PROCEEDINGS OF SCIENCE

A Lamb-Shift Polarimeter for $\vec{\mathrm{H}}_2$ and $\vec{\mathrm{D}}_2$ Molecules

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A prototype of a source of polarized hydrogen and deuterium molecules has been developed at the Budker Institute of Nuclear Physics (BINP) in Novosibirsk. The Molecular Beam Source (MBS) is based on the Stern-Gerlach principle. First tests indicate that the separation of $\vec{\mathrm{H}}_2$ and $\vec{\mathrm{D}}_2$ molecules in the different nuclear spin projection states is possible. To verify this, a measurement of the nuclear spin polarization is needed. A Lamb-Shift Polarimeter (LSP) is well suited for this purpose. Therefore, an LSP has been built at the Institut für Kernphysik (IKP) of the Forschungszentrum Jülich. It has been shipped to Novosibirsk and there first successful tests were performed.

23rd International Spin Physics Symposium - SPIN2018 -
10-14 September, 2018
Ferrara, Italy

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1. Introduction

Originally, Lamb-Shift Polarimeter (LSP) were used to measure the nuclear spin polarisation of proton or deuteron beams with kinetic energies up to a few keV [1]. With an additional ionizer, the nuclear polarization of hydrogen or deuterium atoms can be measured, too. Most commonly, LSP are used to verify the proper function of Atomic Beam Sources (ABS). These, e.g., provide polarized atoms for internal targets in storage rings. It has been shown that the LSP is also capable of measuring the nuclear spin polarisation of $\overrightarrow{\mathrm{H}}_2$, $\overrightarrow{\mathrm{D}}_2$ and $\overrightarrow{\mathrm{HD}}$ molecules and the corresponding molecular ions $\overrightarrow{\mathrm{H}}_2^+$, $\overrightarrow{\mathrm{D}}_2^+$ and $\overrightarrow{\mathrm{HD}}^+$ [2]. This capability shall be used to study the possibility to achieve high-polarized molecular hydrogen and deuterium beams. These, e.g., may feed fusion reactors [3] or improve internal gas targets [4].
An effort to realize such a source was started at the Budker Institute of Nuclear Physics (BINP) in Novosibirsk [5]. It makes use of the set-up of superconducting coils, producing the magnetic sextupol field in the Cryogenic Atomic Beam Source (CABS), when this source is not installed at the VEPP-3 electron-storage ring to feed the gas-storage cell. The Molecular Beam Source (MBS) is based on the Stern-Gerlach principle. Here, due to the electron pairing, the separation of the molecules in the different spin substates is caused by the magnetic moment of the nuclei, which is by about three orders of magnitude weaker than that of the unpaired electron in H or D atoms. The current status of the project is presented in a contribution to the present conference [6].

2. Molecular Beam Source (MBS)

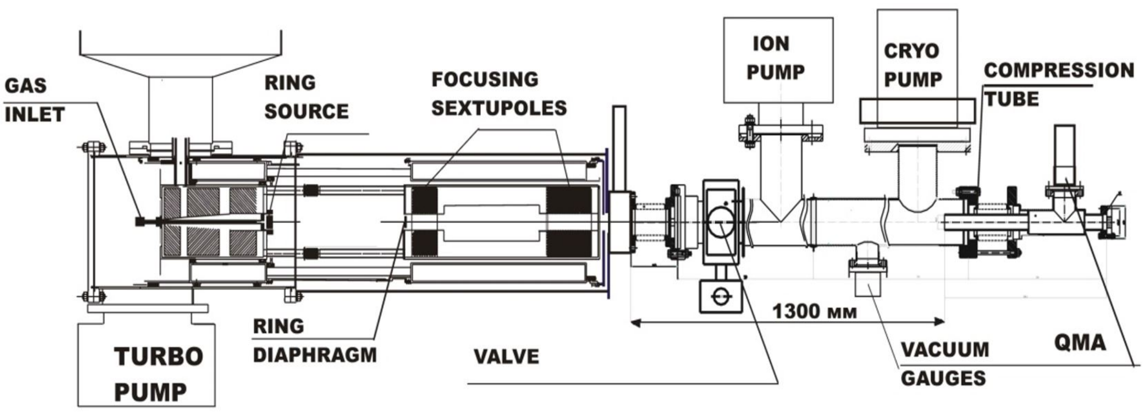

Figure 1: Schematic drawing of the MBS at the BINP [7].

A schematic drawing of the MBS is shown in Figure 1. Unpolarised H_2 or D_2 is injected through a ring shaped nozzle, which is cooled to temperatures below 30 K. This way a cold, slow, and ring-shaped gas jet is formed. The slightly wider aperture, which is ring-shaped as well, confines the gas jet. Both the nozzle and the aperture are coaxial with the subsequent two superconducting sextupol magnets. The hydrogen or deuterium molecules pass the sextupol magnets close to the pole surface. Due to the high magnetic field gradient near the poles, the molecules are deflected depending on their nuclear spin projection m_I. This deflection of the different m_I states

in magnetic gradient fields is similar to the original Stern-Gerlach experiment. Contrary to the original Stern-Gerlach experiment the total electron angular momentum quantum number is zero for H_2 and D_2. Therefore, the deflection is due to the total nuclear spin projection of the molecules. Hydrogen molecules can have total nuclear spins I of either $I = 0$ (para-hydrogen) or $I = 1$ (ortho-hydrogen). Therefore their possible nuclear spin projections m_I are $m_I = -1, 0, 1$. Hydrogen molecules with $m_I = -1$ are focused towards the axis of the magnets, while hydrogen molecules with $m_I = 1$ are defocused and hydrogen molecules with $m_I = 0$ are not affected. Deuterium molecules can have a total nuclear spin of $I = 0, 1, 2$ and therefore their nuclear spin projections are $m_I = -2, -1, 0, 1, 2$. Both the $m_I = -2$ and $m_I = -1$ molecules are focused towards the axis of the magnets, though the $m_I = -1$ molecules are less deflected than the $m_I = -2$ molecules, so that mostly deuterium molecules with $I = 2$ and $m_I = -2$ should be selected.
In the current state of the experiment, a compression tube is installed behind the magnets. Whenever the sextupol magnets are switched on, more molecules (the focused hydrogen molecules with $m_I = -1$ or the deuterium molecules with $m_I = -2$) enter the compression tube and increase the pressure in it.
For the next step, an LSP will be utilized to measure the polarization of these molecules. The LSP will be used to study the efficiency of the molecule separation according to their spin orientation.

3. Lamb-Shift Polarimeter (LSP)

In the present overview, only the functional principle of the LSP is described. The detailes are found in refs. [1, 8]. A schematic overview of the LSP is given in Figure 2.

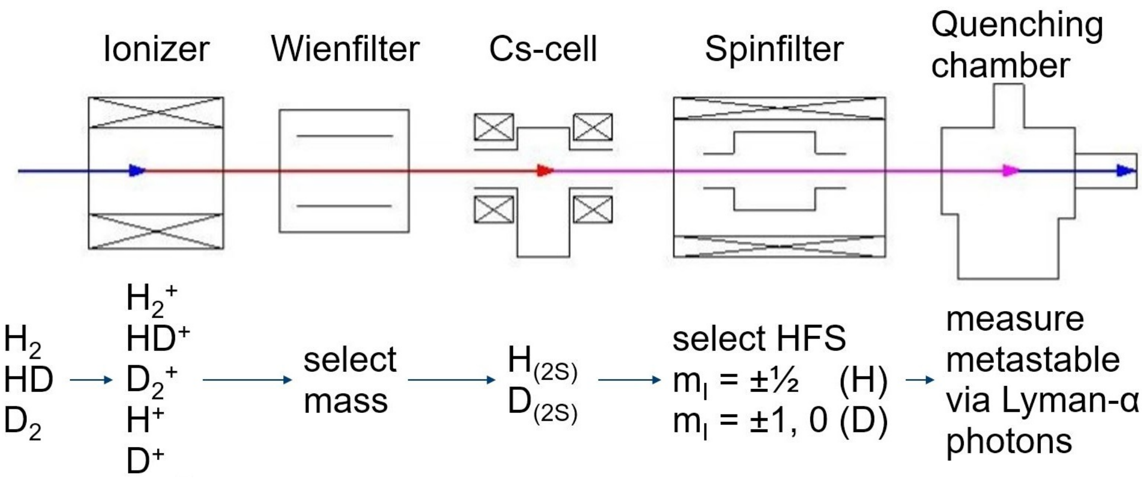

Figure 2: Scheme of the LSP components, with the beam passing from left to right. The coils of the ionizer, the cesium cell, and the Spinfilter each produce longitudinal magnetic fields along the beam axis. In the Wienfilter the magnetic field, the electric field, and the beam direction are perpendicular to each other.

3.1 Ionizer

An ionizer is needed in case of neutral beams such as the molecular beam of the MBS to allow for the mass separation in the Wienfilter and the production of metastable neutral hydrogen or deuterium atoms in the cesium cell. The ionization process is realized by electron impact. A strong magnetic field is needed to retain the polarization during the ionization process. It also helps to shape the electron beam. The ionizer for the present set-up was built at the BINP based on a design made at the IKP in the Forschungszentrum Jülich.

3.2 Wienfilter

The Wienfilter is used to separate atomic and molecular ions in the beam according to their masses. The mass separation is achieved by the combination of an electric and a magnetic field, perpendicular to each other and both perpendicular to the beam direction. It ascertains whether the measured polarization is associated to atoms or molecules, as both are produced in the ionizer. Furthermore, the behavior of the single-electron ions H_2^+ and D_2^+ differs from that of the protons and deuterons. Entering the range of the magnetic field with (anti-)parallel spin orientation against the beam direction, the ions start to precess around the magnetic field direction with the Larmor frequency $\omega_{Larmor} = \hbar^{-1} \cdot g \cdot \mu \cdot B$, with g being the g-factor, μ the magnetic moment of the precessing particle, and B the magnetic field strength. For typical parameters of an LSP, the polarization vector of the protons can rotate by up to about one full rotation. The Spinfilter determines the projection of the proton polarization to the beam axis. Thus the measured polarization depends on the angle the spin is rotated by in the Wienfilter. Consequently, only rotations which are multiple of half rotations are desirable. In the left panel of Figure 3 the polarization of protons as a function of the magnetic field of the Wienfilter is shown as measured with a set-up at the IKP of the Forschungszentrum Jülich.
Since the magnetic moment of the electron is much larger than that of the proton or the deuteron, their Larmor frequency in equally strong magnetic fields is about three orders of magnitude larger. As a consequence the magnetic moment of the electron follows the direction of the magnetic field adiabatically. Since the magnetic field of the electron acting on the protons is of the order of 10 T, the proton spin follows the electron spin. The polarization of H_2^+, measured behind the Wienfilter, is independent of the magnetic field strength of the Wienfilter. This is demonstrated in the right panel of Figure 3. In addition to the mass separation, the difference in the effect by the magnetic field allowes one to verify whether the metastable atoms, injected into the spinfilter, stem from polarized atoms or molecules.

3.3 Cesium cell

The purpose of the cesium cell is to produce metastable hydrogen H_{2S} or deuterium D_{2S} atoms, which then are injected into the spinfilter. The process to produce H_{2S} or D_{2S} atoms from protons or deuterons by charge exchange in cesium vapor $(H^+(D^+) + Cs \rightarrow H_{2S}(D_{2S}) + Cs^+)$ is well known [9]. It is most efficient for a proton energy of 0.5 keV (1 keV for deuterons) and an areal number density of 1.2×10^{14} Cs atoms per cm^2 [9]. It has been shown, that the production of metastable atoms from molecular ions in a Cs vapor is possible, too [2, 10]. However, the optimum values of beam energy and areal number density of the Cs vapor are unknown. Therefore, dedicated measurements are being performed at the IKP in Jülich, aiming at optimal H_2^+ and D_2^+ energies and Cs vapor density. To preserve the nuclear spin polarization of protons or deuterons during the charge exchange a strong magnetic field is needed. The cesium cell for this set-up is equipped

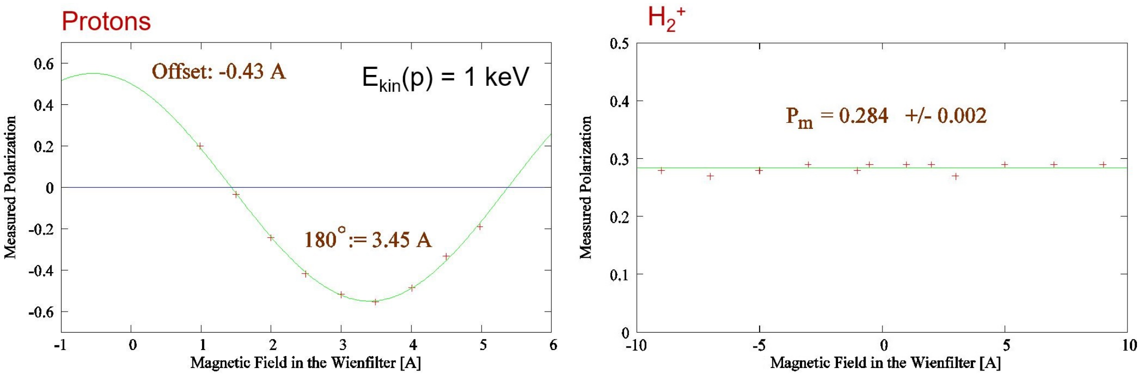

Figure 3: Polarisations of protons (left panel) and H_2^+ ions (right panel) as function of the magnetic field in the Wienfilter. The offset in the proton curve is caused by the magnetic hysteresis of the steel in the Wienfilter.

with two coils, which produce a longitudinal magnetic field of up to about 50 mT. At these field strengths more than 99% of the initial polarization is retained in the metastable atoms [2].

3.4 Spinfilter

In the spinfilter single hyperfine states of the metastable atoms (H_{2S} or D_{2S}) can be transmitted at certain magnetic field strength while all other states are quenched to the ground state. The hyperfine substates with total electron angular momentum projection $m_J = -1/2$ are coupled to the short lived $2P_{1/2}$ state. This is done with a combination of a magnetic and electric field. From the $2P_{1/2}$ state these atoms decay into the ground state and are from there on invisible for the rest of the apparatus. The hyperfine states with total electron angular momentum projection $m_J = 1/2$ are coupled to the $2P_{1/2}$ state with a radio frequency in a cavity. The cavity is tuned to have a resonant frequency of 1.60975 GHz and a width between about 0.5 MHz and 1.5 MHz. At a magnetic field of 53.5 mT the radio frequency needed to couple the $2S_{1/2}$, $m_J = 1/2$, $m_I = 1/2$ state of the hydrogen atom to the $2P_{1/2}$ state matches the resonant frequency of 1.60975 GHz. Around the resonance the coupling between the two states becomes strong enough, that the atoms are trapped in an oscillation between these states and only a fraction can decay into the ground state. Therefore, at 53.5 mT the $2S_{1/2}$, $m_J = 1/2$, $m_I = 1/2$ state of the hydrogen atom is transmitted through the Spinfilter while all other states are quenched to the ground state. Likewise the $2S_{1/2}$, $m_J = 1/2$, $m_I = -1/2$ state of the hydrogen atom is transmitted at 60.5 mT. For deuterium atoms the $2S_{1/2}$, $m_J = 1/2$, $m_I = 1$ state is transmitted at 56.5 mT, the $2S_{1/2}$, $m_J = 1/2$, $m_I = 0$ state is transmitted at 57.5 mT and the the $2S_{1/2}$, $m_J = 1/2$, $m_I = -1$ state is transmitted at 58.5 mT.

3.5 Quench Chamber

Inside the quench chamber the Stark effect is used to quench all transmitted metastable atoms to the ground state, with emission of Ly-α photons, detected by a photomultiplier. The photomultiplier signal as function of the magnetic field in the spinfilter yield a spectrum with separated peaks for the hyperfine substates transmitted by the spinfilter.

4. Current Status and Outlook

The components of the LSP, constructed at the IKP in Jülich, has been shipped to the BINP in Novosibirsk. There, the LSP has been assembles and tested successfully. However, polarization measurements on atoms or molecules could not be made up to now, since the CABS had to be installed at the VEPP-3 ring. Measurements with the MBS and the LSP will start as soon as the CABS is available again.

Acknowledgments

This work is supported by the Deutsche Forschungsgemeinschaft (grant no. BU 2227/1-1) and the Russian Science Foundation (grant no. RSF 16-42-01009).

References

[1] S.K. Lemieux et al.; Nucl. Instrum. Meth. A **333** (1993) 434.

[2] R. Engels et al.; Rev. Sci. Instr. **85** (2014) 103505.

[3] R. Engels et al.; PoS (SPIN2018) 099.

[4] R. Engles; PoS (PSTP2015) 008.

[5] D.K. Toporkov et al.; Nucl. Instrum. Meth. A **868** (2017) 15.

[6] D.K. Toporkov et al.; PoS (SPIN2018) 178.

[7] Yu.V. Shestakov et al.; J. Phys. Conf. (DSPIN-2017) 012035.

[8] R. Engels; PhD Thesis (2002).

[9] P. Pradel et al.; Phys. Rev. A **10** (1974) 797.

[10] T.B. Clegg et al.; TUNL Annual Report (1997/98) 114.