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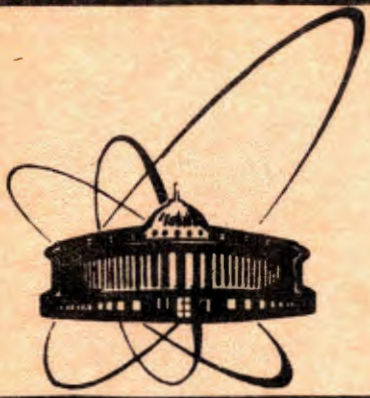

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E3-92-254

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REESTIMATION OF NEUTRON POLARIZABILITY FROM CROSS SECTION OF ^{208}Pb

1992

Now it is becoming obvious that the problem of the determination of the neutron polarizability (which is investigated last years by scientific groups in Garching, Dubna, Oak Ridge) is connected with a rather intricate question of an accuracy of the description of neutron interaction with nuclei. Existing mathematical models of neutron cross sections, which were developed by using the R-matrix or one level Breit-Wigner approaches, were intended for the description of numerous experimental data with the aim of its practical applications and for the verification of the ground assumptions of the neutron-nuclear interaction according to properties of the nuclei. Up to now the question did not arise with what exactness theoretical formulae of cross sections correspond to experimental data and describe the observed energy dependencies. In practice it was supposed satisfactorily if the accordance between theoretical and experimental cross sections was about a percent in the case of far resonances or for the resonance structure region. We do not know an example of checking up unanimously a description of the observed neutron cross sections in the resonances and between them

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with a relative accuracy of 10^{-4} and higher. Such precision to the experiment and mathematical interpretation is demanded in the problem of neutron polarizability determination from measurements of scattering cross section for the heavy nuclei.

In recent paper of Schmiedmayer and colleagues [1] the new result on the neutron electric polarizability was obtained from its specific contribution to the energy dependence of scattering cross section of ^{208}Pb . The transmission measurements for ^{208}Pb were performed with a high accuracy by using the time of flight method on the ORELA. The neutron polarizability is evaluated to be

$$\alpha_n = (1.20 \pm 0.15 \pm 0.20) \times 10^{-3} \text{ fm}^3 ,$$

where the uncertainties 0.15 and 0.20 have statistical and systematical character, respectively. The total cross sections of measured in [1] samples, mainly consisting of the ^{208}Pb isotope, were used for an extraction of scattering cross section of ^{208}Pb. One takes into account the resonance contributions, the capture cross section, and neutron-electron and the Schwinger scattering. The authors of [1] have described the obtained "pure potential" scattering cross section σ_s in the interval 50 eV - 50 keV by a polynomial formula over the powers of the neutron wave number k

$$\sigma_s(k) = 11.508(5) + 0.69(9)k - 448(3)k^2 + 9500(400)k^4 . \quad (1)$$

The choice of power polynomial terms was made by the authors from assumptions of contributions to the total neutron scattering cross section of s- and p-waves nuclear and polarizability interactions. In the case of absence of systematical distortions in σ_s (for example, due to an incorrect account of the background) the first

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power term upon k corresponds to the contribution of polarizability scattering.

On the ground of our experience of neutron polarizability estimates according to the way of the experimental data analysis and to consideration of different corrections [2,3,4] it was of interest to investigate a stability of the results [1] to variations of the analysis. In fact, for any nuclear model the polynomial coefficients in the formula (1) are closely connected by a model parameters. If the obtained in [1] coefficients do not correspond to such standard relationship, then, most probably, this may indicate a systematical error (for example, in the background, dead time correction, etc.).

According to refs [2,3,5] we can write the scattering cross section as

$$\sigma_s = \frac{4\pi}{k^2}\sin^2(\delta_0) - \frac{2\pi}{k}\sin(2\delta_0)\sum \frac{g\Gamma^\circ_{ni}\Delta E_i}{0.002197[\Delta E_i^2+(\Gamma^\circ_{ni}\sqrt{E}+\Gamma_\gamma)^2/4]}$$

$$+\pi\cos(2\delta_0)\sum \frac{g\Gamma^{\circ 2}_{ni}}{(0.002197)^2[\Delta E_i^2+(\Gamma^\circ_{ni}\sqrt{E}+\Gamma_\gamma)^2/4]} + \frac{12\pi}{k^2}\sin^2\delta_1 \quad , \qquad (2)$$

where

$$\delta_0 = -k(R'_0 + b_{ne}F(E) + b_p P) \ ,$$

$$P = 1 - \frac{\pi}{3}kR + \frac{(kR)^2}{3} - \frac{2}{135}(kR)^4 \ ,$$

$$\delta_1 = -k\frac{(kR)^2}{3}R'_1 - kb_p[\frac{\pi}{15}kR - \frac{1}{9}(kR)^2 + \frac{2}{135}(kR)^4] \ .$$

Here F(E) is the atomic form factor, b_{ne} the n,e-scattering length, $b_p = -\frac{M}{R}\left(\frac{Ze}{\hbar}\right)^2\alpha_n$ is the polarizability scattering length, R'_0, R'_1- nuclear s-,p- wave scattering radii. Formula (2) does not include the term considering inter- resonance interference. But

for α_n estimation it is not important because far from resonances the inter- resonance term does not carry an additional energy dependence in the σ_s and it leads just to renormalization of R'_0. Thus the inter- resonance interference gives a less significant correction for the energy dependence of σ_s as compared with the contribution of the neighbouring resonances and the interference of resonance and potential scattering. At the one level approximation the formula (2) takes into account the contribution of s-resonances and s-,p-wave potential scattering. After subtraction of the n,e-scattering contribution the cross section of σ_s can be expanded in powers of k in the polynomial

$$\sigma_s = \text{const} + ak + bk^2 + ck^3 + dk^4 \quad . \qquad (3)$$

In doing so under decomposition of (2) in the form (3) the pure nuclear terms from $\sin^2\delta_0/k^2$ and the resonance expressions will contain only the even powers of k. The first power of k takes place only in the cross nuclear-polarizability term

$$\frac{8\pi^2}{3}\,kRR'_0b_p \ , \qquad (4)$$

the third power can be present in the case of the visible contribution of p-wave potential scattering to σ_s due to the term of

$$12\pi\frac{2\pi}{15}(kR)^3R'_1b_p \ .$$

Hence it appears that the coefficient of a in (3) is equal to the expression (4). Just the comparison of (4) with the coefficient 0.69±0.09 from (1) gives α_n=1.1 (±13%). Besides, incorrect consideration of the background in transmission measurements can also give the term with k^3 in σ_s^{exp}. It should be noted once more that in the expression of cross section by the polynomial (3) its coefficients are in close relations by means of the nuclear parameters.

However, the satisfactory description of the "pure potential" scattering cross section (1) by means of formula (2) (more correct by the term of $4\pi\sin^2\delta_0/k^2$ after the correction on resonance 507 keV) is not a success (see Table 2). This indicates the impossibility of the description of potential cross section with the nuclear phase of $\delta_0=-kR'_0$ and leads to the necessity of using the formalism with an additional parameter which gives in the scattering amplitude the term depending linearly upon the neutron energy (see,for example, [7], chap.IV). In the R-matrix approximation one takes usually the following R-matrix

$$R=\sum\frac{\gamma^2}{E_\lambda-E-i\Gamma_\lambda/2}+R^\infty+R_c(E-E_c)\ ,$$

where R^∞ is the background matrix (the contribution of far resonances), E_c is the center of an energy interval for the parameterized cross section . In this case the S-matrix being far from resonances can be expressed as

$$S\simeq\exp[-2ika(1-R)]=\mu\exp(2i\delta_0)\ ,$$

where $$\mu=\exp\left(-\frac{1}{2}\sum\frac{\Gamma_{ni}\Gamma_i}{(E-E_{0i})^2+\Gamma_i^2/4}\right)$$ and a-channal radius,

$$\delta_0=-k[R'_0+\frac{1}{2k}\sum\frac{\Gamma_{ni}(E-E_{0i})}{(E-E_{0i})^2+\Gamma_i^2/4}+R_c(E-E_c)+b_{ne}F+b_pP]\ ,$$

$$R'_0=a(1-R^\infty)\ .$$

Then the scattering cross section (for $\ell=0$) is

$$\sigma_s=\frac{\pi}{k^2}|1-S|^2=\frac{\pi}{k^2}(1+\mu^2-2\mu\cos2\delta_0)\ . \qquad (5)$$

We imitated pseudo experimental cross section $\sigma_s(E)$ by means of formula (1) in our calculations. A total of 103 points were assumed in the interval 50-50000 eV. In accordance with the uncertainties of coefficients in (1) we must assign to an imitated

cross section a statistical errors ≃0.007 b. But the inverse fit of these pseudo experimental σ_s values with the help of the FUMILI-code completely reproduces the polynomial coefficients (1) and their errors only in case when the accuracy of each point is ≃ 1 mb. The imitated cross section and a difference $\Delta=\sigma_s(0)-\sigma_s(E)$ were analyzed later by the FUMILI-code in accordance with formulae (2) and (5). The authors understand that under the reverse fitting the use of a "smooth" pseudo experimental cross section without an accidental point dispersion decreases χ^2. However, it must not influence the conclusion about a role of different factors at the estimation of the α_n value. One has only to bear in mind that for the reliable α_n estimation from the real experimental data still less errors than we have attributed to the pseudo experimental cross section are required.

Table 1

χ^2 per point	const	a	b	c	d
$\Delta\sigma$=0.007 b					
10^{-5}	11.508(5)	0.69(56)	-448(17)	0±0	9520(3330)
$\Delta\sigma$=0.001 b					
10^{-4}	11.508(1)	0.69(8)	-448(2)	0±0	9500(480)
0.05	11.506(7)	1.15(10)	-484(4)	1011(51)	0±0
0.09	11.5110(4)	0±0	-400(3)	-1270(160)	20840(1870)
0.74	11.5130(3)	0±0	-427.8(5)	0±0	5850(220)
10^{-3}*	12.325(1)	0.69(8)	-467(2)	0±0	9810(480)
10^{-3}**	10.667(1)	0.72(8)	-358(3)	0±0	5369(480)

* - the 507 keV resonance correction is considered;
** - the -507 keV resonance is introduced;
0±0 - this parameter is fixed as zero.

The results of the fitting of the pseudo experimental cross section by the polynomial (3) are shown in Table 1 (for various accepted errors $\Delta\sigma$).

From Table 1 one may deduce that in order to obtain the precision of the coefficients a, b, d corresponding to that of [1] we must have the errors of the original cross section ≃1 mb per one point. But if we are using $\Delta\sigma$=0.007 b (this would seem real from the error of const=11.508±0.005), then the error of Δa is 7 times greater. One may assert that even under $\Delta\sigma$=1 mb it is possible (see χ^2) to describe the pseudo experimental cross section by a polynomial with the powers n=0, 2, 3, 4 and n=0, 2, 4 , i.e. at a=0. Therefore, the [1] description of the scattering cross section is not a single- valued one if the errors of experimental points are not essentially smaller than 1 mb. One can also confirm that the initial data may be described by the values of the coefficient a which lies in the limits 0.-1.2,satisfies the quantity of $\alpha_n \simeq 0.-2$. That is why to our mind the result of ref. [1] is to be interpreted as $\alpha_n \leq 2$.

As has been mentioned above, we completed the analysis of pseudo experimental values of σ_s and $\Delta=\sigma_s(0)-\sigma_s(E)$ (by analogy with [1]) by using the FUMILI-code and the formulae (2) and (5), containing the nuclear parameters. As the cross section (1) was deduced by the authors of [1] after the subtraction of n,e-scattering we supposed that $b_{ne}=0$ and it was fixed (i.e. in σ_s and Δ we excluded all terms containing b_{ne}). In our calculations the influence of resonance corrections was checked on the fitted parameters. Some fits are shown in Table 2.

Table 2

χ^2 per point	R'_0 (10^{-12} cm)	α_n	$R_c \times 10^6$	
	σ_s			
260	0.9331(1)	-8.8(1)	0±0	Without resonances
50	0.9888(1)	-3.7(1)	0±0	With resonance 507 keV
4.10^{-3}	0.9551(1)	1.1(1)	-0.235(1)	Without resonances
0.23	0.9979(2)	0.6(1)	-0.087(1)	With resonance 507 keV
0.06	0.9164(1)	1.5(1)	-0.115(1)	With resonance -507 keV
0.03	0.9587(1)	1.0(1)	-0.014(1)	With 2 res.: ±507 keV
2.3	0.9531(1)	0±0	-0.2107(4)	$\Delta\sigma$=0.001 b } Without
0.06	0.9531(3)	0±0	-0.211(3)	$\Delta\sigma$=0.007 b } resonances
0.2*	0.9564(1)	1.5(1)	-0.254(1)	} Without resonances
0.2**	0.9547(1)	0.6(1)	-0.215(1)	}
	$\Delta=\sigma_s(0)-\sigma_s(E)$			
10^{-3}	0.951(6)	1.1(1)	-0.25(3)	Without resonances
1.3	1.009(2)	0.5(1)	0±0	- " -
10^{-3}	0.954(8)	1.2(1)	-0.28(3)	With resonance 507 keV
10^{-3}	0.940(6)	1.1(1)	-0.09(2)	With resonance -507 keV
1.1	1.035(3)	0+0	0.13(1)	$\Delta\sigma$=0.002 b } Without
0.58	0.987(5)	0.2(1)	-0.08(2)	} Shift 5 mb } reso-
0.55	0.899(7)	2.2(1)	-0.48(3)	} of Δ -5 mb } nances

* } to the cross section (1) is added (*) or subtracted (**)
** } p- wave term $12\pi\sin^2\delta_1/k^2$ with R'_1=1 fm.

This fitting variants demonstrate the impossibility of the satisfactory description of the pseudo experimental cross section without the introduction of the term proportional to E (i.e. k^2) into the scattering amplitude. The errors in all calculations with the exception of those specially marked in Table 2 were 0.001 b. Physically the parameter R_c is conditioned by the slope of σ_s due to the interference between the resonance and the potential scattering and it corresponds to the contribution to σ_s of the

resonances close to the investigated energy interval. Therefore, the direct account of known resonances must influence the value of this fitting parameter. In principle, in order to take into account the resonance "tails" from the levels situated outside the energy interval, it is enough to introduce one parameter R_c. From the results presented in Table 2 one can see that the estimates of the polarizability coefficient depend on the consideration of the nearest resonances. As a consequence we have the physical uncertainty in α_n estimates. A negative resonance has been introduced with the parameters of a well-known resonance at 507 keV. That resonance would give in the thermal point the equivalent contributions, as the positive resonance, to capture and scattering cross sections. It is not contradictory to the experimental data because of the uncertainty of radiation widths for s-resonances ^{208}Pb. Also it is possible to describe the pseudo experimental cross section with α_n=0 if the errors of σ_s are greater than 0.001 b.

The general applicability of the formula (5) with the additional parameter R_c in phase was checked for the cross section of carbon obtained also by Schmiedmayer and colleagues in the polynomial form in the region up to 20 keV [6]. Table 3 contains the results of fitting σ_s for carbon with the introduction of the parameter R_c and without it. It is obvious that the experimental behavior of $\sigma_s(E)$ is not well described by the phase without R_c.

Table 3

χ^2 per point	R'_0	b_p	$R_c x10^6$
2.6	0.5992(4)	0.0155(4)	0±0
0.003	0.6154(16)	-0.0018(17)	-0.24(2)

It should be noted that in all descriptions of σ_s in the frame of the accepted cross section model we have obtained the estimates of α_n which are in agreement with corresponding values of the polynomial approach (3). The existence of the α_n correlation with resonance corrections in the physical model (5) and the absence of changing a (α_n) in the case of formal polynomial approach (3) is essential.

From the analysis of $\Delta=\sigma_s(0)-\sigma_s(E)$ it follows that the extracted parameters R'_0, α_n, R_c for the variant without correction for resonances agree with the analogous fitting of σ_s. However in the case of the Δ analysis the α_n estimates do not depend on the resonance corrections, the same as the polynomial fitting. That is clear because the sensibility $\Delta=\sigma_s(0)-\sigma_s(E)$ to the R'_0 parameter is weaker than for $\sigma_s(E)$ values. In contrast each set of the considered resonances under the fitting of $\sigma_s(E)$ requires its own different value of R'_0. This R'_0 correlation with α_n leads to the dependence of the obtained from σ_s estimates of α_n according to the accepted resonance set. Let us note that there is the visible influence of the zero shift of difference Δ in the error limits of const ≈0.005 b on the value of α_n. So the question arises about the reliability of extrapolation of σ_s to the value at E=0 depending on the accuracy of corrections for the capture cross section, the resonances of other isotopes, the air.

What experimental data description is more grounded with point of view of the reliability of the polarizability estimate? One should assume if there is the confidence in the lack of systematical errors for $\sigma_s(E)$ (due to the background, the dead time and other corrections mentioned above), then the polynomial approach should be chosen which considers a nucleus just formally. However, in this case the physical bond between the polynomial coefficients (1,3) is lost and a danger appears to obtain non-physical values of the coefficients and of their errors. Therefore, we believe that the most physically grounded method of the polarizability determination is the fitting of the scattering cross section itself because only in this case (if the exact mathematical formula was guessed) realistic errors of estimated parameters will be obtained. These errors are conditioned by the functional dependence of parameters and by their correlations under the experimental data fitting. We have drawn the conclusion that in the statistical accuracy Schiedmayer and colleagues [1] have approached the expecting value of the polarizability coefficient. Unfortunately, as well as in papers of other authors, the estimates of α_n are dependent upon mathematical formalism, resonance corrections and here also upon a p-wave scattering radius R_1'.

- Apparently further improvements and the analysis of, in fact, approximate formulae for the description of scattering cross section, considering the electromagnetic interactions, are needed.
- The question about an accuracy of the experimental cross section is maintained. It is obvious that in order to obtain the necessary

precision of α_n the errors of σ_s are to be lower than 1 mb in a rather wide energy interval. The time-of-flight method of the transmission measurement must give the accuracy of the background determination, assuring the lack of distortions in cross section with a relative precision of about 10^{-4}. At present the real situation is that the more exact data for natural lead [5,6], pretending to the accuracy higher than 5 mb, have the following difference (after necessary correction)

Energy , eV	1.26	5.19	18.8	130	1970
σ_s[5]-σ_s[6], mb	1.7	3.5	2.4	-3.6	-44.4
$\frac{8\pi^2}{3}kRR_0'b_p$, mb	0.1	0.3	0.6	1.4	5.6

The expecting for α_n=1 contribution to σ_s of the energy dependent polarizability term is shown here also. One may see how small this cross section part is, and why the requirement of very high measurement accuracy arises.

- Our calculations point to a necessity of the determination of a p-wave scattering radius of R_1' with a sufficient accuracy. The supplement control measurements of σ_t and the investigation of the differential scattering cross section $\sigma_s(\theta)$ in order to determine R_1' are needed.
- For the check of the experimental studies and the analysis methods the measurements with light nuclei are required as it was done in the early paper [6].

The authors are indebted to Mrs. T.Filimonycheva for valuable help in the preparation of the English version of this paper. We also wish to thank G.Samosvat and V.Furman for helpful discussions.

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Received by Publishing Department

on June 18, 1992.

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E3-92-254

Переоценка поляризуемости нейтрона из сечения рассеяния ^{208}Pb

С использованием измеренного в Ок-Ридже сечения рассеяния ^{208}Pb исследована устойчивость оценки поляризуемости нейтрона α_n к различным поправкам и методам обработки данных. Показано, что результат, полученный Шмидмайером с коллегами, следует интерпретировать как $\alpha_n \leq 2$. Предложен другой метод описания сечения рассеяния, в котором используется ядерный радиус рассеяния с дополнительным членом, пропорциональным энергии нейтрона.

Работа выполнена в Лаборатории нейтронной физики ОИЯИ.

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