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1. Introduction

One of the basic problems in particle physics is the investigation of the nucleon-nucleon interaction. At low energies it is well described by the one pion exchange picture, whereas at high energies the interaction is understood on the quark level.

However, the simplest properties of few-nucleon systems such as their binding energies, density distributions, quadrupole and magnetic moments cannot be accurately determined by considering only the interactions between the nucleons in the framework of a potential theory. In models improvement is achieved by including the exchange of more and heavier mesons like ρ, ω...and isobar configurations. An open question is also the possible configuration of exotic states such as dibaryons (six quark configurations).

The deuteron is a two-nucleon system, where all these aspects are relevant. There are no problems with the many particle approximation as exists with other heavier nuclei. The deuteron is the simplest of all nuclear systems and its properties are as important in nuclear physics as the hydrogen atom was in atomic physics. However, both the theoretical and the experimental situation at intermediate energies are unsatisfactory. It is obvious that a thorough understanding of the deuteron is extremely necessary for all other nuclei.

At intermediate energies measurements from a tensor polarized deuteron target are being prepared for the following reactions: the photodisintegration of the deuteron, the elastic pion-deuteron scattering and the elastic electron-deuteron scattering. The experimental situation of the polarization experiments for these reactions is briefly discussed in section 2. In section 3 the definitions of the deuteron polarization and the possibilities to determine the vector and tensor polarization are given. Present tensor polarization values and further improvements in this field are reported in section 4.

2. Deuteron polarization experiments

2.1 Deuteron photodisintegration

The motivation for recent measurements of the deuteron photodisintegration reaction $\gamma d \rightarrow pn$ at intermediate energies has been the possible existence of exotic states, such as dibaryons.

Due to the complicated spin structure of the deuteron photodisintegration reaction, 12 complex helicity amplitudes are required to characterize completely the $\gamma d \rightarrow pn$ process; hence 23 different observables have to be measured as a function of the photon energy and the proton c.m.s. angle. Only few experiments have been performed to investigate single polarization quantities like target asymmetry T (using a vector polarized deuteron target), beam asymmetry Σ (using linearly polarized photons) and recoil nucleon polarization P /1/.

Recently some data from double polarization experiments, performed with linearly polarized photons combined with a recoil nucleon polarization

measurement, has become available. Compared to the number of observables the number of experiments is still deplorably small, too small to allow reliable analyses.

It is unlikely that a complete measurement of the 23 observables will ever be made. However, the number of measured polarization observables can be increased in the near future with improved experimental techniques, e.g. tagged polarized photon beam and high vector polarized deuteron target. In addition, experiments with a tensor polarized deuteron target are possible (see section 4). Such measurements are now being planned /2/.

2.2 Elastic pion-deuteron scattering

There are two different spin observables measured for this reaction: the vector polarization T_{11} /3/ and the tensor polarization T_{20} of the recoil deuteron, which has been measured by two groups /4/ /5/. However, the experimental results for T_{20} are very different. Both groups used a double scattering technique where the tensor polarization of the recoiling deuteron in the π-d scattering reaction is determined from the cross section of the $d\,^3He \rightarrow p\,^4He$ reaction.

In view of the present discrepancy in the T_{20} data it is difficult to interpret the results. Therefore, an independent experiment – the π-d elastic scattering from a tensor polarized deuteron target – is planned to resolve this discrepancy /6/.

2.3 Electron-deuteron elastic scattering

Polarization experiments are expected to play a central role in studies of the electric form factors of the nucleons. For the deuteron three form factors are required to specify completely its electromagnetic current: The charge monopole F_c, the charge quadrupole F_Q and the magnetic dipole F_M. Measurements of the differential cross section have provided a sum of all three form factors and by means of a Rosenbluth separation F_M can be obtained. The separation of F_c and F_Q requires the measurement of at least one polarization observable. To achieve the separation of F_c and F_Q, work has been started at the MIT-Bates Linear Accelerator Center by measuring the recoil tensor polarization in electron-deuteron elastic scattering /7/. One main problem of this experiment is the low analysing efficiency of the polarimeter.

Contrary to this external beam experiment, the deuteron form factors could be studied by the use of polarized internal targets in an electron storage ring. However, a considerable increase of the atomic beam density (about a factor of 100) is needed to achieve high enough luminosities. New techniques are under development and a new generation of atomic beams is expected /8/.

A further possibility to separate F_c from F_Q can be obtained by elastic scattering of the electrons from a tensor polarized deuteron target. This experiment is beeing prepared in Bonn. The advantage of this type of experiment is, that 'conventional' polarized target techniques can be used. However, a large solid angle detection and of course a deuteron target with high tensor polarization are decisive for the success of the measurements/9/.

3. The deuteron as a polarized target

The deuteron as a target in scattering experiments introduces some additional problems compared to the proton. Fermi motion between the nucleons and final state interaction must be considered. In the case of polarized deuteron target experiments, the measurements are lengthy, as the polarization is relatively small (in comparison to the proton). Furthermore, the detection of the polarization signal and the polarization determination is difficult.

3.1 Definitions of the deuteron polarization

The orientation of the deuteron spin system (I=1) along an axis O_z can be described by the vector polarization

$$P = \langle I_z/I \rangle \quad (1)$$

and the tensor polarization or alignment, defined as

$$A = \langle 3I_z^2 - I(I+1) \rangle / I^2 \quad (2)$$

If a deuteron is subjected to a magnetic field H in the direction O_z, the Zeeman interaction gives a set of 3 sublevels. The polarization of the deuteron can be calculated from Eqs. (1) and (2) to be

$$P = (p_+ - p_0) + (p_0 - p_-) = p_+ - p_- \quad (3)$$

and

$$A = (p_+ - p_0) - (p_0 - p_-) = 1 - 3p_0 \quad (4)$$

where p_+, p_0 and p_- are the fraction of the spins in the magnetic sublevels $m = I_z = +1, 0$ and -1, respectively. The sum of p_m is normalized to 1. The vector polarization varies between -1 and +1, whereas A has values between -2 and +1.

3.2 Determination of the deuteron polarization

The polarization is normally measured by the nuclear magnetic resonance (NMR) method. If the deuteron spins are in thermal equilibrium (T.E.) with the solid lattice at a known temperature T in a known magnetic field H, the deuteron polarization is calculable using the Eq.

$$P = \frac{4\tanh\frac{\mu H}{2kT}}{3+\tanh^2\frac{\mu H}{2kT}} \quad (5)$$

where μ is the magnetic moment and k is the Boltzmann constant. The vector polarization P of the target is obtained by comparing the T.E. signal (P=0.05% at 1 K and 2.5T) with that of the enhanced signal (T.E. method). If we neglect the small quadrupole interaction, the tensor polarization A is given by

$$A = \frac{4\tanh^2\frac{\mu H}{2kT}}{3+\tanh^2\frac{\mu H}{2kT}} \quad (6)$$

From these definitions it follows that under thermal equilibrium A and P are related by

$$A = 2 - \sqrt{4 - 3P^2} \quad (7)$$

In practice, the tensor polarization A is calculated from the measured vector polarization P.

The shape of the deuteron magnetic resonance (DMR) signal offers another possibility to measure the polarization. In an external magnetic field the energies of the three magnetic sublevels can be written as

$$E_m = -h\nu_D m + h\nu_Q \left[(3\cos^2(\theta)-1)\right]\left[3m^2 - (I(I+1)\right]$$

where ν_D is the deuteron Larmor frequency and $\nu_Q = 1/8(eq\psi_{zz}/h)$, eq is the deuteron quadrupole moment and ψ_{zz} is the value of electrical field gradient along the principal axis of the field gradient tensor. θ is the angle between this axis and the direction of the magnetic field.

The quadrupole interaction shifts the levels depending on the angle between the magnetic field H and the electrical field gradient ψ_{zz}, as shown in fig. 1. This gives rise to two transitions. The corresponding lines are smeared out, since we do not have a single crystal. The two lines partially overlap each other, and the observed DMR signal is a superposition of them, as indicated in fig. 2. The two peaks correspond to $\theta=90°$, the pedestals to $\theta=0°$. The right peak and the left pedestal correspond to the m=+1 to m=0 transition with an intensity I_+, and the other peak and pedestal to the m=0 to m=-1 transition with an intensity I_-. At high polarization the intensities, which are proportional to the difference in the populations p_m of the corresponding states become different and the DMR signal shows an asymmetry. If we define $R = I_+/I_-$ and assume a Boltzman distribution among the sublevels the vector polarization is given by

$$P = (R^2-1)/(R^2+R+1) \quad (8)$$

and the tensor polarization by

$$A = (R^2 - 2R + 1)/(R^2+R+1) \quad (9)$$

as follows from the definitions.

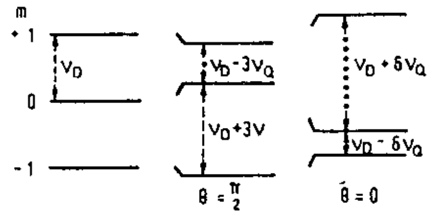

Fig. 1:
Energy level diagram of the deuteron spin system. The quadrupole interaction shifts the levels depending on the angle θ between the magnetic field H and the electrical field gradient ψ_{zz}

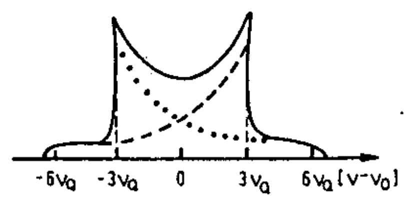

Fig. 2:
Theoretical deuteron line shape, which is the sum of the two possible transitions m=-1 to m=0 (dashed line) and m=0 to m=1 (dotted line). Some line broadening has been taken into account. Otherwise the peaks would tend to infinity.

An alternative method for the determination of the deuteron polarization can be used, if different kinds of nuclei in one material have an equal spin temperature. Consequently the temperature T in Eqs. (5) and (6) can be replaced by the spin temperature T_s, which can be calculated from the proton polarization measurements performed in the deuterated sample (normally the target materials are not fully deuterated).

It is obvious that in all cases very precise NMR-measurements must be done, to obtain the tensor polarization value with sufficient accuracy. An accuracy for P of ±5% is reported /10/ /11/, using the T.E. calibration method. This gives an accuracy for A of about ±10-±12%, depending on the degree of the polarization (A=12-25%). A T.E. signal of deuterated ammonia taken at 1 K and 2.5 T and the dynamically enhanced signal corresponding to 44% vector polarization and 15% tensor polarization are shown in fig. 3.

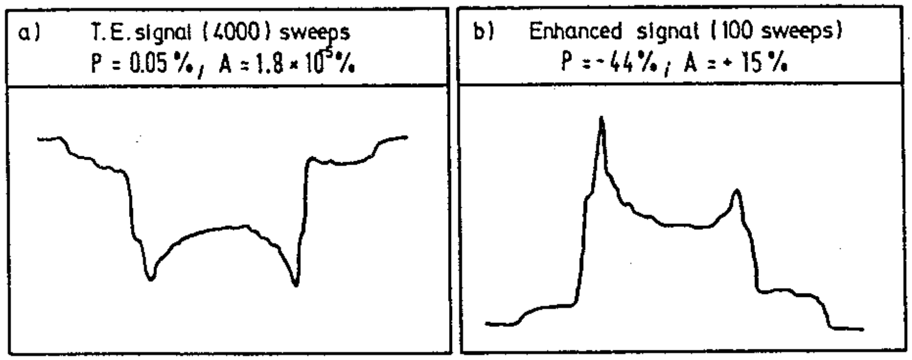

Fig. 3:
Deuteron magnetic resonance signals of deuterated ammonia.
(a) T.E. signal taken at 1 K and 2.5 T - plotted after 4000 sweeps.
(b) Dynamically enhanced signal taken at 200 mK - plotted after 100 sweeps. From the vector polarization of -44% the tensor polarization of 15% is calculated using eq. (7).
The small structures in the enhanced signal are typical for slowly frozen samples.

4. Values of the tensor polarization

In the normal case a vector polarized deuteron target is automatically tensor polarized. As can be seen from fig. 4, noticeable tensor polarization A demands high vector polarization P, which can be obtained in dilution refrigerators. Typical values for P are 35-45%, from which A is calculated to be 10-15%. Of course, higher tensor polarization values are desirable to perform experiments with good efficiency.

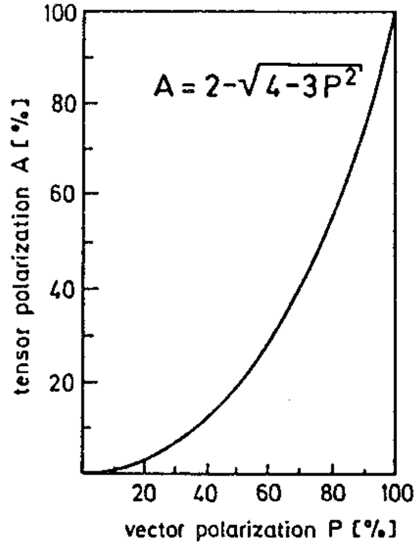

Fig. 4:
Tensor polarization versus vector polarization of the deuteron assuming a Boltzman distribution among the magnetic levels

The highest deuteron polarization was measured in ^{6}LiD in a dilution refrigerator at a very high magnetic field of 6.5 T /12/. The polarization results are shown in fig. 5. As a comparison the maximum value obtained in ND_3 is plotted. In both materials the radicals were produced by irradiation /13/. It is expected, that at higher magnetic fields (>2.5 T) an increase of the tensor polarization can also be obtained in the currently used target material ND_3. Measurement at 3.5 T are under investigation.

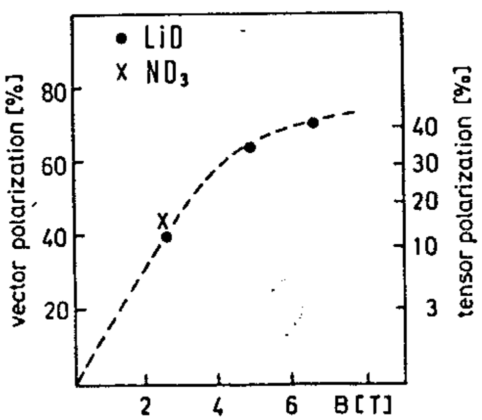

Fig. 5:
Polarization of LiD in dependence of the magnetic field. For comparison the maximum polarization of ND_3, obtained at 2.5 T is also shown.

Another method of enhancing the tensor polarization consists of disturbing the thermal equilibrium of the deuteron spin system. The inhomogeneous behaviour (see section 3.2) of the deuteron spin system makes it possible to 'burn holes' in the DMR line with a saturating RF field /14/. This always changes the population p_0 of the level m=0, thus changing $A=1-p_0$. From fig. 6 it can be seen that if the deuteron spin system saturated at a frequency $\nu = \nu_D - \delta$ this decreases p_0 of the corresponding deuterons, thus enhancing the line at $\nu = \nu_D + \delta$.

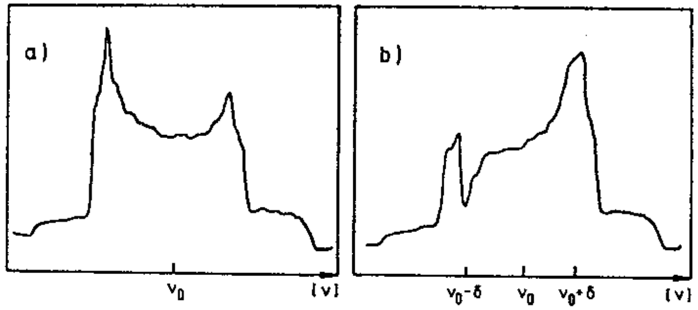

Fig. 6:
(a) DMR signal of deuterated ammonia corresponding to P=37%.
(b) This DMR signal was obtained from the original signal after application of a saturating RF field at a frequency $\nu_D - \delta$ (see text).

Of course, the tensor polarization cannot be changed independently of the vector polarization by this method. It is clear, that best results are obtained in a frozen spin target starting with a high deuteron polarization.

First measurements of the tensor polarization in ND_3 gave values up to 20%. This was achieved by irradiating the sample with a frequency-modulated RF field around the peak position on the right and around the pedestal position at the left side of the DMR signal (fig. 7).

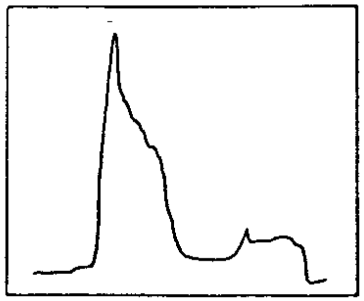

Fig. 7:
DMR signal of deuterated ammonia obtained after irradiating the sample with a frequency-modulated RF field (see text).

Contrary to these methods, which prepare a mixture of vector and tensor polarization, a pure tensor polarization of the deuteron spin system can also be obtained under special conditions. This could be demonstrated in samples, in which a strong thermal contact between a proton spin-spin interaction reservoir and the deuteron quadrupole interaction reservoir exist /15/. A DMR signal of pure tensor polarization is shown in fig. 8.

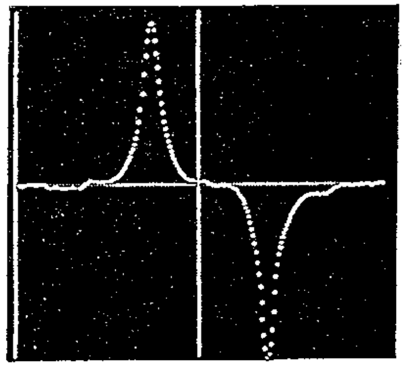

Fig. 8:
DMR-signal under 'RF field induced alignment': P = 0,
A = -0.20 (from Ref. 15).

5. Summary

In the last few years the study of polarization phenomena at intermediate energies has become of great interest. The motivation for recent deuteron polarization experiments in photon induced reactions as well as in the elastic pion-deuteron scattering has been the possible existence of exotic states.

Looking at polarized target experiments only measurements with a vector polarized deuteron target have been performed. These measurements became possible after the development of ^{3}He-refrigerators in the early seventies. In the meantime dilution refrigerators have become more and more the standard equipment of a polarized target system, as in dilution refrigerators the highest deuteron polarization values can be obtained. Measurements with a tensor polarized target are now being prepared.

Further developments in the field of polarized target materials allow improved experiments with intense beams such as electrons. Form factor measurements of the deuteron by means of electron scattering from a tensor polarized deuteron target are under preparation. It is expected that in addition to recoil tensor polarization measurements independent results are accessible. Furthermore, experiments at higher q^2 (of the virtual photon values) are planned, where the sensitivity to the differences between theoretical models becomes higher. Although in future there will be other possibilities for electron scattering experiments, such as internal targets, the polarized target will be with us for some time to come. This is certainly the case for experiments on photon induced reactions.

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