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Polarization of 16-MeV neutrons due to elastic scattering

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Measurements of the polarization of 16.1-MeV neutrons due to elastic scattering by Cu and Pb are presented over the angular range 20°–90°. The polarization values for scattering angles around 20° differ markedly from the values calculated with the optical model using global fit parameters. This is in contrast to the situation reported recently at 10.4 MeV.

[NUCLEAR REACTIONS Cu, Pb(n,n), E_n=16.1 MeV; measured $P(\theta)$; $\theta=20°-90°$; optical model analysis.]

Although Bjorklund and Fernbach[1] have long since published optical model calculations of the angular dependence of the polarization of 14 MeV neutrons due to elastic scattering, there have been no measurements made in this energy region. A survey[2] of experiments on the angular dependence of neutron polarization due to elastic scattering shows a concentration of effort on neutron energies of 4 MeV and below, where interpretation in terms of the optical model is complicated by competing compound elastic scattering. Indeed the only higher energy measurements are for 24 MeV neutrons[3] and recently for 10.4 MeV neutrons[4]. Because of this paucity of polarization measurements on neutron elastic scattering and because of the large polarization magnitudes predicted around 14 MeV the present measurements were undertaken. It was found that whereas the 10.4 MeV data were well fitted by the optical model[4] using the global fit parameters of Becchetti and Greenlees[5], the present 16.1 MeV data for scattering angles around 20° could not be fitted in this way.

The polarization $P(\theta)$ due to elastic scattering (or strictly the equivalent analyzing power) is determined by observing the right-left asymmetry in the scattering through an angle θ of neutrons incident with known polarization P_n, when

$$P(\theta)P_n=[N_R(\theta)-N_L(\theta)]/[N_R(\theta)+N_L(\theta)]\,,$$

where $N_R(\theta)$ and $N_L(\theta)$ are the numbers of neutrons scattered in a given time through angle θ to "right" and to "left" in the plane normal to the polarization vector P_n. The $^3H(d,n)^4He$ reaction, which with deuterons of a few hundred keV is such a convenient and prolific source of 14 MeV neutrons for differential cross-section measurements, provides neutrons with negligible polarization unless the deuteron energy exceeds 1.5 MeV. The measurements reported below were made with 16.1 MeV neutrons obtained from the $^3H(d,n)^4He$ reaction at 75° to the 2.8 MeV deuteron beam. At this energy and angle of emission the neutron polarization is about −0.24[6,7].

The deuteron beam from the pulsed Van de Graaff accelerator IBIS provided 1 ns pulses of deuterons of mean energy 2.8 MeV in a tritium gas target 1 cm long and filled to a pressure of 1 atmosphere. Neutrons emitted at 75° passed through a throated collimator in a 120 cm diameter by 120 cm high water tank to impinge on a scattering sample of Cu or Pb of about 5 cm diameter by 10 cm high at a distance of 166 cm from the neutron source (Fig. 1). The scattering asymmetry was determined simultaneously for three scattering angles by three pairs of neutron detectors. Each neutron detector was 30 cm from the scattering sample and consisted of a bubble free cell of NE213 liquid scintillator 5 cm in diameter by 15 cm high and viewed by a fast photomultiplier. The system of scatterer and scattered neutron detectors comprising the neutron polarimeter could rotate about the collimated neutron beam direction as axis to interchange the right and left

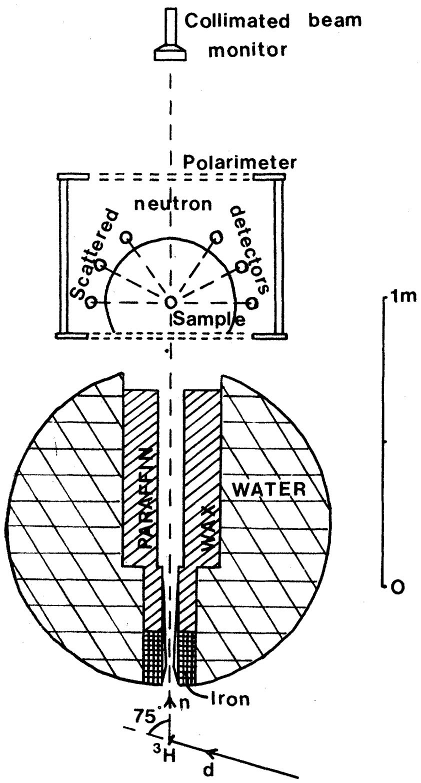

FIG. 1. The experimental arrangement.

detectors and so eliminate any instrumental asymmetry due to a difference in detector efficiencies or scatterer-to-detector distances. The neutron polarimeter is discussed in detail in Ref. 8. Pulse shape discrimination against γ rays was applied to the detectors and a linear bias was applied at $\frac{2}{3}$ of the maximum recoil proton energy to reduce the importance of inelastically scattered neutrons. The neutron time-of-flight spectrum associated with each detector was accumulated in one of six memory areas of a multichannel pulse height analyzer for a period of 2048 s after which the right and left detectors were interchanged. Measurements were also interspersed with the scattering sample removed in order to correct for the significant time correlated background. The final analysis was based on the summation of many 2048 s runs in each measurement condition. Two other detectors monitored the running conditions. One monitored the collimated neutron beam (Fig. 1) and was based on a 12.7 cm diameter by 3.8 cm thick cell of NE213 liquid scintillator. Like the scattered neutron detectors it functioned with pulse shape discrimination against γ rays and generated a neutron time-of-flight spectrum, the peak of which was selected by a single channel analyzer and used for monitoring purposes. The other, a ^{6}LiI(Eu) crystal surrounded by 10 cm of paraffin wax as neutron moderator, was mounted on the

TABLE I. Polarization and differential cross-section data for Cu and Pb listed under laboratory scattering angle. $P_{\rm expt}$ is the uncorrected measured polarization; $P_{\rm Monte}$ is the polarization corrected for finite geometry and multiple scattering; $\sum\epsilon\sigma_{\rm in}$ is the inelastic component in the scattered neutrons; $\sigma_{\rm el}$ is the elastic differential cross section; P_e is the polarization of elastically scattered neutrons assuming the inelastic component to have zero asymmetry; $\pm\Delta P$ is the maximum possible correction required to P_e, i.e., if the inelastically scattered neutrons had symmetry ±1.

Laboratory angle	20°	34°	48°	62°	76°	90°
Cu $P_{\rm expt}$	+0.39 ± 0.03	+0.18 ± 0.08	−0.25 ± 0.06	−0.83 ± 0.15	−0.21 ± 0.09	−0.67 ± 0.19
$P_{\rm Monte}$	+0.39 ± 0.03	+0.20 ± 0.09	−0.28 ± 0.07	−0.95 ± 0.18	−0.24 ± 0.10	−0.81 ± 0.23
$\sum\epsilon\sigma_{\rm in}$ mb/sr	···	4.5 ± 2.0	5.5 ± 3.0	3.5 ± 2.0	3.5 ± 2.0	3.0 ± 2.0
$\sigma_{\rm el}$ mb/sr	1200 ± 100	100 ± 10	30 ± 5	10 ± 2	20 ± 2	30 ± 3
P_e	+0.39 ± 0.03	+0.21 ± 0.09	−0.33 ± 0.08	−1.26 ± 0.26	−0.28 ± 0.12	−0.87 ± 0.25
$\pm\Delta P$	···	0.05	0.18	0.33	0.18	0.10
Pb $P_{\rm expt}$	+0.71 ± 0.03	+0.13 ± 0.04	+0.04 ± 0.03	+0.41 ± 0.07	−0.24 ± 0.11	−0.14 ± 0.13
$P_{\rm Monte}$	+0.72 ± 0.03	+0.15 ± 0.05	+0.04 ± 0.03	+0.48 ± 0.08	−0.28 ± 0.13	−0.18 ± 0.17
$\sum\epsilon\sigma_{\rm in}$ mb/sr	9 ± 2	7 ± 2	6 ± 2	5 ± 2	4 ± 2	3 ± 1
$\sigma_{\rm el}$ mb/sr	800 ± 100	450 ± 50	150 ± 15	45 ± 5	70 ± 5	10 ± 2
P_e	+0.73 ± 0.03	+0.15 ± 0.05	+0.04 ± 0.03	+0.53 ± 0.09	−0.30 ± 0.14	−0.23 ± 0.22
$\pm\Delta P$	0.01	0.02	0.04	0.11	0.06	0.30

target side of the water tank to monitor the neutron yield from the target.

For each scattering angle the polarization was evaluated from the scattering asymmetry assuming a value of −0.24 for the polarization of the neutrons from the $^3H(d,n)^4He$ reaction. The resulting values are listed along with statistical errors as P_{expt} in Table I. There is of course some uncertainty about the polarization of the neutrons from the $^3H(d,n)^4He$ reaction. From consideration of all the measurements from 1.5 to 4.5 MeV deuteron energy and 70° to 80° angle of emission[6,7,9,10] a value of -0.24 ± 0.03 is appropriate. Thus the absolute values of the polarizations quoted in Table I are in doubt by ±12.5% which is less than the statistical error for both Cu and Pb at all angles except 20°. The values P_{expt} were corrected for finite-geometry and multiple scattering effects by a Monte Carlo program[11] to give the values tabulated as P_{Monte}. Because of the short distance (30 cm) from scatterer to detector, inelastic scattering could not be distinguished by time of flight. The linear discriminator bias associated with each scattered neutron detector served to eliminate neutrons inelastically scattered by states of excitation energy greater than about 5 MeV and for neutrons inelastically scattered by lower energy states to reduce the detection efficiency relative to that for elastically scattered neutrons. In Table I the entry $\sum\epsilon\sigma_{in}$ indicates the sum over the relevant excited states of the inelastic differential cross sections modified by appropriate detection efficiency factors. For Cu, 14.5 MeV inelastic scattering data[12] were used and for Pb, 14 MeV data[13]. The elastic scattering differential cross sections, entered in Table I as σ_{el}, were obtained from the same references. Clearly inelastically scattered neutrons are only a small component in the neutrons detected and for which P_{expt} and P_{Monte} were evaluated. It is easy to show that if a polarization P is deduced from the measurement on a mixture of elastically scattered neutrons of polarization P_{el} and inelastically scattered neutrons of asymmetry P_{in}, then

$$P_{el}=P\left(1+\frac{\sum\epsilon\sigma_{in}}{\sigma_{el}}\right)-P_{in}\frac{\sum\epsilon\sigma_{in}}{\sigma_{el}}\ .$$

It is tempting to assume that $P_{in}=0$ since P_{in} will be an average over more than one excited state in more than one isotope. Under this assumption P_e in Table I has been evaluated. There are no data on the asymmetry of inelastically scattered neutrons. For the case of 15.7 MeV polarized protons inelastically scattered by ^{63}Cu and ^{65}Cu, the angular dependence of the asymmetry is essentially the same for the first three excited states of each isotope[14]. Thus it may be worth noting

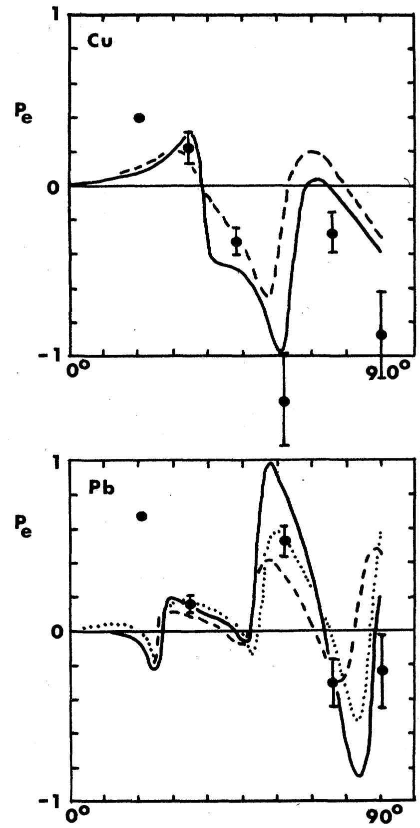

FIG. 2. Comparison of the 16 MeV neutron polarization measurements with optical model curves calculated with the parameters of Becchetti and Greenlees (Ref. 5) ——, Rosen *et al.*, (Ref. 16) — — —, and Fu and Perey (Ref. 13) ······.

the worst possible consequence of $P_{in}\neq0$, that is for $P_{in}=\pm1$, which would change P_e by $\mp\Delta P=\sum\epsilon\sigma_{in}/\sigma_{el}$. Table I shows ΔP to be either smaller or similar in magnitude to the statistical uncertainty in P_e. Clearly for both Cu and Pb the angular dependence of polarization due to the elastic scattering of 16 MeV neutrons is not critically dependent on any of the corrections.

The values of P_e are compared in Fig. 2 with the results of the optical model calculation made using the computer program RAROMP.[15] For Pb Hussein *et al.*[4] found that the global fit parameters of Becchetti and Greenlees[5] provided a good fit to their polarization and differential cross-section data for the elastic scattering of 10.4 MeV neutrons through angles up to 65°. The present data on Pb are not so well fitted by the Becchetti and Greenlees[5] parameters and the parameters proposed by Rosen, Beery, and Goldhaber[16] do not provide a better fit. A better fit between 40° and 90° is provided by the parameters proposed by Fu and Perey[13] to describe scattering by Pb. Irrespective of which of the calculations is considered there is a very marked difference between the measurement at 20° and the calculation.

For Cu there are no previous polarization measurements for a neutron energy greater than 4 MeV. The trend of the present measurements is reproduced a little better by using the Becchetti and Greenlees[5] parameters rather than the Rosen *et al.*[16] set. Again there is a marked difference between the data point at 20° and the calculated curves.

The measurements at 20° are statistically the most accurate and they are least influenced by corrections to the raw experimental data (Table I). They had also the most favorable peak-to-background ratio, 1.2 for the Cu run and 1.4 for the Pb run. The background showed no significant asymmetry, a value of 0.001 ± 0.004 is found for both the Cu and the Pb runs. Careful tests of the polarimeter system for any instrumental asymmetry gave no reason to doubt the validity of the measurements. Uncertainty in the polarization of the neutrons from the $^3H(d,n)^4He$ reaction could not explain the occurrence of a significant difference between measurements and calculations only in the 20° region and in any case could not explain a difference of the magnitude found at 20°. It may also be noted that 20° is much too large an angle for the Mott-Schwinger interaction between the neutron magnetic moment and the Coulomb field of the nucleus to have any significant influence.[17,4] Thus it is concluded that the usual optical model parameter sets[5,13] which satisfactorily fit elastic scattering differential cross-section data for neutrons of about 14 MeV energy fail to fit 16 MeV polarization data for scattering angles around 20°. A search for parameters to give an improved fit to the polarization must await the accumulation of a larger body of experimental data.

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[1]F. Bjorklund and S. Fernbach, Phys. Rev. 109, 1295 (1958).
[2]R. B. Galloway, Proc. R. Soc. Edin. A70, 181 (1972).
[3]C. Wong, J. D. Anderson, W. J. McClure, and B. D. Walker, Phys. Rev. 128, 2339 (1962).
[4]A. H. Hussein, J. M. Cameron, S. T. Lam, G. C. Neilson, and J. Soukup, Phys. Rev. C 15, 233 (1977).
[5]F. D. Becchetti, Jr., and G. W. Greenlees, Phys. Rev. 182, 1190 (1969).
[6]J. R. Smith and S. T. Thornton, Nucl. Phys. A187, 433 (1972).
[7]W. Busse, J. Christiansen, D. Hilscher, U. Morfeld, J. A. Scheer, and W. U. Schroder, Nucl. Phys. A100, 490 (1967).
[8]R. B. Galloway and A. Waheed, Nucl. Instrum. and Methods 128, 515 (1975).
[9]G. Hentschel, Z. Phys. (Leipzig) 219, 32 (1969).
[10]J. Christiansen, F. W. Busser, F. Niebergall, and G. Sohngen, Nucl. Phys. 67, 133 (1965).
[11]B. Holmqvist, B. Gustavsson, and T. Wielding, Ark. Fys. 34, 481 (1967).
[12]J. H. Coon, R. W. Davis, H. E. Felthauser, and D. B. Nicodemus, Phys. Rev. 111, 250 (1958).
[13]C. Y. Fu and F. G. Perey, At. Data Nucl. Data Tables 16, 409 (1975).
[14]M. Dost, C. Glashausser, C. F. Haynes, H. Preissner, and H. Schneider, in *Polarization Phenomena in Nuclear Reactions*, edited by H. H. Barschall and W. Haeberli (Univ. of Wisconsin Press, Madison, 1971), p. 714.
[15]G. J. Pyle and G. W. Greenlees, Phys. Rev. 181, 1444 (1969).
[16]L. Rosen, J. G. Beery, and A. S. Goldhaber, Ann. Phys. (N.Y.) 34, 96 (1965).
[17]J. Schwinger, Phys. Rev. 73, 407 (1948).