RECENT DEVELOPMENTS IN POLARIZED SOLID DEUTERON TARGETS

ST. GOERTZ, J. HARMSEN, J. HECKMANN, W. MEYER,
E. RADTKE, G. REICHERZ

Institut für Experimentalphysik der Ruhr-Universität Bochum, Universitätsstr. 150, 44780 Bochum, Germany,
E-mail: meyer@ep1.ruhr-uni-bochum.de

The development, in the early 1960s, of the dynamic nuclear polarization scheme in solid diamagnetic materials, doped with paramagnetic radicals, led to the use of solid polarized H and D targets in numerous nuclear and particle physics experiments. Since then steady progress has been made in all contributing sub-systems so that proton polarization values around 90 % and deuteron polarization values between 30 % and 50 % have been routinely achieved in various set-ups. Many experiments with reasonably high luminosities have taken advantage of these developments and many more are being planned, especially with electromagnetic probes. However higher deuteron polarization values are wanted.

1. Introduction

The advent of solid polarized targets in the early 1960s opened up a new era in the study of particle interactions. Meanwhile quantum chromodynamics (QCD) has led to a theoretical description of the strong interaction in terms of the fundamental constituents, quarks and gluons. The Standard Model, the strong interaction theory of QCD, tells that the valence quarks and the sea quarks are spin-1/2 objects bound by gluons which are spin-1 objects. The presence of particles with spin inside the hadrons has moved the question of spin phenomena to the forefront; at SLAC and at CERN, polarized solid state proton and deuteron (neutron) targets have been operated in an electron and muon beam, respectively, for deep inelastic measurements of the spin structure of the nucleon. Nowadays the COMPASS experiment at CERN is focussed on the measurement of the gluon spin contribution to the nucleon spin.

However, up to now the interaction of hadrons at lower energies cannot be described by perturbative calculations and here the understanding of the saturation of the color forces is still incomplete. The fundamental

quark-gluon degrees of freedom in QCD are replaced by so-called effective degrees of freedom of nucleons and mesons. These underlie effective field theories, which include the symmetry of QCD and describe to some extent in phenomenological models the internal structure of nucleons and mesons.

In the energy range up to several GeV, a rich program is in progress at the electron beam facilities at the University of Bonn, the University of Mainz, MIT-Bates and Thomas Jefferson National Accelerator Facility (TJNAF). In addition polarization experiments are prepared at LEGS (Brookhaven), GRAAL (Grenoble) and SPRING8 (Osaka). From the list of proposed experiments at these facilities, it is clear that measurements involving spin degrees of freedom are becoming increasingly common, perhaps even prevalent. Experiments are now underway that address outstanding fundamental questions in nucleon and nuclear structure:

- Measurements of the Gerasimov-Drell-Hearn sum on the proton and neutron.
- Measurements of the charge distribution or electric form factor G_E^n of the neutron.

In this report the major pieces of equipment necessary to realize an operational polarized solid target are listed below. In Section 3 the importance of the choice of an appropriate solid polarized target material is summarized. Especially new polarization results for ^{6}LiD and D-Butanol, prepared by irradiation techniques, are given.

2. Polarized Target Equipment

The starting-point of any general discussion of polarized solid targets is the magnetic moment of each of the particles of interest, i.e. the electron and proton or deuteron. A polarized solid target can be assumed to be an ensemble of such particles placed in a very high magnetic field and cooled to very low temperature. Despite of these extreme conditions (i.e. 2.5 T and 0.5 K) the thermal equilibrium polarization of the proton or deuteron is very small. However, electrons with their much higher magnetic moment ($\mu_e = 660\mu_p$) are highly polarized close to -100% at the values given above. Finally the technique of dynamic nuclear polarization (DNP) allows very high nucleon polarizations to be obtained. The basic idea, to obtain a high polarization $P_I =< I_Z > /I$ of nuclear spins, consists of using a microwave field in a high magnetic field, to transfer the polarization $P_S =< S_Z/S >\approx -100\%$ of some electron spins to these nuclei. The

electron spins are added to the target material by various doping methods. Figure 1 shows a schematic of a generic polarized target, showing

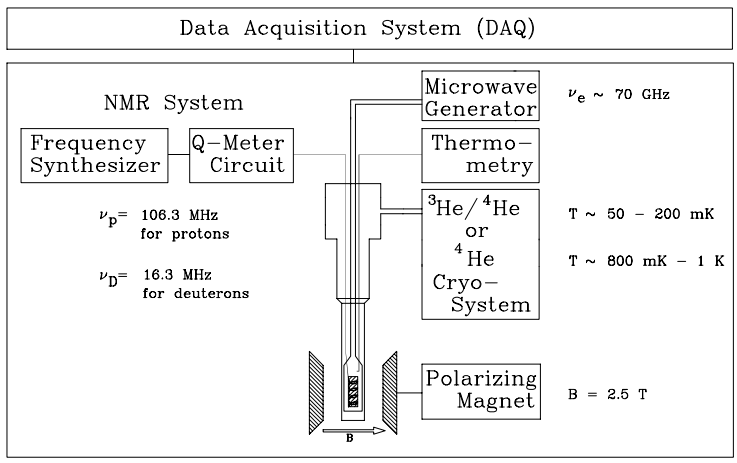

Figure 1. A generic polarized target showing the major sub-systems and typical operational parameters. Not shown are the standard vacuum and Roots pumping systems

all the necessary subsystems. In addition to the low temperature and high magnetic field mentioned above a nuclear magnetic resonance (NMR) system measures the degree of polarization. Not shown are the complicated vacuum and pumping systems and instrumentation.

From the 1960s to the end of the 1970s important progress has been made in the field of cryogenics and magnet technology. By the development of ^{3}He/^{4}He dilution refrigerators and the use of superconducting polarizing magnets the B/T value could be increased from 2 to 100 Tesla/Kelvin. Polarization values of nearly 100% for protons and up to 50% for deuterons have been obtained in spezial prepared target materials. For more details see Refs. [1,2]

3. Target Materials

Important criteria for the choice of a material suitable for particle physics experiments are (a) the degree of polarization P and (b) the dilution factor f, which is the ratio of free polarizable nucleons to the total number of nucleons in the target material.

The counting rate in experiments from a polarized target a polarization transverse (up↑) to the production plane is $N_\uparrow \propto \sigma(1+PA)$ where σ is the differential cross section. A, the asymmetry of interest, can be obtained in the case of a spin $\frac{1}{2}$ target particle from the counting rate asymmetry

$$\varepsilon = \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} \tag{1}$$

by

$$A = \frac{1}{P} \cdot \varepsilon \tag{2}$$

If the target (as seen by the beam) contains, in addition to the fraction f_A of polarized nuclei, a fraction (1-f_A) of unpolarized material, the asymmetry A has to be corrected by the dilution factor f i.e.

$$f = \frac{f_A \sigma}{(1-f_A)\sigma_0 + f_A \sigma} \tag{3}$$

where σ_0 is the average cross section for the unpolarized atoms. Then we get

$$A = \frac{1}{f} \cdot \frac{1}{P} \cdot \varepsilon \tag{4}$$

Since $N\uparrow + N\downarrow$ is proportional to the measuring time, the beamtime t to reach a certain statistical error ΔA shows the following dependency on material properties

$$t^{-1} \propto n_t \; (f \cdot P)^2 \qquad , \tag{5}$$

where n_t is the number of target particles per cm^2. This expression shows the importance of the values P and f, which have to be optimized.

Further important requirements for the use of a polarized target material are: (a) simple target preparation and ease of handling;(b) short polarization build-up time; (c) good polarization resistance against radiation damage, with the possibility to repair the radiation damage and (d) presence of other polarizeable nuclei.

$^6LiD, NH_3$ and ND_3 have the highest dilution factors f of 0.5, 0.18 and 0.3 respectively. In all three materials the paramagnetic radicals have been introduced by irradiation methods. They possess the highest polarization resistance against radiation damage. The radiation dose ϕ_0 which reduces the polarization by e^{-1} of its starting value is higher than 10^{16} particles/cm^2 [3,4]. Therefore they are used in scattering experiments with electron beams, where a luminosity in the order of $10^{35} s^{-1} \cdot cm^{-2}$ have been

achieved. However, the polarized spectator nuclei like lithium and nitrogen are polarized, so that the physics results have to be corrected accordingly.

For present day polarization experiments with low intensity particle beams (e.g. tagged photon beams or muon beams with $\approx 10^7$ particles/cm^2), the radiation damage resistance of the standard alcohol butanol ($\phi_0 = 10^{14} particles/cm^2$) is sufficient. Therefore this material - chemically doped with radicals like porphyrexide, EHBA or TEMPO - with its spinless spectator nuclei C and O is normally used. Nevertheless, there is further work going on to develop target materials with spinless spectator nuclei but with a higher dilution factor than that of the alcohols [5]. On the other hand, polarizable materials, which are solid and can be handled at room temperature for at least several hours, could provide new experimental possibilities in particle physics experiments along with their obvious practical advantages in the loading of refrigerators.

3.1. *Lithium Deuterides*

^{6}LiD is of special interest as a polarized neutron target with its high dilution factor $f \simeq 0.5$ for neutrons. Compared to other deuterated target materials the deuteron and ^{6}Li thermal equilibrium (TE) polarization signal is much easier to detect, because there is no quadrupole splitting of the energy levels in these spin-1 systems due to the vanishing electric field gradient in the face-centered, cubic lattice structure. This circumstance allows an accurate measurement of both the deuteron and the ^{6}Li polarization via the TE method. Investigations demonstrate a high polarization resistance against radiation damage [6,4].

Pioneering work to prepare ^{7}LiH, ^{6}LiH, and ^{6}LiD for the DNP process has been done by different groups at Saclay [7,8,9,10]. Systematic studies of the optimum preparation method including the behavior of the materials under an intense electron beam have been also performed in Bonn [6].

At room temperature the lithium compounds are in their solid state phase, and the paramagnetic impurities (so-called F-centers) are introduced by irradiation. In contrast to the ammonia targets, the temperature during irradiation has to be between 180 and 190 K. EPR studies of the F-center concentration showed that it is not the production efficiency, which defines the rather narrow temperature window, although it seems to be maximum around these temperatures. In the framework of the most recent study of ^{6}LiD for the CERN COMPASS experiment [11] the electron spin resonance (EPR) of these paramagnetic centers was investigated under the condition

of partial and complete saturation [5].

Meanwhile the COMPASS experiment with ^{6}LiD as target material ($\approx 0.5 ltr$) has started to measure the gluon spin contribution to the nucleon spin. The target material was prepared for DNP by irradiation at a temperature of $(190 \pm 2)\,K$ with a total dose of 10^{17} electrons/cm^2. The irradiation was performed at the $20\,MeV$ Bonn injection linac. So far maximum polarization values of $(+54 \pm 2)\,\%$ and $(-47 \pm 2)\,\%$ have been reached. The polarization build-up curves as measured with 5 NMR coils in each target cell are shown in figure 2. Similar polarization results in a small sample of ^{6}LiD are reported in Ref. [12].

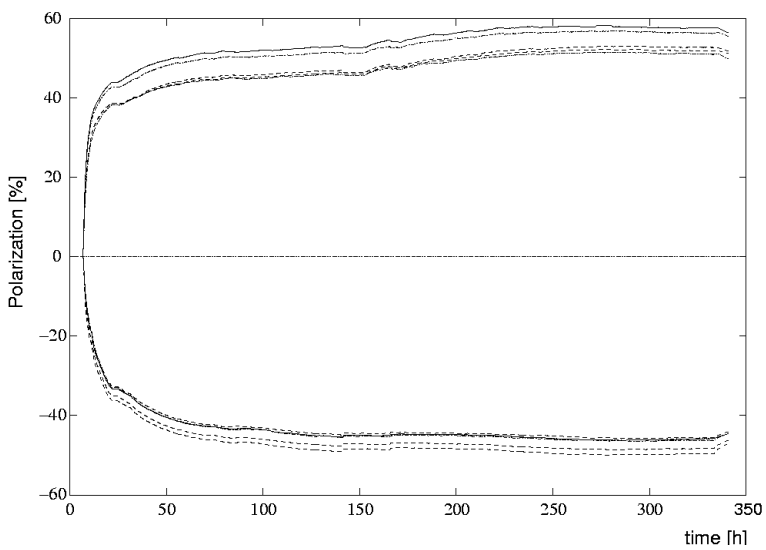

Figure 2. Polarization build-up of the deuteron polarization in ^{6}LiD as measured with 5 NMR coils in each target section of the COMPASS target operated at CERN.

3.2. *Carbohydrate Compounds*

Although ^{6}LiD delivers the highest overall polarization of all the established deuterated target materials at given magnetic field and temperature conditions (e.g. more than 50 % at $2.5\,T$ in a ^{3}He/^{4}He dilution refrigerator) it is best suited only for those experiments, in which the highly polarized proton and neutron within the ^{6}Li nucleus can be regarded as quasi free.

A large step forward towards a highly polarized deuteron (neutron) target for physics experiments at intermediate energies was recently done by the extension of the radiation doping method to the carbohydrate compounds, which are free of any polarized background. Using an electron beam in the MeV range the application of a total dose of some $10^{15}\,e^-/cm^2$ at liquid argon temperature is sufficient to create paramagnetic defects in the respective CH_2-chains with a concentration high enough for the DNP process to function. Systematic EPR studies in a variety of different carbohydrate compounds have shown that these defects – independent of the particular material – consist in a proton or deuteron vacancy along the chain, i.e. the paramagnetic center can be identified with the alkyl radical ($-\dot{C}H-$). In the special case of the normal (straight chained) alcohols like 1-butanol – frozen in glassy beads – the vacancy is most likely located at the hydroxyl carbon of the molecule having the supposed structure $-\dot{C}H-OH$ [5].

In contrast to the commonly used chemical dopants the radiation induced radicals possess a much smaller g-factor anisotropy leading to a considerably narrower EPR line at the high magnetic fields of a polarization experiment. This circumstance is advantageous in two respects. Firstly it is immediately clear from the spin temperature theory that a narrower EPR line enables the creation of higher inverse spin temperatures and thus of higher nuclear polarizations. Secondly the magnetic field may be increased to higher values than in the case of chemically doped butanol, in which the linearly increasing EPR line width eventually prevents the existence of a unique spin temperature throughout the electron system. Experimentally the maximum deuteron polarization in chemically doped alcohols and diols at the temperatures of a $^3He/^4He$ dilution refrigerator was measured to be maximum around $2.5\,T$ followed by a rapid decrease with increasing magnetic field [13,14]. Recent measurements are shown in figure 3. In contrast, the maximum deuteron polarization in irradiated butanol increases with increasing magnetic field at least
up to $5\,T$ (see figure 3). Although systematic investigations concerning the optimum irradiation dose have not yet been done, deuteron polarizations of more than 50 % at $2.5\,T$ and more than 70 % at $5\,T$ have already been achieved. Besides the alcohols first studies of radiation doped polyethylene are under way, which show that in these substances not only radicals of the alkyl type can be created but also other types, some of which being stable at room temperature for weeks [5,15]. Together with first successful attempts to polarize radiation doped perdeuterated polyethylene [16] the techniques of radiation doping appears to open new horizons in prepar-

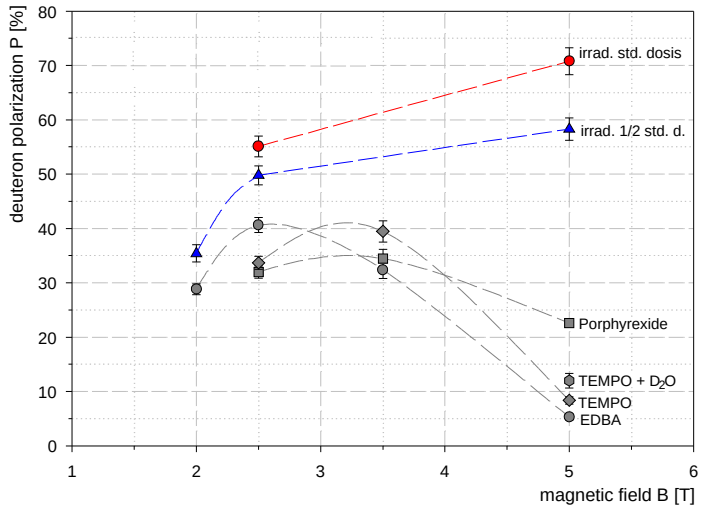

Figure 3. Deuteron polarization in dependence of the magnetic field for various chemically and radiation doped D-butanol samples measured in a ^{3}He/^{4}He dilution refrigerator.

ing polarized target materials with much higher performance for particle physics experiments at intermediate particle energies.

4. Summary

The use of solid polarized targets in nuclear and particle physics experiments since the early 1960s has led to better understanding of the role of spin in many particle interactions. Permanent developments in the field of cryogenics and magnet technology and important progress in producing better polarized target materials have opened up new experimental possibilities and allowed a choice of approaches to a particular physics problem.

The parallel development of polarized particle beams has enhanced this ability to study some of the outstanding and fundamental problems of particle physics. The Bjorken sum rule in deep inelastic lepton scattering and the Gerasimov-Drell-Hearn sum-rule were formulated in 1966, but they have only been tested through experiments in the 1990s, using state-of-the-art polarized targets. Radiation doping for the DNP process, which is already done very successfully in ^{6}LiD, NH_3 and ND_3, gave deuteron polarization values in D-Butanol up to 70 % at $5\,T$. Further developments in the field of polarized solid targets materials are still on the horizon which will further

improve the quality of the data in particle physics experiments as well as will enable new types of experiments.

References

1. D.G. Crabb and W. Meyer, *Annu. Rev. Nucl. Part. Sci* 47 (1997) 67
2. St. Goertz, W. Meyer, and G. Reicherz to be published in *Prog. Nucl. Part. Phys.* Springer Verlag (2002)
3. D.G. Crabb et al., *Phys. Rev. Lett.* 65 (1990) 3241
4. S. Bültmann et al., *Nucl. Inst. and Meth.* A 425 (1999) 23
5. St. Goertz, Habilitation thesis, University of Bochum, Germany (2002)
6. St. Goertz et al., *Nucl. Instr. and Meth.* 356 (1995) 20
7. Y. Roinel et al., *J. de Physique* 39 (1978) 1097
8. A. Abragam et al., *Phys. Lett.* 41 (1980) 309
9. V. Bouffard et al., *Rev. Phys. Appl.* 13 (1978) 304
10. P. Chaumette et al., *Proc. 8th Int. Symp. High Energy Spin Physics*, ed. K.J. Heller, *AIP* No. 187 (1988) 1275
11. A. Meier, Ph.D. thesis, University of Bochum, Germany (2001)
12. B. van den Brandt et al., *Proc. 9th Int. Symp. High Energy Spin Physics,* eds. W. Meyer, E. Steffens, W. Thiel, Vol. 2, Springer Verlag (1991) 320
13. S. Trentalange et al., *in Ref.* [12] p. 325
14. J. Harmsen, Ph.D. thesis, University of Bochum, Germany (2002)
15. St. Goertz, to be published
16. N. Doushita et al., *Proc. Int. Workshop Polarized Sources and Targets,* eds. A. Gute, S. Lorenz, E. Steffens, *Univ. of Erlangen-Nürnberg* (1999) p. 344