Suppression of Penning ionization by spin polarization of cold He(2 3S) atoms

Norbert Herschbach, Paul J. J. Tol, Wim Hogervorst, and Wim Vassen

Division of Physics and Astronomy, Faculty of Sciences, Vrije Universiteit Amsterdam, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands

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We measure the suppression of Penning ionization in an ultracold He(2 3S 1) atomic cloud after spin-polarizing the atoms by optical pumping in a small magnetic field. An upper limit of 6 \times 10^{-12} cm^3/s for the ionization rate constant is deduced, at least a factor 20 lower than measured in an unpolarized gas.

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The internal energy of a metastable triplet helium atom \( \text{He}(2 3S_1) \) (He*) of 19.8 eV is sufficient to ionize most atoms and molecules. The reaction products of this Penning ionization are the ionized atom or molecule, an electron, and a ground-state helium atom \( \text{He}(1S_0) \). When the collision partner is another He* atom the reaction products are a He* (1 2S_1/2) ion, an electron, and a ground-state helium atom; or with a few percent probability [1], a He*+ ion and an electron (associative ionization). In an unpolarized He* gas pair collisions occur within the quasimolecular symmetries \( ^1\Sigma^+_g \), \( ^3\Sigma^+_u \) or \( ^3\Sigma^+_g \) with total spin 0, 1, and 2, respectively. The rate constant \( K_{ss} \) for Penning ionization in this case is large. For totally spin-polarized atoms, which can collide only in a \( 5S_g^+ \) potential, the ionization process is forbidden as the total spin of the products of the ionization reaction is at most 1. A reduction of the Penning ionization rate in collisions between He* atoms was demonstrated around 1970 in the flowing afterglow of helium discharges by measuring the electron density while optically pumping the atoms with circularly polarized 1.08-\mu m light from helium lamps. In \(^4\text{He}^+\) (3He) a reduction in the electron production rate of \( 5\% \) at a degree of spin polarization of 15% (8%) was observed [2,3].

If the cross section for ionizing collisions in a totally spin-polarized He* gas is small enough such that high densities (10^{12} cm^{-3}) can be achieved, and if the ratio of elastic to inelastic collision rate is favorable for effective evaporative cooling, then He* is a promising candidate for an experiment on Bose-Einstein condensation in a dilute gas. A theoretical investigation of the decay kinetics of a trapped, spin-polarized He* gas revealed that, for densities \( \leqslant 10^{13} \) cm^{-3}, where three-body losses are not yet important, the main inelastic processes are spin relaxation and relaxation-induced ionization, which are induced by the spin-dipole interaction in pair collisions. In low magnetic fields (\( B \leqslant 100 \) G) and at temperatures \( T \leqslant 10 \) mK the calculations predict relaxation-induced ionization to be the dominant process, with a rate constant \( K_{ss} \sim 10^{-14} \) cm^3/s, four orders of magnitude smaller than in the unpolarized case. This indicates that the ratio of elastic to inelastic collision rate can be large over the relevant ranges of temperature and magnetic fields, so that the prospects for evaporative cooling are promising [4,5].

Experiments concerning the suppression of Penning ionization in the spin-polarized gas compared with the unpolarized case have not advanced substantially since the 1970s. In this Rapid Communication we discuss an experiment that demonstrates in a straightforward way the suppression of Penning ionization in an ultracold gas of He* when the atoms are spin polarized. It yields an experimental upper bound for the ionization rate constant in the spin-polarized case. We use the atomic cloud released from a magneto-optical trap (MOT), which is more advantageous compared with the techniques applied in former experiments and leads to improved sensitivity. First, the low temperature (1 mK) ensures pure s-wave scattering, and collisions cannot occur in the \( ^3\Sigma^+_u \) potential, which otherwise is also an efficient ionization channel. Second, when loading the MOT from a pure He* atomic beam, under ultrahigh vacuum (UHV) conditions, there are no sources of ions and electrons other than Penning ionization in pair collisions and, to a lesser degree, Penning ionization of background molecules. As a result the detection sensitivity of Penning ionization is substantially increased. Furthermore, by optical pumping with a narrow bandwidth laser close to 100% spin polarization can be achieved.

We load a MOT with atoms from an intense and pure He* beam after deceleration in a two-part Zeeman slower. The He* beam is produced in a liquid-nitrogen-cooled dc-discharge source. In a transversal cooling section based on the curved-wave-front technique the He* beam is collimated and deflected such that ground-state atoms, charged particles, and uv photons from the source are geometrically blocked. The loading rate of the MOT is \( 5 \times 10^8 \) s^{-1} and typically the trap contains about 1 \times 10^9 He* atoms with a central density of \( 4 \times 10^9 \) cm^{-3} and a temperature of 1 mK. For further details on these parts of the setup we refer to our earlier paper [6] and references therein. The fringe magnetic field of the end of the Zeeman slower is overlapping with the quadrupole field of the MOT such that the center of the trap is displaced by about 3 mm from the zero point of the quadrupole field. Thus, when we switch off the MOT, including its quadrupole field, the atomic cloud is left in the fringe field of the Zeeman slower, which has a strength of about 3 G. The homogeneity of this small field is good enough to reach a high degree of spin polarization with optical pumping. For this we use a 1083-nm diode laser (SDL-6702-H1) in an extended-cavity geometry with sub-MHz bandwidth and absolute frequency stability. This laser beam is aligned colinearly with the Zeeman slower and is switched on with an acousto-optic modulator for about 20 \mu s. We produce circu-
larly polarized light using a polarizer and a λ/4 plate in front of the entrance window of the UHV chamber. This window will finally limit the degree of circular polarization that can be achieved. A laser intensity of about 15 mW/cm² is used (saturation intensity 0.16 mW/cm²). For optical pumping the laser is tuned to a frequency close to the $2^3S_1 \rightarrow 2^3P_2$ atomic transition, optimized such that efficient spin polarization is reached. Ions produced by Penning ionization are detected with a double microchannel plate (MCP) detector positioned about 7 cm from the atomic cloud. The exposed negative high voltage on its front plate attracts all positive ions produced in the atomic cloud.

In the MOT optical collisions in the trap laser light cause an enhancement of the Penning and associative ionization processes leading to a large ionization rate constant $\beta$ that depends on the detuning and total laser intensity used for the trap. For the MOT used in this experiment $\beta \approx 5 \times 10^{-9} \text{ cm}^3/\text{s}$. In the absence of light a decrease in the ionization rate constant to $\beta = 2K_{ss} = 2.6(4) \times 10^{-10} \text{ cm}^3/\text{s}$ was found [6]. From the rate equations for absorption in the MOT we deduce that the steady-state populations of the Zeeman substates of He($2^3S_1$) are all close to 1/3 in the center of the atomic cloud, but gradually deviate from this value with increasing distance from the center. Accounting for this deviation a $K_{ss}^{eq} = 1.8(4) \times 10^{-10} \text{ cm}^3/\text{s}$ for the case of equal populations of the magnetic substates is inferred.

In Fig. 1 the ion signal is plotted once with and once without optical pumping. In the curve without optical pumping, the ion signal drops down to the value for collisions in an unpolarized cloud, when the MOT laser is switched off. With optical pumping the ion signal drops significantly below this level: the decrease of the ion signal relative to the unpolarized case is at least a factor of 20. For both helicities of the light pulse equal suppression factors are measured. The displayed curves are averages over about 350 cycles, each taking a few seconds in order to start always with an equilibrated MOT. As the MOT magnetic field is switched off rapidly (5-μs exponential decay time) and the trap is off only for 150 μs the decrease of the density of the released atomic cloud by ballistic expansion is negligible. This is demonstrated by the fact that, when the MOT is switched on again, the ion signal rapidly regains a level near its value at the beginning of the cycle. The ion signal takes somewhat longer to reach its final value when the MOT is switched on again in the case with optical pumping. This can be explained from the different populations of the Zeeman substates in both cases. The short duration of the laser pulse ensures that effects of the radiation pressure force on the velocity distribution of the atoms are negligibly small. The increase in ion signal during the optical pumping laser pulse is caused by the ionization enhancement in optical collisions.

For an atomic cloud with Gaussian density distribution and central density $n_0$, the ion current $\phi$ measured on the MCP detector can be written as [7]

$$\phi = V\left(\epsilon_a n_0 + \frac{\epsilon_b \beta}{4 \sqrt{2} n_0^2}\right),$$

where $\alpha$ is the loss rate due to collisions with background molecules, $\beta$ the loss-rate coefficient for pair collisions, and $V$ an effective volume [6]. In Eq. (1) $\epsilon_a$ and $\epsilon_b$ are the efficiencies for ion production and detection for losses due to background and pair collisions, respectively. Collisions that do not yield ions but induce trap losses include those with ground-state helium atoms, resulting in a reduced $\epsilon_a$, and radiative escape, which may decrease $\epsilon_b$, but only in the MOT situation.

For dark collisions in an atomic cloud the ionization rate coefficient $\beta$ can be written as a sum of the contributions of all symmetries in which collisions occur: $\beta = \beta_{1\Sigma} + \beta_{2\Sigma} + \beta_{3\Sigma}$. Actually, the gas temperature of 1 mK is sufficiently low to assume pure s-wave scattering; the relative probability for p-wave scattering is $\leq 1\%$. Thus pair collisions with $1\Sigma$ symmetry are highly improbable as they can only occur with an odd total orbital momentum quantum number. The contribution to the ionization rate from collisions occurring in the $2\Sigma$ symmetry is predicted to be small ($\sim 10^{-14} \text{ cm}^3/\text{s}$) and lies beyond the sensitivity of the present experiment. Thus the ionization rate coefficient $\beta$ in an atomic cloud with fractional populations $\rho_{-1}$, $\rho_0$, and $\rho_1$ for the magnetic substates $|M\rangle$ ($M = -1,0,1$) is given by

$$\beta = \beta_{1\Sigma} = 18K_{ss}^{eq} \frac{1}{3}(2\rho_{-1}\rho_1 + \rho_0^2).$$

This expression is obtained by averaging the projection operator on the $|1\Sigma\rangle$ quasimolecular state $\langle|1\Sigma\rangle = |[-1,+1]+1/2\rangle$ over an arbitrary distribution of populations $(\rho_{-1}, \rho_0, \rho_1)$. The factor $18K_{ss}^{eq}$ ensures that $\beta = 2K_{ss}^{eq}$ for $\rho_{-1} = \rho_0 = \rho_1 = 1/3$. The dark collision rate constant for Penning ionization takes its maximum, $\beta = 6K_{ss}^{eq}$, when $\rho_0 = 1$ and vanishes for either $\rho_{-1} = 1$ or $\rho_1 = 1$.

The ionization signal after optical pumping is very small and is close to the detection limit of our experiment. This signal is averaged over time in the interval shown in the inset of Fig. 1. An average of 5% of the ionization signal of the
unpolarized cloud is found with an rms deviation of similar size. However, it cannot be concluded that the suppression of Penning ionization in a totally spin polarized sample will be only a factor of 20 compared with the unpolarized case. The residual signal may be due to Penning ionization of molecules from the background gas (typical pressure $5 \times 10^{-10}$ mbar). From measurements of the ionization signal as a function of the atomic density [6] we estimate that this contribution indeed is $\approx 5\%$ of the ionization signal from the dark unpolarized atomic cloud. In addition, spin-polarization is not perfect. From Eq. (2) we deduce that at least 88% of the atoms must be in a single magnetic substate with $|M| = 1$ to observe a suppression by a factor of 20. This appears realistic; we did not particularly try to determine the degree of spin polarization by a different method. An additional contribution to the signal could stem from fast metastable atoms escaping from the MOT while it is switched on. From an earlier calibration of this flux of metastables [6] we conclude that this contribution can be neglected.

To summarize, we deduce from the observed suppression an upper bound $K_{\text{ss}}^{[1]} < 6 \times 10^{-12}$ cm$^3$/s for the ionization rate constant for spin-polarized He$^*$. This value is obtained dividing the previously measured rate constant for the unpolarized case $K_{\text{ss}} = 1.3 \times 10^{-10}$ cm$^3$/s [6] by the observed suppression factor.

To increase the sensitivity to Penning ionization in pair collisions of spin-polarized He$^*$ atoms it is feasible, prior to the optical pumping, to compress the trapped atomic cloud by increasing the gradient of the magnetic field and/or decreasing the laser detuning of the MOT. Furthermore, by selectively detecting He$^+$ ions with mass-spectrometric techniques the measured signal will be free of background molecular ions. However, despite these improvements, the imperfect spin-polarization and the relatively small atomic density will hamper a precise determination of the ionization rate constant in such an experiment. To ensure perfect spin-polarization the cloud released from the MOT can be captured in a magnetostatic trap (MST). A quadrupole MST is advantageous as it can be operated with the same coils used for the MOT, if an appropriate gradient of the field can be reached [8]. In this trap, spin polarization is locally provided everywhere, except for the center of the trap, where the field vanishes. In an MST the ions can be collected over a longer time, and from the time dependence of the decay of the trap it is possible to discriminate between losses due to pair collisions and those stemming from collisions with background gas. We indeed recapture close to 1/3 of the atoms in a quadrupole MST after reducing the temperature of the cloud in a Doppler molasses down to 0.2 mK. Measuring the decay of the MST we found no evidence for a deviation from the exponential behavior characteristic of collisions with molecules of the background gas. However, the density of $10^9$ cm$^{-3}$ reached at that point in our experiment is too small for a significant loss contribution from pair collisions. To reduce the upper bound for $K_{\text{ss}}^{[1]}$ below the measured value of $6 \times 10^{-12}$ cm$^3$/s a central density larger than $10^{10}$ cm$^{-3}$ is required in a quadrupole MST. In a Ioffe-type MST the trapped cloud has a Gaussian density profile and Eq. (1) can be used to estimate that for $(\epsilon_f/\epsilon_i)\alpha = 0.01$ s$^{-1}$ (inferred from measurements in the MOT, Fig. 2 of [6]) a central density of $10^{12}$ cm$^{-3}$ is required in order to observe clearly on an ion detector the loss contribution of pair collisions with the predicted small value of $\beta^{[1]}$. This higher density can be reached by compression in the MST. Ongoing experiments in this direction have to show whether $\beta^{[1]}$ is sufficiently small to allow for effective evaporative cooling and the realization of Bose-Einstein condensation.

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