Nuclear Instruments and Methods in Physics Research A244 (1986) 574–576
North-Holland, Amsterdam

Letter to the Editor

TENSOR POLARIZATION OF DEUTERONS IN IRRADIATED ND_3

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Received 18 October 1985

We have dynamically polarized the deuterons in deuterated ammonia (ND_3) at a temperature of about 200 mK. Maximum vector polarizations of -0.44 ± 0.02 in a magnetic field of 2.5 T and -0.49 ± 0.04 at 3.5 T have been obtained. From these values the deuteron tensor polarization is calculated to be 0.15 ± 0.02 and 0.19 ± 0.03, respectively.

Significant improvements in the field of polarized target materials have taken place in the last five years [1]. After the initial discovery of dynamic nuclear polarization (DNP) in irradiated ammonia (NH_3) [2] as well as in irradiated deuterated ammonia (ND_3) [3], both materials are now used in high or intermediate energy physics experiments. Up to now only measurements with a vector polarized deuteron target have been performed [4]. Before the discovery of NH_3 and ND_3 as polarized target materials especially the relatively low polarization resistance to radiation damage of the available target materials did not allow electron scattering off polarized deuterons. Using ND_3 this situation has now changed and first measurements with a tensor polarized deuteron target have been performed [5].

This Letter reports on the experience with a tensor polarized ND_3 target during deuteron photodisintegration $\gamma d \to pn$ and ed elastic scattering experiments. The orientation of the deuteron spin system ($I = 1$) along an axis O_z can be described by the vector polarization $P(D) = \langle I_z/I \rangle$ and the tensor polarization or alignment, defined as $A(D) = \langle 3I_z^2 - I(I+1) \rangle / I^2$. If deuterons are subjected to a magnetic field B in the direction O_z, the Zeeman interaction gives a set of three sublevels. The polarization of the deuteron spin system can be calculated from the population numbers:

$$P(D) = (p_+ - p_0) + (p_0 - p_-) = p_+ - p_-,$$

and

$$A(D) = (p_+ - p_0) - (p_0 - p_-) = 1 - 3p_0,$$

where p_+, p_0 and p_- are the fractions of the spins in the magnetic sublevels $I_z = +1, 0$ and -1, respectively. The sum of p_m is normalized to 1. Assuming a Boltzmann distribution of the deuteron spin orientation with a spin temperature T_s, the population of the magnetic sublevels at DNP can be described by:

$$p_+ = c e^{+\mu B/kT_s},$$

$$p_0 = c,$$

$$p_- = c e^{-\mu B/kT_s},$$

where μ is the magnetic moment of the deuteron and k is the Boltzmann constant. Taking also into account that the quadrupole interaction is small with respect to the deuteron Zeeman splitting in a magnetic field of 2.5 T (24 kHz compared to 16.34 MHz [6]) $A(D)$ and $P(D)$ are related by

$$A(D) = 2 - \sqrt{4 - 3P(D)^2}. \qquad (1)$$

Thus the tensor polarization $A(D)$ can be calculated from the vector polarization $P(D)$, which is measured by standard nuclear magnetic resonance (NMR) techniques.

The experimental conditions were as follows: The radicals which are necessary for the DNP process are generated in the ND_3 samples by irradiation, using 20 MeV electrons from the injection linac of the Bonn synchrotron. During the irradiation the ND_3 samples are cooled in liquid argon at a temperature of about 90 K ("high temperature" irradiation). The accumulated flux is $\sim 10^{17}$ electrons/cm^2, corresponding to 2.5 h irradiation time. Detailed information about the ND_3 preparation for the DNP measurements can be found in ref. [7]. ND_3 samples of 6–10 cm^3 prepared in this way are cooled to about 200 mK in a $^3He/^4He$ dilution refrigerator [8]. DNP is achieved with microwave irradiation close to 70 GHz in a magnetic field of 2.5 T and about 98 GHz at 3.5 T. The state of the D spin system is monitored by its magnetic resonance absorption signal (DMR signal). The vector polarization $P(D)$ is obtained by comparing the thermal equilibrium (TE)

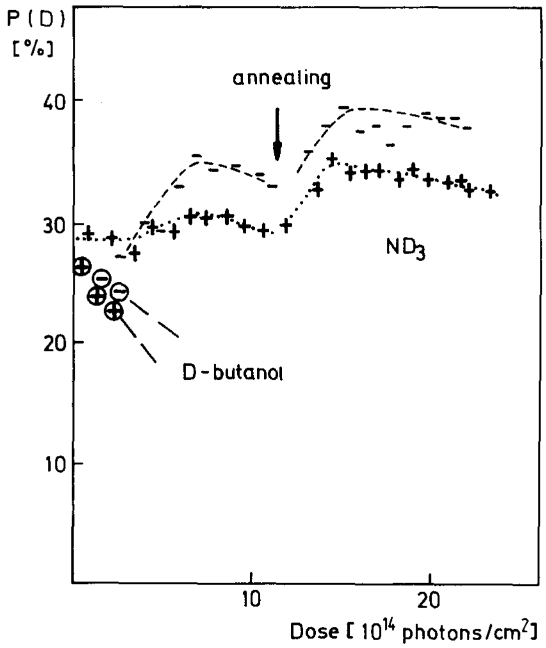

Fig. 1. Deuteron vector polarization of "high temperature" irradiated ND_3 as a function of the accumulated radiation dose, obtained at low temperatures (~ 250 mK) in a photodisintegration experiment $\gamma d \to pn$. The measurement shows the increase in polarization of ND_3 (positive "+" and negative "−" polarization), whereas the polarization of D-butanol (circles) decreases immediately with the radiation. The subsequent decrease in polarization of ND_3 is much slower than that of D-butanol. Lines are drawn to guide the eye.

signal ($P(\mathrm{D}) = 5.4 \times 10^{-4}$ at 1 K and 2.5 T) with that of the dynamically enhanced DMR signal (TE method) [9]. The tensor polarization $A(\mathrm{D})$ is then calculated using eq. (1).

Typical vector polarization values obtained in "high temperature" irradiated ND_3 at 2.5 T and at about 200 mK are +0.31 and −0.29, corresponding to tensor polarizations of 0.073 and 0.064, respectively. To achieve higher polarization values a further irradiation at low temperature (reirradiation) performed in the polarized target refrigerator is necessary. In our experiment with photon beams the optimum reirradiation dose is 8×10^{14} equivalent quanta/s. As experience shows, an annealing process of the target material at a temperature of ~ 80 K followed again by a reirradiation gives the best polarization values. A polarization history obtained during a photodisintegration experiment $\gamma d \to pn$ is shown in fig. 1. Without photon beam heating a maximum vector polarization of −0.44 corresponding to a tensor polarization of 0.15 could be obtained.

A further increase of the tensor polarization could be achieved during an electron deuteron scattering experiment [5] by using a 3.5 T superconducting magnet. At this field a maximum tensor polarization of 0.19 was measured at about 200 mK. Due to the electron beam heating (0.2–0.4 nA electron beam current was tolerated) the tensor polarization was typically in the range of 0.15–0.17. A thermal equilibrium signal and a dynamically enhanced DMR signal corresponding to −0.46 vector polarization and 0.165 tensor polarization are shown in fig. 2. The sequence of the ND_3 target preparation is the same as in the case of the photodisintegration experiment ("high temperature" irradiation with 20 MeV electrons at 90 K – reirradiation at low temperature (1 K) – annealing at about 80 K – reirradiation). The optimum reirradiation dose was found by detailed polarization studies [10] made at 1 K and 2.5 T (fig. 3).

The increase of the deuteron polarization in ND_3 during the irradiation at low temperature is not observed for the alcohol materials (see fig. 1) and neither

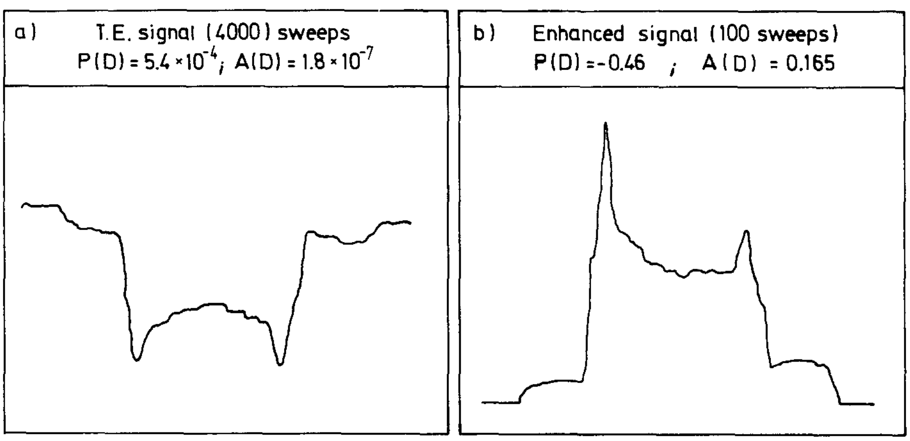

Fig. 2. DMR-signals of deuterated ammonia. (a) TE signal – plotted after 4000 sweeps. (b) Dynamically enhanced signal taken at about 250 mK – plotted after 100 sweeps. From the vector polarization of −0.46 the tensor polarization of 0.165 is calculated using eq. (1). The small structures in the enhanced signal are typical for polycristalline ND_3 samples [13].

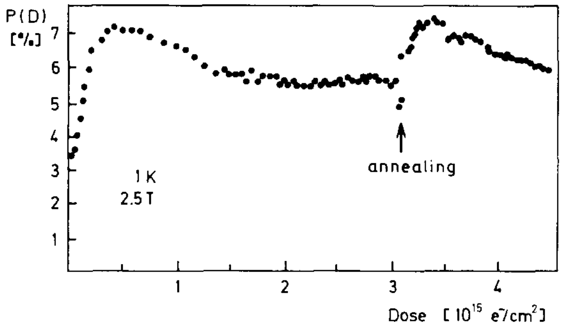

Fig. 3. Polarization behaviour of high temperature irradiated ND_3 during additional low temperature irradiation with electrons measured at 1 K and 2.5 T. As can be seen the best polarization results are obtained after an annealing process of the target material at about 80 K, followed by a reirradiation dose of 4×10^{14} e^-/cm^2.

for NH_3 [1]. In the alcohol materials the prompt decrease of the polarization at irradiation is explained by the production of new radicals which are not useful for the DNP process [12]. We noted that in ND_3 the optimum microwave frequency (which gives the highest polarization value) shifted as the accumulated radiation dose increased. At the end of the photodisintegration experiment the separation of the polarization maxima was 210 MHz, compared to 120 MHz at the beginning ("high temperature" irradiated ND_3). Also the much shorter polarization buildup time indicated that a great amount of additional radicals is generated during the low temperature irradiation. These radicals – as we know from annealing procedures [10] – are different from the $\dot{N}D_2$ radicals which are mainly produced at high temperature irradiation [13]. Up to now systematic studies of the prevailing DNP polarization mechanism have not been performed in low temperature reirradiated samples. As in the case of high temperature irradiated material a knowledge of the EPR spectrum would be very helpful [13]. From such a measurement we expect important information to explain the influence of the annealing process which leads to the highest polarization value.

We conclude that irradiated ND_3 improves significantly the experimental situation for polarized deuteron experiments. Especially experiments with electron beams are possible and a first measurement with a tensor polarized deuteron target has been performed. Using higher magnetic fields a further increase of the tensor (vector) polarization of the deuterons in irradiated ND_3 is expected.

Acknowledgment

We would like to thank B. Boden, R. Dostert, G. Kroesen,, M. Leenen, W. Mehnert, R. Sauerwein and H.H. Schmitz for their help during the experiments, and the Bundesministerium für Forschung und Technologie for financial support.

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