



Technical Notes

Uncertainty minimization in NMR measurements of dynamic nuclear polarization of a proton target for nuclear physics experiments[☆]



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ARTICLE INFO

Article history:

Received 19 February 2013

Received in revised form

12 June 2013

Accepted 27 June 2013

Available online 4 July 2013

Keywords:

Uncertainty minimization

NMR

Dynamic nuclear polarization

Proton target

ABSTRACT

A comprehensive investigation into the measurement uncertainty in polarization produced by Dynamic Nuclear Polarization is outlined. The polarization data taken during Jefferson Lab experiment E08-007 is used to obtain error estimates and to develop an algorithm to minimize uncertainty of the measurement of polarization in irradiated $^{14}\text{NH}_3$ targets, which is readily applied to other materials. The target polarization and corresponding uncertainties for E08-007 are reported. The resulting relative uncertainty found in the target polarization is determined to be less than or equal to 3.9%.

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1. Introduction

Nuclear and particle physics experiments using solid polarized targets attempt to extract a number of polarized observables, frequently an asymmetry associated with the target polarization. As a result, a large contribution to the observables systematic uncertainty can come from the limited precision in the Nuclear Magnetic Resonance (NMR) measurement of polarization.

The uncertainty in the calibration of the polarization measurement primarily comes from measurement limitation of area of the NMR signal and temperature of the target material at thermal equilibrium. There is also an uncertainty in the polarization caused by changes in the experimental environment that can affect the NMR signal or the coupling of the target material to the NMR circuit. In order to accurately represent and minimize the experimental error, it is important to determine when such changes have and have not occurred.

There are several contributions to polarization uncertainty that depend on the experimental configuration such as target length, beam intensity, and target material type. For the error analysis presented here the focus is on proton targets using $^{14}\text{NH}_3$ at the electron beam intensity of (~ 100 nA) which is of most interest for past and future Thomas Jefferson National Accelerator Facility (TJNAF) Hall A and Hall C polarized target experiments. There

have already been multiple experiments with similar beam intensity such as E93-026, E01-006, E08-027, E07-003, and E06-014 at Jefferson Lab and E143, E155, and E155x at SLAC. High intensity beams lead to quicker polarization decay and can also lead to more frequent changes in the materials ability to polarize and hold polarization. The effects on systematics from these changes can be taken into account with frequent NMR target calibration measurements and careful control of the beam size on the target face.

During an experiment, the number of target calibration measurements may be limited due to time constraints resulting in a larger uncertainty in the target data that is not well defined. Here a systematic procedure is outlined to obtain the integrated systematic uncertainty associated with a single calibration measurement over a section of physics data. A minimization can then occur with multiple target calibrations on consecutively used material. A χ^2 -minimization technique is used weighting each calibration by its combined total uncertainty. To illustrate these details a full target data analysis for TJNAF Hall A experiment E08-007 is completed obtaining the final polarization for each production run and the associated polarization uncertainties. Though a proton target is used the procedure presented is readily applied to any polarized target material which uses a thermal equilibrium calibrated NMR to probe polarization during nuclear physics experiments.

The goal of experiment E08-007 was to study the proton elastic form factor ratio $\mu G_E/G_M$ in the range $Q^2 = 0.01\text{--}0.7\text{ GeV}^2$. The experiment was carried out with the hope of improving the knowledge of the ratio at low Q^2 . In this low Q^2 range, substantial deviations of the ratio from unity have been observed [1–3], and

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data, along with many fits and calculations, continues to suggest that structures might be present in the individual form factors, and in the ratio. Experiment E08-007 made precise measurements of the polarized beam-polarized target asymmetry which can be used in an attempt to resolve these possible structures.

The experiment took place using the TJNAF Continuous Electron Beam Accelerator Facility (CEBAF) in Hall A with the beam energy between 1.1–2.2 GeV at a beam current of 100 nA.

2. The solid polarized target

A solid polarized target has the advantage over gaseous targets of being high in nucleon density. In addition the nucleon density can also be made very stable within the temperature control of the cryostat. Combined with high beam current solid polarized targets provide the highest luminosity experiments that can be done to extract polarized target observables.

Dynamic Nuclear Polarization (DNP) of the solid material used in nuclear experiments can be achieved at ~ 1 K using a homogeneous magnetic holding field and a microwave field to transfer the polarization to the nuclear spins. For materials of interest DNP is not well described by the solid-state effect in which the interaction between paramagnetic spins can be neglected. The equal spin temperature theory is required to address dipolar interactions between electrons seen in materials with high electron density. The spin-spin interaction between electrons produce a separate energy reservoir dependent on the Zeeman and lattice energies only through the characteristics of transverse relaxation and diffusion. The nuclei become polarized by the coupling of the nuclear spin and the paramagnetic spin systems. Microwaves are used to change the spin temperature, which in turn interacts with the proton Zeeman system. Nuclear spin relaxation must be orders of magnitude slower than the relaxation of the paramagnetic centers so that the rate of polarization is higher than the rate of depolarization allowing polarization to be built and maintained by the microwaves. Depending on the tuning of the microwave frequency the proton spins become polarized parallel or antiparallel to the magnetic field. As an example using microwaves of slightly less than the Zeeman energy leads to the spin system emitting energy resulting in transitions that lead to positive spin temperature corresponding to positive polarization. The contrary is true to achieve negative polarization.

For experiment E08-007 the target polarization performance was optimized by the use of irradiated ammonia target material and a high power EIO microwave tube characterized to oscillate in a range around ~ 140 GHz. The solid polarized target system, see Fig. 1, used a ^4He evaporation refrigerator with sufficiently high cooling power to minimize the heating effects of the microwave and high beam current. A 5 T superconducting magnet was used to polarize and maintain polarization of the target during the experiment.

The following includes some introductory discussion on the target material preparation, radiation damage, and performance.

2.1. Preparation of material

Experiment E08-007 required the fabrication of ammonia $^{14}\text{NH}_3$ beads to serve as target material. This fabrication was done by the University of Virginia (UVA) polarized target lab [4]. Ammonia gas is condensed by sealing it in a Teflon coated stainless steel tube under a liquid nitrogen (LN_2) bath. This freezes the ammonia into a solid. Once in the solid form, the ammonia is crushed through mesh screens to form beads approximately 2 mm in diameter.

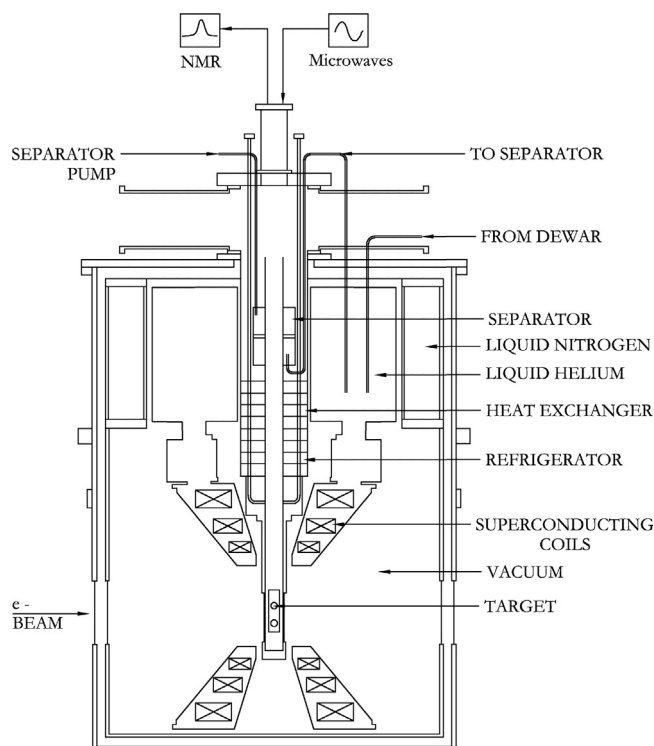


Fig. 1. Polarized target system for NH_3/ND_3 at 5 T used to achieve a temperature of ~ 1 K.

The ammonia beads for the experiment were then irradiated to introduce paramagnetic radicals to optimize polarization performance [5,6]. The preparation technique used was first developed and implemented with NH_3 in 1979 [7,8]. A high-intensity beam from a traveling-wave electron linac was used to irradiate the ammonia approximately $10^{17} \text{ e}^-/\text{cm}^2$ (120 min). The irradiation leads to protons being knocked-out of the NH_3 molecule to form NH_2 paramagnetic centers. The irradiation took place at the Medical Industrial Radiation Facility (MIRF) at the National Institute of Standards and Technology (NIST) in Gaithersburg, MD, using the MIRF 14 MeV electron beam at $\sim 10 \mu\text{A}$ to strike the material under a ~ 87 K liquid argon (LA) bath. The prepared material was then stored in liquid nitrogen until installed into the experiment target insert at Jefferson Labs.

2.2. Material radiation damage

Radiation damage to the target material happens when additional radicals in the target materials are created during the experiment. The radiation-produced radicals populate the NH_3 distorting the DNP process. As radical density increases, it affects the relaxation processes, shortening relaxation time and reducing nucleon polarization.

The polarization reduction from radiation damage can be almost completely recovered by heating or annealing the target material, not to exceed about 20 K below the devitrification temperature [9,10]. The amount of radiation damage sustained with the same dose increases after each anneal until the material must be changed. The radiation damage over the course of the experiment can be seen by studying polarization changes with respect to dose on the material from the CEBAF electron beam. The beam dose is measured as electrons pass into the circular area of the target cell. The charge accumulation is obtained using the Hall A beam current monitors (BCMs) [11]. The polarization as a function of dose is shown in Fig. 2. The same ammonia sample

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