Microwave trap for atoms and molecules

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We demonstrate a trap that confines polarizable particles around the antinode of a standing-wave microwave field. The trap relies only on the polarizability of the particles far from any resonances, so can trap a wide variety of atoms and molecules in a wide range of internal states, including the ground state. The trap has a volume of about 10 cm$^3$, and a depth approaching 1 K for many polar molecules. We measure the trap properties using $^7$Li atoms, showing that when the input microwave power is 610 W, the atoms remain trapped with a $1/e$ lifetime of 1.76(12) s, oscillating with an axial frequency of 28.55(5) Hz and a radial frequency of 8.81(8) Hz. The trap is particularly well suited to sympathetic cooling and evaporative cooling of molecules.

Almost all research using cold atoms, molecules and ions relies on trapping. The trap confines the particles to a small volume so that they can be cooled to low temperature, collide with one another, and be studied and controlled with high precision. Thus, the trap is a key tool in frequency metrology, quantum information processing, quantum simulation, field sensing, cavity quantum electrodynamics, studies of quantum degenerate gases, tests of fundamental physics, and many other topics. New traps often stimulate new applications, and new research areas often call for new traps. Here, we demonstrate a trap that confines particles around the electric field antinode of a standing-wave microwave field formed inside an open resonator, realizing the proposal of DeMille et al. [1]. The trap relies only on the polarizability of the particles at microwave frequencies, far from any resonances, so is suitable for trapping a wide variety of atoms and molecules.

For atoms, the microwave trap has a depth similar to an optical dipole trap, but its volume is a million times larger so it can trap samples with a much lower phase-space density. Importantly, heating due to spontaneous emission, which often limits the lifetime of an optical trap, is eliminated in the microwave trap. The usefulness of a microwave trap for atoms was recognized long ago [2] in the context of evaporative cooling to quantum degeneracy. Such a trap was developed specifically for ultracold Cs [3], but it used the magnetic dipole interaction at a frequency almost resonant with the ground-state hyperfine transition, so was specific to that particular atom. More recently, a similar species-specific microwave-induced force has been used to generate spin-dependent potentials on atom chips, where strong gradients can be produced in the near-field of coplanar waveguides and resonators [4][5]. By contrast, ours is a very general trap that uses the electric dipole interaction far from any resonance.

Especially important at present is the development of new traps for cold, polar molecules, which can be used to test fundamental physics [6][7], study cold chemistry [8][17], process quantum information [18][20], and explore interacting many-body quantum systems [21][24]. Some molecular species can now be formed at submillikelvin temperatures by direct laser cooling [25][26], optoelectrical cooling [27], or by association of ultracold atoms [28][29], and they have been confined in magnetic traps [30][31], electric traps [27], and optical traps [32][34]. A wider variety of molecules can be produced in the 10-100 mK range using a set of techniques that includes buffer-gas cooling, Stark, Zeeman and centrifuge deceleration [33][38]. These warmer molecules could be sympathetically cooled to much lower temperatures through collisions with co-trapped ultracold atoms [39][40]. This requires trapping of ground-state molecules so that inelastic collisions that inhibit sympathetic cooling are energetically forbidden. Unfortunately, ground-state particles are always strong-field-seeking, so cannot be confined in static electric and magnetic traps [41]. One possible solution is the ac electric trap [42], whose operating principle is similar to that of a Paul trap for charged particles. However, this method suffers from a small trap depth, typically below 10 mK, and a small volume of around 10$^{-2}$ cm$^3$, and is not compatible with sympathetic cooling [39]. Optical dipole traps can also trap ground-state molecules, but usually have depths below 1 mK and volumes of about 10$^{-3}$ cm$^3$. By contrast, the microwave trap has a volume of about 10 cm$^3$ and a depth in the range 0.1–1 K for many polar molecules. It has previously been shown that microwave fields in high-quality-factor resonators can be used to deflect or focus beams of NH$_3$ [43], CH$_3$CN [44] and PbO [45], and to decelerate a beam of NH$_3$ by a few m/s [46]. However, atoms and molecules have never previously been trapped this way. Using ultracold $^7$Li, we show that the trap works and we measure its properties.

Figure 1 illustrates the microwave trap and the moving magnetic trap that delivers the atoms. The design of the microwave trap follows that of Ref. [37]. Two copper mirrors, cooled using water flowing at 0.51 min$^{-1}$, form a Fabry-Pérot cavity. The mirrors have diameter 90 mm, radius of curvature $R_m = 73$ mm, and a center-to-center separation of $L = 35$ mm. We use the lowest-order Gaussian mode with longitudinal mode index $n = 3$ (TEM$_{003}$), whose resonant frequency, $f_n$, is near 14.27 GHz. For
This mode, the unloaded quality factor at room temperature is $Q_0 \approx 2 \times 10^4$. Power is coupled into the cavity through a hole, of diameter $d_h = 4.63 \text{ mm}$ and thickness $t = 0.7 \text{ mm}$, at the centre of one mirror. For this choice of hole size, 95% of the incident power is transmitted into the cavity. The perfect Gaussian mode would have a beam waist of $w_0 = 14.7 \text{ mm}$, but the coupling hole broadens the mode, and we measure $w_0 = 17.25 \text{ mm}$. To feed the cavity, the signal from a microwave oscillator is amplified by a klystron, which provides 80 dB gain and a maximum output power of 2 kW. The power is delivered via a waveguide which interfaces directly with the coupling hole. A window in the waveguide flange seals the vacuum. A sinusoidal frequency modulation of amplitude 40 kHz and frequency 20 kHz is applied to the oscillator. Directional couplers pick off $-40$ dB of the incident and reflected powers, and the ratio of these signals is used as the input to a lock-in amplifier which locks the microwave frequency to the cavity resonance by minimizing the reflected power. We define $P$ to be the incident power transmitted into the cavity, and determine its value by measuring the power output from the klystron and accounting for the fraction absorbed by the waveguide and reflected by the cavity. The electric field amplitude at the centre of the cavity is

$$\mathcal{E}_0 = \left( \frac{4PQ_0}{\pi^2 \epsilon_0 f_n w_0^2 L} \right)^{1/2}. \quad (1)$$

When $P = 700 \text{ W}$, $\mathcal{E}_0 \approx 20 \text{ kV cm}^{-1}$. For Li, whose static scalar polarizability is $\alpha_s = 2.70 \times 10^{-39} \text{ Jm}^2/V^2$ [48], the corresponding trap depth is $U_0 = \alpha_s \mathcal{E}_0^2/4 \approx 200 \mu \text{K}$.

Each experiment begins by loading $1 \times 10^8$ $^7\text{Li}$ atoms into a magneto-optical trap (MOT) at a temperature of 1.07(6) mK. The atoms are cooled further, to 50 $\mu$K, using Raman gray molasses on the $D_1$ line [49], then optically pumped into the $|F = 2, m_F = 2\rangle$ state. These atoms are trapped in a magnetic quadrupole trap using coils inside the MOT vacuum chamber, which produce an axial field gradient of 32 G cm$^{-1}$. Then, they are transferred adiabatically to a second quadrupole trap, formed by coils external to the vacuum chamber and mounted on a motorized translation stage. The axial field gradient is ramped up to 50 G cm$^{-1}$ and then the trap is translated horizontally by 600 mm, bringing the atoms to the center of the microwave trap which is housed in a separate vacuum chamber from the MOT. At this point the magnetic trap contains about $2 \times 10^7$ atoms, at a phase space density of $3.6(2) \times 10^{-7}$. Next, the microwave power is ramped linearly in 200 ms from an initial value $P$ of 10 W at $t = -\tau_{\text{ramp}}$, to the final trapping power, $P$, at $t = 0$. The magnetic trap currents are ramped down over the same period, reaching zero at $t = 0$, which defines the start of the microwave trapping period. Unless stated otherwise, we use $\tau_{\text{ramp}} = 200 \text{ ms}$. After a variable hold time in the microwave trap, we return the atoms to the magnetic trap and turn off the microwave trap. The density distribution of the atoms, in either the microwave trap or magnetic trap, is measured by absorption imaging using light resonant with the $F = 2 \rightarrow F' = 3 D_2$ transition.

Figure 2 shows the fraction of atoms recaptured into the magnetic trap at $t = 200 \text{ ms}$, as a function of $P$. At low power, we do not recapture any atoms because the sum of the microwave and gravitational potentials does not form a trap until $P$ exceeds a threshold value $P_0$. The fraction recaptured, $\eta$, then increases with $P$, and begins to saturate at $P \approx 600 \text{ W}$. Only two of the five $F = 2$ transitions

FIG. 1. Illustration of the experiment, showing the microwave trap and the transport coils.

FIG. 2. Fraction of atoms recaptured into the magnetic trap as a function of input microwave power, $P$. Dashed line: fit to Eq. (2), fixing $\beta = 0.28 \mu \text{K W}^{-1}$.

1 This small initial power is needed to maintain the frequency lock. It is insufficient to form an axial trap when the gravitational potential is included.
states are magnetically trappable, so no more than 40\% would be recaptured from a randomized spin ensemble. Since we recapture a greater fraction than this, we conclude that the spin polarization is fairly well preserved in the microwave trap due to a small background magnetic field. We fit the data in Fig. 2 with the simple model

$$\eta = \eta_{\text{max}} \int_0^{\beta(P-P_0)} \frac{2\sqrt{E}}{\sqrt{\pi k_B T}} \exp\left(-\frac{E}{k_B T}\right) dE.$$  \hspace{1cm} (2)

Here, the integrand is the initial distribution of energies $E$, characterized by the temperature $T$, and we integrate this up to the trap depth, $\beta(P - P_0)$, where $\beta = 0.28 \, \text{mK} \, \text{W}^{-1}$ is the calculated gradient of the trap depth versus power. The best fit parameters are $T = 44(12) \, \text{mK}$, $\eta_{\text{max}} = 90(9)\%$, and $P_0 = 180(20) \, \text{W}$. For atoms loaded exactly at the antinode of the microwave field, the calculated threshold power is 150 \, \text{W}. The fitted value is consistent with loading the trap about 1 mm too high.

Figure 3 shows the number of atoms recaptured into the magnetic trap as a function of hold time in the microwave trap, with $P = 600 \, \text{W}$. (a) Absorption images at selected times. (horizontal and vertical directions are radial (x) and axial (z), and the image size is 5.5 mm $\times$ 3.7 mm). (b) Centre-of-mass motion along z. (c) Centre-of-mass motion along x. Black, dashed lines are fits to a sinusoidal model.

The fits give axial and radial oscillation frequencies of $\Omega_z/(2\pi) = 28.55(5) \, \text{Hz}$, and $\Omega_x/(2\pi) = 8.81(8) \, \text{Hz}$.

To measure the subsequent evolution of the density distribution. Our measurements begin at $t = 50 \, \text{ms}$ to allow eddy currents induced in the cavity assembly to decay. Figures 4(b,c) show the axial and radial positions of the centre of the cloud as a function of time, with $r = r_0 + a_r \sin(\Omega_r t + \phi_r)$, where $r \in \{ z, x \}$. The fits give axial and radial oscillation frequencies of $\Omega_z/(2\pi) = 28.55(5) \, \text{Hz}$, and $\Omega_x/(2\pi) = 8.81(8) \, \text{Hz}$.

By expanding the potential energy of the atoms to second order in $x$ and $z$, we find that the angular oscillation frequencies are

$$\Omega_x = \sqrt{\frac{\alpha_s c_s^2}{m u_0^2}}, \quad \Omega_z = \sqrt{\frac{\alpha_s c_s^2 k^2(1 - 2 \epsilon + 2 \epsilon^2)}{2m}},$$  \hspace{1cm} (3)

where $k$ is the wavevector, $m$ is the mass, $\epsilon = 1/(k z_0)$, and $z_0$ is the Rayleigh range. Figure 5(a) shows how the oscillation frequencies vary with $P$, and compares
these measurements with Eq. (3). The measured frequencies are close to the predictions, but systematically a little higher, implying that the electric field amplitude is slightly greater than expected. Figure 5(b) shows the ratio $\Omega_z/\Omega_x$, which is independent of the power as we would expect. The mean ratio is 3.33(6), consistent with the predicted value of 3.28.

The atoms cool as they expand from the magnetic trap into the microwave trap. From the measured cloud sizes and trap frequencies, the relation $k_B T = m\Omega^2 \sigma^2$, and the assumption that the two radial directions are equivalent, we deduce a geometric mean temperature in the microwave trap of $T = 22(3)$ µK. This is within 2σ of the temperature deduced from the fit in Fig. 2 and is a more reliable measurement. The density of atoms in the microwave trap is $1.5(3) \times 10^8$ cm$^{-3}$, and the corresponding dimensionless phase-space density is $4(1) \times 10^{-7}$. This is consistent with the phase-space density of $3.6(2) \times 10^{-7}$ measured in the magnetic trap, implying that, within the uncertainty of 25%, there is no loss of phase-space density in transferring atoms into the microwave trap.

The microwave trap will work for most other laser-coolable atoms, especially the alkali and alkaline-earth atoms, whose polarizabilities are all similar to, or larger than, that of Li [51]. It is a particularly useful atom trap for applications where ground-state atoms are needed, or where heating due to spontaneous emission must be eliminated, or where a uniform magnetic field must be applied. To overcome gravity, the heavier atoms will require a larger threshold power or the use of a magnetic field gradient to levitate the sample. The microwave trap is very deep for a wide range of polar molecules. For example, using the electric field strength demonstrated in the present work, we estimate a trap depth of 0.09 K for LiH, 0.48 K for CaF, 0.48 K for YbF, and 0.65 K for CH$_3$CN. At higher electric fields, the trap depth may be limited by multi-photon absorption processes [1], but these do not become limiting until the depth is similar to the rotational constant, which is typically of order 1 K. The use of circularly-polarized microwaves avoids this problem altogether [1]. Its large depth and volume make the trap suitable for capturing molecules from Stark, Zeeman or centrifuge decelerators [30–32, 54], or directly from a cryogenically-cooled buffer gas beam [55]. The trap could also be used to compress samples of ultracold molecules produced by direct laser cooling, which tend to have large sizes and correspondingly low densities. For the 5 µK CaF clouds recently produced [56–57], an adiabatic compression in the microwave trap, by gradually increasing the power, would increase the density by a factor $10^3$. Alternatively, it could be used to implement the rapid compression method described in Ref. [57], potentially increasing the density by a factor $10^5$. The microwave trap offers a particularly favourable environment for sympathetic cooling of molecules using ultracold atoms [39, 40], or evaporative cooling of molecules, so will be an important tool for cooling a much wider range of molecules to low temperature than is currently possible. It has been noted that, in the trap, the strong microwave-induced dipole-dipole interactions between molecules result in very large elastic collision cross-sections, which increase as the temperature decreases, and that this is ideal for runaway evaporative cooling of molecules [11, 58].

Underlying data may be accessed from Zenodo and used under the Creative Commons CC0 license. We thank Jon Dyne and Giovanni Marinaro for their expert technical assistance. We are grateful to Stefan Truppe, Lyra Dunseith, Ben Sauer and Ed Hinds for earlier work on the design of the experiment. S. Wright gratefully acknowledges support from the Imperial College President’s PhD Scholarship scheme. This was supported by EPSRC under grants EP/I012044/1, EP/M027716/1 and EP/P01058X/1.

\[1\] D. DeMille, D. R. Glenn, and J. Petrichka, “Microwave traps for cold polar molecules,” Eur. Phys. J. D 31, 375–384 (2004).
\[2\] C. C. Agosta, I. F. Silvera, H. T. C. Stoof, and B. J. Verhaar, “Trapping of neutral atoms with resonant microwave radiation,” Phys. Rev. Lett. 62, 2361–2364 (1989).
\[3\] R. J. C. Spreeuw, C. Gerz, Lori S. Goldner, W. D. Phillips, S. L. Rolston, C. I. Westbrook, M. W. Reynolds, and Isaac F. Silvera, “Demonstration of neutral atom trapping with microwaves,” Phys. Rev. Lett. 72, 3162–3165 (1994).
\[4\] P. Trentlein, T. W. Hänsch, J. Reichel, A. Negretti, M. A. Cirone, and T. Calarco, “Microwave potentials and optimal control for robust quantum gates on an atom chip,” Phys. Rev. A 74, 022312 (2006).

\[2\] 10.5281/zenodo.3237240
[39] S. K. Tokunaga, W. Skomorowski, P. S. Zuchowski, R. Moszynski, J. M. Hutson, E. A. Hinds, and M. R. Tarbutt, “Prospects for sympathetic cooling of molecules in electrostatic, ac, and microwave traps,” Eur. Phys. J. D 65, 141 (2011).

[40] J. Lim, M. D. Frye, J. M. Hutson, and M. R. Tarbutt, “Modeling sympathetic cooling of molecules by ultracold atoms,” Phys. Rev. A 92, 053419 (2015).

[41] S. Earnshaw, “On the nature of the molecular forces which regulate the constitution of the luminiferous ether,” Trans. Camb. Philos. Soc. 7, 97–112 (1842).

[42] J. van Veldhoven, H. L. Bethlem, and G. Meijer, “ac electric trap for ground state molecules,” Phys. Rev. Lett. 94, 083001 (2005).

[43] H. Odashima, S. Merz, K. Enomoto, M. Schnell, and G. Meijer, “Microwave lens for polar molecules,” Phys. Rev. Lett. 104, 253001 (2010)

[44] S. Spieler, W. Zhong, P. Djuricanin, O. Nourbakhsh, I. Gerhardt, K. Enomoto, F. Stienkemeier, and T. Momose, “Microwave lens effect for the j = 0 rotational state of CH3CN,” Molecular Physics 111, 1823–1834 (2013)

[45] K. Enomoto, N. Hizawa, Y. Puruta, N. Hada, and T. Momose, “Focusing of a cold PbO molecular beam with a superconducting microwave resonator,” Journal of Physics B: Atomic, Molecular and Optical Physics 52, 035101 (2019)

[46] S. Merz, N. Vanhaecke, W. Jäger, M. Schnell, and G. Meijer, “Decelerating molecules with microwave fields,” Phys. Rev. A 85, 063411 (2012).

[47] D. P. Dunseith, S. Truppe, R. J. Hendricks, B. E. Sauer, E. A. Hinds, and M. R. Tarbutt, “A high quality, efficiently coupled microwave cavity for trapping cold molecules,” J. Phys. B 48 (2015), 4/045001

[48] R. W. Molof, H. L. Schwartz, T. M. Miller, and B. Bederson, “Measurements of electric dipole polarizabilities of the alkali-metal atoms and the metastable noble-gas atoms,” Phys. Rev. A 10, 1131–1140 (1974).

[49] A. T. Grier, I. Ferrier-Barbut, B. S. Rem, M. Delehaye, L. Khaykovich, F. Chevy, and C. Salomon, “A-enhanced sub-Doppler cooling of lithium atoms in D1 gray molasses,” Physical Review A 87, 063411 (2013).

[50] S. C. Wright, A microwave trap for atoms and molecules, Ph.D. thesis, Imperial College London (2019).

[51] P. Schwerdtfeger and J. K. Nagle, “2018 table of static dipole polarizabilities of the neutral elements in the periodic table,” Mol. Phys. 117, 1200–1225 (2019).

[52] A. Osterwalder, S. A. Meek, G. Hammer, H. Haak, and G. Meijer, “Deceleration of neutral molecules in macroscopic traveling traps,” Phys. Rev. A 81, 051401(R) (2010).

[53] N. Akerman, M. Karpov, Y. Segev, N. Bibelnik, J. Narevicius, and E. Narevicius, “Trapping of molecular oxygen together with lithium atoms,” Phys. Rev. Lett. 119, 073204 (2017).

[54] X. Wu, T. Gantner, M. Koller, M. Zeppenfeld, S. Chervenkov, and G. Rempe, “A cryofuge for cold-collision experiments with slow polar molecules,” Science 358, 645–648 (2017).

[55] H. I. Lu, I. Kozyryev, B. Hemmerling, J. Piskorski, and J. M. Doyle, “Magnetic trapping of molecules via optical loading and magnetic slowing,” Phys. Rev. Lett. 112, 113006 (2014).

[56] L. W. Cheuk, L. Anderegg, B. L. Augenbraun, Y. Bao, S. Burchesky, W. Ketterle, and J. M. Doyle, “A-enhanced Imaging of Molecules in an Optical Trap,” Phys. Rev. Lett. 121, 083201 (2018).

[57] L. Caldwell, J. A. Devlin, H. J. Williams, N. J. Fitch, E. A. Hinds, B. E. Sauer, and M. R. Tarbutt, “Deep laser cooling and efficient magnetic compression of molecules,” (2018).

[58] A. V. Avdeenkov, “Dipolar collisions of ultracold polar molecules in a microwave field,” Phys. Rev. A 86, 022707 (2012).