Zeitschrift: Helvetica Physica Acta
Band: 59 (1986)
Heft: 4

Artikel: Review of operational polarized targets
Autor: Meyer, W.
DOI: https://doi.org/10.5169/seals-115747

Helvetica Physica Acta
Vol. 59, 1986 728-736

018-0238/86/040728-09$1.50+0.20/0

REVIEW OF OPERATIONAL POLARIZED TARGETS

W. Meyer

Physikalisches Institut der Universität Bonn
Bonn, F.R. Germany

ABSTRACT

The current situation of the polarized targets for their use in external particle beams is reviewed. This includes some general remarks on polarized target experiments, a brief description of the dynamic polarization principle and a review of the present-day target instrumentation: target materials, magnetic fields, refrigerator systems and target size, microwaves systems and polarization measurements. Finally two recent experiments are briefly discussed.

1. Introduction

The importance of spin in 'high energy' (some hundred MeV) nuclear reactions was known in the early 1950s. However, extensive experimental studies of spin effects in high or intermediate energy particle interactions have only been available for about 20 years. One reason for this delay is that such experiments were difficult or impossible to perform before polarized targets and polarized beams came into operation. If we are able to measure the spins of the incoming and outgoing particles as well as the target nucleon in a certain reaction the corresponding observables give a great deal of information which is totally inaccessible to the spin-averaged cross section measurements. That is, many of the most interesting and important features involved with a nucleon interaction can only be discovered by directly measuring the spin dependence. This requires the use of polarized targets, polarized beams and (or) the final-state polarizations.

The study of polarization phenomena in high energy physics using polarized targets began with the development of polarized solid-state proton targets at Saclay and Berkeley in the early 1960's /1/. Since then steady progress in this field has been made. The majority of these targets are used in quite an appreciable number of particle experiments in order to study spin effects up to the highest energies. These experiments are performed with primary beams such as protons, photons and electrons as well as with secondary beams such as pions, kaons and muons. Up to now neutron scattering off polarized targets is mostly performed at low energies. It is impossible to list all the experiments here, but they can be classified into one of the two categories given below:

i) study of the dynamics of interactions (spin parameter)
ii) determination of quantum numbers (spin and parity).

Recent surveys of the polarization phenomena and results are given in the proceedings of several conferences on polarized beams and polarized targets /2, 3, 4/. However, due to the complexity of the materials in which the particles of interest for such experiments - the proton or the deuteron - have been polarized, it was not possible to carry out all of the proposed experiments with sufficient accuracy. This is particularly true in the domain of the electromagnetic interactions. Fortunately, significant improvements have taken place both in polarized target materials and instrumentation during the last five years, which will probably extend the range of practical applicability of the polarized solid-state targets.

2. Polarized Solid-State Targets

The starting point of any general discussion of polarized targets is the magnetic moment of the particle of interest - in the case of particle experiments - the proton or the deuteron. A polarized target can be assumed to be an ensemble of such particles placed in a high magnetic field and cooled to a low temperature. Unfortunately the magnetic moment of the proton is small, and that of the deuteron is even smaller. As a consequence the polarization obtained in this way is very small. A simple calculation, using the Boltzmann equation gives 0.5% for protons and 0.1% for deuterons in a magnetic field of 2.5 T and at a temperature of 0.5 K. Of course, these polarization values are not very useful for experiments. However, the technique of dynamic nuclear polarization (DNP) - developed in 1953 for metals (Overhauser effect) and in 1958 for solid insulators (solid effect) /1/ - allows very high nuclear polarization to be obtained.

A simplified description of the DNP process can be given as follows. A suitable solid target material with a high concentration of H or D atoms is doped with paramagnetic radicals which provide unpaired electron spins. As the magnetic moment of the electron is very much larger than that of the nucleon the electron polarization is very high (99% at 2.5 T and 0.5 K). The dipole-dipole interaction between the nucleon and electron spins leads to hyperfine splitting. Application of microwaves at a frequency very close to the electron spin resonance frequency induces a double spin flip of an electron-nucleus pair followed by a relaxation back flip of the electron spin. The DNP works because the electron spins relax much faster than the proton spins, which results in a greatly enhanced proton polarization. The nucleon polarization can be directed either parallel or antiparallel to the applied magnetic field by using slightly different values of frequency. No other parameter which can influence the experiment must be changed. This is a very important feature of the DNP, as systematic errors are reduced to a very low level. It has turned out that the DNP is a very practical technique and it is used in almost all polarized targets.

The main problem with DNP is finding a suitable combination of hydrogenous material and paramagnetic radicals (electrons). Suitable means, that the relaxation time of the electron spins is small (msec) and that of the nucleons is long (min.). The ideal target material, hydrogen, is at low temperature in the para-state with spin zero and hence unpolarizable.

The model of the resolved solid effect /5/ describes well the situation in the first successful polarized target material $La_2Mg_3(NO_3)_{12}\ 24\ H_2O$ (LMN), a crystalline salt doped with neodymium, which provides the unpaired electron spins. For several years, from 1962 - 1967, LMN was the main proton target material for experiments.

In the late sixties LMN was replaced by organic substances, alcohols (butanol) chemically doped with free radicals (porphyrexide), and diols (propanediol) doped with CR^V-complexes. In amorphous materials, such as these frozen alcohols and diols, the process of dynamic polarization is somewhat different from the simple scheme of the resolved solid-state effect and is described by the equal spin temperature theory (EST) /6/.

The obvious advantage of the alcohol and diol materials for the scattering experiments is the improved hydrogen content. For alcohols with about 14% hydrogen, proton polarizations of 85% are obtainable, while the corresponding figures for the diols are 11% and nearly 100%, respectively. These polarization values were only achieved after a considerable improvement in cryogenics: the development of dilution refrigerators /7/. It also turned out that the polarization in alcohol materials is by about a factor of 100 less sensitive to radiation damage than that of LMN. The characteristic integrated flux of minimum ionising particles, which causes the polarization to decrease by 1/e is of the order of 5 x 10^{14} cm^{-2} for butanol. The introduction of these materials opened a new range of possible experiments. In particular, experiments with electron and photon beams became feasible.

With the development of ^3He-refrigerators and dilution refrigerators, scattering experiments from polarized deuterons (neutrons) could also be studied. It became apparent that the use of dilution refrigerators is even more important for polarized deuteron targets than for proton targets. A deuteron polarization between 25% and 45% can be obtained if deuterated alcohol (diol) materials are used. Of course a higher deuteron polarization is desirable. This is especially valid, when experiments with a tensor polarized deuteron target are required /8/. In the late seventies nearly all polarized targets (fig. 1) used in the field of particle physics operated with the DNP in an alcohol or diol material at a temperature below 0.5 K and in a magnetic field of 2.5 T. At that time it became clear that further improvement for polarized target experiments could only be obtained by new target materials.

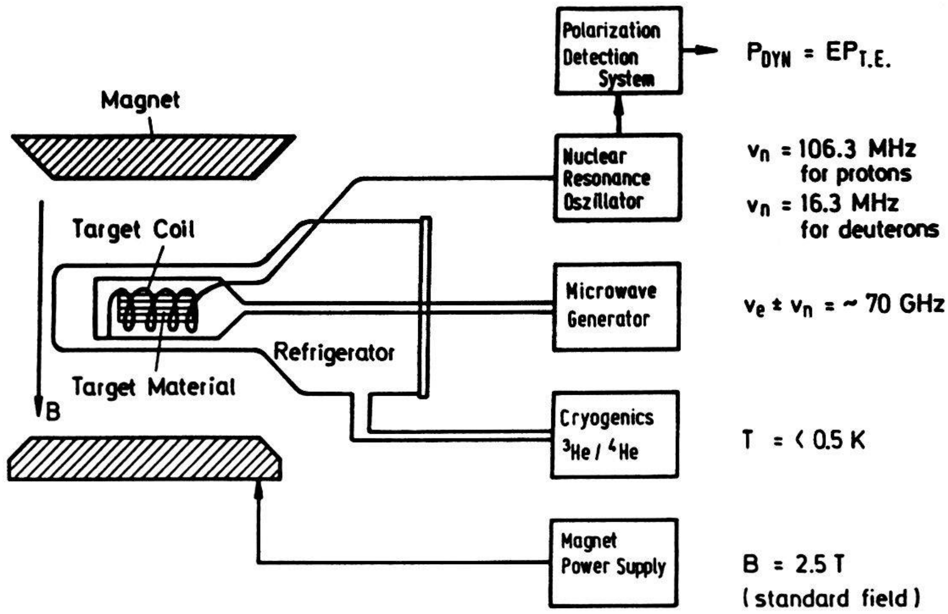

Fig. 1: Schematic diagram of the main components of a polarized solid-state target.

3. New Target Materials

For reasons known to everyone at this workshop, there has been a strong need for more pure and radiation-resistant polarized target materials. Improvements in the target material cannot only save money, an important point since particle physics experiments are expensive, but even more important, they can enable new types of scattering experiments which are presently unfeasible.

In the last years progress in the development of polarized targets has been made by investigating such target materials /9, 10, 11/. The main effort was put on ammonia. Ammonia (NH_3) contains 17.6% (by weight) of polarizable free hydrogen compared to 14.6% in butanol. The content of polarizable free deuterons in d-ammonia (ND_3) is 30% compared to 23.8% in d-butanol and 19% in d-propanediol. In addition, ammonia has a relatively high solid density (approximately the same as the alcohols) and it is not too difficult to handle. It has the important advantage that no changes in the standard target equipment are required.

In 1979 a breakthrough occured when it was discovered that high proton polarization ($>$ 90%) in NH_3 could be obtained using paramagnetic radicals, generated by irradiation /12/. Some time later it was also demonstrated that this preparation technique works in ND_3 /13/. As experience shows, the ND_3 target preparation for the DNP by irradiation is more difficult compared to that of NH_3. Decisive is the temperature at which the radicals are produced. Highest deuteron polarization values (up to 49%) can only be achieved by means of 'low temperature' irradiation (performed in the polarized target refrigerator) /14/. However, the biggest advantage of ammonia is its extremely good polarization resistance to radiation damage which is mainly a result of the radiation induced radicals. It turns out that the depolarizing dose in ammonia is by an order of magnitude higher compared with that in butanol (fig. 2). It is now clear that the development of ammonia as a practical target material has led to a big improvement on the quality of data obtainable from some current particle physics experiments.

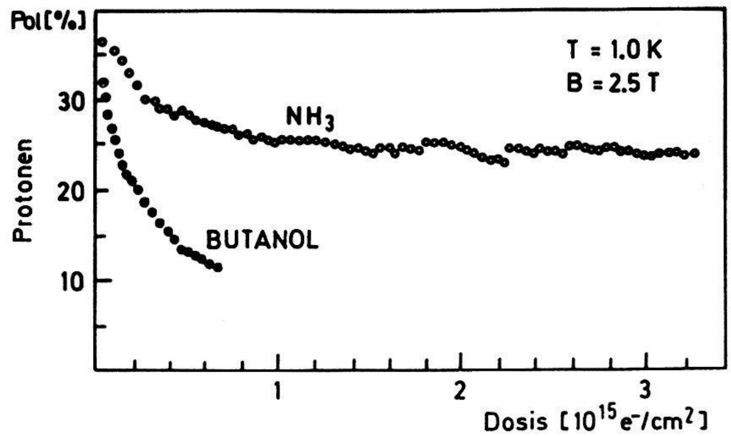

Fig. 2: Polarization behaviour of the protons in NH_3 and butanol in dependence of the electron irradiation dose at 1 K and 2.5 T.

Other new materials with high polarizable hydrogen content such as borohydrides NH_3BH_3 (19.5% hydrogen) and NH_4BH_4 (24.5% hydrogen) and lithium hydride (^7LiH) have also been investigated. At present, chemical doping of the pure borohydrides does not seem to be possible. However, very good results (~ 80% polarization) have been obtained with chemically doped mixtures of borohydrides and organic amines /15/. These mixtures have a hydrogen content very similar to ammonia and they could be better materials to use in certain circumstances, particularly if fast reversal of the polarization is a critical experimental factor. It should be noted, however, that the boron (^{11}B) nuclei are also polarized in an analogous way to the nitrogen nuclei (^{14}N) in ammonia.

Very high deuteron vector polarization (70%) was measured in irradiated ^6LiD /16/. However, the sample size was very small and the result quoted was obtained at a field of 6.5 T. Work is now being carried out to overcome the practical difficulties related to the manufacture of the material and the irradiation techniques /17/. If it is assumed, from the point of view of the particle experiments, that the ^6Li looks like a polarized deuteron weakly bound to an alpha particle (the magnetic moment of ^6Li is just 4% smaller than that of the deuteron and has the same spin 1), then the total polarizable nucleon content is 50%. This makes ^6LiD an attractive target for some types of experiments. In table I a revised list of the hydrogen (deuterium)-rich target materials used in present-day particle experiments is presented.

Table I: Present-day target materials for particle experiments

Material	Polarizable nucleons (%) a)	Doping method and paramagnetic impurities b)	maximum polarization(%)	max.average polarization (%) c)	Ref. No
C_4H_9OH	13.5	CHEM: POR	80	11	/19/
$C_5H_{11}OH$	13.6	CHEM: CRV	95	13	/9/
$C_3H_6(OH)_2$	10.8	CHEM: CRV	98	11	/20/
NH_3	17.6	IRR: NH_2	92	16	/12/
NH_3 MA BA d)	17.4	CHEM: CRV	79	14	/15/
TiH_2 e)	4.0	-	60	2	/21/
C_4D_9OD	23.8	CHEM: POR CHEM: CRV	27 35	6 8	/19/ /22/
$C_3D_6(OD)_2$	19.0	CHEM: CRV	45	8	/23/
ND_3	30.0	IRR: ND_2	49	15	/24/

a) weight percentage of free protons (deuterons)

b) CHEM = chemical doping; IRR = irradiation;
POR = porphyrexide; CRV = chromium V centers

c) Maximum average polarization of all nucleons
(polarization of ^{14}N and ^{11}B in the ammonia samples is not considered)

d) MA = methylamine; BA = borane-ammonia

e) Brute force polarization (see chapter 6)

4. Frozen Spin Polarized Target

Some special requirements are needed (given below) for the polarizing target magnet (continuous mode operation). These put strong constraints on its design. In particular the field must be uniform to better than 1 part in 10^4 over the whole target volume as the electron spin resonance line width is relatively narrow. Special pole tips are therefore required which should also allow maximum experimental access for the beam and the scattered particles.

All early targets used a C-type electromagnet combined with horizontal refrigerators. With this type of target the polarization direction, which is parallel to the magnetic field direction, can only be oriented perpendicular to the scattering plane of the produced particles. For experiments which require other polarization orientations superconducting magnets must be used. With a split pair configuration all three possible orientations of the polarization direction with respect to the scattering plane can be obtained by rotating the coils. The superconducting magnets are normally operated in conjunction with a vertical refrigerator. Nevertheless, the experimental access is limited by the finite dimensions of the coils.

This limitation is serious if experiments with small cross sections or low intensity beams, e.g., tagged photon beams are performed. To obtain a reasonable counting rate a large solid angle has to be covered simultaneously. This can be achieved with a frozen spin target. Its operation depends on the experimental fact that the nucleon relaxation time T_n is a very steep inverse function of the temperature. T_n characterizes the polarization decay, after the polarizing mechanism (microwaves) is switched off. Typical values for T_n are minutes at a temperature of 1 K and days at 100 mK. The principle of the frozen spin operation mode is to polarize the material at, e.g. 2.5 T and around 100 mK. After reaching the maximum polarization the microwave power is turned off. Then the spin is 'frozen in' and the target can be placed into a 'holding' field which can be much lower than the polarizing magnet field. An appropriate setting of the holding magnet allows the target to be polarized in three orthogonal directions combined with an excellent experimental access.

At present time frozen spin targets exist at KEK, LAMPF, TRIUMF and in Saclay and they are used in many experiments, especially at intermediate energies (some hundred MeV). As the cooling power of the $^3He/^4He$ dilution refrigerators operating at these very low temperatures is relatively low the beam intensity is limited. The maximum flux which has been reported is 10^7 - 10^8 particles/sec /18/.

5. Miscellaneous Parameters - Some Comments

a) Refrigerator systems and target size

All the polarization values listed in table 1 are obtained with $^3He/^4He$ dilution refrigerators, which are now the standard equipment of a polarized target system. For most of the particle experiments high luminosities (target nuclei per cm^2 x incident particles per sec) are wanted. As a consequence for polarized targets the beam heating effects and microwave power, respectively, must be compensated by high cooling power refrigerators. At 0.5 K good results have been recently obtained using ^3He-refrigerators operating with a mixture of ^3He and ^4He /25/. At lower temperatures a cooling power in the order of μW in the millikelvin region ($<$ 5 mk) up to 200 mW at 0.2 K are obtainable. Typical target volumes in particle experiments vary between 2 cm^3 and 50 cm^3, generally determined by the experiment requirements, but the scale extends from some mm^3 (mostly used in solid-state physics experiments) up to 2 litres (EMC-target at CERN).

b) Microwave systems

Microwave generators with frequencies up to 180 GHz (corresponding to a target operation of 6.5 T) and higher are commercially available. Carcinotrons, klystrons and recently also gun diodes /26/ with sufficient power are used to polarize the target materials. Direct frequency counting up to 110 GHz facilitate a constant target operation, especially if target materials (e.g. ND_3) with a narrow electron spin resonance line are polarized.

c) Polarization measurement

The polarization is measured by the nuclear magnetic resonance method. The system is calibrated using the calculable polarization at thermal equilibrium of the nucleon spins with the solid lattice at a known temperature in a known magnetic field. The relative polarization can be determined to an accuracy of better than ±1% for the protons and ±5% for deuterons. This is achieved by using the signal averaging techniques to overcome signal to noise ratio problems. Absolute measurements are more difficult, where in the case of high intensity beams non-uniform radiation damage is the most significant problem.

6. New Polarized Target Experiments

a) Neutron scattering off polarized biological material

The interest in polarized targets originates from the well-known spin dependence of the interaction of neutrons and protons. Recently polarized targets have been used in biological structure research performed with (polarized) neutrons /27/. Neutron scattering can be done in combination with a brute force polarized target (very high magnetic fields $\sim$ 10T and extremely low temperaturs T $\sim$ 10 mk) /21/. However, at such a low temperature the heat conductivity and spin-lattice relaxation for electrical insulators will be too low. Dynamic nuclear polarization could now be achieved in biological targets doped with deuterated CRV complexes. The polarization results are comparable to those obtained in materials used in high-energy physics research /28/.

b) Elastic electron scattering off a tensor polarized deuteron target

Previous electron scattering experiments with a polarized proton target (alcohol materials) were limited by the relative low polarization resistance to radiation damage /29/. Up to now measurements with a polarized deuteron target did not exist. The discovery of ammonia as a target material and its much less sensitivity to radiation damage makes such experiments now possible. It is obvious that ^3He-^4He dilution refrigerators must be used to achieve a very high target polarization. This is especially valid if a high tensor polarization of the deuteron is required.

The measurement of the elastic electron deuteron scattering off a tensor polarized deuteron target can be used to separate the charge monopole factor F_C and the charge quadrupole formfactor F_Q. This experiment was recently started at the 2.5 GeV electron synchrotron in Bonn. A first measurement with a

ND_3 target shows that an electron (2 GeV) beam current of 0.4 nA could be tolerated without considerable loss of polarization. An average deuteron tensor polarization of 0.17 ± 0.02 could be obtained in a 3.5 Tesla magnetic field. The target size was 6.5 cm^3 and the cooling power of the used dilution refrigerator is 20 mW at 270 mk.

This first measurement was performed at a four momentum transfer $Q^2 = 0.5$ GeV^2. It is planned to extend this measurement to higher Q^2-values, ($Q^2 < 2$ GeV^2), where the sensitivity to the differences between theoretical models increases. However, at these large Q^2-values the cross section is considerably reduced. Therefore a large solid angle detection and a highly tensor polarized deuteron target, which can withstand some nA electron beam current are decisive for the success of the experiments in the Q^2-region of about 1 GeV^2. The maximum luminosity which then can be tolerated by a large solid angle detector in electron scattering experiments can become the limiting factor. Fortunately, background problems should be reduced by the significantly improved duty cycle of the next accelerator generation at intermediate energies - like stretcher rings /30/.

7. Conclusion

For about twenty years polarized target experiments have been and still are a powerful tool in the particle physics to study spin effects. During that time there has been a steady progress - often influenced from the solid-state physics - in the field of polarized target instrumentation: target materials, cryogenics, magnet and NMR-technology. Hence, many of the requirements for the particle experiments, such as high polarization, high proportions of free polarizable nucleons, high absolute nucleon density, big samples, short polarization times (permitting frequent polarization reversals or on the contrary very long relaxation times for the so-called frozen spin targets), high polarization resistance against radiation damage etc. have been significantly improved. However, further efforts can and must be done. This is particularly valid for the polarized deuteron target and as a natural continuation of the solidstate target material development, it seems to me, that now also more effort should be put on polarizing heavier nuclei.

References

/1/ A. Abragam, High Energy Physics with Polarized Beams and Targets, AIP Conf. Proc., 51 (1978) p. 1

/2/ C. Joseph and J. Soffer, eds. 1981, Proc. of the Int. Symp. on High Energy Physics with Polarized Beams and Polarized Targets (Birkhäuser, Basel)

/3/ G.M. Bunce, ed. 1983, Proc. Conf. on High Energy Spin Physics, AIP Conf. Proc. no. 95

/4/ J. Soffer, ed. 1985, Proc. of the 6th Int. Symp. on High Energy Spin Physics, Journal de Physique, Colloque C2, 1985

/5/ M. Borghini, Proc. on the 2nd Int. Conf. on Polarized Targets, ed. G. Shapiro, Berkeley 1971, p. 1

/6/ M. Borghini, Phys. Lett. 26A (1968) 242

/7/ T. Niinikoski, Conf. on High Energy Physics with Polarized Beams and Targets, AIP Conf. Proc., 35 (1976) p. 458

/8/ W. Meyer and E. Schilling, BONN-HE-85-06

/9/ G.R. Court et al., ed. 1980, Proc. on the 2nd Workshop on Polarized Target Materials, Rutherford Lab., RL80-080 (1980)

/10/ Workshop on Polarized Targets, in Ref. 3, p. 473-533

/11/ W. Meyer, ed. 1985, Proc. of the 4th Workshop on Polarized Target Materials and Techniques (Physikalisches Institut Bonn 1985)

/12/ T. Niinikoski and J.-M. Rieubland, Phys. Lett. 72A (1979) 141

/13/ U. Härtel et al., in Ref. 2, p. 451
M.L. Seely et al., Nucl. Instr. and Meth. 201 (1982) 303

/14/ W. Meyer et al., Nucl. Instr. and Meth. 227 (1984) 35

/15/ D. Hill, J. Hill and M. Krumpolc, in Ref. 11, p. 84

/16/ A. Abragam et al., J. Physique-Lettres 41 (1980) L-309

/17/ G. Durand in these proceedings

/18/ J. Ball in Ref. 11, p. 112

/19/ E. Schilling, BONN-IR-82-12

/20/ W. de Boer and T.O. Niinikoski, Nucl. Instr. and Meth. 114 (1974) 495

/21/ W. Heeringa, in Ref. 11, p. 129

/22/ G. Wait, these proceedings

/23/ T.O. Niinikoski, Proc. Conf. on High Energy Physics with Polarized Beams and Targets, AIP Conf. Proc. no. 35, p. 458

/24/ W. Meyer et al., to be published in Nucl. Instr. and Meth.

/25/ P.R. Cameron et al. in Ref. 11, p. 143

/26/ S. Mango, private communication

/27/ W. Knop, in these proceedings

/28/ H.B. Stuhrmann et al., submitted to Nature

/29/ V. Hughes et al., in Ref. 2 p. 331; SLAC-PUB-2674 (Febr. 1981)

/30/ K.H. Althoff et al., Proc. 11th Int. Acc. Conf., CERN 1980, p. 196
D. Husmann, IEEE Transactions on Nucl. Sc. Vol. NS-30, No. 4 Aug. 1983