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Polarization of 14 MeV neutrons in forward angle scattering by Cu and Pb

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The polarization of 14.2 MeV neutrons elastically scattered through 20° by Cu and Pb is found to be substantially larger than calculated from standard optical model potentials, a similar effect to that reported recently for 16 MeV neutrons. It is proposed that these effects may be related to the geometry of the spin-orbit term in the optical model potential.

[NUCLEAR REACTIONS Cu, Pb(n,n), $E_n = 14.2$ MeV; measured $|P(\theta)|$; $\theta = 20°$, 34°; optical model analysis]

I. INTRODUCTION

Recently Galloway and Waheed[1] reported polarization values for the elastic scattering of 16.1 MeV neutrons by Cu and Pb covering the angular range 20°–90°. For both samples they found a substantially larger value of polarization at 20° than was obtained from optical model calculations using the global parameters of Becchetti and Greenlees[2] or of Rosen, Beery, and Goldhaber[3] or, in the case of Pb, of Fu and Perey.[4] This contrasts with the observation by Hussein, Cameron, Lam, Neilson, and Soukup,[5] for 10.4 MeV neutron elastic scattering by Bi and Pb between 2° and 65°, that their polarization and differential cross-section data were well fitted by optical model calculations based on the Becchetti and Greenlees[2] parameters. In the absence of any other neutron polarization data between 4 and 24 MeV, it was decided to undertake measurements at 14 MeV. The ^{3}H$(d,n)^4$He reaction with deuterons of a few hundred keV energy provided a convenient source of 14 MeV neutrons which have, however, a negligible polarization.[6] Consequently, a double scattering measurement was necessary to obtain polarization information and this was practicable only because of the high differential cross-section for 20° scattering and because of the low background attainable with the associated particle time-of-flight technique applied to the ^{3}H$(d,n)^4$He reaction.

In addition to the experimental investigation, optical model calculations were undertaken to seek some explanation of the observed effects.

II. THE EXPERIMENTAL SYSTEM

The 14 MeV neutron double scattering arrangement is illustrated in Fig. 1. A 350 keV deuteron beam of about 2 mm diameter from the Edinburgh University Van de Graaff accelerator passed through a position defining aperture, then through a liquid nitrogen cooled copper tube which served to reduce target contamination by organic vapors in the vacuum system and so on to a water cooled ^{3}H-Ti target. Alpha particles emitted at an angle of 80° to the deuteron beam were detected in a 0.9 mm thick NE 102A plastic scintillator. The scintillator was mounted on a Perspex window in the vacuum chamber so that the photomultiplier type 56 AVP, and associated electronic components, need not be under vacuum. The scintillator was covered by an aluminum foil 0.002 mm thick to exclude elastically scattered deuterons and any light from the target. Further, an aperture was mounted in front of the scintillator of dimensions chosen to ensure that the cone of associated neutrons was of just the correct size to illuminate all of the first scattering sample.

The associated neutrons were emitted at a mean angle of 88° to the deuteron beam. To determine the precise location of the cone of neutrons coincident with detected alpha particles, and so the proper location of the first scattering sample, a thin (3 mm) stilbene crystal was used as a neutron detector and scanned through the beam. The neutron time-of-flight spectra obtained with the stilbene detector showed a time resolution of 2 ns and a typical beam profile is illustrated in Fig. 2. The stilbene scintillation counter was mounted on a rail system so that it could be removed from the vicinity of the first scatterer but could conveniently be used from time to time during the measurements to ensure that the scattering sample was always correctly located in the neutron beam. The first scattering sample was 15.5 cm from the target and in each case measured 25 mm in diameter by 46 mm high.

Neutrons scattered through 20° by the first scattering sample passed through a throated collimator in the iron shielding and so were incident on

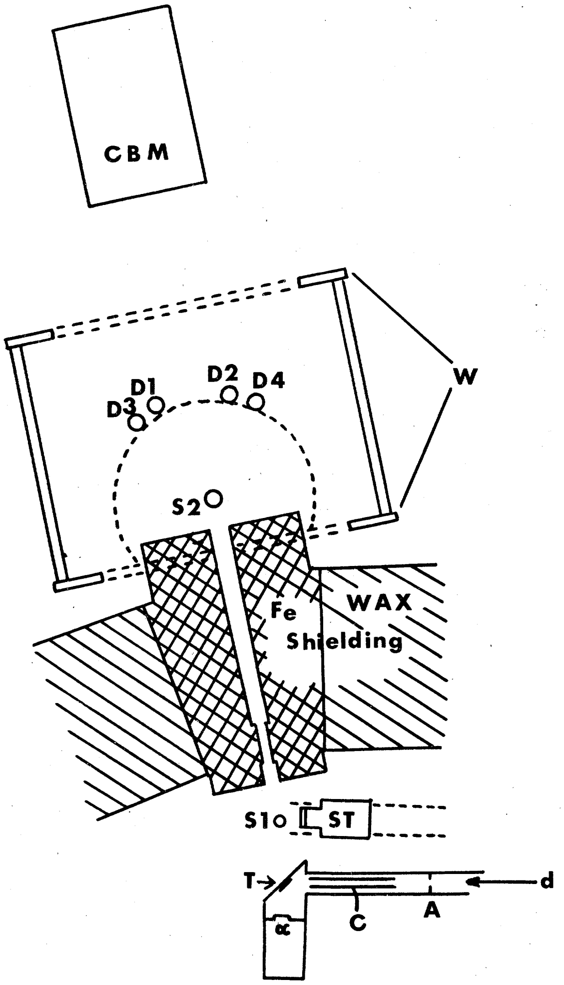

FIG. 1. The layout of the experimental equipment. Legend: d, incident deuteron beam; A, defining aperture; C, Liquid nitrogen cooled copper tube; T, ^{3}H-Ti water cooled target; α, alpha-particle detector; S1, first scattering sample; ST, thin stilbene detector on rails to scan coincident neutron beam; S2, second scattering sample; D1–D4, scattered neutron detectors; W, wheels for interchange of right and left detectors; CBM, collimated neutron beam monitor.

the second scattering sample, which measured 50 mm in diameter by 150 mm high in each case, and was 92 cm from the first sample. The second sample was mounted in the same neutron polarimeter as was used in the study of 2.9 MeV polarized neutron scattering[7] so that the polarimeter is described only in outline here. Neutrons scattered to "right" and to "left" through 20° were detected by a pair of NE 213 liquid scintillation counters with bubble free scintillator containers 50 mm in diameter by 150 mm high. Two similar scintillation counters were mounted at a scattering angle of 34°. The scatterer to detector separation was 30 cm. The liquid scintillation counters and the scattering sample were mounted on a table fixed between two large wheels which could be rotated about the collimated neutron beam direction as an axis to interchange the right and left detectors and so cancel any instrumental asymmetry due to differences in detector efficiencies. A similar rotational polarimeter arrangement with a ^{4}He scattering sample has proved reliable in an extensive study of the polarization of neutrons from the ^{2}H$(d,n)^3$He reaction.[8-11] Alignment of the system was by telescope looking through 2 mm axial holes in inserts fitted into both wheels and into each end of the rectangular cross-sectioned collimator. Fine reference lines were machined onto the scattering samples as a further aid to accurate alignment. Iron shielding 66 cm in thickness was necessary to reduce to an acceptable level the intensity of neutrons scattered from the first sample into the liquid scintillation counters. Background measurements were made by removing the second sample from the collimated neutron beam. Measurements with the second sample in and out of the collimated neutron beam could be alternated automatically by a pneumatic control of the sample position. This pneumatic movement of the sample, with accurate location of the sample when in the neutron beam, comprised the main change in the polarimeter since its previous use.[7]

The intensity of the singly scattered collimated neutron beam was monitored using the time-of-flight spectrum from a NE 102A plastic scintillator 30 cm in diameter by 5 cm thick coupled to an XP 1040 photomultiplier[12] as a check on the correct performance of the associated particle system during measurement. A small plastic scintillation counter below the target served to monitor the neutron yield directly from the target.

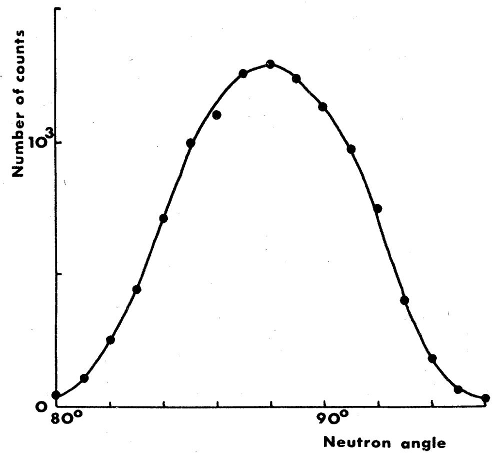

FIG. 2. Coincident neutron beam profile determined with the thin stilbene detector.

III. THE MEASUREMENTS

Experiênce with neutron polarimeters involving interchange of the scattered neutron detectors by rotation as described above[7-10] has shown only one source of significant instrumental asymmetry, namely small changes in detector efficiency on rotation. This has on occasion been attributed to slight movement of components causing a change in stray capacitance or to a change in the magnetic field affecting the photomultiplier gain despite the use of a mu-metal shield. In view of the possible magnetic influence of the large mass of iron shielding and the steel supports for the system, careful tests were carried out with a ^{60}Co source mounted in place of the second scattering sample to establish that no significant change in detector efficiency occurred on rotation. The worst instrumental asymmetry observed in this way was 0.0029 ± 0.0002.

In order to reduce the influence of inelastically scattered neutrons, an energy discrimination level of 10 MeV was applied to each scattered neutron detector. The scattering data were collected in the form of time-of-flight spectra. A deuteron beam current of 2 μA was adopted to avoid excessive pileup in the alpha-particle detector. The time-of-flight spectra associated with each detector for each measurement position and for the second sample in and out were accumulated in a PDP11/05 computer which also controlled the measurement sequence. Measurements were made in each condition in turn for a period of 1000 s and data accumulated over a total period of about 100 h for each scattering material. Typical resultant time-of-flight spectra for the second sample in and out are shown in Fig. 3. The peak in the sample out case was found to be due to neutrons scattered by the first sample penetrating the iron shielding. Additional shadow shielding of the detectors could not readily be introduced within the rotating polarimeter system.

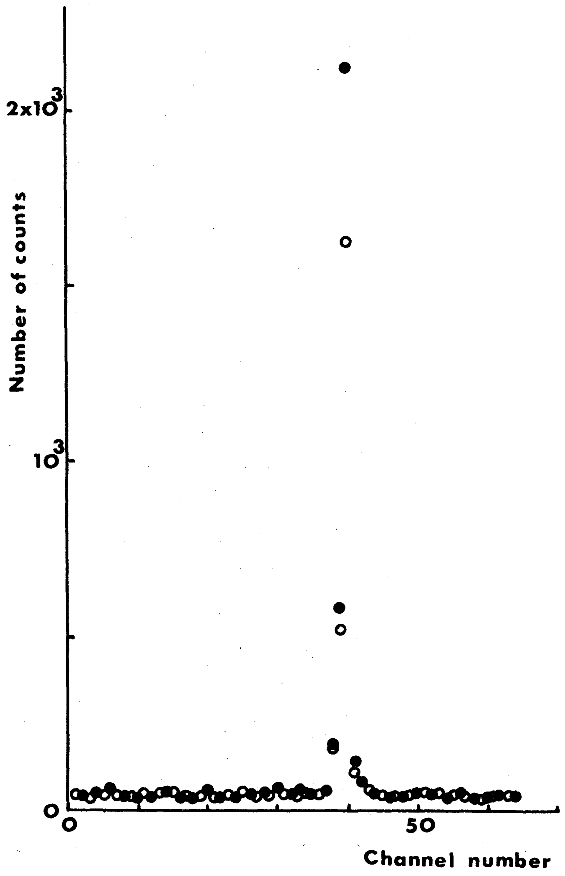

FIG. 3. Time-of-flight spectra: (a) for 20° double scattering by Cu samples (solid circles) and (b) with the second sample removed (open circles).

The measured scattering asymmetries are listed in Table I. The asymmetry in the double scattering of initially unpolarized neutrons is just the product of the polarizations associated with each scattering, that is, for 20°, $P^2(20°)$ and for 34°,

TABLE I. Measured asymmetry and magnitude of polarization for 14.2 MeV scattering by Cu and Pb.

	Cu		Pb	
	20°	34°	20°	34°
Measured asymmetry	0.13 ± 0.04	-0.08 ± 0.11	0.24 ± 0.09	0.14 ± 0.12
Polarization[a]	0.36 ± 0.06	-0.22 ± 0.30	0.49 ± 0.09	0.29 ± 0.25
16 MeV polarization[b]	0.39 ± 0.03	0.21 ± 0.09	0.73 ± 0.03	0.15 ± 0.05
Optical model[c]	0.06	0.19	-0.04	0.14
Optical model and Mott-Schwinger	0.01	0.19	-0.11	0.14

[a] 20° value arbitrarily taken to be positive.

[b] Galloway and Waheed, Ref. 1.

[c] Calculated from the parameters of Becchetti and Greenlees (Ref. 2) and smeared over the 13° spread in scattering angle of the experimental system.

$P(20°)P(34°)$. Thus, in Table I, $P(20°)$ and $P(34°)$ are also listed on the arbitrary assumption of a positive sign for $P(20°)$. The possible influence of multiple scattering was considered using the Monte Carlo program of Holmqvist, Gustavsson, and Wiedling.[13] As was found by Galloway and Waheed,[1] for 16 MeV neutrons on 50 mm diameter by 100 mm high samples at the angles concerned here the multiple scattering effect is negligible, as indeed is the influence of inelastic scattering.

As can be seen from Table I, similarly large magnitudes of polarization were found in the present 20° measurements as were found by Galloway and Waheed[1] for 16 MeV neutrons. Not much can be said about the present 34° measurements because of their large statistical uncertainty. An unacceptably long measuring time, say 1000 h, would be required for each sample to give a useful improvement in this respect. The present 34° values are, however, not inconsistent with the 16 MeV values.

IV. DISCUSSION

Table I also provides a comparison with polarization values obtained from optical model calculations, made using the computer program RAROMP,[14] for the parameters of Becchetti and Greenlees[2] and smeared over the 13° spread in scattering angle of the experimental system. In calculating the smeared polarization value, the weighting for each angular element within the finite angular range of the experimental system was provided by the calculated differential cross-section. This procedure should be valid since the calculated optical model and experimental 14 MeV differential cross sections agree.[2,4] The effect of the finite angular smearing is to reduce slightly the magnitude of the polarization at 20°; the unsmeared 20° values for Cu and Pb are 0.07 and −0.05 respectively. Thus, the smearing procedure is not critical in the comparison of the optical model calculations and the measurements.

Similar polarization values result from using the parameters of Rosen, Beery, and Goldhaber[3] and, for Pb, of Fu and Perey.[4] Thus, the marked discrepancy between measured and calculated values of polarization[1] found for 16 MeV neutrons at 20° is found also at 14 MeV. In the 16 MeV case[1] it was easy to dismiss the possibility that Mott–Schwinger[15] scattering was responsible, not only because of the small magnitude of such an effect but also because the Mott–Schwinger scattering would produce a polarization of opposite sign to that observed. Since in the present double scattering measurement only the magnitude and not the sign of the polarization is determined, it may be appropriate to comment briefly on the influence of Mott–Schwinger scattering on the magnitude of the polarization. The $\cot(\theta/2)$ angular dependence of the small angle polarization from this effect[15] has been well established experimentally over a wide range of neutron energies[16-19] and can be seen merging into the optical model polarization values at about 20° in the 10.4 MeV calculations of Hussein *et al.*[5] Taking the Mott–Schwinger effect and the finite angular range of the measurements into account gives 20° polarization values of 0.01 and −0.11 for Cu and Pb respectively, as included for completeness in Table I. The discrepancies remain.

As the experimental system for the present measurements was different from that used for the 16 MeV measurements[1] and was set up at a different accelerator in a different laboratory, it is unlikely that there is a common undetected instrumental asymmetry responsible for the discrepancies. Consequently, some calculations were undertaken to see whether an acceptable modification of the conventional optical model parameters could accommodate the 20° observations.

Increasing the radius or the diffuseness of the spin-orbit term in the optical model potential was

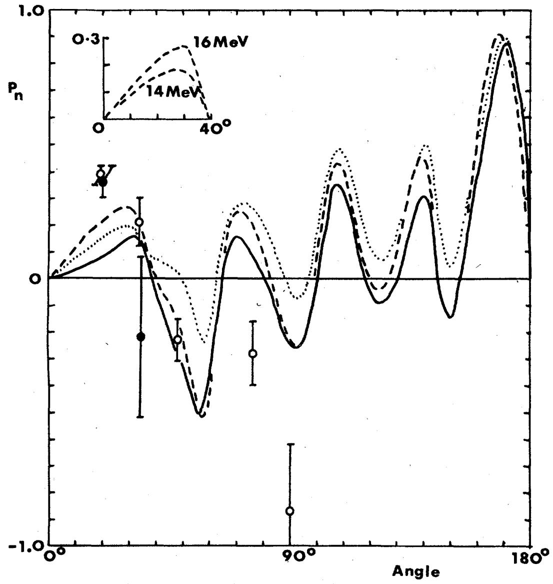

FIG. 4. Optical model calculations of the polarization due to the elastic scattering of 16 MeV neutrons by Cu smeared over the angular spread in the present measurements. The solid line comes from the parameters of Rosen *et al.* (Ref. 3); for the dashed line the diffuseness parameter of the spin-orbit term is 1.0 fm; for the dotted line the radius of the spin-orbit term is 1.4 fm. The insert compares 16 and 14 MeV calculations at forward angles. The present measurements are indicated by solid circles and the 16 MeV measurements of Ref. 1 by open circles.

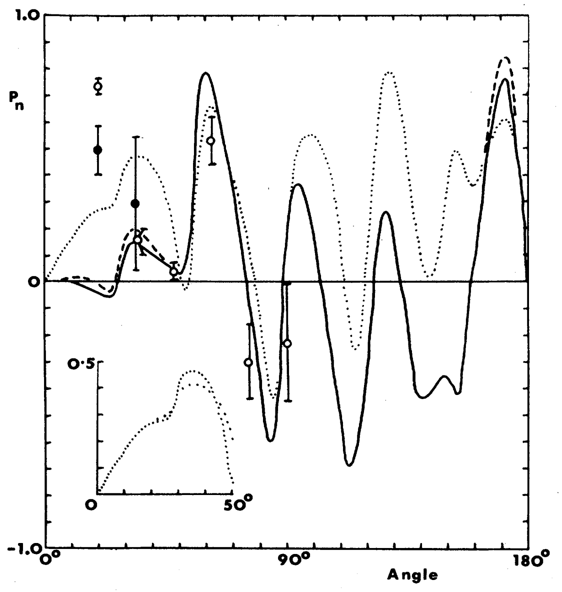

FIG. 5. As for Fig. 4, for scattering by Pb with the calculations based on the parameters of Becchetti and Greenlees (Ref. 2).

found to increase the polarization at forward angles while having little effect on the differential cross section. This is illustrated in Fig. 4 for calculations for 16 and 14 MeV neutron scattering by Cu based on the parameters of Rosen *et al.*[3] with the spin-orbit radius parameter increased from 1.25 to 1.4 fm and with the spin-orbit diffuseness increased from 0.65 to 1.0 fm. There is little difference between the 16 and 14 MeV calculated polarizations at forward angles. It is clear that the increased diffuseness increases the calculated polarization around 20°, bringing it closer to the experimental values, with little effect at larger angles. Similar effects were observed in calculations based on the Becchetti and Greenlees[2] potential. Figure 5 shows the results of such calculations for Pb and the parameters of Becchetti and Greenlees.[2] In this case the spin-orbit radius clearly has much more influence than the diffuseness, although changing the radius alone is unlikely to lead to fitting both the 20° and the 34° measurements. Similar fitting of the forward angle data results from basing the calculations on the parameters of Rosen *et al.*[3] or of Fu and Perey.[4] In relation to the 10.4 MeV neutron scattering data for Pb and Bi by Hussein *et al.*[5] a substantial increase in the spin-orbit radius parameter alone would not be acceptable.

It is concluded that similarly large values of polarization are found for 14 MeV neutron scattering through 20° by Cu and Pb as were found for 16 MeV neutron scattering and that these effects may be related to the geometry of the spin-orbit term in the optical model potential.

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