Polarization in some (d, n) and (d, p) reactions : principle of ring polarimeter

Polarization in Some (d, n) and (d, p) Reactions Principle of Ring Polarimeter

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1. Introduction

In the past years we studied the polarization of neutrons from the $D(d, n)He^3$ and $T(d, n)He^4$ reactions (Pasma [1][1])), and the polarization of protons from the $Be^9(d, p)Be^{10}$ and $Li^6(d, p)Li^7$ reactions (van Beek and André [2]). In each case we shall report the results of our thin target measurements, only briefly indicating the method used for measuring the polarization. Finally a new geometry for the measurement of nucleon polarization will be discussed.

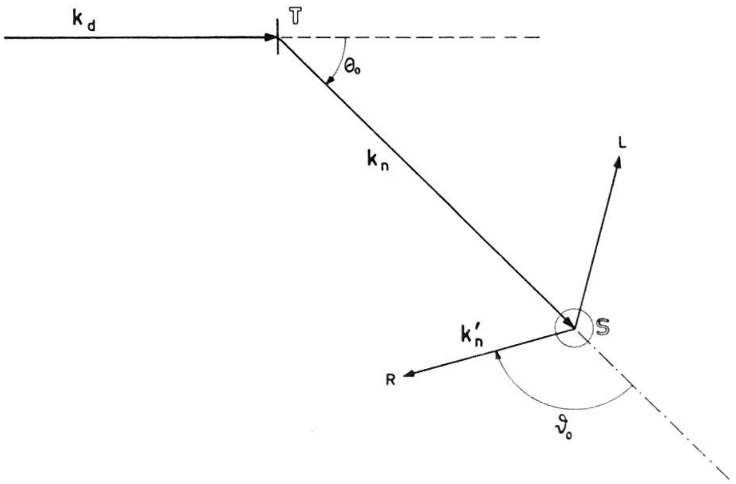

Figure 1

We are dealing with nuclear reactions in which the incident particles and the target nuclei are unpolarized, whereas the observed outgoing particles are nucleons (spin 1/2). Polarization of these nucleons may result from spin-orbit coupling. The polarization vector $\boldsymbol{P}_n$ is always normal to the reaction plane, defined by the paths of incoming and outgoing

[1]) Numbers in brackets refer to References, page 174.

particle. If $\boldsymbol{P}_n$ has the direction of $\boldsymbol{k}_d \times \boldsymbol{k}_n$ the polarization is called positive. The degree of polarization is a function of the energy of the incident particles E_d and the angle of emission θ_0 (lab. system) of the nucleons. The value of P_n is found from the left-right asymmetry in scattering the nucleons by spin zero nuclei. We used He^4 as the scatterer.

When an *un*polarized beam of spin 1/2 particles is scattered by a zero spin scatterer, the beam becomes polarized, the polarization vector $\boldsymbol{P}_s$ being perpendicular to the scattering plane, its magnitude a function of the energy E_n and the scattering angle ϑ_0 (lab. system), the left hand scattering being equal to the right hand scattering. The function $P_s(E_n, \vartheta)$ is called the *polarization efficiency* or 'analyzing power' of the scatterer. If P_s has the direction $\boldsymbol{k}_n \times \boldsymbol{k}_n'$ the polarization is called positive.

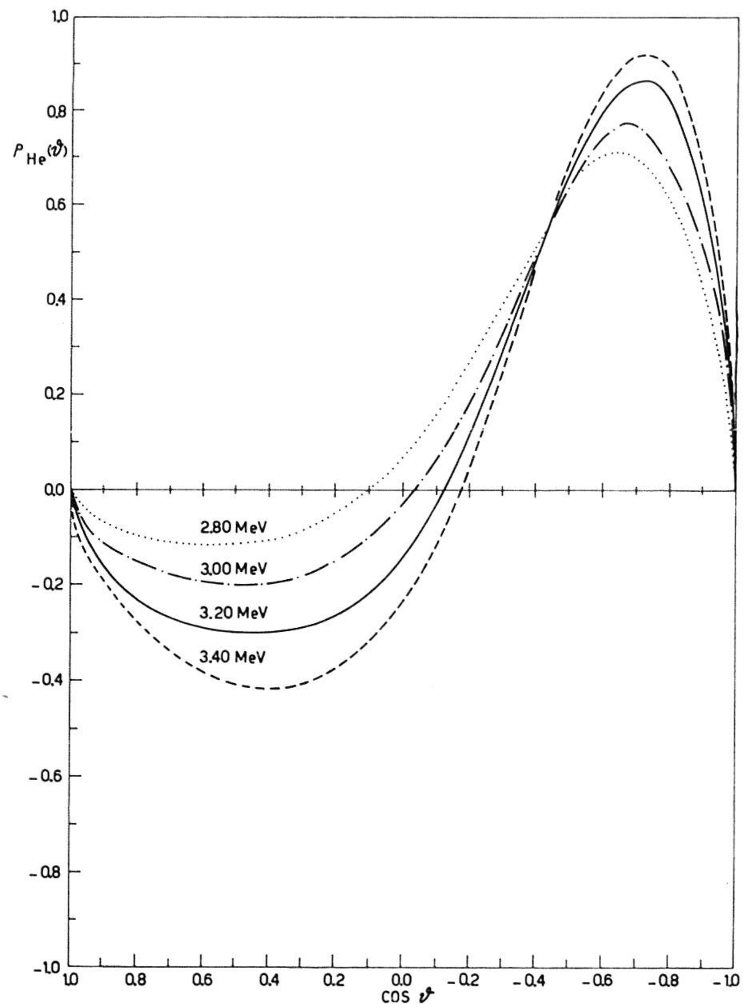

Figure 2

Neutron polarization by n-α scattering as a function of c. m. angle ϑ
(Van Wageningen [3])

However, if the nucleons incident on the scatterer have the polarization degree P_n, and if we take the scattering plane normal to the vector $\boldsymbol{P}_n$, then the left scattering with intensity L is no longer equal to the right scattering R (fig. 1). The left-right asymmetry, defined as

$$\varepsilon = \frac{L-R}{L+R} \tag{1}$$

turns out to be

$$\varepsilon(E_d, \theta_0, \vartheta_0) = P_n\,(E_d, \theta_0) \cdot P_s\,(E_n, \vartheta_0) \tag{2}$$

From the measured value of ε the value of P_n can be found if the polarization efficiency P_s of the scatterer is known. This is for instance the case for He^4. Figure 2 shows, by way of example, the value of $P_s(\vartheta)$ for 2.8–3.4 MeV neutrons scattered by He^4 (ϑ is the scattering angle in the c. m. system). Similar curves exist for higher neutron energies. These curves, calculated by VAN WAGENINGEN [3], are consistent with those computed by LEVINTOV [4] *et al.*, and are based on the accurate measurements of the differential neutron scattering cross sections for helium by SEAGRAVE [5]. Also in the case of proton scattering reliable curves for the polarization efficiency of He^4 exist. In actual experiments one has to use average values of P_s, accounting for a spread in the scattering angles due to the finite size of the scatterer and of the detectors at R and L. Further one has to correct the measurements for possible geometrical asymmetries, differences in sensitivity of the counters, background counts and the like. In positions where the left-right asymmetry must be essentially zero (either P_n or P_s being zero), test measurements were made.

2. Results

D(d, n)He^3. For this reaction the neutron polarization was determined from the left-right asymmetry, induced when the neutrons are scattered elastically by He^4 nuclei. The experimental arrangement is shown in figure 3. The well collimated neutron-beam ($\theta_0 = 47°$–$50°$) is scattered by the helium-filled gas scintillation counter S. The neutrons, scattered over 123° in the reaction plane, are detected by the two liquid scintillation counters R and L when in coincidence with the gas scintillation counter S. The choice of helium as the scatterer enabled us to employ this coincidence technique.

The angular distribution of neutrons (in the c. m. system) from the D(d, n)He^3 reaction is rather pronounced, even at low deuteron energy, showing that P-waves of the incident deuteron are involved in the reaction. The differential cross section is proportional to $1 + A(E_d) \cdot \cos^2\theta$. The degree of polarization P_n is a function of the c. m. angle θ of the emitted neutron and the deuteron energy E_d. According to BLIN-STOYLE [6] we have at low energies ($E_d < 0.5$ MeV), where only S-and P-waves are effective:

$$P_n(E, \theta) = C \cdot \frac{A(E_d) \cdot \sin\theta \cos\theta}{1 + A(E_d) \cdot \cos^2\theta} . \tag{3}$$

Thus we have $P_n = 0$ at $\theta = 0$ and $\theta = \pi$, what follows from general symmetry conditions already. Since the colliding particles are identical in this reaction, we must also have $P_n = 0$ at $\theta = \pi/2$, in accordance with the

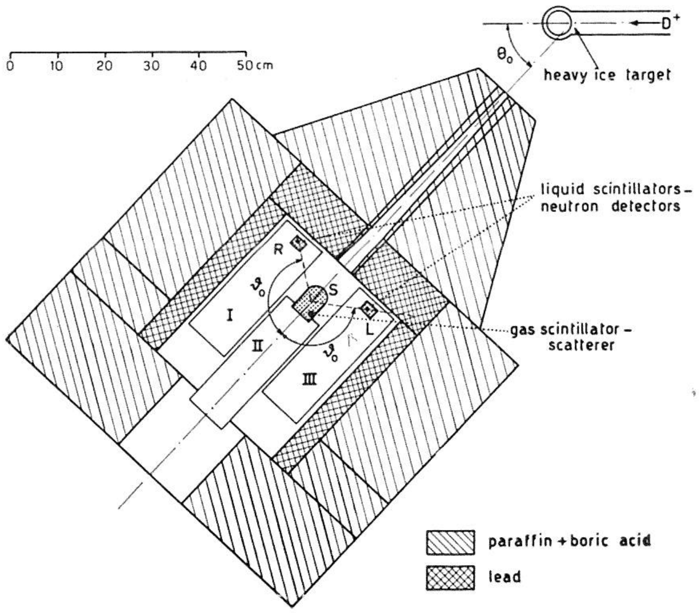

Figure 3
Arrangement used in $D(d, n)He^3$ neutron polarization experiments by PASMA [1]

formula. At low deuteron energies the maximum polarization P_n^{max} can be expected near $\theta_0 = 50°$ ($\theta = 58°$). The highest value of ε occurs if P_s is maximum; this corresponds to $\vartheta_0 = 123°$ ($\cos\vartheta = -0{,}7$; $\vartheta = 135°$) and P_s about $+80\%$. The results obtained by PASMA [1] are summarized in figure 4. The 3 MeV neutrons, emitted under 47° to 50° from thin heavy ice targets (50 keV) show a negative polarization P_n^{max} of 6 to 9% depending on the deuteron energy, varied between 200 and 500 keV. In the same figure the maximum values of P_n, calculated from the thin target results obtained by MEIER, SCHERRER, and TRUMPY [7] at 600 keV (using C^{12} as a scatterer) and those obtained by LEVINTOV and coworkers [4] at energies between 900 and 1800 keV deuteron energy (He^4 scatterer) are shown. The thin target polarization data, obtained by various authors using different experimental techniques, appear to fit in a smooth curve. At low deuteron energies the measured polarizations are in accordance with theoretical values, calculated by CINI [8] and BLIN-STOYLE [6]. The recent experiments by DUBBELDAM [9] at deuteron energies between 300 and 500 keV, using the solenoid method for determining the neutron polarization, yield values in accordance with PASMA's curve. Recent thick target measurements by KANE [10] at an average deuteron energy of 93 keV and emission angles of 43° and 53° in the laboratory system yield rather high P_n^{max} values of about $-$ 10%. This would be in disagreement with the curve of figure 4, when extrapolated to low energies. Including the thin target and thick target results published by various authors, KANE concludes that the polarization of neutrons from the DD-reaction is independent of the deuteron energy between 93 keV and 700 keV. We believe this conclusion and his measurement to be incorrect.

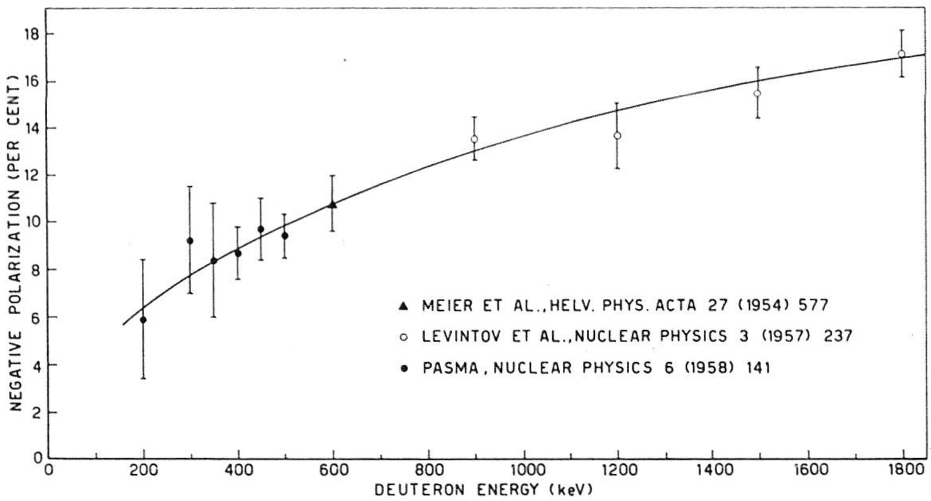

Figure 4

Thin target $D(d, n)He^3$ neutron polarization data as a function of deuteron energy

$T(d, n)He^4$. The 14.8 MeV-neutrons from this reaction, emitted under 45° (θ_0) from a tritium loaded zirconium target, bombarded with deuterons of 100 to 300 keV, showed no polarization, as can be expected. The measurements (PASMA [1]) were done with the same equipment as described for the DD-neutrons. The accuracy in the measured left-right-asymmetries was less, however, due to a much larger background and the lower scattering cross section of He^4 for fast neutrons. The polarization efficiency of helium for 14.8 MeV neutrons has a pronounced minimum at $\vartheta_0 = 76°$ ($\cos\vartheta = -0.1$) and a pronounced maximum at $\vartheta_0 = 123°$ ($\cos\vartheta = -0.7$). Measurements in both circumstances proved the degree of polarization of the DT-neutrons to be zero ($\pm$ 2%). This result is in accordance with the zero angular momentum of the resonance in the reaction cross section at 110 keV. At higher energies (1800 keV) LÉVINTOV and coworkers [11] measured maximum polarizations of about 10%.

$Be^9(d, p)Be^{10}$ and $Li^6(d, p)Li^7$. VAN BEEK (Groningen) and ANDRÉ (Trondheim) [2] measured the polarization of the protons to the ground state of Be^{10} and to the ground state and first excited state of Li^7. A beam of 5 μA 1.63 MeV deuterons, produced with the Van de Graaff generator of the Physical Institute of the Norwegian Technical University at Trondheim, was bombarding thin Be^9 and Li^6O_2 targets (90 μgs/cm^2 and 130 μgs/cm^2 respectively, supported by a 0.12 mm copper backing) for about 10 hours. The protons emitted under 40° entered the scattering chamber through a 10 μ nickel foil. The chamber was filled with helium of 2.5 and 1.5 atm respectively (fig. 5). The scattered protons, the scattering angle of 67.5° being defined by slits, are hitting the photographic plates under 15° (dip angle). Between target chamber and scattering chamber a paraffin-borax shielding reduced the neutron background. An area of 14 × 17 mm of the left and the right plate has been scanned, carefully selecting the appropriate proton tracks. The degree of polarization has been calculated from the left-right asymmetry, using the p, α polarization efficiencies given by BROCKMAN [12]. In our experiments P_{He} amounted to − 43% (beryllium reaction) and − 54% and − 42% respectively (lithium reaction). The accuracy of our proton polarization measurements is rather unsatisfactory, since only a small number of tracks could be used and a disturbing background existed.

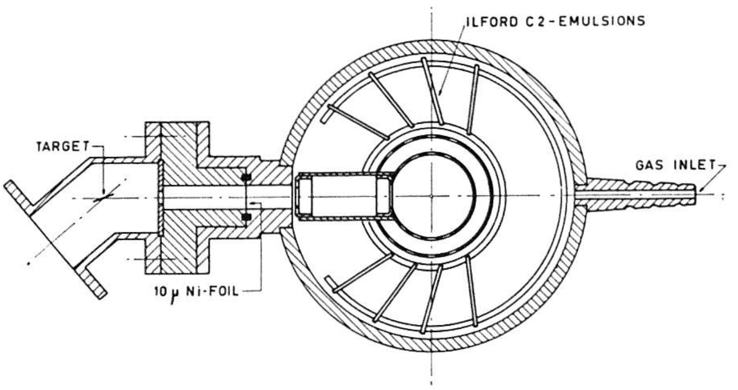

Figure 5
Scattering chamber used by VAN BEEK and ANDRÉ [2]

The ground state protons of $Be^9(d, p)Be^{10}$ showed a very weak polarization if any; we found $P_p = 1(\pm 7)\%$ at $\theta_0 = 40°$. The ground state protons and the first excited state protons of Li^7 could just be resolved ($\Delta E = 0.48$ MeV). We found a negative polarization of both proton groups: $P_p^{(0)} = -48\ (\pm 16)\%$ and $P_p^{(1)} = -63\ (\pm 14)\%$ at $\theta_0 = 40°$, that is near the stripping peak (ANDRÉ [2]).

3. Ring Geometry for Polarization Measurements

In determining the degree of polarization from the left-right asymmetry, one compares the left intensity L (at $\varphi = 0$) proportional with $1 + P_n P_s$ and the right intensity R (at $\varphi = \pi$) proportional with $1 - P_n P_s$. Both intensities are observed at the *same* scattering angle ϑ, preferably chosen at an extremum of the polarization efficiency or 'analyzing power' of the scatterer.

However, since the complete polarization efficiency function $P_s(\vartheta)$ is known, one may in principal just as well compare any two intensities corresponding to *different* scattering angles ϑ_1 and ϑ_2, for which the polarization efficiencies are P_{s1} and P_{s2} respectively, taking the azimuthal angle *either* $\varphi = 0$ *or* $\varphi = \pi$. Before comparing these intensities one has to account for the differences in the scattering cross sections at ϑ_1 and ϑ_2, for differences in geometry and for possible differences in the response of the two counters due to the change in energy of the scattered nucleons. This reduction of the measurements to 'identical geometry' offers no principal difficulties, however. Denoting the *reduced* intensities as I_1 and I_2, one finds:

$$\varrho = \frac{I_1 - I_2}{I_1 + I_2} = \frac{P_n\,(P_{s1} - P_{s2})}{2 + P_n\,(P_{s1} + P_{s2})}\,. \qquad (4)$$

In the usual left-right asymmetry arrangement with $\varphi_L = 0$, $\varphi_R = \pi$ and $\vartheta_1 = \vartheta_2$ one has $P_{s1} = -P_{s2}\ (= P_s)$, so that $\varrho_{LR} = \varepsilon = P_n P_s$. In the more general case of $\vartheta_1 \neq \vartheta_2$ and constant φ it can be concluded from equation (4) that optimal values of ϱ are obtained at angles ϑ_1 and ϑ_2 for which the nominator is large and the denominator small. If P_n has a small value it is important only to make $P_{s1} - P_{s2}$ large, that is to choose ϑ_1 and ϑ_2 such that P_{s1} is a maximum and P_{s2} a minimum of the polarization efficiency curve (or vice versa). If P_n has a high value, one may try to find with the aid of the given $P_s(\vartheta)$-curve other values of ϑ_1 and ϑ_2 for which ϱ is optimal. The ϱ-values can be made about as large as the ε-values in the usual left-right asymmetry set-up. If the geometry corresponding with optimal ϱ would become unpractical, one might measure at a ϑ_1 with large $|P_{s1}|$ and a ϑ_2 with $P_{s2} = 0$ (or vice versa).

We can take advantage of the mentioned more general possibility of measuring the polarization degree of nucleons emitted in a nuclear reaction by using the *ring geometry* schematically shown in figure 6. It is easy to see that in each plane through the direction of incidence of the bombarding particles, the arrangement of scatterer and counter is equally sensitive to the polarization of the emitted nucleons. If by way of example the polarization of 3.4 MeV DD-neutrons, emitted under 45°, must be determined, using helium as the ring scatterer, one should take $\vartheta_1 \approx 120°$ (P_{s1} max) and $\vartheta_2 \approx 65°$ (P_{s2} min) for optimal ϱ, which is quite feasible. However one can choose other ϑ values as well or one may place more than two counters along the axis of the ring polarimeter, combining the intensities belonging to different $P_s(\vartheta)$ values. It will be obvious that the principle of the ring polarimeter is applicable for all reaction angles θ_1. Under suitable circumstances one may use two (or more) coaxial ring scatterers and measure simultanuously at angles θ_1 and θ_2, using an additional pair of counters.

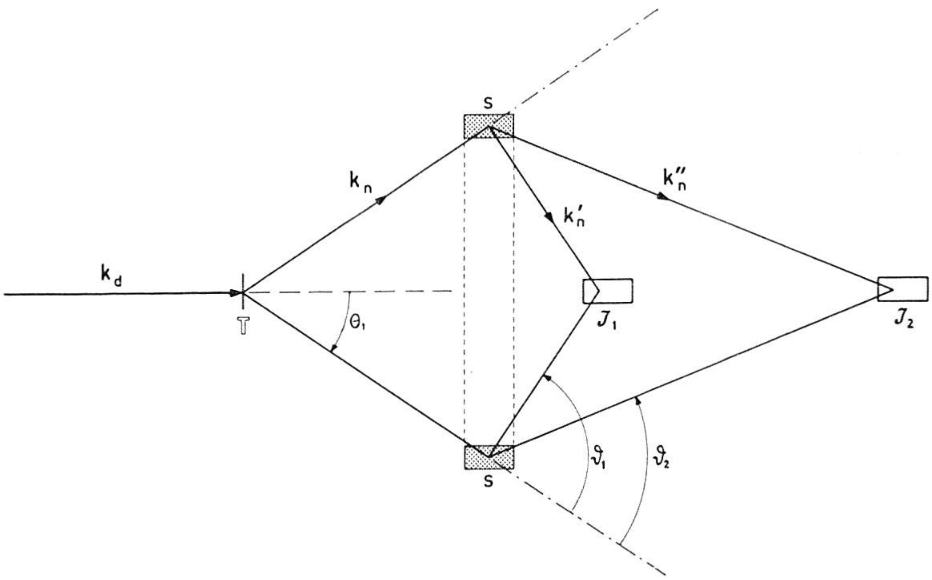

Figure 6
Principle of ring polarimeter

In the ring geometry of figure 6 the counters are in line with the primary beam, hence instrumental asymmetries are unlikely to occur, whereas it will be relatively easy to shield the counters from stray radiation. An important advantage of the ring polarimeter is the appreciable increase of the measured intensity of scattered particles for a given geometry. A disadvantage is that a coincidence technique, as employed in the neutron polarization measurements by PASMA, may give practical difficulties. If polarization measurements of charged particles are envisaged, specially shaped scintillation crystals or semiconductor counters may be necessary. This ring geometry will be applied in polarization measurements in the Groningen Physical Institute. The proposed ring geometry has great advantages over the one obtained when rotating figure 1 about the direction of incidence of the bombarding particles, in which case one would need extensive ring counters except at very small angles θ and ϑ.

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