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Current developments of polarized sources and polarimeter at FZ Jülich and further applications

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A new theoretical concept of the quantum mechanical processes in spin filter for the separation of metastable hydrogen atoms in individual hyperfine substates enables a number of new applications. For example, it is now possible to build a new generation of Lamb-shift polarimeter that can separate not only α but also the β substates with $m_J = -1/2$. This opens up completely new possibilities for the search of hydrogen atoms in forbidden substates after the bound beta decay of the neutron. At the same time, corresponding simulations also provide the parameters for designing a Lamb-shift polarimeter for $^3He^+$ ions. Furthermore, it has recently been shown that classical Lamb-shift polarimeter can determine the polarization, in addition to protons/deuterons and H/D atoms, of H_2/D_2 molecules as well as all possible ion beam species, i.e. $H_2^+/D_2^+/HD^+$, H^-/D^- or even H_3^+.

In parallel, this knowledge might help to create a new type of optically pumped polarized source by transferring a laser-induced polarization of the rotational magnetic moment to the nucleons in H_2/D_2 and HD molecules. These techniques might also be used for the production and detection of polarized fuel for the enhancement of the energy output of nuclear fusion reactors or the production of hyper-polarized probes in medicine.

A recent application was a proof-of-principle measurement of the polarization conservation in H_2 molecules after recombination of polarized atoms in a carbon-coated storage cell, similar to the cell that is foreseen for a planned polarized target at the LHCb experiment. In addition, in some more exotic experiments the components of a Lamb-shift polarimeter can be used to detect axions or "dark hydrogen".

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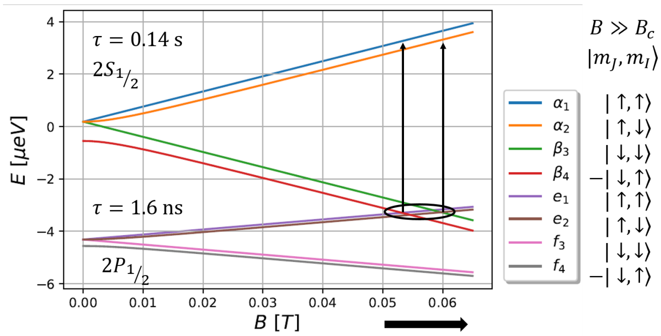

Figure 1: The Breit-Rabi diagram of hydrogen in the $2S_{1/2}$ and the $2P_{1/2}$ state shows the Lamb shift in between and the energy levels of the hyperfine substates as function of a magnetic field.

1. Introduction

The investigation of the spin-dependency of the nuclear forces at accelerators demands polarized beams and targets. During its operation from 1993 until 2023 the cooler synchrotron COSY at the research center Jülich provided both for different types of experiments in "Hadron Physics" and starting from 2015 in "Precision Physics" [1]. To optimize the polarization values of the polarized sources different types of polarimeter were in use for the complete energy range from sub-eV to GeV. Besides the normal operation during beam times especially the Lamb-shift polarimeter (LSP) allowed further research in various fields and could be developed even further.

2. The Lamb-shift polarimeter

The main component of a Lamb-shift polarimeter is the spinfilter that induces a solenoidal magnetic field, a static vertical electric field and a radio-frequency (RF) at 1.60975 GHz in the TM_{010} mode inside a cavity with an RF power about 100 mW. By that, the lifetime of individual hyperfine substates can be manipulated as it was shown by Lamb and Retherford in their famous experiment [2]. Here, the magnetic field induces a crossing of the energy levels of the β-substates of the metastable $2S_{1/2}$ states and the short-living e-substates of the $2P_{1/2}$ state. Now, the electric field couples those states (Stark-Effect) and the RF couples the α-states to the e-states. By choosing the electric field strength and the RF power and distribution the lifetime can be manipulated to quench all four metastable substates into the ground state (see Fig. 1). Nevertheless, at dedicated resonance conditions metastable atoms in a single substate, i.e. $\alpha 1$ or $\alpha 2$, can survive long enough to pass such a spinfilter. The occupation numbers of the these substates can be simulated within the density matrix formalism by implementing the influence of the different electromagnetic fields [3]. In Fig. 2 the result of such a simulation is shown in comparison to a measurement with an unpolarized proton beam. Based on this formalism, new types of such spinfilter can be developed to also select single β states as well as extending it for $^3He^+$ ions, where the latter is still in progress. The experimental setup for such a measurement is shown in Fig. 3: After the ionization of the polarized atoms or molecules the produced ions are accelerated to a few keV beam energy and sent through a Wien filter to separate the different ions due to their velocity. By charge exchange

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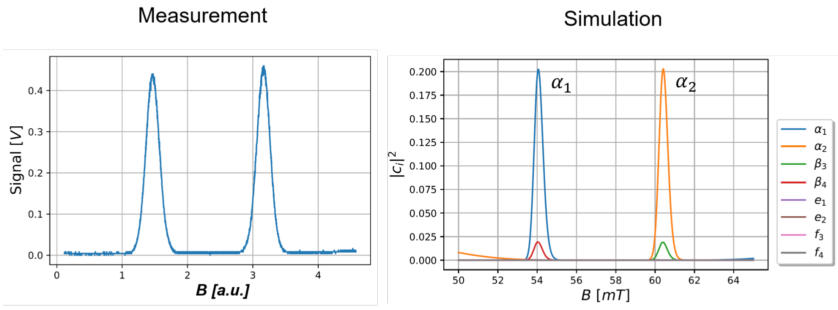

Figure 2: Measured (left) and simulated (right) amount of unpolarized metastable hydrogen atoms in a single hyperfine substate as function of the magnetic field in the spinfilter.

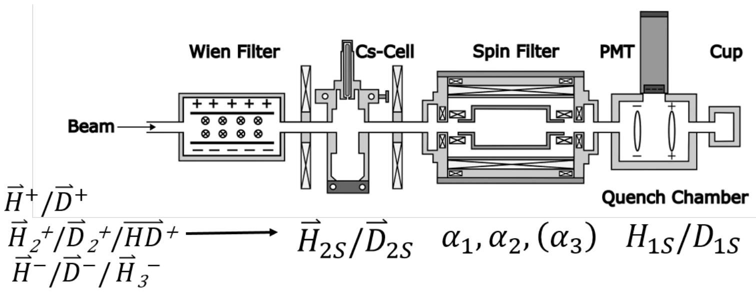

Figure 3: The setup of a Lamb-shift polarimeter.

with cesium vapor metastable atoms in the 2S state are produced in a strong magnetic field to preserve the nuclear polarization. In the spinfilter metastable atoms with a dedicated nuclear spin survive at the corresponding resonance conditions and their amount is determined by quenching them into the ground state and register the induced Lyman-α photons with a photomultiplier. In its normal operation mode the LSP was used to tune the polarized atomic beam source (ABS) of the ANKE@COSY experiment.

3. A Lamb-shift polarimeter for the pulsed polarized H^-/D^- source

Of course, LSP's are used to determine the polarization of polarized proton and deuteron beam sources [4] or in combination with an ionizer of an atomic beam from an ABS [5, 6]. At COSY it was now demonstrated that an LSP is even able to measure the polarization of a pulsed polarized H^-/D^- beam. For this purpose the corresponding beam of the polarized source at COSY [7] in the few keV energy range was deflected several times to reach the LSP [8]. That the polarization of negative ions can be detected too is possible due to another charge-exchange reaction into metastable hydrogen atoms in the cesium cell. The efficiency of this process is decreased by three orders, but is still possible even for the small beam intensities reaching the LSP. By that, the tuning of the polarized ion source could be done in parallel to other beam times, because the acceleration with the cyclotron to MeV energies and a polarization measurement with nuclear reactions within a low-energy polarimeter (LEP) are not needed anymore.

4. A Lamb-shift polarimeter to determine the nuclear polarization of molecular hydrogen and its isotopes

That the nuclear polarization of hydrogen and deuterium atoms survives partially during the possible recombination into molecules inside a storage-cell target was shown at storage rings like IUCF, NIKEF and HERMES@DESY. A dedicated investigation of these processes was conducted with the ABS from the ANKE@COSY experiment and different storage cell coatings inside a superconducting solenoid [9]. This was possible because the LSP proofs that it works for molecular ions too, even when the charge exchange cross section in the cesium cell was reduced by a factor 35±5 compared to the proton beam. Therefore, it was possible to demonstrate that by the recombination on a Fomblin surface of polarized hydrogen and deuterium atoms, both produced with the ABS in parallel, the polarization of the nucleons in the HD molecule nearly fully survives [10]. In the meantime the corresponding apparatus was used to test a possible amorphous carbon coating of future storage cells at LHCb [11]. In addition, these measurements have shown that the nuclear polarization even was preserved in H_3^+ ions [12].

5. More applications for a Lamb-shift polarimeter

The option of a spinfilter to separate single hyperfine substates of metastable hydrogen atoms and its isotopes is very useful for several other experiments:

5.1 Motion-induced transitions

When a beam of particles with the velocity v is passing through a sinusoidal magnetic field with the wavelength λ produced by two coils with opposite field direction, the particles experience in their system at rest an incoming electromagnetic wave pulse with the frequency $f = v/\lambda$. The corresponding energy of the coherent photons is $E_{Ph} = h \cdot f = h \cdot v/\lambda$. Thus, a beam of metastable hydrogen atoms in a single hyperfine substate with an energy of about 1 keV ($v \sim 10^5$ m/s) moving through such solenoids with a distance of about $d = 0.1$ m $= \lambda/2$ ($\rightarrow f \sim$ MHz) interacts with photons in the energy range of a few neV. The energy differences to other substates within the Breit-Rabi diagram due to the magnetic field amplitudes produced by the coils, allows magnetic dipole transitions that can be measured with a following spinfilter and a quenching region [13]. In principle, this method is similar to laser spectroscopy with a single wave pulse and the photon energy is tuneable between peV (thermal beams with $v < 10^3$ m/s, $\lambda \sim 1$ m) [14] and keV (accelerated ion beams with $v \sim 10^8$ m/s, $\lambda \sim 10^{-10}$ m) [15] by chosing the necessary beam velocity and the wavelenght λ.

5.2 The bound-beta decay

Parallel to the well-known neutron decay $n \rightarrow p + e + \bar{\nu}$ a 2-body decay $n \rightarrow H + \bar{\nu}$ is possible. In this case, the hydrogen atom will have a kinetic energy of 325 eV and must be in an S-state, which perfectly fits to the Lamb-shift polarimeter. Thus, the ratio of the occupation numbers of the hyperfine substates can be determined for the metastable $2S$ atoms to prove the corresponding predictions. For example, the $\beta 3$-substate with antiparallel electron and proton spin is forbidden because of helicity conservation, but might be populated due to the V-A theory [16]. A dedicated experiment is in preparation at the TU München [17].

5.3 Production of polarized fuel for fusion reactors

The idea of "polarized fusion", i.e. the usage of polarized particles in nuclear fusion reactors to manipulate the cross section of the fusion reactions, is very attractive and offers many advantages for the energy production [18]. Nevertheless, for this purpose macroscopic amounts of polarized D, T or ^{3}He are needed, either as fast intense neutral beams or pellets. Until now, optical pumping of the electron spin of the ^{3}He atom and a spin transfer to the nucleus due to the hyperfine coupling allows to produce large amounts of polarized ^{3}He with polarization values up to 0.8. But normal optical pumping is not efficient for deuterium atoms. Nevertheless, P. Rakitzis and C. Kannis recently supposed a new technique through optical pumping of the rotational magnetic moment J of cold HD molecules in a thermic beam with a sharp velocity distribution. Again, the hyperfine interaction between J and the nuclear spins I_d and I_t transfers some polarization to the nucleons and, by repeating this process a few times, large polarization values above 0.9 are accessible [19, 20]. To optimize this polarizing method a Lamb-shift polarimeter can be used that is able to determine the nuclear polarization of both nucleons in real time.
In a next step the beam intensity of this technique can be scaled up to macroscopic amounts and the cold HD molecules can be collected on a cold surface inside a strong magnet to preserve the nuclear polarization.

5.4 Future application: Dark hydrogen and axion search

In principle, the Dirac equation for the hydrogen atom allows a second solution very similar to the classical shell model. But based on E. Oks [21] ideas this solution fixed the angular momentum of the electron to $l = 0$ and, therefore, these atoms can be found in S states only. In this case, electric dipole transitions between states with different main quantum number n are not allowed and these atoms will be dark. Their existence would be able to solve several problems in modern physics like the baryonic contribution to dark matter or the neutron-lifetime puzzle. Here, the components of the Lamb-shift polarimeter might be used for a first test of their existence: When protons catch an electron in the cesium cell metastable atoms in both flavors should be produced. As next, the spinfilter is able to regulate the amount of metastable hydrogen in the classical flavor between 0 and 100%, but it cannot influence the amount of metastable atoms of the second flavor. Afterwards, the (metastable) atoms will be ionized with an electron-impact ionizer where the electron energy can be manipulated to ionize only metastable atoms. If now all hydrogen atoms are quenched to the ground state and still some protons leave the ionizer it will give a first hint of the existence of these dark hydrogen atoms.
A transition between hyperfine substates can also be induced by absorption of an axion. Similar what Yang and Dong supposed for ground state atoms in the 1S state [22] a beam of metastable hydrogen atoms in a single hyperfine substate can be produced with a spinfilter. When now these atoms are passing a solenoidal magnetic field the energy difference between the substates can be manipulated within the Breit-Rabi diagram. If such a magnetic field is ramped, then at one dedicated magnetic field such a transition will happen and can be registered with a second spinfilter.

6. Conclusion and outlook

During its operation at the Institute for Nuclear Physics in the research center Jülich the LSP has shown that it can measure the nuclear polarization of all manifestations of hydrogen and deuterium, i.e. $p, d, H^-, D^-, H_2^+, D_2^+, HD^+$ and H_3^+. It was not just a very useful tool for polarized beams and targets at the accelerators COSY, but it was and can be helpful in many other fields.

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