

Production of a spin-polarized, metastable He(2^3S) beam for studies in atomic and surface physics

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This beam was developed as a target for a crossed-beam electron-atom scattering experiment on the interaction of a polarized spin- $\frac{1}{2}$ electron with a polarized spin-1 atom. In the future this beam will be used in “Spin-Polarized Metastable Atom Deexcitation Spectroscopy” (SPMDS) for studying ferromagnetic surfaces without and with adsorbate layers. We use a discharge source for producing a beam of metastable helium atoms, a permanent sextupole magnet with a central stop at its exit for selecting He(2^3S) atoms in the Zeeman substate $m_s = +1$, a zero-field spin flipper for reversing the atomic beam polarization with respect to a magnetic guiding field, and a Stern-Gerlach magnet for analyzing the atomic polarization. At a distance of 90 cm beyond the exit of the sextupole, in the “interaction region” of an experiment, the polarized beam has a circular cross section of about 6 mm FWHM and a particle density of $1 \cdot 10^7$ atoms/cm³. The reversible spin polarization was determined as $P = 0.90 \pm 0.02$. A possible contamination of the beam with metastable singlet atoms is included within this value; the ground-state He atoms are not considered to be part of the polarized beam. An observed contamination with long-lived Rydberg atoms can easily be destroyed by applying a high electric field.

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Introduction

In developing our discharge source we utilized the experience of Fahey et al. [1] and of Ruf et al. [2] with similar sources. The design of the permanent sextupole magnet was mainly based on the work of Kramer [3] and our own extensive experience with such devices [4–6]. Independent of this work Slobodrian et al. [7] employed similar techniques to produce a polarized ^3He ion beam for nuclear physics experiments.

Our beam system has already been used in an experiment on the ionization of polarized He(2^3S) atoms by impact of polarized electrons [8], the very first atomic physics electron scattering experiment involving polarized spin-1 particles. In surface physics “Metastable Atom Deexcitation Spectroscopy” (MDS) was developed to a very useful tool in recent years [9]. The spin-polarized version of this spectroscopy (SPMDS) has been pioneered by the Rice Uni-

versity group [10, 11]; they use optical pumping for polarizing their metastable atoms [10, 12]. With the increased polarization and current of our beam the feasibility of ferromagnetic surface studies will also increase.

Experimental arrangement

The arrangement of the various components is shown schematically in Fig. 1. The radiative lifetime of the He(2^3S) atoms of about 10^4 s [13] is “infinitely” long compared with the millisecond flight time through the apparatus. Differential pumping is essential for several reasons: The first two chambers have to be pumped vigorously in order to remove the helium gas from the He* source. The pumping in the other chambers is aimed at ultrahigh vacuum in order to minimize the ion background from Penning ionization of rest gas molecules and to provide clean condi-

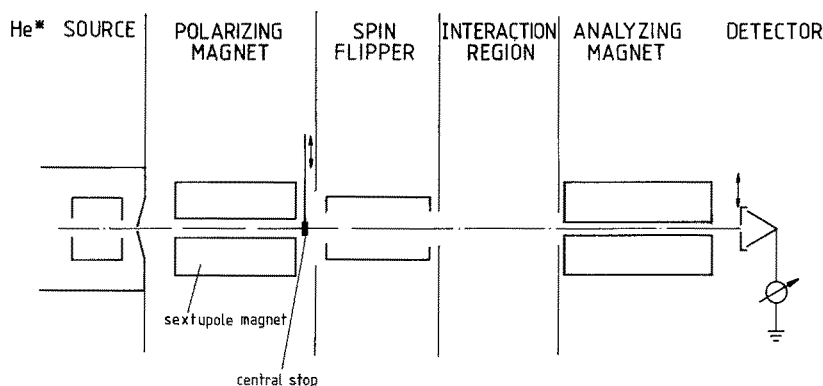


Fig. 1. General layout of the apparatus (not to scale)

tions for surface studies. The source chamber has a 570 l/s turbomolecular pump in series with a two-stage, 30 m³/h rotary forepump. With differential pumping in the magnet chamber (570 l/s) and in the spin-flipper chamber (270 l/s) the gas input into the interaction region is reduced to about $5 \cdot 10^{-6}$ mb l/s. The interaction chamber is UHV compatible and bakeable. Certain components in the other chambers, however, can be baked only mildly, e.g., the sextupole magnet up to 250 °C.

The discharge source produces a beam which contains ground-state He(1^1S) atoms, metastable He(2^1S) and He(2^3S) atoms as well as long-lived Rydberg atoms. The sextupole magnet acts as a polarizer by preferentially transmitting the atoms with magnetic quantum number $m_s = +1$ and strongly suppressing the ones with $m_s = -1$. Without the central stop at the magnet exit, the atoms with $m_s = 0$ – including all the ground-state and the metastable singlet atoms – are transmitted if their straight-line trajectories can clear the magnet. With the central stop in place, ideally only the He(2^3S) atoms in Zeeman state $m_s = +1$ are transmitted. The spin flipper is a device for polarization reversal, that is, for transferring the atoms from $m_s = +1$ into the Zeeman state with $m_s = -1$. The Stern-Gerlach magnet and, alternatively, another sextupole magnet is used for analyzing the atomic polarization.

Not indicated in Fig. 1 is the magnetic guiding field, necessary in order to prevent depolarizing Majorana transitions within the Zeeman-state multiplet. Between the components along the beamline the guiding field is provided by a longitudinal field of about 10^{-4} T. Within the sextupole and the Stern-Gerlach magnet the ferromagnetic poles provide strong inhomogeneous fields orthogonal to the beam axis, overriding the weak guiding field. (In the fringe fields at the entrance and the exit of both magnets the atomic spins follow the change of the local field direction adiabatically.) The spin flipper is surrounded by a magnetic shield which keeps the guiding field out and

allows to establish conditions for either adiabatic or diabatic transitions. The interaction region is also shielded magnetically. Here the guiding field is reduced to 10^{-5} T. At this level a cross-fired electron beam is not much deflected from a straight path.

Beyond the spin flipper the metastable beam current is measured by utilizing surface deexcitation followed by electron emission and collection. In the interaction region the beam profile is measured by moving a channel electron multiplier (CEM) with a 0.2 mm slit in front of it across the beam. Similarly, another CEM is used to determine the beam profiles produced by the analyzing Stern-Gerlach magnet.

For absolute flux measurements, without beam-profile determination, we used a Faraday cup 80 cm behind the exit of the polarizing sextupole magnet. The metastable atoms hit a stainless steel plate of 20 mm diameter and eject secondary electrons with a quantum efficiency of about 0.7 [14]. With a bias of +10 V the emitted electrons are drawn to a copper pipe surrounding the plate and their current is measured with an electrometer.

Discharge source

A cross section of the source is shown in Fig. 2. The tungsten needle as cathode is connected to a 1.3 kV dc voltage via a 50 k Ω load resistor. The nozzle aperture as anode is grounded. In order to contain the discharge radially the needle is surrounded by a ceramic tubing (Degussit) and the inside of the front part of the enclosure is covered by a ceramic plate (Aremcolox) of 1 mm thickness, exposing only the rim of the nozzle through a 1.5 mm diameter hole.

The distance between needle and nozzle is 5 mm. The source (except for the tungsten needle and the ceramic parts) and the skimmer are made of stainless steel (German steel code 1.4571). The skimmer opening has a diameter of 0.6 mm and is located 5 mm downstream of the nozzle. The skimmer potential is variable.

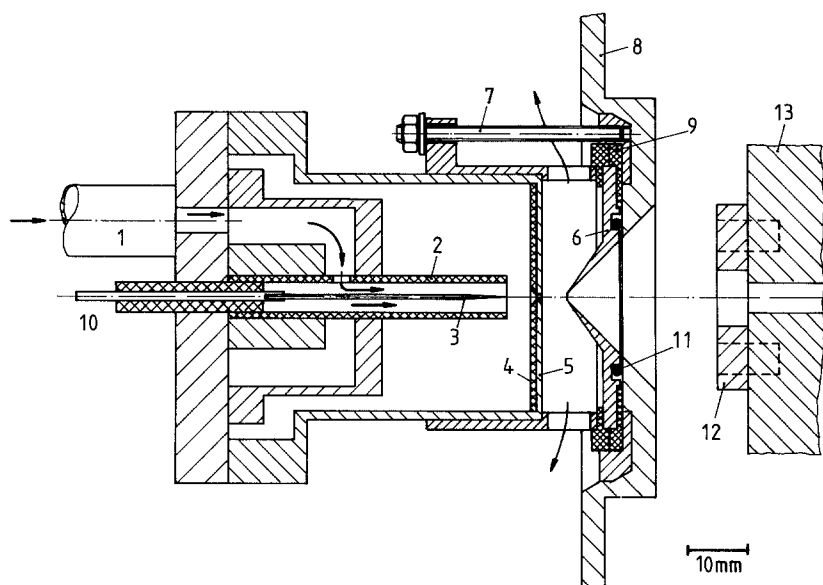


Fig. 2. Cross section of the discharge source. (1) Helium gas inlet; (2) ceramic tubing; (3) tungsten needle; (4) ceramic plate; (5) source enclosure; (6) skimmer; (7) spacer; (8) partition of vacuum chamber; (9) insulating disk (Teflon); (10) electrical connector; (11) O-ring (Viton); (12) retainer with spacers; (13) sextupole magnet

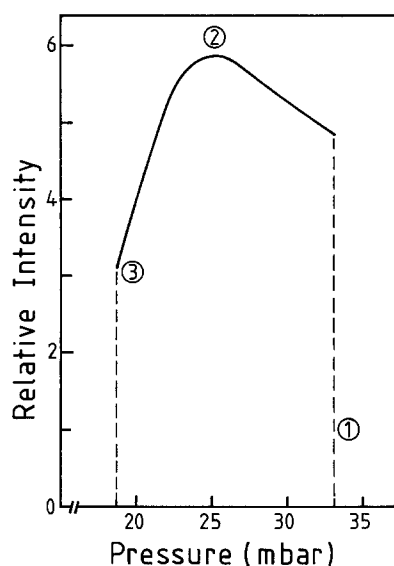


Fig. 3. Relative beam intensity vs. helium pressure of the inlet line. In raising the pressure the discharge ignites at (1); in reducing the pressure the optimum operating point (2) is found. Further reduction of the pressure leads to the extinction of the discharge at (3)

The light from the discharge region was viewed from the side through a prism periscope. It was found that a steady and intense glow between nozzle and skimmer is an indication of nearly optimum source performance. Figure 3 displays the typical dependence of the current of polarized metastable atoms on the helium pressure in the inlet tube. We obtained very satisfactory performance for over one year by running the discharge with about 20 mA current and applying a potential of +180 V to the skimmer. The

pressure in the inlet line of the source was kept at about 25 mbar. The source performance was optimized with respect to intensity while monitoring the current of the $\text{He}(2^3S, m_s = +1)$ atoms. For keeping optimum values of the intensity in long term operation, fine adjustments to the pressure setting were necessary.

The discharge source is mounted on a flange which is inserted in the source chamber. In order to insure that helium gas can get into the adjacent magnet chamber *only* through the skimmer hole, a seal is made between source insert and the chamber partition. For that purpose the skimmer has on its back side a groove with inserted O-ring which is pressed against the chamber partition by the atmospheric pressure. A bellows portion on the source assembly provides the necessary flexibility in length.

Sextupole magnet

For atoms with a field-strength independent magnetic moment, such as $^4\text{He}(2^3S)$, the inhomogeneous magnetic field in the pole gap of a sextupole magnet provides a force which is proportional to the atoms' radial distance from the axis and directed towards it if $m_s > 0$, away from the axis if $m_s < 0$, and no force acting if $m_s = 0$. It can be shown [15] that for atoms with $m_s > 0$ the sextupole magnet acts like a positive lens which is free of aberrations except of the chromatic aberration which restricts the focussing for thermal atomic beams to a portion of their velocity distribution.

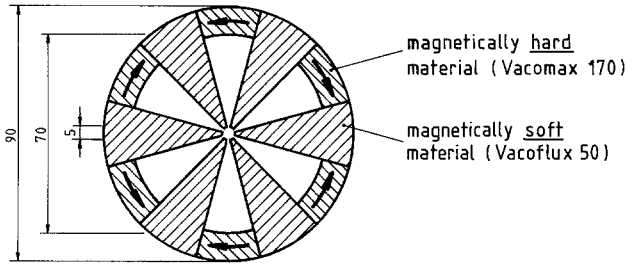


Fig. 4. Cross section of sextupole magnet. The arrows show the direction of the permanent magnetization. Diameters are given in mm

Permanent sextupole magnets can be put conveniently into UHV systems. A disadvantage in comparison to electromagnets is that their pole tip field strength cannot easily be varied. Therefore their design and length have to be accurately matched to the given application. The cross section of our sextupole magnet is shown in Fig. 4. The magnet length is 100 mm. The magnetic pole tips and drivers were manufactured to our specifications by Vacuum-schmelze GmbH. The magnetically hard material is the rare earth-cobalt alloy Vacomax 170 which has a remanence of 0.9–1.0 T, and a coercive force of 660–780 kA/m. The magnetically soft material is the cobalt-iron alloy Vacoflux 50 which has a permeability of 1000 (at $H = 4$ mA/cm), a coercive force of 1.1 A/cm, and a saturation of the magnetic flux density at

2.35 T. The sextupole pole tips are positioned on each end with molybdenum-rod spacers which are retained in copper rings. This holds the assembly firmly together (see Figs. 2 and 5). Due to the linear behavior of the demagnetization curve for the rare earth-cobalt alloys no magnetizing in situ is necessary. The working point is reached merely by assembling the pre-magnetized pieces of the magnetic circuit. By using a Hall probe (F.W. Bell) with a thickness of 0.12 mm and with an active area of small dimensions (diameter 0.76 mm) we measured the pole tip magnetic flux density directly as 0.8 T.

The position of the sextupole magnet can be adjusted under vacuum. The central stop at the magnet exit is a 1.5 mm diameter disk held by a thin needle. It can be moved in and out and is aligned with respect to the magnet axis by using a telescope.

The magnet design parameters are based on phase-space considerations [16]. We wanted an intense and highly polarized beam in the interaction region of an experiment. The relevant phase diagrams for calculating the transmitted beam intensity are given in Fig. 6. The normalized distance from He beam axis, $\xi = x/R$, and the normalized slope of the trajectory, $\eta = (dx/dz)/(kR)$ build the coordinate system. The pole tip radius is $R = 0.25$ cm and the atom-trajectory wave number $k = R^{-1} [\mu\text{B}/kT]^{1/2} = 0.125 \text{ cm}^{-1}$.

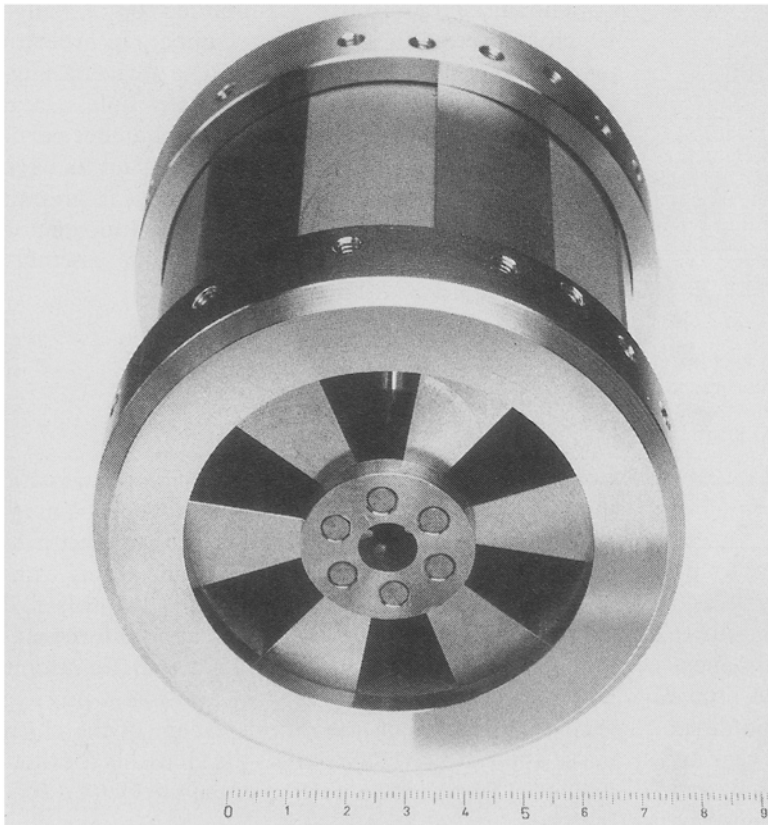


Fig. 5. Sextupole magnet assembly (units on the scale are cm)

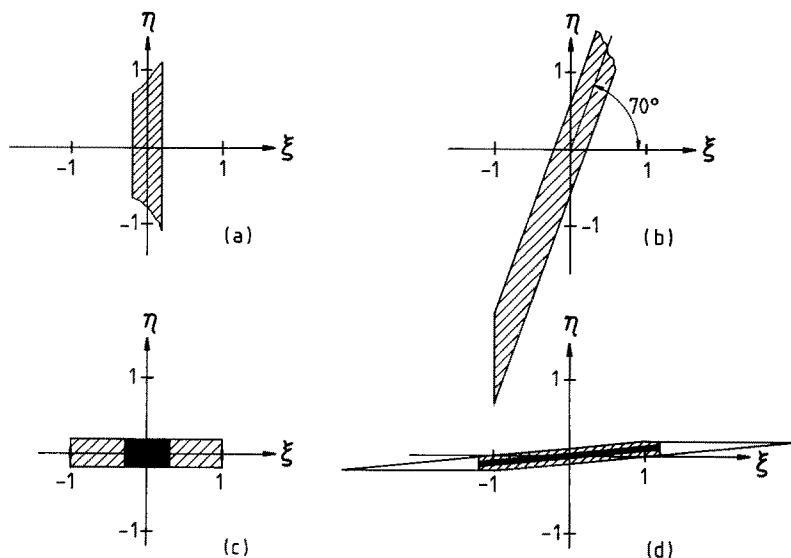


Fig. 6a-d. Phase-space diagrams of the atomic beam at different locations along the beam axis. (a) At the source, $z=0$; (b) at the entrance of the sextupole, $z=3$ cm; (c) at the exit of the sextupole, $z=13$ cm, with the central stop inserted (which covers the black portion of the diagram); (d) at the interaction region, $z=103$ cm

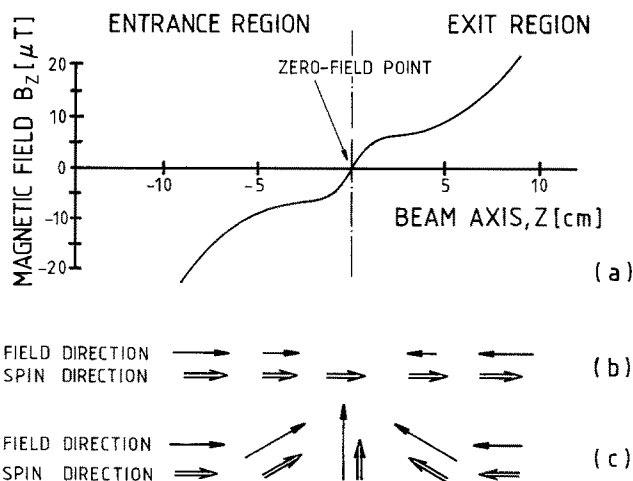


Fig. 7a-c. Passage of the beam through the spin flipper. (a) Magnetic field along the beam axis for the diabatic case; (b) spin motion in the diabatic case (schematic); (c) spin motion in the adiabatic case in which an additional transverse field of $100 \mu\text{T}$ is applied at $Z=0$ (schematic)

From the properties of the sextupole magnet and the average velocity of metastable helium atoms we calculated the *acceptance solid angle* as $4.5 \cdot 10^{-3}$ sr without central stop and $3 \cdot 10^{-3}$ sr with central stop. This means that $\text{He}(2^3S, m_s = +1)$ atoms from the source forward into this solid angle are transmitted and focussed into the interaction region.

Spin flipper

In polarization experiments on electron-exchange one has to take measurements with antiparallel and parallel relative spin orientation of the two interacting par-

ticle beams. Reversing the polarization of the $\text{He}(2^3S)$ beam by reversing the magnetic guiding field is not acceptable because the field change can introduce large systematic errors by affecting the intensity and position of the electron beam. Using a spin flipper [17] provides a method which reverses the polarization while keeping the guiding field constant. Such a reversal corresponds to a Zeeman transition from $m_s = +1$ to $m_s = -1$. The axial field strength inside the spin flipper and its actions in the diabatic and adiabatic mode of operation are shown in Fig. 7. The efficiency of the spin flipper was determined to be 100%, that is, one obtains equal beam-polarization values for the reversed and the not-reversed case.

Analyzing magnets

For analyzing beam intensity, beam composition and polarization we used first a Stern-Gerlach magnet and later an additional sextupole magnet.

a. Stern-Gerlach magnet

We took an electromagnet from a commercial Stern-Gerlach demonstration experiment (Phywe). A $0.3 \text{ mm} \times 4 \text{ mm}$ slit in front of the magnet defines the atomic beam for the polarization analysis. At a distance of 40 cm behind the Stern-Gerlach magnet the profile is measured by means of a CEM which has a $0.2 \text{ mm} \times 4 \text{ mm}$ slit. A bellows permits the transverse motion of this CEM. The parameters of the analyzer allow an almost complete separation of the three Zeeman components ($m_s = +1, 0, -1$) of our $\text{He}(2^3S)$ beam.

b. Analyzing sextupole magnet

This sextupole was a commercially fabricated magnet (Frequency and Time Systems, Inc.) with Alnico 8a as the hard magnetic driver material and Permendur pole pieces. The magnet has a bore diameter of 3.2 mm, a length of 150 mm, and a pole tip field of 0.85 T. These characteristics ensure that atoms with $m_s = -1$ are not transmitted through the magnet. The analyzing method relies on the reversal of the beam polarization with the spin flipper. The beam signal obtained within the adiabatic mode of the spin flipper (superscript N for “No Flip”) is proportional to the beam components of the $m_s = +1$ and $m_s = 0$ atoms,

$$I^N \propto (I_+ + I_0),$$

whereas in the diabatic mode (superscript F for “Flip”)

$$I^F \propto (I_- + I_0).$$

Then, to a very good approximation, one can calculate the metastable beam polarization from

$$P = (I^N - I^F) / (I^N + \frac{1}{2} I^F).$$

The validity of this formula implies the following assumptions: (1) The $m_s = 0$ and the $m_s = -1$ beam components are small and of equal magnitude (this follows from the results obtained with the Stern-Gerlach magnet). (2) The $m_s = 0$ and the $m_s = +1$ beam components are equally well transmitted through the analyzer (approximately true for the given case of atomic trajectories which enter and leave the analyzing magnet nearly parallel to the beam axis).

Results

The source was very stable in its operation with regard to intensity and polarization. Initially the He inlet-line was set to a pressure of 23 mbar to get maximum intensity (see Fig. 3, operating point (2)). After several hours the intensity maximum decreased and shifted to slightly higher pressure values (about 27 mbar). Therefore, adjustments were made now and then to stay at the optimum setting. We obtained a flux of $5 \cdot 10^{11}$ atoms/s through the interaction region. Over many months of operation this value dropped by about a factor 5 due to degradation of the orifices in the discharge source. However, these parts can be refurbished easily so that in principle the average flux can be close to the stated initial one. Even with the central stop in place our metastable beam was not free of ground-state He atoms, they were present with a flux of about $5 \cdot 10^{13}$ atoms/s.

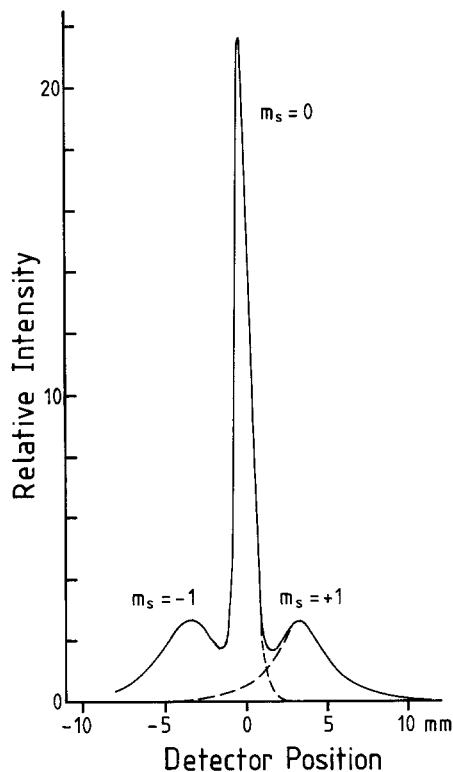


Fig. 8. Stern-Gerlach profile of the unpolarized He* beam showing the contributions from the different magnetic substates

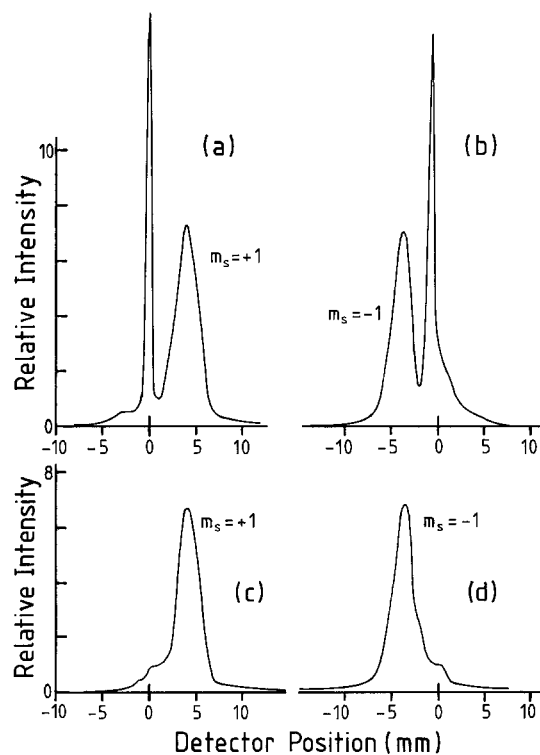


Fig. 9a-d. Stern-Gerlach profiles of the polarized He* beam. (a) Without central stop, adiabatic mode of spin flipper; (b) without central stop, diabatic mode; (c) with central stop, adiabatic mode; (d) with central stop, diabatic mode

Figure 8 shows the three-component Stern-Gerlach spectrum of an unpolarized beam (polarizing sextupole magnet removed). The area of the center peak is two times larger than that of either side peak. This indicates that triplet and singlet atoms are present in accordance with their statistical weights. Displayed in Fig. 9 are the Stern-Gerlach profiles of the polarized beam for the adiabatic (a and c) and the diabatic (b and d) setting of the spin flipper, each taken without (a and b) and with the central stop (c and d) at the sextupole exit. Evaluation of the profile of Fig. 9c and of the profile of Fig. 9d with respect to its composition of atoms with $m_s = +1$, $m_s = 0$, and $m_s = -1$ components yields the beam polarization of $P = 0.90 \pm 0.02$. Theoretically we expected a polarization of 1 as the polarizing sextupole deflects all atoms with $m_s = -1$ sufficiently strong, and the central stop blocks all atoms with $m_s = 0$ on their straight line trajectories such that neither of them can reach the interaction region. To explain the value of 0.9 we assume, that in fact metastable atoms will make small angle scattering with He atoms in the beam or with residual He gas atoms and that the shadow region behind the central stop will acquire some small fraction of $m_s = 0$ and $m_s = -1$ atoms. With the central stop removed the beam polarization is reduced to 0.8 ± 0.02 , whereas the beam intensity is increased by a factor of 1.5.

The polarization value obtained from the Stern-Gerlach analysis is in accordance with the analysis using sextupole and spin flipper arrangement. Here ratios of $I^F/I^N = 1/14$ were obtained, leading to the polarization of 0.90. After weeks of operation of the discharge source the polarization dropped gradually to 0.84. This is consistent with the explanation given above for $P < 1$: Due to enlargement of the skimmer and source orifices by the discharge, the residual He pressure in the sextupole chamber and in the spin-flipper chamber is increased; consequently, more $\text{He}^* - \text{He}$ scattering will occur and more wrong-state atoms will reach the interaction region.

Comparison with other polarized beam sources

Polarizing the $\text{He}(2^3S)$ atoms by optical pumping could, in principle, also lead to near unity polarization. So far, only about $P = 0.4$ has been achieved [10]. This indicates that optical pumping is a more difficult and less stable operation than the state selection by static fields. We estimate that using that source instead of ours the atomic flux available in the interaction region would have been about two orders of magnitude smaller, mainly because a focussing element is absent in that beam line.

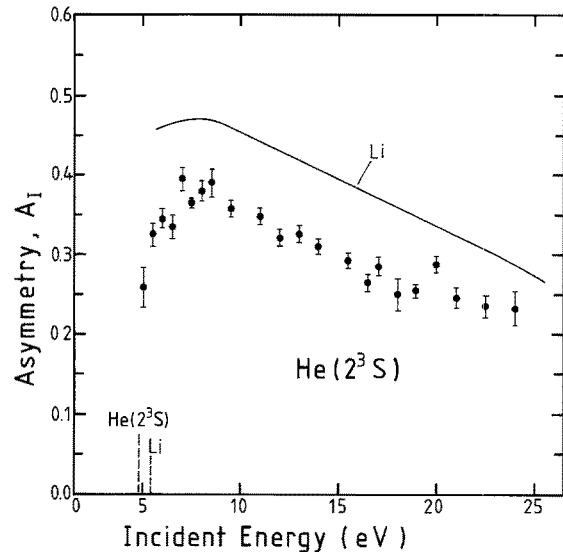


Fig. 10. First results of the ionization asymmetry of $\text{He}(2^3S)$ as function of the incident energy. The data points are compared with the results for lithium from [19]. The respective thresholds are indicated

Another polarized-beam system is that of Slobodrian et al. [7]. Their source is aimed at producing polarized ^3He ions for nuclear physics experiments. They also use a sextupole magnet which, however, is partially tapered and has dipole/quadrupole polarities to accommodate for the HFS interaction of the ^3He atom. Without employing a central stop a polarization of 0.95 is obtained. A dynamical method is used for reversal of the polarization. Compared to our source they seem to have a somewhat higher intensity ($\text{atoms} \cdot \text{s}^{-1} \cdot \text{sr}^{-1}$) but, because of the larger magnet exit diameter, a smaller flux density ($\text{atoms} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$). We estimate that the usable beam flux ($\text{atoms} \cdot \text{s}^{-1}$) through an interaction region like ours would be about the same as that achieved by us.

Applications

Our system is being employed in studies on the spin dependence of electron-impact ionization. In order to reduce the background of ions present in total cross section measurements to a tolerable level a quadrupole mass analyzer had to be incorporated into the ion-detection arrangement. Furthermore, the background was considerably reduced by applying a strong electric field in front of the interaction region which removed Rydberg atoms from the beam by field ionization. The remaining background with a rate of about 1 s^{-1} is being attributed to $\text{He}^* - \text{He}^*$ collisions within the beam [18]. The first results on

the polarization asymmetry

$$A = (\sigma^{\downarrow\uparrow} - \sigma^{\uparrow\uparrow}) / (\sigma^{\downarrow\uparrow} + \sigma^{\uparrow\uparrow})$$

for the ionization of He(2^3S) are shown in Fig. 10 and are compared with the results of lithium [19]. If only the $2s$ -electron interacted with the beam electron, the asymmetry should be the same as that for Li because the characteristics of the $2s$ -electron are very similar for the He* and Li atoms. The measured asymmetries for H and Na are also very similar to that of Li. We presume that the deviation exhibited in Fig. 10 has to be attributed to the influence of the unpaired and polarized $1s$ electron of the metastable helium atom.

The employment of the He* beam system in surface studies is being prepared. Asymmetry measurements in Penning ionization of polarized atoms on magnetized surfaces or adsorbate atoms can directly be related to the spin density at the surface or to spin orientation of the adsorbate layer, thus opening a wide field of studies [11], particularly if it is combined with energy analysis of the emitted electrons. The Penning ionization process is strongly surface specific, probing the very first layer or the adsorbate atoms directly. The interpretation of the observations becomes more complicated if the metastable triplet level lies energetically above the Fermi energy of the surface and, therefore, empty states are accessible to the excited electron. In that case resonance tunneling with ionization and subsequent neutralization by Auger processes will occur.

Conclusion

For the development of a versatile polarized He(2^3S) beam system useful for atomic physics and surface physics studies, we used the combined technologies of He* effusion from an intense helium discharge, of polarization of the triplet atoms by passage through a permanent sextupole magnet, of reversal of the atomic polarization in a spin flipper, and of analysis of the atomic polarization by means of a Stern-Gerlach or sextupole magnet.

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