Prospects for Bose-Einstein condensation of metastable neon atoms


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The calculated upper limit $k_B T < 10^{-14} \text{cm}^2/\text{s}$ of the rate constant for suppressed ionization in a gas of metastable Ne($3P_2$) atoms in the fully aligned $|J=2, m_J=2\rangle$ state is used as input to investigate the prospects for achieving Bose-Einstein condensation (BEC). The heating rate of the trap population by secondary collisions of the hot products of the process of ionization—i.e., ground-state atoms, ions, and dimer-ions—with cold trapped metastable atoms is discussed in terms of a semiclassical model. An important step lies in limiting the depth of the magnetic trap to a value of a few millikelvin, to limit the range of small-angle scattering that contributes to heating. Also, a tight radial confinement reduces the probability for secondary collisions. At a trap depth of 10 mK, a radial dimension of 3 $\mu$m, and a density of $2 \times 10^{13} \text{cm}^{-3}$ the heating rate is $1.4 \mu\text{K/atom}$, which should be compared to the transition temperature to BEC of 0.6 $\mu\text{K}$. The collisional heating is dominated by ion—metastable-atom collisions, due to their long-range charge-induced dipole interaction. Keeping the evaporative cooling switched on at $T = T_C$ reduces the heating a hundredfold. Using a bright beam of laser cooled neon atoms, an initial population of $> 10^9$ atoms can be loaded into a magneto-optical trap in one second. Tight magnetic traps are easy to achieve for metastable neon atoms, due to their magnetic moment of 3 $\mu_B$. We conclude that achieving BEC is feasible for metastable neon. This also holds for triplet metastable helium, once the loading rate of traps has been improved. Finally, the semiclassical model used for calculating the heating rate is applicable to a wide range of inelastic collisions in trapped alkali gases and/or collisions with background gas.

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I. INTRODUCTION

Bose-Einstein condensation occurs when the mean interatomic distance becomes of the same order as the thermal De Broglie wavelength of the atoms, with the transition temperature $T_C$ defined by the condition

$$D = n \Omega^3 = n (2 \pi \hbar^2 / mk_B T_C)^{3/2} = 2.61.$$  \hspace{1cm} (1)

Here, $D$ is the phase space density, $n$ the number density, $m$ the atomic mass, and $k_B$ Boltzmann’s constant. In 1995, Bose-Einstein Condensation (BEC) was first observed in a cold dilute sample of trapped alkali atoms, by three groups using Rb [1], Na [2], and Li [3], respectively. For temperatures below $T_C$, a macroscopic population of a single quantum state is obtained. Recently, in 1998 BEC was also achieved in a dilute gas of H atoms [4,5]. Since the first observation of BEC in a dilute gas, a whole new field of atom optics and coherent matter has emerged.

At this moment, most efforts in the field are still directed to Bose-Einstein condensation of the alkali atoms. Emphasis has been laid on Rb, the work horse in this new field, with Na as the runner up. For Cs it is not clear if BEC can be reached, due to the recently found experimental evidence on large dipolar relaxation rates for the $|F, m_F = 4, 4\rangle$ and $|3, 3\rangle$ states. For potassium, the main interest lies in producing a trapped, quantum-degenerate Fermi gas.

The advantages of investigating the alkali atoms are paramount. First, because the alkali atoms are trapped in their ground state, vapor-cell atom traps can be applied for achieving high density samples. Dual-chamber schemes result in trapped samples of the order of $10^8$ atoms, using a pulsed or continuous cycle and a loading time of a few seconds. An atomic beam approach using a thermal source and a simple Zeeman slower results in even higher loading rates, of the order of $10^{10}$ atoms/s. Second, there is a large body of spectroscopic and collision data on the alkali dimers. This allows one to extract accurate information on the potential surfaces involved. Third, based on this information, detailed calculations have been performed on the scattering of (ultra)cold atoms, resulting in reliable information on the scattering length. Also, the two- and three-body collisions that lead to the loss of atoms in the final magnetic trap, have been investigated. In most cases reliable rate constants for these loss processes are available; in some cases only lower or upper limits for these rate constants are available.

For the metastable rare-gas atoms the experimental conditions are less favorable. First, because the electronic energy of the metastable states is of the order of 8 eV (xenon) to 20 eV (helium), the relative population in a gas discharge or an atomic beam is only a fraction $10^{-4}$ or $10^{-3}$ of the total density. Therefore, techniques of beam brightening have to be used to obtain sufficiently large fluxes for loading atom traps. Second, the process of Penning ionization of two colliding metastable atoms is an important loss process. For an unpolarized sample, the rate constant is of the order of $10^{-10} \text{cm}^3/\text{s}$ [6–9]. In a spin-polarized sample, however, ionization is strongly suppressed by spin selection rules. For helium, theoretical estimates predict a suppression by a factor $10^4$ to $10^5$ [10,11]. This shows promise for trapping and evaporative cooling of metastable atoms in a magnetic trap [12,13]. For xenon, however, recent experiments show no evidence of suppression of ionization [8]; for a polarized sample the ionization rate is even larger by 50%. Third, the time scale for experiments is limited by the long but still finite lifetime of the metastable states. For triplet helium we
The advantages of using metastable rare-gas atoms are the excellent real-time diagnostics of the sample of trapped atoms, both in the stage of cooling above $T_C$ as well as the stage below $T_C$ where the condensate and the thermal cloud coexist (Fig. 1). Both the UV photons that are emitted when the metastable state decays as well as the ions produced in the still remaining ionizing collisions provide diagnostics for the density and the sample size. By combining this information with the geometry of the trapping field, we can also determine the temperature in a noninvasive way.

In this paper we investigate the feasibility of reaching conditions where Bose-Einstein condensation occurs for metastable neon. We have investigated two geometries of the sample in a magnetic trap, resulting in two different, cylindrically symmetric geometries of the final state condensate. First, a high density final state with a small aspect ratio is discussed, with the latter defined as the ratio of the long over the short axis of the ellipsoidally shaped thermal cloud of trapped atoms. Second, a low density final state with a very large aspect ratio is investigated. The former is close to the geometry used by the group of Ketterle for achieving BEC in sodium [19]; the latter corresponds to the geometry used for the recent BEC experiments with atomic hydrogen [4,5]. Typical values of the sample size, aspect ratio and number density are given in Table I for the two geometries, together with the transition temperature $T_C$.

To provide a reference frame for the disturbing effects of heating of the sample, we first discuss the creation of hot

![Harmonic potential](image)

**FIG. 1.** Harmonic potential (with $\omega_z \ll \omega_r$) with a schematic view of the Bose condensate in the quantum mechanical ground state with energy $\hbar \omega_r$ [fraction $1-\left(T/T_C\right)^3$] and the thermal cloud at temperature $T \approx \hbar \omega_r/k_B$ [fraction $(T/T_C)^3$]. In this schematic view the self-energy of the condensate has been neglected.

find $\tau=9000\ s$, which decreases to $\tau=24\ s$ for neon [14] and $\tau=43\ s$ for xenon [15] in the $^3P_2$ states. Finally, hardly any theoretical or experimental data on binary metastable atom collisions or interaction potentials are available [6,16] with He as an exception [9].

The outlook of a Bose-Einstein condensate of metastable rare gas atoms is promising enough to tackle all these difficulties. The idea of an atom laser of electronically excited atoms is tantalizing. Moreover, one can speculate on collective phenomena in a condensate with a large internal electronic energy, e.g., collective electronic deexcitation. Also, a condensate of metastable rare-gas atoms seems an ideal candidate for loading an optical lattice [17,18].

### Table I. Characteristic parameters for neon of the initial state of evaporative cooling and two final states in the magnetic trap at the onset of BEC. The count rate and decay time of the real time diagnostics are given for all three states.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial state</th>
<th>Final state (high density)</th>
<th>Final state (low density)</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius ($\mu$m)</td>
<td>10</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>length ($\mu$m)</td>
<td>22</td>
<td>250</td>
<td></td>
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<tr>
<td>aspect ratio</td>
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<td>population N (no. of atoms)</td>
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<td>$10^6$</td>
<td>$2 \times 10^3$</td>
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<tr>
<td>number density $n$ (cm$^{-3}$)</td>
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<td>$10^{14}$</td>
<td>$2 \times 10^{13}$</td>
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<tr>
<td>temperature $T$ (µK)</td>
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<td>0.6$^a$</td>
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<td>phase space density</td>
<td>3$ \times 10^{-7}$</td>
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<td>2.61</td>
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<tr>
<td>rate constant $K_{el}$ (10$^{-12}$ cm$^3$ s$^{-1}$)</td>
<td>2300 ($a_{2,2}/50a_0$)$^2$</td>
<td>6.6 ($a_{2,2}/50a_0$)$^2$</td>
<td>3.9 ($a_{2,2}/50a_0$)$^2$</td>
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<tr>
<td>“good-to-bad” ratio $\eta K_{el}/(nK_{gas})^b$</td>
<td>2260 ($a_{2,2}/50a_0$)$^2$</td>
<td>665 ($a_{2,2}/50a_0$)$^2$</td>
<td>389 ($a_{2,2}/50a_0$)$^2$</td>
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<tr>
<td>“good-to-bad” ratio $K_{el}/(K_{pol})_{max}^c$</td>
<td>113 ($a_{2,2}/50a_0$)$^2$</td>
<td>665 ($a_{2,2}/50a_0$)$^2$</td>
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<td>elastic collision rate $nK_{el}$ (s$^{-1}$)</td>
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<td>UV count rate $S_{uv}$ (s$^{-1}$)</td>
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<tr>
<td>ion count rate $S_i$ (s$^{-1}$)</td>
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<td>$3.2 \times 10^5$</td>
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<td>probe ion count rate $S_{i}$ (s$^{-1}$)</td>
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<td>$8 \times 10^6$</td>
<td>$3.2 \times 10^5$</td>
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<tr>
<td>UV decay time $\tau_{uv}$ (s)</td>
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<td>ionization decay time $\tau_i$ (s)</td>
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<tr>
<td>probe decay time $\tau_p$ (ms)</td>
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<td>0.125</td>
<td>0.625</td>
</tr>
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</table>

$^a$Equal to the transition temperature $T_C$.

$^b$At a background pressure of $10^{-9}$ Torr.

$^c$Exciting a fraction $10^{-3}$ of the total population.
(dimer-) ions and ground-state atoms by ionization in terms of an equivalent background pressure in the trapping chamber. This approach provides an easy comparison to experiments with alkali atoms, where background gas scattering is the dominant loss process at low densities of the trapped atoms. In this case, hot ground state atoms invade the trapped sample, causing an extra trap loss and an extra heating of the sample of trapped atoms. For this reason, in most alkali experiments, the evaporative cooling is not switched off after reaching BEC. For the two final state geometries (Table I) of our trapped metastable neon atoms, the ionization rate is equal to $N_f = 10^8 \text{ s}^{-1}$ and $N_f = 4 \times 10^8 \text{ s}^{-1}$ for the high-density and the low-density case, respectively. These rates correspond to an equivalent background pressure of $3 \times 10^{-10}$ Torr and $3.6 \times 10^{-12}$ Torr, respectively. This approach gives some feeling to what extent the condensate is disturbed by the hot products of residual ionization.

However, we have to keep in mind that these hot products consist of both (dimer) ions and atoms in the ground state [see Eq. (2)] with a wide range of collision energies, ranging from 2 to 125 K for the neon system. Both features have a major influence on the cross sections involved and the resulting influence on both particle loss and heating. For example, the (dimer) ion—metastable-atom interaction is dominated by the charge-induced dipole interaction with its long-range $C_4/R^5$ potential. Only a very careful, fully quantitative analysis of the collision processes involved can resolve the major question of this paper: can BEC be reached for metastable neon? Also, we want to identify the most favorable experimental conditions for achieving BEC. For comparison, we finally apply our thorough analysis to the case of triplet metastable helium to answer the same question of the feasibility of BEC.

In Sec. II, the suppression of ionization in a realistic situation of trapping and cooling is presented, based on the recent work by Doery et al. [6]. In Sec. III, we discuss the dynamics of the ionizing collisions to determine the energy released in the hot products. The heating of the sample by inelastic collisions and the recoil due to radiative decay is treated in Sec. IV. First, we present a semiclassical framework for accurately describing the heating rate of the sample by the secondary collisions of the hot products $\text{Ne}^+(\Sigma_g^+) + \text{Ne}^+(\Sigma_g^+) \rightarrow \text{Ne}^+(\Sigma_g^+) + \text{Ne}^+(\Sigma_g^+)$, and $\text{Ne}^+(\Sigma_g^+) + \text{Ne}^+(\Sigma_g^+) \rightarrow \text{Ne}^+(\Sigma_g^+) + \text{Ne}^+(\Sigma_g^+)$ with $m_j$ indicating the magnetic substate. The kinetic energy of the electron is of the order of 12 eV, as determined by the difference potential of the initial and the final state. In the first reaction (Penning ionization, or PI), the final state neon ions and atoms in the ground state each carry a kinetic energy on the order of 100 to 500 K, depending on the energy gained in the well of the initial state potential and the internuclear distance where ionization occurs. In the second reaction path, usually referred to as associative ionization (AI), almost all of the initial state kinetic energy is stored in the molecular ion as vibrational energy. The kinetic energy of the molecular ion in the final state is due to the center-of-mass energy of the colliding $\text{Ne}^+$ atoms.

The dominant process leading to ionization is the exchange mechanism based on the Coulomb interaction of the electrons involved. In this case the valence electron of atom (1) transfers to the available core-state of atom (2), leaving the core of atom (1) to form a positive ion. The valence electron of atom (2) is no longer bound and leaves the scene [24–26]. The radiative mechanism is absent for these metastable atoms, because it requires the existence of a dipole-allowed transition to a lower state.

Because the Coulomb interaction does not affect the electron spin, the magnetic quantum number $m_s$ of the total spin $S$ does not change. For two atoms in a pure $|J=2,m_J=2\rangle$ state the process of ionization is spin forbidden. However, the anisotropic nature of the long-range electrostatic interaction due to the $(2p)^{-1}$ core hole will apply a torque that can rotate the total angular momentum $J$ of the atoms with respect to each other. This will result in a residual ionization, even for initially fully aligned atoms [6].

Detailed quantum-mechanical calculations of the ionization rates for (ultra) cold collisions have very recently been performed by Doery et al. [6]. Both the electrostatic dipole-induced dipole $V_{DD}=C_4/R^6$ and the quadrupole-quadrupole term $V_{QQ}=C_5/R^5$ (due to the core only) are included in the long range potentials. For the short range, information is derived from the $N_{8\Sigma}^+(\Sigma_u^+)$ and $N_{8\Sigma}^+(\Sigma_u^+)$ potentials. The results show that the anisotropy $\Delta C_5$ in the quadrupole-quadrupole interaction (defined as the range of $C_5$ values found for the different molecular potentials, with $\langle C_4 \rangle = 0$) is the dominant driving force for the residual ionization (Fig. 2). Its influence exceeds the effect of the dipole-induced dipole term by a factor of 12. For neon, we find $\Delta C_5 = 0.84$ a.u. [6] and $\Delta C_6 = 4.5$ a.u. at $C_6 = 1952$ a.u. [6]. The rate constants $K_i$ and $K_i^{pol}$ for the unpolarized and polarized case, respectively, are given by

$$K_i = 8 \times 10^{-11} \text{ cm}^3/\text{s},$$
When varying the phase of the Na$_2$ singlet potential, the value of $\mathcal{K}_{i}^{\text{pol}}$ never exceeds the upper limit of Eq. (4).

Of course, we should keep in mind that the treatment of Doery et al. [6] does not provide a final answer, in the sense that other mechanisms for spin-flips exist that have not been taken into account. For instance, at short range ($R<10a_0$) orientation of the core of the metastable atoms could lead to a splitting among the nine possible spin-polarized potentials. A full theoretical treatment awaits the development of reliable ab initio short-range potentials, such as currently undertaken by Kotochigova et al. [23].

An effect of second order spin-orbit splitting, that turned out to be important for the heavier alkali atoms, is not to be expected for metastable neon atoms due to its scaling with $Z^2$ with $Z$ the nuclear charge. Another process that has not been taken into account in the calculation of the residual ionization is the magnetic dipole-dipole interaction, which is the cause of residual ionizing collisions in a spin-polarized gas of triplet metastable helium atoms. However, the resulting rate constant for this process is roughly $10^{-14}$ cm$^3$ s$^{-1}$ for this system, the same value as the upper limit for the rate constant which we use throughout this paper for investigating the role of residual ionization for metastable neon atoms.

On the other hand, the occurrence of a resonance might not be prohibitive at all for reaching the transition to BEC in metastable neon. First, one can always switch to the other abundant isotope $^{22}$Ne. Second, resonances can be shifted by applying homogeneous magnetic fields. Thirdly, the occurrence of a resonance in the ionization rate constant is probably accompanied by an analogous resonance in the scattering length $a_{2,2}$. The ratio of “good-to-bad” collisions, which is the important number for effective evaporative cooling, is then not influenced and keeps the road to BEC quite open (Sec. VI D).

The definitive answer on the actual magnitude of the suppression of ionization in a spin-polarized gas of metastable neon atoms has to be provided by future experiments, by looking at the ion yield of a sample trapped in a magnetic trap (Sec. VII). The proof of the pudding is in the eating.

In Table I we present the ionization decay time for the two geometries investigated, resulting in $\tau_i=1$ s and $\tau_i=5$ s for the high density and low density case, respectively. Both decay times are much shorter than the finite lifetime $\tau_{\text{av}}=24$ s of the metastable state, i.e., ionization fully determines the time available for measurements in the final state.

### III. ENERGY RELEASE IN IONIZING COLLISIONS

Once the rate constant for ionization has been determined in a quantum-mechanical calculation, the energy release can be described in fully semiclassical terms [22]. A schematic view of the initial and final state potentials of the process of Eq. (2) is given in Fig. 4. The energy of the electron is determined by the difference potential $|V^*-V^+|$, with $V^*$ and $V^+$ the real potentials corresponding to the Ne$^*+Ne^*$ initial state and Ne$^*+Ne^+(1S_0)$ final state, respectively. The imaginary part of the interaction potentials, the so-called auto-ionization width $\Gamma(R)$, is an exponentially decaying function with a characteristic length on the order of $2a_0$ [6].
FIG. 4. Schematic view of the initial state Ne(2S) + Ne(2S) potential $V(R)$ and the final state Ne(1S0) + Ne(1S0) potential $V^*(R)$ in the process of collisional ionization. At a distance $R$, the electron leaves the scene with energy $E_{el} = E^* + V(R)$, without changing the local kinetic energy $E^* - V(R) = E' - V(R)$ of the colliding atoms in the initial and final state, respectively. Both the PI and AI processes of ionization are indicated, together with the initial-state asymptotic energy $E$ and the final-state asymptotic energy $E'$ (PI process) or vibrational quantum number $v'$ (AI process).

Semiclassically, the autoionization width can be interpreted as a decay rate $\Gamma(R)/\hbar$ for the transition to the ionic final state. The largest probability to ionize is at the classical turning point of the initial state potential, where the atoms spend most of their time. This results in a rather peaked yield of ions in this range of $R$ values. When ionization occurs, the electron leaves the scene instantaneously, compared to the heavy particle motion. The kinetic energy of the two colliding particles is conserved, if we neglect the recoil kick by the electron. At low collision energies, the local kinetic energy of the initial state atoms is fully determined by the local depth of the potential, with the well depth as an upper limit. Depending on the details of the initial and final state potentials, the final state products will end up as a molecular ion $\text{Ne}_2^+$ or two free particles $\text{Ne}^+$ and $\text{Ne}(1S_0)$. At low collision energies, the branching ratio for associative ionization is usually in the range of 0.01 to 0.1, fully determined by the details of the initial and final state potentials.

A. Penning ionization

The major part of the ionizing collisions will result in the first reaction path of Eq. (2), with the release of an ion and a ground-state atom with thermal energies. The maximum available kinetic energy now is equal to the well depth of the initial state potential, which is on the order of 250 K. This value is a suitable estimate for the total kinetic energy of the products, equally divided into a kinetic energy $E_{PI} = 125$ K for each of the two heavy particles with equal mass $m$. The recoil of the electron can be neglected in this case. Secondary collisions of these room-temperature ions and ground state atoms can result in trapped metastable neon atoms being accelerated to thermal velocities, i.e., a finite probability for the extra loss of trapped atoms. Grazing collisions can result in heating of the sample of trapped atoms. Both effects are discussed in Sec. IV.

B. Associative ionization

In the center-of-mass system, all energy gained in the potential well of the initial state is stored in the internal degrees of freedom of the final-state dimer ion. In the laboratory system, the dimer ion has an average kinetic energy equal to half the thermal energy of the trapped atoms, as determined by the velocity of the center-of-mass system. This would imply that the dimer-ions, that are in a $2\text{P}_{1/2}$ or in a $2\text{P}_{3/2}$ state with an associated magnetic moment $\mu = \frac{1}{2} \mu_B$ and $2\mu_B$, respectively, would still be trapped in the magnetic trap.

However, in this case, the recoil of the electron has to be taken into account. The increase in energy related to the recoil is

$$E_{AI} = (m_e/m)E_e,$$

with $m_e$ and $E_e$ the electron mass and kinetic energy, respectively. Inserting $E_e = 12$ eV we find $E_{AI} = 1.96$ K corresponding to $\Delta v = 40$ m/s. It is clear that the dimer-ion is not trapped, because the depth of the magnetic trap is much smaller. However, secondary collisions of the hot dimer-ion can result in a small additional loss of trapped atoms per ionization event. Also, grazing collisions can heat up the trapped atoms. These effects are discussed in Sec. IV. Because the cross sections for vibrational and rotational relaxation of the molecular ion are very small, of the order of $10a_0^2$ and less, no internal energy of the dimer ions will be dissipated in the sample of trapped atoms.

IV. HEATING RATE OF TRAPPED ATOMS

Ionizing collisions of the metastable rare gas atoms directly result in the loss of trapped atoms. As shown in Sec. III, the final state products will have large kinetic energies, due to the conversion of potential energy at short range—in the well region—into radial motion. This gives rise to a secondary effect on the trapped atoms: the hot products can collide with a cold trapped atom due to their finite mean free path in the trap. The effect of these secondary collisions is twofold: extra loss and heating.

All large-angle collisions will result in a transfer of energy that is larger than the trap depth $\mathcal{E}$. This results in an extra loss fraction $\varepsilon$ of trapped atoms, as given by

$$\dot{N}_l = \dot{N}_l(1 + \varepsilon),$$

$$\varepsilon = \langle l \rangle / \lambda_{sec} = n \langle l \rangle Q_{sec},$$

with $\dot{N}_l$ the production rate of hot products; $\lambda_{sec}$ and $Q_{sec}$ are the mean free path and the total cross section for secondary elastic collisions of these hot products with cold trapped atoms, respectively. The distance that a fast particle travels in the trap, averaged over all spatial directions, is indicated by $\langle D \rangle = (\pi D/2)$ with $D$ the diameter of the sample. To obtain insight we can insert typical values $Q_{sec} = 10^3 a_0^2$ and $5 \times 10^4 a_0^2$ for atom–metastable-atom and ion–metastable-atom collisions (Sec. V), respectively. For the two final state geometries of the sample in the magnetic trap, we then find
\[ \lambda_{\text{sec}} = \frac{70 \, \mu m}{s}, \quad \epsilon = 0.14 \quad \text{and} \quad \lambda_{\text{sec}} = 360 \, \mu m, \quad \epsilon = 0.008, \] 
respectively. The additional loss fraction is thus fully determined by the secondary ion-atom collisions. Clearly, however, the extra loss fraction \( \epsilon \) is only a minor effect and can be neglected in first order.

But we also have to consider small angle scattering of the hot products with the cold trapped atoms, with a transfer of kinetic energy that is less than the trap depth \( \mathcal{E} \), which is generally on the order of 10 to 30 mK. However, these small angle collisions will result in trapped atoms with an energy much larger than the trap temperature \( T \), which is in the millikelvin to microkelvin range. All of this energy will finally be dissipated in the population of trapped atoms, resulting in an effective heating rate. For a collision of a hot particle (atom, ion, or dimer ion) with velocity \( \mathbf{v} \) and kinetic energy \( E = \frac{1}{2} m v^2 \) on a stationary target atom, the velocity transfer to the cold atom is given by \( \Delta \mathbf{v} = v (\mu/m) \), with \( \mu = m/2 \) and \( m = 2m/3 \) for the hot atoms, atomic, and dimer ions, respectively (Fig. 5).

The finite depth \( \mathcal{E} \) of the trap results in an upper bound for the energy transfer that will still result in heating but not in the loss of an atom, as determined by \( \frac{1}{2} m (\Delta v)^2 = \mathcal{E} \). This in turn limits the range of scattering angles that we have to take into account

\[ \theta_{\text{sec}} = \frac{m/\mu)(\mathcal{E}/E)^{1/2} = \theta_{\text{max}}. \]  

(7)

For collisions with thermal neon atoms at an energy \( E_{\text{PI}} = 125 \, \text{K} \) in the laboratory system and a trap depth of 50 Gauss (corresponding to \( \mathcal{E} = 10 \, \text{mK} \)), the maximum scattering angle is \( \theta_{\text{max}} = 18 \, \text{mrad} \). This determines the angular range where we need a correct description of the differential cross section \( \sigma_{\text{sec}}(\theta) \). In the Sec. IV A we will investigate semiclassical scattering theory, that provides an excellent analytical framework for describing small-angle scattering in thermal collisions [27–30]. In Secs. IV B and IV C we apply these results to obtain an accurate description of the heating rates for atom–metastable-atom and (dimer) ion–metastable-atom secondary collisions.

A. Small-angle differential cross section

In semiclassical theory [27–31], the small-angle differential cross section \( \sigma_{\text{sec}}(\theta) \) scales with the characteristic diffraction angle

\[ \theta_{0,\text{sec}} = \left( \frac{4 \pi k^2 Q_{\text{sec}}}{\lambda^2} \right)^{1/2}. \]  

with \( k = \mu v / \hbar \) the wave number and \( v \) the relative velocity of the collision partners. For an inverse power-law potential \( V(R) = C_s / R^s \) (with \( s = 4 \) for the charge-induced dipole interaction of ion-atom scattering, \( s = 6 \) for the induced dipole-dipole nature of atom-atom scattering), simple analytical formulas are available.

For angles \( \theta \leq \theta_{0,\text{sec}} \) we observe a diffraction peak, which can be approximated by [31,32]

\[ \sigma_{\text{sec}}(\theta) / \sigma_{\text{sec}}(0) = 1 - \alpha_1(s)(\theta / \theta_{0,\text{sec}})^2, \]  

(9)

with \( \alpha_1(s) \) a numerical constant given in Table II. For angles \( \theta > \theta_{0,\text{sec}} \) we find the classical result [29–31]

\[ \sigma_{\text{sec}}(\theta) / \sigma_{\text{sec}}(0) = \alpha_2(s)(\theta / \theta_{0,\text{sec}})^{-(s+1)/s}, \]  

(10)

which corresponds to refraction, in analogy to geometrical optics when scattering light on an inhomogeneous medium. The constant \( \alpha_2(s) \) is given in Table II. Successful semiempirical formulas connecting the two regions are given by several authors [29,31]. The absolute value of the differential cross section \( \sigma_{\text{sec}}(0) \) in the forward direction and the total elastic cross section \( Q_{\text{sec}} \) are given by [33,34]

\[ \sigma_{\text{sec}}(0) = k^2 Q_{\text{sec}} / \{16 \pi^2 \cos^2[\pi/(s-1)]\}, \]  

(11)

\[ Q_{\text{sec}} = \alpha_3(s)(C_s / \hbar v)^{(s-1)/s}, \]

with \( \alpha_3(s) \) given in Table II. To obtain insight in the fraction of the total cross section in the forward diffraction peak for \( \theta \leq \theta_{0,\text{sec}} \) and the refraction dominated range for \( \theta > \theta_{0,\text{sec}} \), we can calculate the integral of these approximations of the differential cross section in these intervals. We find that 15 to 25 % of the cross section is in the diffraction peak (depending on the value of \( s \)), with the remainder in the refraction dominated region.

Typical values of the cross sections are given in Table II for both Ne\(^{1}(S_0) \)+ Ne\(^{+}\) and Ne\(^+\)+ Ne\(^{+}\) secondary collisions at an energy \( E_{\text{PI}} = 125 \, \text{K} \), as relevant for the PI process. For the AI process typical values of the cross sections are given for Ne\(^{3}\)+ Ne\(^{+}\) secondary collisions at an energy \( E_{\text{AI}} = 2 \, \text{K} \), as determined by the recoil of the electron.

The lower limit on the energy where this semiclassical description starts to fail is determined by the condition that sufficient partial waves contribute to the scattering cross sections. For the neon system \( p \) waves start to contribute at 10 mK [6]. This implies that the lower limit for our model for heat transfer is still valid at 2K, the energy release in associative ionization. We can now identify which models we have to apply to calculate the heating rates for the case of atom–metastable-atom scattering and (dimer) ion–metastable-atom scattering, by comparing the maximum scattering angle to the scaling angle.

1. Atom–metastable-atom scattering: \( s = 6 \)

For thermal collisions of neon atoms in the ground state with trapped metastable atoms the collision process is dominated by the induced dipole-dipole interaction, characterized by the long range \( C_0 / R^6 \) potential. In this case, the maximum scattering angle \( \theta_{\text{max}} \) is always much smaller than the

FIG. 5. Newton diagram of the secondary collision of a hot product, atom or ion, with velocity \( \mathbf{v} \) with a cold trapped atom, showing the corresponding velocity transfer \( \mathbf{v}/2 \) for reduced mass \( \mu = m/2 \).
TABLE II. Parameters for secondary collisions of hot, final state products of residual ionizing Ne(2,2) + Ne(2,2) collisions with cold trapped atoms, assuming a kinetic energy $E_{PI} = 125$ K and $E_{AI} = 2$ K for the hot product from the PI and the AI process, respectively. The resulting heating rate $\dot{T}_{sec}$ of the total population of trapped atoms is given for both the high-density--low-aspect-ratio and low-density--high-aspect-ratio case of the final state. The depth of the magnetic trap is fixed to $\varepsilon = 10$ mK.

<table>
<thead>
<tr>
<th></th>
<th>Ne(1S$_0$) + Ne*</th>
<th>Ne$^+$ + Ne*</th>
<th>Ne$^+_1$ + Ne*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_{PI} = 125$ K</td>
<td>$E_{PI} = 125$ K</td>
<td>$E_{AI} = 2$ K</td>
</tr>
<tr>
<td>$s$</td>
<td>6</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>$a_1(s)$</td>
<td>0.9975</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$a_2(s)$</td>
<td>0.2846</td>
<td>0.1920</td>
<td>0.1920</td>
</tr>
<tr>
<td>$a_3(s)$</td>
<td>8.083</td>
<td>11.37</td>
<td>11.37</td>
</tr>
<tr>
<td>$C_s$ (a.u.)</td>
<td>52.7</td>
<td>103.9</td>
<td>103.9</td>
</tr>
<tr>
<td>$\mu$ (a.u.)</td>
<td>10</td>
<td>10</td>
<td>13.33</td>
</tr>
<tr>
<td>$v$ (m/s)</td>
<td>322</td>
<td>322</td>
<td>57</td>
</tr>
<tr>
<td>$k$ $(a_0^{-1})$</td>
<td>2.7</td>
<td>2.7</td>
<td>0.63</td>
</tr>
<tr>
<td>$Q_{sec}$ $(a_0^2)$</td>
<td>$1.35 \times 10^3$</td>
<td>$9.03 \times 10^4$</td>
<td>$2.88 \times 10^5$</td>
</tr>
<tr>
<td>$\sigma_{sec}(0)/(a_0^2)$</td>
<td>$1.28 \times 10^3$</td>
<td>$1.50 \times 10^9$</td>
<td>$8.36 \times 10^8$</td>
</tr>
<tr>
<td>$\theta_{0,sec}$ (mrad)</td>
<td>36</td>
<td>4.4</td>
<td>10.5</td>
</tr>
<tr>
<td>$\theta_{max}/\theta_{0,sec}$</td>
<td>0.50</td>
<td>4.1</td>
<td>7.3</td>
</tr>
<tr>
<td>$\Delta Q_{sec}/Q_{sec}$</td>
<td>0.095</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta E (\theta_0)$(mK)</td>
<td>0.60</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>$\dot{T}_{sec}$ $(\mu K/s)$ b</td>
<td>$0.60 \times \eta_{PI}$</td>
<td>$104 \times \eta_{PI}$</td>
<td>$249 \times \eta_{AI}$</td>
</tr>
<tr>
<td>$\dot{T}_{sec}$ $(\mu K/s)$ c</td>
<td>$0.007 \times \eta_{PI}$</td>
<td>$1.25 \times \eta_{PI}$</td>
<td>$3.0 \times \eta_{AI}$</td>
</tr>
</tbody>
</table>

References [36] and [35].

bHigh density case with $T_C=1.7$ $\mu$K (Table I).

Low density case with $T_C=0.6$ $\mu$K (Table I).

characteristic angle $\theta_{0,sec}$ (Table II and Fig. 6). This statement holds for a wide range of collision energies, due to the scaling law $\theta_{max}/\theta_{0,sec} \approx E^{-1/2(s-1)}$, that can easily be derived using Eqs. (8) and (11). Therefore the diffraction region in the differential cross section [Eq. (9)] will be most important for calculating the heating rate for atom–metastable-atom collisions.

2. Ion–metastable-atom scattering: $s=4$

For thermal collisions of neon ions and dimer ions with the trapped metastable atoms the interaction is determined by the charge-induced dipole interaction, characterized by a long range $C_4/R^4$ potential that extends to larger internuclear separations $R$. In this case, the total cross section is much larger than for the thermal collisions with the ground-state atoms, resulting in a much smaller value of the characteristic angle $\theta_{0,sec}$. In this case, the maximum scattering angle is always much larger than the characteristic angle. The refractive region of the differential cross section [Eq. (10)] will give the largest contribution to the heating rate.

FIG. 6. Small-angle differential cross section $\sigma_{sec}(\theta)/\sigma_{sec}(0)$ for the case of a $C_4/R^4$ potential for atom–metastable-atom thermal collisions. Full line: quantum-mechanical calculations; dashed line: classical mechanics. The results are also indicative for scattering on a $C_4/R^4$ potential for ion–metastable-atom collisions. Typical values for the maximum scattering angle $\theta_{max}$ are indicated for the case of atom–metastable-atom and ion–metastable-atom secondary collisions, respectively.
The heating rate of the trapped atoms in a harmonic potential then is equal to

\[
\dot{U} = (3k_B T) N = \langle \dot{Q} \rangle E \dot{N}_i \text{,}
\]

\[
\dot{T} = 0.25 \langle \dot{Q} \rangle [E^{3/4} (\theta_{0,sec})^{1/3} / 3k_B] / \tau_i \text{.}
\]

Compared to the expression for the heating rate for atom–metastable-atom collisions in Eq. (14), the major difference is the occurrence of the full value of the total cross section \(Q_{sec}\) in the collision probability “density \(\times\) length \(\times\) cross section” in Eq. (18) as compared to the much smaller fractional cross section \(\Delta Q_{sec}\) in Eq. (14). This results in a scaling \(\dot{T} \sim E^{3/4}\) of the ion–metastable-atom heating rate with the trap depth \(E\): lowering the trap depth thus results in a much slower decrease of the heating rate than is the case for atom–metastable-atom collisions.

The implications for the heating rate by dimer ion–metastable-atom collisions are even more severe. Due to the very small collision energies of the dimer ions (resulting from the recoil kick of the electron in the AI process) and the scaling \(Q_{sec} \sim E^{-1/4}\), we expect a large cross section and thus a large heating rate for these collisions. However, a small value of the branching ratio \(\eta_{AI}\) to the process of Associative Ionization will most likely limit the effect on the heating rate.

D. Heating by UV-photon recoil

Finally, we also have to consider the heating effect by the recoil kick of the UV photon emitted in the radiative decay of the metastable atom. This kick corresponds to an energy \(\Delta E_{uv}\) in the 50 \(\mu\)K to 1 mK range. At these collision energies only s waves contribute to the scattering process, with a cross section fully determined by the scattering length. However, in this case it concerns the scattering length \(a_{0,2}\) for collisions of atoms in the ground state with the trapped metastable atoms. The effective heating rate is then given by

\[
\dot{U} = (n\langle l \rangle Q_{T-0}) (E_{uv}) \dot{N}_{uv} \text{,}
\]

\[
\dot{T} = 0.25 \langle n\langle l \rangle Q_{T-0} \rangle (E_{uv})^{1/4} / \tau_{uv} = (E_{uv})^{1/4} / \tau_{uv} \text{,}
\]

with \(Q_{T-0} = 8 \pi a_{0,2}^2\) the s-wave scattering cross section. To obtain the second equation we have substituted \(\dot{N}_{uv} / N = 1 / \tau_{uv}\). Again we have assumed a harmonic trap with six degrees of freedom. Compared to the results for atom–metastable-atom and ion–metastable-atom scattering, the finite depth of the trap plays no role because \(E_{uv} \ll E\). The heating rate only depends on the finite radial dimension \(\langle l \rangle\) of the trap. The upper limit corresponds to the case of an infinite scattering length \(a_{0,2} \rightarrow \infty\), when the total recoil energy is dissipated in the sample.

V. HEATING RATES FOR NEON

In Table II we have listed the collision parameters that serve as input for the calculation of the heating rate for neon. The \(C_4\) [35] and \(C_6\) [36] values originate from theory, but
TABLE III. Heating lifetime $\tau_{\text{heat}} = T_C / T_{\text{sec}}$ of the total population of trapped atoms by secondary collisions of hot, final-state products of residual ionizing collisions with cold trapped atoms at the onset of condensation at temperature $T_C$. In these calculations we have assumed continuous evaporative cooling with a cutoff at an energy $\varepsilon = 6k_B T_C$. The results are given for neon and helium, using the input data of Tables II and V. Both the high-density–low-aspect-ratio and the low-density–high-aspect-ratio of the condensate state are investigated.

<table>
<thead>
<tr>
<th></th>
<th>High density</th>
<th>Low density</th>
<th>High density</th>
<th>Low density</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R(^1S_0) + R^*$</td>
<td>$2.7 \times 10^7 / \eta_{\Pi}$</td>
<td>$6.6 \times 10^8 / \eta_{\Pi}$</td>
<td>$1.8 \times 10^7 / \eta_{\Pi}$</td>
<td>$3.8 \times 10^8 / \eta_{\Pi}$</td>
</tr>
<tr>
<td>$R^* + R^*$</td>
<td>$2.9 / \eta_{\Pi}$</td>
<td>$183 / \eta_{\Pi}$</td>
<td>$4.9 / \eta_{\Pi}$</td>
<td>$313 / \eta_{\Pi}$</td>
</tr>
<tr>
<td>$R^<em>_2 + R^</em>$</td>
<td>$1.2 / \eta_{\Pi}$</td>
<td>$77 / \eta_{\Pi}$</td>
<td>$2.5 / \eta_{\Pi}$</td>
<td>$159 / \eta_{\Pi}$</td>
</tr>
</tbody>
</table>

are expected to be close (within 10%) to reality considering the current status of this type of calculations. For the energy of the ion and atom released in the process of Penning ionization we have used $E_{\Pi} = 125$ K, as discussed in Sec. III. The scaling law $\dot{T} = E^{-2/3}$ can always be applied to obtain the heating rate at other values of the energy release. For the process of associative ionization we have used the recoil energy of the electron as the collision energy (Sec. III). The $C_4$ value for the $\text{Ne}_2^+ + \text{Ne}^*$ system has been fixed at the value for the $\text{Ne}^+ + \text{Ne}^*$ system. The depth of the trap has been fixed to $\varepsilon = 10$ mK, resulting in a maximum scattering angle $\theta_{\text{max}} = 18$ mrad for atom–metastable-atom and ion–metastable-atom scattering and $\theta_{\text{max}} = 76$ mrad for the low energy dimer ion–metastable-atom collisions.

To compare the contributions from the PI and the AI process we assume a branching ratio $\eta_{\Pi} = 0.1$. We observe that ion–metastable-atom collisions, resulting from the long-range ion-induced dipole interaction, are the dominant contribution to the heating rate. Due to the small branching ratio, the even larger heat transfer per collision for the dimer ion results in a smaller contribution to the heating rate.

For the scaling of the heating rate with respect to the number density and the geometry of the sample of trapped atoms we find

$$\dot{T} \sim n^2 \langle I \rangle,$$

which is obtained by substituting $\tau_{\ell} = 1 / (\kappa_{\ell}^\text{pol} n)$ in Eq. (18). To decrease the heating rate without affecting the conditions where BEC occurs, we have to choose for a tighter confinement in the radial direction. By lowering the number density $n$ we also lower the value of the transition temperature $T_C$ according to Eq. (1). The heating lifetime $\tau_{\text{heat}}$ at the transition temperature $T_C$ then scales as

$$\tau_{\text{heat}} = T_C / \dot{T} \sim n^{-4/3},$$

which helps us to choose favorable geometries for obtaining BEC.

The heating rates have been calculated for both final state trap geometries. For the value of $\langle I \rangle$ we use the radial size given in Table I. For the high-density–low-aspect-ratio case the total heating rate of 119 $\mu$K/s is fatal for achieving BEC at the transition temperature $T_C = 1.7$ K. For the low-density–high-aspect-ratio case the total heating rate of 1.4 $\mu$K/s compares favorable to the value $T_C = 0.6$ K, resulting in a heating lifetime of approximately 0.5 s. This value has to be compared to the lifetime $\tau_{\ell} = 5$ s for ionization.

Finally, we have also investigated the heating rate at the BEC transition temperature, where we assume that the process of evaporative cooling is left switched on with a cutoff at $6k_B T_C$. This results in an effective trap depth $\varepsilon$ equal to this cutoff value, which limits the scattering angle $\theta_{\text{max}}$ to values much smaller than $\theta_{\text{sec}}$ with a correspondingly smaller heating rate for the ion–metastable-atom collisions. In Table III we show the heating lifetime $\tau_{\text{heat}}$ [Eq. (21)] for the final state at the transition temperature $T_C$. Typical lifetimes $\tau_{\text{heat}}$ are then always much larger than the lifetime for ionization, both for the high-density and the low-density case. Keeping the process of evaporative cooling switched on in the final state at the transition temperature is thus very effective: the heating rate is lowered by two orders of magnitude while we also profit from the ongoing cooling effect. The latter has not been taken into account in this calculation.

The decay of the metastable state with a lifetime $\tau_{\text{uv}} = 24$ s results in the emission of a UV photon with a wavelength of 70 nm, with an associated recoil kick of the atom equal to 25 cm/s corresponding to an energy $E_{\text{uv}} = 60$ $\mu$K. No information at all is available on the actual value of the scattering length $a_{0,2}$ for cold atom–metastable-atom collisions, which is required for evaluating Eq. (19). If we assume a scattering length $a_{0,2} = 100 a_0$, we find a mean free path $(nQ_{T=0})^{-1} = 14$ and 71 $\mu$m for the high-density–low-aspect-ratio and the low-density–high-aspect-ratio cases, respectively. The resulting heating rates are given in Table IV. For this value $a_{0,2} = 100 a_0$ of the scattering length, the heating rate is always less than the heating rate for ion–metastable-atom collisions. This even holds for the case of an infinite scattering length $a_{0,2}$.

We conclude that the low-density–high-aspect-ratio final state is the best choice for achieving BEC. Keeping the process of evaporative cooling switched on at $T_C$ extends the heating lifetime to values larger than the ionization lifetime of 5 s.

VI. TRAPPING AND COOLING FEATURES

A. Bright atomic beam

For loading the trap, an atomic beam of cold atoms is the only choice [37–42]. In Eindhoven, a bright beam line is
available for this purpose, routinely delivering a total flux of $5 \times 10^{10}$ metastable neon atoms per second in the $^3P_2$ state [39]. The beam characteristics are an axial velocity of 100 m/s in a 1 mm diameter beam with a divergence of 3 mrad, designed for applications in intrabeam scattering experiments. By combining a beam stop in the upstream part with a beam-limiting collimator in the downstream end beyond the beam compressor, the atomic beam only consists of cold $^{20}\text{Ne}(^3P_2)$ metastable atoms. All undesired beam components are removed, such as thermal energy neon atoms in the ground state, thermal $^{22}\text{Ne}(^3P_0)$ and $^{22}\text{Ne}(^3P_2)$ metastable atoms, and UV photons from the discharge-excited atomic beam source.

A variety of laser cooling techniques is used in this beam line. The atoms leaving a LN$_2$-cooled discharge-excited beam source are captured in a collimator with a 100 mrad acceptance; after an extra transverse Doppler-cooling stage, the atoms enter a midfield-zero Zeeman slower. Then, a magneto-optical compressor tightens the beam to its desired diameter, with a sub-Doppler transverse cooling stage to mold it into the desired beam divergence. A single cw dye laser is used for operating the beam line, using AOM’s to shift the laser frequency for the different stages of laser cooling.

### B. MOT

To be trapped in a magneto-optical trap (MOT), the beam of cold atoms has to be decelerated from its original velocity of 100 m/s to a velocity less than 15 m/s. The stopping distance is on the order of 10 mm, leaving a variety of methods to achieve this. First, the MOT laser beams, crossing the atomic beam at a 45° angle and red detuned by a few linewidths, are nearly sufficient to slow the atoms to the trapping velocity. Also, an extra laser beam can be employed, with a free choice of angle and detuning. For the MOT, we opt for a low density and a large diameter, to avoid large trap losses due to ionization of the unpolarized population. Typically, we can load $N \approx 10^{10}$ atoms in the MOT with a loading time of 1 s. As a radius we choose $r = 5$ mm, resulting in an equilibrium density of $1.9 \times 10^{10}$ cm$^{-3}$ with a corresponding decay time for ionization equal to $\tau_i = 0.7$ s. For the temperature in the MOT we expect a value of the order of $T = 100$ $\mu$K.

### C. Magnetic trap

Finally, the population has to be transferred from the MOT to a magnetic trap. The Ne($^3P_2$) state has a Landé factor $g_J = 1.5$, leading to a dipole moment of $3 \mu_B$ with a potential energy of 0.202 mK per Gauss. For a threedimensional harmonic trap the BEC condition of Eq. (1) can be written as [43]

$$k_B T_c = 0.94 \hbar \bar{\omega} N^{1/3}, \quad (22)$$

with $\bar{\omega} = (\omega_x^2 \omega_y \omega_z)^{1/3}$ the geometric mean value of the frequencies of the confining potential. For the high-density–low-aspect-ratio and the low-density–high-aspect-ratio cases we find $\bar{\omega} = 382 (2 \pi)$ Hz and $224 (2 \pi)$ Hz, respectively. To satisfy our demands on the tight radial confinement, with a typical radial dimension of 10 and 3 $\mu$m, we find radial frequencies equal to $\omega_r = 500 (2 \pi)$ Hz and $\omega_r = 1000 (2 \pi)$ Hz for the high- and the low-density cases, respectively. The corresponding axial frequencies and aspect ratios $A$ then are $\omega_z = 222 (2 \pi)$ Hz, $A = 2.2$, and $\omega_z = 12 (2 \pi)$ Hz, $A = 83$.

Both a Ioffe-Pritchard trap [44] or a clover-leaf trap [19] can be used for a trap with a tight radial confinement and a large aspect ratio, the latter choice being required to obtain a sufficiently large population $N$ of trapped atoms. Using a clover-leaf coil configuration, a radial frequency $\omega_r = 1000 (2 \pi)$ Hz can be achieved with a radial gradient $B'_r = 150$ G/cm and a bias field $B_0 = 0.5$ G. The former gradient can be readily achieved in a clover-leaf coil configuration with a 100 mm distance between the two planes where the coils are located, leaving sufficient space for a trapping chamber and diagnostics.

To match the size of the magnetic trap to the MOT, it is required to widen up the trap by increasing the bias field $B_0$, thus decreasing the radial frequency and increasing the radial dimensions to a few mm. We assume that $10^{10}$ atoms in the $|2,2\rangle$ state are loaded in the trap. Next, we apply an adiabatic compression by a decrease of the bias field, with a decrease in volume and a corresponding increase in temperature. At the onset of evaporative cooling, we assume a temperature $T = 2$ mK and a density of $n = 5 \times 10^{11}$ cm$^{-3}$ with an associated trap lifetime for residual ionization of $\tau_i = 200$ s.

### D. Evaporative cooling

In this section we use the recent review paper by Ketterle and Van Druten [21] as a starting point. The essential parameter of evaporative cooling is the ratio $R$ of “good collisions” to “bad collisions.” The larger this number is, the
easier it is to get into the regime of runaway evaporative cooling with an increasing elastic collision rate. As yet, no accurate information at all is available on the potentials for binary collisions of metastable neon atoms. The scattering length $a_{2,2}$, which determines the cross section $Q_{\text{el}} = 8 \pi a_{2,2}^2$ and the rate constant $K_{\text{el}} = \langle v \rangle Q_{\text{el}}$ for elastic scattering at these low energies, are thus unknown.

For the alkali gases, collisions with the background gas are the dominant factor for the loss of atoms from a magnetic trap. For the metastable rare gases the situation is different. At a background pressure of $10^{-9}$ Torr, the trapping time due to these collisions is on the order 20 s, using a typical rate constant $K_{\text{gas}} = 1.6 \times 10^{-9}$ cm$^3$ s$^{-1}$ for collisions with the background gas. In the initial state of the trapped metastable neon atoms, with $\tau_i = 200$ s, the collisions with the background gas determine the trapping time. This situation is identical to the alkali gases. For the two final state geometries of Table I, the lifetime $\tau_f$ for ionization is at least a factor four smaller than the trapping time for background collisions.

In the final state, the residual ionizing collisions of the polarized metastable neon atoms are the dominant contribution to the “bad collisions.” This is identical to the case of H atoms, where spin-changing binary collisions are the major loss process [20]. The elastic collision rate $n_{\text{gas}} K_{\text{el}}$ as well as the rate of suppressed ionization $n_{\text{gas}} K_{\text{pol}}$ then have the same dependency on the density $n$ in the trap: the ratio $R$ of “good collisions” to “bad collisions” is independent of density and scales as $T^{1/2}$.

For the case of metastable neon, the evaporative cooling thus evolves from an “alkali-like” initial state to a “hydrogen-like” final state. For the initial and final state the ratio $R$ is given by

\[ R = \frac{n_{\text{gas}} K_{\text{el}}}{n_{\text{gas}} K_{\text{pol}}}, \quad \text{initial state}, \]
\[ R = \frac{K_{\text{el}}}{K_{\text{pol}}}, \quad \langle v \rangle 8 \pi a_{2,2}^2 (K_{\text{pol}}^{\text{max}}) = R_{\text{min}}, \quad \text{final state}, \]

with $\langle v \rangle$ the average velocity of the trapped atoms and $(K_{\text{pol}}^{\text{max}})$ given in Eq. (4). Numerical values for $R_{\text{min}}$ are given in Table I. We have to compare these minimum values to the requirement $R \geq 120$ and 450 for run-away cooling in a linear trap (initial state at $T = 2$ mK) and a harmonic trap (final state), respectively. For the initial state, it is very easy to achieve conditions of runaway cooling. Depending on the actual value of the scattering length $a_{2,2}$, the cooling can slow down when getting closer to the final state. In the case of scattering length $a_{2,2} \approx 50 a_0$ the conditions of runaway cooling are fulfilled in the whole cooling range from 2 mK to 1 $\mu$K.

To estimate the time required for the phase of evaporative cooling, we use the results of Van Druten and Ketterle. For the case of a harmonic potential and a cutoff at an energy equal to $6k_B T$, we find an increase of phase space density by a factor $10^5$ in 600 elastic collision times with a loss in total population by a factor 100. Lowering the cutoff to, e.g., a value of $5k_B T$ gives the same increase in phase-space density in half the number of collisions, at the price of ending up with five times fewer atoms. For the case of metastable neon we find an elastic collision rate of $113$ s$^{-1}$ for the initial state; for the final state we find 665 and 78 s$^{-1}$ for the high-density and the low-density case, respectively, when assuming a scattering length equal to $a_{2,2} = 50 a_0$. Cooling times of a few seconds can be achieved in this case, especially if we keep in mind that we have assumed a loss in population by a factor $10^4$ throughout this paper. This opens the possibility of applying rather low values of the cutoff, resulting in cooling times that are always much less than the ionization time. This always holds for the initial state with $\tau_i = 200$ s; only a small fraction of the cooling time is most likely spent close to the final state densities with $\tau_f = 1$ and 5 s, respectively.

Because ionization is a two-body collision process, the loss of metastable atoms will preferentially occur on the $z$ axis of the magnetic trap where the density is high. These atoms have a lower than average potential energy: their loss will thus result in an effective heating of the remaining population of trapped atoms. If we assume an average potential energy of $k_B T/2$ of these centerline atoms, the effective energy transfer is equal to the remaining fraction $k_B T$ of potential energy. We can directly derive a heating rate equal to $T = (2T/3)/\tau_f$. For the final state geometries investigated, this results for neon in $T = 1.1 \mu$K/s and $T = 0.08 \mu$K/s for the high density and low density case, respectively. These rates are independent of the depth of the trap. Keeping the evaporative cooling switched on after having reached BEC is the solution for this problem.

### E. Minimizing the trap depth

Looking at the scaling of the heating rates with the trap depth, we conclude that it is important to choose for the lowest value of $E$ that can be experimentally obtained for metastable atoms escaping in all directions. A simple method is to add an open-ended glass tube with radius $r_w$, placed on axis with the $z$ axis of the magnetic trap. The inner wall of the tube now acts as a “wall of death” for atoms with an energy larger than the magnetic energy $\mu B r_w$: metastable atoms are de-excited by a surface collision. For neon atoms with a magnetic energy of 0.202 mK/G, a trap depth of 10 mK corresponds to a maximum magnetic field $B = 50$ G. With a gradient of 100 G/cm this translates to $r_w = 5$ mm. Care has to be taken, however, that the MOT laser beams are not disturbed in such a way that insufficient atoms can be loaded. The actual design is clearly a tradeoff between these two demands.

### VII. REAL-TIME DIAGNOSTICS

A spin-polarized sample of metastable atoms trapped in a magnetic trap can be monitored by observing the loss processes. First, the finite lifetime of the metastable state ($\tau_{uv} = 24$ s for neon) results in a flux of UV photons by the radiative decay to the ground state. The trapped population $N(t)$ decays exponentially according to $N(t) = N(0) \exp(-t/\tau_{uv})$, which can be easily monitored using a channeltron. The count rate $S_{uv}$ for UV-photons is equal to...
with $\eta_{uv}$ the quantum efficiency of the detector and $\Omega_{uv}$ the solid angle acceptance. Assuming $\eta_{uv} = 1$ and $\Omega_{uv} = 10^{-2}$ sr, the count rate ranges from $S_{uv} = 2.8 \times 10^3$ s$^{-1}$ in the initial state of the trapped sample to the order of 10 s$^{-1}$ in the final state (Table I). These count rates are quite sufficient to track the evolution of the population during the phase of evaporative cooling.

The residual ionization of the trapped atoms results in ions leaving the sample at a rate $S_i$ of

$$S_i = -\frac{dN_i}{dt} = (K_{i,pol}^0)^2 V = (K_{i,pol}^0)nN/2,$$

with $V = N/n$ the effective volume of the trapped sample. This results in an ion count rate $S_i = 5 \times 10^7$ in the initial state; in the final state we find $S_i = 10^6$ and $4 \times 10^5$ s$^{-1}$ for the high density and the low density case, respectively, assuming a quantum efficiency of unity for the detector used. These count rates allow us to measure the evolution of the density of the sample on a time scale of microseconds to milliseconds, an interesting prospect.

Finally, we can also measure the density of the trapped atoms by an external probe. A short laser pulse, at a frequency tuned to a transition to a short-lived Ne(3$^2$P$_J$, $J=1; m_J=1$) state, will result in a small fraction of atoms in the ionizing Ne(3$^2$S$_1$) metastable state. The extra yield $S_x$ of ions due to this ionizing fraction is given by

$$S_x = -\frac{dN_x}{dt} = K_{x,p} n N_x = N_x / \tau_x,$$

with $N_x$ the total number of atoms in state $x$. The decay time $\tau_x = (nK_{x,p})^{-1}$ of the extra contribution to the ion count rate is a direct measure for the absolute density $n$ of the trapped [2,2] state. The calculated value for $K_{x,p}$ is the scaling factor relating the time scale to the density scale. For the initial state we find $\tau_x = 25$ ms; for the final state $\tau_x = 125$ and 625 $\mu$s for the high and the low density case, respectively. When ionizing a fraction $N_x = 10^{-3}$ of the total population per probe pulse, the peak count rates $S_x$ for the initial and final state are always larger than the steady-state ion signal $S_i$ (Table I). In all cases we find $S_i/S_x \geq 8$, which is a sufficient signal-to-background ratio for an accurate measurement of the decay time.

Using Eqs. (24), (25), and (26) we have three linear equations with two parameters, i.e., the density $n$ and the population $N$ of the trapped [2,2] atoms. The ionization rate constant $K_{i,p}$ can be determined reliably from intra-beam collision experiments with cold atoms, with an estimated accuracy of 20 to 30%. At the initial state conditions, with fairly high count rates for all three diagnostics, we can then determine the rate constant $K_{x,pol}^0$ for the residual ionization. When this calibration has been done, we can limit ourselves to the two non-invasive measurements of $S_{uv}$ and $S_i$; the probe pulse method is only necessary for small sample sizes, where the UV count rate gets too low for accurate data on $N$ in a short time step.

The measured values for $n$ and $N$ can be combined with the field geometry of the magnetic trap to reveal the temperature $T$ of the trapped atoms. At high temperatures, as encountered in the initial stage at the onset of evaporative cooling, the trap is linear in the radial direction and harmonic in the axial direction. At low temperatures the trap is harmonic in all three dimensions. This results in

$$N/n \sim V = \frac{(2k_B T/m)^{1/2}}{\omega_x} \left( \frac{k_B T}{3 \mu_B B_x} \right)^2 \sim T^{1/2}, \text{ high } T,$$

$$N/n \sim V = \frac{3}{\omega_j} \left( \frac{2k_B T/m}{3 \mu_B B_x} \right)^{3/2} \sim T^{3/2}, \text{ low } T,$$

where we have set the temperature equal to the trapping potential to calculate the characteristic size of the sample. We conclude that the density, temperature, and total population of a sample of metastable atoms trapped in a magnetic trap can be monitored in real time using two channeltrons for detecting the ions and the UV photons, respectively.

VIII. COMPARISON TO METASTABLE HELIUM

Currently, the group of Hogervorst in Amsterdam is actively pursuing BEC in metastable helium. [12,13]. At first glance, the triplet metastable He* $(1S)/(2S)$ $^3S_1$ atom with its long lifetime of 9000 s [45] and an isotropic electrostatic interaction, seems to be the best candidate for achieving BEC. The first theoretical results for the calculated small rate constant for residual ionization, driven by magnetic dipole-dipole interactions, indicate a suppression of $10^4$. However, the large recoil related to its light mass results in drawbacks in laser cooling and trapping of large fluxes of atoms. This implies lower trap densities, smaller values of the transition temperature $T_C$ and correspondingly longer evaporative cooling times. This longer time scale results in a stronger influence of trap losses and associated heating by collisions with the background gas.

However, for our comparison of helium with neon, we assume equal loading rates and equal densities. This avoids a long discussion on experimental advantages and disadvantages of both systems. At the final density, the lifetime of the trapped helium atoms is equal to the neon results, due to the comparable values of the rate constant for residual ionization. At equal density, the transition temperature scales as $T_C \sim m^{-1/2}$, resulting in $T_C = 8.6 \mu$K and $2.9 \mu$K for the high density and low density case, respectively.

In Table V we have listed the parameters used to calculate the heating rate for the trapped metastable helium atoms in the final state. Because the well depth of the initial state is on the order of 1000 K, deeper than is the case for neon, we have used $E_{PI} = 500$ K for the product energy in the PI process. For the AI process we have used $E = 17$ K as determined by the electron recoil. For helium the branching ratio for ionizing collisions has been determined experimentally by Müller et al. and Mastwijk, resulting in $\eta_{AI} = 0.07$ at $E = 17$ K [9] and $\eta_{AI} = 0.030$ at 0.1 $\mu$K [41], respectively.

For the high density case the total heating rate then is
TABLE V. Parameters for secondary collisions of hot, final state products of residual ionizing He\((1,1) + \text{He}^+\) collisions with cold trapped atoms, assuming a released kinetic energy per particle of \(E_{\text{PI}} = 500\) K for the PI and \(E_{\text{AI}} = 17\) K for the AI process. The resulting heating rate \(\dot{T}_{\text{sec}}\) of the total population of trapped atoms is given for a depth \(\mathcal{E} = 10\) mK of the magnetic trap. Both the high-density–low-aspect-ratio and the low-density–high-aspect-ratio cases of the final state are investigated.

|                | He\((1S_0) + \text{He}^*\) & He\(^+ + \text{He}^*\) & He\(^+ + \text{He}^*\) |
|----------------|--------------------------|--------------------------|--------------------------|
|                | PI, \(E_{\text{PI}} = 500\) K | PI, \(E_{\text{PI}} = 500\) K | AL, \(E_{\text{AI}} = 17\) K |
| \(s\)         | 6                        | 4                        | 4                        |
| \(\alpha_1(s)\) | 0.9975                   | 0.1920                   | 0.1920                   |
| \(\alpha_2(s)\) | 0.2846                   | 11.37                    | 11.37                    |
| \(\alpha_3(s)\) | 8.083                    | 21.82                    | 157.8                    |
| \(C_s\) (a.u.) | 2                        | 2                        | 2.66                     |
| \(v\) (m/s)   | 1442                     | 1442                     | 373                      |
| \(k\) (\(a_0^{-1}\)) | 2.41                     | 2.41                     | 2.41                     |
| \(\sigma_{\text{sec}}(a_0^2)\) | \(5.20 \times 10^2\) | \(4.40 \times 10^4\) | \(1.08 \times 10^5\) |
| \(\sigma_{\text{sec}}(0)(a_0^2)\) | \(1.52 \times 10^4\) | \(2.84 \times 10^8\) | \(2.05 \times 10^8\) |
| \(\theta_{\text{sec}}\) (mrad) | 64 | 7.0 | 13 |
| \(\theta_{\text{max}}/\theta_{\text{sec}}\) | \(1.4 \times 10^{-1}\) | 1.3 | 2.0 |
| \(\Delta \dot{Q}_{\text{sec}}/\dot{Q}_{\text{sec}}\) | \(7.4 \times 10^{-3}\) | 6.1 | 2.5 |
| \(T_{\text{sec}}(\mu K/s)^{b,c}\) | \(0.02 \eta_{\text{PI}}\) | \(91 \times \eta_{\text{PI}}\) | \(179 \times \eta_{\text{AI}}\) |
| \(T_{\text{sec}}(\mu K/s)^{b,d}\) | \(0.0002 \times \eta_{\text{PI}}\) | \(1.1 \times \eta_{\text{PI}}\) | \(2.1 \times \eta_{\text{AI}}\) |

\(^{a}\)See Ref. [46].

\(^{b}\)See Table I for density, aspect ratio, and ionization decay time.

\(^{c}\)High density case with \(T_C = 8.6\) \(\mu\)K.

\(^{d}\)Low density case with \(T_C = 2.9\) \(\mu\)K.

95 \(\mu\)K/s (assuming \(\eta_{\text{AI}} = 0.05\)), which should be compared to \(T_C = 8.6\) \(\mu\)K and \(\tau_C = 1\) s. It is clear that this does not lead to BEC. For the low density case the conclusion is positive: the total heating rate is 1.2 \(\mu\)K/s at a transition temperature \(T_C = 2.9\) \(\mu\)K. When sufficiently high loading rates can be achieved to obtain an initial population of the trap of \(10^5\) to \(10^6\) atoms, reaching BEC seems feasible. Looking at the heating rates, we can also decide on choosing for a smaller value of the transition temperature, e.g., \(T_C = 0.5\) \(\mu\)K, with a factor 13 lower demand on the number density. With the number of trapped atoms \(>10^8\) the chance of success is high. This would be an important milestone in the field of BEC related physics.

Finally, we have also investigated the heating rates for the situation at the transition temperature \(T_C\) when the evaporative cooling is not switched off. The trap depth is then limited to \(\mathcal{E} = 6k_B T_C\), reducing the heating rates considerably. In Table III the resulting values of the heating lifetime \(\tau_{\text{heat}} = T_C / \dot{T}\) are given. We observe the same trend as for neon: the lifetime for heating \(\tau_{\text{heat}}\) typically is a factor 4 to 10 larger than the lifetime for ionization, both for the high density and the low density case.

The UV photon emitted by the radiative decay of triplet metastable helium has an energy of 19.6 eV, corresponding to a wavelength of 56 nm. The recoil kick of the photon results in an energy transfer \(E_{\text{res}} = 1.11\) mK, i.e., a velocity of 2.2 m/s. The upper limit of the heating rate is then equal to \(\dot{T} = 0.04\) \(\mu\)K/s, which is a factor 20 smaller than for neon due to the much longer lifetime of the triplet metastable state of helium. With the same assumption for the \(\text{He}(1S_0) + \text{He}(1,1))\) scattering length as for neon (Sec. V), the heating rates are given in Table IV for the two final state geometries. Compared to the heating rate for ion–metastable-atom collisions, this contribution is negligible. Collisional heating is clearly the most important factor.

IX. CONCLUDING REMARKS

Metastable neon is an ideal gas for efficient handling of beams and traps of cold atoms. It is the equivalent of Na in many respects. The good suppression of ionization of a spin-polarized sample opens the road to BEC. Compared to the alkali’s, the metastable atoms have the advantage of excellent real-time diagnostics of the trapped dilute gas, due to the UV photons and ions released by radiative decay and residual ionization, respectively. The associated side effect of heating of the trapped metastable atoms by collisions with hot (dimer) ions resulting from residual ionization can be controlled by a careful design of the trap. By choosing a trap geometry with a tight radial confinement and a depth in the 10 mK range, both the probability for a secondary collision and the energy transferred in small angle scattering are limited to acceptable values. Typical lifetimes of the trapped sample are 1 s. Keeping the evaporative cooling switched on
after BEC has been reached results in an extension of the condensate lifetime to the ionization lifetime of five seconds.

The success of evaporative cooling is determined by the magnitude of the scattering length $a_{2,2}$ for metastable-atom–metastable-atom collisions. As yet, no information is available on its actual value. For the upper limit $(\kappa^{\text{pol}})^{\text{max}} = 10^{-14}$ cm$^3$ s$^{-1}$ for the ionization rate constant used throughout this paper, a scattering length $a_{2,2} \geq 50a_0$ is required to remain in the regime of runaway cooling. The actual lower limit for $a_{2,2}$ is determined by the actual value of the ionization rate constant for a polarized gas of metastable atoms. This is one of the first data that have to be measured.

10% natural abundance, serves as a rain check when the $^{22}$Ne isotope are readily produced, with a factor five loss of intensity as the only difference.

For metastable helium the prospects for reaching BEC are favorable. At the same density, the larger DeBroglie wavelength relaxes the demand on the final temperature. The calculated heating rates are slightly larger than for metastable neon, due to the larger value of the charge-induced dipole interaction. The major difference with metastable neon is the demand for a stronger radial gradient of the trapping field of the magnetic trap, to obtain the same confinement with a smaller magnetic moment $\mu = 2\mu_B$.

Of the heavy rare gases Ar$^+$ through Xe$^+$, the suppression of ionization is less efficient due to their larger anisotropy of the quadrupole-quadrupole interaction of the core hole [6]. Experiments with these species are limited to an investigation of cold collisions in magnetic traps, still yielding a rich field of physics [16]. Experiments as photoassociative ionization and Penning ionization in spin-aligned states can reveal interesting details on the "dimer" potentials of the metastable states. These experiments can also still open the door to BEC for metastable argon. The currently available best value for the suppression is a factor $10^4$. When nature helps us, this can perhaps be improved by a factor 2 or 3, opening the road to low temperature traps and possibly BEC.

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