Zeitschrift: Helvetica Physica Acta

Band: 34 (1961)

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

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DOI: https://doi.org/10.5169/seals-513277

Energy Variation of Neutron Polarization in Scattering from Zinc, Copper, Molybdenum and Cadmium

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1. Introduction

The polarization of neutrons of energy less than 2 MeV scattered from medium and heavy nuclei has been studied by a number of workers [1, 2, 3, 4][2]). Measurements have been restricted to only two energies – 380 KeV and 980 KeV and three angles – 55°, 90° and 130°. The variation of polarization with respect to the parameter A, the atomic weight, has been relatively extensively explored. The most comprehensive set of results in this field is that of Clement *et al.* [5], at neutron energies of 380 KeV and 980 KeV. They found that an optical model with spin-orbit coupling gave a general description of their results giving the change in sign indicative of the p-wave size resonance.

Bjorklund, using a refined optical model with spin-orbit coupling reported attemps [6] to fit the data in more detail. He found that the calculated polarizations were in general too large, and the parameters required to fit the data fluctuated considerably from element to element.

The present series of measurements was undertaken to explore the variation with energy in more detail. For four elements measurements have been made at 50 KeV intervals from 350 KeV up to 1600 KeV. These measurements were made at 55° and 90° scattering angles, these angles being chosen for the comparison with the results of earlier workers.

Using the optical model potential proposed by Bjorklund and Fernbach the polarization was computed for the cases of interest. The general overall agreement was poor though it was clear that reasonable parameters could be found to fit particular points.

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2) Numbers in brackets refer to References, page 301.

2. Experimental Procedure

The experimental arrangement used is shown in figure 1. Protons from the Harwell 5.5 MeV Electrostatic Generator are brought to a focus through a 5 mm diameter collimator onto a target of Li_3 N. This material was chosen because of its high lithium content and low yield of high energy gamma rays. Neutrons from the reaction $Li(p, n)Be^7$ emitted at an angle $\phi = \pm 50°$ to the proton beam pass through a collimator to the scatterer 50 cm distant. The neutron energy spread due to target thickness is about 40 KeV. The main shield is formed of boron loaded paraffin. The first half of the collimator is slightly tapered with a mean width of 2 cm, the second half broadens out into a trumpet shape such that no part was nearer to the sample than 5 cm. The sides of the collimator were fitted with carbon liners to depth of 2.5 cm to reduce small angle scattering.

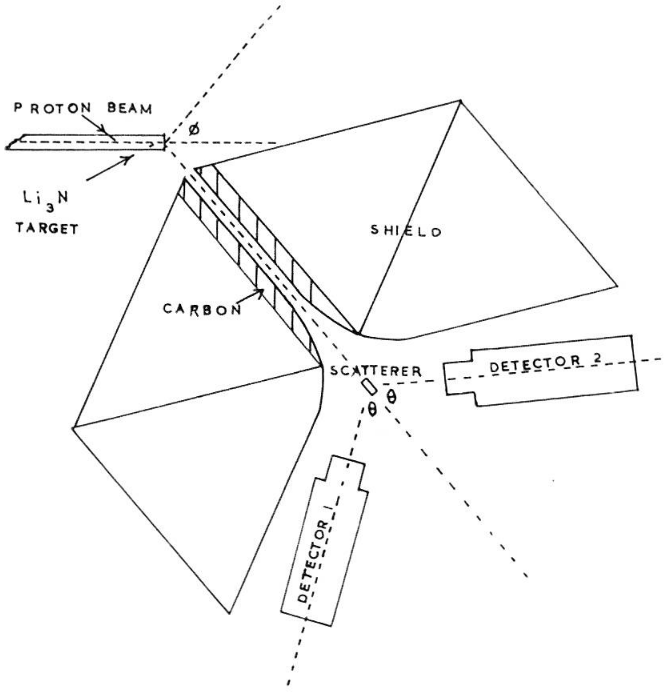

Figure 1
General arrangement of the apparatus

The scatterers were rectangular blocks 1.9 cm × 3.2 cm × 7.5 cm. The two detectors were scintillation counters consisting of cylinders of stilbene 4 cm diameter by 2.5 cm long mounted on E.M.I. type 6097 photomultipliers. The distance from the centre of the scatterer to the centre of each detector was 12 cm. The response of the two detectors was closely similar (though this was not in fact essential). Pulse shape discrimination [7, 8] was used in the detector in order to distinguish neutrons from gamma rays. The circuitry used for this purpose was similar to that described by OWEN [8]. The voltage between the last dynode and the collector ($\sim$ 2–3 volts) was supplied from a battery and potentiometer. This voltage was adjusted so that the integrated pulse at the last dynode had a positive sign for a neutron pulse and a negative sign for a pulse due to a γ-ray. A linear pulse was derived from an earlier dynode so that normal pulse height selection could also be applied. Thus only those events satisfying the two criteria of having linear amplitude between appropriate limits, and giving a positive pulse at the last dynode, were counted as neutrons. This procedure enabled low energy neutrons and gamma rays to be excluded from the counters. This feature greatly assisted in the reduction of background.

In order to reduce background due to neutrons scattered from the floor, and surroundings, the experiments were conducted at a target position 320 cm above the floor in a large aircraft hangar. The shields and counters were supported on a light framework which was pivoted, so that the whole apparatus could rotate about the target as centre.

With the pulse height selection set so as to exclude neutrons from the reaction $Li^7(p,n)Be$,[7] and neutrons which had lost energy by inelastic scattering, the background, measured by removing the sample, was found to be $\sim 30\%$ of the total count at incident neutron energies of 400 KeV, rising to about 50–60% for neutrons of 1600 KeV. A «long-counter» was used as a monitor to relate the «scatterer in» runs to those with scatterer out.

The experiment was carried out by measuring N_1 and N_2 the true counts, *i.e.* total counts minus background, in each of the counters 1 and 2 with the assembly in a position corresponding to $\phi = +50°$. The measurement was then repeated with $\phi = -50°$ giving N_1^1 and N_2^1. Clearly, if the incident polarization in the first case is P_1 then in the second it is $-P_1$. Also if L/R is the true asymmetry

$$\left(\frac{N_1}{N_2}\right)\left(\frac{N_2^1}{N_1^1}\right) = \left(\frac{L}{R}\right)^2 ;$$

it is this quantity L/R that we have chosen to plot.

At a later stage in the experiment a simpler method was used. Here ϕ was kept constant. The positions of detectors 1 and 2 were adjusted so that their geometrical efficiencies were identical. Instead then of moving to $-\phi$ counters 1 and 2 were interchanged. The method of analysis is very similar to that described above.

The sign convention used in this paper is that the positive direction of the polarization is in the direction $\boldsymbol{n} = \boldsymbol{k}_0 \times \boldsymbol{k}$, where $\boldsymbol{k}$ = momentum vector of the outgoing particle,

$\boldsymbol{k}_0$ = momentum vector of the incident particle.

In evaluating P_2 we have assumed a constant value of $P_1 = +0.40$ throughout the energy range. ADAIR [1], and OKAZAKI [3] found polarization values of $+0.40^{\pm .02}$ in the range 210 KeV to 600 KeV. STRIEBEL *et al.* [9] give the value $+0.30^{\pm .02}$ for the range 700 KeV to 1.5 MeV but this is not well supported by CRANBERG [10] who finds $+0.44^{\pm .03}$ at 1. 494 MeV, and $+.37^{\pm .05}$ at 1.95 MeV.

The polarization of neutrons scattered from carbon for neutrons of energies less than 1 MeV should be zero as there are no strong p-wave or higher resonances in this region. This material was used as a check that we had eliminated artificial asymmetries. This topic is discussed in some detail in the Appendix.

3. Results

Using the methods described above, the asymmetry has been measured at scattering angles $\phi = 55°$ and $\phi = 90°$ for copper and molybdenum. In view of the somewhat surprising nature of the results considerable pains were taken to ensure their consistency and reliability. Measurements were made using both methods described above and within the errors there appeared to be good agreement. Carbon checks were made during the course of these measurements. The results at 55° are shown in figures 2 and 3.

Since over a large part of the energy region the two materials have opposite signs of polarization a further check was to make alternate measurements with copper and molybdenum. These measurements were again consistent with our previous measurements. There can be little doubt that the polarization is not a smooth monotonic function of energy. This is confirmed by the measurements at 90° which are shown in figures 4 and 5. In order to investigate these effects further the experiments were repeated for zinc and cadmium. Here fewer points have been taken (figures 6 and 7) but the same general features appear.

Taking the assumptions described above the polarizations were calculated. These have not been corrected for the effect of multiple scattering in detail. The order of magnitude of this correction is estimated to be about 30%, i.e. the observed polarization should be increased by about 30%. When this correction is taken into account there is in general fair agreement between our measurements and those of CLEMENT *et al.* though there are one or two discrepancies well outside the experimental error.

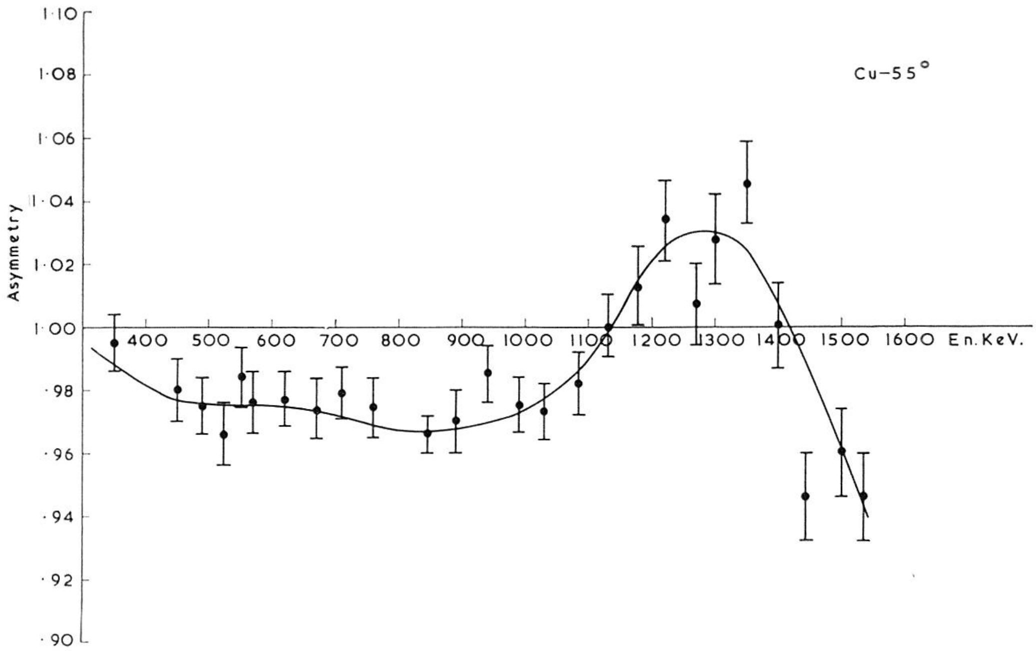

Figure 2. The variation of the polarization of neutrons scattered from copper at 55°

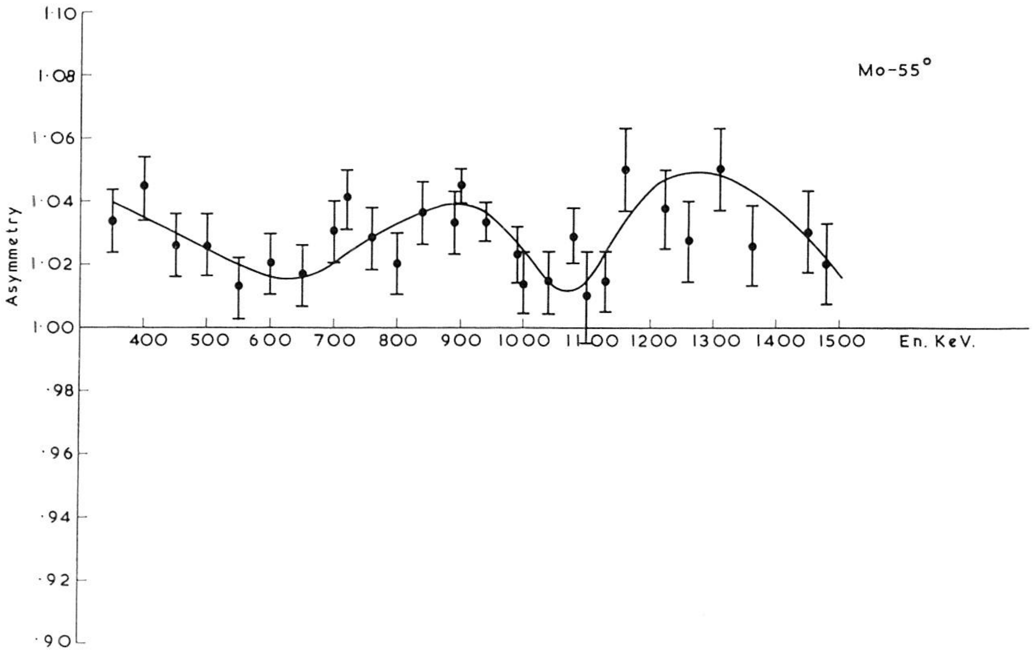

Figure 3. The variation of the polarization of neutrons scattered from molybdenum at 55°

4. Discussion

Calculations were made using the version of the optical model with spin orbit coupling proposed by BJORKLUND and FERNBACH. The para-

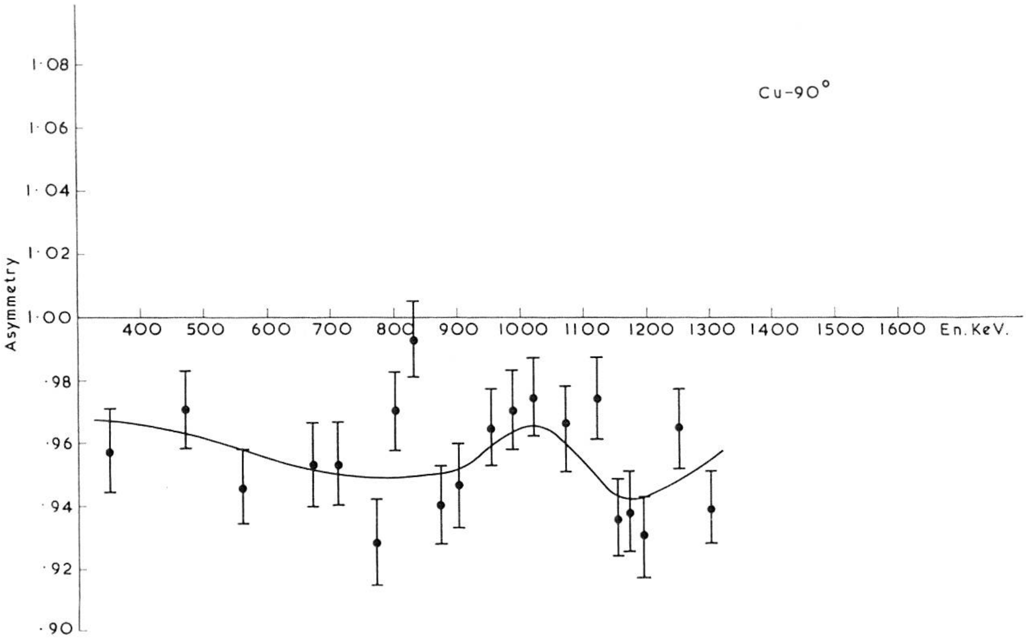

Figure 4. The variation of the polarization of neutrons scattered from copper at 90°

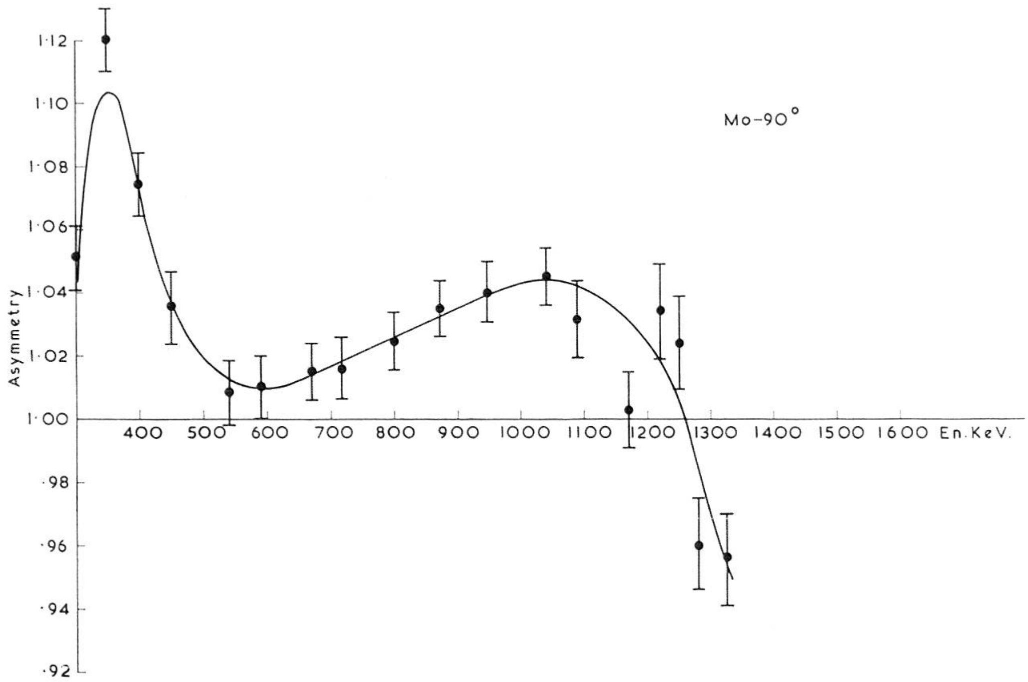

Figure 5. The variation of the polarization of neutrons scattered from molybdenum at 90°

meters were taken from their summary of best values given at the Florida Conference in 1959. They were $V_{cn} = 56$ MeV, $V_{ci} = 2$ MeV,

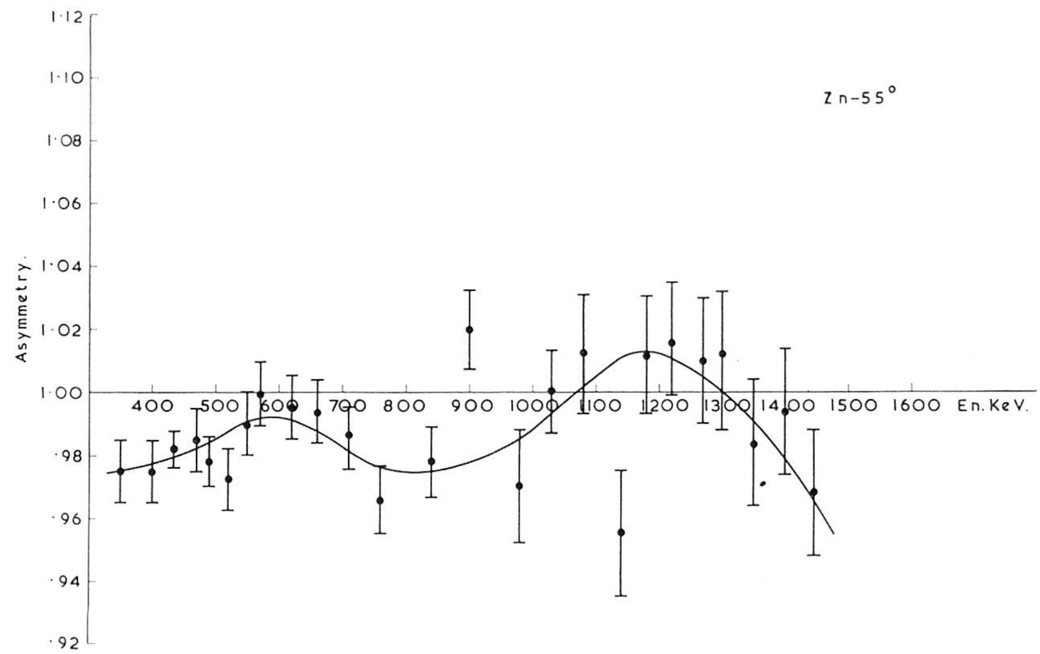

Figure 6. The variation of the polarization of neutrons scattered from zinc at 55°

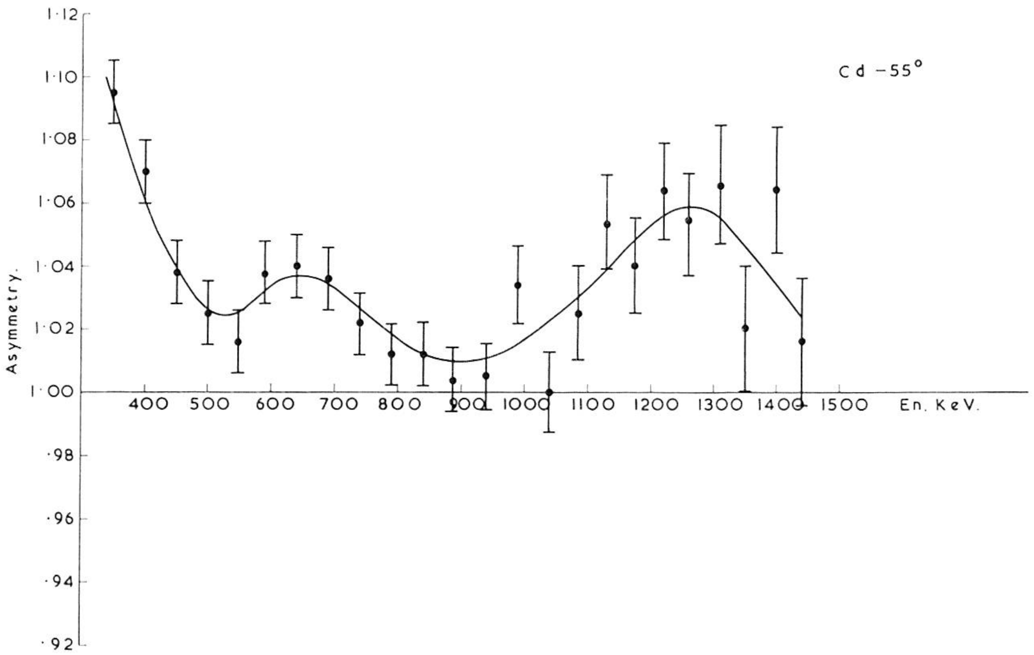

Figure 7. The variation of the polarization of neutrons scattered from cadmium at 55°

$V_{sn} = 10$ MeV, $a = 0.65$ or 0.4, $b = 1.0$, using the notation of these authors. The comparison of these calculations with the data is shown

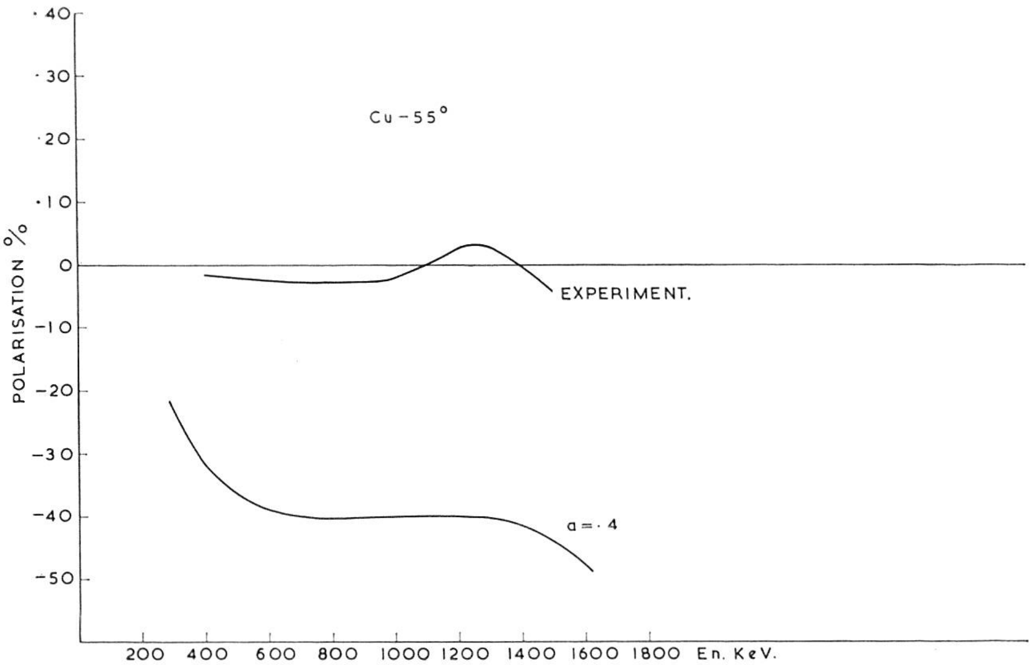

Figure 8. Comparison of the experimental polarization on scattering from copper at 55° with calculation on the basis of the optical model

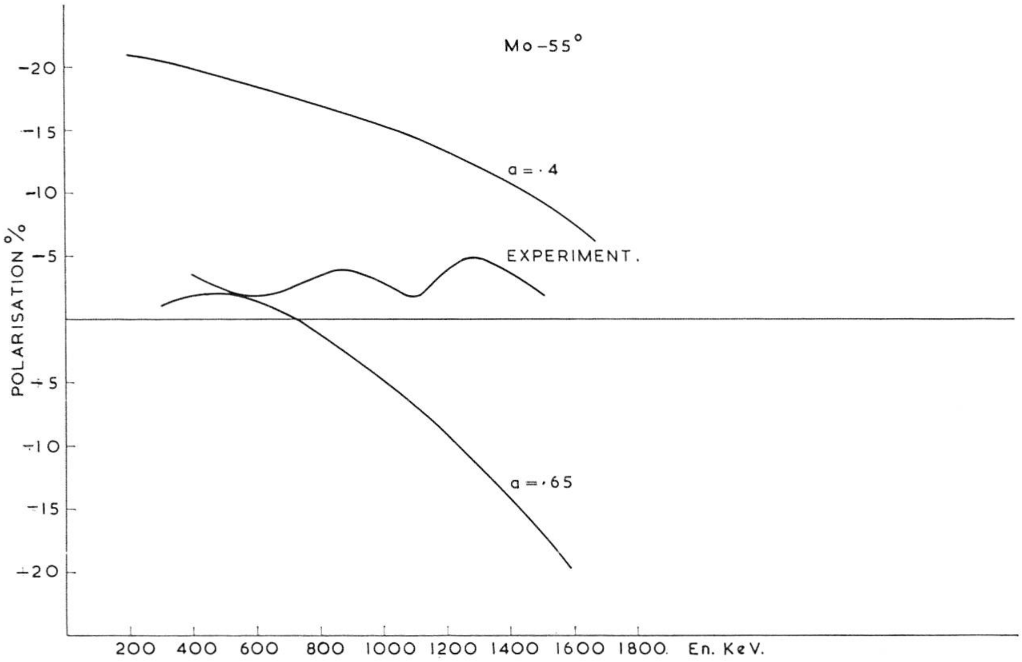

Figure 9. Comparison of the experimentally measured polarization on scattering from molybdenum at 55° with calculations on the basis of the optical model

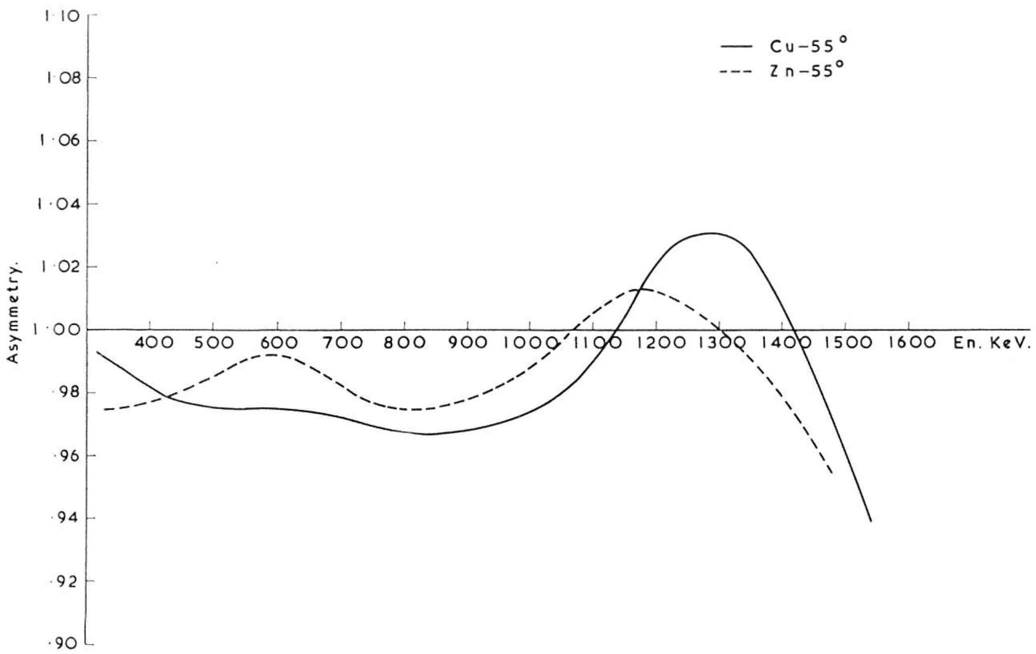

Figure 10. Comparison of the experimentally measured polarizations for scattering from copper and zinc at 55°

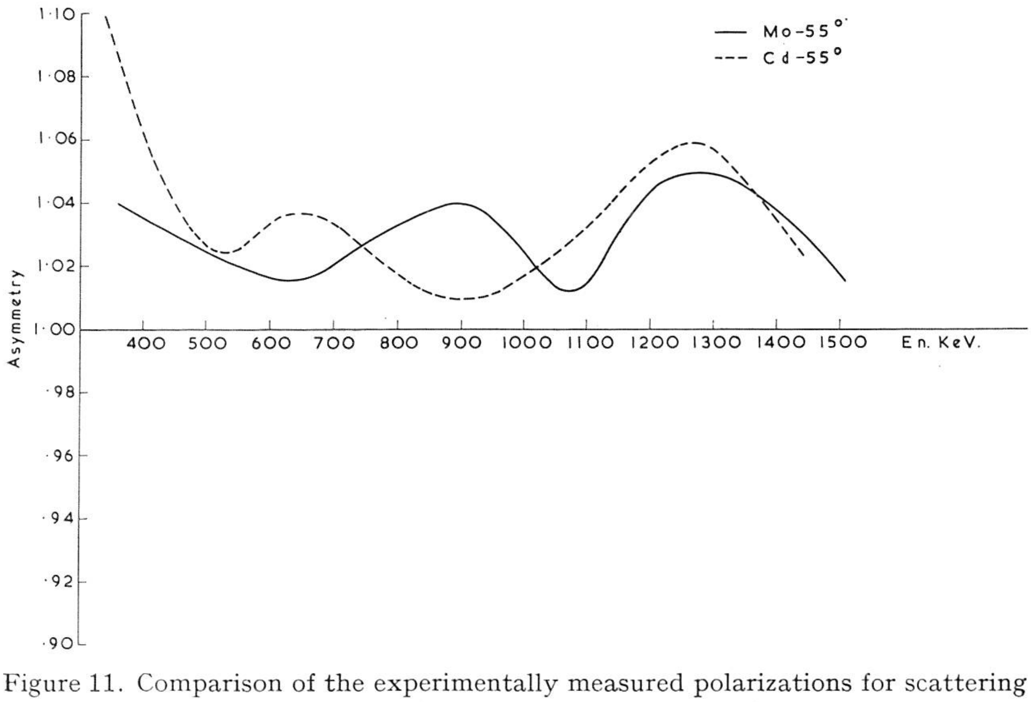

Figure 11. Comparison of the experimentally measured polarizations for scattering from molybdenum and cadmium at 55°

in figures 8 and 9. It is clear that the optical model cannot reproduce the detailed features observed. Although no serious exploration of the parameter space could be undertaken through lack of computer time, it appeared that with some quite reasonable variation of the parameters each point could be fitted. Using the same parameters the calculated angular distribution of scattered neutrons at 1 MeV fitted the work of Walt and Barschall [12] fairly well.

The question then arose as to whether the variation with energy observed was simply peculiar to the individual nuclei or whether there was some greater regularity. As a first step in investigating this point the measurements on zinc and cadmium were made. Figures 10 and 11 show this comparison. Though not conclusive there is sufficient similarity present to make us anxious to pursue this matter further.

In terms of the optical model division of elastic scattering into shape elastic and compound elastic, it is fairly certain that any explanation of these phenomena will primarily concern the compound elastic processes. An explanation could be in terms of a departure from the statistical distribution of levels in the compound nucleus allowing one or two dominant levels to decide the polarisation, i.e. the compound elastically scattered neutrons may be polarised. There is as yet, however, too little data to provide a worthwhile basis for computation. It is our intention to extend this work to a further series of elements using a transverse magnetic field to rotate the spins of the incident neutron.

Appendix

False Asymmetries

Many of the asymmetries which may be observed in scattering experiments arise from causes other than polarization. The principal causes of these may be summarized as under:

a) Unequal efficiency of the two counters.
b) Uneven illumination of the sample due to:
   i. Variation of the cross-section for the Li (p,n) reaction with angle.
   ii. Unequal scattering off the sides of the collimator due to displacement of the source.
c) The variation of the polarization of the incident neutrons P_1 across the sample.
d) The variation of P_2 with angle of scattering.

The experimental procedure described above clearly eliminates (a) in this case. (The somewhat simpler procedure of interchanging the two counters also eliminates (a)). In principle (b)ii is also eliminated. However, precise rotation of the assembly about the target spot is difficult to achieve and unless this effect is made small false asymmetries may appear. This may be achieved by keeping the width of the sample small compared with mean width of the collimator and by lining the latter with carbon. The effects mentioned at (b) i, (c) and (d) have been considered in detail by EVANS [11]. He shows that the expression for the asymmetry may be written

$$\frac{R}{L} = \frac{1+(\alpha-\beta)\,\frac{\theta_1^2}{3} + P_1P_2\left[1+(\gamma+\delta)\,\frac{\theta_1^2}{3}\right]}{1+(\alpha+\beta)\,\frac{\theta_1^2}{3} + P_1P_2\left[1+(\gamma-\delta)\,\frac{\theta^2}{3}\right]}\,.$$

The functions α and β depend only on the angular distribution $\sigma(\theta)$ of the neutrons from the Li(p,n) reaction and $\sigma'(\theta)$ its derivative with respect to θ. The functions γ and δ contain not only σ and σ' but also P and its derivative with respect to θ, P'. θ_1 is the angle subtended by the scatterer at the source.

If we consider scattering from carbon we should expect that for neutrons less than 1 MeV P_2 should be zero: in those circumstances

$$\frac{R}{L} = \frac{1+(\alpha-\beta)\,\frac{\theta^2}{n}}{1+(\alpha+\beta)\,\frac{\theta^2}{3}}\,.$$

We have measured the quantity R/L for carbon for several energies up to 900 KeV and find that within our statistical errors it is unity. Consequently the terms in α and β which contain only the parameters of the Li(p,n) reaction must be negligible with the solid angles used.

Insufficient data is available to compute γ and δ precisely but using reasonable estimates it would seem unlikely that these terms would give rise to significant asymmetry. Experimentally, the use of a magnet to rotate the spins of the incident neutrons would eliminate the effect due to this cause. Until this is done there must remain a residual uncertainty on this point.

From this discussion, the checks using carbon as a scatterer would appear to remove the main uncertainties and to give reasonable confidence that only true asymmetries were being observed.

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