**Zeitschrift:** Helvetica Physica Acta

**Band:** 34 (1961)

**Heft:** [6]: Supplementum 6. Proceedings of the International Symposium on polarization phenomena of nucleons

**Artikel:** Polarization of elastically scattered 3.4-MeV neutrons

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**DOI:** https://doi.org/10.5169/seals-541274

# Polarization of Elastically Scattered 3.4-MeV Neutrons[1])

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In order to determine the suitability of optical model descriptions of the elastic scattering of nucleons by nuclei it is important to measure both the differential cross section and the polarization of the scattered nucleons. In a continuation of a program begun a few years ago at the University of Virginia, we[2]) have recently measured the polarization of 3.4-MeV neutrons elastically scattered by S, Cu, and Zn. Differential cross sections have been reported for these elements at approximately the same energy (3.7 MeV) by SNOWDEN and his co-workers [1][3]). A by-product of the experiment reported here was the accumulation of a considerable amount of data on the polarization of neutrons scattered by C.

## Experimental Method

Partially polarized neutrons of mean energy 3.4 MeV were obtained from bombardment of a thick heavy ice target with 1 MeV deuterons. After collimation at 45° (lab) as shown in figure 1, the neutrons were scattered by cylindrical scatterers. The intensities of neutrons scattered to the right and left were recorded simultaneously and the polarization produced by the scatterer inferred from the polarization-asymmetry relation,

$$P_n \, P_{sc}(\theta) = \frac{R(\theta) - L(\theta)}{R(\theta) + L(\theta)}$$

where $P_n$ and $P_{sc}$ represent the magnitudes of the incident neutron polarization and that produced by the scatterer. In both cases positive polarization is considered to be in the direction of $\boldsymbol{k}_i \times \boldsymbol{k}_f$, where $\boldsymbol{k}_i$ and $\boldsymbol{k}_f$ are the momenta of incoming and outgoing particles.

[1]) Supported by U. S. Atomic Energy Commission and OOR, U. S. Army.

[2]) The experiments reported here constituted part of the Ph. D. dissertations of Drs. G. C. COBB (now at North Carolina State College), and H. O. FUNSTEN (now at Princeton University). Dr. T. G. WILLIAMSON (now at University of Virginia Nuclear Engineering Department) also participated in the work.

[3]) Numbers in brackets refer to References, page 310.

The polarization of the D$(d,n)$ neutrons, $P_n$, is known best from measurements made using He$^4(n,n)$ for analysis [2]. For 1 MeV deuterons on a thick target and for the neutron detector bias used in this experiment, the mean polarization of 45° neutrons was 11.6%. The uncertainty of this value is difficult to assess; we estimate it to be about $\pm$ 1%.

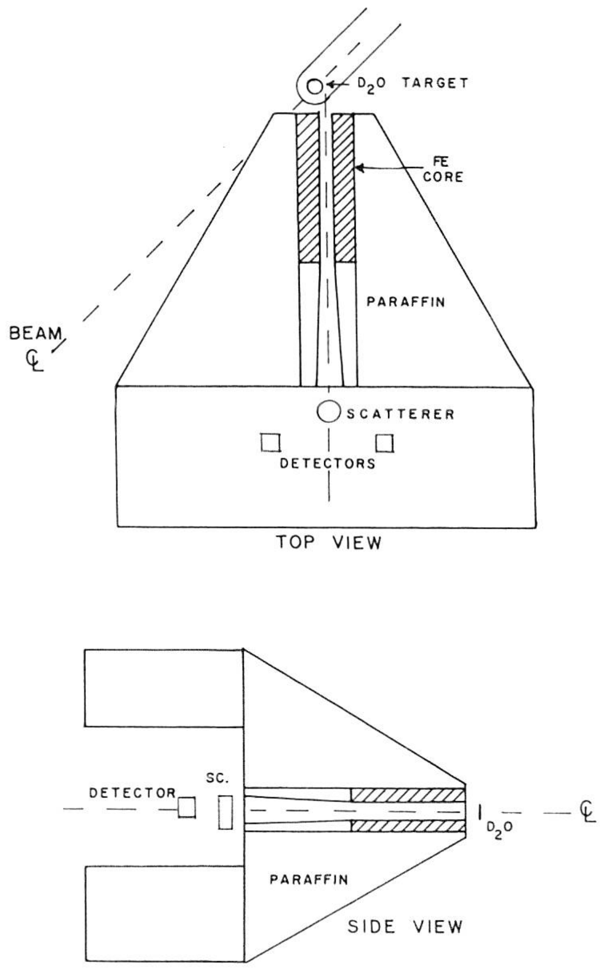


Figure 1

Top view and side view of the collimator, scatterer, and scintillation detectors

Several improvements have been made in the technique used in previous measurements [3]. Specifically these involve the following innovations. Scattered neutrons were detected by pulse-shape discriminating neutron counters [4]. By utilizing the difference in pulse shapes for neutron and gamma induced pulses from stilbene scintillators, it has been possible [5] to achieve neutron to gamma efficiency ratios as high as 1000. At the same time the counters reproduced well the neutron pulse height spectrum making possible discrimination against inelastically scattered neutrons. Neutrons scattered to the right and left were detected simultaneously and the pulses were displayed on 50-channel sections of a 100-channel pulse analyzer. The analyzer was gated to count only neutrons by 'pulse shape' signals. The scattered neutron intensity was measured as the 'scatterer in minus scatterer out' counting rate. The 'scatterer out' rate could be held to approximately 30% of the 'scatterer in' rate at forward angles, and to 70% at backward angles. Neutron intensity was monitored by a stilbene detector placed above the collimator, viewing the deuterium target at 45°, and with the same bias as the scattered neutron detectors.

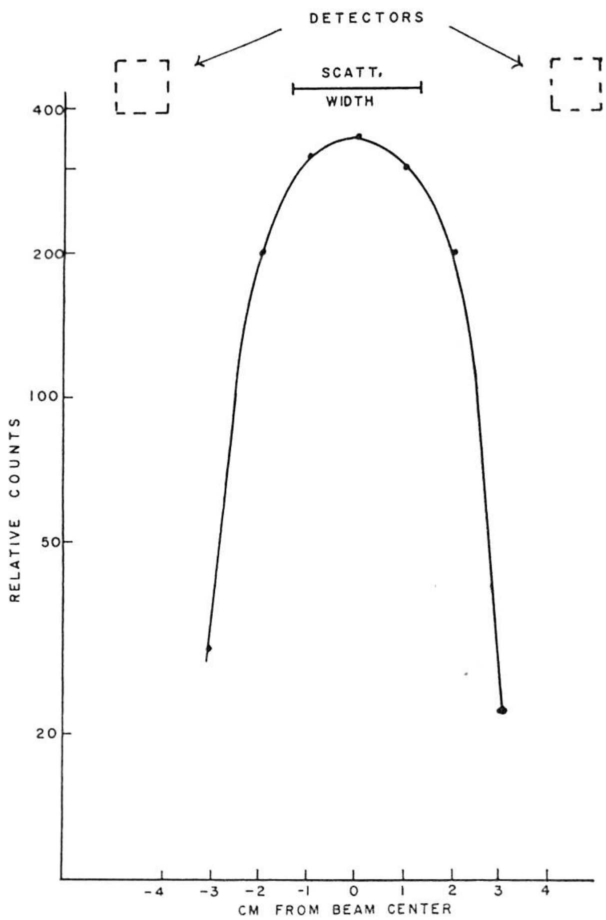


Figure 2
The observed profile of neutron intensity emerging from the collimator. Size and position of the scatterer and detectors are also shown.

The profile of neutrons emerging from the collimator and the energy spectrum of neutrons contributing to the data are shown in figures 2 and 3. The energy spectrum $N(E)$ was calculated from the following expression,

$$dN = C\,\sigma\,(E_d)\left(\frac{d\,E_d}{dx}\right)^{-1} \varepsilon\,(E_n)\,dE_d$$

where $C$ is a constant, $\sigma(E_d)$ the differential reaction cross section at 45°, $dE_d/dx$ the deuteron energy loss in $D_2O$, and $\varepsilon(E_n)$ the neutron counter efficiency for neutron energy $E_n$ produced by deuterons of energy $E_d$.

Instrumental asymmetries were observed and eliminated by taking data alternately with neutrons emitted to the "right" and "left" of the deuteron beam, for which cases the sign of $P_n$ is opposite. The entire apparatus was frequently checked by measuring the right-left asymmetry at 45° for a carbon scatterer, which asymmetry is now well known from previous measurements [3, 6].

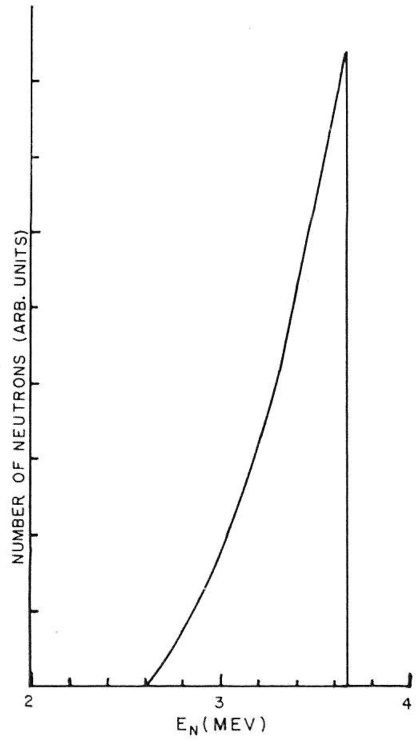


Figure 3

The neutron energy spectrum calculated as described in the text

Recording of the differential pulse spectra of both the right and left counters made possible a determination of the influence of inelastically scattered neutrons. Only pulses occuring above the inelastic energy were accepted. The angular resolution of the scatterer-detector geometry employed varied from 10° to 28° for different scattering angles.

## Results

The observed values of polarization, corrected for finite geometry, are shown in figures 4, 5, and 6 for S, Cu, and Zn together with the differential cross sections observed by MACHWE, KENT, and SNOWDEN [1] (solid lines). It can be seen that the polarization goes through zero near the first diffraction minimum for each of the scatterers. Also, for forward angles the sign of the polarization corresponds to the slope of the cross section. These two features are in accord with RODBERG's approximate calculation [7] which is probably not accurate for large angles. Correspondingly, the polarization produced by Cu and Zn fails to go to zero at the first maximum (100°) and second minimum (140°) although for both elements a slight decrease in the positive polarization is evident near these angles.

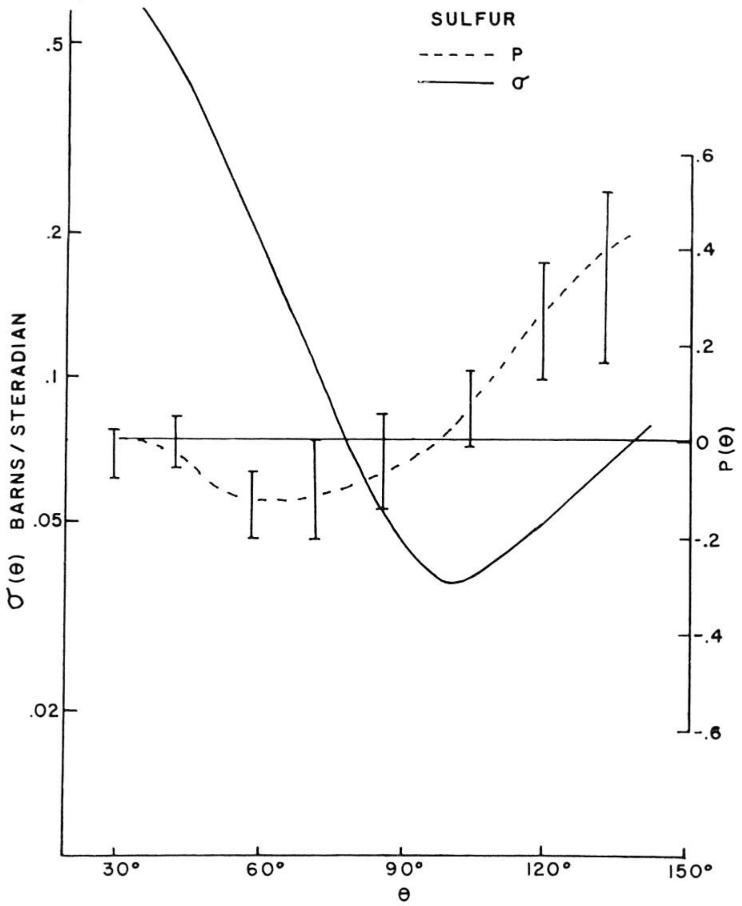


Figure 4

Experimental points and dotted line show the observed polarization produced by sulfur (scale on the right). The solid curve represents the differential cross section measurements of MACHWE *et al.*[1]) (scale on the left).

Both the polarizations and differential cross sections for Cu and Zn are very similar, which one expects to be the case for shape elastic scattering by neighbouring elements. The Zn polarization is compared with an optical model calculation made by BJORKLUND[4]) in figure 7. The curve shown is BJORKLUND's curve corrected for finite detector geometry. Agreement is fair up to about 100° but the predicted change of sign at 110° was not observed. The influence of compound elastic scattering was undoubtedly appreciable. A computed optical model cross section [2] accounts for only about one half of the observed cross section integrated beyond 100°. Comparison of the Cu polarization data with the calculated curve is about as inconclusive as is the case with Zn.

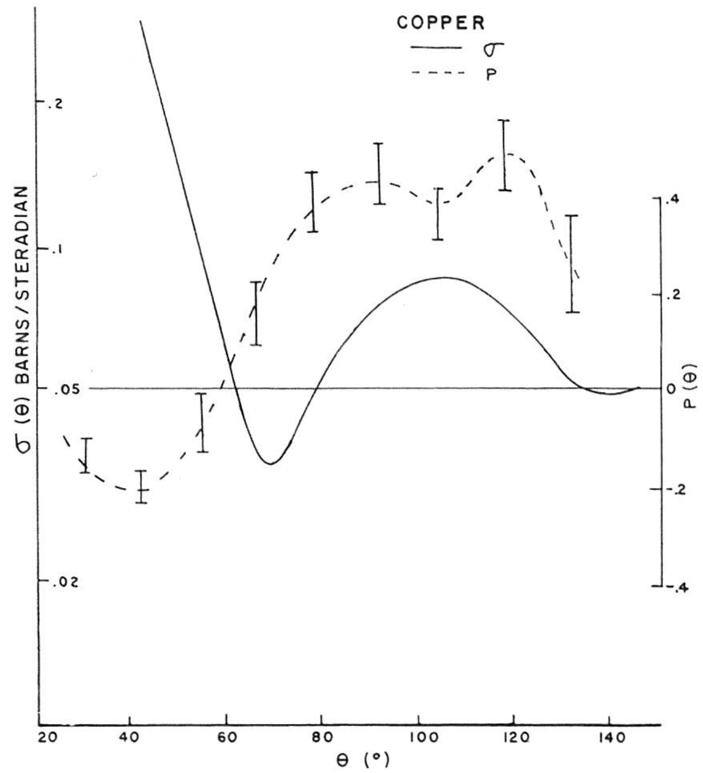


Figure 5
Same as figure 4, but for copper

The frequent checks of the instrumental asymmetry with a carbon scatterer yielded considerable data on the polarization produced by carbon. It is interesting to compare the result with that computed from the phase shifts of MEIER, *et al.* [6] and WILLS, *et al.* [8] for the neutron energy spectrum employed. One finds

$$P_c\,(45°) = \left\{ \begin{array}{l} -\,0.52,\ \text{Meier, } et\ al. \\ -\,0.33,\ \text{Wills, } et\ al. \\ -\,0.64 \pm 0.04,\ \text{Observed} \end{array} \right.$$

[4]) BJORKLUND, private communication. The potential used in these calculations was that described by BJORKLUND and FERNBACH, Phys. Rev. *109*, 398 (1958) with $V_{CR} = 47$, $V_{CI} = 7$, $V_{SR} = 5$, $V_{SI} = 0$.

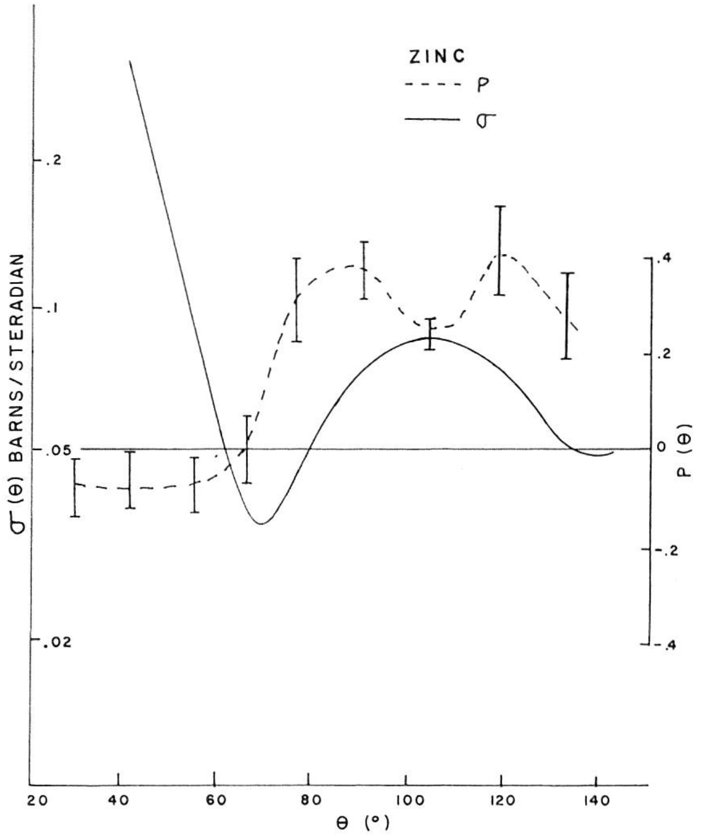


Figure 6
Same as figure 4, but for zinc

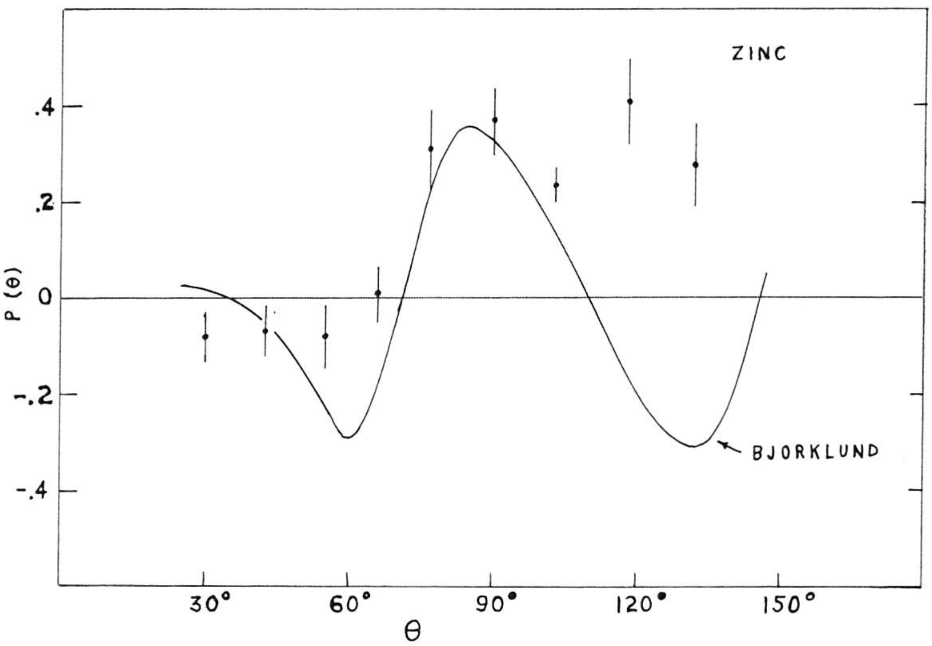


Figure 7
Comparison of the zinc polarization measurements with BJORKLUND's optical model calculation[4])

As in the case of previous results [3, 9], this measurement is in better agreement with the polarization predicted by the Meier phase shifts. Figure 8 shows results obtained previously [3] on the polarization of neutrons scattered at 45° from carbon for neutron energy between 2 and 4 MeV. The uncertainty in knowledge of the $D(d,n)$ neutron polarization introduces possibly a 10% uncertainty in the observed values in addition to the statistical errors. It seems unlikely, however, that the assumed neutron polarization could be in error by a factor of two.

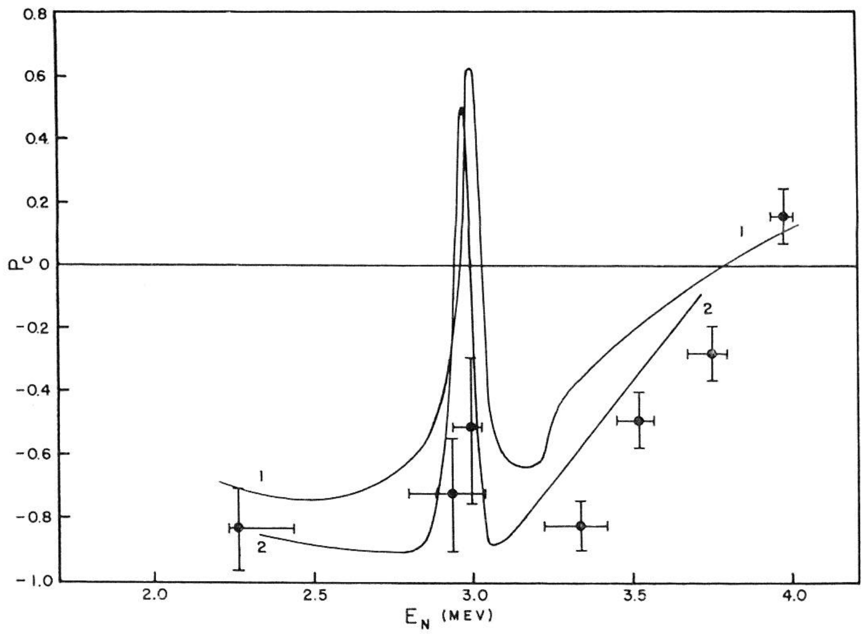


Figure 8

The polarization of neutrons scattered at 45° from carbon. Curve 1 was computed from the phase shifts of WILLS *et al.* [8]; curve 2 from those of MEIER *et al.* [6].

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