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Polarized ^{3}He Ion Source based on a Metastable Atomic Beam

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Abstract

This source is based on the use of a beam of neutral metastable ^{3}He* atoms in the 2^3S_1 state (with $\mu_F \cong 2\mu_B$ and 4166s lifetime). Polarization is achieved by multipole selection of hyperfine components (Stern-Gerlach method) followed by an adiabatic RF transition (Abragam-Winter) and ionization in a strong B field. It is operational in the HV terminal of a CN van de Graaff (7.5 MV). A beam of ^{3}He$^+$ ions has been accelerated with preliminary values of polarization between 50 and 80% and maximum intensity of 300 nA.

§1. General Introduction

Polarized ^{3}He ion sources have been discussed in the literature[1,2]. In addition polarized atomic beams of metastable atoms of ^{4}He* and ^{3}He* in the 2^3S_1 state are important in their own right[3]. A polarized ^{3}He ion source has been operated in conjunction with the Birmingham cyclotron, based on a Lamb shift technique applied to the ^{3}He$^+$ ion in the 2s state[4]. Beams on target were in the range of 2 nA with 60 to 70% polarization. A new scheme based on the 2^3S_1 state of the neutral atom was proposed recently[2]. The metastable atoms have a long lifetime, infinite for all practical purposes dealing with atomic beam techniques, which bear promise of intense polarized beams in general[5]. The present source was designed taking into account the limitations in the HV terminal of a Van de Graaff[6].

Indicating the total angular momentum of the ^{3}He atom by $\vec{F} = \vec{J} + \vec{I}$, where $\vec{J}$ and $\vec{I}$ correspond to the electronic and nuclear angular momenta, it is useful to represent the wave functions of hyperfine states by

$$|F=1/2,\ M_F= 1/2> = \sqrt{2/3}|m_J=1>\ |m_I=-1/2> - \sqrt{1/3}|m_J=0>\ |m_I=1/2> \quad (1)$$

$$|F=3/2,\ m_F= 3/2> = |m_J=1>\ |m_I=1/2> \quad (2)$$

$$|F=1/2,\ m_F=-1/2> = -\sqrt{2/3}|m_J=-1>\ |m_I=1/2> + \sqrt{1/3}|m_J=0>\ |m_I=-1/2> \quad (3)$$

$$|F=3/2,\ m_F= 1/2> = \sqrt{2/3}|m_J=0>\ |m_I=1/2> + \sqrt{1/3}|m_J=1>\ |m_I=-1/2> \quad (4)$$

$$|F=3/2,\ m_F=-1/2> = \sqrt{2/3}|m_J=0>\ |m_I=-1/2> + \sqrt{1/3}|m_J=-1>\ |m_I=1/2> \quad (5)$$

$$|F=3/2,\ m_F=-3/2> = |m_J=-1>\ |m_I=-1/2> \quad (6)$$

The Breit-Rabi diagram of the Zeeman hyperfine components of the 2^3S_1 state of ^{3}He is shown in fig. 1 , where the numbers correspond to those of equations (1) - (6). It is clear that 1 and 2 are strongly focussed by a multipole field. In a weak magnetic field they would yield a nuclear polarization $|P_N| = 0.33$ if their proportions were identical. Due to the difference in effective magnetic moments between components 1 and 2, particularly below 0.1T, a quadrupole field can enhance the selection of component 2 which is pure over component 1 which is mixed in electronic and nuclear spin. An adiabatic transition of the Abragam and Winter[7] type may be used to reverse $m_F \to -m_F$, transforming components 1-2 into 3-6. The latter would produce a nuclear polarization $|P_N| \cong 1.00$ in a strong magnetic field with $B \geq 0.2T$. After the use of the adiabatic transition it is necessary to ionize in a strong field in order to produce a polarized beam. Fig. 2 shows the sequence of steps of the $^3\vec{He}$ polarized ion source, it is also a schematic of it.

§2. Detailed Description of the Polarized Ion Source Steps

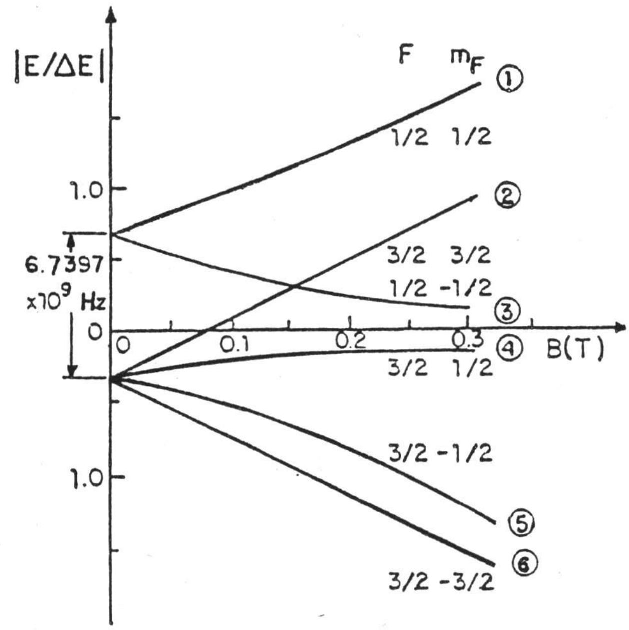

Fig. 1. Breit-Rabi diagram of hyperfine components

2.1 Thermal metastable source

There are two main techniques for the production of metastable atoms[3]. One is based on the electron capture by He^+ ions, the other is based on direct excitation of atoms. The latter utilizes diverse methods for the excitation, ranging from particle bombardment[8] to photon bombardment[9] with intense laser discharges. For atomic beams subject to Stern-Gerlach selection the velocity of atoms should be as small as possible. We have constructed a source producing a beam of thermal metastable atoms with energies around 0.085 eV, suitable for atomic beam techniques, following the design of Fahey et al[10] with some changes destined to increase the flux of metastables. It is a cold cathode discharge source with tungsten points and a quartz tube capped by a BN piece with a 0.17mm ϕ nozzle. The discharge current can reach 30 mA with a metastable flux of 6×10^{15} Ns^{-1}. The discharge is initiated by an auxiliary electrode located between the nozzle and a 0.6 mm ϕ skimmer, which defines the beam sent to the multipole region. Discharge voltage range between 500 and 700 V, and pressures are between 1 and 2×10^{-3} torr. The gas injection pressure may range between 50 and 80 torr. Pumping in the discharge region is provided by a turbomolecular pump with a speed of 360 ℓs^{-1} backed by a sealed mechanical pump which recirculates the gas, through lines provided with filters to purify the ^{3}He. The energy distribution of the metastable beam is Maxwellian but slightly epithermal with a mean velocity of 2.5×10^5 cm s^{-1}, due to the additional recoil energy from electron impact and some gas heating in the discharge tube. The diagnostics of the beam of metastable is particularly simple because with proper biasing an electric current is produced from the bombardment of a metal surface, gas contaminated surfaces of metals tend to yield a conversion factor to free electrons $\gamma < 1$. Howard et al. [11] have determined $\gamma = 0.74$ for stainless steel, which we have used throughout our work. It is safe to assume that the electron current provides a lower bound to the metastable current. Using this technique we have determined a maximum metastable current useful for the next step close to 1000 nA. A schematic of the metastable source is seen in Fig. 2.

2.2 Stern-Gerlach Selection

The inhomogeneous magnetic field of a multipole exerts a focussing radial force (toward the axis) for magnetic moments corresponding to states with $m_F > 0$ and reciprocally, a defocussing force for states with $m_F < 0$. In a strong field only components 1 and 2 are focussed, components 5 and 6 are defocussed and components 3 and 4 are slightly affected. In addition, a quadrupole field will select preferentially component 2 over component 1. The multipole of the present source is an electromagnetic sextupole with pole pieces 140 mm long, with a tapered gap over the first 70 mm to 5 mm to 10 mm, and straight over the following 70 mm. The acceptance angle is 2.40 when used as a sextupole. The sextupole field is of the form $B=B_0r^2$ and can produce a harmonic motion of focussed particles with fixed modal points. However, the forces for small amplitudes on the magnetic dipoles are small ($|F| = kr$), and the effect on a fine pencil beam as produced by the metastable source is rather weak. A quadrupole field is of the form $B=B_0r$, and the forces on the magnetic dipoles are constant ($|F| = B_0$) but strong for small amplitudes. We are using the sextupole in a non conventional way. The polarities (N, north; S, south) are in the sequence N-S-S-N-S-S, resulting in a hybrid field possessing a quadrupole gradient for small amplitudes and a sextupole gradient for large amplitudes. There is a gain of focussed beam in our source by a factor of three over the conventional sextupole field[12]. It produces

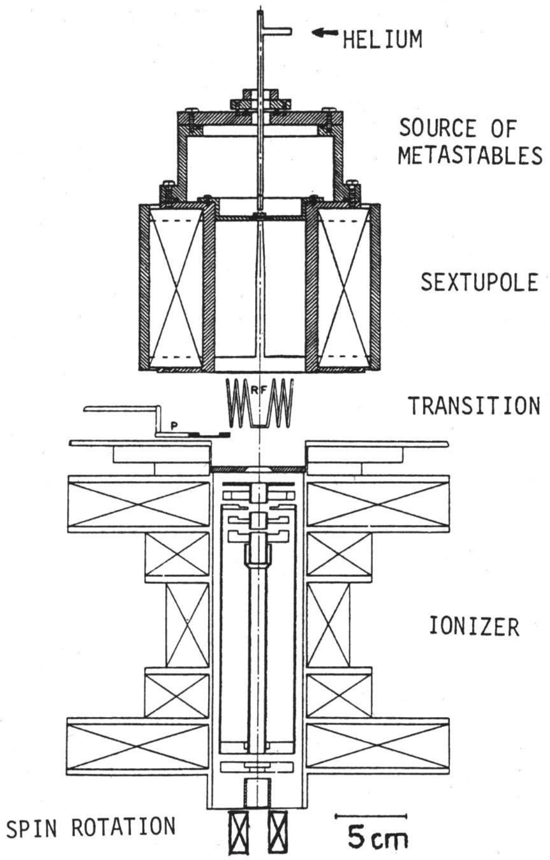

Fig. 2 · Schematic of the source (pumping systems not shown)

also a better rejection of unwanted components. The polarization P of the atomic beam has been determined by a Stern-Gerlach deflection in an inhomogeneous magnetic field, the value is $P_z \simeq 0.95$[12]. A criterion which has guided the design of the source is the reduction of the flight distance of the metastable beam to a minimum, maintaining the vacuum in the sextupole region to a low value ($\sim 3\times10^{-6}$ torr-gauge). Collisional loss is the main reason for the attenuation of the metastable beam intensity. The sextupole design is original with pole pieces in vacuum and coils outside the vacuum chamber, pumping is provided by a 360 ℓ sec^{-1} turbomolecular pump attached to a box following the sextupole. All components have been built in-house (see Fig. 3).

2.3 Adiabatic RF transition, ionisation and spin reversal

The transition following Abragam and Winter[7] requires a linearly varying magnetic field $\vec{B}$ (with distance) in a region where an RF coil produces a time dependent $\vec{B}_1$ with a frequency ω_L, perpendicular to $\vec{B}$. The particular sequence of polarities used in the sextupole produces an axial field B beyond the pole pieces, diminishing linearly with distance, hence with an RF field perpendicular to the beam trajectory it is possible to reverse the spin orientation transforming (1) and (2) into (3) and (6). The RF power injected is 45w at 30 MHz. The transition is complete and instantaneous, as determined using Stern-Gerlach deflection methods in an inhomogeneous magnetic field [12].

The ionisation potential of the helium metastables is 4.6 eV. We have built an electron bombardment ionizer, with a field of 0.2T, adapted to the conditions of our polarized atomic beam. The ionisation region is 10mm ϕ and 150 mm long. The magnetic field is obtained with five coils of variable diameter in order to minimize the weight and power consumption (2.5 Kw). Liquid cooling is used for the ioniser, the sextupole and the turbomolecular pumps. The liquid is conveyed by polyethylene tubing to the terminal and heat is exchanged at the base of the accelerator. The filament in the ioniser is almost redundant as its current can be reduced to zero once the plasma discharge is established inside the ioniser volume. The pressures at the bottom of the ioniser are in the range of 10^{-7} torr. It is possible to operate the ioniser in a mode which discriminates between the metastables and the background atoms in the ground state, producing thus $^3He^+$ ions from the polarized metastable atoms. Ionisation to $^3He^{++}$ can be done efficiently at about 0.9 MeV ($\langle z \rangle = 1.9$) via foil stripping. This step can be effected by insertion of a foil at about 1/7 of the length of the accelerating tube. A foil changer has been designed and a tube extension is to be added. For the initial operation $^3He^+$ is accelerated and stripped at the base of the accelerator prior to the 90° analysing magnet, to avoid depolarisation in the strong magnetic field.

Spin reversal of these ions is effected with a small magnetic field (10 to 20 gauss) in the region following the ioniser. Here there are also deflecting plates and an einzel lens to steer and focus the beam. The spin rotation field will be used also to properly orient the spin with respect to the scattering plane at the experimental area.

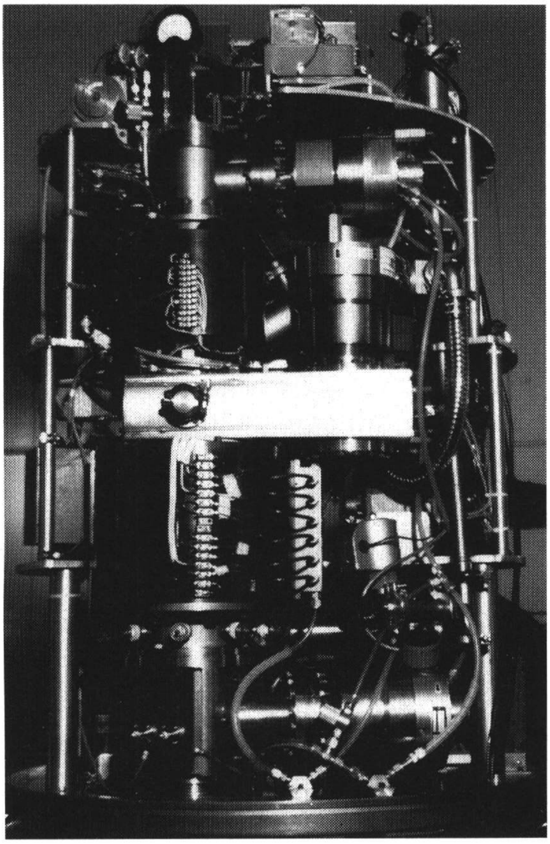

Fig. 3 · Polarized ^{3}He ion source installed in the terminal of the CN van de Graaff.

2.4 Performance of the source

After successfull operation on a test bench, the $^3He^+$ ions produced by the ioniser were mass analysed and proven to originate from the metastable atom beam, the source has been installed on the H V terminal (Fig. 3). Vacuum is provided by two sealed mechanical forevacuum pumps and three 360 ℓ^{-1} turbomolecular pumps. The former are driven directly by V-belts transmitting power from the main belt axle inside the terminal. The turbos are fed by a three phase A.C. generator at 400 Hz, with 1.5 Kw power capacity. Voltage and current readouts are transmitted via light emitting diodes and optic fibers coupled to digital displays. The hostile environment of a pressurized high voltage terminal has conspired against a quick commissioning of the ion source. Leaks of insulation gas into the ^{3}He recirculation system and electronic burnouts have been the main obstacles. However, most difficulties are now under control. Currents of $^3He^+$ at the base of the accelerator reach 300 nA. The RF transition is still subject to improvements, in order to stabilize the resulting nuclear polarizations. The latter are monitored using the analysing power of the $^3\vec{He}$ (d,p) ^{4}He reaction[13] available between E_d = 2.8 and 10 MeV, 4.2 to 15 MeV using $^3\vec{He}$ as projectiles. The high Q-value allows easy discrimination of protons. Polarisations lie between 50% and 80%, these results being preliminary.

Acknowledgements

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DISCUSSION

HAEBERLI: How was the polarization of the ^{3}He-beam determined?

SLOBODRIAN: We used (^{3}He,p) on deuterium with deuterated polyethylene foil. No analyzing power is known.

FICK: Can you comment on your surface ionizer which you mentioned briefly?

SLOBODRIAN: The surface ionization with the Langmuir-Saha law was rather unsuccessful. The reduction of negative ions looks promising, particularly for tandem accelerators. There was a 50% efficiency for production of negative ions, but one would need polarized electrons to produce a pure spin state (5/2,5/2).