SEARCH FOR P-ODD EFFECTS IN INTERACTION OF POLARIZED NEUTRONS WITH NATURAL LEAD

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Abstract. The lead isotopes have no any suitable pairs of *s*- and *p*-resonances that may be responsible for P-odd effects in reactions with neutrons. Nevertheless, in two independent experiments a large effect of the neutron spin rotation in natural lead sample was observed. Another measurement of $\Delta\phi$ was done with a sample enriched in the ^{204}Pb isotope. The obtained result is somewhat smaller than it is necessary to reproduce the effect in natural lead, but ^{204}Pb could be considered as a source of the *P*-odd effects. To explain this effect in the framework of two levels mixing mechanism the existence of a negative p- wave resonance in ^{204}Pb was suggested. However it is not confirmed experimentally.

Additional information can be obtained from other *P*-odd effects. Using the two levels approximation the *P*-odd effects in the interaction of polarized neutrons with ^{204}Pb isotope were evaluated the followings: the neutron spin rotation, total cross section asymmetry, as well as the asymmetry in radiative capture cross section and the asymmetry of emitted neutrons with respect to the spin of incident neutrons. The calculations were performed for two sets of resonance parameters: 1) for the known resonances of ^{204}Pb with $E_S = -2980\ eV$ and $E_P = 480\ eV$ and 2) for the suggested negative p-wave resonance with energy $E_P = -16\ eV$. The energy dependences of the effects have been obtained. The results have been rescaled to the natural composition of lead isotopes. The calculations are compared with the experimental values from literature. On the base of this analysis two experiments are proposed: the measurement of the asymmetry in total cross section and in radiative capture cross section. Although these effects are much weaker than that in the $\Delta\phi$ measurement *but* the realization of these experiments is much easier methodologically. The experiments are planned to be performed at the PF1B instrument of the ILL reactor. It is shown that with use of our developed technique and equipment we can reach an accuracy of $\sim 1.5\cdot 10^{-8}$ for the first effect and $\sim 7\cdot 10^{-8}$ for the second one for 50 days of measurements.

INTRODUCTION

Low energy nuclear reactions with neutrons, for a long time have demonstrated their importance in the field of fundamental physics. In the scattering of thermal neutrons on heavy nuclei experimentally were evidenced large parity violation effects like spin rotations, longitudinal polarization or asymmetry of emitted neutrons.

Parity violation effects in nuclear reaction were discovered in the ’60 years of the last century in the capture of thermal transversal polarized neutrons by ^{113}Cd nucleus [1]. In this reaction experimentally was measured a non zero asymmetry of emitted gamma quanta and the results was interpreted by the existence of weak non leptonic interaction between nucleons in the compound nucleus. This first experimental result gave a serious impulse of theoretical and experimental developments of parity violation (PV) question in nuclear reactions.

The weak interaction acts in the background of strong interaction (with order of magnitude higher) and therefore it is very difficult to observe and evidence it. One possibility is the evaluation of asymmetry effects induced by PV phenomena.

For neutrons scattering there are a few asymmetry effects (like polarization of incident neutron beam, spin rotation and emitted neutrons asymmetry of incident transversal polarized neutrons) explained by the presence of weak interaction.

In natural Lead were observed an unexpected experimental high value of neutron spin rotation due to the PV phenomena [2]. The natural Lead contains four isotopes (^{204}Pb *(1.43%)*, ^{206}Pb *(24.15%)*, ^{207}Pb *(22.4%)*, ^{208}Pb *(52.4%)*) and the main contribution to the PV effects is given by ^{204}Pb [3]. Further to explain the high value of neutron spin rotation it was supposed the existence of a new negative P resonance with energy $E_P = -16\ eV$ [3].

THEORY. RELATIONS OF DEFINITION. FORMULAS

After the experimental discovery of PV effects in nuclear reaction [2] were proposed a number of theoretical models and approach to explain them. One of the most successful theoretical approaches is the model of the mixing states of the compound nucleus proposed by Flambaum and Sushkov [4, 5]. In this approach the nuclear reaction is going by formation of a compound nucleus which is supposed that is characterized by finite quantum numbers and a set of quantum states (resonances). Resonant states with the same spin and opposite parities “interfere” in the amplitude of reaction due to the weak non leptonic interaction between nucleons. Based on the experimental values of widths [6] in the entrance and outgoing channels the amplitude not conserving the parity due to weak interaction has the form:

$$f_{PV} \sim \frac{\sqrt{\Gamma_f}\langle S|H_{weak}|P\rangle\sqrt{\Gamma_i}}{\left(E-E_S+i\frac{\Gamma_S}{2}\right)\left(E-E_S+i\frac{\Gamma_S}{2}\right)}\exp\left[i\left(\varphi_f-\varphi_i\right)\right] \qquad (1)$$

$W_{SP} = \langle S|H_{weak}|P\rangle$ = weak matrix element between S and P states of compound nucleus

H_{weak} = Hamiltonian of the weak interaction

It is very difficult to evidence the weak interaction because in nuclear reactions it is acting in the background of strong interaction usually with few order of magnitude greater. One appropriate way to measure PV effects it is to use neutron reactions and asymmetry coefficients. The presence of resonances assures the conditions for all amplification mechanisms [4,5,7].

In this work will evaluate the following PV effects in the scattering of thermal and resonant neutrons and they are: the asymmetry of emitted neutrons, the spin rotation and longitudinal polarization. Shortly we describe the mentioned PV effects. In the case of initial transversal polarized neutrons, due to the presence of weak interactions it is possible to measure the asymmetry of emitted neutrons (α). Also, if the incident neutrons are transversal polarized, take place the spin rotation of emitted neutrons (Φ). For incident neutrons longitudinal polarized or unpolarized it appears in the exit channel the longitudinal polarization of emitted neutrons (*P*). All these three effects are result of the presence of weak interaction between nucleons and they can be evaluated by corresponding asymmetry coefficients. The relations of definition of the mentioned three PV effects are [8]:

- asymmetry of emitted neutrons:

$$\alpha = \frac{\frac{d\sigma(\uparrow)}{d\Omega} - \frac{d\sigma(\downarrow)}{d\Omega}}{\frac{d\sigma(\uparrow)}{d\Omega} + \frac{d\sigma(\downarrow)}{d\Omega}} \qquad (2)$$

- spin rotation

$$\Phi = \frac{1}{N\sigma_{tot}} \frac{d\Phi}{dz} = \frac{\mathrm{Re}(f_- - f_+)}{\mathrm{Im}(f_- + f_+)} \qquad (3)$$

- longitudinal polarization

$$P = \frac{\sigma_- - \sigma_+}{\sigma_- + \sigma_+} \qquad (4)$$

Related with spin rotation we have de spin rotation on the length unit and is defined as:

$$\frac{d\Phi}{dz} = N\lambda\,\mathrm{Re}(f_- - f_+) \qquad (5)$$

- $d\sigma(\uparrow\downarrow)/d\Omega$ = differential cross section of scattered neutrons with spin up (↑) and down (↓) related to the initial neutrons spin direction.
- f_+, f_- = scattering amplitude on zero degree direction with positive (+) and negative (-) neutron helicity
- σ_-, σ_+ = total cross section with negative (-) and positive (+) helicity
- N, λ = number of target nuclei on volume unit and neutron wave length

These effects can be also interpreted as correlations between vectors from ingoing and outgoing channels. Then the PV effects from relations (2-5) represent correlations between unit vectors as following:

$$\alpha \to \left(\vec{\sigma}_i \cdot \vec{n}_f\right),\ \Phi \to \left(\vec{\sigma}_i \times \vec{\sigma}_f\right) \cdot \vec{n}_f,\ P \to \left(\vec{\sigma}_f \cdot \vec{n}_f\right) \qquad (6)$$

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

In many cases for incident thermal and resonant neutrons the so called “two levels approximation” it is very useful in order to obtain the order of magnitude and energetic dependences of the effects. In this case if we consider that the compound nucleus can be described by one S state and one P state, formed by interaction of neutrons with orbital momentum $l=0$ and $l=1$ respectively, using the Born approximation and the optical theorem [8] and relations of definition (2-5), the PV effects, α, Φ, P have the form:

$$\alpha = 2W_{SP}\sqrt{\Gamma_S^n\Gamma_P^n}\,\frac{\Gamma_S^n(E-E_P)-\Gamma_P^n(E-E_S)+2kR(E-E_S)(E-E_P)}{(\Gamma_S^n)^2[P]+(\Gamma_P^n)^2[S]+4(kR)^2[S][P]} \qquad (7)$$

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

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

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, R = nucleus radius

$[S]=(E-E_S)^2+\dfrac{\Gamma_S^2}{4}$, $[P]=(E-E_P)^2+\dfrac{\Gamma_P^2}{4}$, $(kR)^2$ = due to the potential scattering which is about of order of magnitude higher than resonance scattering.

For spin rotation on unit length we have:

$$\frac{d\Phi}{dz} = \frac{N\lambda^2}{\pi}\,\frac{4W_{SP}\sqrt{\Gamma_S^n\Gamma_P^n}}{[S][P]}\left\{(E-E_S)(E-E_P)-\frac{\Gamma_S^n\Gamma_P^n}{4}\right\} \qquad (10)$$

PV EFFECTS ON ^{204}Pb

In the scattering of slow neutrons on natural Lead was obtained an unexpected high value of spin rotations. For the energy of incident neutrons $E_n = 1.76 \cdot 10^{-3}\ eV$ were obtained two values for neutron spin rotation on unit length [2].

$$\frac{d\Phi}{dz}^{\exp} = (2.24\pm0.33)\cdot10^{-6}\,rad/cm,\ \frac{d\Phi}{dz}^{\exp} = (3.53\pm0.79)\cdot10^{-6}\,rad/cm \qquad (11)$$

After the correction due to the isotope composition of natural Lead we obtain for ^{204}Pb nucleus the following values:

$$\frac{d\Phi}{dz}^{\exp} = (2.47 \pm 0.23)\cdot 10^{-4}\, rad\,/\,cm\,,\ \frac{d\Phi}{dz}^{\exp} = (1.71 \pm 0.55)\cdot 10^{-4}\, rad\,/\,cm \qquad (12)$$

Comparing these values theoretical evaluation taking into account one *S* and one *P* resonance with parameters from [6] (E_S = *-2980 eV* and E_P = *480 eV*) and relation (10) we obtain for spin rotation at neutron energy $E_n = 1.76 \cdot 10^{-3}$ *eV* the value:

$$\frac{d\Phi}{dz}^{theor} = -2.51\cdot 10^{-8}\, rad\,/\,cm \qquad (13)$$

For other two PV effects with the same resonance parameters and $E_n = 1.76 \cdot 10^{-3}$ *eV* we obtained:

$$\alpha^{theor} = -1.5\cdot 10^{-16},\ \Phi^{theor} = -9.2\cdot 10^{-8} \qquad (14)$$

For thermal neutrons $E_n = 2.53 \cdot 10^{-2}$ *eV* theoretical value for longitudinal polarization is:

$$P^{theor} = -1.5\cdot 10^{-11} \qquad (15)$$

This value is also much smaller than the experimental value obtained for the same incident neutrons energy [9].

$$P^{\exp} = (-0.7 \pm 0.8)\cdot 10^{-6} \qquad (16)$$

Fro theoretical evaluation it is easy to understand that practically the asymmetry α it is impossible to evaluate experimentally and from (160 the longitudinal polarization is situated at the limit of experiment possibilities.

All these after an analysis of existent experimental data and big discrepancies between theoretical and experimental evaluation led the author of [3] to affirm the following: 1) the PV effects in natural Lead is given mainly by ^{204}Pb isotope and 2) the difference between theory and experiment can be explained by the existence of a so called *P* “negative” under the threshold resonance. In [3], using the two levels approximation for slow neutrons the author had proposed for the negative resonance the same neutron widths as proposed in [6] and the energy E_P = *-16 eV*.

With the new values for negative P resonance the theoretical evaluation are:

$$\frac{d\Phi^{theor}}{dz}\left(E_n = 1.75\cdot 10^{-3} eV\right) = 7.54\cdot 10^{-7}\, rad/cm \qquad (17)$$

$$P^{theor}\left(E_n = 0.0253 eV\right) = -2.58\cdot 10^{-8} \qquad (18)$$

The spin rotation is closer to the experimental value (17) and what is important the experimental and theoretical values have the same sign. The longitudinal polarization it has changed with three orders of magnitude but still is far from experimental value (16). The asymmetry of emitted neutrons also still remain very far for experimental possibilities.

Now it is the time to show the energetic dependences of the PV effects (α, Φ, P) because from there shapes it is possible to answer if the negative resonance, with energy E_P = *-16 eV* exist or not.

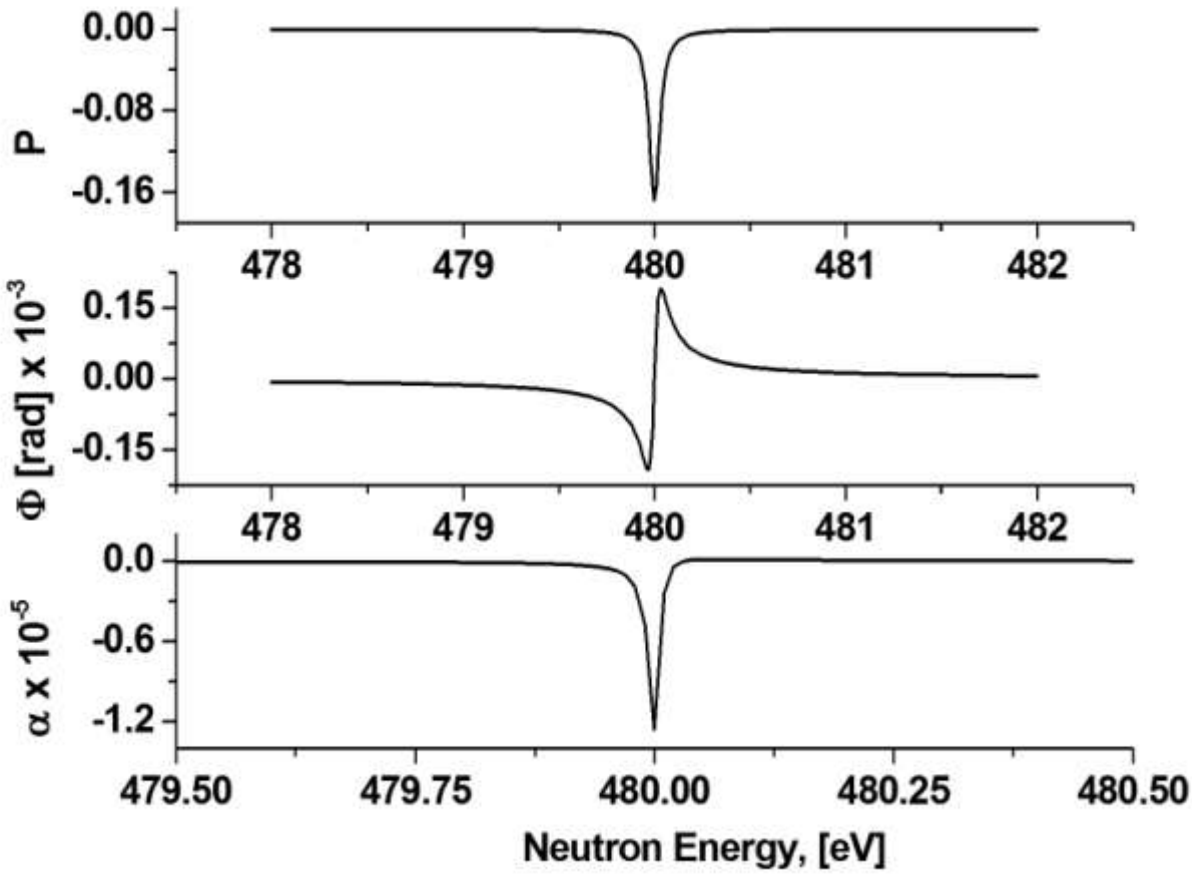

Figure 1. The PV effects in the scattering of neutrons on ^{204}Pb with following resonance parameters: $E_S^+ = -2980\,eV$, $E_P^- = 480\,eV$ [6], $W_{SP} = 2\cdot10^{-4}\,eV$ [8]

The standard set of neutron resonance parameters [6] shows an important modification of PV effects energetic dependences around P resonance (E_P = *480 eV*) with maximal values in the resonance as predicted in [8].

In the case of the existence of the negative resonance (E_P = *-16 eV*) the shape of energetic dependence will be changed. If we neglect the presence of the resonance with energy *480 eV* the dependence is showed in Figure 2. As we can see we have only smooth dependence which is decreasing with energy. If we take into consideration the state with energy *480 eV* the maximum from Figure 1 will be shifted about *100-200 eV* to the left. This qualitative changing of energetic dependence can be an answer to the questions of the existence of the negative *P* resonance proposed in [3]. Unfortunately neutrons sources with enough intensity necessary to evaluate in a reasonable time the spin rotation and longitudinal polarization in the present does not exist. Therefore in the next paragraph it is proposed a method allowing us to extract the weak matrix element and the energy of the *P* resonance using the existing experimental data and theoretical relations of PV effects. This was applied by authors to obtain the weak matrix element in the $^{35}Cl(n,p)^{35}S$ reaction with thermal and resonant neutrons in the two levels approximation [10]. With neutron resonance parameters from [6] the weak matrix element in [10] was $W_{SP} = (0.057 \pm 0.012)\ eV$.

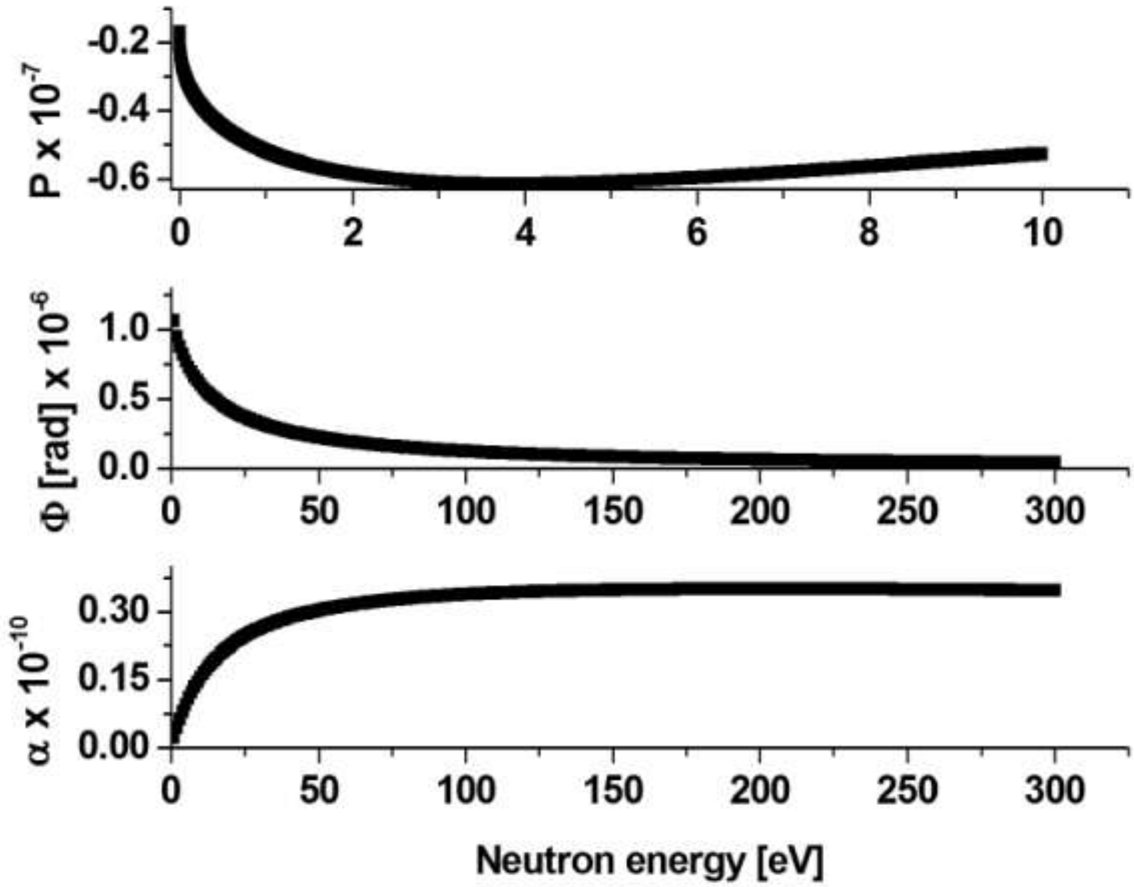

Figure 1. The PV effects in the scattering of neutrons on ^{204}Pb with following resonance parameters: $E_S^+ = -2980\, eV$ [6] **,** $E_P^- = -16\, eV$ [3], $W_{SP} = 2 \cdot 10^{-4}\ eV$ [8]

EXTRACTION OF THE WEAK MATRIX ELEMENT AND P RESONANCE POSITION

To obtain the weak matrix element and the energy of the P resonance we use the experimental data on spin rotation (12) and longitudinal polarization (16) and their theoretical evaluations (9, 10) . Also we maintain the neutron widths from [6] and from (16) we took the maximum and the minimum values possible from longitudinal polarization *P*.

For the first and second sets of data (by solving numerically)

$$\frac{d\Phi^{exp}}{dz}\left(E_n = 1.76\cdot 10^{-3} eV\right) = 2.47\cdot 10^{-4} rad/cm \text{ and } P^{exp}\left(E_n = 0.0253 eV\right) = -1.5\cdot 10^{-7}$$

$$\frac{d\Phi^{exp}}{dz}\left(E_n = 1.76\cdot 10^{-3} eV\right) = 2.47\cdot 10^{-4} rad/cm \text{ and } P^{exp}\left(E_n = 0.0253 eV\right) = 10^{-8} \quad (19)$$

we obtain: 1) $W_{SP} = 3.7\cdot 10^{-4} eV$, $E_P = -9 eV$ and 2) $W_{SP} = 5.6\cdot 10^{-3} eV$, $E_P = 135 eV$

From the relations (19) we see that if the signs of PV effects are the same in theoretical and experimental evaluations and with their experimental values indicate the possibility of the existence of negative P resonance with energy $E_P = -9\ eV$ with a matrix element with an expected value of order of 10^{-4}. If the longitudinal polarization changes the sign the position of P resonance becomes $E_P = 135\ eV$. This result may suggest us that it is not necessary to introduce the negative resonance E_P, it is enough to have a weak matrix element of order of $10^{-3}\ eV$ (which is with order of magnitude higher than expected) to describe the experimental data.

DISCUSSIONS

The analysis effectuated above suggests first of all new experimental data on spin rotation and longitudinal polarization obtained in scattering of slow neutrons. A set of energetic dependences in the range of neutron energy around *480 eV* will give us an answer related with the introduction of negative resonance. The results of system of equations (19) can be considered qualitatively because we maintained the widths as suggested in atlas of neutron resonance parameters [6]. A more quantitative significance of the equations (19) will have if a new experimental data in the neutron capture analogues to the longitudinal polarization. This new effect is the asymmetry of emitted gamma quanta in the radiative capture cross section and is defined as:

$$A_{n\gamma} = \frac{\sigma_{n\gamma}^{-} - \sigma_{n\gamma}^{+}}{\sigma_{n\gamma}^{-} + \sigma_{n\gamma}^{+}} \quad (20)$$

This asymmetry will not be affected by the potential scattering which is very high for thermal neutron scattering (*12 b* for potential scattering – two order of magnitude higher than resonant scattering for ^{204}Pb) and therefore will be easier to measure in comparison with P. A third equation in system (19) will give a more precise answer on position of P resonance and weak matrix element W_{SP}.

Our analysis is effectuated using the two levels approximation due mainly to the lack of experimental data but in future it is necessary to evaluate the influence of others resonances of ^{204}Pb (in spite of the fact that this nucleus has not so much resonances).

In [3] was affirmed that the PV effects in natural Lead is mainly caused by the ^{204}Pb isotope but still is necessary in future to analyze the contribution of each isotopes to the PV effects because, as we already seen, the experimental data are obtained mainly on natural Lead.

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