PROCEEDINGS OF SCIENCE

Polarized Hydrogen/Deuterium molecules: a new option for polarized targets?

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In the last decades different types of storage cells have been used to increase the target density of polarized internal targets in storage rings, fed with atoms from an atomic beam source. Most of these cells are optimized to avoid recombination of the polarized hydrogen or deuterium atoms into molecules and to preserve the nuclear polarization at a high level between 0.75 and 0.9. Independently, groups at AmPS[1], IUCF[2], and HERMES[3] have shown that nucleons of recombined molecules can still be polarized. In a collaboration between the Petersburg Nuclear Physics Institute, the University of Cologne and the Forschungszentrum Jülich we have built a dedicated apparatus to measure the polarization of hydrogen(deuterium) atoms and molecules in cells of different surface materials for temperatures between 45 and 120 K, and in magnetic fields up to 1 T. In addition, the recombination probability of atoms and the number of wall collisions of molecules inside the cells have been measured with good precision. First measurements on a gold surface, on fused quartz and on FOMBLIN oil will be presented.

XVth International Workshop on Polarized Sources, Targets, and Polarimetry,
September 9-13, 2013
Charlottesville, Virginia, USA

PoS(PSTP 2013)019

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1. Introduction

For more than 30 years T-shape storage cells have been used to increase the target density of polarized internal targets in storage rings like COSY at the research center Jülich. With this method the target density of the polarized atomic jet from an atomic beam source (ABS) of about $\sim 10^{11}$ can be raised to 10^{14} atoms/cm^2. The price one has to pay is the expanded interaction region of the ion beam and the polarized target and a smaller polarization due to several effects. During wall collisions and spin-exchange interactions of the atoms, the polarization is partly lost. Even recombination of the atoms into molecules on the cell wall decreases the polarization of the protons (deuterons) in the cell. In addition, a jet target is passing the ion beam and can be dumped afterwards. With a storage cell this is not possible and the higher residual gas pressure can again reduce the polarization and disturb the ion beam. How to minimize these effects was studied for the first time by Price and Haeberli in 1993 [4]. Following their experience, the storage cells for the ANKE experiment are made from aluminum which is covered by Teflon. In the same measurements they showed that the recombined molecules have in first order no polarization [5].

The best results for such storage cells were delivered by the HERMES group which reached a polarization of 0.9 and could avoid the recombination for several weeks in a cooled cell at $T \sim 100$ K. Here, the surface of the cell was made from DryFilm which was covered by frozen water delivered mainly from the ABS itself. When this surface was damaged, e.g. by the beam, polarization was partially lost and the recombination was increased a lot. But this 'opportunity' was used to show that even the molecules could preserve the polarization substantially to some amount above 0.5 [3]. In parallel, Wise et al. [2] showed in a dedicated experiment that the polarization of hydrogen molecules depend on the magnetic field along the storage cell and the temperature.

2. The experimental setup

Price and Haeberli [4] suggested to measure the polarization of atoms and molecules in a storage cell by ionizing both particles in a strong magnetic field and accelerating the produced ions into a Lamb-shift polarimeter to investigate the nuclear polarization of atoms and molecules independently. Based on this idea a collaboration between the PNPI in St. Petersburg, the University of Cologne and the research center Jülich built a vacuum chamber with a superconducting solenoid at liquid helium temperatures (see Fig. 1). Inside this solenoid is a 40 cm long storage cell with 10 mm inner diameter made from fused quartz. The inner surface was covered e.g. with a thin gold film or other materials like liquid Fomblin. The cell can be cooled down to temperatures around 40 K via contact to the liquid helium tanks and can be heated up to 120 K without reasonable helium losses. To feed the cell with polarized hydrogen (deuterium) atoms an ABS [6] is mounted on top of the vacuum chamber. On the left side an electron gun produces an electron beam of 0.1 - 1 μA at about 100 eV beam energy which is focused through the storage cell. The storage cell itself can be set to a potential up to +8 keV to accelerate the ionized particles, protons and H_2^+-ions into the Lamb-shift polarimeter (LSP) [7]. To measure the polarization of the molecules it was planned to strip the residual electrons off the H_2^+-ions with a thin carbon foil and to separate the protons from the atoms and the molecules via their different velocities with the Wien filter of the LSP. But

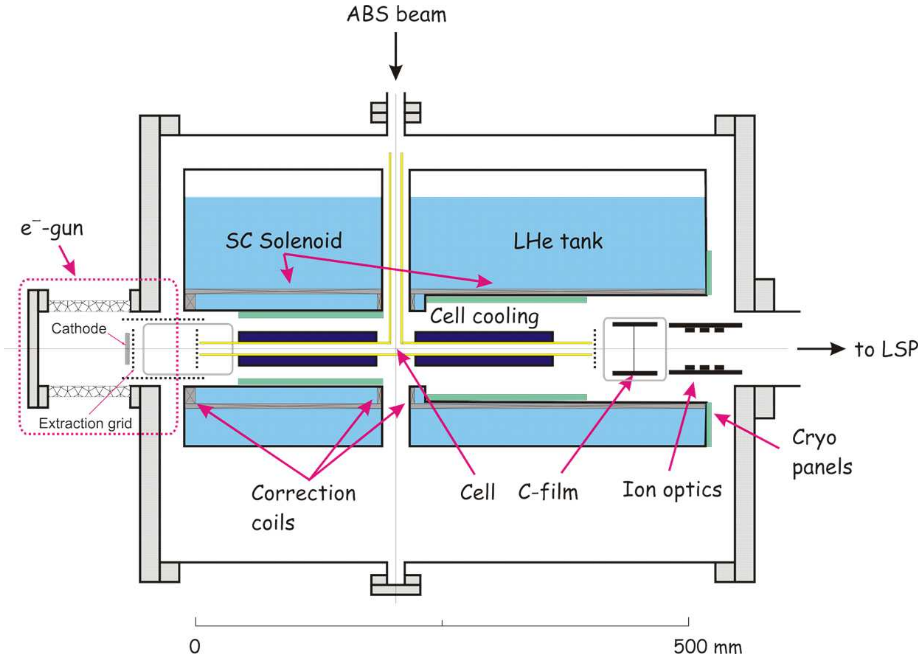

Figure 1: The experimental setup: Inside a superconducting solenoid, storage cells with different surfaces are set to a potential of 1 keV. The storage cells are fed with the polarized hydrogen (deuterium) atoms from an ABS above. An electron beam ionizes both atoms and recombined molecules into protons or H_2^+-ions, which will be accelerated and focused into the Lamb-shift polarimeter on the right side.

during the measurements it was obvious that the polarization of the H_2^+-ions and, therefore, of the molecules can be determined with the LSP directly. In this case one has to be aware that the Wien filter, depending on the magnetic field inside, will rotate the polarization of the protons, e.g. for 180° for a perfect mass separation. The direction of the polarization of the H_2^+-ions is dominated by the magnetic moment of the residual electron, which is much stronger than that of the proton. The polarization of the H_2^+-ions will follow adiabatically the direction of the magnetic field inside the Wien filter and will be perpendicular to the beam direction behind the Wien filter. Afterwards, both types of ions will reach the Cs cell where they will build up metastable hydrogen (deuterium) atoms by charge exchange with the Cesium in a strong magnetic field (~ 50 mT). The only difference in this processes is the cross section which is about 35 times smaller for the production of metastable atoms from the H_2^+-ions as compared to the protons. Again, the polarization of the H_2^+-ions will follow this longitudinal field immediately. Therefore, the magnetic field of the Wien filter does not influence the polarization of the H_2^+-ions, but it rotates the polarization of the protons (deuterons). Due to the mass separation with the Wien filter the amount of protons and H_2^+-ions can be measured independently to determine the recombination inside the storage cell. But several effects have to be considered: The cross section for the ionization of a H_2 molecule into a H_2^+-ion is about twice larger than to produce a proton from an atom. With electron bombardment even protons are produced from H_2 molecules with a 10 times smaller cross section compared to the H_2^+-ions. The biggest influence on the ratio of the H_2^+-ion current to the protons current is the fact that the average free path length of the H_2^+-ions in the used storage cells is shorter than the length of the cells itself. Therefore, a huge number of H_2^+-ions are lost and these losses depend on the ABS atomic flux and the magnetic field inside this cell. Especially due to this effect a measurement of the recombination inside the cell with the different ion currents seems to be impossible.

3. Results

When a molecule hits a wall it will lose an amount of polarization which depends on a so-called critical magnetic field B_c, defined by the molecule properties and an external magnetic field. Therefore, Wise et al.[2] showed that the average polarization of the molecules $P_{(B,n)}$ inside of a storage cell as a function of an external magnetic field B and the average number of wall collisions n can be discribed as:

$$P_{molecules,(B,n)} = P_m \cdot e^{\,n\,(\frac{B_C}{B})^2}$$

with:
P_m:= nuclear polarization of the molecules after recombination

If the nuclear polarization is not disturbed during the ionization of the molecules and the charge exchange reaction in the Cs cell this function can be measured with the polarization measurement of the H_2^+-ions in the LSP.

When the polarization of the protons is measured the situation is changed, because the protons produced from the molecules will show the same dependence on the magnetic field as the molecules. But the polarization of the atomic hydrogen shows a different behaviour. If only hydrogen atoms in hyperfine state 1 are injected, the polarization does not depend on the magnetic field B and the polarization of the protons is:

$$P_{protons\ (B,n)} = a \cdot P_a + b \cdot P_m \cdot e^{\,n\,(\frac{B_C}{B})^2}$$

with:
a:= relative amount of the protons produced from atoms,
b:= relative amount of the protons produced from molecules
P_a:= polarization of the atoms.

With the known relation of the ionization cross section of $\sigma_{H_2->H^+} = 0.2 \cdot \sigma_{H->H^+}$ the recombination c:= (Number of molecules) / (number of all particles in the cell) can be calculated very precisely:

$$c = \frac{b}{b + a/5}$$

An example of such measurements on a FOMBLIN film inside the fused quartz cell is shown in Fig. 2. Here, only hydrogen atoms in the hyperfine state 3 are injected into the storage cell that was cooled down to 100 K. The different polarization values of the H_2^+-ions (green points) are fitted by the given formula (blue). Therefore, the polarization of the molecules was $P_m = -0.84 \pm 0.02$ and the number of wall collisions was $n = 217 \pm 24$. When the polarization of the protons was measured (red points) it was obvious that the recombination inside the storage cell was very high.

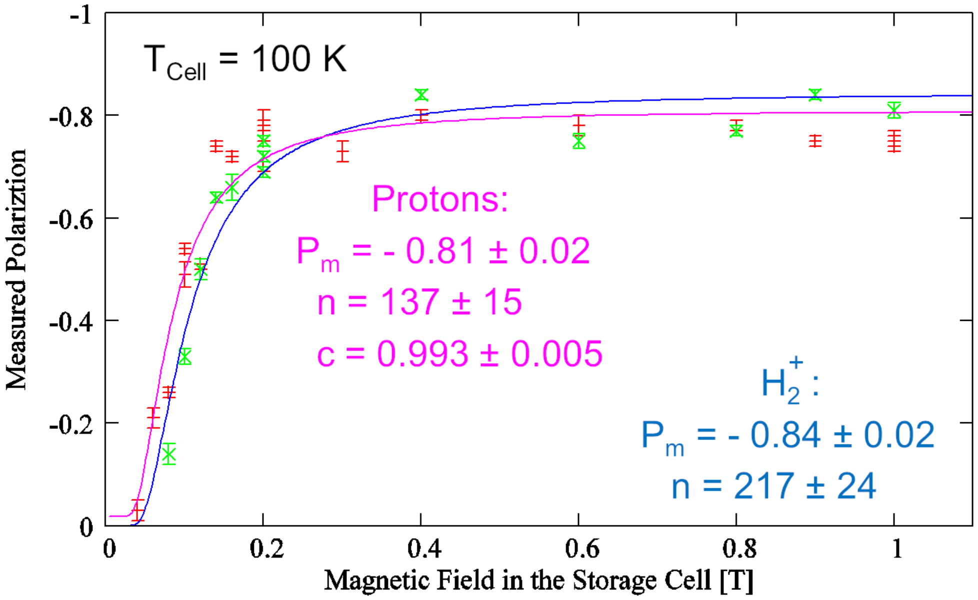

Figure 2: The measured polarization of the H_2^+-ions (green) and the protons (red) as a function of the magnetic field inside of the storage cell (T=100 K) when hydrogen atoms in hyperfine state 3 are injected. From a fit a nuclear polarization of the molecules of $P_m = -0.84 \pm 0.02$ was determined.

A fit to the measured data delivers $c = 0.993 \pm 0.005$ and a polarization of the molecules of $P_m = -0.81 \pm 0.02$. Within the errors the results of the different measurements agree. Nevertheless, a little bit lower proton polarization is possible due to the fact that during ionization an unpolarized proton background will be produced from residual gas, e.g. water, much more often than H_2^+-ions. Another interesting fact is the difference in the average numbers of wall collisions determined with both particles. Like described before, the H_2^+-ions, which are leaving the storage cell for the LSP, are produced mainly at the ends of the cell. Therefore, the average number of $n = 217 \pm 24$ must be higher, because the molecules with just a few wall collisions in the center of the cell do not contribute to this number. This value corresponds to the average number of wall collisions the molecules undergo when they are leaving the cell. The average number of wall collisions for all molecules in the cell is measured with the protons and $n = 137 \pm 15$ fits to the simulated average number of wall collisions inside the cell when only elastic scattering at the wall is assumed.

The other investigated surface materials so far, gold and fused quartz, show a similar behaviour. The recombination was large ($c > 95\%$) and the molecules are partly polarized with e.g. $P_m = 0.45 = 1/2 \cdot P_a$ for the gold surface.

Only water prevents the recombination at 100 K efficiently and and only at lower temperatures of about 50 K the recombination increased to $c \sim 0.8$. Here, it should be mentioned that a cold surface in vacuum will adsorb a water film from the residual gas very fast. Even the cryo panels mounted at the liquid helium tank could not avoid this effect for more than a few hours, because the major amount of the water comes from the ABS. Only heating of the surface at least twice per day could avoid this water film in first order.

A first measurement with deuterium atoms in a fused quartz cell showed that the critical field for vector-polarized deuterium is $B_c(D_z) = 8 \pm 1$ mT and for tensor-polarized deuterium $B_c(D_{zz}) = 11 \pm 1$ mT. In this first step a vector polarization of $P_m(D_z) = -0.4 \pm 0.01$ and a tensor polarization of $P_m(D_{zz}) = -0.24 \pm 0.03$ was reached for the deuterium molecules when deuterium atoms in the hyperfine state 3 and 4 are injected into the cell.

4. Conclusion

With this setup it is now possible to measure the polarization of atoms and molecules in different storage cells at magnetic fields up to 1 T with very good precision. In addition, the recombination on different surfaces can be determined in a temperature range between 40 and 120 K. Following the idea of Wise et al.[2] even the average number of wall collisions of the molecules inside the cell and at the cell exits can be measured. Investigations with different surface materials at different temperatures show that the recombination of hydrogen atoms is very large and independent of the temperature. This and the large polarization of the molecules, e.g. $P_m = -0.84 \pm 0.02$ after recombination on FOMBLIN, is in contradiction with the literature [4], [5]. This might be explained with the build up of a water layer on the cold surfaces in the other experiments. In our case, only water was able to avoid the recombination of hydrogen atoms at these low temperatures and to avoid the water build up on different surfaces was one of the major problems during our measurements.

In principle, with this knowledge a new storage cell can be built were the atoms might recombine on a FOMBLIN film into fully polarized molecules at very low temperatures. Then, the polarization is conserved but the target density is increased due to the lower velocity of the molecules as compared to the atoms. But in this case, magnetic holdings fields of 0.3 T or more are needed, depending on the number of wall collisions, to avoid the polarization losses of the molecules and the build up of a water layer must be suppressed.

A first experiment with deuterium atoms recombining on fused quartz showed that even deuterium molecules can preserve the polarization partly. A vector polarization of $P_m(D_z) = -0.40 \pm 0.01$ and a tensor polarization of $P_m(D_{zz}) = -0.24 \pm 0.03$ was reached. When materials like FOMBLIN will allow a high conservation of the atomic polarization in the molecules it is possible to produce polarized deuterium for the use as polarized fuel in nuclear fusion [8].

5. Acknowledgment

This work was supported by the International Science and Technology Center (ISTC No. 1861) and the Deutsche Forschungsgemeinschaft (DFG Project 436 RUS 113/977/0-1).

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