Runaway evaporation for optically dressed atoms

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Abstract

Forced evaporative cooling in a far-off-resonance optical dipole trap is proved to be an efficient method to produce fermionic- or bosonic-degenerated gases. However, in most of the experiments, the reduction of the potential height occurs with a diminution of the collision elastic rate. Taking advantage of a long-living excited state, like in two-electron atoms, I propose a new scheme, based on an optical knife, where the forced evaporation can be driven independently of the trap confinement. In this context, the runaway regime might be achieved leading to a substantial improvement of the cooling efficiency. The comparison with the different methods for the forced evaporation is discussed in the presence or absence of three-body recombination losses.

Quantum degenerate gases are now being routinely produced in tens of laboratories across the world. The current methods, even if they differ in their approaches, rely on their final stage for forced evaporative cooling in a conservative trap. Two classes of traps, a high-field-seeking magnetic trap and a far-off-resonance optical dipole trap, are used independently, or in combination. In addition to design constraints, such as optical access, robustness and reproducibility, the experimental apparatus should produce a degenerate gas with the largest number of atoms and the best duty cycle. The new evaporation scheme, I describe in this paper, goes in that direction.

Forced evaporative cooling in a magnetic trap is usually performed using a RF probe or knife to couple a trapping state to an anti-trapping one. The frequency of the RF knife is swept to lower the energy barrier of the truncated potential. During forced evaporation the confinement of the ultracold gas remains almost unchanged. In an optimized scenario, when the evaporation occurs on the whole surface where the RF resonance is fulfilled, the spatial density increases faster than the inverse of the mean velocity leading to a net increase of the elastic collision, the so-called runaway regime [1].

For some atomic species, evaporation towards quantum degeneracy is difficult in a magnetic trap. In those cases, evaporation in an optical dipole trap is an alternative. Elements, such as Cs [13, 14] or $^{85}\text{Rb}$ [15], for example, have unfavourable collision properties and their scattering length needs to be tuned thanks to a magnetically induced Feshbach resonance [16]. Two-electron atoms, which carry any electronic magnetic momentum in their fundamental level, have also to be cooled with all optical methods. Recently, the Bose–Einstein condensate (BEC) of $^{40}\text{Ca}$ [17], $^{84}\text{Sr}$ [18, 19], $^{174}\text{Yb}$ [20] and $^{170}\text{Yb}$ [21], Fermi sea of $^{87}\text{Sr}$ [22] and $^{173}\text{Yb}$ [23] and degenerate mixtures of $^{88}\text{Sr}$–$^{87}\text{Sr}$ [24], $^{170}\text{Yb}$–$^{174}\text{Yb}$, $^{173}\text{Yb}$–$^{174}\text{Yb}$ [25] have been reported.

In dipole traps no energy-selective coupling to an anti-trapping state, similar to the RF knife, has been implemented so far. Evaporation takes place because hottest atoms, with a mechanical energy higher than the potential height, are escaping the trap. Thus, the dipole trap might fulfill at least two major requirements. First, the potential height has to be in the order of few thermal energy, $k_B T$, such that the evaporation rate is significant. Second, the spatial confinement
and the compression of the atomic gas have to be such that elastic collisions can take place leading to fast thermalization. Different strategies have been used to improve the preparation of the cold sample before evaporation. For alkali atoms, Raman [14] or polarization gradient cooling [26] has been implemented to lower the temperature. For two-electron atoms, low temperatures are achieved with Doppler cooling on the intercombination lines [17–20, 27–29]. The improvement of the spatial density in the dipole trap is also reported using adiabatic compression by dynamically changing the trap geometry, for example with an additional dimple trap [14] or a zoom lens to displace one of the beams’ waist position [26]. The forced evaporation is performed by dynamically lowering the potential height.

In the original experimental realizations of the BEC [30] and the Fermi gas [5] in all optical devices, the gas was confined in a cross dipole trap to ensure a good 3D confinement. The forced evaporation was carried out by lowering the power $P$ of the trap light field. As a consequence, the trapping frequencies,

$$\omega \propto \sqrt{P}, \quad (1)$$

and the trap confinement are also reduced. In this situation and in a sharp contrast with the RF knife, the elastic collision rate decreases during the forced evaporation and no runaway occurs [31]. Thus, it is crucial to counteract the reduction of efficiency of cooling during evaporation with a very good starting elastic collision rate.

New optical-based trap schemes have been successfully implemented to limit and event almost suppress the reduction of trapping confinement during the forced evaporation. Those realizations have the same underlying idea which consists in decoupling the potential height driving the evaporation and the trap confinement controlling the thermalization rate. In [32] a tilt trap was used where spin-polarized atoms of caesium are held in a fixed dipole trap with a superimposed varying magnetic field gradient. The extra constant force pulls the atoms out of the trap. In all optical schemes, different versions of the dimple trap have been explored. In those schemes, the trap is made of at least two independent laser beams: a tightly confining one for 2D trapping and a wider one to close the trap in the third dimension. In an ideal scenario, only the power of wider beam is reduced [17, 20]. Clément and co-authors [33] report the 3D confinement and runaway evaporation in a stumble misaligned version of the dimple trap which works in a similar manner as the tilt trap of [32].

In this paper, I propose a new method for runaway evaporation in an optical trap. In contrast with the methods implemented so far successfully, evaporation is not based on lowering the trapping lasers power but on a potential truncated with an optical knife. The paper is organized as follows. In section 1, I define the general requirements to implement the forced evaporation with an optical knife in a dipole trap. On the basis of a thermodynamical quasi-equilibrated state, I derive rate equations which govern the evolution of some macroscopic quantities of the ultracold gas in the trap (section 2). Different evaporation strategies can be put in place according to the strength of the three-body recombination loss rate. Finally, I draw the conclusion of this work in section 3.

### 1. Dipole trap with an optical knife

I consider a two-level system in the optical domain where the excited (ground) state, labelled $|e\rangle$ ($|g\rangle$), has a radiative lifetime long enough to disregard any spontaneous emission. Like in other evaporation schemes, far-off-resonance lasers ensure the 3D confinement of the cold gas in the $|g\rangle$ state. It is crucial however that $|e\rangle$ has to be an anti-trapping state. The $|g\rangle \rightarrow |e\rangle$ transition is driven with a quasi-resonant optical field at a detuning $\delta$ with respect to the bare frequency difference of the two states. In the RWA approximation, the eigenenergies are

$$E_{\pm} = \frac{s}{2} \left( 1 \pm \sqrt{1 - 4\frac{p - \Omega^2}{\delta^2}} \right), \quad (2)$$

where $s = V_e(\vec{r}) - \delta + V_g(\vec{r})$ and $p = (V_e(\vec{r}) - \delta) \cdot V_g(\vec{r})$ are respectively the sum and the product of the ground- and excited-state energies dressed with the far-off-resonance trapping lasers. $\Omega$ is the Rabi frequency of the quasi-resonant field. This field is supposed to give any extra light shift contribution. In the adiabatic regime, an atom, initially in the trap, i.e. in the $|g\rangle$ state, is resonantly brought into the anti-trapping state $|e\rangle$ at a distance where the avoid crossing occurs $(V_e(\vec{r}) = -V_g(\vec{r}) + \delta)$. Hence, the forced evaporation might be achieved by sweeping the detuning of the quasi-resonant field from zero towards a blue value.

For a practical implementation, two-electron atoms are a straightforward choice since one of the long-living states in the triplet spectrum can be used as an excited state. The $^3P_0$ state is of particular interest because of the absence of an electronic magnetic momentum. Thus, the forbidden $^1S_0 \rightarrow ^3P_0$ transition can be almost decoupled to stray magnetic fields. For odd isotopes, the $^1S_0 \rightarrow ^1P_0$ transition, due to hyperfine mixing, becomes weakly allowed to single-photon direct excitation. The bare linewidth of the transition is in the range of few mHz [34] which prevents any spontaneous emission during evaporation and provides enough coupling strength among the two states. For the even isotopes, the $^1S_0 \rightarrow ^3P_0$ transition is strongly forbidden. In that case, the $^3P_0$ state is needed to be mixed to another short-living states as depicted in [35, 36].

Besides the issues of getting favourable conditions for evaporation, one has also to keep in mind that the light shift due to the off-resonance lasers should create an anti-trapping state for $|e\rangle$. Supposing that $|g\rangle$ is a trapping state, this condition automatically gets fulfilled for a two-level system, whereas in real atoms light shift values can be engineered almost at will according to the presence of the other excited levels. If far-infrared traps have to be excluded because they give the same negative sign of the electrical polarizability for both states at play, then it seems, however, that this new constraint can be overcome in most cases. For $^{19}$Yb, a popular near-infrared laser is suitable [37], whereas for $^{87}$Sr a dipole trap made with a red laser might be an alternative. For the latter case, the $5s^2^1S_0 \rightarrow 5s6p^1P_1$ and $5s5p^3P_0 \rightarrow 5s6s^1S_1$ transitions respectively at 461 nm and 679 nm give the major contribution to the states’ light shifts (see figure 1(a)). An example of the
the 1S0 → 3P0 transition. The coupling laser has a power of 50 mW focused on a 50 μm spot size. The Rabi frequency is \( \Omega = 2\pi \times 40 \) kHz. The dipole trap is produced with 660 nm crossed laser beams focused on a 50 μm spot size. The total power is 1 W for a mean radial trap frequency of 270 kHz. (b) The energy radial distribution, in waist unit, of the potential in energy recoil unit. The dashed blue (red) curve corresponds to the 1S0 ground (3P0 excited) state in interaction with the trapping laser only. The plain curves indicate the adiabatic potential dressed with the optical knife. In this example, the detuning of the knife is \( \delta = 2\pi \times 340 \) kHz.

2. Evaporation in a fix or varying trap

I have shown that an ultranarrow (or clock) transition may be used as an optical knife for evaporation in a dipole trap. The initial high confinement is then kept almost fixed, in contrast with the original evaporation technique in which the trap height is reduced. Let us now compare the two cases. As far as the elastic collision rate ensures a good dynamics of the ultracold gas in the finite depth trap for both, the starting point would be to set a kinetic equation of the quantities that characterize the efficiency of the evaporation. Their expressions are given for a 3D harmonic trap. The exact expressions, in the second column, are extracted from [1]. The third column gives approximated expressions and last column shows their validity domain within an error smaller than 5%.

| \( \gamma_\nu/\gamma \) | Exact | Approximated | Validity |
|-----------------|-------|-------------|---------|
| \( \delta \)    | 1 - \( \frac{\hbar \Omega}{k_B T} \) | 1 - \( \frac{1}{\kappa \hbar} \left( 1 - \frac{\eta^4}{\kappa_4} \right) \) | \( \eta \geq 4 \) |
| \( \gamma \)     | \( \gamma_\nu(\eta) \) | \( \gamma_\nu(\eta) \) | \( \eta \geq 7 \) |
| \( \varphi \)    | \( \frac{\gamma_{1+}(\eta) \kappa_{3,3}}{\gamma_{1+}(\eta) \kappa_{4,4}} \) | \( \frac{3 - \frac{\eta^4}{\kappa_4}}{3 - \frac{\eta^4}{\kappa_4}} \) | \( \eta \geq 6 \) |
| \( \alpha \)     | \( \frac{\nu}{\kappa_4} - 1 \) | \( \frac{\nu}{\kappa_4} - 1 \) | \( \eta \geq 9 \) |

large and constant. Here, \( T \) is the temperature of the gas. Hereafter these conditions are supposed to be always fulfilled. Following [1] and [31], a thermodynamical model of evaporation can be resumed in a set of rate equations, governing the temporal evolutions of the number of atoms \( N \) in the trap and their temperature. Here, \( \gamma_\nu(n, T) \) is the evaporation rate related to the elastic collision rate \( \gamma(n, T) = \Lambda n \sigma v \) (see table 1). \( A \) is a dimensionless parameter. Its value depends on the type—fermionic or bosonic—of the atom and on the number \( n_s \) of spin states which involve in the s-wave-scattering process. For spin-polarized bosons, \( A = 1 \). For unpolarized fermions, \( A = \frac{n_s - 1}{n_s} \). \( \nu \) and \( \sigma \) are respectively the thermal velocity and the elastic-scattering cross section. The expressions of \( A \) and \( \nu \) are also given in table 1. \( \gamma_\nu(n, T) \) stands for the atoms’ loss rate of the three-body recombination. Other loss processes such as one-body and two-body losses

Figure 1. (a) Simplified energy diagram and states involved in the forced evaporation of \(^{87}\text{Sr}\) with an optical knife in quasi resonance with the 1S0 → 3P0 transition. The coupling laser has a power of 50 mW focused on a 50 μm spot size. The Rabi frequency is \( \Omega = 2\pi \times 40 \) kHz. The dipole trap is produced with 660 nm crossed laser beams focused on a 50 μm spot size. The total power is 1 W for a mean radial trap frequency of 270 kHz. (b) The energy radial distribution, in waist unit, of the potential in energy recoil unit. The dashed blue (red) curve corresponds to the 1S0 ground (3P0 excited) state in interaction with the trapping laser only. The plain curves indicate the adiabatic potential dressed with the optical knife. In this example, the detuning of the knife is \( \delta = 2\pi \times 340 \) kHz.
are neglected [39]. The extra heating rate of the three-body recombination corresponds to the second term on the right-hand side of equation (5). It comes from the fact that the recombination rate scales like $n^3$ and thus occurs most likely in the high-density region of the cloud where the potential energy is lower than its mean value [40].

Initially, I set $\gamma(n, T) = 0$ and three-body recombination losses will be discussed later on. After the simplification of equations (5) and (4), it turns out that $N$ and $T$ are linked through the simple relation

$$T \propto N^{2\alpha}.$$  \hspace{1cm} (6)

From equation (6), one derives other relations among quantities of interest such as the peak spatial density $n_0$, the elastic collision rate $\gamma$, the phase space density $D$, or if it concerns fermions, the temperature in the Fermi unit $T/T_F$. These quantities also depend on the confinement of the gas and on the trap-truncated energy $\epsilon_t$. Taking into account the Gaussian shape of the dipole trap, expressions can be derived from [41]. However, when $\eta \gg 1$, the atoms are present at the bottom of the potential where it can be approximated by an harmonic potential characterized by its mean oscillation frequency $\omega$. In the fixed trap configuration, $\omega$ remains constant during the evaporation. In contrast, in the varying one, where the total power of the trapping laser is reduced and with respect to relations (1), (3) and (6), one has $\omega \propto N^{2/3}$. Both trap configurations can be modelled introducing a parameter $\theta$ such that

$$\omega \propto N^{2\alpha}/\theta,$$  \hspace{1cm} (7)

where $\theta = 0 (= 1)$ means that evaporation occurs in a fixed (varying) 3D trap. Finally, from relations (6) and (7), one sets

$$\begin{align*}
n_0 & \propto N^{1-\frac{2}{3}(1-\alpha)\theta}, \hspace{2cm} (8) \\
\gamma & \propto N^{1-(1-\frac{2}{3})\alpha}, \hspace{2cm} (9) \\
D & \propto N^{1-\frac{1}{3}(2-\alpha)\theta}, \hspace{2cm} (10) \\
\frac{T}{T_F} & \propto N^{-\frac{1}{3}+(2-\alpha)\theta}. \hspace{2cm} (11)
\end{align*}$$

Since $\alpha > 1$, these relations clearly show some differences among the two configurations ($\theta = 0, 1$). Firstly, the runaway regime, i.e. an increase in $\gamma$, could be reached only if $\theta = 0$. As a direct consequence, the cooling time is shortest for a fixed trap. Secondly, and without any surprise, $D (T/T_F)$ increases (decreases) for both configurations. However, the $\theta = 0$ configuration leads to a better efficiency of the evaporation.

One has to keep in mind however that relations (6)–(11) are expressed only in a lossless trap ($\gamma(n, T) = 0$) and for $\eta$ being large and constant. Those assumptions are not necessarily fulfilled in some experiments. Thus, a comparison between the model predictions and the documented evaporative schemes can be carried out only with great care. Nevertheless, an attempt is summarized in tables 2 and 3 where the raw data of some successful experiments towards degenerate gases of two-electron atoms are compared with the results of the model presented in this work. As was already mentioned and discussed in the original papers [18] and [19] and also confirmed here, the experimental evaporation ramps for $^{84}$Sr reasonably stick to the $\theta = 1$ model. In contrast for $^{40}$Ca, $^{87}$Sr, $^{173}$Yb and $^{174}$Yb, either of the two evaporation models match with the experimental data. Here, the trap is made with two intensity-independent dipole lasers to which more complex experimental ramps are done. It is worth mentioning however that experimental data might be constrained between the two-trap configuration model, where the $\theta = 0$ one stands to be the most efficient in terms of the evaporation time $t_{evap}$ and remaining atoms $N_f$.

Let us now analyse how the three-body recombination losses affect the previous results. Indeed, [17] addresses the three-body recombination as a major loss mechanism. It has also been reported that the three-body recombination limits the elastic collision rate in a trap configuration close to the $\theta = 0$ configuration [33]. Firstly, I recall that the three-body recombination event scales with $n^3$. Thus, equation (8) and tables 2 and 3 indicate that the fixed trap configuration may be more affected than the varying one. The three-body recombination atoms loss rate is given by

$$\gamma_f(n, T) = L_3(n^2),$$  \hspace{1cm} (12)

The table below presents the experimental data and numerical results for bosons. The simulation stops when $D = 1$, whereas $N_f$ for the experimental data are given for a similar condition. n.a. means data not available.

| Type       | $N_f$ ($10^5$) | $T_f$ ($\mu$K) | $n_i$ ($10^{14}$ cm$^{-3}$) | $\Gamma_e$ ($10^5$ s$^{-1}$) | $N_f$ ($10^5$) | $T_f$ ($\mu$K) | $\Gamma_e$ ($10^5$ s$^{-1}$) | $t_{evap}$ (s) | $\eta$ |
|------------|----------------|----------------|-----------------------------|-------------------------------|----------------|----------------|-------------------------------|----------------|-------|
| $^{40}$Ca  | 50             | 20             | 0.3                         | n.a.                          | 0.09                        | 0.26           | n.a.                          | 1.5             | 5     |
| Varying    | 50             | 20             | 0.3                         | 40                            | 0.03                        | 0.005          | $3 \times 10^{-4}$           | 1.4             | 56    |
| Fixed      | 50             | 20             | 0.3                         | 40                            | 6.5                         | 2              | $4 \times 10^{-4}$           | 0.002           | 5     |
| $^{84}$Sr  | 10             | 10             | 1.2                         | 3.5                           | 3                           | 0.4            | $\approx n_i$                | 0.7             | 6     |
| Varying    | 10             | 10             | 1.2                         | 5.5                           | 3                           | 0.4            | 0.3                          | 0.3             | 4     |
| Fixed      | 10             | 10             | 1.2                         | 5.5                           | 6                           | 2.5            | 5                            | 14              | 0.2   |
| $^{84}$Sr  | 30             | 5              | 0.4                         | 1                             | 3                           | 0.4            | n.a.                         | n.a.            | 3     |
| Varying    | 30             | 5              | 0.4                         | 1.3                           | 3.5                         | 0.1            | 0.5                          | 0.02            | 8.5   |
| Fixed      | 30             | 5              | 0.4                         | 1.3                           | 13                          | 1.1            | 1.6                          | 2.6             | 0.2   |
| $^{174}$Yb | 10             | 180            | 4.7                         | n.a.                          | 0.05                        | 0.8            | 4.7                          | n.a.            | 2     |
| Varying    | 10             | 180            | 4.7                         | 0.6                           | n.a.                        | 4              | No atoms left                | 4               |       |
| Fixed      | 10             | 180            | 4.7                         | 0.6                           | 0.08                        | 2.8            | 20                           | 0.3             | 2     |

| Type       | $N_i$ ($10^5$) | $T_i$ ($\mu$K) | $n_f$ ($10^{14}$ cm$^{-3}$) | $\Gamma_{el}$ ($10^5$ s$^{-1}$) | $\Gamma_{d}$ ($10^5$ s$^{-1}$) | $\tau_{d}$ (s) | $\eta$ |
|------------|----------------|----------------|-----------------------------|-------------------------------|-------------------------------|----------------|-------|
| $^{40}$Ca  | 50             | 20             | 0.3                         | n.a.                          | 0.09                        | 0.26           | n.a.                          | 1.5             | 5     |
| Varying    | 50             | 20             | 0.3                         | 40                            | 0.03                        | 0.005          | $3 \times 10^{-4}$           | 1.4             | 56    |
| Fixed      | 50             | 20             | 0.3                         | 40                            | 6.5                         | 2              | $4 \times 10^{-4}$           | 0.002           | 5     |
| $^{84}$Sr  | 10             | 10             | 1.2                         | 3.5                           | 3                           | 0.4            | $\approx n_i$                | 0.7             | 6     |
| Varying    | 10             | 10             | 1.2                         | 5.5                           | 3                           | 0.4            | 0.3                          | 0.3             | 4     |
| Fixed      | 10             | 10             | 1.2                         | 5.5                           | 6                           | 2.5            | 5                            | 14              | 0.2   |
| $^{84}$Sr  | 30             | 5              | 0.4                         | 1                             | 3                           | 0.4            | n.a.                         | n.a.            | 3     |
| Varying    | 30             | 5              | 0.4                         | 1.3                           | 3.5                         | 0.1            | 0.5                          | 0.02            | 8.5   |
| Fixed      | 30             | 5              | 0.4                         | 1.3                           | 13                          | 1.1            | 1.6                          | 2.6             | 0.2   |
| $^{174}$Yb | 10             | 180            | 4.7                         | n.a.                          | 0.05                        | 0.8            | 4.7                          | n.a.            | 2     |
| Varying    | 10             | 180            | 4.7                         | 0.6                           | n.a.                        | 4              | No atoms left                | 4               |       |
| Fixed      | 10             | 180            | 4.7                         | 0.6                           | 0.08                        | 2.8            | 20                           | 0.3             | 2     |
are given for a similar condition. n.a. means data not available.

| Type     | $N_f$ ($10^4$) | $T_f$ ($T_F$) | $n_i$ (10$^{14}$ cm$^{-3}$) | $\Gamma_{\text{ev}}$ (10$^3$ s$^{-1}$) | $N_f$ ($10^4$) | $T_f$ ($T_F$) | $n_i$ (10$^{14}$ cm$^{-3}$) | $\Gamma_{\text{ev}}$ (10$^3$ s$^{-1}$) | $t_{\text{exp}}$ (s) | $\eta$ | Reference  |
|----------|----------------|---------------|-----------------------------|------------------------------------------|----------------|---------------|-----------------------------|------------------------------------------|------------------------|-------|------------|
| $^{87}$Sr | 30 2.7 0.25    | 10 1          | n.a.                        | n.a.                                     | 30 2.7 0.25    | 10 1          | n.a.                        | n.a.                                     | 4 7                     | 22    |            |
| Varying  | 30 2.7 0.25    | 15 3          | 0.15                        | 0.03                                     | 0.004         | 36 7         | 10 1                        | n.a.                                     | 1 7                     | 23    |            |
| Fixed    | 30 2.7 0.25    | 15 3          | 0.15                        | 0.03                                     | 0.004         | 36 7         | 10 1                        | n.a.                                     | 1 7                     | 23    |            |
| $^{171}$Yb | 3 100 n.a.     | n.a.          | 0.013                       | 5.6                                      | n.a.          | 2 7          | n.a.                        | 3 0.8                                    | 1 7                     | 42    |            |
| Varying  | 3 100 2.5      | 25            | 0.25                        | No atoms left                            | 3 0.8         | 1 7          | n.a.                        | 3 0.8                                    | 1 7                     | 42    |            |
| Fixed    | 3 100 2.5      | 25            | 0.25                        | 0.5                                      | 6             | 3            | 0.8                         | 1 7                                     | 23    |            |

**Figure 2.** Remaining atoms at $D_f = 1$ after a forced evaporation for different scattering length values ranging from 10–2000 $a_0$. Each point corresponds to a simulation at a given scattering length. For all points $\eta = 10$, $N_i = 10^4$, $T_i = 20 \mu$K and $n_i = 1.3 \times 10^{14}$ cm$^{-3}$ leading to an initial phase space density of $D_i = 10^{-2}$. The red (blue) curves correspond to $\theta = 0 (= 1)$ configuration whereas the stars (dots) referred to $n_C = 16.5(210)$ (see the text). The dashes lines disregard the loss induced by the three-body recombination ($n_C = 0$) for the $\theta = 0$ (blue) and $\theta = 1$ (red) configurations. The inset shows, as a function of the initial atoms number for $n_C = 16.5$, the critical values $a_C$ of the scattering length for which the two-trap configurations give the same result.

with

$$L_3 = n_C \frac{\hbar}{m} a^4.$$  

(13)

Here, $n_C$ stands for the mean number of atoms lost per collision event. $0 < C < 70$ is a dimensionless factor that might also vary with the scattering length $a$ (see [40] and references therein). Both values of $n_C$ and $C$ are of crucial importance for quantitative evaluation of the three-body recombination losses, but unfortunately they are not well documented for two-electron atoms. In [17], the authors report $L_3 = 3 \times 10^{-22}$ cm$^3$ s$^{-1}$ for $^{40}$Ca which can be converted into $n_C = 16.5$. Plugging this value into the model, the efficiency of the evaporation is shown in figure 2. The blue (red) stars correspond to the $\theta = 0$ (1) configuration. One notices that at low scattering length the three-body losses have a limited impact and the $\theta = 0$ configuration remains the best option (for more detail about the comparisons see the figure caption). However, above a characteristic value of the scattering length, $a_C \sim 385$ $a_0$ in that case, it seems more relevant to use the varying trap where the spatial density remains moderate. Similar conclusion can be drawn if one uses the most pessimistic value $n_C = 3 \cdot 70$. In this case, the inversion of the efficiency among the two-trap configuration is observed at a lower value $a_C \sim 105$ $a_0$. The values of $a_C$ are non-universal and may be figured out for any experimental realization. For example, in the inset of figure 2 the variation of $a_C$ as a function of $N_f$ is shown.

### 3. Conclusion

If three-body recombination losses can be disregarded, the dynamics of the evaporation at constant $\eta$ is ruled by a simple set of nonlinear equations for $N$ and $T$. The forced evaporation in two configurations of the dipole trap has been compared: the varying trap where the laser power of the dipole trap is ramped down leading to a reduction of the spatial confinement and the fixed trap where the spatial confinement is kept constant. I show that the runaway regime, characterized by an increase of the elastic collision rate, is reached only in the fixed trap configuration. As a consequence, the efficiency of the evaporation in terms of remaining atoms and cooling time is significantly improved. However, the spatial density increases during the evaporation and three-body recombination losses have also to be considered. In this context, I show that there exists a characteristic scattering length above which the varying-trap configuration, with lower spatial confinement, becomes the best choice.

A practical implementation of the fixed trap can be done using the $^1S_0$ long-living excited state in two-electron atoms as an anti-trapping state. Just like with the RF knife for magnetic traps, the dipole trap can be truncated using a quasi-resonant optical field on the $^3S_0 \rightarrow ^3P_0$ transition. The forced evaporation is obtained sweeping the laser detuning.

The discussion in this paper has been carried out considering the lower branch of the adiabatic potential (in blue, figure 1(b)). If the atoms are now transferred to the upper branch (in red, figure 1(b)), they are confined in a quasi 2D bubble-like optically dressed trap. Similar types of traps have been already proposed [42] and accomplished [43] with a RF-dressed state in magnetic traps. In those, the interplay between the Zeeman sublevel structure and the vectorial nature of the RF field creates some holes through which evaporation
is done [44]. In a bubble-like optically dressed trap, such holes do not exist at least in the two-level scheme considered here. However, the forced evaporation can still take place sweeping the dressed laser frequency in the opposite direction to the one used for the forced evaporation in the lower branch of the adiabatic potential.

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