# REVIEW OF POLARIZED INTERNAL DEUTERIUM TARGETS

B. VON PRZEWOSKI

*Indiana University Cyclotron Facility,*
*Milo B. Sampson Lane,*
*Bloomington, IN 47408, USA*
*E-mail: przewoski@iucf.indiana.edu*

Today, several polarized, internal deuterium targets are in operation or being commissioned worldwide. Polarized gas from either an atomic beam source (ABS) or laser driven target (LDT) is admitted to an open ended storage cell which enhances the target thickness by approximately two orders of magnitude. ABS technology is mature. Polarizations of up to 85 % of the theoretically possible polarization have been reached. The output of all atomic beam sources in operation today is in the range of 5-7$\cdot 10^{16}$ atoms/s. On the other hand LDT technology is relatively new. Although optically driven sources fulfilled their promise of fluxes up to $\simeq 10^{18}$ atoms/s, the measured nuclear polarization is only $\sim$0.1. Therefore, laser driven sources have not yet reached the figure of merit of atomic beam sources. While the present review concentrates on polarized deuterium targets, it should be mentioned that ABS and LDT alike are capable of producing polarized hydrogen as well.

## 1. Introduction

Since the first polarized, internal target was commissioned in the VEPP-3 ring at Novosibirsk in 1988[1,2], it was demonstrated repeatedly that stored, polarized beams and internal, polarized targets are experimental tools of choice to measure spin dependent observables with high precision. At present, storage cells fed by atomic beam sources are in operation at VEPP-3, IUCF[3,4,5,6], COSY[7] and DESY. The latter was in use at the TSR[8] before it was installed for HERMES. The ABS formerly installed at NIKHEF[9] has been moved to Bates and is currently being refurbished for BLAST[10]. Laser driven sources are being developed at MIT for RpEX[11] at BLAST and also at Erlangen[12] and Tohoku University[13]. The only LDT that was used in a nuclear physics experiment so far was developed at Argonne and was installed at IUCF until 1999[14,15,16].

## 2. Atomic Beam Source

An ABS consists of a RF dissociator which is typically operated at 10-30 MHz and 50-300W, yielding a dissociation fraction of 80-90 %, provided a small amount (∼0.1 %) of $O_2$ is admixed to the deuterium. The atoms emerge through a 99.5 % pure aluminum nozzle which is cooled to 80-100 K. After passing through a skimmer and collimator, the atoms enter a set of sextupoles (usually permanent magnets with ∼1.5 T pole tip field). There, atoms are separated according to their electron spin polarization. After emerging from the sextupoles the atoms pass through a RF transition unit, where transitions between hyperfine states are induced. Such a transition unit consists of a magnetic gradient field superimposed on a static magnetic field, perpendicular to which an RF field is applied. After the desired hyperfine transitions have been made, a second set of sextupoles again eliminates unwanted states. Further transitions may be induced in a second set of RF transition units. In summary, using the combination of Stern-Gerlach separation and induced transitions between hyperfine states, an atomic beam with high nuclear polarization can be prepared.

Moreover, it is possible to prepare a beam with either pure vector or pure tensor polarization. It is important to realize that the nuclear polarization in a weak field is coupled to the electron spin, but decoupled from the electron spin in a strong field. Consequently, in the absence of any RF transitions, the deuteron polarization vanishes in a strong field, whereas it is a mixture of 1/3 vector and -1/3 tensor in a weak field. The principle of operation of an atomic beam source is described in detail in [17].

Polarization reversal is accomplished by either preparing different hyperfine states or by reversal of the holding field over the target cell. The latter is only an option for vector polarization as the tensor polarization does not flip sign with inversion of the holding field. One of the major advantages of an internal, polarized target is that the direction of the target polarization can be changed while the beam is stored in the ring, thus sampling the same stored beam but with different target polarizations.

Intensities of existing atomic beam sources are remarkably similar. All sources deliver typically $5\text{-}7 \cdot 10^{16}$ atoms/s in two substates. Higher intensities would be desirable for many experiments. However, at this point in time no single "order of magnitude" improvement has been identified.

## 3. ABS performance

The theoretical maximum polarization depends on whether the atoms are in a weak or strong field[17]. In a weak field the maximum vector polarization is $\pm 2/3$ and the maximum tensor polarization is $\pm 1$. In a strong field, these values change to $\pm 1$ for vector and $+1/-2$ for tensor polarization. Various effects, such as recombination and depolarizing collisions of the atoms with the storage cell walls (see below) reduce the polarization. For example, the measured nuclear vector polarization of the HERMES target was $0.85 \pm 0.03$ during the year 2000[18]. As explained above, polarizations in a weak field are smaller, but offer greater flexibility in changing the spin direction by changing the direction of the holding field, since weak fields present less of a disturbance to the stored beam.

In the case of tensor polarization it should be noted that for small storage cells where the target density is high (see below), spin exchange in dd collisions is expected to reduce the tensor polarization[19]. The spin exchange cross section increases as the holding field decreases. The effect of spin exchange on the tensor target polarization has been observed at IUCF by measuring the target polarization as a function of the atomic beam intensity. Smaller target polarizations for higher beam intensities where observed[20]. Another study of spin exchange effects in a polarized deuterium target was conducted at NIKHEF[21].

Another interesting question is whether recombined molecules retain some of the polarization of the atoms. Aside from possible applications where polarized deuterium or hydrogen might be bottled and shipped, this question needs to be answered to assess the target polarization from a measurement of the atomic beam polarization using, e.g., a Breit-Rabi polarimeter (see below). After an exploratory measurement at NIKHEF[22] which suggested that deuterium molecules might indeed be polarized, a dedicated experiment was carried out at IUCF[23]. It was found that hydrogen atoms which are exposed to a Cu surface recombine into molecules which retain about 1/2 of the original polarization of the atoms. This is consistent with the naive picture that the first of two atoms is adsorbed by the depolarizing Cu surface where it recombines with the second atom which retains its polarization.

## 4. Polarimetry

Most experiments require that the polarization of either ABS or LDT targets is known. In general, there are two ways to accomplish this. One is to

use a Breit Rabi polarimeter which is aptly described as an "inverted ABS". In a typical arrangement, gas from inside the target cell emerges through an inspection hole and enters the polarimeter. The polarized deuterium is analyzed for its hyperfine content by passing in sequence through an RF transition unit and a set of sextupoles. A QMS mass spectrometer detects the beam at the exit of the sextupoles. Usually, a chopper in front of the QMS allows one to measure the background. An arrangement like the one just described, but without RF transition, serves as an electron polarimeter and is commonly used to measure the electron polarization for LDT targets (see below).

Another way of measuring the target polarization is to use a nuclear reaction with a known analyzing power. Then, from the observed experimental scattering asymmetry, one can deduce the target polarization.

In addition, a Lamb-shift polarimeter is being developed at COSY[24].

## 5. Storage cells

Both ABS and LDT type sources are used to fill so-called storage cells[25]. For a given flow the target thickness depends inversely on the third power of the cell diameter, making it advantageous to tailor the cell to the beam dimensions at the target location. Cells used for ABS targets are coated with either drifilm or teflon in order to prevent wall depolarization. Often, these cells are cooled to about 100 K in order to further enhance the target thickness which also depends inversely on the square root of the cell temperature. At even lower temperatures, the sticking time of the atoms on the cell walls increases, thus resulting in depolarization despite the coating[25]. An average number of wall collisions in a storage cell is 300-400 and the associated target thickness is typically $5{\cdot}10^{13}$ at/cm$^2$.

Unlike cells that are used with atomic beam sources, cells that are used for laser driven targets are heated to about 200 C in order to prevent potassium, which is needed for optical pumping (see below) from condensing on the cell walls. Drifilm, which withstands this temperature, is used to coat these cells.

## 6. Laser driven targets

Laser driven targets are manufactured as a single piece of glassware, consisting of a RF dissociator connected to a spin cell for optical pumping which also has a heated potassium ampoule connected to it. The spin cell is rigidly connected to the heated storage cell by a glass feedtube. When

the ampoule is heated to about 200 C, potassium vapor is released into the spin cell. A strong magnetic field (∼100 mT) is imposed over both spin- and target cell parallel to the direction of the light from a circularly polarized 770.1 nm Ti-Sapphire laser. Thus, the laser serves to transfer total angular momentum to the system. The electron polarization of the potassium atoms is first transferred to the electrons of the deuterium atoms by spin exchange collisions. Subsequently, through dd spin exchange collisions, the deuterium nuclei become polarized, as long as the system is in spin temperature equilibrium. Spin temperature equilibrium is defined as the most probable substate population for a given total angular momentum of the system[19].

As mentioned before, in a weak field the nucleon spin of the deuterium is coupled to the electron spin, and spin temperature equilibrium is reached after few dd collisions. A strong magnetic field requires many spin exchange collisions to reach spin temperature equilibrium. Unfortunately, a strong magnetic field is needed over the spin cell in order to avoid radiation trapping of the laser light[26].

It can be shown that the number of spin exchange collisions necessary to achieve spin temperature equilibrium is proportional to the square of the ratio of pumping field over critical field of the deuterium ($T_c$=11.7 mT). It has been tried without any improvement to the polarization to use a gradient field over the pumping cell in order to maintain a high field region for efficient pumping and a low field region for spin exchange dd collisions[27].

All surfaces of the apparatus have to be heated to 200 C to avoid condensation of the potassium. The direction of polarization can be reversed simply by reversing the helicity of the laser light. LDTs to date have achieved potassium polarizations of ∼90 % and electron polarizations of H or D atoms of ∼50 % at flowrates of $\sim 10^{18}$ atoms/s. The nuclear polarization falls short of expectation as only ∼10 % nuclear vector polarization has been measured to date[27]. Contamination of the wall surface by potassium, which is unavoidable by construction, constitutes the most serious problem of the LDT. For example, a dissociation fraction of ∼90 % in the absence of potassium is reduced to only ∼60 % once the potassium ampoule is heated[11]. Even elaborate coating techniques for the glass ware[28] have not alleviated the basic problem of potassium contamination.

## 7. The Argonne LDT at IUCF

To date only one LDT has been used as a target in a nuclear physics experiment. Until 1999 the Argonne target[14,15,16] was installed at the IUCF Cooler and used for a measurement of a spin correlation coefficient in pd elastic scattering[29]. Two charged particles were detected in coincidence by left and right detector stacks consisting of scintillators and wire chambers. The laser light was transmitted to the target through optical fibers with ∼80 % efficiency thus making the installation of a laser hut in the immediate vicinity of the target unnecessary. The nuclear vector polarization of the target was measured using quasifree pp scattering. Throughout the experiment the electron polarization was 40 %, but the nuclear polarization did not exceed 10 % [27] at a flux of $1{\cdot}10^{18}$ atoms/s. From monitoring the atomic fraction as a function of time it is evident that the potassium contamination is getting worse with proponged use of the target.

During the same experiment the target was also intermittently operated with hydrogen, where pp elastic scattering was used to analyze the target polarization. In this case the nuclear polarization was 15 %.

## 8. LDT tensor polarization

One of the advantages of an ABS is that pure vector or pure tensor polarization can be prepared by suitable combination of RF transitions. The LDT always produces a mixed vector and tensor polarized target. One can calculate[30] that in spin temperature equilibrium for an electron polarization of +1, both nuclear vector and tensor polarization are also +1. If the electron polarization is −1 (as can be achieved by inverting the helicity of the laser light) the vector polarization inverts sign as well, but the tensor polarization is again +1. Just as it is not possible to flip the tensor polarization of an ABS fed target with the holding field, it is not possible to flip the tensor polarization of an LDT target with the laser light.

The nuclear tensor polarization can be measured directly using the t(d,n)$\alpha$ reaction at low (70 keV) energy[31]. The polarized deuterons in the target are ionized by a 2 keV electron beam, extracted and accelerated toward a tritiated foil target. The reaction neutrons are detected in scintillators which are positioned at $0^o$ and $90^o$ relative to the spin alignment axis of the deuteron beam. Since the tensor analyzing power is known, the tensor polarization of the deuterium can be measured. A small, positive (0.03) tensor component was indeed found[30], but much smaller than would be expected in spin temperature equilibrium. The electron polarization

during this particular experiment was 0.3.

## 9. Summary

In a direct comparison, atomic beam sources still win out over LDTs. ABS technology is mature, where LDT technology is still in it's infancy. ABS produce pure vector or tensor polarization, LDTs produce a mixture of vector and tensor polarization. In one spin state a typical ABS produces $3.5{\cdot}10^{16}$ atoms/s where an LDT produces $1{\cdot}10^{18}$ atoms/s. The nuclear vector polarization in a strong field produced by an ABS can be as high as 85 % and is sustained for months of running, whereas the nuclear vector polarization of an LDT is only about 10 %. It is often argued that an LDT is more compact and does not require the additional complication of RF transitions. One has to keep in mind, however, that in a weak field a dissociator and a set of sextupoles (with no RF transition) still produce polarized atoms with a mixture of 1/3 vector and -1/3 tensor polarization. Both types of target allow fast flipping of the sign of the polarization, either by changing the helicity of the laser light (LDT) or by selecting a different combination of RF transitions (ABS). The vector polarization in the target cell may also be flipped by changing the sign of the holding field. The numbers above result in figures of merit ($P^2{\cdot}I$) of $2.8^{16}$ atoms/s for the ABS and $1.0^{16}$ for the LDT. Not even taking into account that higher polarization is always advantageous in suppressing systematic effects, the LDT has not yet equaled the ABS' performance.

## 10. Outlook

Obviously, a serious limitation of the LDT is presented by the surface degradation caused by the potassium. Since it is a necessity in the first place, it is difficult to imagine a remedy.

Although ABS targets have high polarization, their intensity is presently limited to a gas throughput of 1-2 mbarl/s. Tests indicate that a $\mu$-wave dissociator instead of a conventional RF dissociator would allow a factor of 2-3 higher gas flow in the dissociator[32]. However, as the beam density increases, intra beam scattering needs to be considered as a limiting factor for intensity. Presently, studies are under way[33] to better understand beam formation and propagation along the ABS axis.

## References

1. V.F. Dimitriev et al., *Phys. Lett.* **157B**, 143 (1985).

2. R. Gilman et al., *Phys. Rev. Lett.* **65**, 1733 (1990).
3. T. Wise et al., *Nucl. Instr. and Meth.* **A336**, 410 (1993).
4. M.A. Ross et al., *Nucl. Instr. and Meth.* **A344**, 307 (1994).
5. W.A. Dezarn et al., *Nucl. Instr. and Meth.* **A362**, 36 (1995).
6. W. Haeberli et al., *Phys. Rev.* **C55**, 597 (1997).
7. M. Mikirtytchiants et al., *9th Int. Workshop on Polarized Sources and Targets, Nashville, IN 2001, editors V.P. Derenchuk and B. von Przewoski* **World Scientific 2002**, 47.
8. F. Stock et al., *Nucl. Instr. and Meth.* **A343**, 334 (1994).
9. D. Szczerba et al., *Nucl. Instr. and Meth.* **A455**, 769 (2000).
10. H. Kolster et al., *9th Int. Workshop on Polarized Sources and Targets, Nashville, IN 2001, editors V.P. Derenchuk and B. von Przewoski* **World Scientific 2002**, 37.
11. Crawford et al., *9th Int. Workshop on Polarized Sources and Targets, Nashville, IN 2001, editors V.P. Derenchuk and B. von Przewoski* **World Scientific 2002**, 78.
12. J. Stenger et al., *Phys. Rev. Lett.* **78**, 4177 (1997).
13. Tadaaki Tamae et al., *7th Int. Workshop on Polarized Gas Targets and Polarized Beams, Urbana, IL 1997, editors R. Holt and M. Miller* **AIP CP421**, 434 (1998).
14. C. Coulter et al., *Phys. Rev. Lett.* **68**, 174 (1992).
15. M. Poelker et al., *Nucl. Instr. and Meth.* **A364**, 58 (1995).
16. M. Poelker et al., *Phys. Rev.* **A50**, 2450 (1994).
17. W. Haeberli, *Ann. Rev. Nucl. Sci.* **17**, 373 (1967).
18. P. Lenisa, *9th Int. Workshop on Polarized Sources and Targets, Nashville, IN 2001, editors V.P. Derenchuk and B. von Przewoski* **World Scientific 2002**, 26.
19. T. Walker and L.W. Anderson, *Nucl. Instr. and Meth.* **A334**, 313 (1993).
20. B. von Przewoski et al., *9th Int. Workshop on Polarized Sources and Targets, Nashville, IN 2001, editors V.P. Derenchuk and B. von Przewoski* **World Scientific 2002**, 57.
21. H.J. Bulten et al., *Phys. Rev.* **A58**, 1146 (1998).
22. J.F.J. van den Brand et al., *Phys. Rev. Lett.* **78**, 1235 (1997).
23. T. Wise et al., *Phys. Rev. Lett.* **87**, 042701-1 (2001).
24. R. Engels et al., *9th Int. Workshop on Polarized Sources and Targets, Nashville, IN 2001, editors V.P. Derenchuk and B. von Przewoski* **World Scientific 2002**, 52.
25. K. Zapfe et al., *Nucl. Instr. and Meth.* **A368**, 293 (1996).
26. D. Tupa and L.W. Anderson, *Phys. Rev.* **A36**, 2142 (1987).
27. C.E. Jones, *8th Int. Workshop on Polarized Sources and Targets, University of Erlangen, Germany, 1999, editors A. Gute, S. Lorenz and E. Steffens* **ISBN 3-00-005510-X**, 204.
28. J.A. Fedchak et al., *Nucl. Instr. and Meth.* **A391**, 405 (1997).
29. R.V. Cadman et al., *Phys. Rev. Lett.* **86**, 0031-9007 (2001).
30. J.A. Fedchak et al., *Nucl. Instr. and Meth.* **A417**, 182 (1998).
31. S. Price and W. Haeberli, *Nucl. Instr. and Meth.* **A326**, 416 (1993).

32. N. Koch and E. Steffens, *Rev. of Sci. Instr.* **70** 1631 (1999).
33. A. Nass et al., *9th Int. Workshop on Polarized Sources and Targets, Nashville, IN 2001, editors V.P. Derenchuk and B. von Przewoski* **World Scientific 2002**, 42.