaluate the energetic dependence of the three mentioned effects in the two levels approximation for elastic scattering of neutrons on ^{204}Pb nucleus, first using the resonance parameters from [2]. After we compare the results with the values obtained with parameters for negative resonance from [3]. According with [2] the *S* and *P* resonance parameters for ^{204}Pb nucleus with widths parametric expressions from [2] and [6] are:

$$E_S = -2980\ eV \text{ and } E_P = 480\ eV \tag{1}$$

The negative *P* resonance parameters proposed in [3] extracted from the comparison between experimental [4, 5] and theoretical values [3] are :

$$E_P = -16\ eV \text{ and } \Gamma_P = 3 \times 10^{-3}\ eV \tag{2}$$

Main formulas

Now it is the time to define the parity violation effects. Let suppose that we have a transversal polarized neutrons beam interacting with a target nucleus. Due to the presence of weak interaction, in the process of scattering in the outgoing channel appears an asymmetry of scattered neutrons and by definition this effect has the following form:

$$\alpha = \frac{\frac{d\sigma(\uparrow)}{d\Omega} - \frac{d\sigma(\downarrow)}{d\Omega}}{\frac{d\sigma(\uparrow)}{d\Omega} + \frac{d\sigma(\downarrow)}{d\Omega}} \tag{3}$$

$\frac{d\sigma(\uparrow)}{d\Omega}, \frac{d\sigma(\downarrow)}{d\Omega}$ = differential cross section of scattered neutrons with spin up (↑) and down (↓) related to the initial neutrons spin direction.

For the rotation angle of initial neutron spin on length unit we have:

$$\frac{d\Phi}{dz} = -N\lambda \operatorname{Re}(f_+ - f_-) \tag{4}$$

With simple transformations the neutron rotation angle can be written as:

$$\Phi = \frac{1}{N\sigma_{tot}} \cdot \frac{d\Phi}{dz} = \frac{\operatorname{Re}(f_- - f_+)}{\operatorname{Im}(f_- + f_+)} \tag{5}$$

The terms in relations (4), (5) are: N = number of target nucleus on volume unit, λ = neutron wave length, f_+, f_- = scattering amplitude on zero degree direction with positive (+) and negative (-) neutron spirality, σ_{tot} = the total cross section.

The last effect is the longitudinal polarization of an incident not polarized neutron defined by the relation:

$$P = \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+} \tag{6}$$

σ_-, σ_+ = total cross section with negative (-) and positive (+) spirality.

The physical quantities defined in relations (3), (4) and (6) correspond to the following correlations between main vectors (as neutron spins and neutron initial and outgoing directions):

$$\alpha \to \left(\vec{\sigma}_i \cdot \vec{n}_f\right),\ \Phi \to \left(\vec{\sigma}_i \times \vec{\sigma}_f\right) \cdot \vec{n}_f\ ,\ P \to \left(\vec{\sigma}_f \cdot \vec{n}_f\right) \tag{7}$$

$\vec{\sigma}_i, \vec{\sigma}_f, \vec{n}_i, \vec{n}_f$ = initial (i) and final (f) unit vectors of neutron spin and impulse directions.

Using the relations of definition (3), (4), (6) and the approach described in [1] we have obtained the following expressions for the asymmetry of emitted neutrons (α), rotation angle of outgoing neutron spin (Φ) and longitudinal polarization (P) in the two levels approximation in the case elastic scattered neutrons on ^{204}Pb nucleus:

$$\alpha = 2W_{SP}\sqrt{\Gamma_S^n\Gamma_P^n}\,\frac{\Gamma_S^n(E-E_P)-\Gamma_P^n(E-E_S)+2kR(E-E_S)(E-E_P)}{(\Gamma_S^n)^2[P]+(\Gamma_P^n)^2[S]+4(kR)^2[S][P]} \tag{8}$$

$$\Phi = \frac{4W_{SP}\sqrt{\Gamma_S^n\Gamma_P^n}}{[S][P]}\cdot\frac{(E-E_S)(E-E_P)-\dfrac{\Gamma_S^n\Gamma_P^n}{4}}{\dfrac{\Gamma_S\Gamma_S^n}{[S]}+\dfrac{\Gamma_P\Gamma_P^n}{[P]}+4(kR)^2} \tag{9}$$

$$P = -2W_{SP}\sqrt{\Gamma_S^n\Gamma_P^n}\,\frac{(E-E_S)\Gamma_P+(E-E_P)\Gamma_S}{\Gamma_S\Gamma_S^n[P]+\Gamma_P\Gamma_P^n[S]+4(kR)^2[S][P]} \tag{10}$$

The factors of $(kR)^2$ present in (8-10) are due to the potential scattering included in calculations. The elements of (8-10) are: Γ_S, Γ_P = total S, P widths, Γ_S^n, Γ_P^n = neutron S, P widths, E_S, E_P = S, P resonance energy, k = neutron wave number, R = nucleus radius, W_{SP} = weak matrix element; $[S]=(E-E_S)^2+\frac{\Gamma_S^2}{4}$, $[P]=(E-E_P)^2+\frac{\Gamma_P^2}{4}$.

Results

Experimental results for the spin rotation around the impulse direction of polarized transversal neutrons are [3-5]:

$$\Phi = (2.24 \pm 0.33)\cdot 10^{-6} \text{ and } \Phi = (3.53 \pm 0.79)\cdot 10^{-6}\,\text{rad} \tag{11}$$

Using the resonance parameters from [2] and considering for the weak matrix element a value of order of $W_{SP} = 2\cdot 10^{-4}\ eV$ (fair value for heavy elements [1], [3]) the theoretical estimation gives for spin rotation for thermal neutrons the result:

$$\Phi = -6.28\cdot 10^{-8}\,\text{rad} \tag{12}$$

With P resonance parameters suggested in [3] ($E_P = -16\ eV$) and S resonance parameters from [2] we have for spin rotation a value in a very good agreement with experimental data (11):

$$\Phi = 1.88 \cdot 10^{-6} \text{ rad} \tag{13}$$

The asymmetry (α) and longitudinal polarization (P) for incident thermal neutrons are of order of 10^{-15} and 10^{-11} respectively with parameters from [2] and higher with resonance parameters from [3] (10^{-14} and 10^{-8} order magnitude) but still very difficult to measure in the experiment and therefore we did not insisted in the analysis of them.

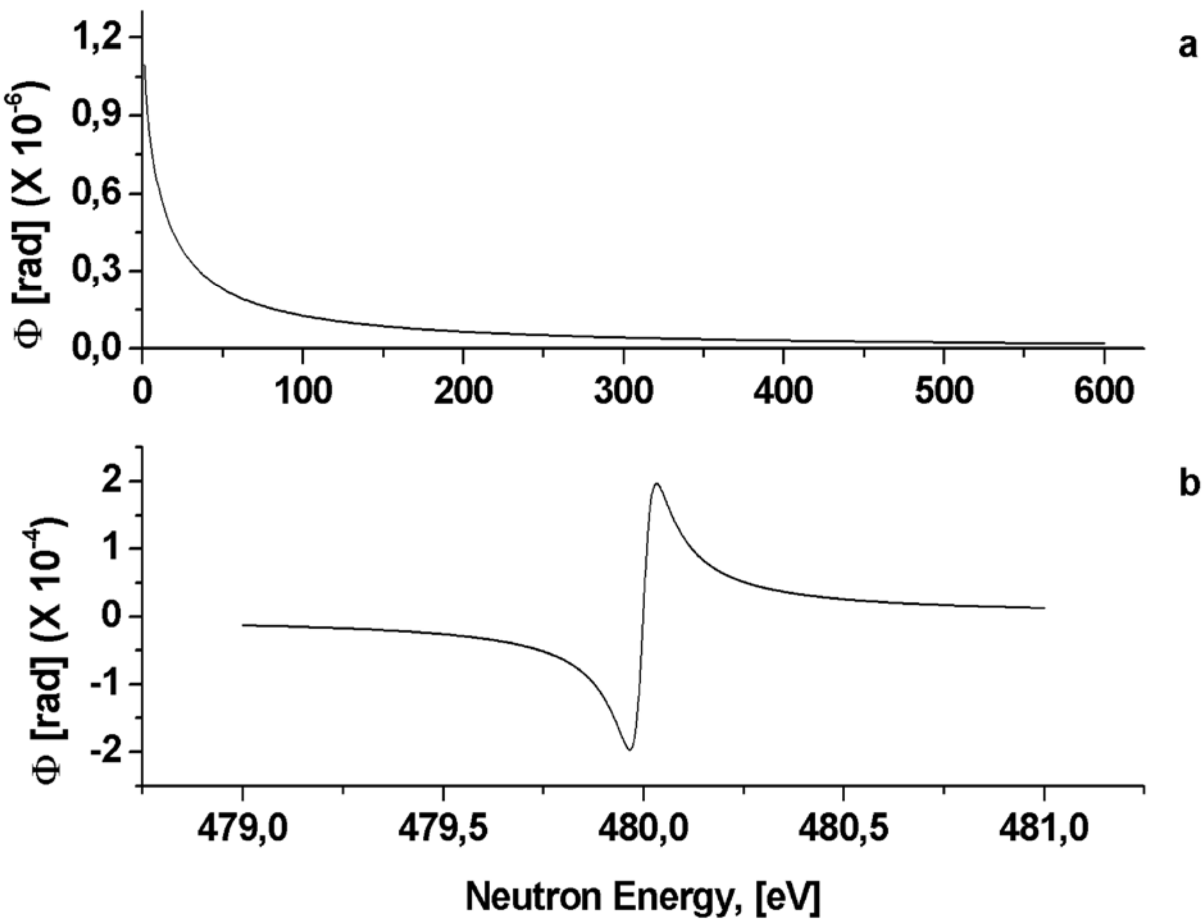

Figure 1. Spin rotation for neutrons scattering on ^{204}Pb in the two levels approximations using
a) parameters from [3] supposing the existence of negative P resonance, $E_P = -16\ eV$
b) parameters from [2] around the S resonance with $E_S = 480\ eV$ energy

In Figure 1 we have illustrated two interesting cases of spin rotation angle using different resonance parameters. In the case a) due to the fact that in the estimation we used two negative resonances (one S and one P) the spin rotation angle is decreasing with the energy. In the second b) case with one S negative resonance ($E_S = -2.98\ keV$) and one P resonance ($E_P = 0.48\ keV$) we obtained the well known expected shape of asymmetry effects in the two levels approximation estimated by authors for *(n,p)* reaction for ^{35}Cl and ^{14}N [7] nuclei.

We have obtained the energetic dependences in the scattering of neutrons on ^{204}Pb nucleus for other parity violation effects i.e. asymmetry of emitted neutrons (α) and longitudinal polarization (P) but there are not presented here because they are some order of magnitude lower than the spin rotation (Φ) and therefore very difficult to be experimentally measured but their shape are similar to those from Figure 1 a) and b).

Discussion

We have evaluated the asymmetry effects due to the presence of weak interaction in the two levels approximation using two sets of resonance parameters [2], [3]. The parameters from [2] are universal accepted but the evaluated effects for thermal incident neutrons energy ($E_{th} = 0.0253\ eV$) have very low values that are very difficult to measure experimentally. As we mentioned before the coefficients α and P in the thermal point are lower than 10^{-10} and the spin rotation Φ is of order of 10^{-8}.

The situation is changing in better with resonance parameters from [3] where the main idea is that the author had obtained from experimental data and theoretical evaluation in the two levels approximation for thermal energy the existence of an negative P resonance with energy $E_P = -16\ eV$. The α and P effects increase with two or three order of magnitude and the spin rotation Φ is of order $10^{-5} - 10^{-6}$ in a very good agreement with the experiment (see relations (11-13)). This fact makes sense to effectuate an experiment for measurement of spin rotation angle of neutrons scattered on ^{204}Pb in thermal region.

In Figure 1 a) and b) we have the energetic dependence of spin angle rotation for the two sets of resonance parameters. From Figure 1 b) (resonance parameters from [2]) results that around the P resonance $E_P = 480\ eV$ the spin rotation reaches the values 10^{-4}, change it sign in a very short energy interval (about 2 eV) and is zero in the resonance. In the experiment it is more easier to evaluate a 10^{-4} effect but here it is very difficult to find source that can give us the necessary intensity for incident transversal polarized neutrons with energy around $480\ eV$.

Finally it is of interest to evaluate the effect of other resonances in spite of the fact that in many papers their influence is neglected due to the very low value of the cross section.

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References

[1] V.E. Bunakov, V. P. Gudkov, Materials of XVIth Winter School of Leningrad Institute for Nuclear Physics, p. 32-52, UDK 539.172, Leningrad, USSR, 1981 (in Russian)

[2] Mughabghab S.F., Divadeenam M., Holden N.E. – Neutron Cross Sections. NY, Academic Press, 1981, v.2

[3] G. A. Lobov, Yadernaya Fizika v. 63, № 8, p. 1465-1468, 2000 (in Russian)

[4] G. A. Lobov, Preprint of Institute for Theoretical and Experimental Physics (ITEF), ITEF-20, Moscow, 1982 (in Russian)

[5] Heckel B.R. et all., Phys.Lett. v. B119, p.209, 1982

[6] Radiatsionyi zahvat neytronov - Compendium, EnergoAtomIzdat, Moskva, 1986 (in Russian)

[7] A. I, Oprea, C. Oprea, Yu. M. Gledenov, P.V. Sedyshev, C. Pirvutoiu, D. Vladoiu, Romanian Reports in Physics, v.63, № 2, p357-375, 2011