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Measurement of the occupation number of metastable atoms in the hyperfine-substate β_3 in an atomic hydrogen beam

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After its discovery in 1947 by Willis Eugene Lamb and Robert C. Retherford the Lamb shift was used to create Lamb shift polarimeter to separate the $2S_{1/2}$ α_1 and α_2 hyperfine substates of hydrogen as well as the α_3 substate of deuterium. But for a new project at the Technical University of Munich, investigation of the bound-beta decay of a neutron into a hydrogen atom and a neutrino, a Lamb shift polarimeter is needed that is also capable of separating the β_3 substate of hydrogen. Unfortunately, our first attempt to use a Sona transition unit to exchange the occupation numbers between α_1 and β_3 failed, because of the unexpected complexity of the transitions in this unit [1]. The second idea of using a new kind of spinfilter which uses two radio frequencies to separate all four hyperfine substates of hydrogen also failed. Our third attempt is now to build a transition unit that can induce magnetic dipole transitions between α_2 and β_3 as well as between α_2 and β_4 (π transitions, i.e. an exchange of the occupation numbers of these states). This is a similar transition to what is used in atomic beam sources, in this case not for ground state atoms but for metastable atoms, which requires a much lower radio frequency. Another difference of this new idea is the smaller interaction time of the atoms with the photons inside the transition unit due to their much higher velocity of roughly $2 \cdot 10^5$ m/s compared to velocities of about 10^3 m/s in an atomic beam source.

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1. Motivation: Neutron Bound Beta Decay

The Neutron Bound Beta Decay (BOB) experiment in Munich [2] tries to further investigate the natural decay of neutron. In general, neutrons decay into a proton, an electron and an electron antineutrino. But in one of a million cases the proton and the electron are emitted in a bound state i.e. the hydrogen atom. In this case the decay is a two body decay and the momentum of the hydrogen atom and the electron antineutrino must be equal. Besides the decay into the ground state 1S even a decay into the metastable state 2S (branching ratio 10^{-7}) is possible. Due to momentum and spin preservation there are multiple different spin combinations of the particles involved which are shown in the table below [2]. But only the upper options are allowed, because for the known

Configuration, i	$\bar{\nu}$	**n**	**p**	e^-	$W_i(\%)$	**F**	m_F	$\lvert m_s m_I\rangle$	**HFS**
1	$\leftarrow$	$\leftarrow$	$\leftarrow$	$\rightarrow$	44.14 ± 0.05	0,1	0	$\lvert +-\rangle$	α_2
2	$\leftarrow$	$\leftarrow$	$\rightarrow$	$\leftarrow$	55.25 ± 0.04	0,1	0	$\lvert -+\rangle$	β_4
3	$\leftarrow$	$\rightarrow$	$\rightarrow$	$\rightarrow$	0.622 ± 0.011	1	1	$\lvert ++\rangle$	α_1
4	$\rightarrow$	$\leftarrow$	$\leftarrow$	$\leftarrow$	0.0	1	-1	$\lvert --\rangle$	β_3
2’	$\rightarrow$	$\rightarrow$	$\rightarrow$	$\leftarrow$	0.0	0,1	0	$\lvert -+\rangle$	β_4
1’	$\rightarrow$	$\rightarrow$	$\leftarrow$	$\leftarrow$	0.0	0,1	0	$\lvert +-\rangle$	α_2

Figure 1: All spin combinations of the 4 particles involved in the free neutron decay [2, mod.]

trajectory spin down of the electron antineutrino would lead to left-handed helicity, which is not allowed for antineutrinos. This prediction should be tested by measuring the forbidden hyperfine substate β_3 of the hydrogen atom. A successful measurement of this state would mean a violation of the helicity conservation and would lead to new physics. But unfortunately the β_3 state cannot be measured dirctly with our standard tool, a Lamb-shift polarimeter (LSP). Therefore, a new tool is needed to upgrade our setup [3].

2. Traditional Spin Filters

The idea was to upgrade our LSP with a new kind of spin filter with a new separation technique compared to the traditional one.

The traditional spin filter consists of a quartered pillbox cavity embedded in a solenoid (see Fig. 2 (a)). The solenoid is used to create a homogeneous magnetic field to realize the hyperfine splitting (HFS) of the meta stable hydrogen beam going through it. Also by selecting a magnetic field of 53.5 mT or 60.5 mT it can be decided for which of the two $2S_{1/2}$ α states has to be filtered. The cavity is used for two purposes. The first one is to provide an electric field to deexcite the $2S_{1/2}\beta$ states into the $2P_{1/2}$ state. From there they deexite to ground state due to the short lifetime of the $2P_{1/2}$ state. The second is to provide a resonance radio frequency inside the cavity of about 1.60975 GHz. This radio frequency fills the energy gap between the $2S_{1/2}$ α states and the $2P_{1/2}$ e states. This induces a strong coupling between the two states while the other is coupled weakly, resulting in an oscillation for the strong coupled pair while the weakly coupled $2S_{1/2}$ α state deexcites into the corresponding $2P_{1/2}$ e state. After the beam has passed the cavity half of the atoms of the oscillating pair are in the $2S_{1/2}$ α state and the other half in the $2P_{1/2}$ e state, which then deexcite into ground state. This leaves us with a polarized beam with all meta stable atoms in one of the $2S_{1/2}$ α states. The whole filtering process is visualized in Figure 2 (b).

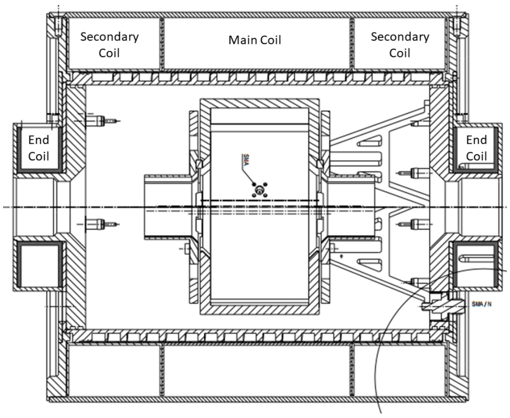

Figure 2 (a): Sketch of the traditional spin filter.

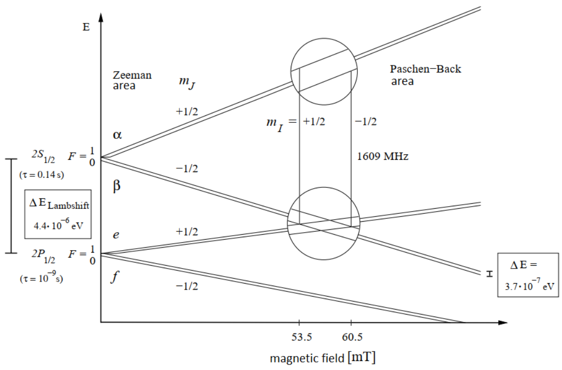

Figure 2 (b): Breit-Rabi-diagram of the HFS splitting in the Zeeman and Paschen-Back area for the $2S_{1/2}$ and the $2P_{1/2}$ states in the hydrogen atom with the transitions of the traditional spin filter [3].

3. New Spin Filter Concept

The new spin filter features a rectangular cavity instead of a round one and would need no electric field. Instead it would use two different radio frequencies. Depending on the magnetic field which is chosen it would couple three of the $2S_{1/2}$ states weekly to the $2P_{1/2}$ states resulting in a deexitation into the $2P_{1/2}$ states and from there to the ground state. The fourth state would be coupled strongly to induce an oscillation of which half of the atoms will survive after passing the spin filter. This creates a polarized beam of one $2S_{1/2}$ state which can be chosen freely. The cavity and the filtering mechanism are shown in Figure 3.

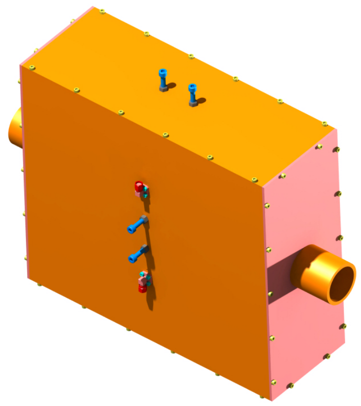

Figure 3 (a): Sketch of the rectangular cavity of the new spin filter

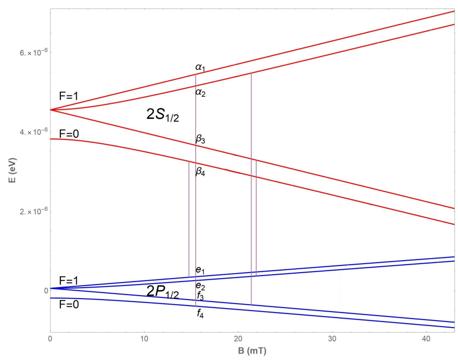

Figure 3 (b): Breit-Rabi-diagram of the HFS splitting $2S_{1/2}$ and the $2P_{1/2}$ states in the hydrogen atom with the transitions of the new spin filter

Unfortunately, this technique has a significant drawback. When experimentally investigating the principle of the new spin filter by using our current setup we discovered a huge background with very tiny peaks for the α states. The background comes from the ions which are no longer deflected by the electric field. The small peaks shown in Figure 4 (a) are a result of a lack of lifetime increase of the $2P_{1/2}$ e states in the presents of an electric field. Because of the short lifetime of the $2P_{1/2}$ states this results in an intensity loss due to the deexciting into ground states which leads to a huge damping of the oscillation and, as a result, nearly no atoms left in the filtered state. Those lifetimes are increased due to the coupling of the $2P_{1/2}$ e states to the long-living $2P_{1/2}$ β states by the electric field (Stark effect) and are shown in Figure 4.

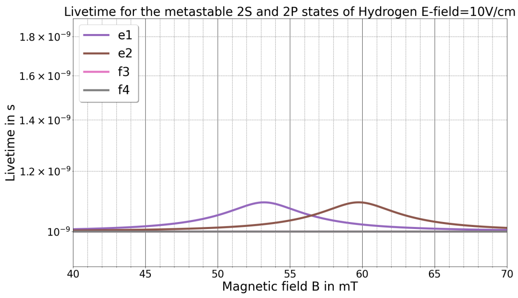

Figure 4 (a): Lifetime of the $2P_{1/2}$ states for an electric field of 10 V/cm

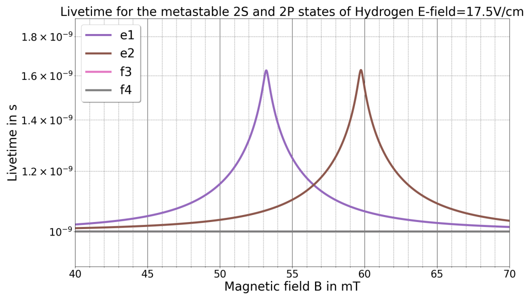

Figure 4 (b): Lifetime of the $2P_{1/2}$ states for an electric field of 17.5 V/cm

4. Transition Unit

After the new spin filter had failed it was decided to build a medium-field transition unit similar to those in the ABS used at the ANKE Experiment at COSY/ Jülich [4]. But this transition unit should be used for metastable instead of ground state atoms. The transition unit should be able to induce transitions from the $2S_{1/2}$ α_1 and α_2 states into the β_3 state and vice versa. This can be done with photon-induced transitions between these states. Nevertheless, a direct transition between α_1 and β_3 does not exist, thus it can happen only in two steps via α_2. This can be done by providing a radio frequency of 30 MHz inside a perpendicular magnetic gradient field. This will provide the right magnetic field at some point of the trajectory of the matastable atoms through the radio frequency region. Here, the photon energy will fit between the binding energy differences between the states and can induce an exchange of the occupation numbers. In Figure 5 (a) the Breit-Rabi diagram of the $2P_{1/2}$ α_1, α_2 and β_3 states is shown as well as the energy difference of 30 MHz between them. Thus, the transition from α_1 to α_2 happens at a higher magnetic field than the transition between α_2 and β_3. When the α_1 to α_2 transition has to happen first, the gradient will be placed as a falling flank in beam direction.

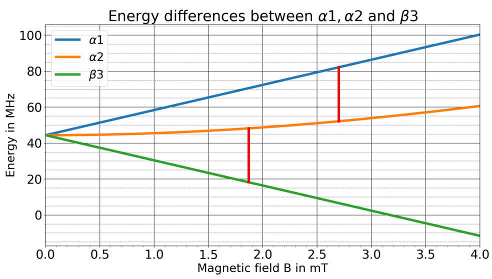

Figure 5 (a): Breit-Rabi diagramm of the $2S_{1/2}$ α_1, α_2 and β_3 states and the transitions between them.

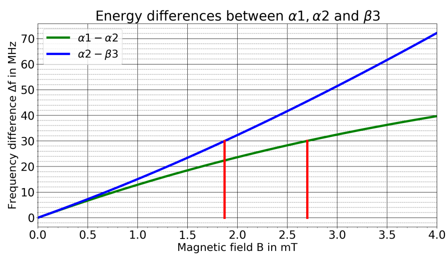

Figure 5 (b): Plot of the energy differences between the mentioned HFS.

To simplify the process the design of the existing transition unit of the ANKE ABS [5] was used and modified to our needs. To identify the necessary changes the magnetic coils were simulated as well as the magnetic field they create. In Figure 6 (a) the coil windings and the measurement lines for the magnetic field are shown. The corresponding magnetic field at those lines are shown in Figure 6 (b).

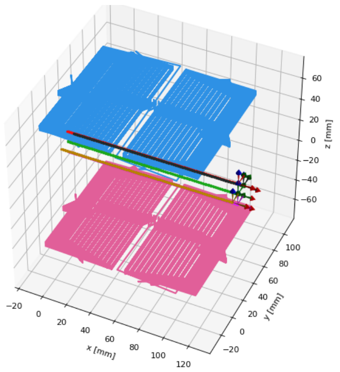

Figure 6 (a): Simulated windings of the gradient coil of the Transition Unit.

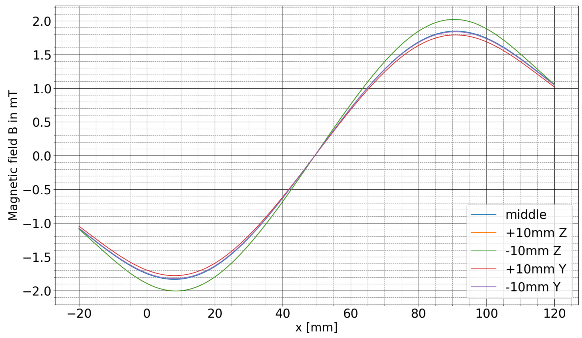

Figure 6 (b): Simulated magnetic field gradient in the Transition Unit.

The next step is now the installation of the transition unit into our LSP and corresponding tests. This can be done by using our two existing spin filters. One of them creates a polarised beam in a single HFS and with the second spin filter induced transitions in between can be verified. This method should indicate if the transition unit is good enough to be used in the BoB experiment.

5. Conclusion

Unexpectedly, filtering of the $2S_{1/2}\,\beta_3$ HFS is more complicated than expected. But with our newest attempt of using the already known principle of the medium and weak field transition units we are confident of fulfilling that goal.

References

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