Zeitschrift: Helvetica Physica Acta

Band: 34 (1961)

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

Artikel: Survey of experiments on the polarization in reactions

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DOI: https://doi.org/10.5169/seals-513267

II.

Generation of Polarized Nucleons and Deuterons by Reactions

Survey of Experiments on the Polarization in Reactions

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The possibility to polarize fast neutrons by scattering from suitable nuclei was first suggested by SCHWINGER [1][1]. Shortly thereafter WOLFENSTEIN [2] proposed that neutrons produced in a reaction might already be polarized. This suggestion was based on a paper by KONOPINSKI and TELLER [3] who had shown that the interpretation of the *d–d* reaction requires a large amount of *p*-wave interaction with strong spin-orbit coupling.

The polarization of neutrons or protons produced in a reaction can be detected by the arrangement shown in figure 1. An unpolarized beam $\boldsymbol{k}_0$ from an accelerator is incident on target 1. The polarization P_1 of the outgoing nucleons $\boldsymbol{k}_1$ is normal to the reaction plane. The magnitude of the polarization is defined as $(N_+ - N_-)/(N_+ + N_-)$, where N_+ and N_- are the numbers of nucleons with spin up and spin down, respectively. Two conventions are in use as to which direction is to be called «up».

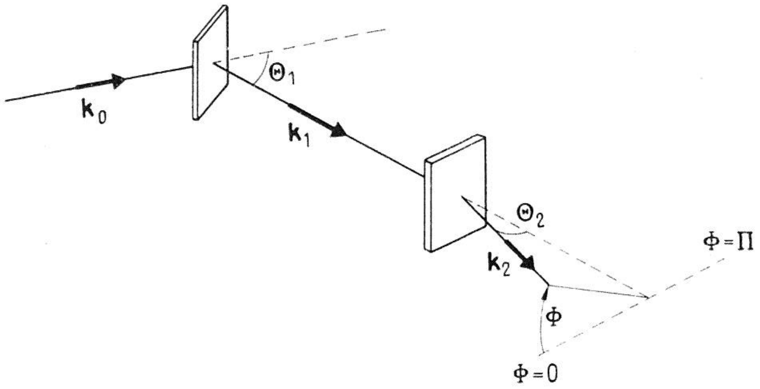

Figure 1

An unpolarized beam from an accelerator is incident in the direction $\boldsymbol{k}_0$. Neutrons or protons originating in the first target move in the direction $\boldsymbol{k}_1$. Particles emitted by the second target in the direction $\boldsymbol{k}_2$ are detected.

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[1] Numbers in brackets refer to References, page 158.

SCHWINGER chose $\boldsymbol{k}_1 \times \boldsymbol{k}_0$ as the «up» direction, while WOLFENSTEIN and others chose the opposite convention. In this paper WOLFENSTEIN's convention will be used.

The second target serves to detect the polarization of the nucleons emitted by the first one. Without making specific assumptions about the reaction mechanism one can predict that the flux of particles from the second target at a fixed reaction angle θ_2 will depend on the azimuthal angle ϕ. The azimuthal dependence of the cross section in the second reaction is given by

$$\sigma(\theta_2, \phi) = \sigma_0(\theta_2)\,[1 + P_1 \cdot A(\theta_2) \cos\phi], \qquad (1)$$

where $\sigma_0(\theta_2)$ is the differential reaction cross section. The quantity $A(\theta_2)$ depends on the particulars of the second reaction. It usually is called the «analyzing power» or the «asymmetry» of the reaction. SIMON [4] showed that A is equal to the polarization of the outgoing nucleons of the inverse reaction, induced with an unpolarized beam: $A = P_{inverse}$. For the case of elastic scattering there is no difference between the reaction and its inverse. In this case A of equation (1) is usually replaced by the symbol P_2. The analyzing properties of different scatterers will be discussed in session 3 of this symposium. In the following it will be assumed that there are scatterers available for which P_2 is known.

The first experiments which showed that nucleons produced in a reaction are polarized were reported in 1952 for the d–d reaction. BISHOP and others [5] observed the polarization of protons, while HUBER and BAUMGARTNER [6, 7] and RICAMO [8] experimented with neutrons.

The experimental arrangement which HUBER and BAUMGARTNER used is shown in figure 2. Neutrons originating from the D(d, n)He^3 reaction were scattered from a graphite sample. Neutrons scattered to the «left» ($\phi = 0$) and the «right» ($\phi = \pi$) were detected with scintillation counters. From the left-to-right ratio of counting rates and the known value of $P_2 = A$ the polarization P_1 of d–d neutrons can be found by means of equation (1).

In a number of recent experiments the polarization of d–d neutrons was measured over a wider range of energies. Figure 3 shows the results of PASMA [9], MEIER *et al.* [10], LEVINTOV *et al.* [11] and BAICKER [12] for a neutron emission angle of about 45°. Except for one, all experiments used helium as an analyzer. A recent experiment [13] at a deuteron energy of 8.2 MeV indicates that the polarization above 4 MeV remains almost constant. For protons from the d–d reaction measurements have been reported for deuteron energies of 0.3, 0.64 and 1.2 MeV [5, 14, 15]. The magnitude of the proton polarization is systematically larger than the neutron polarization at the same angle and energy, but in view of the experimental uncertainties the difference is probably not significant.

Beiduk, Pruett and Konopinski [16] tried to explain the energy dependence of the *d–d* reaction cross section by simple assumptions. They showed that the variation of the cross section with energy can be attributed entirely to the energy variation of the barrier penetrability for deuterons of different orbital angular momentum. For deuteron energies up to a few hundred kilovolts only *s*- and *p*-waves are effective. For this energy region Blin-Stoyle [17] and Cini [18] predicted that the polarization as a function of angle should be of the form $P \sim (\sin 2\,\theta)/\sigma(\theta)$. The measurements by Meier *et al.* [10] and McCormac *et al.* [19] for a deuteron energy of 600 KeV agree well with this prediction. No such measurements have been reported for higher bombarding energies. At higher energies terms containing $\sin 4\theta$, $\sin 6\theta\ldots$ may be expected.

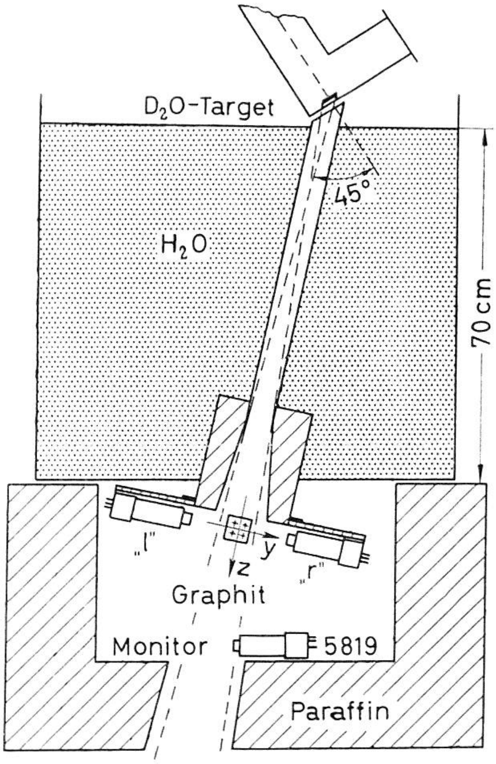

Figure 2

Arrangement used by Huber and Baumgartner (references [6] and [7]) to detect the polarization of neutrons from the *d-d* reaction.

Pruett, Beiduk and Konopinski [20] discussed the question whether the strong spin-orbit coupling which they found necessary to interpret the *d–d* reaction could be accounted for by the nucleon-nucleon tensor force. The results were inconclusive. However, if the tensor force mainly provides the spin-orbit coupling, Fierz [21] showed that the angular and energy dependence of the polarization is predictable up to about

2 MeV deuteron energy. The angular dependence should remain the same as that at low energies. At a fixed angle, the energy dependence of the product $P\sigma(\theta)$ should be given by the function σ_1 of reference [16] i.e. by the reaction probability of $l = 1$ deuterons. In figure 4 the points of figure 3 are replotted in this way. The differential reaction cross sections $\sigma(\theta)$ were taken from a number of different sources [22, 23, 24]. The agreement is better than can be expected from the experimental uncertainties of σ and of P.

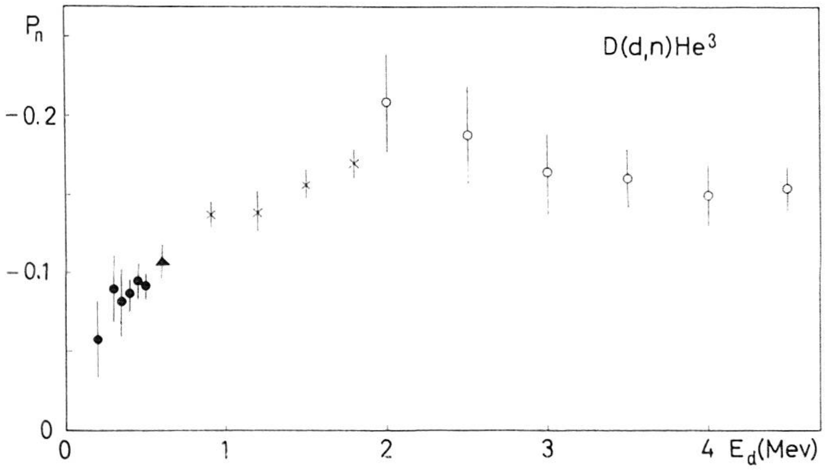

Figure 3

Polarization of neutrons from the $D(d, n)He^3$ reaction as a function of bombarding energy. In order of increasing energy the data are by PASMA, MEIER *et al.*, LEVINTOV *et al.*, BAICKER *et al.* (references [9, 10, 11, 12]) and apply to laboratory angles of 47°, 50°, 49° and 40°, respectively.

Another reaction which has been widely used as a source of neutrons is the $Li^7(p, n)Be^7$ reaction which has a threshold of 1.88 MeV. The polarization of the outgoing neutrons has been investigated extensively by BARSCHALL's group at Wisconsin. Recent results for proton energies up to 3.1 MeV and a neutron emission angle $\theta = 50°$ are shown in figure 5. After the early work by ADAIR [25] at Wisconsin and WILLARD [26] at Oak Ridge there remained the question if in the vicinity of 2.1 MeV the polarization varies appreciably with energy or not. The recent measurements by DARDEN [27] show a very rapid rise between 2 and 2.1 MeV which is followed by a maximum and a slow decrease. The polarization seems to pass through a minimum at 2.5 MeV and then rises slowly. The trend of the curve at higher energies was established by the experiments of CRANBERG [31] and of BAICKER [12]. The results are shown in figure 6, together with the low energy data. For proton energies above 4 MeV the measurement did not discriminate against neutrons to the first excited state of Be^7. For comparison the $Li^7(p, n)Be^7$

total cross section [32] is also shown in figure 6. It is apparent that the variation in the polarization near 2.2 MeV is associated with the well known resonance at 2.25 MeV. The variation near 5 MeV may be caused by the broad resonance which appears in the $Li^7(p,n)$ cross section at this energy. An interpretation of the $Li^7(p,n)$ differential reaction cross section and the polarization in terms of the virtual states of Be^8 was attempted by DARDEN and AUSTIN. Some results of this analysis will be presented in another paper at this symposium.

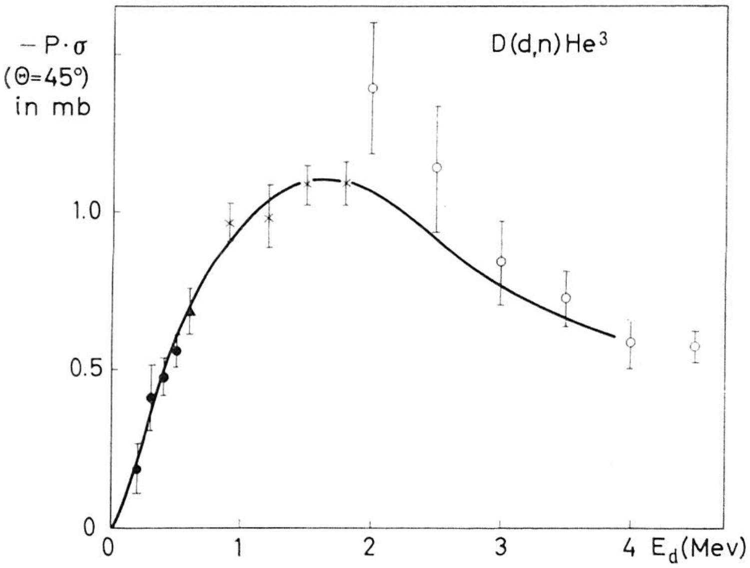

Figure 4

The polarization of neutrons from the $D(d,n)He^3$ reaction, multiplied by the reaction cross section (in units of 10^{-27} cm²) as a function of deuteron bombarding energy. The points are those of figure 3. The solid curve is the function σ_1 of reference 16, multiplied by an arbitrary scale factor.

In the experiments summarized so far the polarization was measured by scattering from light nuclei like helium, carbon or oxygen. The analyzing power $A = P_2$ is computed from phase shifts which are obtained from an analysis of differential cross section experiments. This procedure is rather indirect and it usually is difficult to estimate the uncertainty of the computed analyzing power. A method which eliminates this problem was proposed by BARSCHALL [33]. In this method the polarization of neutrons or protons from a reaction is measured by using the inverse reactions as an analyser. Thus to observe the polarization of $T(p,n)$ He^3-neutrons, He^3 would be used as the second target. Since the analyzing power of a reaction is equal to the polarization in the inverse reaction, and the two successive reactions are chosen to be the inverse of each other, P_1 and A of equation (1) are equal to each other.

This, of course, presumes that both reactions take place at the same center of mass angle and energy, i. e. the velocity of the neutron relative to the He^3 nucleus is to be the same in both reactions. For a given bombarding energy there is at most one reaction angle for which

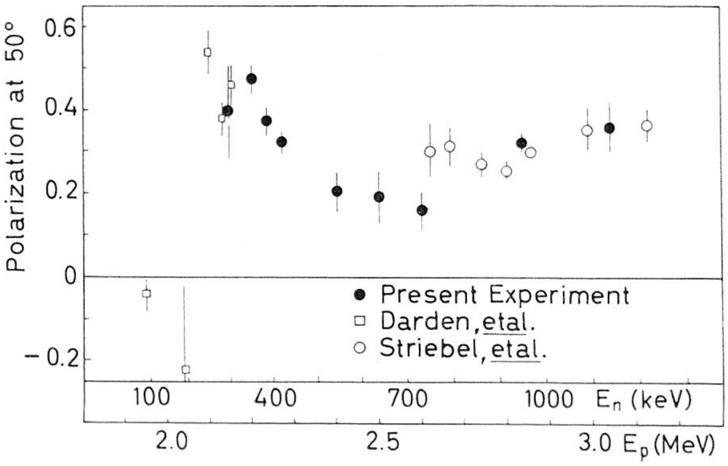

Figure 5

Polarization of neutrons emitted by the Li^7(p, n)Be^7 reaction at 50° for proton energies between the threshold and 3.1 MeV. In order of increasing bombarding energy the measurements are those of DARDEN *et al.*, AUSTIN, and STRIEBEL *et al.* (references [27, 28] and [29]). The figure is taken from reference [28].

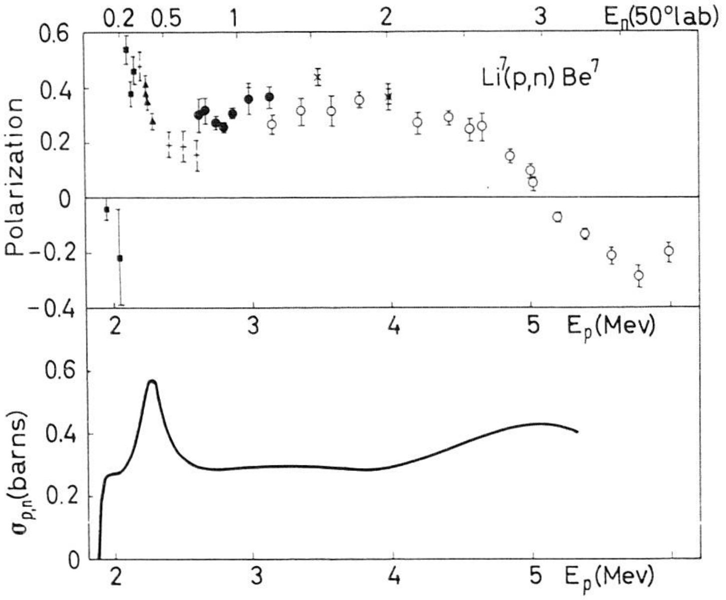

Figure 6

Polarization of neutrons emitted by the Li^7(p, n)Be^7 reaction at 50° for proton energies up to 6 MeV. The data are from references [27] (■), [28] (+), [29] (●), [30] (▲), [31] (×), [12] (○).

this condition is satisfied. Whether there is such an angle or not depends on the Q-value of the reaction, the masses and the bombarding energy.

In a recent experiment ARTEMOV, VLASOV and SAMOILOV [34] used BARSCHALL's method to study the T(p,n) reaction for proton energies between 6 and 10 MeV. For $E_p = 10$ MeV a scattering angle of 16.5° has to be chosen to satisfy the conditions of the method. At this angle the polarization was found to be quite small, so that the asymmetry (which depends on the square of the polarization) was difficult to measure. Most measurements where carried out for a reaction angle of 40°. At this angle the neutrons have an energy of 7.7 MeV rather than the required 8.8 MeV. However the conditions of the method still apply approximately because the polarization in this reaction presumably varies rather slowly with energy. The results of the experiment are shown in figures 7 and 8. The angular dependence (figure 7) indicates a maximum polarization of 0.3 for a center of mass reaction angle of about 50°. For 8 MeV proton energy a similar angular dependence was found. Figure 8 shows the dependence of the polarization of neutrons from the T(p,n) He^3 reaction and of the asymmetry parameter A in the He^3 (n,p)T reaction as a function of incident particle energy for an angle of 40°. The polarization increases with energy up to a value of 0.3 at 9.9 MeV proton energy. This corresponds to a neutron energy of 7.7 MeV. The sign of the polarization is not known.

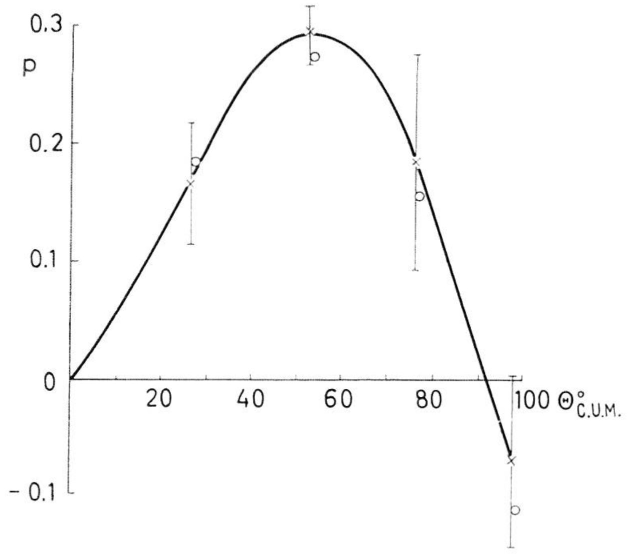

Figure 7

Polarization of T(p, n)He^3 neutrons as a function of center of mass angle for E_p = 9.9 MeV, obtained from measurements of the asymmetry in the He$^3(n, p)$T reaction for four different angles of proton emission. × $\theta_1 = 40°$, $E_n = 7.7$ MeV; ○ $\theta_1 = 16.5°$, $E_n = 8.8$ MeV. The figure is from reference [34].

Brief mention should be made of two experiments on the T(d,n) He^4 reaction, since it is a widely used source of high energy neutrons. For deuteron energies up to 300 keV, PASMA [9] detected no polarization. Measurements were also made with 1.8 MeV deuterons for a number of neutron emission angles by LEVINTOV, MILLER and SHAMSHEV [35]. The largest observed polarization²) was .12 ± .03 for 67.5°. According to the authors this value is to be considered a lower limit of the polarization because the nonisotopic angular distribution of the neutrons causes instrumental asymmetries which in this experiment tended to give too small a polarization. Of course the problem of distinguishing between instrumental asymmetries and true polarization effects arises in all polarization experiments. An elegant method to avoid this problem was proposed by HILLMAN, STAFFORD and WHITEHEAD [36]. It makes use of the fact that a magnetic field between the first and second target changes the direction of the polarization vector but does not affect the intensity distribution of the neutrons. The method has recently been applied by DUBBELDAM, JONKER and BOERSMA [37] to 3 MeV neutrons from the d–d reaction.

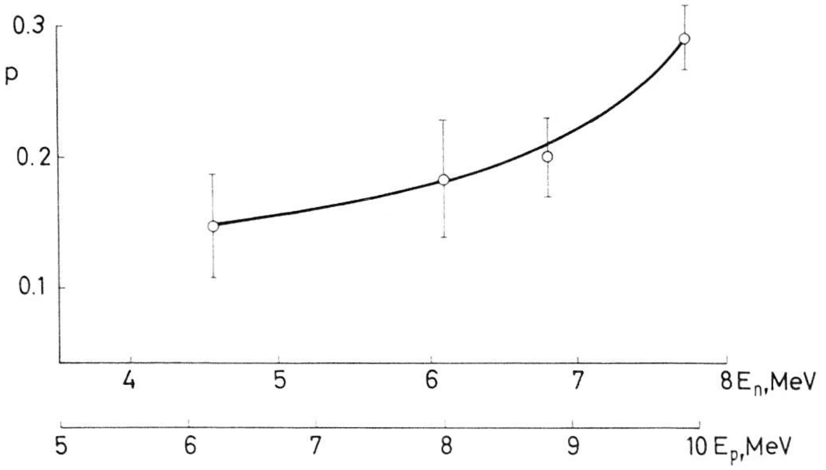

Figure 8

Polarization of neutrons from T(p, n)He^3 and asymmetry of protons from He$^3(n,p)$T as a function of incident particle energy at 40° in the laboratory system. The figure is from reference [34].

Little needs to be reported here on proton polarization experiments. Proton beams of high degree of polarization can be prepared by elastic scattering, in particular from helium and carbon. Consequently there has been little reason to search for reactions which produce highly polarized protons. The main motivation to study polarization in proton

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²) Reference [35] does not define the direction of positive polarization.

producing reactions has been the possibility of obtaining information about the reaction mechanism. Indeed a considerable number of such experiments has been reported, but practically all of them pertain to the study of (d,p) stripping reactions. This topic will be discussed at this symposium in a paper by HIRD. In some cases it has been found that stripping reactions are useful sources of polarized nucleons. In an experiment on the $C^{12}(d,n)N^{13}$ reaction HAEBERLI and ROLLAND [38] found that neutrons emitted near the foreward peak of the angular distribution have a relatively high degree of polarization. The angular distribution of polarization is shown in figure 9 for two different bombarding energies. The Liverpool group [39, 40] found the $C^{12}(d,p)C^{13}$ reaction to be a useful source of 9 MeV polarized protons. For a reaction angle of about 45° the polarization reaches nearly 0.5. To obtain maximum proton yield the internal deuteron beam of the cyclotron was used to bombard a graphite target. The proton beam was focussed into a chamber several meters away from the cyclotron.

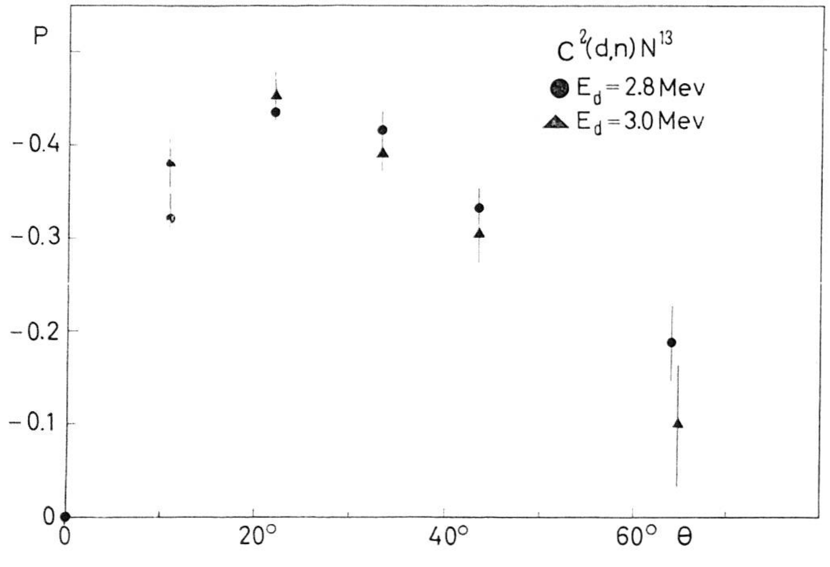

Figure 9

Polarization of neutrons from the $C^{12}(d, n)N^{13}$ reaction as a function of center of mass angle of neutron emission for two different bombarding energies. The data are from reference [38].

One may well ask what has been accomplished so far in the study of polarization in reactions. In the first place one now has available sources of polarized neutrons of any energy between 0.2 and 8 MeV. In figure 10 the polarization in different neutron producing reactions is shown as a function of neutron energy. Over much of the energy range neutron sources of higher degree of polarization are obviously needed.

The curves of figure 10 are not to be taken literally since the uncertainties are still rather large.

Another accomplishment of these experiments has been the development of techniques to measure the polarization of nucleons. This development clearly is not completed but much progress has been made during the last eight years.

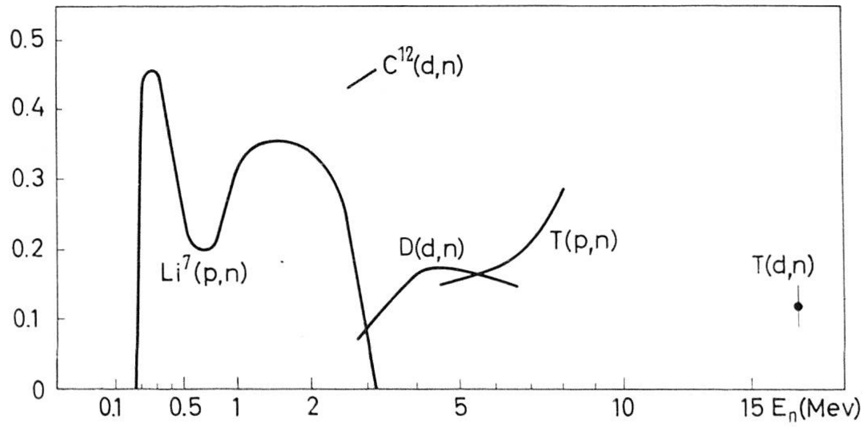

Figure 10

Dependence of the neutron polarization on neutron energy for different reactions. The curves are not to be taken literally, since the experimental uncertainties are rather large.

Finally an obvious conclusion from the experiments summarized here is that polarization in reactions is a very common phenomenon. Since spin-orbit coupling is a necessary condition for polarization to occur one may say that the experiments provide rather direct evidence for the importance of spin-orbit coupling. Thus one has become more cautious about accepting calculations based on the assumption of central forces. It would appear, therefore, that polarization experiments have helped to make the interpretation of reactions more realistic.

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