

Polarization of Neutrons Scattered by Intermediate
and Heavy Nuclei^{**}

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Abstract

Measurements of the polarization produced in the scattering of neutrons from heavy nuclei have been carried out at neutron energies of 380 keV and 980 keV. The Li^7 (p,n) Be^7 reaction was used as a source of polarized neutrons. Right-left asymmetries in scattering of these neutrons from several elements ranging in atomic weight from 55 to 238 were measured at scattering angles of 55° , 90° , and 130° . With few exceptions the observed polarizations vary smoothly with atomic weight. Measured values of the polarization range from -0.11 to +0.15 at 380 keV, and from -0.17 to +0.20 at 980 keV. The results at 380-keV neutron energy are compared with values predicted by the complex square well potential modified by a surface spin-orbit interaction.

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Using several sets of well parameters it has not been possible to reproduce the experimental results.

1. Introduction

Experiments on the scattering of polarized neutrons from nuclei provide a straightforward method for investigating spin-orbit forces in the neutron-nucleus interaction. If such forces are present, the scattered neutron flux exhibits a right-left asymmetry in the scattering plane which is chosen perpendicular to the direction of polarization of the incident neutrons. This asymmetry depends on the polarization of the incident neutrons and on the quantity $P(\theta)$. $P(\theta)$, the polarization which would be produced in an unpolarized beam upon being scattered through the angle θ , depends on the strength of the spin-orbit interaction.

Adair¹ and Okazaki² have used 380-keV polarized neutrons from the $\text{Li}^7(p,n)\text{Be}^7$ reaction to investigate polarization effects in scattering from intermediate and heavy nuclei for a scattering angle of 90° . Data obtained from a number of elements indicated that $P(\theta)$ varies fairly smoothly with atomic weight. These results were compared with polarizations calculated assuming a complex square well potential modified by a spin-orbit interaction. Qualitative agreement between computed and measured polarizations was found for nuclei in the atomic weight region of the giant P-wave resonance observed in the total cross sections at this energy. Polarization experiments involving

heavy nuclei have also been carried out at a neutron bombarding energy of 3.2-Mev^{3,4} as well as at energies in the 100-Mev region.*

* A summary of high energy measurements is given.⁵

The present experiments continue the previous work^{1,2} at 380-kev neutron energy and extend the measurements to scattering angles of 55° and 130°, where one would expect the effect of a D-wave splitting on the polarization to be more prominent. In addition, measurements were carried out at a neutron energy of 980 kev for scattering angles of 55°, 90°, and 125°.

2. Experimental Procedure

The experimental arrangement used for measuring the right-left asymmetries was similar to that employed by Adair¹ and Okazaki² and is shown in Fig. 1. Neutrons were produced by bombarding an evaporated metallic lithium target with protons from an electrostatic generator. The target chamber was connected to the generator beam tube by a metal bellows, which allowed the chamber to be rotated around the beam direction during bombardment. This, together with air cooling of the target permitted 6 μ amp proton beam to be used over a period of a few hundred hours before deterioration of the target set in. Neutrons emitted at a laboratory angle of 50° with respect to the proton beam were collimated by a paraffin shield. The collimator hole was tapered such that the direct neutron beam

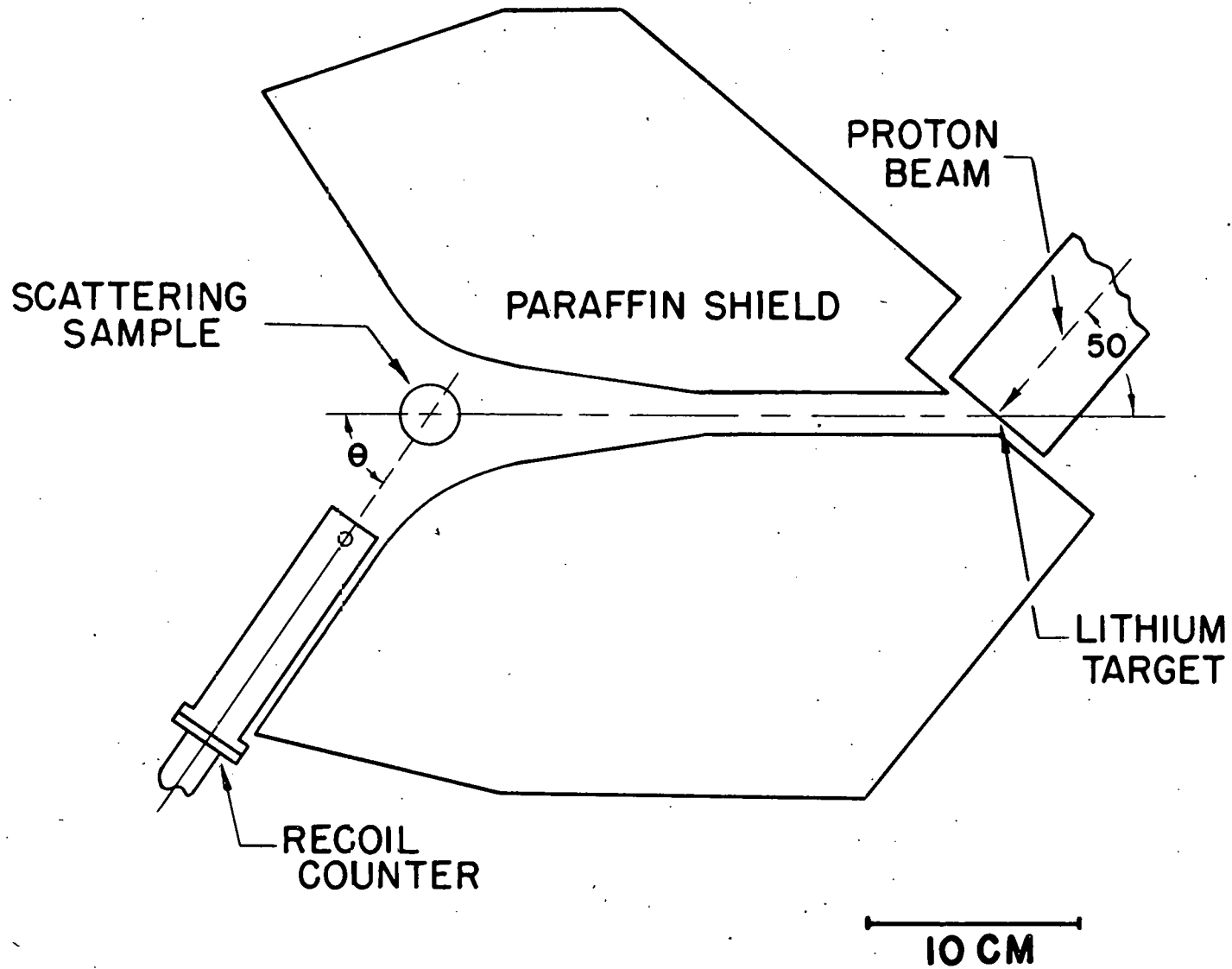


FIG. 1

Top view of the experimental arrangement used for a scattering angle of 55° .

could not strike any part of the collimator surface exposed to the counter. The energy spread of the neutrons was inferred from the target thickness which was determined by the rise method⁶ and from a measurement of the apparent width of the 620-kev resonance in the total cross section of Be. The two values reduced to a proton bombarding energy of 2.3 Mev were 80 kev and 92 kev.

The scattering samples were in the form of right circular cylinders, most of which had lengths of 6 cm and diameters between 1.5 and 2.5 cm. Three of the rare earth samples[†] had lengths of 4 cm and the U sample was 8.5 cm

† The authors wish to thank F. H. Spedding of the Ames Laboratory of the U. S. Atomic Energy Commission for granting the loan of the rare earths Sm, Nd, and Er.

long. The liquid Br and Hg as well as the powdered Mn and V were contained in thin-wall stainless steel cylinders. Scatterers were aligned with axes perpendicular to the scattering plane. The collimated neutron beam irradiated all samples except the uranium sample over their entire lengths.

Neutrons scattered through the angle θ were detected with a cylindrical proportional counter. The counter was filled with five atmospheres of hydrogen for the 380-kev measurements and with 15 atmospheres of helium for the 980-kev measurements. The counter pulses were recorded on two scalars having different discriminator settings. For the

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lower energy experiment the discriminator levels corresponded to recoil energies of 200 kev and 150 kev respectively. For the measurements at the higher energy the corresponding figures are 300 kev and 570 kev.

The counter was mounted upon a movable support which could be rotated around the axis of the sample. The intensity of neutrons scattered through a given angle was determined by measuring the number of counts obtained with the sample in position for a run during which a fixed charge was collected on the target and subtracting from this number the counts obtained during a corresponding run with the sample removed. Right-left intensity ratios were obtained by alternately carrying out this procedure for right and left scatterings. Background counts averaged 20 to 40% of the sample-in counts at the forward scattering angles, and 50 to 60% at the back angle.

In order to avoid false asymmetries, an accurate determination of the counter position corresponding to a scattering angle of 0° is necessary, particularly in cases for which the differential cross section varies rapidly with angle. For this purpose the transmission of a sample was measured as a function of the angular position of the counter for scattering angles near 0° . The setting about which the transmission curve is symmetric could be determined within $\pm 0.25^\circ$ and was taken to be the 0° setting. This procedure was repeated several times during the experiments. In order to check other aspects of the align-

ment, such as the constancy of the distance from the sample axis to the counter, the right-left asymmetries of neutrons scattered from carbon was measured for scattering angles of $\theta = 55^\circ$, 90° , and 130° at the lower neutron energy. No appreciable asymmetry is expected at this energy since the contribution to the scattering by neutrons with angular momenta larger than zero is negligible. No asymmetry was observed within the statistical uncertainties of the measurements (see Table I).

3. Polarization of the $\text{Li}^7(p,n)\text{Be}^7$ Neutrons

Since the right-left asymmetry in the scattering of polarized neutrons from nuclei depends on the polarization of the neutrons being scattered,¹⁾ the polarization P_1 of the $\text{Li}^7(p,n)\text{Be}^7$ neutrons must be determined in a separate experiment. Measurements of the polarization of 980-keV neutrons are reported in the following paper. Previous measurements^{1,2)} at 380 keV have been repeated. A value of $P_1 = -0.38 \pm 0.045^+$ was found for neutrons emitted

⁺ The positive direction of the polarization is in the direction of the vector $\mathbf{n} = \mathbf{k} \times \mathbf{k}_0$, where \mathbf{k} and \mathbf{k}_0 are the propagation vectors of the outgoing and incident beams respectively.

at a laboratory angle of 50° with respect to the proton beam direction. This value is consistent with Okazaki's result of -0.41 ± 0.02 . At the higher energy a value of

$P_1 = -.30 \pm .02$ was used. The quoted error limits include in addition to the usual statistical uncertainties, uncertainties in the calculation of $P(\theta)$ of the oxygen analyzer,¹ errors in the determination of the target thickness, and uncertainties in the multiple scattering corrections. At both energies it was assumed that P_1 does not vary with energy over the energy spectrum of the neutrons. Since at the lower energy previous measurements suggest that P_1 may vary rapidly with energy this assumption introduces an additional uncertainty in P_1 of 6% of its value.

4. Results and Discussion

Right-left ratios measured for the intermediate and heavy elements are summarized in Tables I and II. Since no significant differences between the results obtained at the two bias settings were found, the values used are those having the smaller statistical uncertainty. These ratios were then corrected for the variation of the neutron flux across the sample and for the effect of neutrons scattered more than once before leaving the sample. The correction for flux variation increased the measured ratios by about one per cent. The procedure followed in correcting for multiple scattering is similar to that used by Walt and Barschall.⁷ In making this correction it was assumed that the multiply scattered neutrons exhibit no right-left asymmetry. Consequently the corrections have the effect of increasing the magnitude of the measured polarizations. At 380-kev neutron energy the average value of this correction is about 25% of the value of the polarization. At

the higher neutron energy the average corrections amounted to 16%, 23%, and 30% of the value of the polarization at scattering angles of 55° , 90° , and 125° respectively. Corrected values of P_2 are given in the last three columns of Tables I and II.

The assumption that the multiply scattered neutrons exhibit no appreciable right-left asymmetry requires some justification. It was tested by a numerical calculation of the number of doubly scattered neutrons in Bi. The results of this calculation indicated that if the singly scattered neutrons exhibit a right-left ratio of 1.11 for a scattering angle of 90° , the doubly scattered neutrons will exhibit a ratio of 1.04 for the same angle. This number varies from element to element. Bi was chosen for the numerical calculation, since qualitative considerations indicated that for other elements this ratio is closer to unity. In this particular case, the assumption that the multiply scattered neutrons exhibit no right-left asymmetry introduces an error in the multiple scattering correction of $1/3$ of its value. Since the average value of the multiple scattering correction was 25%, an error of 8% has been included in the uncertainties given in Tables I and II.

The measured polarizations are plotted as a function of atomic weight in Figs. 2 and 3. For the lower neutron energy, measurements of the angular dependence of the polarizations are shown in Fig. 4 for a number of elements. With few exceptions, the polarization varies

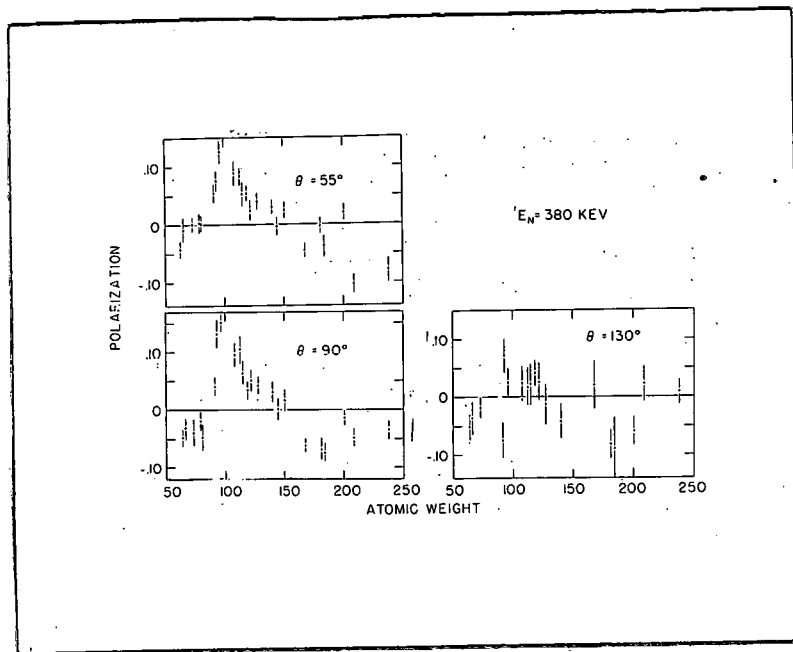


FIG. 2

Measured polarizations as a function of atomic weight for a neutron energy of 380 keV. The scattering angle is indicated in the upper right hand corner of the graph.

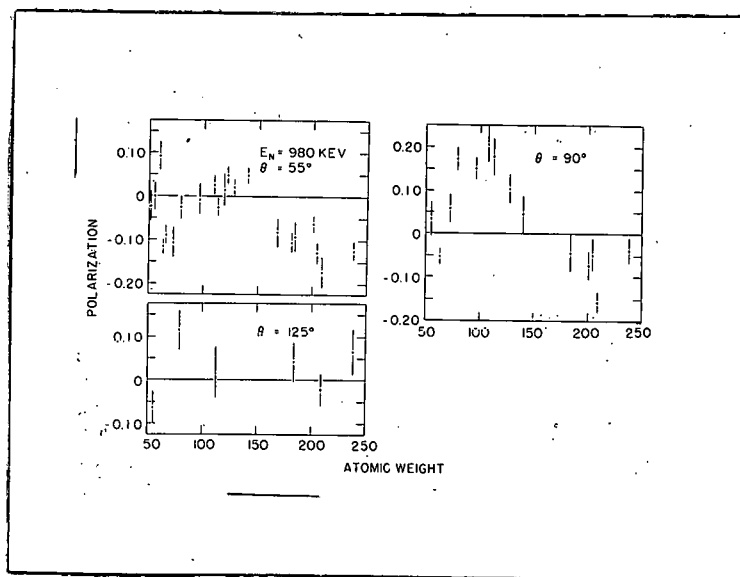


FIG. 3

Measured polarizations as a function of atomic weight for a neutron energy of 980 keV. The scattering angle is indicated in the upper right hand corner of the graph.

smoothly with atomic weight. No dependence on the spin of the target nucleus is evident. At the lower neutron energy the polarizations are small, having a maximum value of 0.15. The most prominent feature of these data is the peak in the atomic weight region of 100 for scattering angles of 55° and 90° . Negative polarizations are observed in the vicinity of $A = 75$ for 90° and 135° and in the region of the heavier elements for all angles. The 90° data are in fair agreement with the results of Adair¹ and of Okazaki². The small negative polarizations in the neighborhood of $A = 75$ and $A = 175$ do not appear in Okazaki's data. At the higher neutron energy the polarizations are similar in magnitude to those observed at 330 kev. However, at the higher energy there is more pronounced change in the polarization in going from the scattering angle of 55° to the angle of 90° .

Measurements^{3,4} have been performed for a neutron energy of 3.2 Mev. At this energy polarizations in excess of 0.5 have been reported, and in addition the data seem to exhibit a more complex angular dependence.

The energy spread of the neutron beam used in the present experiments is large compared to the level spacing of the compound nucleus for most of the elements studied. Consequently the measured polarizations are averages over many levels, and theories of the average properties of the neutron-nucleus interaction might be expected to reproduce the general features of the observed polarizations, since other features of the neutron-nucleus interaction have been

reproduced using such theories.⁸⁾ Naturally the potential used must be modified to include spin-orbit coupling in order to account for the observed polarizations.

Calculations⁺ were available for a potential of

⁺These calculations were performed by the late R. G. Thomas.

the form

$$V(r) = \begin{cases} -V_0(1+\zeta i) - \frac{q\hbar^2}{RM} \delta(r-R) \underline{L} \cdot \underline{S} & r \leq R \\ 0 & r \geq R \end{cases}$$

where M is the neutron mass. The target nucleus was assumed to have zero spin. q is a measure of strength of the spin-orbit coupling. The nuclear radius R was taken to be $R = 1.45 A^{1/3} \times 10^{-13}$ cm. Total cross sections, calculated on the basis of this model have been compared⁹⁾ with the observed total cross sections as a function of atomic weight for a neutron energy of 380 keV. Qualitative agreement between the measured and calculated values was found. However, the agreement becomes appreciably poorer as the absorption parameter ζ is increased from 0.03 to 0.1 and/or as a significant amount of spin-orbit coupling is added. The polarizations predicted by the model have been compared with the results of the present experiment, using values of the parameter q between 0.5 and 6.0 and values of ζ of 0.03 and 0.10. For all the values of q and ζ tried, the calculated curves exhibit in the atomic weight region near $A = 100$ structure which is associated with the splitting of the giant P-wave resonance in this region. This feature is evident in the 55° and 90° data. Some of the calculated curves are shown in Fig. 5 for a

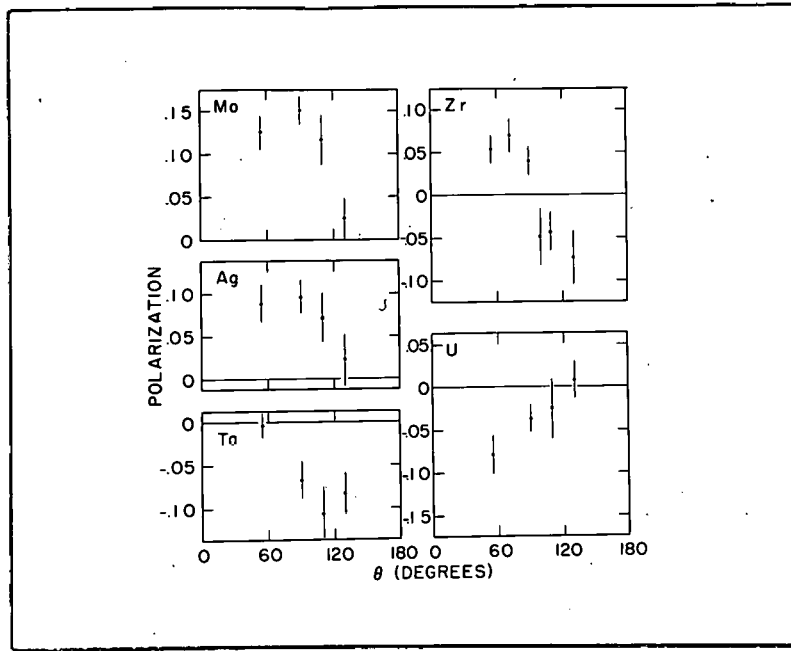


FIG. 4

Polarization versus scattering angle for Zr, Mo, Ag, Ta and V. The data are for a neutron energy of 380 keV.

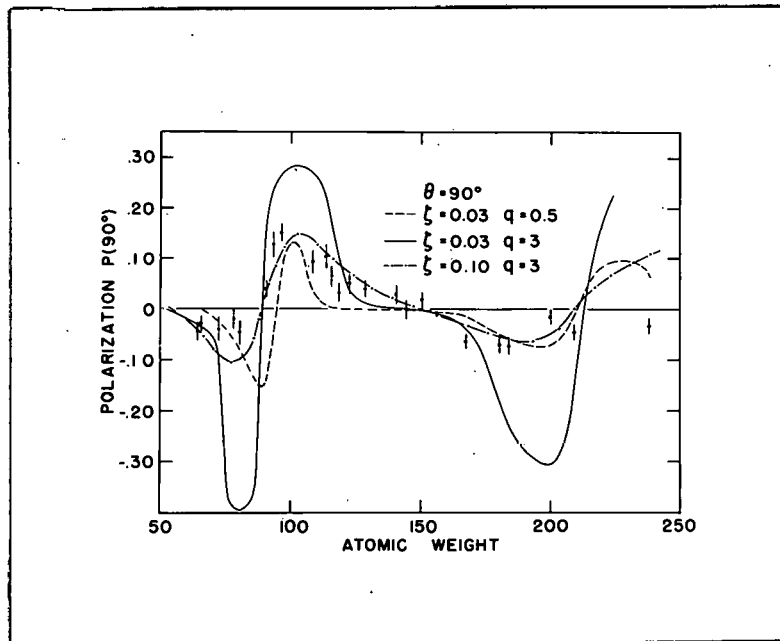


FIG. 5

Calculated values of the polarization produced in shape elastic scattering for a scattering angle of 90° and a neutron energy of 380 keV. The curves were computed from the potential (1), using the parameters given in the figure. The experimental data are also shown.

scattering angle of 90° . It can be seen that with the smaller value of ζ , which is indicated by the measured total cross sections, the correct amount of polarization at the $A = 100$ peak is obtained. However, the peak is much too narrow and the negative polarizations below $A = 100$ are too large in magnitude. The peak can be widened by increasing the spin-orbit coupling, in which case, however, the polarizations are too large in magnitude. The magnitude of the predicted polarizations may be reduced without strongly affecting the width of the peak by increasing the absorption parameter to 0.1, but this drastically reduces the P-wave peak in the total cross section. The behavior at the other scattering angles is similar, except that at 130° the calculated polarizations for $q = 3$ are larger than the measured ones by an order of magnitude, even with $\zeta = 0.1$.

The comparison between theory and experiment is complicated by the fact that the model predicts only the polarization of the shape elastically scattered neutrons. The effect of compound elastically scattered neutrons may be taken into account by assuming that they are on the average unpolarized¹ and that their angular distribution is isotropic. This will have the effect of reducing the predicted polarizations in the atomic weight region near $A = 100$ by as much as 20%, 30%, and 50% for the scattering angles of 55° , 90° , and 135° respectively. The amount of this reduction depends upon the fraction of absorbed

neutrons which are re-emitted elastically. At a neutron energy of 400 keV the amount of reduction quoted above would be expected to hold since at this energy inelastic scattering is relatively unimportant.

It is not surprising that calculations based on a square well potential fail to reproduce the measured polarizations since this model has already been shown to be unsatisfactory. The introduction of rounded wells has considerably improved the agreement between the calculated and the measured differential cross sections.⁸⁾ However, parameters obtained from such comparisons are uncertain to the extent that the effect of spin-orbit coupling has not been considered in such potentials. Calculations¹⁰⁾ for a complex potential with rounded edges including a spin-orbit coupling are in progress.

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- 10) R. F. Bjorklund, private communication.

Figure Captions

- 1) Top view of the experimental arrangement used for a scattering angle of 55° .
- 2) Measured polarizations as a function of atomic weight for a neutron energy of 380 keV. The scattering angle is indicated in the upper right hand corner of the graph.
- 3) Measured polarizations as a function of atomic weight for a neutron energy of 980 keV. The scattering angle is indicated in the upper right hand corner of the graph.
- 4) Polarization versus scattering angle for Zr, Mo, Ag, Ta and V. The data are for a neutron energy of 380 keV.
- 5) Calculated values of the polarization produced in shape elastic scattering for a scattering angle of 90° and a neutron energy of 380 keV. The curves were computed from the potential (1), using the parameters given in the figure. The experimental data are also shown.

TABLE I

SUMMARY OF EXPERIMENTAL
RESULTS FOR $E_n = 380\text{KEV}$

| ELEMENT | A | MEASURED R/L | | | | | |
|---------|--------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| | | 55° | 90° | 130° | 55° | 90° | 130° |
| C | 12.0 | .995 [±] .004 | .997 [±] .006 | 1.000 [±] .009 | -.004 [±] .006 | -.009 [±] .008 | -.010 [±] .016 |
| Cu - | 63.5 | 1.020 [±] .011 | 1.024 [±] .009 | 1.028 [±] .018 | -.047 [±] .018 | -.048 [±] .015 | -.050 [±] .030 |
| Zn - | 65.4 | 1.001 [±] .014 | 1.014 [±] .010 | 1.018 [±] .017 | -.009 [±] .021 | -.031 [±] .016 | -.035 [±] .029 |
| Ge - | 72.6 | .990 [±] .009 | 1.020 [±] .015 | 1.008 [±] .019 | .000 [±] .012 | -.039 [±] .024 | -.018 [±] .018 |
| Se - | 79.0 | .990 [±] .012 | 1.008 [±] .011 | | .007 [±] .018 | -.020 [±] .017 | |
| Br - | 79.9 | .991 [±] .014 | 1.024 [±] .016 | | .001 [±] .014 | -.047 [±] .023 | |
| Zr | 91.2 | .965 [±] .010 | .973 [±] .009 | 1.040 [±] .018 | .054 [±] .017 | .040 [±] .017 | -.074 [±] .032 |
| Nb | 92.9 | .954 [±] .008 | .924 [±] .013 | .957 [±] .015 | .076 [±] .019 | .131 [±] .027 | .072 [±] .029 |
| Mo - | 96.0 | .929 [±] .010 | .914 [±] .005 | .984 [±] .013 | .126 [±] .023 | .152 [±] .019 | .025 [±] .024 |
| Ag - | 107.9 | .941 [±] .013 | .938 [±] .012 | .983 [±] .018 | .088 [±] .023 | .096 [±] .022 | .023 [±] .031 |
| Cd - | 112.4 | .948 [±] .008 | .935 [±] .013 | .986 [±] .019 | .083 [±] .018 | .105 [±] .026 | .017 [±] .033 |
| In | 114.76 | .963 [±] .013 | .956 [±] .012 | .982 [±] .022 | .052 [±] .022 | .065 [±] .021 | .021 [±] .036 |
| Sn - | 118.7 | .963 [±] .008 | .975 [±] .010 | .980 [±] .014 | .054 [±] .014 | .033 [±] .016 | .040 [±] .023 |
| Sb - | 121.8 | .979 [±] .012 | .963 [±] .011 | .979 [±] .020 | .024 [±] .018 | .051 [±] .020 | .025 [±] .033 |
| Te - | 127.6 | .968 [±] .009 | .965 [±] .010 | 1.000 [±] .022 | .039 [±] .015 | .043 [±] .016 | -.013 [±] .036 |
| Ce - | 140.1 | .976 [±] .007 | .972 [±] .011 | 1.022 [±] .020 | .029 [±] .012 | .032 [±] .018 | -.043 [±] .031 |
| Nd | 144.3 | .999 [±] .012 | .996 [±] .015 | | -.004 [±] .016 | .000 [±] .020 | |
| Sm | 150.4 | .980 [±] .011 | .986 [±] .013 | | .024 [±] .015 | .017 [±] .018 | |
| Er - | 167.2 | 1.025 [±] .007 | 1.036 [±] .008 | .984 [±] .027 | -.045 [±] .012 | -.062 [±] .013 | .020 [±] .042 |
| Ta - | 180.9 | 1.000 [±] .009 | 1.041 [±] .013 | 1.051 [±] .015 | -.003 [±] .014 | -.068 [±] .020 | -.083 [±] .025 |
| W - | 183.9 | 1.021 [±] .012 | 1.043 [±] .012 | 1.055 [±] .033 | -.038 [±] .019 | -.073 [±] .016 | -.090 [±] .054 |
| Hg - | 200.6 | .983 [±] .009 | 1.004 [±] .009 | 1.033 [±] .015 | .018 [±] .015 | -.014 [±] .014 | -.061 [±] .023 |
| Bi - | 209.0 | 1.065 [±] .011 | 1.026 [±] .011 | .982 [±] .018 | -.104 [±] .018 | -.048 [±] .016 | .021 [±] .031 |
| U - | 238.1 | 1.051 [±] .015 | 1.023 [±] .011 | .994 [±] .014 | -.079 [±] .023 | -.036 [±] .017 | .008 [±] .022 |

TABLE II

SUMMARY OF EXPERIMENTAL
RESULTS FOR $E_{\alpha} = 980$ KEV

| ELEMENT | A | MEASURED R/L | | | P_2 | | |
|---------|-------|--------------|------------|------------|------------|------------|------------|
| | | 55° | 90° | 125° | 55° | 90° | 125° |
| V | 51.0 | .497±.017 | | | -.022±.037 | | |
| Mn | 54.9 | .992±.017 | .975±.017 | 1.021±.018 | .000±.033 | .034±.040 | -.063±.037 |
| Co | 59.0 | .950±.015 | | | .093±.034 | | |
| Cu | 63.5 | 1.050±.006 | 1.016±.008 | | -.115±.017 | -.052±.018 | |
| Zn | 65.4 | 1.036±.010 | | | -.088±.022 | | |
| Ge | 72.6 | 1.052±.017 | .964±.015 | | -.107±.034 | .058±.033 | |
| Se | 79.0 | 1.003±.014 | .912±.010 | .940±.017 | -.025±.027 | .173±.027 | .117±.041 |
| Mo | 96.0 | .997±.015 | .932±.010 | | -.060±.033 | .150±.026 | |
| Ag | 107.9 | .979±.012 | .907±.016 | | +.027±.023 | .207±.042 | |
| Cd | 112.4 | 1.003±.010 | .920±.016 | .987±.028 | -.023±.020 | .177±.044 | .016±.055 |
| Sn | 118.7 | .984±.018 | | | .017±.037 | | |
| Sb | 121.8 | .966±.010 | | | .050±.020 | | |
| Te | 127.6 | .978±.008 | .948±.013 | | .023±.017 | .103±.034 | |
| Ce | 140.1 | .967±.007 | .975±.015 | | .050±.018 | .046±.043 | |
| Er | 167.2 | 1.037±.018 | | | -.080±.034 | | |
| Ta | 180.9 | 1.048±.010 | | | -.103±.022 | | |
| W | 183.9 | 1.040±.016 | 1.011±.018 | .975±.021 | -.090±.034 | -.043±.043 | .041±.045 |
| Hg | 200.6 | 1.021±.008 | 1.028±.016 | | -.060±.018 | -.073±.033 | |
| Tl | 204.4 | 1.057±.011 | 1.017±.017 | | -.127±.025 | -.047±.037 | |
| Bi | 209.0 | 1.085±.017 | 1.078±.009 | 1.004±.019 | -.173±.036 | -.157±.025 | -.023±.037 |
| U | 238.1 | 1.061±.010 | 1.013±.016 | .962±.027 | -.120±.023 | -.037±.030 | .065±.053 |