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POLARIZATION EFFECTS IN COULOMB SCATTERING OF 4 MeV NEUTRONS BY COPPER, LEAD, AND URANIUM NUCLEI

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Coulomb scattering of neutrons is due to the interaction of the magnetic moment of the moving neutron with the Coulomb field of the nucleus. In the scattering of unpolarized neutron beams through small angles, Coulomb scattering leads to an intense polarization of the scattered neutrons and to an increase in the differential scattering cross section, especially substantial for heavy nuclei. Expressions describing these effects were first obtained by Schwinger (^{1}) in the Born approximation with the introduction of a number of simplifying assumptions, apparently valid for energies of the scattered neutrons of the order of one to several million electron volts. They have the form

$$\sigma(\theta) = \sigma_{se}(\theta) + \nu^2 Z^2 \operatorname{ctg}^2 \frac{\theta}{2} \left(\nu = \frac{|\mu_n|}{2} \frac{e^2}{Mc^2} \right), \tag{1}$$

$$\mathbf{P}(\theta) = -\frac{\nu k \sigma_t Z \operatorname{ctg} \theta/2}{\sigma(\theta)} \mathbf{n}. \tag{2}$$

Here Z is the charge of the scattering nucleus; σ_t is the total cross section for the interaction of neutrons with the nucleus; $\sigma_{se}(\theta)$ is the differential cross section of potential nuclear scattering; M, μ_n, and k are, respectively, the mass, magnetic moment, and wave number of the neutron; $\mathbf{n}$ is the unit normal vector to the scattering plane. Later, more exact calculations (^{2}) showed the validity of expressions (1) and (2) in the region of scattering angles $20' < \theta < 10^\circ$.

The existence of an asymmetry in the scattering of polarized neutron beams by heavy nuclei at small angles and the sharp increase in the differential scattering cross section of unpolarized neutrons with decreasing scattering angle were observed in works ($^{3-5}$). An experimental study of the applicability of the concepts developed by Schwinger to the case of scattering of neutrons with an energy of 4 MeV was planned by us as the first stage in the study of the processes leading to elastic scattering of neutrons through small angles at this neutron energy. Elastic scattering of neutrons through small angles occurs with a small change in the initial momentum of the scattered neutron, which may be caused both by scattering of the neutron by the potential of nuclear forces and by potentials describing other possible interactions of the neutron with the nucleus. The experiment provides information on the differential cross section of all processes leading to elastic scattering through small angles; therefore, the study of any of these processes encounters the problem of excluding the contribution from the others, which is greatly complicated by interference effects. In our experiment, with a measurement accuracy of 1-2%, apparently only two processes are significant: Coulomb scattering and nuclear scattering ([6,7]).

We carried out an experimental study of the scattering of polarized neutrons with an energy of 4.00 ± 0.13 MeV through angles of 2°, 4°, and 6° by copper, lead, and uranium nuclei. The differential cross sections of elastic-

scattering in the plane perpendicular to the direction of polarization of the neutron beam, as well as the total cross sections for the interaction of neutrons with nuclei.

The source of polarized neutrons was the D—D reaction (energy of the accelerated deuterons $E_D = (1.2 \pm 0.2)$ MeV; $\alpha_{\text{lab}} = 37°$; polarization in the neutron beam $\sim 14\%$ ([8])). The target and collimator used in the experiment are described in ([9]). The cylindrical scatterers were placed immediately behind the exit aperture of the collimator in such a way that the cylinder axis coincided with the beam axis, and they completely covered the beam. The scatterers had their natural isotopic composition.

The scattered neutrons were detected by four scintillation counters with stilbene crystals, arranged pairwise symmetrically with respect to the beam of scattered neutrons. The γ-background counts were discriminated by the shape of the scintillation pulse. Stabilization of the entire detector amplification chain was used.

In the measurements with uranium the background amounted to about 20%, and in the measurements with copper to 40%, of the total number of detector counts in the presence of the scatterer. Background measurements were made in the absence of the sample, with a modulator (a Plexiglas plate) completely covering the beam at the entrance to the collimator channel. The transparency of the modulator coincided with the transparency of the samples (0.55). In this way the modulation of the background by the samples was taken into account, and the flux of neutrons scattered by the sample was determined as the difference between the detector counts in measurements with the sample and in measurements with the modulator.

The values of the differential neutron-scattering cross sections were calculated from the measurement results with allowance for multiple scattering, computed for the specific conditions of the present experiment. Whereas the largest errors in the angular distribution, corresponding to copper, do not exceed 2%, the error in determining the differential cross section reaches ±7%.

Despite the small magnitude of the polarization in the beam of scattered neutrons, in the experiment a noticeable scattering asymmetry was observed for all nuclei, indicating the presence of a polarizing ability of appreciable magnitude and of negative sign for copper, lead, and uranium nuclei, which is in agreement with the ideas developed by Schwinger concerning Coulomb scattering of neutrons. The differential cross section for neutron scattering in an unpolarized beam shows a noticeable rise of the cross section at $\theta = 2^\circ$ for lead and uranium, which again is in qualitative agreement with Schwinger' s predictions.

To clarify the agreement between the results obtained by Schwinger and the data of the present experiment, we used the following possibility, from expressions (1) and (2), of determining the polarization in a beam of neutrons scattered through small angles from the difference of the differential scattering cross sections of the polarized beam and the total interaction cross section:

$$P = \frac{h}{v\sqrt{8M}} \frac{\sigma(\theta, \varphi = \pi) - \sigma(\theta, \varphi = 0)}{\sigma_t Z \sqrt{E} \operatorname{ctg} \theta/2}. \tag{3}$$

The use in the calculations of the difference of the differential cross sections makes the result of the calculations independent of the detection by the detector of neutrons caused by any processes leading to symmetric scattering through small angles (whether fission processes, inelastic scattering, etc.). Another advantage of this formula is the possibility of taking into account the experimental angular resolution by introducing the necessary averaging of the term $|\operatorname{ctg}^{1/2}\theta \cos\varphi|$ in the denominator. In the case of applicability of Schwinger' s ideas to the scattering of neutrons with energy 4 MeV for all scattering angles used in the experiment and for all elements, expression (3) should give mutually consistent results.

The polarization values in the beam of scattered neutrons calculated from the experimental data, within the limits of statistical accuracy, proved to be identical. Thus, for example, for uranium, where the statistical accuracy of the measurements is the best, the measurement results for scattering angles $2.2^\circ \pm 0.9^\circ$, $3.9^\circ \pm 0.9^\circ$, and $6.1^\circ \pm 0.9^\circ$ are respectively equal to $-(15.0 \pm 2.3)\%$, $-(14.4 \pm 3.6)\%$, and $-(17.3 \pm 2.6)\%$. The average polarization values in the neutron beam, determined on the basis of the scattering data on copper, lead, and uranium, are respectively $-(11.7 \pm 3.2)\%$, $-(17.5 \pm 2.8)\%$, and $-(15.9 \pm 1.8)\%$. The final result of averaging over all the data obtained in the experiment gives the polarization value in the beam of neutrons from the D–D reaction, emitted at the angle $\alpha_{\text{lab}} = 37^\circ$ at deuteron energy $E_D = 1.2$ MeV, equal to $P_D = -(15.8 \pm 1.6)\%$. This value is in agreement with the value $P_D = -(14.0 \pm 1.5)\%$ cited in the review (^{8}), corresponding to the same deuteron energy and neutron emission angle $\alpha_{\text{lab}} = 49^\circ$. Within the errors, the experimental results are in good agreement with Schwinger' s predictions. Thus, it may be assumed that, in the scattering of 4 MeV neutrons, the polarization effects in the region of small angles are determined mainly by Coulomb scattering.

Fig. 1

Figure 1: Fig. 1

Fig. 1

The formula (2) obtained by Schwinger makes it possible to calculate the polarizing power of nuclei, due to Coulomb scattering, from the magnitude of the differential cross section of potential nuclear scattering, since all the other quantities are known. Such calculations with experimental data on differential nuclear cross sections describe the true polarization in beams of neutrons elastically scattered at small angles, automatically taking into account the contribution of elastic scattering through the compound nucleus.

The differential cross section of elastic nuclear scattering was obtained by us by subtracting from the experimental data, averaged over θ, the Coulomb scattering cross section. For uranium, the contribution of fission neutrons was also subtracted. The contribution of neutrons from inelastic processes under the conditions of the present experiment is small and, at the experimental accuracy indicated above, has no substantial effect on the results. Through the values obtained for the elastic nuclear cross section, a curve smoothly increasing up to $\theta = 0^\circ$ with decreasing scattering angle was drawn.* The weak dependence of the nuclear cross section on the scattering angle eliminated the need to introduce corrections for the finite angular resolution of the experiment. Figure 1 shows the results of calculations of the Coulomb polarization in beams of neutrons elastically scattered at small angles, performed on the basis of the curves of the elastic nuclear scattering cross section obtained in the indicated manner for the angular range $30' \leq \theta \leq 6^\circ$. The accuracy in determining the polarizing power is set mainly by the accuracy of the absolute differential cross section and is about ±8%. A comparison of the calculated values in ([11]) of the polarizing power of lead for scattering of 4 MeV neutrons through angles 1°, 2°, and 3° with the results of the present work shows their good agreement. It is interesting to note that, although the charges of copper and uranium differ by more than a factor of 3, their polarizing abilities are comparable in magnitude at identical scattering angles. This is explained by the fact that, in the expression for the polarizing power of the scattering nucleus (2), the smallness of Z in the case of copper is compensated by the value, larger than for the heavy elements, of the ratio $\sigma_t/\sigma(\theta)$.

In processing the experimental data by extrapolating the cross section down to $\theta = 0^\circ$, a value inaccessible to direct measurements was obtained for the differential cross section of forward elastic nuclear scattering, $\sigma_{el}(0^\circ)$. The optical theorem relates the total interaction cross section to the imaginary part of the

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* The possible arbitrariness in such an operation is limited by the proximity of the experimental points to $\theta = 0^\circ$, and also by the experimentally observed weak dependence of the cross section on the scattering angle.

amplitude of forward elastic nuclear scattering, $\mathrm{Im}\, f_{el}(0^\circ)$.

We give the values of the data obtained in the present work for the forward elastic nuclear-scattering cross sections and for the total interaction cross sections, as well as the results of calculations of $[\mathrm{Im}\, f_{el}(0^\circ)]^2$ and $[\mathrm{Re}\, f_{el}(0^\circ)]^2$, with their errors.

	σ_t	$[\mathrm{Im}\, f_{el}(0^\circ)]^2$	$\sigma_{el}(0^\circ)$	$[\mathrm{Re}\, f_{el}(0^\circ)]^2$
Cu	3.51 ± 0.07	1.51 ± 0.06	1.66 ± 0.12	0.15 ± 0.13
Pb	7.52 ± 0.15	6.94 ± 0.28	7.05 ± 0.50	0.11 ± 0.57
U	7.81 ± 0.16	7.50 ± 0.30	7.40 ± 0.52	-0.10 ± 0.60

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