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First test of a polarized ^{3}He$^+$ ion source

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Polarized ^{3}He ions have promising applications in nuclear physics as an ideal substitute for polarized neutron beams, and in fusion research as fuel for polarized nuclear fusion. However, current methods are limited in achievable intensity or polarization and require complex sources. Our new approach promises to overcome these limitations with an intense polarized ^{3}He beam with a polarization up to $P \sim 0.9$. The method is theoretically well understood and uses single radio wave pulses to induce transitions within the hyperfine structure in the Zeeman region of ^{3}He$^+$. In this way, the three substates of the $F = 1$ triplet can be pumped into a single one, leading to a nuclear polarization. Experimentally, the achievable polarization is planned to be measured after acceleration of the ^{3}He ions with the cyclotron JULIC using the known analyzing powers of the elastic scattering on protons in the 10–100 MeV energy range.

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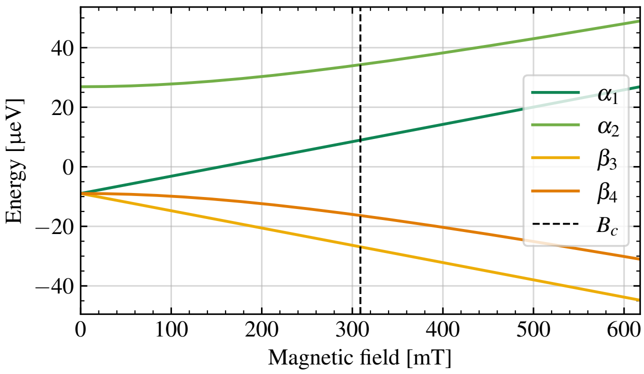
1. Introduction

Polarized ^{3}He ion sources were first tested in the 1960s [1], but either the nuclear polarization and/or the usable intensity of the corresponding beams were rather small [2, 3]. Since then, several groups have been working on the realization of an efficient polarized ^{3}He ion source for injection into storage rings, which would open a new window to investigate the spin-dependence of nuclear forces [4]. For ^{3}He the spin dependent part of the differential cross section stems in first order from the neutron spin, thus, nuclear polarized ^{3}He beams can be regarded as an ideal substitute for polarized neutron beams [5]. Additionally, the use of polarized ^{3}He in the ^{3}He-d fusion reaction increases the cross section and also allows to control the direction of ejectiles [6]. The application of this reaction in future power plants may enable more efficient energy production if the necessary amounts of polarized fuel can be produced.

Current sources for polarized ^{3}He atoms are based on optical pumping of either rubidium atoms (SEOP) or metastable ^{3}He atoms (MEOP) and subsequent spin-exchange reactions to transfer the polarization to ground state ^{3}He [5]. The new method, proposed in Ref. [7], is similar to optical pumping but instead of pumping between fine structure states with laser beams, here single radio wave pulses are used to induce transitions within the hyperfine structure directly. The corresponding photons are coherent and monochromatic and the induced transitions are at an energy level of 10^{-7} eV. For specific magnetic field configurations it is possible to achieve high polarization by absorbing the energy of few photons per ion, enabling even the polarization of macroscopic probes.

2. Theory

The aforementioned transitions are induced by the interaction between external electromagnetic fields and the hyperfine states of $^3\mathrm{He}^+$. Their level scheme in the presence of a constant homogeneous magnetic field is introduced in figure 1.



	$B \ll B_c$		$B \gg B_c$	
BRS	F	m_F	m_J	m_I
α_1	1	+1	+1/2	+1/2
α_2	0	0	+1/2	-1/2
β_3	1	-1	-1/2	-1/2
β_4	1	0	-1/2	+1/2

Figure 1: Breit-Rabi diagram of $^3\mathrm{He}^+$ and the corresponding spin configuration of the Breit-Rabi states (BRS). The spin $S = J = 1/2$ of the electron ($g_J = 2.0022$) and the spin $I = 1/2$ of the nucleus ($g_I = -4.2551$) couple into four BRS ($E_{\mathrm{HFS}} = -35.84$ µeV), whose energy levels depend on the external magnetic field. For low external fields ($B \ll B_c = 308.9$ mT) the states are well described by the total spin F (Zeeman region), while for high fields ($B \gg B_c$) the states decouple into J and I (Paschen-Back region). [8]

In the Zeeman region, the Breit-Rabi states are well described by the $|F, m_F\rangle$ basis, with $\vec{F} = \vec{I} \otimes \mathbb{1} + \mathbb{1} \otimes \vec{J}$ being the total angular momentum of the helium ion. $\vec{I}$ represents the nuclear spin and $\vec{J}$ the total angular momentum of the electron. $\vec{F}$ describes a hyperfine splitting, which creates a singlet (α_2) with $F = 0$ and the triplet (α_1, β_3 and β_4) with $F = 1$. Inside the triplet it is possible to change the occupation numbers by an interaction of a specific magnetic field configuration (B_{max}<10 mT) with the helium ion, as only a small energy gap ($\Delta E \sim 10^{-7}$ eV) separates the triplet states from each other. To achieve sizable nuclear polarization it is necessary to overpopulate one or two of the BRS compared to thermal equilibrium. This can be achieved by absorbing photons of comparable energy, which would correspond to radio wave pulses (~ MHz).

In the experiment a ^{3}He$^+$ ion beam passes through a longitudinal, sinusoidal magnetic field B_z of wavelength λ as well as a radial field B_r, which can be derived from the longitudinal one via

$$B_r = -\frac{r}{2}\frac{\partial B_z}{\partial z}. \tag{1}$$

A Lorentz transformation into the rest frame of the moving helium ions yields a time-dependent oscillation of the radial electromagnetic field, namely an electromagnetic wave. For a specific choice of wavelength λ and ion velocity v the energy of the corresponding photons is $E = h \cdot v/\lambda$. Due to angular momentum conservation an odd number of these photons can be absorbed by the ions and induce magnetic dipole transitions between the BRS, as described in more detail in Ref. [7].

Quantitatively, the evolution of the occupation numbers can be simulated by solving the Schrödinger equation in the rest frame of the ions. The corresponding Hamiltonian is given by

$$H = E_{\mathrm{HFS}}\, \vec{J} \cdot \vec{I} + \left(g_J \mu_B \vec{J} - g_I \mu_k \vec{I}\right) \cdot \vec{B}(t). \tag{2}$$

To simplify the calculations time-dependent perturbation theory is applied. For each magnetic field amplitude the final point of the solution, when the beam leaves the device, is saved. The ramping of the magnetic field then leads to such a simulation shown in figure 2 for a beam of 7 keV energy. Depending on the input parameters and the specific beam profile a nuclear polarization P of up to 90% can be achieved. More details about the calculations are given in Refs. [9, 10].

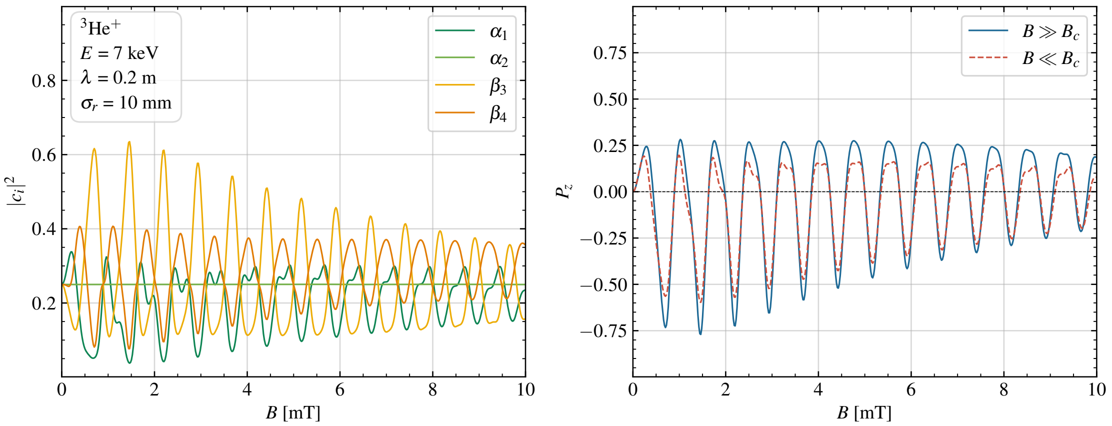


Figure 2: The simulation in the left figure shows the variation of the single probabilities $|c_i|^2$ for each BRS as function of the magnetic field amplitude. In the right figure, the corresponding nuclear polarization is illustrated for the two cases of small ($B \ll B_c$) and large ($B \gg B_c$) magnetic flux densities. The input parameters of the simulation are given above with E the beam energy, λ the wavelength of the sinusoidal magnetic field and σ_r the radial standard deviation for a Gaussian beam profile.

3. Experiment

The theoretical model predicts that an unpolarized ^{3}He$^+$ beam passing through a longitudinal, sinusoidal magnetic field will gain polarization at specific field intensities. Experimentally, this is realized with the setup described in figure 3. The ECR ion source and focusing elements used here were able to produce about 2 µA of ^{3}He$^+$ at 7 keV kinetic energy.

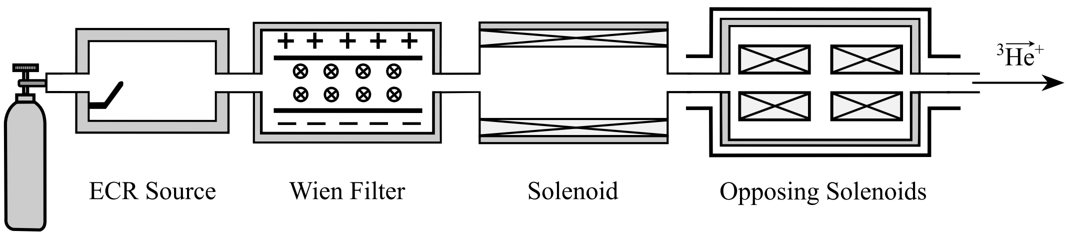


Figure 3: The ion source setup to produce $^3\overrightarrow{\text{He}}^+$. Starting from the left, ^{3}He gas is ionized in an ECR ion source and focused by some electrostatic lenses. Then the ions go through a Wien filter, ensuring that only particles of the correct charge-to-mass ratio pass and also sharpening the velocity distribution. This is followed by a strong solenoid ($B \sim 50$ mT), which defines a longitudinal quantization axis for the spin. The final component is a pair of two solenoids with opposite polarity, providing the described magnetic field configuration.

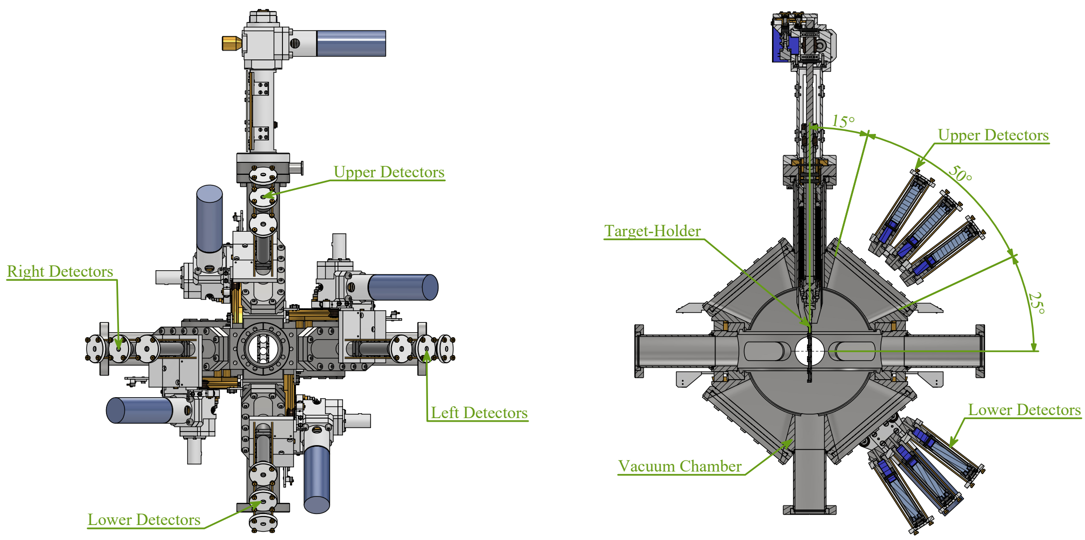
After the opposing solenoids the beam passes through a low-energy beamline to be axially injected into the cyclotron JULIC. As can be seen in Ref. [11], this beamline consists of several dipoles, quadrupoles and solenoids to steer and focus the beam through the hyperbolic inflector at the center of the cyclotron.

The initial plan for the experiment was to accelerate the $^3\mathrm{He}^+$ ions to a final energy around 70 MeV. But because the charge-to-mass ratio of $1/3$ lies on the border of the range of operation of this cyclotron [12], we were not successful to inject the particles at the corresponding settings. Instead, the cyclotron was operated in the 9ω-mode, as described in [12], limiting both the final energy to 14.2 MeV and the beam current to 0.7 nA.

After exiting the cyclotron, the beam is steered through a high-energy beamline onto a polarimeter (Low-Energy-Polarimeter [13]) equipped with a polyethylene target (CH_2). The polarization is measured using the elastic scattering reaction $^1\mathrm{H}(^3\overrightarrow{\mathrm{He}},^3\mathrm{He})^1\mathrm{H}$. Due to the reduced final energy, additionally a deuterated polyethylene target (CD_2) was installed to also evaluate the fusion reaction $^2\mathrm{H}(^3\overrightarrow{\mathrm{He}},^4\mathrm{He})^1\mathrm{H}$. The polarization dependence of the differential cross section $d\sigma/d\Omega$ is described by equation (3), where $d\sigma_0/d\Omega$ is the cross section for unpolarized particles.

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}(E,\theta) \cdot (1 + P_z \cdot A_{0y}(E,\theta) \cdot \cos(\phi)) \tag{3}$$

According to this equation a non-zero, transverse vector polarization P_z of the $^3\mathrm{He}$ particles leads to an azimuthal asymmetry proportional to the analyzing power A_{0y}. The Low-Energy-Polarimeter has twelve detectors, arranged as shown in figure 4, thereby enabling the measurement of both the horizontal and vertical asymmetries for three different polar angles simultaneously.



(a) Back-View **(b)** Vertical Cut-Through

Figure 4: Drawing of the Low-Energy-Polarimeter, initially designed to measure the polarization of H^- and D^- beams before entering COSY [13]. It consists of a movable target ladder mounted inside a vacuum chamber with 8 windows of thin stainless steel foil. Sets of three detectors are mounted in front of the four windows in beam direction, each consisting of a plastic scintillator and a photomultiplier tube.

Under the assumption of a vertical polarization of the beam and following equation (3), the polarization can be determined from the count rates N_L and N_R of a left and right detector at equal polar angles θ via equation (4):

$$P_z = \frac{1}{A_{0y}(E,\theta)} \frac{N_L - N_R}{N_L + N_R} \tag{4}$$

The analyzing power A_{0y} for the elastic $^1H(^3\overrightarrow{He},^3He)^1H$ reaction is sourced from earlier measurements on the kinematically inverse scattering of accelerated protons from polarized ^3He gas targets [14–17]. An interpolation of the data in figure 5 reveals two regions of smoothly varying, non-zero analyzing power for ^3He beam energies above 40 MeV. For a beam energy of 70 MeV the maximum of $A_{0y} = 0.28 \pm 0.02$ around $\theta_{lab} = 23°$ together with the minimum of $A_{0y} = -0.22 \pm 0.01$ around $\theta_{lab} = 46°$ can be used in parallel for a high polarization sensitivity.

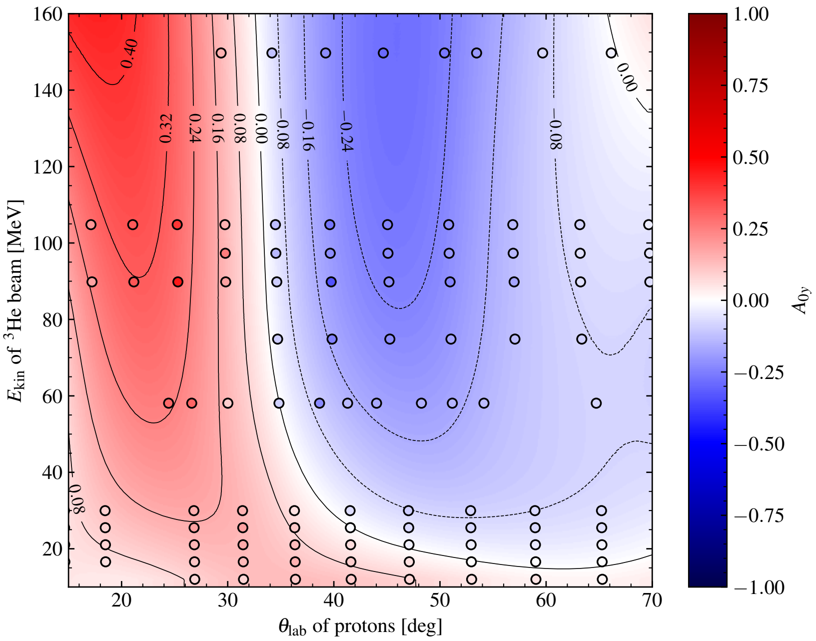


Figure 5: Bivariate spline interpolation for the ^3He analyzing power A_{0y} of $^1H(^3\overrightarrow{He},^3He)^1H$ elastic scattering reaction. Presented in the laboratory frame of resting protons against the polar angle θ_{lab} of proton ejectiles and kinetic energies E_{kin} of ^3He beam. The circles indicate the experimental measurement points [14–17].

For beam energies below 15 MeV the analyzing power of the elastic reaction does not exceed $A_{0y} = 0.15$ and also lacks the second region of negative analyzing power. Here it could be more useful to employ the fusion reaction $^2H(^3\overrightarrow{He},^4He)^1H$. A contour map of the analyzing power for this reaction can be found in Ref. [18], indicating an analyzing power exceeding $A_{0y} = 0.5$ for outgoing protons at detectable polar angles.

4. Conclusion and Outlook

The new polarization method proposed in Ref. [7] can drastically simplify the production of polarized ^3He ion beams, enabling the use in polarized fusion and nuclear physics research. The procedure is theoretically well understood and an experiment to measure the polarization is described here. The experiment could not be performed as intended due to problems inherent to the cyclotron, instead the ^{3}He$^+$ beam was only accelerated to 14.2 MeV. As discussed, here the analyzing power of ^{1}H($^3\overrightarrow{\mathrm{He}}$,^{3}He)^{1}H does not exceed 0.15, together with the low beam intensity drastically reducing the expected sensitivity for polarization. Instead, the attention was shifted to the fusion reaction ^{2}H($^3\overrightarrow{\mathrm{He}}$,^{4}He)^{1}H, which also provides more favorable kinematics. Originally it was also intended to strip the ^{3}He$^+$ into ^{3}He^{++} to avoid depolarization after the cyclotron, which was not possible either with the available target at the lower beam energy. It is also assumed that the long beam transport in front of the cyclotron (compare [11]) could lead to significant polarization loss, as the ^{3}He$^+$ ions are, due to the single electron, about three orders of magnitude more sensitive to external magnetic fields than the more commonly accelerated polarized H$^-$ or D$^-$ beams. The evaluation of the data from the experiment described above is still ongoing, but for future experiments it is strongly recommended to strip the beam to ^{3}He^{++} as early as possible to significantly reduce possible depolarization. For similar reasons further experiments are planned at accelerators with simpler injection schemes, which should allow for a more sensitive test of the proposed polarized ^{3}He ion source.

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