Solid State Polarized Targets for the Study of Nucleon Spin Structure

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Abstract. The dynamically polarized solid state nucleon target has played a very important role in the experiments to study the spin structure of the nucleon which have been carried out over the last two decades. The quality of the data obtainable is critically dependent on the properties of the target materials used. The developments which have been made to improve both target materials and overall target performance during this period are reviewed. The effects that these developments have had on present and future experiments is discussed.

INTRODUCTION

A talk entitled "Polarized Targets – what is happening ?" [1] was given at the Spin Symposium held here at Brookhaven exactly twenty years ago. At that time, dynamic nuclear polarization (DNP) in solid hydrogenous materials was the technique being used to obtain polarized proton and deuteron targets for most high energy spin experiments. This technique, which enables high values of nucleon polarization to be obtained in a limited range of hydrogenous solids, requires that the solid material be maintained in a magnetic field of 2.5T or above and cooled to a temperature in the region of 1K. The technological and experimental problems which arise from these requirements were reviewed in some detail in the talk, and it was concluded that the technology of this type of target was well developed and that it would continue in use for some time to come. In this talk, the progress which has been made to improve the performance of the solid state polarized target, with particular emphasis on its use for the study of the spin structure of the nucleon, will be reviewed.

DYNAMIC NUCLEAR POLARISATION

The static nucleon polarization generated in solids, with practical values of applied magnetic field and temperature, is always much less than 1%. DNP works via free electron spins introduced into the solid matrix by chemical or other means. These spins are essentially 100% polarized under the same conditions and this high electron polarization can be transferred to the nucleons by microwave pumping. The target spin direction relative to the static magnetic field is then reversed by making small changes in the frequency. The electron spin concentration must be maintained within relatively close limits to obtain the highest values of nucleon polarization. DNP targets have a number of intrinsic limitations which need to be accounted for in the design of
experiments and their operation. Firstly, DNP will not work in solid hydrogen so the free nucleon to total nucleon ratio (nucleon dilution factor) in the target material is always less than unity. Secondly, the beam used in experiments causes radiation damage and hence generates free electron spins in the material which can interfere with the DNP process so reducing the polarisation. This can normally be restored to a value close to the initial one by annealing the target material, but only at the cost of lost data taking time. Finally, all nucleons with spins present in the material become polarized to some degree. The DNP process is described in detail in reference [2]

### SPIN STRUCTURE FUNCTION MEASUREMENTS

For over twenty years polarized targets have been an essential tool in the experimental study of the spin structure of the nucleon via DIS. The first series of experiments was done at SLAC in the early 1980s with 20 GeV electrons on a proton target. The results demonstrated that in the kinematic region where the valence quarks carry the bulk of the nucleon's momentum, they account, as expected, for its spin. The target material used in the early stages was an alcohol (butanol), which has a dilution factor of 0.14, doped with a free radical to provide the free electron spins. Proton polarizations in the region of 70% were obtained at an operating field of 5T and a temperature of 1K. These high values of field and temperature were chosen to minimize the effect of beam heating of the target material. The radiation damage effects were severe, and limited the overall statistical accuracy attainable in the experiments.

During the same period a new target material was developed, which was solid ammonia (NH₃) with the electron spins introduced via radiation damage at a temperature in the region of 77 K. This material has a dilution factor of 0.17. The polarizations attainable are high, and the tolerance to beam induced radiation damage much better (~ x30) than for the alcohol materials. It was used in the later stages of the SLAC series of experiments.

The next experiment to study nucleon spin structure was the EMC experiment at CERN which used a 200 GeV polarized muon beam with an NH₃ target. This target was unique in two features[1]. Firstly, it had a much larger target material volume (x20) than any target built previously, and secondly it had two separate sections with opposite polarization directions which were mounted in tandem. This latter arrangement helped to minimize systematic uncertainties caused by beam intensity fluctuations and loss of data during polarization direction reversals. The proton polarization was in the region of 80% at a field of 2.5T and a temperature of less than 0.5K. Radiation damage was not an issue as the beam intensities were very low. It was necessary to make small corrections for the relatively small spectator nucleon (¹⁴N) polarization which was measured separately. The data from this experiment revealed that the initial nucleon structure picture was overly simple, and that proton spin was attributable to a combination of a contribution from sea quarks and gluons and possibly angular momentum.
This unexpected result inevitably generated a great deal of theoretical interest, which stimulated programmes at both CERN (SMC) and SLAC to further explore the nucleon spin structure. The main motivation was to confirm and improve the precision of the EMC result for the proton and obtain data for the neutron. The latter is normally achieved by using polarized deuterons, which have spin one, and are effectively a polarized proton combined with a polarized neutron. The deuteron polarization attainable is always lower than the proton, with values of around 50% being attainable in deuterated butanol, and between 20 and 40% in deuterated ammonia. A third entirely new programme (HERMES) was started at DESY using gaseous state polarized targets of hydrogen, deuterium and $^3$He in the HERA electron storage ring. This type of target has the advantage of dilution fraction at or close to unity, but it can only provide practical luminosities when used with stored beams. It is an important tool for nucleon spin structure studies but will not be discussed further in this talk.

The SMC programme started with a modified version of the EMC target which was later replaced with a new target of similar design. The target materials used for most of the data taking were ammonia for protons and deuterated butanol for deuterons. The latter was used because it has a better figure of merit in this situation, which was further enhanced when it was discovered that frequency modulation of the microwave source increased the polarization from its normal value of around 30% to, on average, over 50%.

The SLAC programme started with a gaseous $^3$He target for neutron measurements. This was later replaced by a solid state target using both NH$_3$ and ND$_3$ operating at 5T and 1K. Radiation damage was again a serious problem, with the consequence that with protons the mean value of the polarization was of the order 70% when the initial value was close to 100%. With ND$_3$ it was found that the deuteron polarization actually increased by a factor of up to three during the initial phase of beam irradiation, before returning to normal behavior at higher dose levels, so giving a higher than expected figure of merit. The materials actually used were $^{15}$NH$_3$ and $^{15}$ND$_3$. This obviates the need to make a correction for the effective neutron polarization in the $^{14}$N as well as simplifying the measurement of spectator nuclear polarization.

In the later stages of the SLAC programme an entirely new material, lithium deuteride ($^6$LiD), was introduced as an alternative deuteron target material. The electron centres needed for DNP were again generated by radiation damage of the solid, but at a temperature of 185 K. The $^6$Li and the deuteron both become polarized to a level of about 25% under normal conditions. If it is assumed that the $^6$Li nucleus looks, as seen by the DIS process, like an $^4$He nucleus (spin zero) plus a polarized deuteron, then the effective dilution factor, and hence figure of merit, is much larger than the equivalent figure for ND$_3$.

Spin structure functions for both the proton and the neutron have now been measured to high precision over a wide range of both Bjorken-x and $Q^2$. The HERMES data, obtained with a gaseous target, agrees very well with that obtained by
both groups using different solid state targets. This gives confidence that the systematic errors in the target polarization measurement for both types of target are known and well understood.

POLARIZATION MEASUREMENT

The standard technique for monitoring and measuring the polarization in solid state targets involves measuring spin state populations by observing NMR with a linear RF Q-meter system. A high precision version of this system was originally developed for the EMC target and the same system is still being used with virtually all targets in current operation [3]. The overall systematic uncertainty attainable with this system is in the range 2 to 5% for both protons and deuterons, depending on the specific target operating conditions. In some recent experiments the uncertainty in the target polarization has been higher than this, and has dominated the overall uncertainty in the experiment. Development work has therefore been carried out to improve both the linearity and intrinsic signal to noise ratio of the system [4]. Lower systematic uncertainties in target polarization measurement should now be attainable using this new system.

CURRENT AND FUTURE EXPERIMENTS

A precise interpretation of this world data set on spin structure functions suggests that the gluons carry a large proportion of the nucleon spin, so a number of experiments have been proposed to make a direct measurement of this contribution. HERMES has already attempted such a measurement, which was severely limited by statistical and systematic uncertainties. Another experiment of this type is under way at CERN (COMPASS) using an upgraded version of the SMC target with $^6$LiD as target material. Polarizations of over 50% are being attained largely due to the low target operating temperature (< 500 mK). There is also an approved experiment at SLAC (E161) which will use $^6$LiD with a polarized real photon beam, so measuring the gluon contribution via real photon interactions. The lower effective beam intensity will reduce the effect of radiation damage and allow operation at temperatures below 500 mK. It is also proposed to use a 6.5T static field which in combination with this low operating temperature should enable polarizations in the region of 70% to be achieved.

There are currently a number of experiments proposed or already under way, at SLAC and TJNAF and other laboratories, to study spin structure in a lower $Q^2$ regime. These generally need to operate with high intensity beams and therefore a target material with a high radiation damage tolerance is required. However, the assumptions made about the nuclear properties of $^6$Li which make it equivalent to a polarized deuteron do not apply in all situations and it is then necessary to use ND$_3$.  

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CONCLUSIONS

A critical factor in the design of all nucleon spin structure experiments using fixed targets is the properties of the target material itself. The chemically doped target materials available in the early stages of the nucleon spin structure programme had a relatively small dilution fraction (~0.14) and a low tolerance to beam induced radiation damage. The proton polarization attainable was typically in the region of 85%, while the deuteron polarization in fully deuterated materials, was in the range 30 to 45%. A new material, solid ammonia with electron spin centre introduced via radiation damage, came into use at an early stage in the programme. This gives proton polarizations close to 100% with a somewhat improved dilution fraction (0.17) and greatly improved tolerance to radiation damage. Ammonia is still the best available material for proton targets. The deuteron polarization attainable in the deuterated material can, depending on target operating conditions, have values up to 50%.

The successful development of lithium deuteride (\(^6\text{LiD}\)) as a target material using radiation damage centres, and its first use in a nucleon spin structure experiment in 1995, were major breakthroughs. The dilution factor is 0.5 if it is assumed that a \(^6\text{Li}\) nucleus acts like a pseudo deuteron plus an \(\alpha\)-particle. The effective deuteron polarization attainable depends on both operating field and temperature with typical values of 25% at 5T and 1K and over 50% at 2.5T and < 500mK. It is likely that even higher polarization will be attained when operation at low enough temperature and higher magnetic field is possible. This material also has an even better radiation damage tolerance than ammonia. It is interesting to note that \(^6\text{LiD}\) was first suggested as a target material in 1978 [5] and this perhaps highlights the magnitude of the problems which have to be overcome when developing new materials for DNP.

The dynamically polarized solid state target has been used in many nuclear and particle physics experiments during the last twenty years. It is a versatile tool which has played, and still is playing, a dominant role in the experimental study of the spin structure of the nucleons and in many other areas. It seems likely that it will continue to be used to make high precision measurements in many areas of spin physics for some time to come.

REFERENCES

The scope and nature of this talk makes a detailed list of references impractical. Therefore two review papers [1][2] are listed, plus some source references needed to clarify specific points.