PROCEEDINGS OF SCIENCE

New Insights into Sona Transitions

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The Sona method, described in 1968 by Peter Sona, has been used in polarized sources of the Lamb-shift type and is still important at optically pumped ion sources, e.g. at BNL. The trick of this method is that an electron polarization of a hydrogen beam, e.g. produced by charge exchange of a proton beam with optically pumped rubidium atoms, can be transferred into nuclear polarization. For this purpose, the electron-polarized hydrogen atoms have to pass a zero-crossing of a longitudinal magnetic field that acts as quantization axis. This non-adiabatic passage exchanges the occupation numbers of the "pure" hyperfine substates $|1>$ and $|3>$, but keeps the "mixed" states $|2>$ and $|4>$. Thus, the atoms in a hydrogen beam in the states $|1>$ and $|2>$, both characterized by $m_J = +1/2$, will end up in the states $|2>$ and $|3>$ that have both $m_I = -1/2$.
Like other groups operating such a Sona unit for metastable hydrogen atoms, we observed strong oscillations of the occupation numbers of the involved hyperfine substates. These depend on several parameters like the magnetic field shape and amplitude of the Sona unit or the velocity of the hydrogen beam. In this proceeding we discussed the theoretical explanation of this effect and possible application for future polarized sources.

20th International Workshop on Polarized Source, Targets, and Polarimetry (PSTP2024)
22-27 September, 2024
Jefferson Lab, Newport News, VA

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1. Introduction

For more than 50 years "Sona transitions" [1] are an indispensable tool for different kinds of polarized ion sources. With this technique large polarization values up to $P \sim 0.9$ and beam currents up to the mA range are possible for polarized proton sources.

To polarize the electrons of hydrogen atoms in a beam is relatively easy and can be done with several methods. For example, the first polarized proton sources based on the Lamb-shift used "selective quenching" of metastable hydrogen atoms in the $2S_{1/2}$ state to depopulate the β-states with $m_J = -1/2$ but not the α-states with $m_J = +1/2$ [2]. Nowadays, spin-exchange optical pumping (SEOP) [3] is more efficient to polarize a beam of ground-state atoms. To transfer the polarization from the electron to the proton P.G. Sona proposed in 1967 to send the beam through a zero-crossing of a longitudinal magnetic field that is necessary as quantization axis to keep the spin aligned. By that the population numbers of the "pure" hyperfine substates $(\alpha)1$ and $(\beta)3$ are exchanged, contrary to the mixed states $(\alpha)2$ and $(\beta)4$. Thus, the atomic hydrogen beam becomes nuclear polarized and after ionization a H^- or a proton beam with large polarization values can be generated.

At the PSTP conference 2007 in Brookhaven several talks have been given on an unexpected oscillation of the proton polarization as a function of the magnetic field amplitude [4]. Therefore, the population numbers of the hyperfine substates change as function of an external magnetic field. This effect cannot be explained with the classical Sona transition, which shows that this kind of transition has not been fully understood so far [5]. Thus, a better understanding of the electron and nuclear spin interaction with the dedicated external magnetic field of a Sona transition is necessary that may allow to further maximize the polarization values of such polarized ions sources.

2. Theory of the Sona Method

In his method P.G. Sona presumed that a hydrogen atom with the velocity $\vec{\mathbf{v}} = v_z \hat{\mathbf{e}}_\mathbf{z}$ is moving through a magnetic gradient field region with the length $\lambda/2$, which changes its direction along z, (see fig. 1) so fast that the Larmor precessions, dominated by the electron spin, is much slower:

$$\omega_B > \omega_{Lamor} \tag{1}$$

$$\frac{1}{\Delta t} = 2v/\lambda > \mu_e \cdot B_{rad.} = -\frac{e}{2m_e} \cdot \frac{dB_{long}}{dz} \cdot \frac{r}{2} \quad . \tag{2}$$

Thus, the magnetic field gradient should be:

$$\frac{dB_{long.}}{dz} < \frac{8vm_e}{er\lambda} \tag{3}$$

In a realistic example with an atomic beam of 1 keV beam energy ($v \sim 5 \cdot 10^5$ m/s), a beam diameter of 2 cm, i.e. $r \leq 1$ cm and $\lambda = 20$ cm, the magnetic field gradient must be $\frac{dB_{long.}}{dz} < 100$ mT/cm, which can easily be obtained. Therefore, this magnetic field configuration was used at polarized ion sources to exchange the occupation numbers of the "pure" hyperfine substates $(\alpha)1$ into $(\beta)3$ and vise versa for metastable and ground-state hydrogen beams. The mixed states $(\alpha)2$ and $(\beta)4$ with

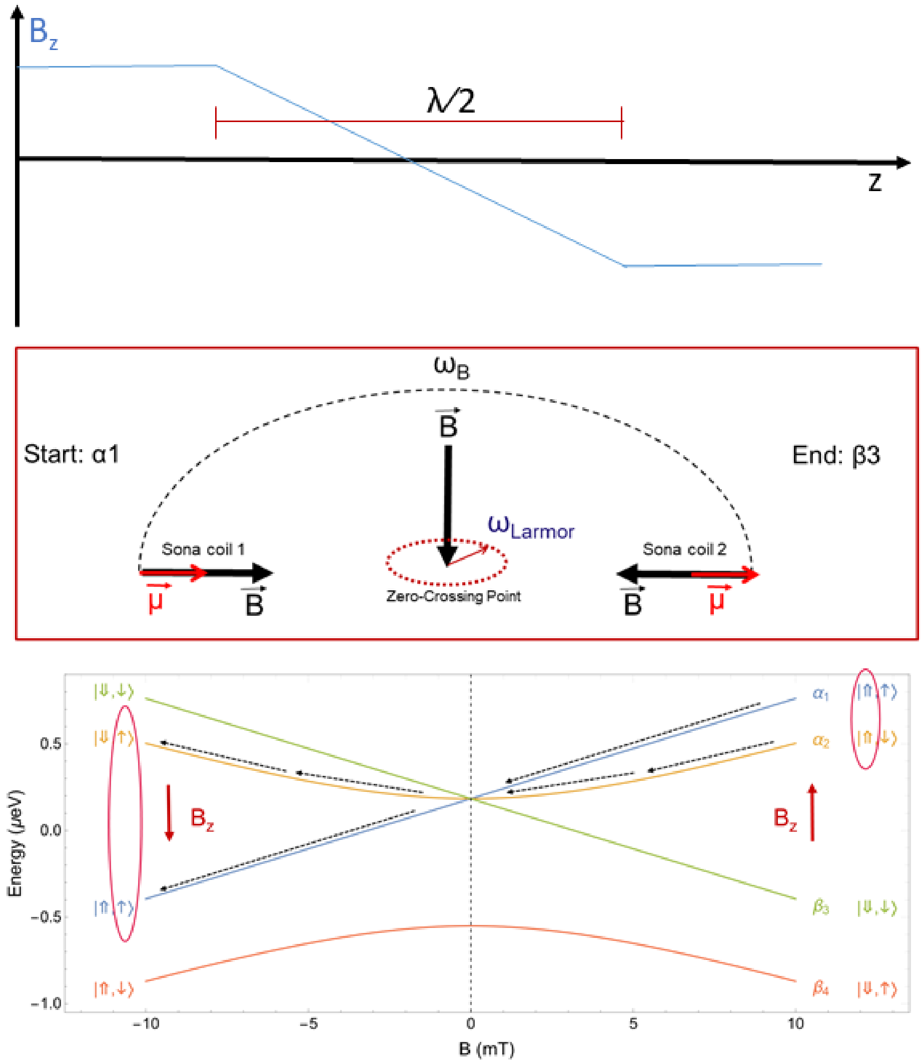

Figure 1: The principle of the classical Sona method: When the magnetic field direction along the *z*-axis is rotated much faster than the Larmor precession, the occupation numbers of the "pure" states are exchanged and a primarily electron-polarized beam becomes nuclear polarized.

$m_F = 0$ are not effected due to their linear combination in the coupled representation. By that, the electron-polarization of an incoming hydrogen beam can be transferred into a nuclear polarization (see fig. 1).

Nevertheless, previous measurements observed that the occupation numbers between the hyperfine substates start to oscillate depending of the magnetic field configuration [4, 6, 7]. In recent investigations with an optimized Sona transition for the BOB experiment [8] we realized that not the magnetic field gradient $\frac{dB_{long.}}{dz}$ in the region of the zero-crossing alone decides about the occupation numbers of the substates. Instead, the complete shape of the magnetic field will decide about an interaction between the different energy levels of the eigenstates within the Breit-Rabi diagramm.

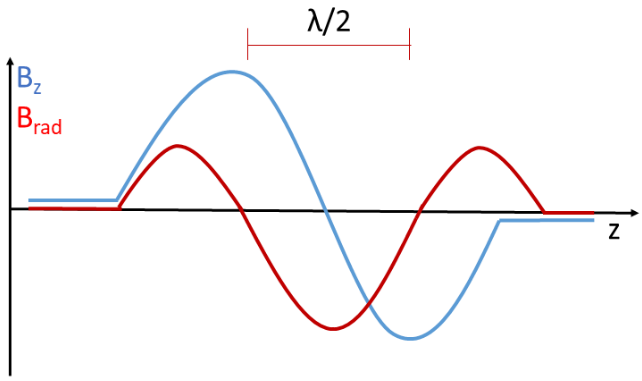

Figure 2: Two opposing solenoids generate a nearly sinusoidal magnetic field along the beam trajectory. The corresponding oscillation of the radial field component has the same frequency, but a much smaller amplitude at a radial distance r within the beam diameter.

These interactions can be calculated by solving the Schrödinger equation

$$i\hbar \frac{d|\phi(t)>}{dt} = H(t)\ |\phi(t)> \tag{4}$$

with the corresponding Hamiltonian

$$H(t) = A\ \frac{\mathbf{I}\cdot\mathbf{J}}{\hbar^2} - (g_J\mu_J\frac{\mathbf{J}}{\hbar} + g_I\mu_I\frac{\mathbf{I}}{\hbar})\cdot\mathbf{B(t)} = H_0 + V(t) \tag{5}$$

of the hyperfine splitting within perturbation theory, where A is the hyperfine energy. Depending on the constant velocity $v_z = \frac{\Delta z}{\Delta t}$ of the beam the occupation numbers of the substates can be described as function of z in the system at rest of the atoms, too.

If now a sinusoidal magnetic field is generated by two opposing coils along the z-axis, the longitudinal component will be dominant. During the flight through this magnetic field the atom experiences in its rest frame an incoming electromagnetic radio wave with the frequency $f = 1/\Delta t = \lambda/v$. The average absolute magnetic field strength during this passage will be $B_{av} = B_{max}/\sqrt{2}$. Of course, the radial magnetic field component $B_{rad.}(z,r) = -dB_z/dz \cdot r/2$ at a radial distance r from the ideal beam axis is induced and depends on the same frequency. This oscillating radial magnetic field can now induce transitions between single substates with $\Delta m_F = \pm 1$. The energy of the correlated photons is $E_{Photon} = \hbar \cdot f = \hbar \cdot v/\lambda$. The typical energy range of these photons for a beam of a few keV beam energy and a distance of the coil centers of $\lambda/2 \sim 0.2$ m is about 10^{-9} eV corresponding to a frequency of about a few MHz.

Every time an odd multiple of this photon energy fits between the energy levels of the eigenstates in the Breit-Rabi diagram (see fig. 1), absorption or stimulated emission of these photons will induce transitions within these states. The energy differences are determined by the magnetic field experienced by the atom, which is B_{av} due to the dominant longitudinal field on the beam axis. Thus, in addition to the classical Sona transition, photon-induced transitions will determine the occupation numbers of the hyperfine substates and in turn the nuclear polarization of the prepared beam.

3. The Setup

The components of a Lamb-shift polarimeter used at the polarized target at ANKE@COSY [9] are very useful to determine and to measure the occupation numbers of hydrogen atoms in single hyperfine substates. As shown in fig. 3 an ECR ion source in combination with a Wien filter is used to accelerate a proton beam up to a sharp beam energy. In a Cs cell metastable atoms are produced by charge exchange with cesium vapor in all four substates. Next, a spinfilter quenches these metastable atoms into the ground state. However, at special resonant conditions of a longitudinal magnetic field, a radial electric field and an induced radio wave at 1.60975 GHz metastable atoms in dedicated substates, either $\alpha 1$, $\alpha 2$, or both at the same time can pass through. With two solenoids

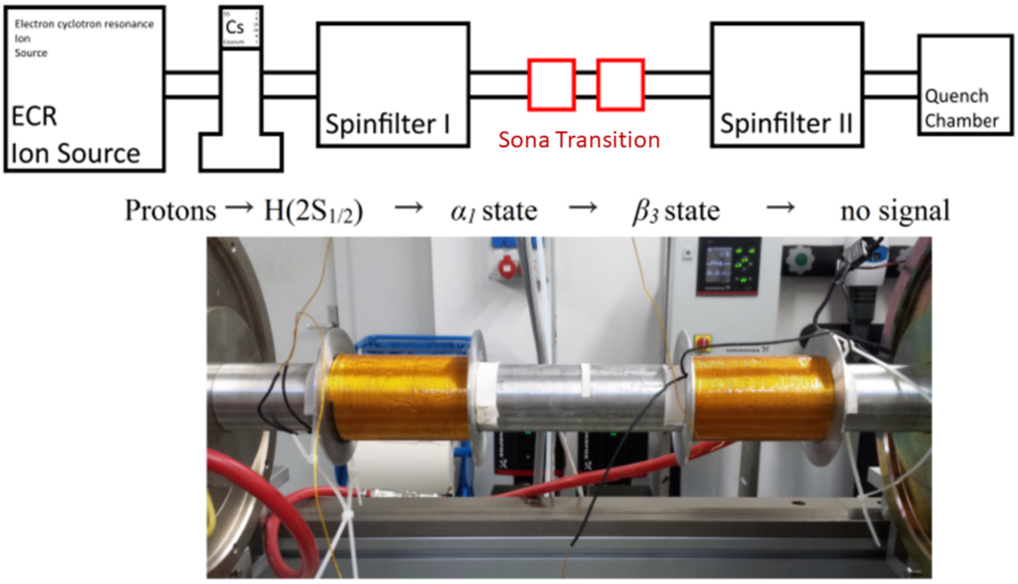

Figure 3: The experimental setup: A proton beam from an ECR source produce metastable hydrogen atoms by charge exchange with Cesium vapor. A spinfilter allows only atoms in a single α substate to transmit, e.g. in the state $\alpha 1$. A classical Sona transition will transfer these atoms into $\beta 3$, a state which can not pass the second spinfilter. If now additional transitions are induced by the radial magnetic field oscillation of the opposing coils one of the α states might be repopulated again, which can be determined in the quenching chamber.

the opposing magnetic field is produced before a second spinfilter is used to separate the occupation numbers of the α states. In the quenching chamber the residual metastable atoms are quenched into the ground state via the Stark effect and the produced Lyman-α photons are registered by means of a dedicated photomultiplier.

4. Results

When the first spinfilter is used to separate metastable atoms in the hyperfine substate $\alpha 1$, all these atoms will be transferred into the state $\beta 3$ by a classical Sona transition. Atoms in this state cannot pass the second spinfilter and, therefore, no metastable will be observed in the quenching chamber. If now the average amplitude of the oscillating magnetic field B_{av} induces an energy difference between the states $\alpha 1$ and $\alpha 2$ within the Breit-Rabi diagram, atoms are transferred from $\alpha 1$ into $\alpha 2$, survive the zero-crossing and can be transferred back into $\alpha 1$ again. This effect can be measured when the amount of metastable atoms is determined in the quenching region as a function of the current through the opposing coils. Thus, B_{av} is increased but λ, i.e. the photon energy, stays constant. The result of a corresponding measurement is shown in fig. 4. Due to the increased magnetic field B_{av} the energy distance between the substates $\alpha 1$ and $\alpha 2$ is increased, too. As expected, when odd multiples of the photon energy E_{Photon} fit to this energy difference, transitions between these states are induced and metastable atoms are found in the state $\alpha 1$ behind the second spinfilter.

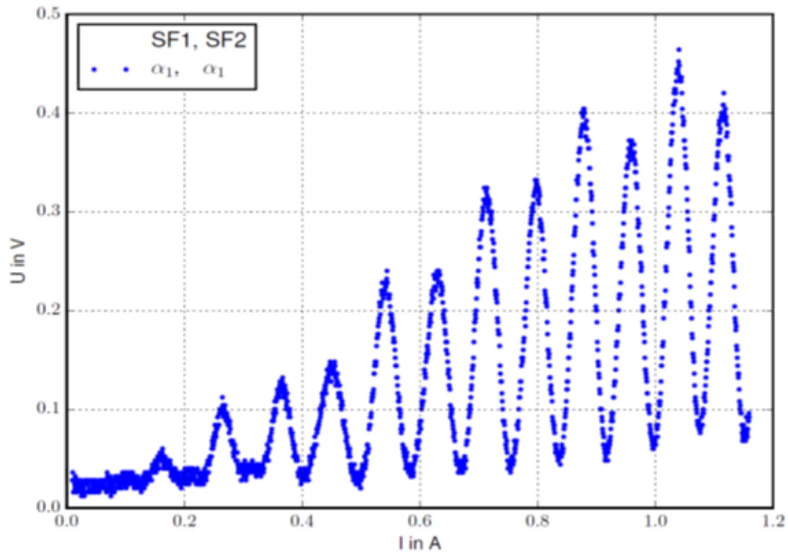

Figure 4: The relative amount of Lyman-α photons registered in the quenching chamber as function of the current in the Sona coils when metastable atoms in state $\alpha 1$ pass the first spinfilter, move through the Sona coils and pass the second spinfilter, which again allows only atoms in state $\alpha 1$ to pass.

When both α states are occupied at the beginning, transitions between the states $\alpha 2$ and $\beta 3$ will be induced as well, and a superposition of both transitions will determine the occupation numbers of the passing beam.

5. Conclusion and Outlook

The extension of the Sona technique by photon-induced transitions due to the radial field component of the magnetic field explains the observations at the polarized proton source driven by optical pumping at RHIC [4, 5]. Of course, avoiding this effect when just the classical Sona transition is needed, like for Lamb-shift sources or optically-pumped H^- sources, can help to further optimize polarized ion sources. Moreover, this additional feature may allow to overcome the limits of d and D^- sources of these types: A fully electron-polarized metastable deuterium beam includes the substates $\alpha 1$ $(m_I = +1)$, $\alpha 2$ $(m_I = 0)$ and $\alpha 3$ $(m_I = -1)$, which are transferred into the combination $\alpha 2$ $(m_I = 0)$, $\alpha 3$ $(m_I = -1)$ and $\beta 4$ $(m_I = -1)$. Therefore, the maximum of the vector-polarization will be $P_z = -2/3$ with a tensor-polarization $P_{zz} = 0$ in parallel. With additional dedicated photon-induced transitions tensor-polarization should be possible by minimizing the occupation numbers of the state $\alpha 2$ $(P_{zz} > 0)$ or increasing it compared to the other states $(P_{zz} < 0)$ and even the vector-polarization might be increased, too.
In principle, the single s-electron of all hydrogen-like atoms or ions can be polarized by optical pumping, too, and then once more this modified Sona transition can be used to transfer the electron polarization to the nucleus. Thus, polarized sources for several heavy elements are possible.
Because of the fixed energy of the induced photons that can be manipulated either due to the beam velocity or the distance of the coils, i.e. the wavelength λ, a new type of spectroscopy is possible [10]. Measured spectra as shown in fig. 4 allows to determine the resonances of different transitions between the hyperfine substates, because the energy difference between these states will be always an odd multiple of the photon energy when the magnetic field is changed. This will allow to determine the g-factors and the hyperfine splitting energies.
Similar to the hyperfine splitting of the hydrogen atom induced by the coupling of the nuclear and the electron spin, there exists a splitting due to the coupling of the nuclear spin to the rotational magnetic moment of the H_2, D_2 or HD molecules. However, these energy splittings are about three orders of magnitude smaller. But if the beam velocity is decreased by the same amount, i.e. thermal beams of 1000 m/s and less compared to beam energies in the keV range, similar transitions can be induced [11].

6. Acknowledgments

C. Kannis acknowledges funding from the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – 533904660.

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