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ELASTIC LOW ANGLE SCATTERING OF FAST NEUTRONS

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The angular distribution of 14.2-MeV neutrons elastically scattered on W, Pb, Bi, Th, and U nuclei is investigated. An anomalous variation of the differential cross section in the low angle region has been found for Th and U.

INVESTIGATIONS by Aleksandrov et al [1-3] of the angular distributions of 2- and 2.8-MeV neutrons elastically scattered by heavy nuclei show a sharp increase in the differential cross section with decreasing angle, starting with 8—10°. This growth in the cross section is connected with the fact that in this region of angles a great contribution to the differential cross section is made not only by the nuclear forces but also by the interaction between the magnetic moment of the neutron and the Coulomb field of the nucleus. However, in the same experiments, an additional contribution to the scattering cross section was observed in the case of Th, U, and Pu nuclei, a contribution which cannot be attributed to the foregoing circumstances. This effect is of great interest, since it can be due to long-range forces. In the present investigation we studied the angular distributions of 14.2-MeV neutrons elastically scattered by W, Pb, Bi, Th, and U nuclei, in order to ascertain whether this anomaly is present at higher energies.

The experimental setup is shown in Fig. 1. The neutron source was the reaction $T(d,n)He^4$. The experiments were carried out with a narrowly collimated neutron beam, which was obtained by selection of the coincidences between the neutron and the alpha particle; an additional steel collimator 20 cm long was also employed. The scatterers were metallic plates which absorbed 30—40 per cent of the incident neutrons. The apparatus employed, was described in detail in an earlier paper [4]. The measurements were carried out in the angle interval 3—20° with angular resolution ±40′. The background consisted essentially of random coincidences but, in the region of angles <5°, a noticeable part of the background was made up of true coincidences.

In order to be sure of the correctness of the account of the background, the experiment was set up in two versions. In one case the scatterer

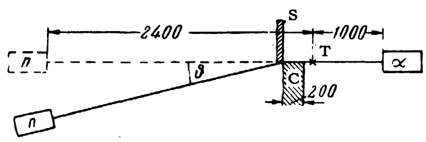

FIG. 1. Diagram of the experiment: T – target, S – scatterer, C – collimator, n and α – neutron and alpha-particle detectors (the dimensions are in millimeters).

placed into the neutron beam covered the beam and part of the collimator, thus decreasing the fraction of the background due to the true coincidences. In the other version the edge of the scatterer was placed in the beam in such a way as not to cover the neutron detector at the 3° angle; in this case the background remained unchanged. The values of the cross section determined in both versions agreed after the suitable corrections were introduced.

The results of the measurements are shown in Figs. 2, 3, and 4. The data presented have been corrected for double scattering; the method of allowance for double scattering is detailed in the Appendix. The error in the measurement of the differential cross section, indicated in Figs. 2—4,

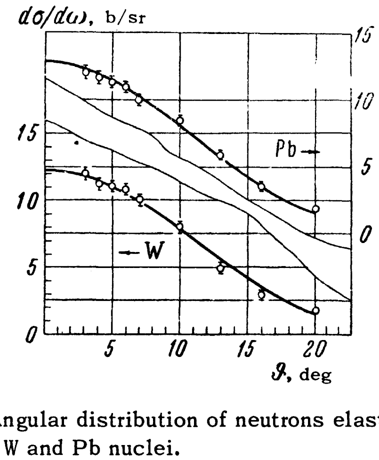

FIG. 2. Angular distribution of neutrons elastically scattered by W and Pb nuclei.

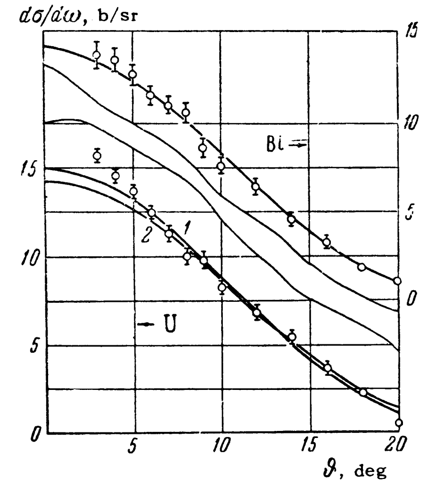

FIG. 3. Angular distribution of neutrons elastically scattered by Bi and U nuclei. Curve 1 is plotted on the basis of all the experimental points and curve 2 on the basis of the points lying in the angle range 6–20°.

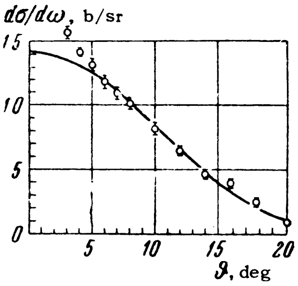

FIG. 4. Angular distribution of neutrons elastically scattered by Th nuclei.

is equal to the standard error (additional experiments have been made and have shown that the fluctuations in the counting rate of the background and of the dn coincidences have normal distributions). The corrections for collimation were not introduced, since they were small and did not change appreciably the course of the angular distribution. The accuracy of measurement of the absolute values of the cross sections was ±10 per cent.

The experimental course of the cross section was compared with an expression describing the diffraction scattering of neutrons by a "black" nucleus:

$$\frac{d\sigma(\vartheta)}{d\omega} = A\left[J_1\left(\frac{R+\lambda\!\!\!^-}{\lambda\!\!\!^-}\vartheta\right)\Big/\frac{R+\lambda\!\!\!^-}{\lambda\!\!\!^-}\vartheta\right]^2, \qquad (1)$$

where ϑ is the scattering angle, $R = r_0A^{1/3}$ is the radius of the nucleus, $\lambda\!\!\!^-$ is the wavelength of the neutron, and A is a constant. For each nucleus, the parameters r_0 and A were chosen to minimize the mean square deviation of the experimental points from the theoretical curve. After reducing the experimental data for the nuclei W, Pb, Bi, and Th, the values of R obtained were respectively 8.0, 7.8, 8.6, and 8.4 F; for U, two values of the radius were obtained: 8.4 (curve 2) and 8.7 (curve 1) (concerning the method of plotting the curves see below). From the experimental values of the cross section we subtracted the following quantity, taken from the paper of Schwinger[5]*

$$\frac{1}{4}\mu_n^2\left(\frac{\hbar}{Mc}\right)^2\left(\frac{Ze^2}{\hbar c}\right)^2\operatorname{ctg}^2\frac{\vartheta}{2},$$

which takes into account the interaction between the magnetic moment of the neutron and the Coulomb field of the nucleus. As can be seen from the foregoing plots, formula (1) describes with sufficient accuracy the experimental course of the differential cross section in the region of the first diffraction p for all the nuclei, except Th and U, in the case of which a noticeable increase is observed in the cross section with decreasing angle in the region 3–5°.

For the nuclei W, Pb, and Bi, the form of the theoretical curve remains practically unchanged regardless of whether the parameters A and r_0 are chosen from all the experimental points or from points located in the region 6–20° only; in the case of U the form of the theoretical curve changes (curves 1 and 2 on Fig. 3). The theoretical curve for Th was plotted from the points located in the region of angles 6–20°. In the case of Th, the additional contribution (compared with the theory) to the differential cross section is somewhat smaller than for U. The indicated anomaly in the angular distribution of the neutrons elastically scattered on the nuclei Th and U cannot be ascribed to the deformation of these nuclei. Indeed, in the case of the W nuclei, which are also deformed, the course of the cross section is well described by expression (1). The same conclusion follows also from the work of Drozdov[6], who considered the behavior of the amplitude of nuclear scattering for deformed nuclei.

From a comparison of the results of Aleksandrov et al[1-3] and the present work it follows, first, that the excess of the scattering cross section above the theoretical value increases with the neutron energy; on the other hand, the indicated effect has been reliably established only for the nuclei Th, U, and Pu and therefore is possibly connected with the specific features of fissionable nuclei. It must be noted that the observed phenomenon has so far not found a satisfactory explanation. Attempts to relate the anomalous course of the cross section in the region of small angles

*ctg = cot.

with the polarizability of the neutron[1,2] contradicts the conclusions of the work of Barashenkov et al[7], in which it is indicated that the effect in this case should decrease with increasing neutron energy, whereas according to the data of Aleksandrov et al[1-3] and the present work one can speak of the opposite effects.

In conclusion, the authors are grateful to D. M. Kaminker for continuous interest in the work.

APPENDIX[1)]

ACCOUNT OF DOUBLE SCATTERING OF NEUTRONS

We consider the following scheme of elementary double scattering. The neutron is scattered first by an angle ϑ_1 in a solid angle $d\omega_1$. The second scattering is in the solid angle $d\omega_0$ in a direction making an angle ϑ_2 with the direction of motion of the neutron after the first scattering, and an angle ϑ_0 with the initial scattering. In the case when the foregoing angles are smaller than 30°, they can be related by the equation

$$\vartheta_2^2 = \vartheta_1^2 + \vartheta_0^2 - 2\vartheta_1\vartheta_0 \cos\alpha,$$

where α is the angle between the planes in which the angles ϑ_1 and ϑ_0 lie.

It is easy to show that the first maximum of the function (1) is well approximated by the Gaussian function

$$\frac{d\sigma(\vartheta)}{d\omega} = \frac{d\sigma(0)}{d\omega} e^{-k^2\vartheta^2},$$

where $k = (R + \lambda\!\!\!^{-})/2\lambda\!\!\!^{-}$. The degree of approximation is seen from Fig. 5.

The total number of neutrons which are doubly scattered in a solid angle $d\omega_0$ at an angle ϑ_0 then amounts to

$$dN_2 = d\omega_0 N_0 \exp(-\sigma_t nd) \frac{(nd)^2}{2}\left[\frac{d\sigma(0)}{d\omega}\right]^2 \exp(-k^2\vartheta_0^2) \times \int_0^\infty \exp(-2k^2\vartheta_1^2)\, \vartheta_1 \left[\int_0^{2\pi} \exp(-2k^2\vartheta_0\vartheta_1\cos\alpha)\, d\alpha\right] d\vartheta_1, \quad (2)$$

where N_0 is the total number of neutrons incident on the scatterer, d is the thickness of the scatterer, n is the number of nuclei per cubic centimeter, and σ_t is the total interaction cross section. Integrating expression (2), we obtain

$$dN_2 = d\omega_0 N_0 \exp(-\sigma_t nd) \frac{(nd)^2}{2}\left[\frac{d\sigma(0)}{d\omega}\right]^2 \frac{\pi}{2k^2} \exp[-(k\vartheta_0)^2] \times \left\{1 + \frac{0{,}64\, k\vartheta_0}{\sqrt{2\pi}} \exp\left[-\frac{(k\vartheta_0)^2}{2}\right][1 + \Phi(k\vartheta_0)]\right\}, \quad (3)$$

where $\Phi(k\vartheta_0)$ is the probability integral.

Calculation of the term in the curly bracket has shown that it can be represented with a high degree of accuracy by the Gaussian function $\exp(-k^2\vartheta_0^2/2)$.

In practice the correction was introduced in the following manner. The experimental points were marked on a plot of $\ln[d\sigma(\vartheta)/d\omega]$ vs. ϑ_0^2. From the front part of the plot, approximately up to half of its decrease, the parameter k was determined from the slope of the straight line; extrapolation to the angle $\vartheta_0 = 0$ yielded the uncorrected value of $d\sigma(0)/d\omega$. Formula (3) was used to plot the angular dependence of the intensity of double scattering, which was then subtracted from the experimental curve. Figure 5 shows the results of such a reduction of the experimental data for a lead scatterer of thickness d = 5 cm.

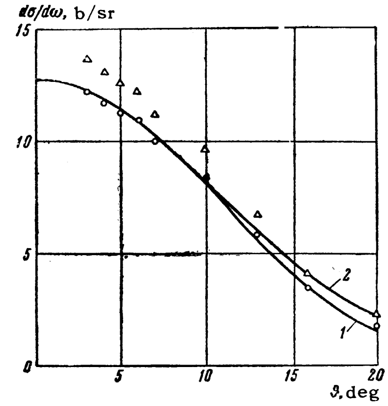

FIG. 5. The function $d\sigma(\vartheta)/d\omega$ from expression (1) (curve 1) and the Gaussian function approximating it (curve 2). The triangles denote the experimental points, and the circles the same points after correction for double scattering, for a lead scatterer 5 cm thick.

[1)]A. I. Slutsker also participated in the calculations presented below.

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