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Hyperfine-spectroscopy measurement of metastable hydrogen atoms with a Sona-transition unit

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During the last 60 years, Sona transition devices have been used to invert the occupation numbers of pure states by a rapidly changing magnetic field across a zero crossing point. The inversion of the magnetic quantisation axis changes so fast that the Lamor precession cannot follow. In addition, spectroscopic measurements of the hyperfine splitting are possible. In the present setup hydrogen atoms move at a constant velocity through the Sona unit. Therefore, the Sona unit provides the region where the beam passes a static magnetic field with a gradient. It has the shape of a sine-function in z- and a cosine-function in radial direction. Thus the hydrogen atom experiences a time-varying electromagnetic field, which leads to transitions between the hyperfine states in the Breit-Rabi diagram. The beam velocity is directly proportional to the "photon" energy necessary to achieve a transition. Finally, the big advantage is that low beam energies (0.5 keV) are already enough to induce the transitions at $E \approx 5$ neV and its odd multiples, which gives the possibility to have a precession high enough to even observe the QED-corrections.

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1. Introduction

In the 1960s P. Sona proposed a new method to increase the nuclear polarization for hydrogen and deuterium beams [1]. His idea was to change the quantization axis of an external magnetic field faster than the electron spin could follow its redirection through Larmor precision. This would lead to an inversion of occupation numbers in the pure states of the hyperfine splitting in which both, proton and electron spin, are aligned in the same direction.
First indications of oscillations in the occupation numbers have been demonstrated during the PSTP conference in Brookhaven [2]. With a new experiment, the bound beta decay, on the horizon it is necessary to build a detector, which should be able to measure the β_3-state, having both spins reversed to the quantization axis [3]. For this reason, a Sona transition unit was proposed by our group to transfer all β_3-states into α_1-states, that can be measured by a Lamb-Shift polarimeter. Therefore, a Sona transition with a stationary, sinusoidal magnetic field was built and tested with the set-up shown in Fig 1.

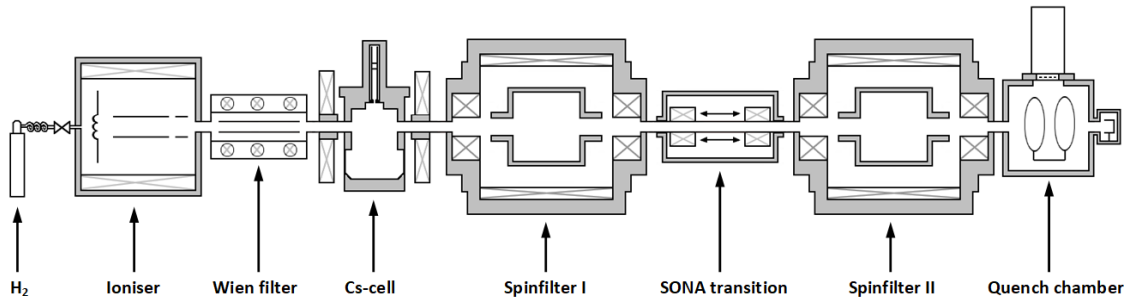

Figure 1: Experimental set-up to investigate the performance of the Sona transition unit [4].

Both spin filters [5] were set such that only atoms in the hyperfine state α_1 can pass and according to Sona's idea [1] no signal should be visible in the quenching chamber. Instead an unexpected oscillation was detected which is shown in Fig. 2.

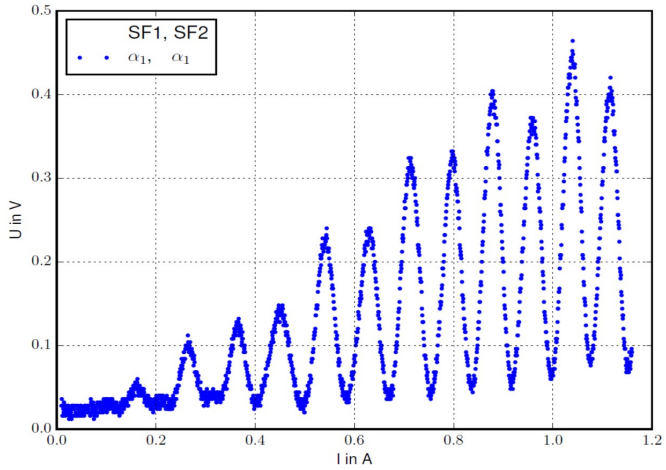

Figure 2: First measurement of the Sona transition leads to a signal of an oscillation in the occupation of the α_1 state, which is proportional to the voltage signal. This voltage is then dependent on the current used to ramp the external magnetic field amplitude [6].

2. Photon model

The Sona system consists of two coils with opposite field direction to produce a sinusoidal field in beam direction. A radial magnetic field results according to Maxwells's equation

$$\vec{\nabla} \cdot \vec{B} = 0 \qquad \Rightarrow B_r = -\frac{r}{2}\frac{\partial B_z}{\partial z}. \tag{1}$$

When the beam of hydrogen atoms enters this system, a Lorentz transformation has to be performed, to go back into the rest frame of the beam. With this the z variable describing the beam direction is transformed to $z = \gamma v t$ with $\gamma = \frac{1}{\sqrt{1+\frac{v^2}{c^2}}} \approx 1$. Additionally, the boost of the electromagnetic tensor produces an electric field out of the radial component of the magnetic field

$$E_\phi = -vB_r. \tag{2}$$

An electromagnetic oscillation in time is now recognizable as a photon with the wavelength of the magnetic field in the laboratory frame shown in Fig. 3.

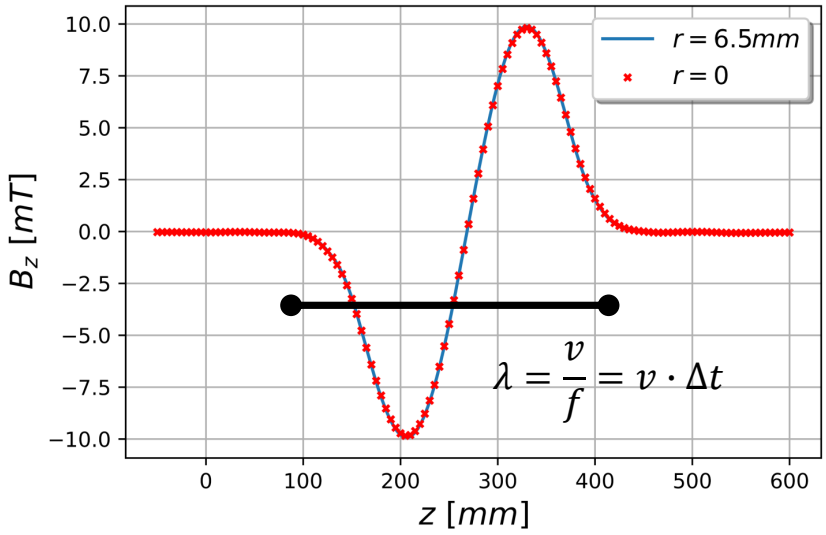

Figure 3: Measurement of the magnetic field component in beam direction.

The Planck-Einstein relation delivers the photon energy

$$E = hf = \frac{h}{\Delta t} = \frac{hv}{\lambda}. \tag{3}$$

The created photons are then responsible for transitions into different states of the Breit-Rabi diagram. The energy splitting in the diagram is weak for small magnetic field amplitudes. Correspondingly, the photons, created already with small beam energys (0.5 keV), are able to induce transitions for an energy difference of $E \approx 5$ neV. In addition, it is important to note that only an odd number of photons can be responsible for transitions according to the transition rules. By taking a closer look at the Breit-Rabi diagram it is understandable that a transition is only possible if the energy difference between the states can be filled up by an odd number of photons at once.

3. Theory

A more theoretical approach is given by solving the Schrödinger equation for the system. Several interaction terms have to be taken into account

$$H_{Hyp} = A\frac{\vec{J}\cdot\vec{I}}{\hbar^2} \qquad V_{Zeeman}(t) = \left(g_j mu_B \frac{\vec{J}}{\hbar} - g_I mu_K \frac{\vec{I}}{\hbar}\right)\cdot\vec{B}(t) \qquad V_{Stark}(t) = -e\vec{\epsilon}(t)\cdot\vec{r}. \tag{4}$$

Unfortunately, this equation is no longer directly analytically solvable. Therefore, a time-dependent perturbation is used. The unperturbed Hamiltonian is given by the hyperfine splitting and solves the following eigenequation

$$H_{Hyp}\,|m_F, F\rangle = E_{m_F,F}\,|m_F, F\rangle\,. \tag{5}$$

Since the $|m_F, F\rangle$-state is part of a full set of an orthonormal basis a transformation for a single state $|\psi\rangle$ is performed. Additionally, a time evolution has to be done

$$|\psi(t)\rangle = \sum_{F=|J-I|}^{J+I} \sum_{m_F=-F}^{F} c_{m_F,F}(t) e^{-i\left(\frac{E_{m_F,F}t}{\hbar}\right)} |m_F, F\rangle \,. \tag{6}$$

Next this state is introduced into the Schrödinger equation and converted into a partial differential equation for the pre-factors

$$\dot{c}_{m_{\tilde{F}},\tilde{F}}(t) = -\frac{i}{\hbar} \sum_{F=|J-I|}^{J+I} \sum_{m_F=-F}^{F} c_{m_F,F}(t) \cdot e^{-\frac{i\left(E_{m_F,F}-E_{m_{\tilde{F}},\tilde{F}}\right)t}{\hbar}} \langle m_{\tilde{F}}, \tilde{F}|V(t)|m_F, F\rangle \,. \tag{7}$$

By solving this differential equation in time with the magnetic set-up given from Eq. (1) the probabilities $|c_{m_F,F}|^2$ are obtained. Since in the experiment the evolution in time is not visible but the change of probabilities by increasing the external magnetic field amplitude of the Sona transition, it is necessary for comparability to do the same in the simulation. Therefore, by using each final point of the simulation where the beam would leave the Sona unit for a fixed amplitude, the measurements can be reproduced. The comparison is shown in Fig. 4. On the y-axis the occupation number of hydrogen atoms in the metastable α_1 state are plotted against the ramped magnetic field inside the Sona transition unit. Each peak is produced due to transitions, mainly coming from the α_2 state.

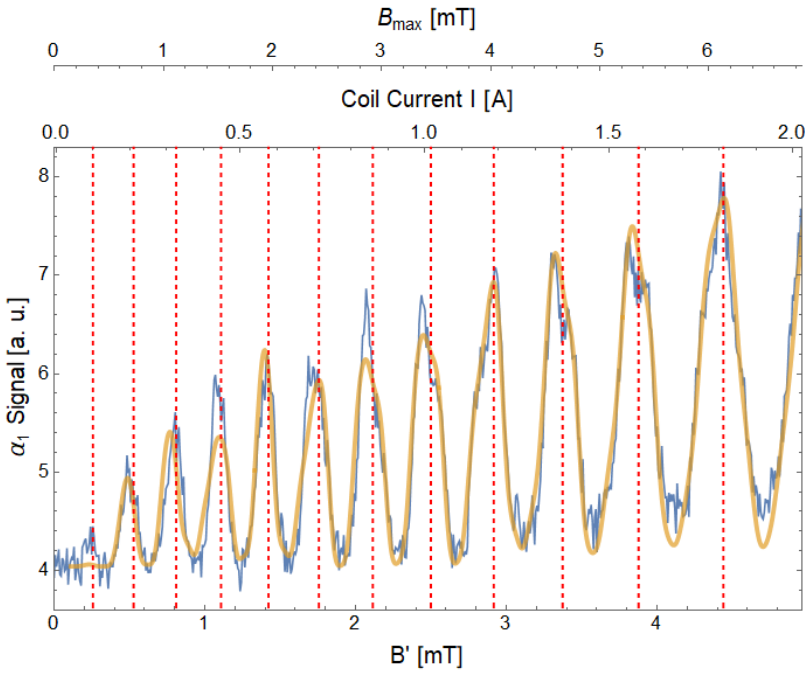

Figure 4: Comparison of a measurement of the α_1 occupation to its simulation with a beam energy of E_{beam} = 1.28 keV [4].

4. Conclusions and Outlook

As mentioned in the last section, the oscillations depend on the magnetic field. Since a huge number of variables make the calculation very complex, it is necessary to use a hit-and-run method to compare the simulation to actual measurements. The starting point is to run a simulation with some initial values for the parameters and compare it with the measurement. If they are not comparable to each other, the parameter for the magnetic field will be adjusted until the comparability is at its peak. The advantage is that without changing any parameters many different kinds of measurements can be obtained by changing the velocity of the beam, which does not influence the settings of the magnetic field but which produces different results in the end. With this in mind, hundreds of measurement can be compared to the best performing simulation from the beginning. Once knowing the exact shape of the magnetic field, the search for QED-corrections, which are manifested in the g-factors, can be continued.
Until now a reproducibility of the measurement with at least a relative uncertainty of 10^{-4} can be achieved.
Finally, the knowledge of the exact magnetic field shape is very important to later verify the QED-corrections.
It is very important to mention that this is a new spectroscopy method for any kind of atoms and molecules as long as they have at least three states created by the hyperfine splitting.

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