STATUS AND PROSPECTS FOR POLARIZED D WITH THE SPHICE HD TARGET SYSTEM

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A deuterium-hydride ice target with frozen spin polarization of both the H and the D is under development for use at LEGS and elsewhere. After a target system overview, we present the methods and prospects for achieving high D polarization. We then illustrate the level of polarization achieved and the high quality of the data recorded with this target in November 2001. We conclude with a summary of the future development steps to be taken.

1. Target Overview

A highly polarized, frozen spin mode, HD ice target, ideally suited for experimental tests of nucleon sum rules with the LEGS Compton backscattered gamma beam, is being developed by the LEGS target group under the acronym SPHICE (Strongly Polarized Hydrogen deuteride ICE).

Figure 1 shows a schematic diagram of the target in use. The target is

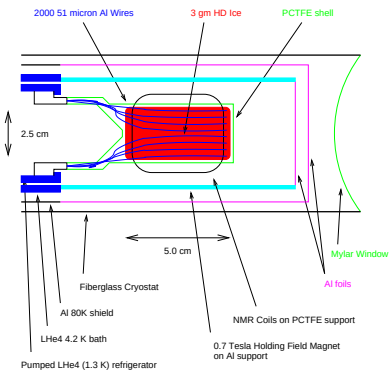


Figure 1. Schematic diagram of the HD ice target in use.

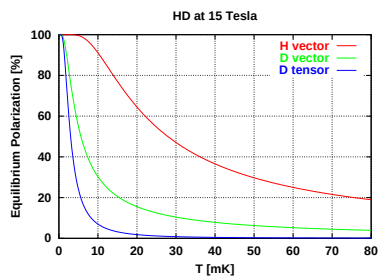


Figure 2. Equilibrium polarizations of H and D atoms in a 15 T field as a function of temperature. From top to bottom the curves are for H vector, D vector and D tensor polarizations.

3 grams of hydrogen deuteride ice, forming a cylinder 5 cm long and 2.5 cm in diameter. The cylinder is held by a shell of 0.5 mm poly chlorotrifluoro ethylene (PCTFE) and is threaded by 2000 aluminum wires, 51 micron diameter, 99.99% purity, having 1% of the target volume and 20% of its mass. The shell and wires are attached to a copper ring screwed into the nose of a pumped liquid He4 refrigerator at 1.3 K. Just outside the shell is a PCTFE form with NMR coils that monitor the polarization. A NbTi solenoid, 0.6 mm thick, on an Al mandrel, 0.5 mm thick, attached to the liquid He4 shield provides a 0.7 T holding field. Next is an 80 K radiation shield followed by a 2 mm thick fiberglass vacuum chamber wall. These characteristics produce a relatively open geometry and favorable dilution factors, particularly, as the wire and shell contributions are readily determinable from empty target measurements. The goals for the frozen spin polarization are 80% H and 50% D, with polarization retention times (T_1's) of 35 days and 100 days, respectively.

2. Target Polarization

Figure 2 shows the H goal of 80% is nearly the thermal equilibrium (TE) polarization under our achieved conditions of 17 mK, and 15 T. However, the HD molecular ground state is spherically symmetric and thus poorly coupled to the lattice vibrations that define the temperature. This is why the T_1 can be greater then 35 days but complicates reaching equilibrium.

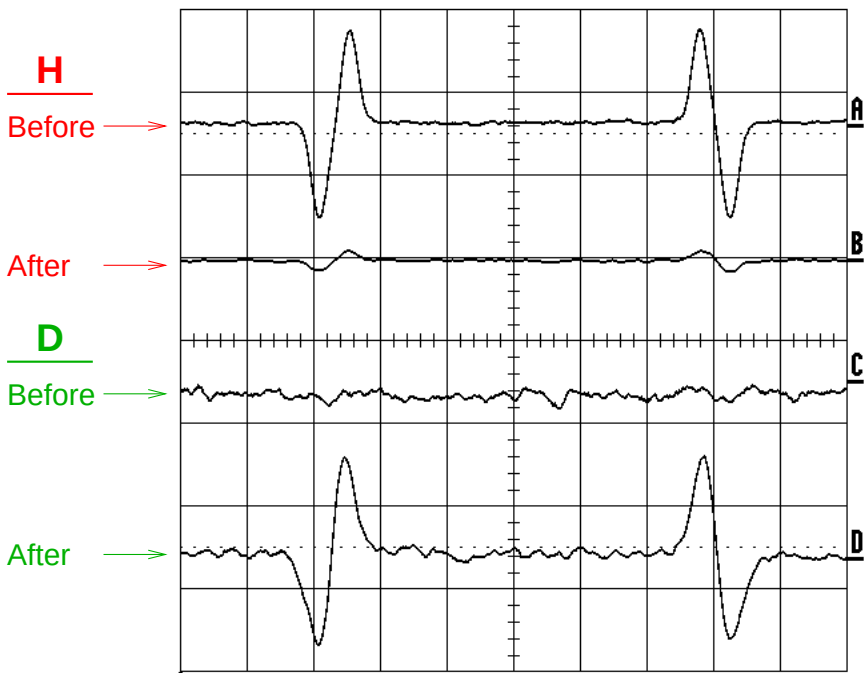
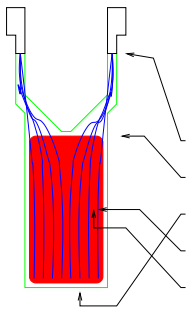


Figure 3. Transfer of polarization from H to D with forbidden adiabatic fast passage (FAFP). From top to bottom, the NMR traces are H before, H after, D before, and D after the FAFP. Transfer efficiency was 67%.

Any additional coupling introduced during the polarization stage must be gone during the frozen spin usage period. The solution is to use a small ($\approx 10^{-4}$) admixture of meta-stable ortho-H_2, which couples well to the lattice and which decays with a 6.5 day meanlife to the spherically symmetric, magnetically inert para-H_2. Initially, H in HD is polarized by spin exchange with ortho-H_2 but, after sufficient decay time under the polarizing conditions, the ortho-H_2 concentration is low enough to permit transfer of the target from the dilution refrigerator conditions to the inbeam cryostat environment.

From Figure 2, TE for D at 17 mK and 15 T is unfortunately less than 20%. Figure 3 shows another method of creating or augmenting the D polarization, transfer from the H via forbidden adiabatic fast passage (FAFP). Because of molecular symmetry, the B-field of the H on the D of the same HD molecule averages to zero and vice versa so there is no spin interaction. But the D may interact with the fields of the H in the



Cooling Wire Calculations

	Old	New	8 Days	Colder DF
Ortho Decay Heating	0.5 uW	0.5 uW	0.125 uW	0.125 uW
Wire material	Al 5056	99.999% Al	99.999% Al	99.999% Al
Number of wires	3000	2000	2000	2000
Diameter of wire	38.1 microns	50.8 microns	50.8 microns	50.8 microns
Thermal Conductivity	0.7 W/K^2−m (AL 5057)	600 W/K^2−m	600 W/K^2−m	600 W/K^2−m
T of wire at ring	17 mK	17 mK	17 mK	12 mK
T of wire at top of HD	113.2 mK	17.36 mK	17.09 mK	12.13 mK
T of wire at end of HD	152.5 mK	17.65 mK	17.16 mK	12.23 mK
T of HD next to wire	133.8 mK	19.84 mK	17.84 mK	13.89 mK
T of HD farthest away	133.8 mK	19.94 mK	17.88 mK	13.97 mK
H Polarization @ 15T	11.4%	64.6%	69.5%	79.9%
D Polarization @ 15T	2.3%	15.6%	17.3%	22.0%
D after 67% FAFP	6.6%	39.1%	42.4%	50.0%

HD Kapitza and bulk conductivity from:
Constable and Gaines. PR B8 (1973) 3966−77.

Figure 4. Calculated temperature rises from ortho-H_2 decay heating with two types of cooling wires. HD Kapitza and bulk conductivities are adapted from Constable and Gaines.[1]

surrounding HD crystal and vice versa. An RF field of sufficient intensity can be used to drive this forbidden transition in such a way as to exchange H and D polarization. Figure 3 results from such an RF transition, in which transfer efficiency of 67% was achieved.

3. Recent Results

In the spring of 2001, sufficient HD had undergone double distillation to begin a multiple target production run. A target was injected with HD and placed in the bottom of the three target positions in the dilution refrigerator in order to study the dependence of the T_1's on temperature and field. The values of T_1^H were in an acceptable range for producing polarization but there was a problem in reaching low temperatures. This was traced to the material chosen for the cooling wire. As column 1 of the table in Figure 4 illustrates, aluminum alloy wire used in this target is unable to remove the heat released by ortho to para conversions of the H_2 impurity. Column 2 shows the effect of pure aluminum, which has a thousandfold higher thermal conduction at these temperatures. The major temperature rise is only 2

mK and is due to the Kapitza resistance at the surface of the wires (row 9). After 2 halflives (column 3), the heating is down by a factor of 4 and the rise is just under 1 mK. This is roughly when the T_1's of H and D, at these field and temperatures, have become too long for the polarizations to respond to further cooling.

On a short timescale, only sufficient pure aluminum wire for one target could be obtained so the third target retained aluminum alloy wires. Both targets were injected on July 27, 2001. On August 1, they went to 17 mK and 15 T to begin the polarization procedure.

After 45 days of aging at polarizing conditions, the field was lowered. NMR measurements on the middle target showed a D polarization of $15 \pm 2\%$, consistent with expectations. There were numerous measurements of T_1 at various fields and temperatures and the equivalent of five transfers between the refrigerator and the inbeam spanning nearly 2 months before the target was finally placed in the beam. At that point, D polarization was $6 \pm 1\%$ and T_1 was 36 days. Two days after the start of bombardment, a magnet power problem resulted in a loss of roughly a quarter of the D polarization, and 1.5 days after that the accelerator shutdown for scheduled maintainance.

The H polarization revealed major problems with the NMR setup. The H signal was too large for the system and suffered from severe non-linearities. Correcting for the problems gives a polarization at the end of the polarizing cycle of roughly 70%, consistent with expectations. At the start of bombardment, the H polarization was $30 \pm 3\%$, as determined from the NMR peak shift due to the internal field, and the T_1 was 13 days. The magnet problem reduced the H polarization by about half.

The target was placed into the beam of the LEGS Compton backscattering facility at the National Synchrotron Light Source electron storage ring located at Brookhaven National Laboratory. Laser photons from 2.4 to 4.7 eV are backscattered off the 2.8 GeV electrons in the ring and the recoil electrons are detected in a magnetic spectrometer to produce tagged gamma's from 150 to 470 MeV. The polarization of these gamma's is determined by the laser with both linear and circular polarization available. By superposing different laser lines the polarization is maintained above 70% across the full energy range.

Detection of the reaction products was by the Spin ASYmmetry array (SASY) (see Figure 5). It consists of a 32 segment plastic scintillator neutron barrel, an equatorial array of 432 NaI crystals, a plastic scintillator bar endwall and a lead glass block endwall. A gas Cerenkov counter vetoes

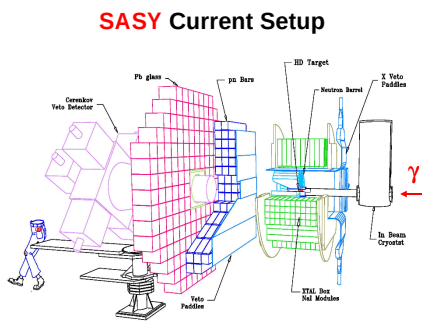


Figure 5. Current configuration of the Spin ASYmmetry array (SASY).

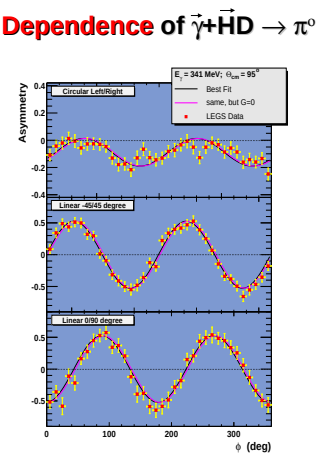


Figure 6. Asymmetries of the 3 pairs of laser polarization states versus ϕ for π^0 production at $E_\gamma = 341$ MeV and $\theta_{cm} = 95°$.

atomic events. All four pion-photoproduction channels can be measured simultaneously.

The beam polarization was regularly cycled between left and right circular polarization and 0° and 90° linear polarization. As a check on systematics, ±45° linear polarization was also done. The longitudinally polarized target then gives access to 4 observables out of 8 required for a model independent analysis. 1) The differential crosssection, $d\sigma/d\Omega(\theta)$, independent of polarization, 2) the beam asymmetry, $\Sigma(\theta)$, sensitive to beam linear polarization, 3) $E(\theta)$, needing beam circular and target longitudinal, and 4) $G(\theta)$, depending on beam linear and target longitudinal. Figure 6 plots the asymmetries observed between the three pairs of laser polarization states. The E asymmetry is a constant offset in the top panel. Although the laser is 98% circularly polarized, that still allows up to 20% linear polarization and this is the origin of the sinusoid seen in the top panel. Note that the sinusoid averages out when integrated over ϕ. The Σ asymmetry has a $\sin 2\phi$ shape in the middle panel and a $\cos 2\phi$ in the bottom, while the G asymmetry has the opposite. The combined cosine and sine dependences means the G asymmetry is revealed by a small phase shift of the sinusoids. The

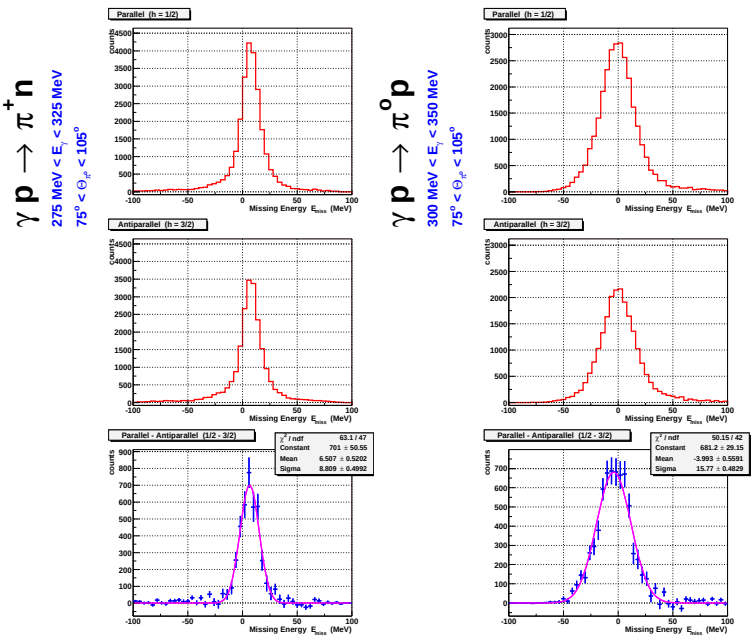


Figure 7. Missing Energy for the reaction $p(\gamma, \pi^+)n$ and $p(\gamma, \pi^0)p$ versus the two helicity states and the difference.

many points in the combined fit to all three panels and the well measured laser polarizations allow us to extract G with confidence.

Figures 7 and 8 show missing energy plots for the four channels. Plots are given for the beam polarization parallel and antiparallel to the target polarization as well as the difference. The spectra clearly demonstrate the polarization of both the H and the D and the relatively clean nature of the target.

Preliminary E and G asymmetries are given in Figures 9 and 10. Note the statistical precision attained in less than 4 days of running with a relatively low target polarization. The G asymmetries for reactions on the proton represent a doubling of the world's data and those for the neutron are the first reported values.

4. Future Steps

As column 4 of Figure 4 shows, lowering the base temperature results in higher polarizations for both H and D. The no-field base temperature is 9 mK so the 17 mK observed in the 2001 production run must be due to

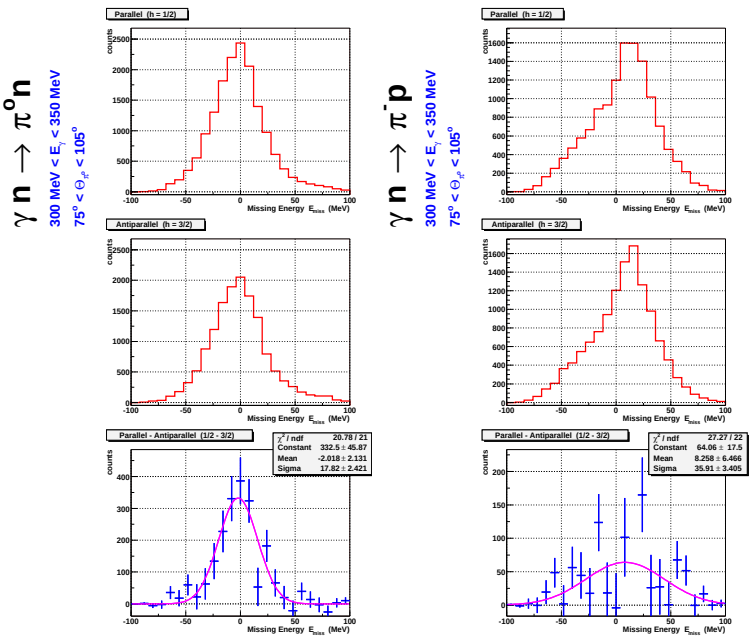


Figure 8. Missing Energy for the reaction $n(\gamma, \pi^0)n$ and $n(\gamma, \pi^-)p$ versus the two helicity states and the difference.

field dependent heating. A likely source for that is vibration producing motion in the field and thereby eddy current heating. A vibration isolation system is now under construction and we expect to reach 80% H and 22% D polarizations.

Next is to reproduce the success of the FAFP test in Figure 3. The bottom row of the table in Figure 4 shows a 67% efficient transfer results in 50% D polarization. Such a highly polarized, clean deuteron target would be a major milestone in polarized target technology.

Acknowledgments

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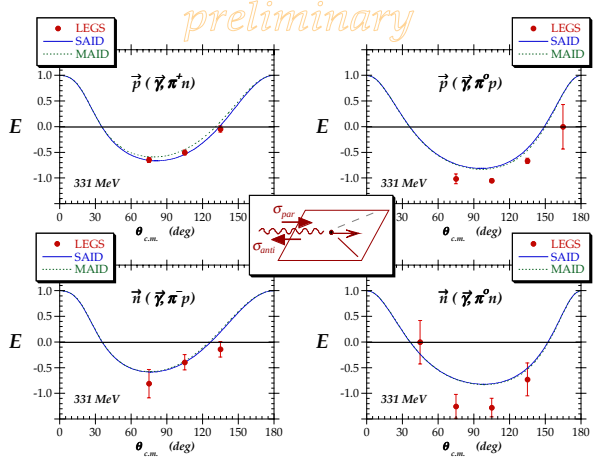

Figure 9. Preliminary E asymmetries at 331 MeV.

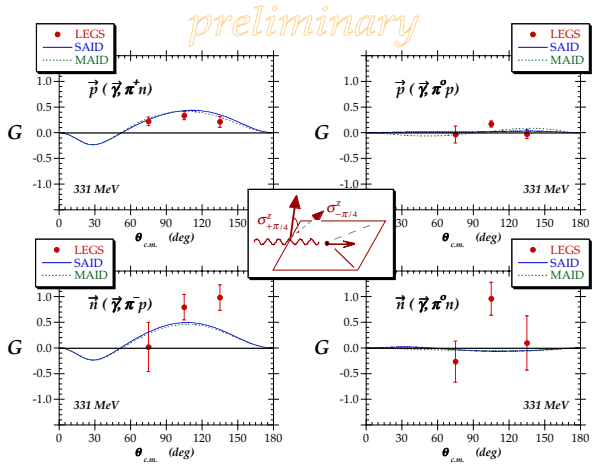

Figure 10. Preliminary G asymmetries at 331 MeV.