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III.

Reactions and Scattering of Polarized Particles

The Scattering of Polarized Particles

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The scattering of polarized particles has been the subject of several recent reviews from which the present survey greatly benefited, particularly FAISSNER's article in the «Ergebnisse der Exakten Naturwissenschaften» [1][1]) and Rosen's report to the International Conference on the Nuclear Optical Model [2].

That beams of scattered particles might be partially polarized was first predicted by MOTT [3] for electrons. The mechanism discussed by MOTT is that the energy of interaction between the magnetic moment of the electron and the electromagnetic field produced by the nuclear charge depends on which side of the nucleus the electron passes the nucleus. This prediction was verified after previous unsuccessful attempts in a double scattering experiment by SHULL, CHASE, and MYERS [4] in 1943.

In 1948 SCHWINGER [5] pointed out that the same effect should be observable in the small-angle scattering of fast neutrons by heavy nuclei. This effect was clearly demonstrated at Harwell in 1956 [6] in the scattering of very high energy neutrons. Its importance lies in the fact that it should be possible to calculate the magnitude of this polarization so that unknown polarizations can be measured by this method. For neutron energies which are to be discussed at the present conference, MOTT-SCHWINGER scattering is much more difficult to observe. GORLOV, LEBEDEVA, and MOROSOV [7] at the Atomic Energy Institute in Moscow studied in 1957 the Mott-Schwinger scattering by Pb of partially polarized 3.7-MeV neutrons from the $D + D$ reaction and deduced from this measurement the polarization of the neutrons. Mott-Schwinger scattering of protons should also occur, but the predominant effect of RUTHERFORD scattering makes it difficult to observe this effect.

A second mechanism which produces polarization in the scattering of particles by nuclei was also first suggested by SCHWINGER [8], *i.e.*,

[1]) Numbers in brackets refer to References, page 238.

spin-orbit coupling. SCHWINGER suggested that this could be observed in a double scattering experiment of neutrons by He. SCHWINGER thought that the observed anomaly in the scattering of 1-MeV neutrons by He could be accounted for by a $P_{1/2} - P_{3/2}$ doublet in He^5 with a splitting of 0.4 MeV. He predicted a large asymmetry in the double scattering of neutrons which had an energy corresponding to the upper member of the doublet in the first collision, and to the lower energy level in the second collision. Schwinger's idea was not pursued experimentally because a double scattering experiment with 1-MeV neutrons appeared too difficult to carry out. Actually the splitting of the $P_{1/2} - P_{3/2}$ doublet in He^5 is much larger than SCHWINGER had thought. On the other hand polarization in scattering does not depend on the particular circumstances originally discussed by SCHWINGER, but occurs quite generally whenever there is interference between two partial waves, at least one of which has a phase shift which depends on the spin orientation of the scattered particle with respect to its orbital motion. As a consequence some polarization is expected in almost all nuclear scattering of particles with spin provided the energy is high enough so that the scattering involves partial waves with angular momentum greater than zero.

Although it was not possible to perform the double scattering experiment on He suggested by SCHWINGER with neutrons, it was pointed out by WOLFENSTEIN [9] that a similar effect would be expected in the scattering of protons by helium since the mirror nucleus Li^5 should also exhibit a large splitting between the $P_{1/2}$ and $P_{3/2}$ levels formed by protons of energies around 2 MeV. This experiment was performed by Williams' group at the University of Minnesota [10] using the experimental arrangement shown in figure 1. A collimated beam of 3.25-MeV protons from an electrostatic accelerator is scattered in helium gas through a CM angle of about 90°. The scattered protons are scattered again by He and are detected in photographic emulsions. By observing the direction of the protons in the photographic emulsion, those protons which were scattered approximately through 90° (CM) in the second collision could be selected. The number of tracks observed in the two emulsions differed by a factor of about two. Thus the polarization in the scattering of fast nucleons was first demonstrated.

From experiments on (p, α) scattering carried out at Minnesota, CRITCHFIELD and DODDER [11] had deduced phase shifts. The data could be fitted by two sets of phase shifts, one corresponding to the assumption the $P_{3/2}$ level in Li^5 lies above the $P_{1/2}$ level, the other corresponding to the opposite order. Under the two assumptions quite different polarizations are expected. In one case, the forward plate would show more tracks, in the other the backward plate. The experiments clearly showed that the $P_{1/2}$ level must lie above the $P_{3/2}$ level, which agreed with an earlier analysis by ADAIR [12] based on (n, α) scattering.

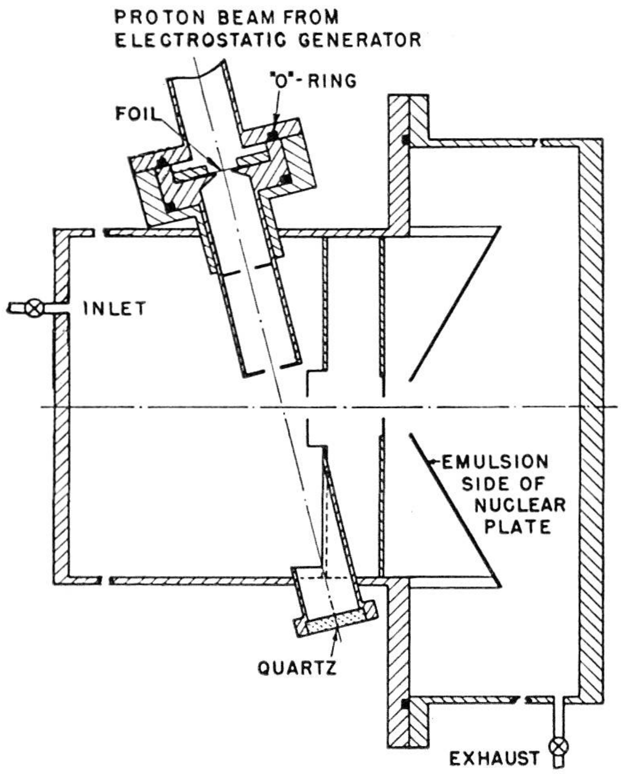

Figure 1

The arrangement used in the experiment of HEUSINKVELD and FREIER [10]. Polarization of protons scattered by helium was observed in a double scattering experiment

It should be pointed out that because of the energy loss in elastic scattering a double scattering experiment of protons (or neutrons) does not permit the determination of the polarization directly from the observed asymmetry, but determines only the product of the polarizations in the two collisions which occur at different energies. A method which allows an absolute determination of a polarization in a double scattering experiment of protons was used by Miss SCOTT [13] at Brookhaven. In this experiment advantage is taken of the fact that charged particles remain polarized when they are slowed down in passing through a foil. By measuring three products of polarizations involving protons of three different energies it was possible to calculate the individual polarizations. In one of the three combinations the proton is slowed down in a foil (figure 1a).

It is thought that the phase shifts for (p, α) scattering are sufficiently well known to enable one to calculate polarizations from (p, α) scattering with an accuracy of the order of ten percent. Figure 2 shows a plot of the calculated polarizations in (p, α) scattering taken from a paper by BROCKMAN [14]. Over most of the energy range there are scattering angles at which the polarization reaches more than 90 percent. That the polarization of protons scattered by helium exceeds 95 percent at certain angles was shown experimentally by ROSEN and BROLLEY [15] for 6.25- and 10-MeV protons.

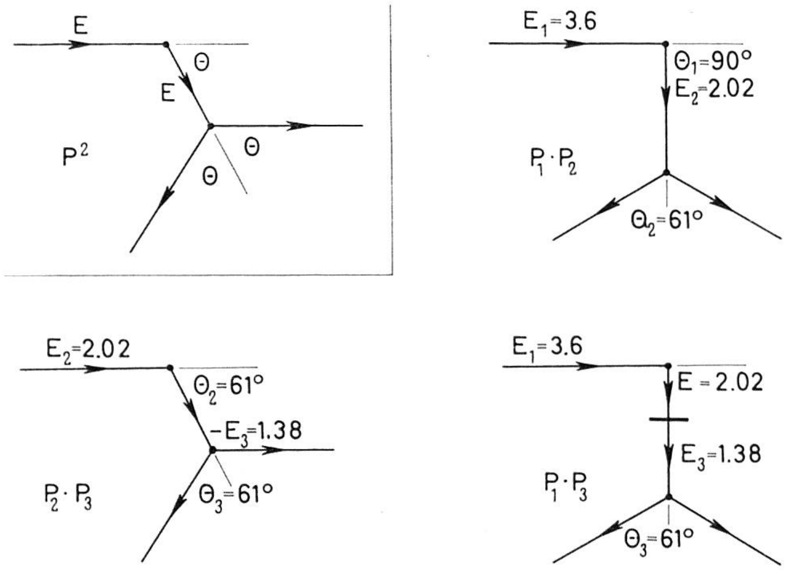

Figure 1a

The only other nucleus for which the proton scattering phase shifts are well enough known to deduce polarizations reliably appears to be C^{12}. Figure 3 shows a plot prepared by TOMBRELLO, BARLOUTAUD, and PHILLIPS [16] in which calculated polarizations in p-C^{12} scattering are given for protons between 1.5 and 5 MeV. These polarizations were computed after adjusting the phase shifts to fit recent experiments at Harwell [17] on the scattering of polarized protons by C^{12}. The more rapid variation of polarization with energy and angle and the occurrence of energy regions in which there is very little polarization makes carbon a less useful polarizer or analyzer than helium in this energy range. On the other hand for some experiments the availability of carbon as a solid target is a great advantage. At higher proton energies the polarization of protons scattered by carbon varies more slowly with energy so that carbon is a more desirable analyzer and polarizer. It was shown by BROCKMAN [14] that between 16 and 18 MeV the polarization is of the order of 50 percent for protons scattered through 45°.

For neutrons double scattering experiments have so far not been possible because of intensity and background difficulties. All experiments on the scattering of polarized fast neutrons have used polarized neutrons from a reaction. These neutrons are then scattered and the left-right asymmetry in the scattering is observed. The application of this procedure to the study of nuclear reactions was discussed at an earlier session. At the present session it will be assumed that we have learned how to produce beams of partially polarized fast neutrons.

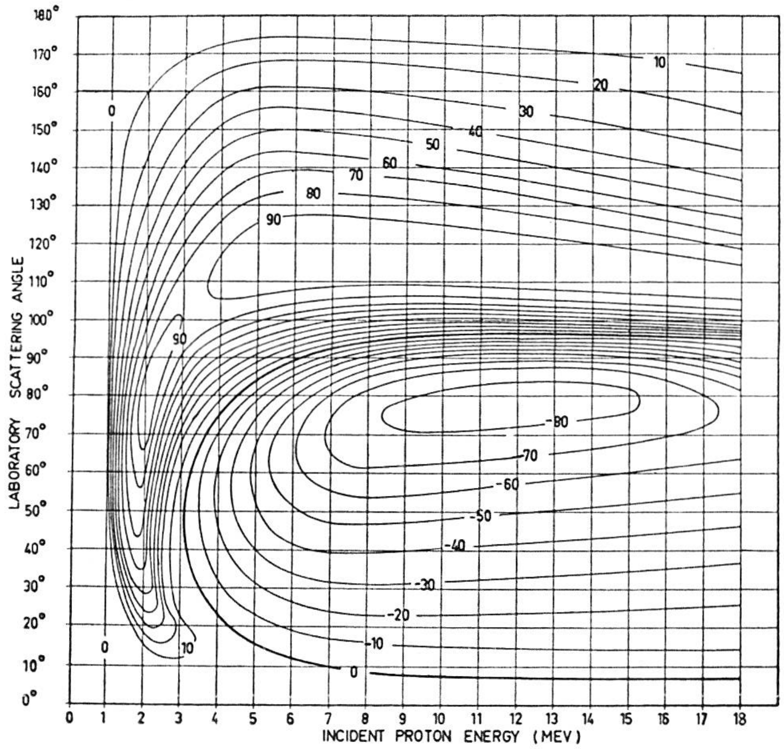

Figure 2

Polarizations calculated by BROCKMAN [14] for the scattering of protons by helium

Polarization in the scattering of fast neutrons was discovered by HUBER and his co-workers in Basel in 1953 [18] and at about the same time by RICAMO [19] and SCHERRER's group [20] in Zürich. Both groups demonstrated asymmetries in the scattering of *d–d* neutrons from carbon. Shortly thereafter asymmetries in the scattering of Li (*p*, *n*) neutrons scattered from oxygen were observed at our laboratory [21]. Figure 4 shows the experimental arrangement which has been used at Wisconsin.

As analyzers of the polarization of neutrons several light nuclei have been used. As in the case of the scattering of protons, helium is a particularly useful analyzer. The polarizations expected in (n, α) scattering are shown in figure 5. This figure is taken from a paper by LEVINTOV, MILLER, and SHAMSHEV [22], and is based on the phase shifts given by SEAGRAVE [23]. It is apparent that the polarization varies slowly with neutron energy and is almost 100% for a CM scattering angle of 135° for neutron energies from 4 to 20 MeV. The difficulty of preparing helium samples of high density is in the case of neutrons an even greater disadvantage than in the case of protons.

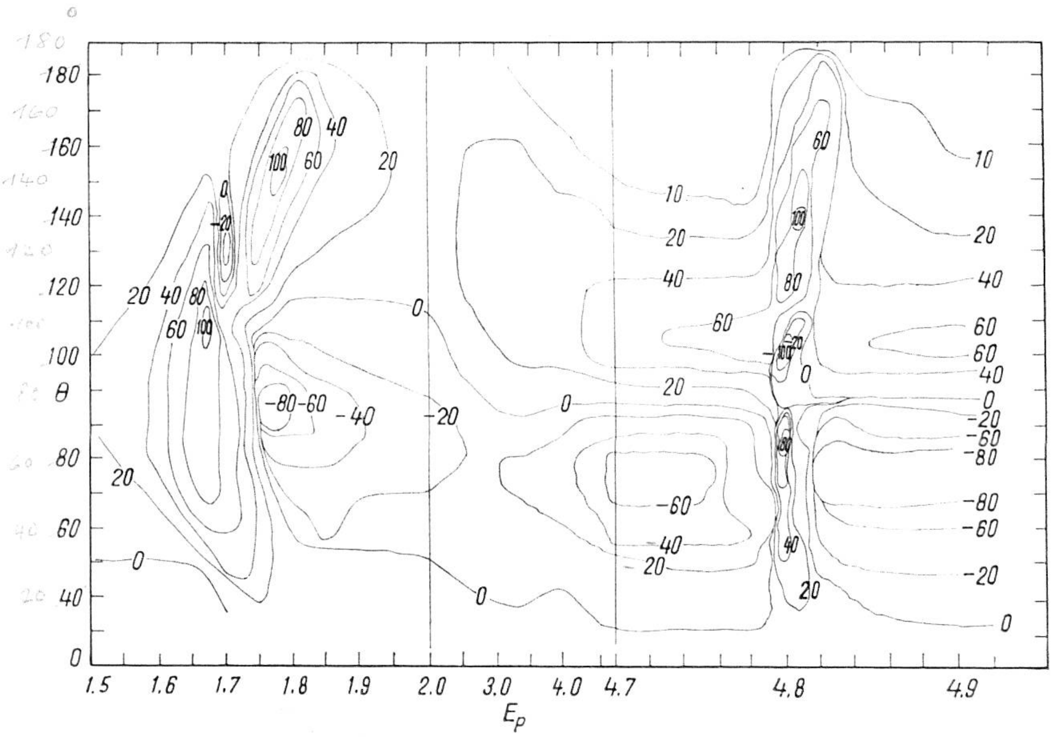

Figure 3

Polarizations calculated in [16] for the scattering of protons by carbon

Although it is difficult to prepare dense helium scatterers, it is easy to detect helium recoils from fast neutrons in counters. The polarization can then be measured by observing a left-right asymmetry of α-particles recoiling in a given direction. This has been done particularly successfully with thin proportional counters by LEVINTOV [22] and co-workers.

Other nuclides for which polarizations in neutron scattering can be calculated fairly well in certain regions are C^{12} and O^{16}. Figure 6 shows calculated polarizations at two angles in the scattering of neutrons by O^{16} [24]. Although the polarization varies rapidly with neutron energy, oxygen has been useful as an analyzer for neutrons of energies around 1 MeV and lower.

In view of the fact that polarization experiments are relatively difficult to carry out and frequently give rather inaccurate results, it is well to examine what experiments on the scattering of polarized particles are likely to give information which cannot be obtained more easily by simpler experiments.

The original Minnesota p-α scattering experiment [10] is an example of an ideal application of the scattering of polarized particles. Only the sign of the polarization needed to be determined to decide the sign of a phase shift difference. Polarization measurements are generally useful to check phase shift analyses, based on angular distribution measurements.

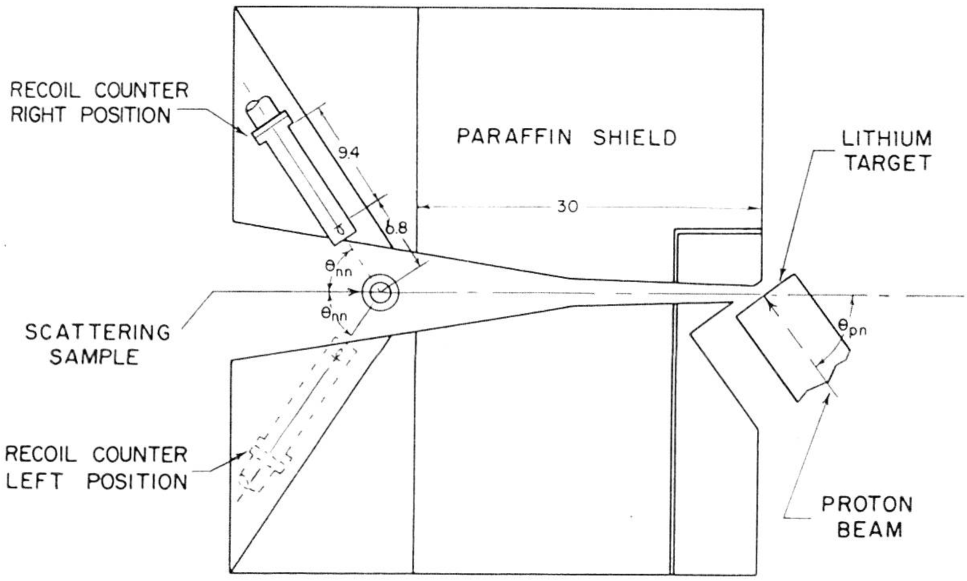

Figure 4
Experimental arrangement
used for observing the scattering of polarized neutrons [24]

The fact that the polarization depends on the interference of partial waves has the effect that the polarization is strongly affected by the presence of partial waves which undergo only a small phase shift. Measurement of the polarization, therefore, enables one to discover the effect of phase shifts which are too small to be noticeable in the angular distribution. An example of a measurement with this aim is the recent determination of the polarization of 3.3-MeV protons scattered by protons carried out by ALEXEFF and HAEBERLI [25]. The experimental arrangement is shown in figure 7. Protons are scattered by hydrogen in the region B and the scattered protons are scattered again by helium in the region D. The doubly scattered protons are detected in two counter telescopes. As an indication of the accuracy that can be obtained in double scattering experiments with protons, a typical result was that 3.3-MeV protons scattered by protons through a CM angle of 45° have a polarization of $(0.25 \pm 0.16)\%$. Measurements of the polarization of scattered neutrons have so far reached only accuracies which are an order of magnitude worse.

Another area in which scattering of polarized particles has produced useful information is the general question of the importance of spin-orbit interactions in nuclear collisions. In general, the scattered particles will be polarized if spin-orbit interactions are present. The observation of polarization will, therefore, indicate the presence of such interactions, although one can construct circumstances under which the absence of polarization does not prove the absence of spin-orbit forces.

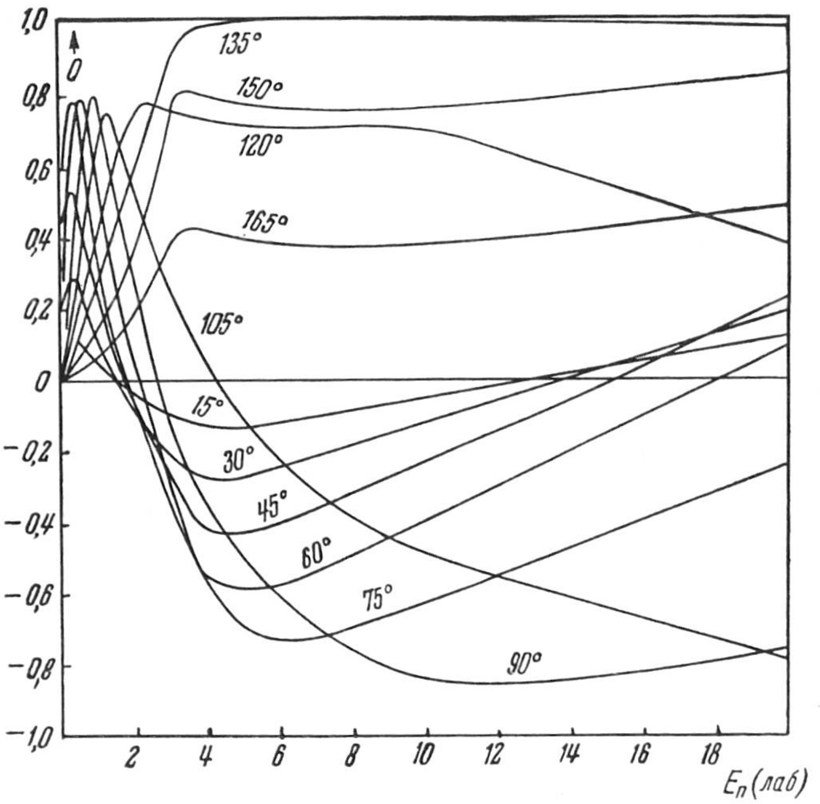

Figure 5

Polarization in the scattering of neutrons by helium taken from [22] and based on the phase shifts of [23]

This aspect became of interest in the development of the nuclear optical model. When the optical model was first developed to account for the observed giant resonances in the scattering of fast neutrons by heavy nuclei, the optical potential which was used did not contain a spin-orbit term. Since the shell model had shown the importance of spin-orbit forces, it appeared that the optical model which is related to the shell model should include a spin-orbit term. The optical model contained, however, too many adjustable parameters to enable one to deduce even the need for a spin-orbit term from the measured cross sections alone. An attempt was made, therefore, to observe the polarization of neutrons scattered by heavy elements and this effect was observed at our laboratory in 1954 for 0.4-MeV neutrons [21]. Since that time more accurate measurements of the scattering of neutrons by heavy elements have been performed at our laboratory both at 0.4 and 1.0 MeV [26]. Typical results are shown in figure 8. It is apparent that spin-orbit effects are important especially for elements around $A = 100$ for which it is known that there is a P-wave giant resonance at this energy. Similar measurements have been performed with $D + D$ neutrons at several laboratories, particularly at the ETH Zürich [27] and at the University of Virginia [28].

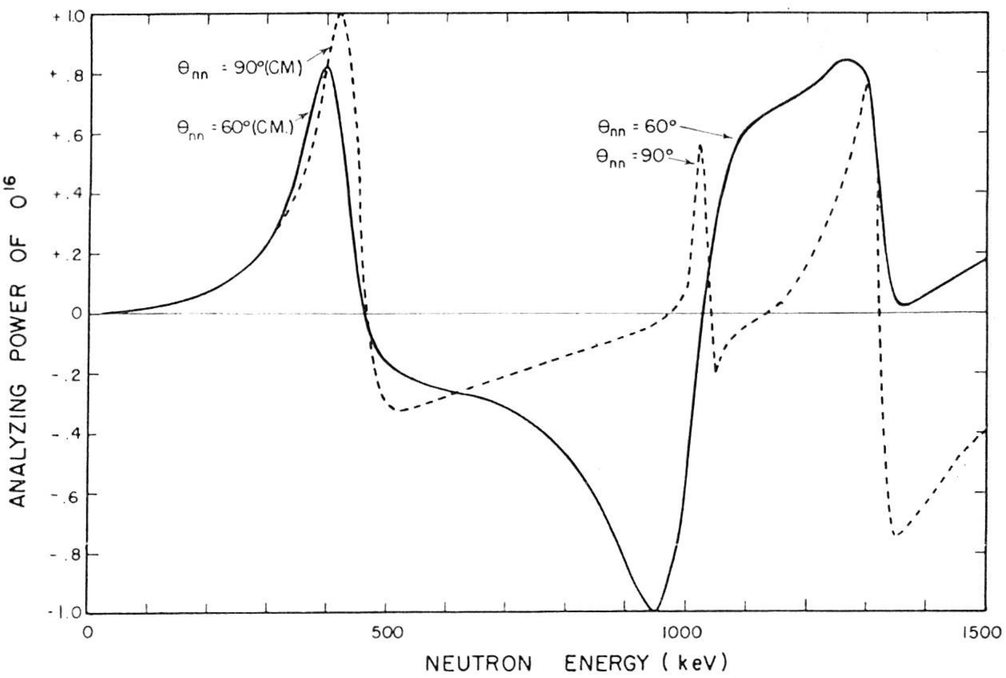

Figure 6
Polarizations in the scattering of neutrons by oxygen taken from [24]

Excellent measurements on the scattering of polarized protons from intermediate and heavy nuclei have been performed at the ETH Zürich at 4 MeV [29], at the University of Rochester [30] for 6- and 7-MeV protons, at Los Alamos [2] at 8 and 10 MeV, and at Princeton University [31] at 17 MeV. Typical results are shown in Figure 9 where the polarization of 17-MeV protons scattered by zinc is plotted against scattering angle. The polarizations are much larger than those observed in low-energy neutron scattering. The solid curve shows an optical model fit to the measurement.

It was recently shown by Rodberg [32] that according to the optical model the polarization should be proportional to the derivative of the angular distribution, *i.e.*, it is zero at the maxima and minima of the angular distribution, in good agreement with experimental results on proton scattering. The magnitude of the spin-orbit term in the potential can be deduced from the magnitude of the polarization and the derivative of the angular distribution for scattering angles near 90°.

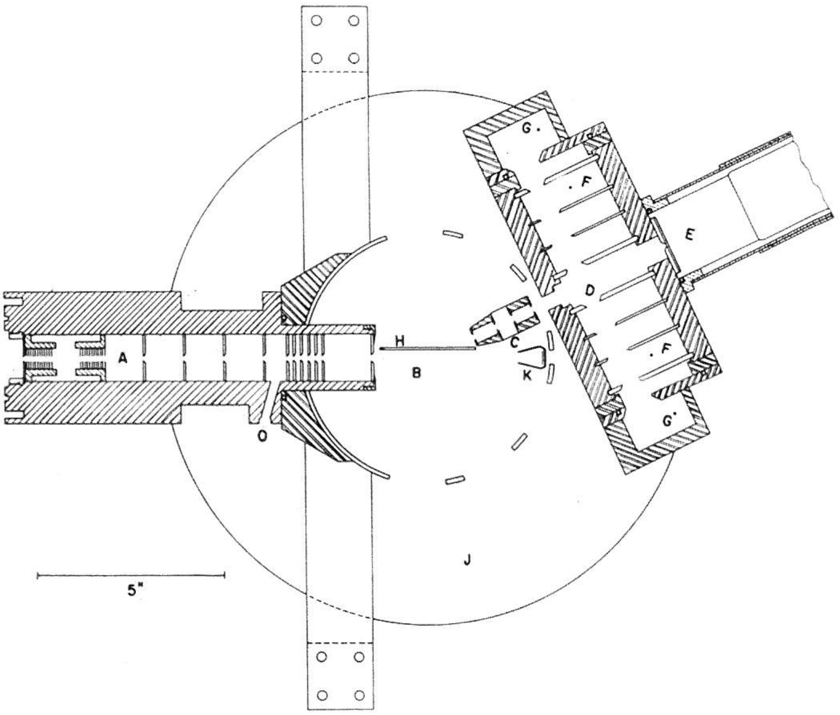

Figure 7
Experimental arrangement used in the measurements of the polarization in proton-proton scattering (from [25])

Many experiments have been performed on the scattering of polarized nucleons by deuterons. Since neutron-deuteron scattering is anisotropic even at quite low neutron energies, one knows that this interaction involves angular momenta different from zero. One might expect, therefore, to observe appreciable polarization in nucleon-deuteron scattering experiments. Experiments have failed, however, to show much, if any, polarization in either neutron or proton scattering by deuterons [33–38]. This result is rather surprising.

In summary, there are a number of applications for which measurements of the polarization of scattered particles give information not readily obtainable by other means. On the other hand, one should examine carefully in each case whether the desired information cannot be obtained by means other than the polarization measurements which are usually rather difficult to perform.

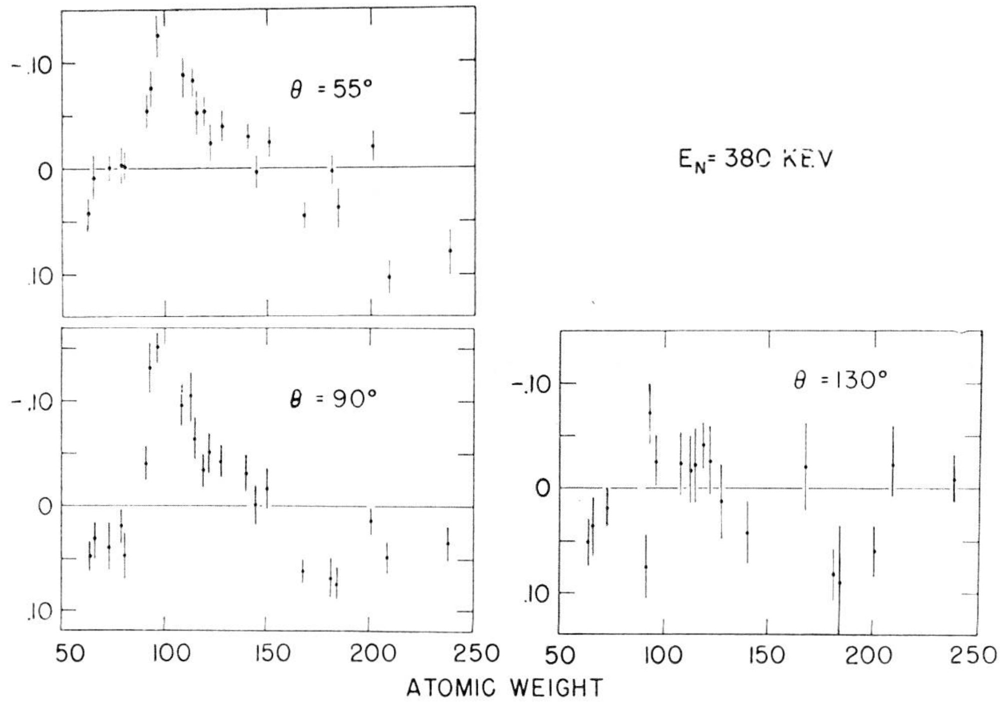

Figure 8

Polarizations measured for the scattering of 350-keV neutrons by intermediate and heavy elements as a function of atomic weight for three scattering angles [26].

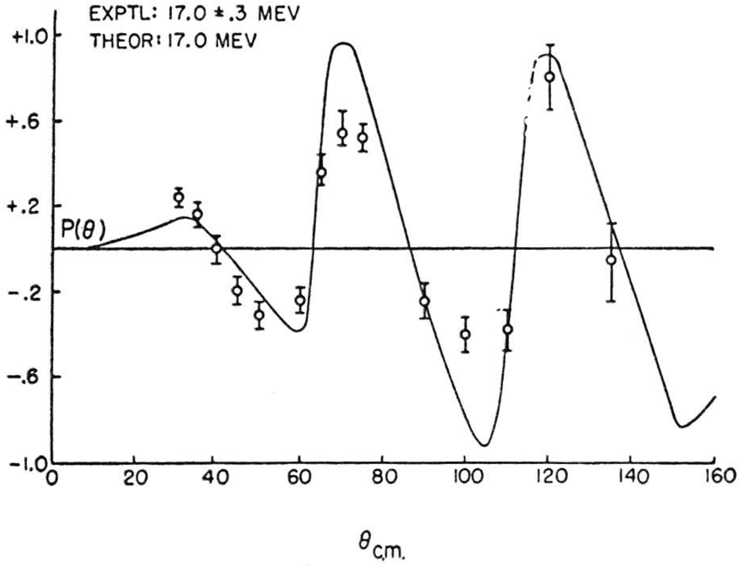

Figure 9

Angular distribution of the polarization of 17-MeV protons by zinc measured by Blanpied [31]

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