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n,e-AMPLITUDE ESTIMATE INDEPENDENT OF NUCLEAR SCATTERING MODEL

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The physical importance of b_{ne} consists in the fact that it allows determination of the neutron mean square charge radius defined as

$$\langle r^2\rangle = \frac{3\hbar^2}{mc^2}(b_{ne}-a_F) \quad , \qquad (1)$$

where the Foldy's term a_F=-1.468 mfm.

In spite of many year investigations of the n,e- interaction amplitude (see table.1) one yet cannot state that the problem of estimating its value has been solved.

As the sign of b_{ne} is negative, the n,e- interaction calls a visible fall of the scattering cross section (e.g. by 260 mb for Pb) due to the atomic form factor $F(E,\theta)$, which changes from zero to unity with decreasing energy from tens electron volts down to zero. It is by comparison of σ_s values at different E and θ that one can determine the b_{ne} value.

Results with better statistics were obtained by four groups: from the energy dependence of the total scattering cross section of Bi[2] in the range of 0.1 - 4 eV, from the angular distributions of elastically scattered thermal neutrons [3,4], from the comparison of $b_{coh}(0)$ and $b_{coh}(E)$ in the interval from 1 up to 2000 eV [5,7-10], and from the neutron diffraction on the mixture of W isotopes with $b_{coh}(0)$ close to zero [6]. After additional investigations by the authors of methods the results of [3,4] and [5,7,9,10] have been obtained to show agreement.

All these results fall into two groups, one with the b_{ne}

values near to -1.55(5) mfm [2,6,8], and the other to -1.32 mfm [4,9,10], thus leading to opposite in sign estimates of $\langle r^2 \rangle$.

As to ref.[8] the obtained in this paper value of b_{ne} differs from the estimates of refs [7,9] by nearly 10 errors. Note that this difference cannot be connected with any discrepancy of experimental data (in fact, the authors of [8] have used the data from [7,9]), but, as we have shown [11], it is connected with different mathematical descriptions of the measured effects. In our opinion the b_{ne} estimates [9,10] earn confidence if the initial data on scattering cross section and coherent amplitude are reliable. It should be emphasized that the difference between the values -1.49(5) [2], -1.55(2) [6] and -1.31(4) [4,10] has not found any explanation yet. This evokes the necessity of analysis of the measurement and data processing methods as well as the staging of new control experiments.

In order to compare different methods of obtaining b_{ne} we present, following [10,11,12], the scattering phase in the far from resonances region, taking into account the electro-magnetic interaction in the form:

$$\delta_0 = -k(R'_{eff} + b_{ne}ZF) = \qquad (2)$$

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

here R_{eff} is the certain effective radius of nuclear scattering changing slowly with energy, F is the atomic form factor, P is the neutron-nuclear polarizability form factor, b_{ne} is the n,e-scattering length, b_p is the polarizability scattering length, E_c is the middle point of the investigated energy interval.

At low energies coherent cross section can be written (after

Table 1

Year	b_{ne} mfm		Reference
1947	-0.1 (1.8)	Fermi, Marshall	
1951	-1.91(36)	Havens et.al.	[2a]
1952	-1.5 (4)	Hamermesh et.al.	[18a]
1956	-1.41(29)	Croch et.al.	[18b]
1953	-1.39(13)	Hughes et.al.	[1]
1959	-1.56(5)	Melkonian et.al.	[2b]
	-1.49(5)	reanalysis in [7]	
1966	-1.34(3)	Krohn, Ringo	[3]
1973	-1.30(3)	- " -	[4]
	-1,33(3)	reanalysis in [7]	
1973	-1.427(23)	Koester	[5]
1974	-1.55(2)	Alexandrov et al.	[6]
1976	-1.378(18)	Koester et.al.	[7]
1985	-1.59(4)	Alexandrov et.al.	[8]
1986	-1.32(4)	Koester et.al.	[9]
1988	-1.31(4)	- " -	[10]

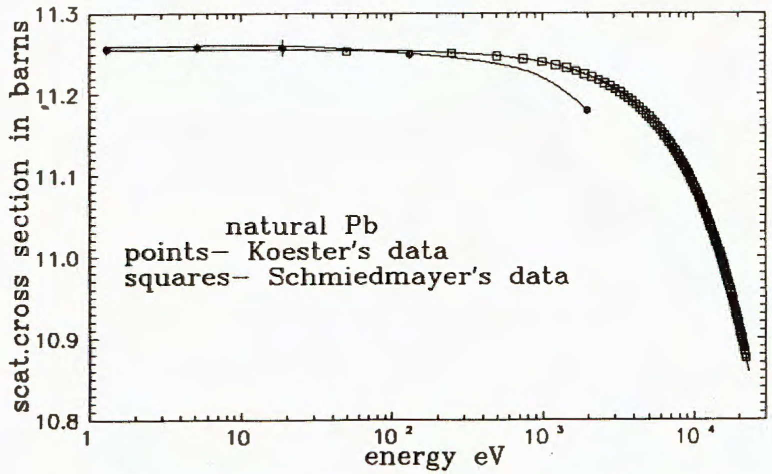

Fig.1 The description of the Pb data. The curves are the fits by formulas (2,3) without resonance, n,e– and polarizability terms.

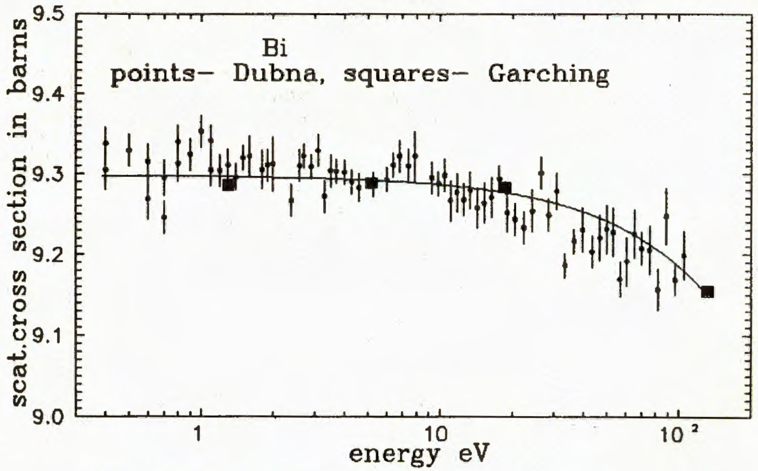

Fig.2 The description of the Bi data. The experimental points are corrected for n,e–scattering (see the text). The curve is fitted under the same conditions as in fig.1.

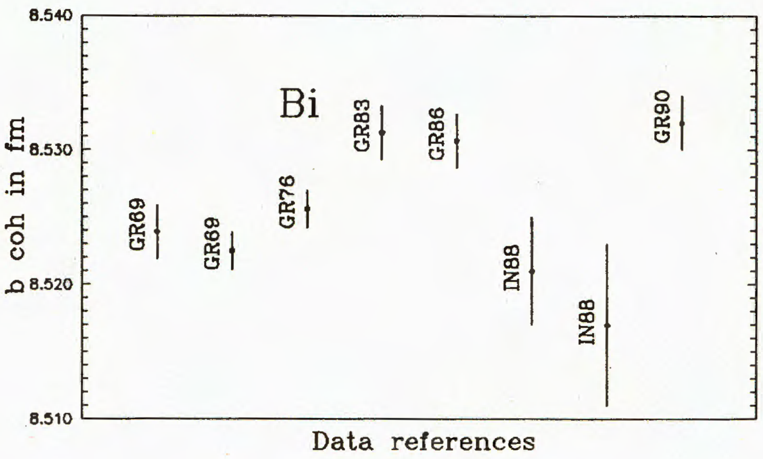

Fig.3 The set of coherent amplitude data for Bi.

making corrections for Schwinger and incoherent scattering, and for solid state effects) as

$$\sigma_s=\frac{\pi}{k^2}\,(1+\mu^2-2\mu\cos 2\delta_0)\quad , \qquad (3)$$

where
$$\mu=\exp\left(-\ \tfrac{1}{2}\sum\frac{\Gamma_{ni}\Gamma_i}{(E-E_{0i})^2+\Gamma_i^2/4}\right)\quad .$$

In [7,9,10] the problem of b_{ne} determination was reduced to precise measurement of $\sigma_t(E)$ in the eV region (1 – 2000 eV), followed by introduction of corrections for the capture cross section, Schwinger and incoherent scattering, and solid state effects, and comparison of the obtained coherent amplitude $b_{coh}(E)$ with the coherent amplitude $b_{coh}(0)=R'_{eff}(0)+b_{ne}Z$ measured with high precision at $\approx 5.10^{-4}$ eV. (Note that F(0)=1).

As is shown in [11] the discrepancy between [7,9] and [8] is conditioned by not taking into consideration the inter-resonance interference in the expression for $\sigma_s(E)$ when it was accounted for in the expression for $b_{coh}(E)$ in [8]. This increases the difference between $b_{coh}(E)$ and $b_{coh}(0)$ (and consequently the module of b_{ne}).

In refs. [10] and [11] there are used similar approaches as to the assumption of the independent of E nuclear scattering radius, when the energy dependence of the potential scattering cross section (and therefore of b_{coh}) is determined by the term $\sin^2\delta_0/k^2$ and by the dependence of δ_0/k on E expressed only via the functions F(E) and P(E). However, this is not so, because of the far lying resonances, which cannot be taken into account directly but can be accounted for by (2) via the parameter R_c. So in [12] it was shown that for ^{208}Pb the term $R_c(E-E_c)$ taking into account the far lying resonances makes a 12% contribution to the part of σ_s linearly dependent on E (≈20 mb at 40 keV) and a 20% contribution to that proportional to E^2. The strong resonance 507 keV makes only a 1.7 times greater contribution. The remaining dependent on E part of σ_s is connected with the constant part R'_{eff}. Thus for Pb one cannot ignore the R'_{eff} dependence on E as it was done in [7-11]. For Bi the term with R_c provides the additional slope of 7 mb between 1 and 130 eV when the -800 eV resonance is taken into account.

So far as different descriptions of nuclear scattering lead to considerable variations of b_{ne} estimates (-1.59 [8] and -1.31 [10,11] for Bi), it is desirable to have an estimate of b_{ne} more independent of nuclear scattering models.

The possibility of "nonmodel" estimate of b_{ne} is based on the following. Let's make use of the fact that the solid state corrections at 50 eV are less than 0.5 mb and the atomic form factor F decreases fast with increasing neutron energy, and so at 50 eV the contribution of n,e-interaction into the cross section makes only 3% of its maximum value. Therefore, in the tens eV region the correction for σ_{ne} with an accuracy of 2-5% allows one to obtain $\sigma_s(E)$ (after n,e-contribution subtraction) with an additional error less than 0.5 mb. For larger E this error is less essential. If so corrected $\sigma_s(E)$, dependent on the nucleus only, is known in a wide enough interval, then by its extrapolation to E=0 one obtains $\sigma_s(0)$. Now the only thing remained is to compare $\sigma_s(0)$ with $4\pi b^2_{coh}$ to find b_{ne}.

In [13,14] by measuring total cross sections by the time-of-flight method in the neutron energy region from 50 eV to 20 keV for Pb and C and up to 45 keV for ^{208}Pb, and by introducing corrections for the capture cross section, n,e- and Schwinger scattering, solid state effects and resonances contributions, the scattering cross sections were obtained of natural Pb,C and ^{208}Pb in the form of polynomials:

$$\sigma_s=11.258(5) + 0.60(51)k - 371(27)k^2 \qquad Pb$$

$$\sigma_s=4.7435(16) + 0.06(22)k - 82(5)k^2 \qquad C$$

$$\sigma_s=11.508(5)+0.69(9)k-448(3)k^2+9500(400)k^4 \qquad {}^{208}Pb .$$

It is essential that in [13,14] the resonance corrections were introduced in a manner that did not change the constants in the polynomials.

Making use of the results obtained within this polynomial description for Pb,C,^{208}Pb and of the scattering cross section data of the Garching group [9,10] (for Pb and Bi) and of the Dubna group [15] (for Bi), the $\sigma_s(E)$ were fitted by formulas (2),(3) and FUMILI-code with two free parameters R'_0 and R_c. Into the data from [9,10,15] necessary corrections for the capture cross section, Schwinger and incoherent scattering, and solid state effects were introduced. In result, the extrapolated to $E=1.10^{-4}$ eV values of σ_s were determined. At this energy the coherent amplitudes are known [17]. Fig.1 and fig.2 show the results of the fitting for natural lead and bismuth. Indeed, our $\sigma_s(0)$ values obtained from the description of the data [13,14] coincide with the polynomial constants. The b_{ne} value was estimated by the formula

$$b_{ne}=\frac{b^2_{coh}-\frac{\sigma_s(0)}{4\pi}\left(\frac{A+1}{A}\right)^2}{2ZR_{eff}},$$

$$R_{eff}=\sqrt{\frac{\sigma_s(0)}{4\pi}}$$

Obtained results are summarized in Table 2.

Table 2

Nucleus	ΔE eV		$\sigma_s(0)$ b	R_cx10^6	b_{coh} fm		b_{ne} mfm
Pb	50-20000	[13]	11.252(5)	-.116(4)	9.4017(20)	[10]	-1.296(35)
	1-2000	[10]	11.256(3)	-1.2(1)	- " -		-1.317(29)
C	50-20000	[13]	4.7437(16)	-.090(2)	6.6448(13)	[17]	-1.38(24)
^{208}Pb	50-45000	[14]	11.508(5)	-.235(2)	9.50(2)	[17]	-1.41(24)
Bi	1-130	[10]	9.2945(34)	-60(2)	8.5307(20)	[10]	-1.33(3)
	-"-	[10,15]	9.2996(20)	-65(2)	- " -		-1.36(3)
	-"-	[15]	9.3079(28)	-96(6)	- " -		-1.40(4)

For Bi the n,e-scattering contribution is essential at low energies (≃40 mb at E=1 eV) and, therefore, several iterations were made. In order to have σ_s corrected we took the initial values of b_{ne} 20% higher and lower than its expected value -1.32 mfm. The iteration results tend to the given in Table 2 values. It is essential that the cross sections [15] are normalized to the σ_s value at 5.2 eV from [9] and consequently the σ_s's [15] are to be considered independent of the scattering cross sections [9] only as the data for the determination of the cross section energy behavior.

The obtained "nonmodel" estimates of b_{ne} agree nicely with the results [4,10].

Let's note that the value of σ_s at E=1970 eV in [9,10] is by 40 mb lower than that in ref.[13].

The obtained by the above discussed methods b_{ne} values for Pb and Bi are compared in Table 3. A remark should be made about the line in Table 3 referring to [11]: we admit the error that was made (pointed to by G.Samosvat in [16]) at introducing the correction for Imb, which led to double account of the imaginary part of the scattering amplitude. We did not notice that in [10] in the mathematical description of the experiment there was used the expression for b_{coh} with the "nuclear" form factor connecting b_{coh} and the phase not in the form sin2δ/2k but in the form sinδ/k (that corresponds to the form factor of the square root of the total scattering cross section). It turned out, that this incorrect for the amplitude form factor actually takes into account the correction for the imaginary part of b_{coh}, which is necessary to be introduced into the expression for the cross section $\sigma_s=4\pi(\mathrm{Re}^2b+\mathrm{Im}^2b)$ in order to obtain the coherent amplitude. Therefore, Table 3 contains our uncorrected for Imb estimates of b_{ne} only.

Table 3

Method	Bi	Pb
1. R'_0=const [7,9,10]	-1.30±0.06	-1.32±0.04
2. R'_0=const [11]	-1.30±0.04	-1.32±0.03
3. Extrapolation $\sigma_s\Rightarrow 0$	-1.33±0.03	-1.32±0.03

Emphasizing the stability of the summarized in Table 3 estimates of b_{ne} to the methods of initial experimental data analysis one should note that the success of the b_{ne} determination depends on the reliability and prècision of coherent amplitude measurement. Unfortunately the real situation is dramatical. So for Bi there is a large set of $b_{coh}(0)$ values, obtained in different years on the gravitational spectrometer and on the interferometer, which differ essentially beyond error limits. These data are illustrated in fig.3. One can see that the values group around the two values: 8.5313 and 8.5220, different by five individual point errors. These values of b_{coh} give for Bi the value of b_{ne} equal to -1.32(3) and -1.43(3). The limit values of b_{coh} give b_{ne}= -1.31 and -1.49. The analogous situation is to be expected for Pb. Thus allowable estimates of b_{ne} lie in the critical for sign assignment to the neutron mean square charge radius interval. The fact that there exist other estimates near -1.5 (see tab.1) forces the conclusion to be made that the existing data on b_{ne} do not allow one to reliably adopt some definite value for this fundamental characteristic and make the conclusion about the sign of $<r^2>$. It is obvious that further experiments are needed.

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Николенко В.Г., Попов А.Б. E3-92-255
Оценка n, е-амплитуды,
независимая от модели ядерного рассеяния

Предложен еще один способ оценки амплитуды n,e-взаимодействия, в котором ядерное сечение рассеяния σ_s (E = 0) рассчитывается экстраполяцией известных сечений рассеяния из энергетической области десятки или сотни электронвольт к E = 0. Значения b_{ne} получены из сравнения $\sigma_s(0)$ и $4\pi b^2_{coh}$ ($b_{coh} = R'(0) + b_{ne}Z$). Авторы обсуждают также различие между существующими экспериментальными оценками b_{ne} и приходят к заключению, что в настоящее время экспериментальные данные не позволяют надежно определить среднеквадратичный зарядовый радиус нейтрона.

Работа выполнена в Лаборатории нейтронной физики ОИЯИ.

Сообщение Объединенного института ядерных исследований. Дубна 1992

Nikolenko V.G., Popov A.B. E3-92-255
n,e-Amplitude Estimate
Independent of Nuclear Scattering Model

One more approach to n,e-amplitude estimation is proposed. The nuclear scattering cross section $\sigma_s(0)$ is calculated by extrapolation of known scattering cross sections from the energy region of tens or hundreds eV to $E \Rightarrow 0$. The values of b_{ne} are obtained from a comparison of $\sigma_s(0)$ and $4\pi b^2_{coh}$ ($b_{coh} = R'(0) + b_{ne}Z$). The authors discuss also discrepancy between existing b_{ne} estimates and conclude that it is yet impossible to reliably determine the neutron mean square charge radius.

The investigation has been performed at the Laboratory of Neutron Physics, JINR.

Communication of the Joint Institute for Nuclear Research. Dubna 1992