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Polarization Resulting from Elastic Nucleon Scattering below 4 MeV

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Herein are described two experiments undertaken at the Swiss Institute of Technology, the first as carried out by H.-J. GERBER[1]) *et al.* and the second by J. SALADIN[2]) *et al.:* a) The elastic scattering of polarized neutrons from deuterons at 3.3 MeV, and b) the polarization of 3.9-MeV protons elastically scattered by medium-heavy nuclei.

The elastic scattering of low-energy neutrons by deuterons has for many years been of great interest both from an experimental and a theoretical point of view. Two-nucleon theory for these low energies is not able to give much information on nuclear forces since practically only s-waves are involved.

The situation is much improved if one considers the three-nucleon problem associated with neutron-deuteron scattering. Three main reasons are reponsible for this: a) This reaction includes neutron-neutron interaction and hence could yield information of great value such as is very difficult to derive from other experiments. b) The exchange forces are not very well known at energies below 10 MeV. Neutron-deuteron scattering experiments assist in distinguishing between different approaches. c) These experiments could, furthermore, provide information on three-nucleon forces, if the latter exist.

Several calculations on low-energy neutron-deuteron scattering have recently been published which involve a tensor force or an explicit spin-orbit coupling apart from a central exchange potential. DELVES and BROWN [1][3]), who included the effects of both tensor force and the distortion of the deuteron in their approximation, predict a polarization of nearly zero for 2-MeV neutrons. BOSE [2] uses in his article a spin-orbit-coupling. BRANSDEN *et al.* [3], assuming central exchange plus

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[3]) Numbers in brackets refer to References, page 290.

tensor force, report in their latest paper that extensive numerical calculations of the neutron-deuteron cross section are in progress. WATANABE [4] has included a spin-orbit term and published a general formulation of the problem as an intermediate report; detailed calculations are to follow. Earlier theoretical work has been reviewed in an article by VERDE [5].

The aim of our experiments was to measure the polarization produced on elastic scattering of polarized neutrons by deuterons. This polarization was evaluated by measuring the left right-asymmetry of the differential cross section using a neutron beam of known polarization.

The relation is [6]:

$$P_1 P_2 = \frac{\sigma(\theta, 0) - \sigma(\theta, \pi)}{\sigma(\theta, 0) + \sigma(\theta, \pi)} \tag{1}$$

P_1 is the (transverse) polarization of the incident neutrons. P_2 is the polarization of an originally unpolarized neutron beam elastically scattered by deuterons. By definition, P is taken to be positive if the polarization vector is parallel to the normal $[\boldsymbol{k}_1 \times \boldsymbol{k}_2]$ of the reaction plane, $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ being respectively the momentum vectors of the incident and the scattered neutron. $\sigma(\theta, \varphi)$ is the differential cross section for elastic neutron-deuteron scattering, where θ is the scattering angle and φ the angle between $\boldsymbol{P}_1$ and $[\boldsymbol{k}_1 \times \boldsymbol{k}_2]$. Formula (1) holds for target nuclei with spin $\neq 0$ assuming time-reversal invariance for the scattering process [6].

Figure 1 shows the general assembly (for a more detailed description of the experiment see GERBER *et al.* [7]). We normally use a 15-μA beam of magnetically analyzed deuterons. The polarized neutrons are produced by the D–D-reaction using a thin heavy ice target. The neutrons have an energy of (3.27 ± 0.04) MeV and a polarization of 11% as given by the measurements of MEIER [8], LEVINTOV [9] and PASMA [10]. The neutron energy is just below the threshold for deuteron break-up, so that elastic scattering is the only possible reaction. The scatterer is cylindrical and consists of deuterated benzene C_6D_6 with the addition of 3 g/l p-terphenyl and 0.1 g/l POPOP. The production of deuterated benzene has been described by MEIER *et al.* [11]. This mixture has the property of acting as a liquid scintillator; its proton-to-deuteron ratio is 1.3 percent. Each scattering event is detected both via the recoil deuteron in the liquid scintillator and via identification of the coincident neutron in a plastic scintillator.

The advantages of this method are obvious. One of the difficulties of nearly all fast-neutron experiments is the high background due to extraneous scattering of neutrons from walls etc., gamma rays, particles which pass through the shield etc. This background is reduced to a very small percentage if only those neutron counter pulses are accepted which coincide with the recoil signal. The second advantage is that one uses the full beam current of the accelerator, not only a small fraction as in some time-of-flight experiments. Of course there is also a great disadvantage: This method is applicable only to those few cases where the scattering material scintillates or can be mixed with a scintillator.

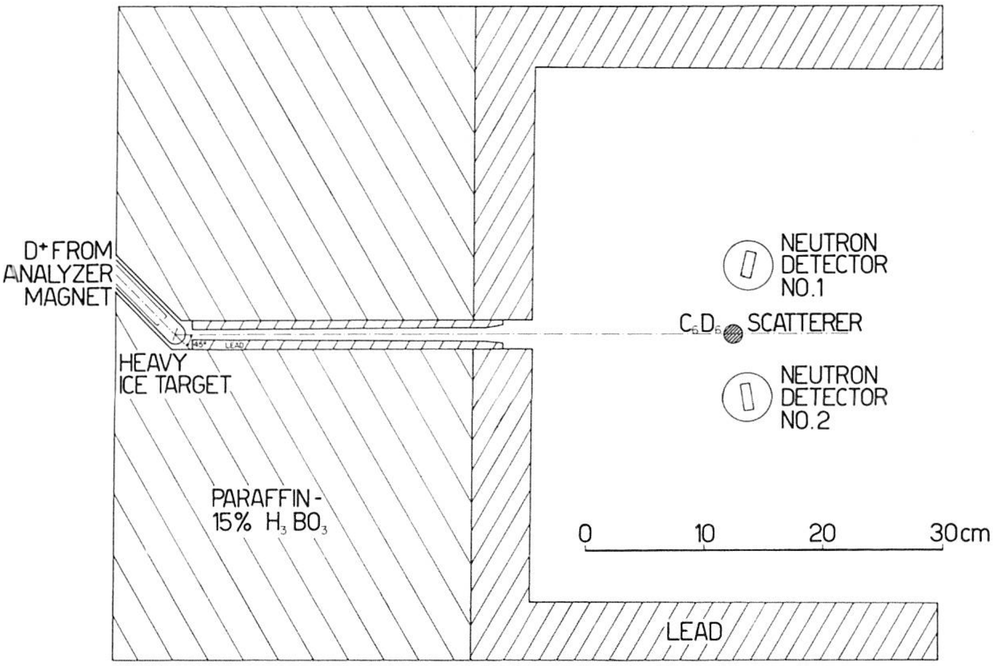

Figure 1
General assembly for neutron-deuteron scattering

This arrangement has been used for two completely independent experiments with different circuitry. In the first, one uses a time-of-flight apparatus, in the second, one simply measures the coincidences between deuteron recoil counter and neutron counter.

The time-of-flight experiment has been carried out in the following manner (figure 2): Start and stop pulses are delivered by deuteron counter and neutron counter respectively. The anode pulses of an RCA 6810 photomultiplier go through a limiter and a fast discriminator and are then clipped to give rectangular pulses of exactly uniform height and length. The neutron and the recoil pulses then have the same shape; they are mixed in a pentagrid tube, so that the resulting anode pulse height is a measure of the overlapping of the two rectangular pulses and hence a measure of the neutron flight time between recoil and neutron counter. The resolving time has been found, using coincident ^{60}Co gamma rays, to be 3.3 ns full width at half height. Very probably the resolving time is essentially determined by the relatively large time-spread of the photomultiplier.

The time-of-flight experiment serves two purposes: a) it is an independent measurement of the polarization; b) it provides a check of whether carbon recoils in the scatterer could produce light pulses of sufficient intensity to influence the measurement of polarization. As is well known [8], carbon is a good polarizer in this energy range and hence could well disturb measurements. If we count neutrons scattered by carbon, then the measured polarization is an indefinite sum of the polarizations produced in deuterium and carbon scattering. This point has been investigated in a separate experiment. However, the test showed that neutrons scattered by carbon are not detected even if the photomultiplier voltage is raised.

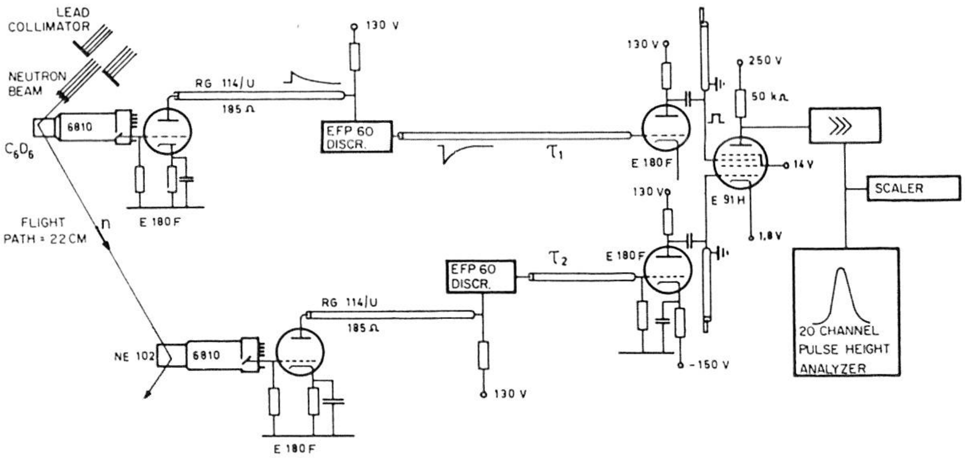

Figure 2

Block diagram of the time-of-flight circuitry for the neutron-deuteron polarization experiment

The results of the polarization measurement as obtained by the time-of-flight experiment agree within experimental error with those of the second experiment (termed the «coincidence experiment»). Thus these results will be discussed together with the latter.

The coincidence experiment mentioned earlier consists simply in counting the coincidences from recoil and neutron counter as can be seen in figure 3. Most of the results have been obtained by this and not by the time-of-flight method thanks to the shorter neutron flight path and hence improved counting rate. The use of two neutron counters has the double advantage of improving counting statistics and of eliminating effects due to variations in intensity of the neutron beam.

Very considerable care has been given to the geometrical adjustments both in this and in the time-of-flight experiments, as it is well known that small misalignments are able to simulate a large polarization if the differential cross section varies markedly with scattering angle. As an example of all the tests, I mention the measurements of the polarization of neutrons scattered by protons. This experiment has been carried out simultaneously with the measurement of the neutron-deuteron scattering simply by replacing the deuterated scatterer by a similar one containing ordinary benzene C_6H_6. The measured neutron-proton polarization at a scattering angle $\theta_{Lab} = 64°$ is (2.2 ± 3) percent as compared with the theoretical value of practically zero at these energies.

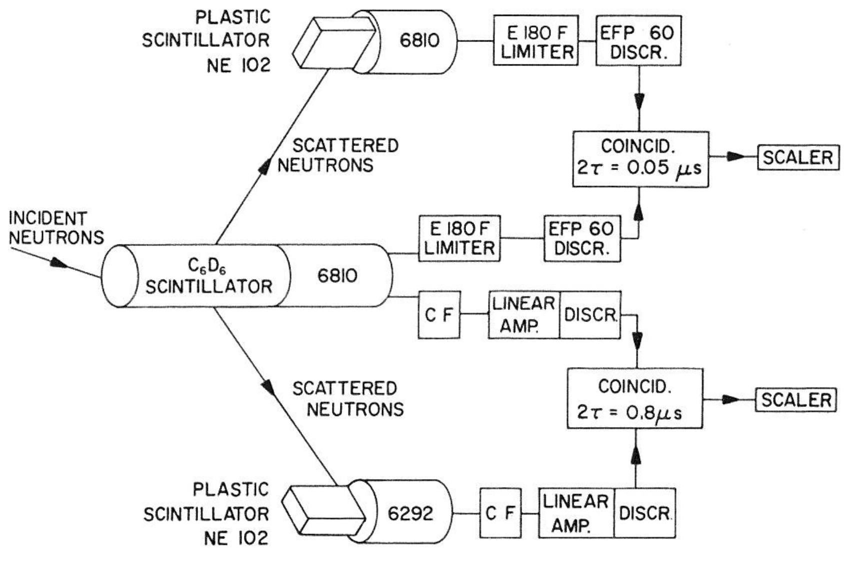

Figure 3

Block diagram of the electronic circuit for the neutron-deuteron polarization experiment, using coincidences between the deuteron-recoil counter and the neutron counter. Two identical neutron counters were used simultaneously.

The measurements have been corrected for the effects of finite geometry, for background, fortuitous coincidences and for multiple scattering. Of all these corrections, only multiple scattering has a perceptible effect on polarization since there are neutrons scattered first by a carbon nucleus, which is a good polarizer, and afterwards by a deuteron. This effect has been evaluated and taken into account.

Figure 4 shows our experimental results [7] together with those of other authors [12–16]. The full circles represent the mean value of the coincidence and the time-of-flight experiment. The values of different authors are in good agreement except for the single value of White *et al.* [14]. It can be seen that the polarization of 2-to-3-MeV neutrons scattered by deuterons is practically zero for all scattering angles. The same seems to be true for proton-deuteron scattering. The experimental values agree essentially with the calculations of Delves and Brown [1] (indicated by the solid line). However, Darden *et al.* [12] who measured the n-d polarization at 1 MeV also find a small value which is in disagreement with the results of Delves.

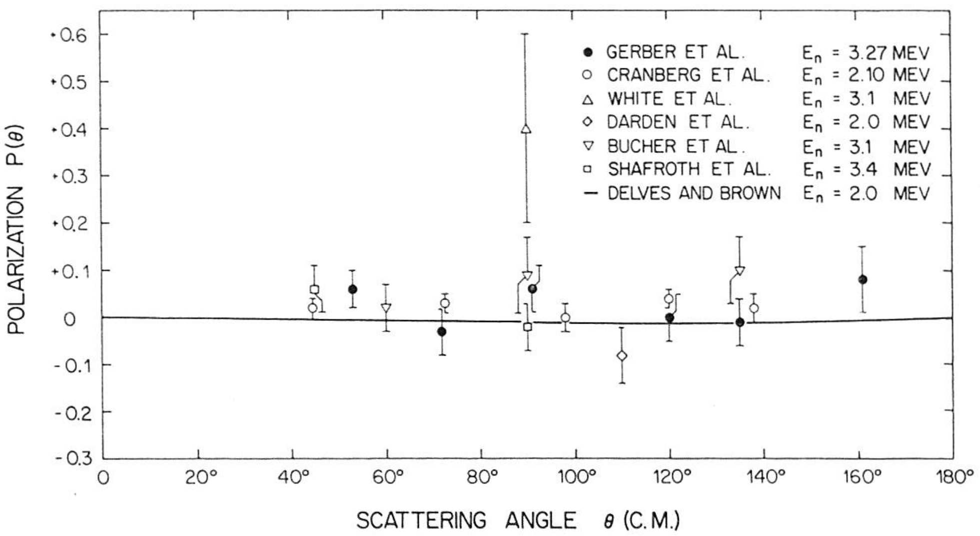

Figure 4

Polarization of nucleons scattered elastically by deuterons. Neutron data are taken from GERBER *et al.* [7], CRANBERG [13], WHITE *et al.* [14], DARDEN *et al.* [12], BUCHER *et al.* [15]. Also included are the proton data of SHAFROTH *et al.* [16]. Energies are given in lab system. The full curve was calculated by DELVES and BROWN [1].

Figure 5 shows the differential cross section of n-d-scattering at an energy of 3.27 MeV (laboratory system), measured at the same time as the polarization. The values show good agreement with those published by SEAGRAVE and CRANBERG [17]. The figure includes the theoretical results of BUCKINGHAM, HUBBARD and MASSEY [18] and of CHRISTIAN and GAMMEL [19], these having been calculated on the basis of a pure central exchange force for the nucleon-nucleon interaction. It is difficult to decide whether the inclusion of a tensor force or a spin-orbit coupling improves the agreement with the experiment since different approximations can be made.

Finally, it can be said that the polarization of neutrons elastically scattered by deuterons around 3 MeV is at all angles smaller than + 10 percent as established by different authors using different methods.

In contrast with the preceding work, this which now follows deals with the many-nucleon problem. SALADIN [20] measured the polarization of protons elastically scattered by magnesium, aluminum, titanium and vanadium. This was undertaken at 4 MeV which is, to our knowledge, the lowest proton energy at which a polarization has been found for medium heavy nuclei. Similar work has been carried out at 6 MeV [21] 9 MeV [22], 10 MeV [23] and 18 MeV [24, 25].

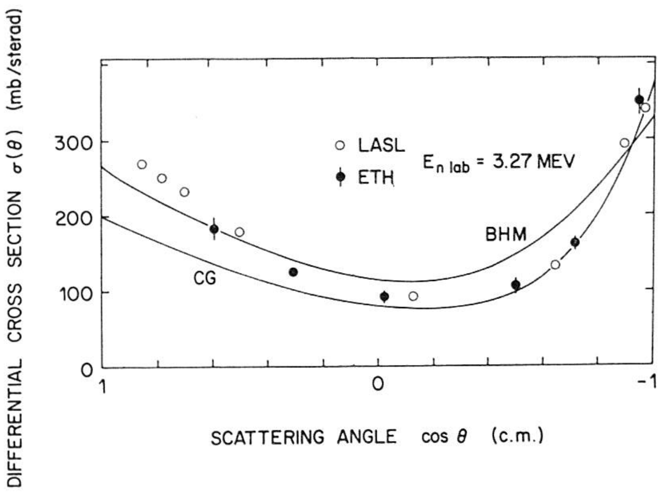

Figure 5

Differential cross section of neutrons elastically scattered by deuterons. Full circles are results due to GERBER *et al.* [7], open circles to SEAGRAVE and CRANBERG [17]. The solid curves represent theoretical results of BUCKINGHAM, HUBBARD, and MASSEY [18] (BHM) and of CHRISTIAN and GAMMEL [19] (CG).

In recent years, the optical model of the nucleus has extensively and with fair success been used to calculate both differential cross sections and polarizations of nucleons elastically scattered by nuclei. (See for example [26].) For a wide range of energies and atomic numbers this model has proved able to account quantitatively for the experimental data.

The measurements to be described now have been undertaken as a test of whether the optical model would apply to scattering even in this low-energy region. There are three main points of interest: a) the value of the parameters describing both the central and the spin-orbit term of the potential; b) the role of compound-elastic scattering which is not well known [26]; c) the influence of the relatively large level separation for light nuclei. Thus if one examines the optical model assumptions, one sees that many levels must contribute to the scattering, and this may not be the case for Mg and Al.

The polarization P_1 has been measured in the usual way by measuring the asymmetry in a double scattering experiment, the second scatterer being helium, whose polarization P_2 is well known [24]. The relation between asymmetry and polarization P_1 is given by equation (1).

Figure 6 shows the general arrangement. The E.T.H. cyclotron was operated at a proton energy of (4.05 ± 0.05) MeV with a mean external beam intensity of 0.8 μA. After passing through a narrow collimator, the protons are scattered by a target foil thinner than 3 mg/cm². One might regard this as the polarizer. Thereafter, the protons pass through a tantalum foil to enter the scattering region of the polarimeter. The protons are there scattered through approximately 70° by helium under a pressure of 4 atmospheres, being finally detected by nuclear photo plates.

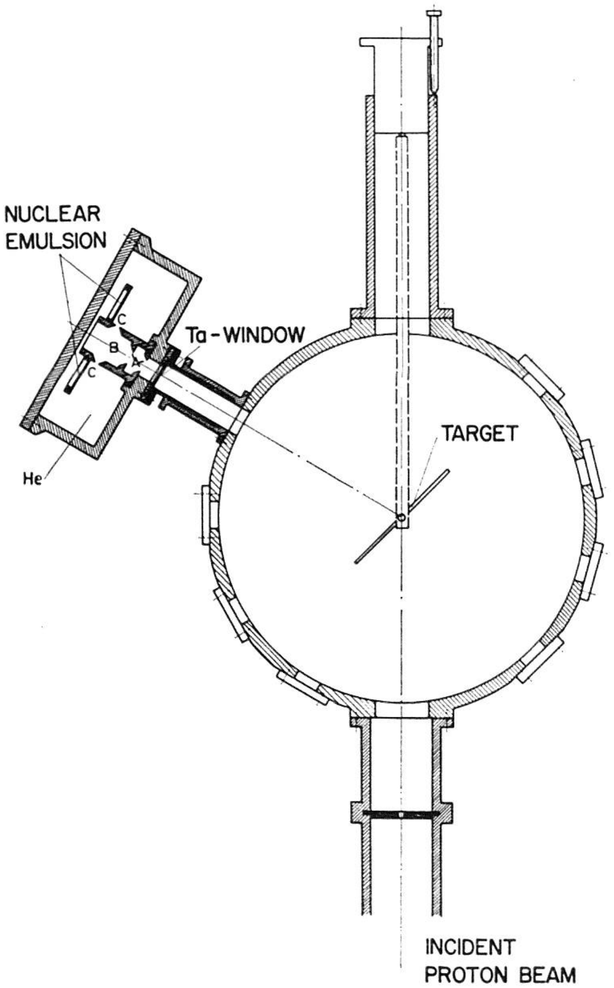

Figure 6

Scattering chamber and helium polarimeter used for polarization measurements on 4-MeV protons elastically scattered by Mg, Al, Ti, V.

As is well known one must take great care either to avoid or at least to take account of any instrumental asymmetry which could falsify the measurements. One of the most important requirements is that the center of the target lie at the intersection of the beam axis with that of the polarimeter. That this was the case at every scattering angle was established to within 0.5 mm optically. The resulting asymmetry was smaller than 1.5% which would throughout be smaller than the statistical error. Secondly, one must ensure symmetry of the helium polarimeter; the mechanical precision of some critical parts approached 0.02 mm. A correction had also to be made for the fact that the beam intensity at the entrance of the helium polarimeter was not uniform due to the rapid variation of cross section for the first scattering event with angle. The resulting asymmetry was measured using gold as a first scatterer (this produces no polarization since only Coulomb scattering is effective). It was found never to exceed 8%, which agrees sufficiently with the estimated value. This effect has been taken into account in all measurements.

Several tests have been undertaken to ensure absence of instrumental asymmetries: a) The helium polarimeter was turned through 90° and then through a further 180°, to make the second scattering plane perpendicular to the first. No asymmetry should occur in such a case. With gold as a first scatterer the asymmetry was found to be $\epsilon = 0.004 \pm 0.014$ and $\epsilon = -0.004 \pm 0.007$ for the two polarimeters respectively. b) The polarisation of carbon was measured at angles of 95° and 152.5° (c.m.) and compared with the values calculated from known phase shifts [27]. Results agree within the experimental error of 6%.

Two other effects could spoil the polarisation measurements, namely production of recoil protons in the nuclear emulsion by neutrons and inelastic scattering of protons in the target material. The former effect proved to be negligible except for vanadium. By shielding stringently with paraffin and cadmium its effect could be reduced to insignificance. The inelastically scattered protons also proved to be altogether un-

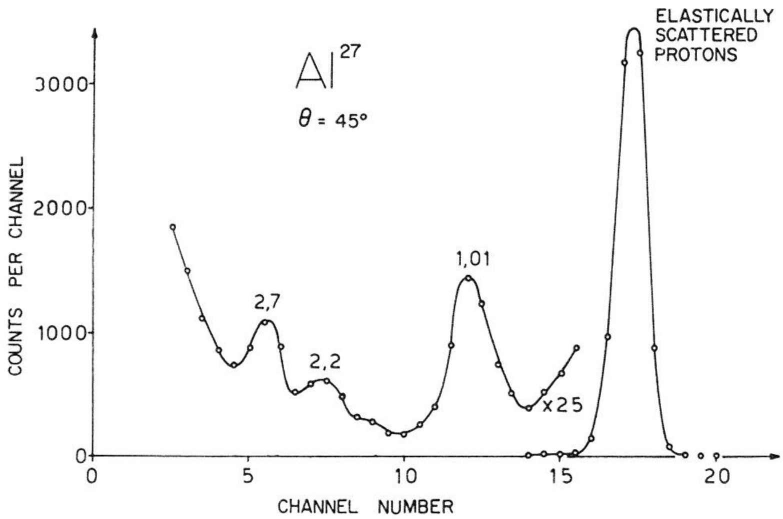

Figure 7

Pulse height spectrum due to 4-MeV protons scattered by Al, as determined using a CsI(Tl) crystal. Scattering angle $\theta = 45°$ (lab). The peak figures indicate the energy loss, in MeV, of the protons.

important. Their intensity was only a few percent of the elastically scattered protons and practically all of them lost 1 MeV or more in the target, as can be seen from figures 7 and 8. These show the energy spectra

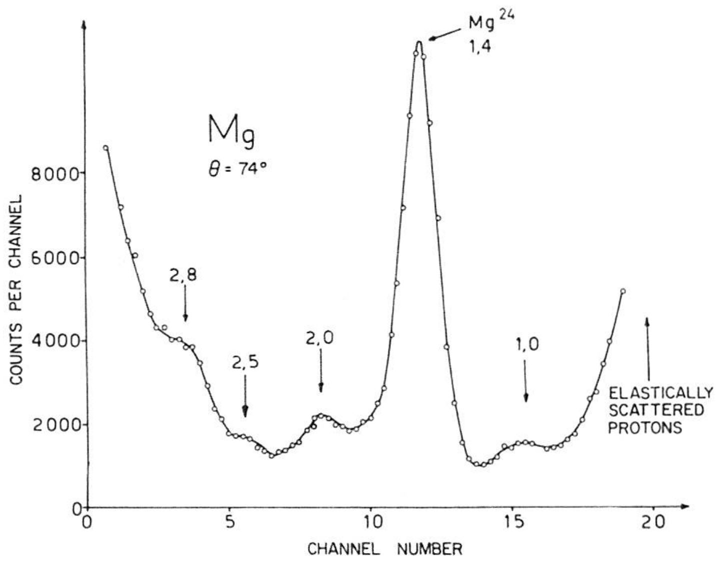

Figure 8

Pulse height spectrum due to 4-MeV protons scattered by Mg, as determined using a CsI(Tl) crystal. Scattering angle $\theta = 74°$ (lab). The peak figures indicate the energy loss, in MeV, of the protons.

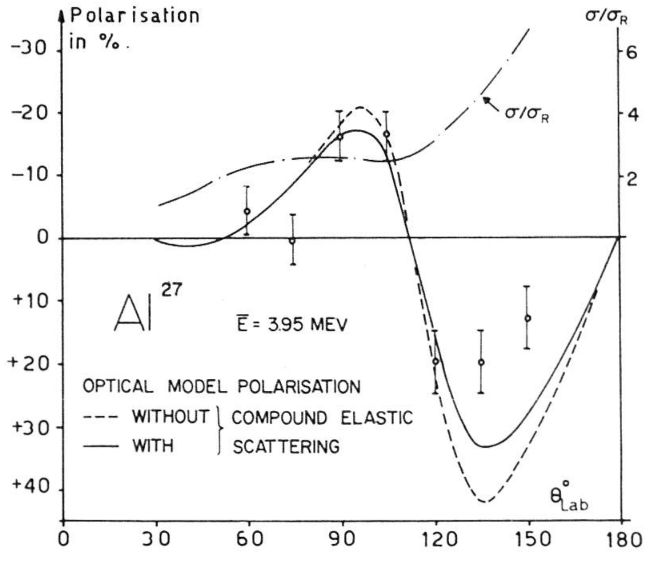

Figure 9

Polarization of 3.95-MeV protons elastically scattered by Al (open circles). The dot-dashed curve represents the ratio of observed elastic scattering to Rutherford scattering. The full and the dashed curves are results of optical model computations by BJORKLUND *et al.*[28] with and without the inclusion of an isotropic compound-elastic scattering term.

of the scattered protons, on replacing the helium polarimeter by a CsI(Tl)-detector. It should be noted that those protons which lost more than 800 keV were rejected in scanning the photo plates.

In figure 9 the results for aluminum are shown. The open circles represent the measured polarization together with the experimental error. Polarizations as high as 20% have been found. The dot-dashed line represents the ratio of observed scatter to Rutherford scatter as measured with a CsI(Tl) crystal and a multichannel pulse height analyzer. It is arbitrarily normalized to unity at 30° in this and in figures 11 and 12. The full and the dashed curves represent the optical model calculations for the polarization with and without the inclusion of an isotropic compound-elastic scattering term of 4 mb/ster. We are indebted to Dr. BJORKLUND and Dr. CAMPBELL [28] for these computations, which

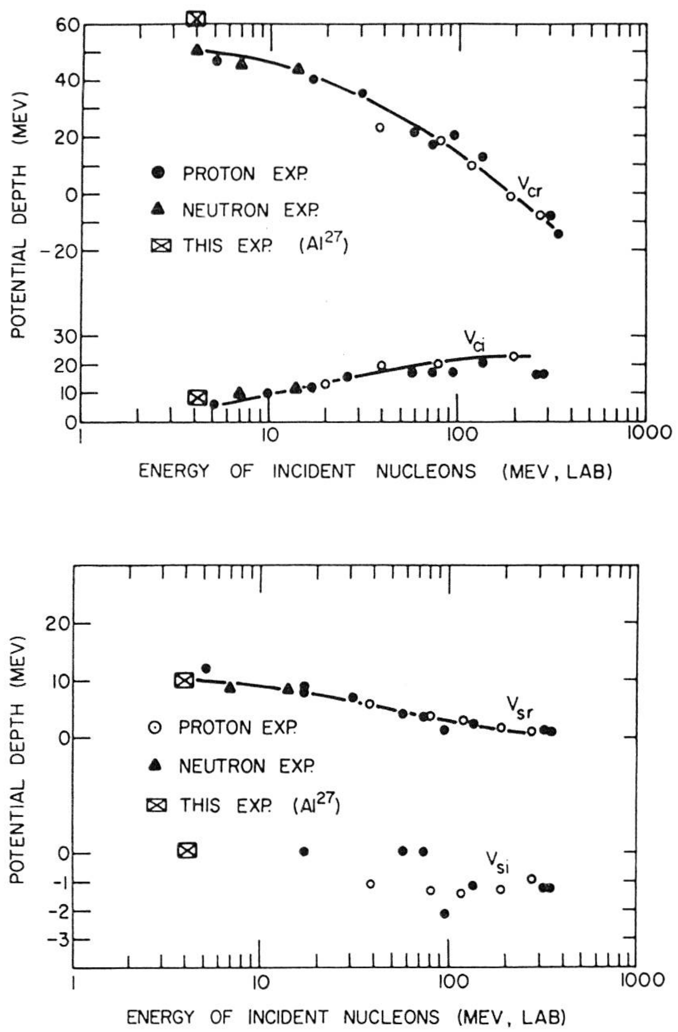

Figure 10

Values of the optical model parameters using the potential of BJORKLUND *et al.* [26]. The values marked by crosses were found to fit the polarization measurement on Al.

they kindly undertook using their rounded potential with surface absorption and a real spin orbit term. As can be seen, good agreement was attained with the experimental data except at back-scattering angles. This may be due to the influence of compound-elastic scattering which can only rather roughly be taken into account. The parameters used in this fit can be seen in Figure 10, together with those at higher energies. The values fit smoothly on to those at energies up to 300 MeV, with the possible exception of V_{cr} which characterises the real central potential. Those parameters which define the diffusesness of the surface have been chosen to be the same as for proton experiments of similar energy.

Figure 11 shows the polarization and the differential cross section for natural magnesium. The polarization data differs markedly from that of aluminum and it seems unlikely that a good fit could be obtained with an optical model calculation using similar parameters as in the case of aluminum. The reason may be that the number of resonances involved in the scattering process is small. The mean level separation is of the same order as the energy spread of the incident protons, thus leaving one of the main assumptions of the optical model unfulfilled. GREENLEES *et al.* [22] in discussing the polarization results of 9-MeV protons elastically scattered by Mg, has come to a similar conclusion.

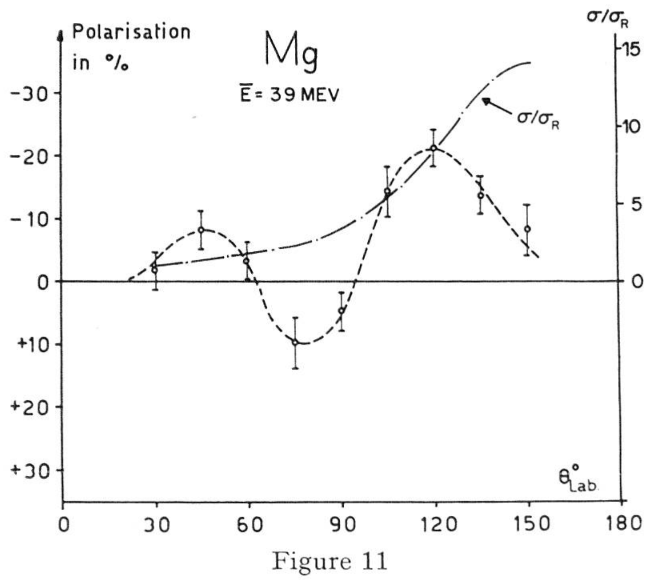

Figure 11

Polarization of 3.9-MeV protons elastically scattered by Mg (open circles). The dot-dashed curve represents the ratio of observed elastic scattering to Rutherford scattering.

The results for natural titanium are represented in figure 12. Counting statistics were rather bad for this element owing to the rapidly decreasing differential cross section. Only small polarization, if any, was observed.

The same holds for vanadium, shown in Figure 13. This behaviour is not unexpected since the Coulomb barrier is high on comparison with the relatively low proton energy.

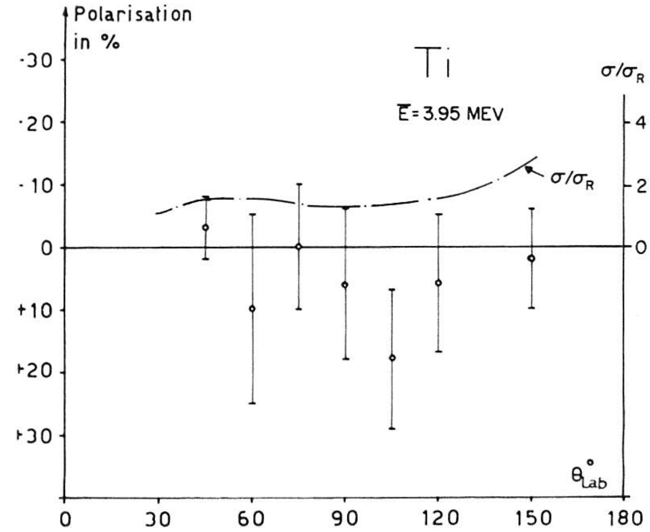

Figure 12

Polarization of 3.95-MeV protons elastically scattered by Ti (open circles). The dot-dashed curve represents the ratio of observed elastic to Rutherford scattering.

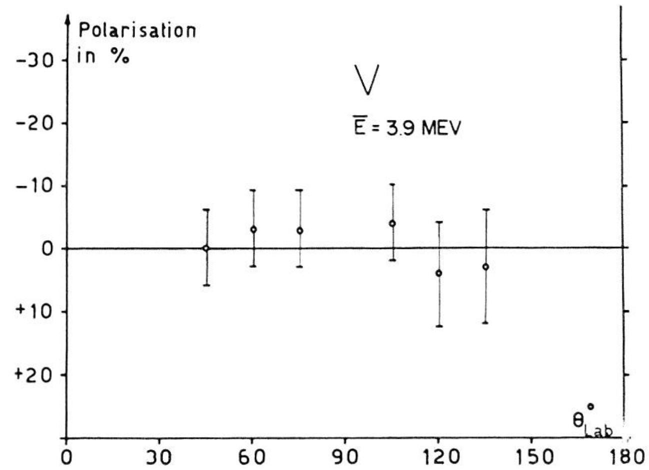

Figure 13

Polarization of 3.9-MeV protons elastically scattered by V (open circles).

In conclusion, polarization has been found to attain as much as 20% for medium heavy nuclei at a proton energy of 3.9 MeV. The optical model, in so far as its assumptions be satisfied, is able on inclusion of a spin-orbit term to account satisfactorily for the results obtained.

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