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THE NEUTRON MEAN SQUARE CHARGE RADIUS AND ELECTRICAL POLARIZABILITY ON THE BASIS OF DATA ON INTERACTION OF NEUTRONS WITH BISMUTH

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Recently[1,2] it has been stated that the precise measurements with eV neutrons of bismuth total cross sections might improve the then existing estimate for the electrical polarizability of the neutron α_n and give additional information on root mean square charge radius of the neutron $<r_{in}^2>_N^{1/2}$. Nowadays such measurements have been done at the pulsed reactor IBR-30 (JINR) and at Garching Laboratory (FRG).

1. MEASUREMENTS AND RESULTS

The measurements were performed by the time-of-flight method at an IBR-30 reactor flight path 60 m long. A beam of neutrons with energies from 1 to 90 eV was transmitted through both a molten bismuth sample and a solid one 18 mm thick. The background level, measured with the plates from Rh, Ag, and W (resonances at 1.26, 5.19, 18.83 eV) placed in the beam, amounted to 0.3-0.4% at 1-6 eV and did not exceed 1.5% at 20 eV. Dead time corrections were found by transmitting the neutron beam through lead plates of various thicknesses. They did not exceed 1.5%.

The energy dependence of the total neutron cross section of bismuth obtained in the reported measurements is given in the figure. The same figure gives σ_{tot} obtained in Garching[3-5]. We used the latter to derive the absolute cross section values of the energy dependence obtained in our experiment. As is seen from the figure there is some discrepancy between our data and theirs [3,5] near 1 eV, but further one may notice that this discrepancy does not affect the results within errors.

2. DATA PROCESSING

In order to obtain information about α_n and neutron-electron scattering length a_{ne}, connected with $<r_{in}^2>_N$, the experimental data were processed by the method proposed in refs. [1,2]*

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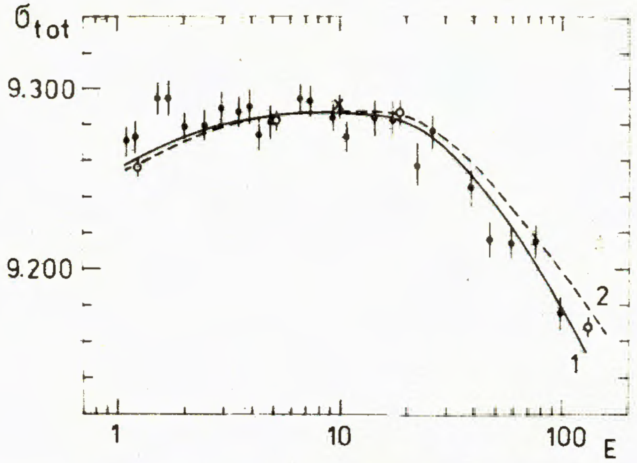
* The corresponding data processing, carried out in refs. [3,5], seems to be not correct enough. In particular, the resonance scattering and the imaginary part of the amplitude are not totally accounted for in ref. [3,5].



Dependence of σ_{tot} *(b) on energy* E *(eV).* • *- our data,* o *- data from refs.*[3,5], × *- data from ref.*[4]. *Curves 1 and 2 are calculated using formula (1) for the two groups of parameters: 1.* $a_{ne} = -1.6\cdot 10^{-3}$ *fm;* $a_n = -4{,}5\cdot 10^{-3}$ *fm*^{3}*; 2.* $a_{ne} = -1.6\cdot 10^{-3}$ *fm;* $a_n = 7\cdot 10^{-3}$ *fm*^{3}.

First the value of σ_{tot} was corrected for the Schwinger scattering and for solid state corrections. They did not exceed 0.8%. The data were processed using the expression obtained in refs.[1,2]:

$$y = \frac{\sigma_{tot}(E')}{4\pi} - a^2_{coh} = a^2(Z^2-2ZF) - 2aa_{coh}(Z-F) - f^2 - 2afF - \frac{2}{3}\pi k'Ra_{coh}f + \tag{1}$$

$$+ (\Sigma_1-\Sigma')[a_{coh} - a(Z-F) - \frac{\pi}{3}k'Rf] + \frac{1}{4}(\Sigma_1)^2 - \frac{1}{2}\Sigma_1\Sigma' + \frac{1}{4}\Sigma'_2 + \sigma_a(E')/4\pi,$$

where

$$a_{coh} = -b_{coh}\frac{A}{A+1}, \quad a = -a_{ne}, \quad f = \frac{M\alpha_n}{R}\left(\frac{Ze}{\hbar}\right)^2, \quad F = \frac{Z}{2}\int_0^{\pi} f\left(\frac{\sin\theta}{\lambda}\right)\sin\theta\, d\theta,$$

where $f(\frac{\sin\theta}{\lambda})$ is the atomic form-factor, M is the mass of the neutron, R is the radius of the nucleus, E and E′ are the neutron energies at which b_{coh} and σ_{tot} were measured,

$$\Sigma_1 = \sum_i \frac{g_i\Gamma_{ni}\Delta E_i}{k(\Delta E_i^2+\Gamma_i^2/4)}, \quad \Sigma' = \sum_i \frac{g_i\Gamma'_{ni}\Delta E'_i}{k'(\Delta E_i'^2+\Gamma_i'^2/4)}, \quad \Sigma'_2 = \sum_i \frac{g_i\Gamma_{ni}'^2}{k'^2(\Delta E_i'^2+\Gamma_i'^2/4)},$$

$$\sigma_a(E') = \frac{\pi}{k'^2}\sum_i \frac{g_i\Gamma'_{ni}\Gamma_{\gamma i}}{(\Delta E_i'^2+\Gamma_i'^2/4)}$$

is the absorption cross section, $\Delta E_i = E - E_i$, $\Gamma_i = \Gamma_{ni} + \Gamma_{\gamma i}$, E_i, Γ_{ni}, $\Gamma_{\gamma i}$ is the energy, neutron and γ-widths of the i-th resonance. The numerical value for b_{coh} = 8.5307 (20) fm was taken from ref.[5].

In the energy range $E \ll E_i$ and $\Gamma_i \ll \Delta E_i$ for the terms containing resonances one may use the following expansion into E′/E series:

$$p_1 = \Sigma_1 - \Sigma' \approx \sum_i \frac{g_i\Gamma_{ni}}{k_i\Delta E_i} - \sum_i \frac{g_i\Gamma'_{ni}}{k'_i\Delta E'_i} \simeq E'\sum_i \frac{g_i\Gamma'_{ni}}{k'_iE_i'^2} + (E')^2\sum_i \frac{g_i\Gamma'_{ni}}{k'_iE_i'^3} + \ldots \simeq$$

$$\simeq E'\frac{k'\sigma_a(E')}{\pi\langle\Gamma_\gamma\rangle} \tag{2}$$

$$p_2 = \frac{1}{4}(\Sigma_1)^2 - \frac{1}{2}\Sigma_1\Sigma' + \frac{1}{4}\Sigma'_2 \simeq \frac{1}{4}\sum_i \frac{g_i\Gamma_{ni}^2}{k_i^2E_i^2} - \frac{1}{4}\left(\sum_i \frac{g_i\Gamma_{ni}}{k_iE_i}\right)^2 - \frac{E'}{2}\Big\{\frac{1}{2}\sum_i \frac{g_i\Gamma_{ni}^2}{k_i^2E_i^3} -$$

$$- \sum_i \frac{g_i\Gamma_{ni}}{k_iE_i^2}\sum_i \frac{g_i\Gamma_{ni}}{k_iE_i}\Big\} + \ldots \tag{3}$$

Introducing into eq.(2) the numerical values for σ_a and $\langle\Gamma_\gamma\rangle$[6] one obtains

$$p_1 = \Sigma_1 - \Sigma' = 0.6\times 10^{-4}\times 10^{-12}E\text{, cm} \tag{2'}$$

Let us make estimates for the first two terms in the expression (3)*:

$$p_2 \simeq \frac{1}{4}\sum_i \frac{g_i\Gamma_{ni}^2}{k_i^2E_i^2} - \frac{1}{4}\left(\sum_i \frac{g_i\Gamma_{ni}}{k_iE_i}\right)^2 \simeq \begin{cases} -0.0030 \text{ b/sr over most strong resonances at } E > 0, \\ \langle g\rangle\left(\frac{\langle\Gamma_{n0}\rangle}{\langle D\rangle}\right)^2\frac{1}{(2.2\times 10^9)^2}\sum\frac{1}{(2i-1)^2} \simeq \\ \simeq 0.0011 \text{ b/sr under approximation} \\ E_i = \langle D\rangle(i-\frac{1}{2}),\ \text{where } \langle D\rangle \text{ is the} \\ \text{mean level spacing.} \end{cases}$$

The estimates show that the contribution of p_2 into y is 10-15% but a lack of information on resonance levels with negative energies does not allow one to find its exact value. Therefore, this contribution was varied to get the best fit of experimental data and appeared to be equal to −0.0023 b/sr.

Though we have information on σ_{tot} up to the neutron energy of about 130 eV, only points up to 30 eV were processes. The matter is that as follows from (1) the term containing α_n (the fifth term in (1)) is proportional to $\sqrt{E}$, while the reso-

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* The terms following them and depending on E in the region up to 30 eV may be neglected.

nance term $p_1 \sim E$. In the energy range up to 30 eV they are comparable, but above 100 eV the contribution of p_1 is about an order of magnitude greater than that of α_n. Therefore, in the energy range near 100 eV one may expect errors not only due to some uncertainties in resonance parameters, but also due to the method of accounting for resonance levels, since (1) is correct only far from any resonance level. However, a good agreement of the calculated curve (with parameters determined from the $E < 30$ eV region) with experimental data obtained at energies up to 130 eV (see the figure) prooves these errors to be not very large.

Experimental data have been processed by the least square method. In order to find the effect on the parameters under investigation of the discrepancy between our experimental data and those in refs.[3,5] at $E \sim 1$-1.5 eV(see the figure), these two groups of data were processed separately. The results are summarized in the Table.

Table

	Data from refs.[3-5]	Our data
a_{ne}	$(-1.57 \pm 0.10) \cdot 10^{-3}$ fm	$(-1.55 \pm 0.11) \cdot 10^{-3}$ fm
α^*_n	$(10 \pm 10) \cdot 10^{-3}$ fm^3	$(-5 \pm 3) \cdot 10^{-3}$ fm^3

There was observed practically no difference for a_{ne} due to a peculiarity in the energy dependence of F which decreases fast with increasing energy. Already at $E \sim 1$ eV the contribution of the $2aa_{coh}(Z-F)$ term approaches its maximum, and at $E > 5$ eV it is practically constant determining the value of a_{ne}. As for polarizability, its contribution into γ at $E \sim 1$ eV is comparatively small, so that the difference seen in the Table is rather due to the difference in energy dependence of the processed points at $E > 3$ eV than due to the discrepancy near 1 eV.

The obtained data are in agreement with the results of the neutron diffraction measurements[7] carried out with the tungsten single crystal ($a_{ne} = (-1.60 \pm 0.05)) 10^{-3}$fm). By using this result in data processing one obtains

$$\alpha^*_n = (1.5 \pm 3.3) \cdot 10^{-3}\ \text{fm}^3 \qquad (4)$$

at $\approx$ 90% confidence level.

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[*] At $R = 8.01$ fm.

3. DISCUSSION

The important result of this work is the determination of a_{ne} which confirmed that, measured by us with other methods[7]. By averaging the reported result and that from ref.[7] we have

$$a_{ne} = (-1.59 \pm 0.04) \times 10^{-3}\ \text{fm} \qquad (5)$$

which is in contradiction with the data obtained at Argonne[8] and Garching[3,5] Labs.* ($a_{ne} = (-1.31 \pm 0.03) \cdot 10^{-3}$fm).

Knowing this value one may find the mean square charge radius of the neutron (eq., e.g.,[9]):

$$\langle r^2_{in} \rangle_N = \frac{3\hbar^2}{Me^2} (a_{ne} - a_F), \qquad (6)$$

where $a_F = \mu_n \frac{e^2}{2Mc^2} = -1.468 \times 10^{-3}$ fm - Foldy term**. By substituting numerical values one has

$$\langle r^2_{in} \rangle^{1/2}_N = (-0.11 \pm 0.02)\text{fm}. \qquad (7)$$

This result is most near to -0.35 fm[10,11] calculated in the frame of the Cloudy Bag Model (CBM) consisting of the three quarks confined inside some volume and interacting with the pion field on the bag's surface. The results of earlier experiments[3,5,8] ($\langle r^2_{in} \rangle^{1/2}_N = (+0.12 \pm 0.02)$ fm) are not consistent, even in sign, with those obtained within CBM.

Though the estimate made here $\alpha_n < 5 \cdot 10^{-3}$ fm^3 does not practically differ from an earlier one[12], it is more reliable. The latter was obtained from the analysis of angular distributions of scattering of neutrons with energies up to 150 keV from the natural mixture of lead isotopes. Nowadays it is known[8] that the isotopes ^{204}Pb and ^{207}Pb have strong resonance levels with negative energies which affect the behaviour of cross sections in the energy range investigated. An attempt to take into account the resonance levels was undertaken in ref.[2]. It changed the estimate as compared with that reported in ref.[12] to be $\alpha_n = (6+3) \cdot 10^{-3}$ fm^3. One should also have in mind that the estimate from ref.[2] also seems to have uncertainties due to a lack of information on resonance levels of Pb isotopes.

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[*] As for systematical uncertainties possibly occuring in those experiments, see the footnotes on page 1 (present paper) and on page 1101 (ref.[2]).

[**] It appears incorrect to omit this term (as, for example, done in ref.[11]) in comparing experimental and theoretical results.

In conclusion, let us note that there are analogous to bismuth precise data on b_{coh} and σ_{tot} of Pb in recent references. However, their use is hindered by impossibility of a correct account for resonances, especially in the negative energy range. Therefore, the measurement of b_{coh} and σ_{tot} of the even-even ^{208}Pb isotope is very much desirable.

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Александров Ю.А. и др. E3-85-935
Среднеквадратичный радиус нейтрона
и его электрическая поляризуемость из данных
о взаимодействии медленных нейтронов с висмутом

Проведены измерения энергетической зависимости полного нейтронного сечения висмута в области энергий нейтронов от 1 до 90 эВ. Результаты обработаны вместе с имеющимися в литературе аналогичными данными. Получено значение среднеквадратичного радиуса нейтрона $<r^2_{in}>^{1/2}_N = /-0,11\pm0,02/$ Фм. Результат сравнивается с теоретическими расчетами в рамках кварковой модели CBM. Получена также оценка электрической поляризуемости нейтрона $\alpha_n < 5\cdot10^{-3}$ Фм^3.

Работа выполнена в Лаборатории нейтронной физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1985

Alexandrov Yu.A. et al. E3-85-935
The Neutron Mean Square Charge Radius
and Electrical Polarizability on the Basis
of Data on Interaction of Neutrons with Bismuth

The dependence of total neutron cross section of bismuth on neutron energy from 1 to 90 eV has been measured. The obtained data were processed together with the reported in literature analogous data. The root mean square charge radius of the neutron was obtained to be $<r^2_{in}>^{1/2}_N = (-0.11\pm0.02)$ fm. It is compared with that calculated within the quark model (CBM). The electrical polarizability of the neutron has also been estimated $\alpha_n < 5\cdot10^{-3}$fm^3.

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

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