A quadrupole magnetic trap using a static electric field to study ultracold atoms

W.A. van Wijngaarden and J. Clarke

Abstract: A neutral atom trap is proposed consisting of a magnetic field generated by a pair of anti-Helmholtz coils and a fringing electric field of a parallel plate capacitor. The electric field shifts the energy minimum of the trap away from the point where the magnetic field is zero thus preventing atom loss from the trap due to Majorana transitions. This trap offers some advantages over existing traps that are used to study cold atoms.

PACS Nos.: 32.80Pj and 03.75Fi

Résumé: Nous proposons un piège pour les atomes neutres et froids, qui serait constitué d'un champ magnétique généré par une paire de bobines anti-Helmholtz bordé par un champ électrique généré par des plaques parallèles. Le champ électrique éloigne le point d'énergie minimum du piège du point où le champ magnétique est zéro, prévenant ainsi la perte d'atomes par transition Majorana. Ce piège offre certains avantages lorsque comparé à d'autres pièges utilisés pour étudier les atomes froids.
[Traduit par la rédaction]

Neutral atom traps have recently been used to cool and trap atoms at ultracold temperatures, which is important for high-precision spectroscopy. A number of exciting phenomena have been observed including novel collision effects [1] and Bose-Einstein condensation [2–5]. A neutral atom having a magnetic moment is trapped using a spatially varying magnetic field. The simplest trap employs anti-Helmholtz coils to generate a magnetic quadrupole field [2]. An atom remains trapped provided its spin remains parallel to the magnetic field. The density of cold atoms that can be collected at the center of the trap where the magnetic field is zero has been shown to be limited by so-called Majorana transitions, which flip the atom's spin. The spin flips can occur when the Larmor precession is less than the angular frequency at which the moving atom perceives the magnetic field $\boldsymbol{B}$ to rotate. Ketterle and van Druten [6] show Majorana transitions may occur when the atom is a distance r from the $B = 0$ point.
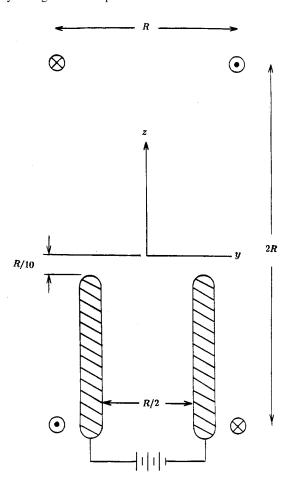
$$r = \sqrt{2\hbar v/\pi \mu_B B'} \tag{1}$$

Here v is the atom's speed, μ_B is the Bohr magneton and B' is the magnetic field gradient. For an alkali atom travelling with a speed of 10 cm s^{-1} experiencing a field gradient of 100 G cm^{-1}, this distance r is approximately 1 μm.

W.A. van Wijngaarden[1] **and J. Clarke.** Department of Physics, York University, 4700 Keele Street, Toronto, ON M3J 1P3, Canada.

[1] Corresponding author: **e-mail:** wvw@yorku.ca
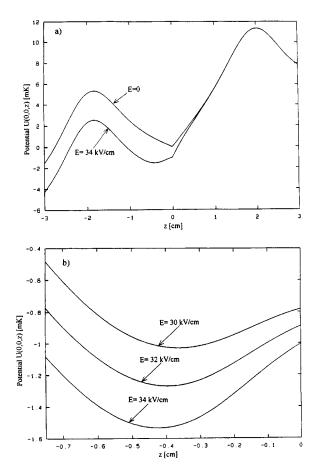
© 1998 NRC Canada

Fig. 1. Trap configuration. The trap consists of anti-Helmholtz coils and a parallel plate capacitor as described in the text. The coil radius is $R = 2$ cm. The dot and cross symbols represent the current going out of and into the page, respectively. The gravitational pull is in the $-z$ direction and the x axis points out of the page.

Several techniques have been developed to prevent Majorana transitions from occurring. The Boulder group initially used an additional pair of coils to generate a rotating magnetic field that moved the location of the zero magnetic field sufficiently quickly to prevent an atom from changing its spin direction [2,7]. Bose-Einstein condensation was first observed using this so-called TOP trap. Shortly thereafter, the group at MIT [3] created a Bose-Einstein condensate of sodium atoms using an argon ion laser detuned to the blue side of the sodium D line, to repel atoms from the trap center. The laser was sufficiently detuned from resonance so that it was not absorbed and did not heat the atoms.

A variety of more complex magnetic field configurations have been used to create traps where the energy minimum occurs at a location where the magnetic field is nonzero. The group at Rice [4,8] used six permanent magnets in an Ioffe configuration to achieve Bose-Einstein condensation using lithium atoms. Recently, the Boulder and MIT groups have refined their traps [9–13] using more elaborate magnetic-field-generating coils, which permit the creation of condensates having an increased number of atoms. This has permitted the study of collective effects of the condensates [14,15] and the creation of an atom laser [11].

Fig. 2. Trap potential vs. z. The trap potential was computed for a cesium atom experiencing electric and magnetic fields as described in the text. (*a*) shows the trap potential has a minimum at a location $z_m = -0.42$ cm relative to the potential minimum generated when the electric field is zero. The potential is asymmetric even when the electric field is zero owing to the gravitation field. This asymmetry is progressively smaller for the lighter alkali atoms. (*b*) shows the trap depth is 533 μK for an electric field between the plates of $E_{\text{opt}} = 34$ kV cm^{-1}. The trap depth decreases rapidly for smaller field strengths.

This paper proposes a trap that retains the simplicity of a magnetic field generated using a pair of anti-Helmholtz coils together with an electric field produced by a parallel plate capacitor as is illustrated in Fig. 1. The capacitor is spatially shifted from the origin where the magnetic field vanishes. The plate separation distance was chosen to be 1 cm corresponding to a magnetic coil radius $R = 2$ cm, which is comparable to that used in existing neutral atom traps. The plates generate an electric field to spatially shift the energy minimum of the trap to a position $z_m \neq 0$.

The behaviour of the trap has been modelled for alkali atoms that have relatively low melting points as well as transitions to the first excited states at wavelengths accessible using dye, diode, or titanium:sapphire lasers. Hence, alkali atoms have been used nearly exclusively in neutral-atom traps. Their electronic structure can also be modelled relatively simply as a single valence electron interacting with the nucleus and closed inner electron core. The potential energy of a trapped alkali atom in its ground $S_{1/2}$ state having its magnetic moment antialigned with the magnetic field B, is

Table 1. Trap parameters for alkali atoms.

Atom	α_o[ref. 24] $(10^{-24}$ cm$^3)$	$B'/(mg/\mu_B)$	E_{opt} (kV cm^{-1})	Trap depth (mK)
^{7}Li	24.4	81	61	0.34
^{23}Na	24.2	25	60	0.36
^{39}K	43.4	15	44	0.38
^{85}Rb	47.3	7	40	0.45
^{133}Cs	59.6	4	34	0.53

given by [16,17]

$$U = mgz - \frac{\alpha_o}{2}E^2 + \mu_B B \tag{2}$$

where m is the atom's mass, g is the acceleration due to gravity, and α_o is the scalar polarizability. The electric field E was found by solving the Laplace equation numerically for the plate configuration shown in Fig. 1. The thickness of the plates was taken to be $R/8$ and the plate edges were rounded with a radius of $R/16$. The plates were considered to have an infinite extent in the x direction necessitating the solution of the two-dimensional Laplace equation.

The trap parameters for the various alkali atoms are listed in Table 1. A magnetic field gradient at the trap center, $B' = 100$ G cm^{-1} was considered, which is substantially larger than that needed to counter gravity as is shown in column 3. The trap potential energy U was computed as a function of the three orthogonal directions x, y, and z. Figure 2 compares the potential energy of cesium atoms obtained when the two plates were grounded and when the electric field between the plates is 34 kV cm^{-1}. The trap minimum was located a distance $z_m = -0.42$ cm away from the origin. Figure 3 shows the trap potential energy as a function of x and y. The electric field between the plates, E_{opt}, was chosen so that the potential well depths in the y and z directions were equal. Smaller electric fields decrease the energy barrier between z_m and the origin while higher field strengths reduce the energy barrier preventing atoms from striking the electric field plates.

The required electric fields are comparable to those routinely generated in our laboratory [18] and are also considerably smaller than those used by Windholz et al. [19] (127 kV cm^{-1}) to study Stark shifts. The electric field strongly affects the trap depth as shown in Fig. 2b. Hence, hot atoms can be expelled from the trap by decreasing the electric field by only a few percent. The trap depths given in Table 1 are larger than the temperatures achieved by a number of groups [2–4,20–23].

An important application of cold atoms is the generation of Bose-Einstein condensates, which occurs when the following condition is satisfied [5].

$$\frac{N}{V}\lambda_{dB}^3 > 2.612 \tag{3}$$

Here N is the number of atoms enclosed in trap volume V and $\lambda_{dB} = \sqrt{2\pi\hbar^2/mkT}$ is the de Broglie wavelength for an atom with mass m. In this trap, atoms at a temperature of 10 μK occupy a volume of approximately 5×10^{-4} cm^3. Hence, the critical number of atoms needed to achieve BEC ranges from 5×10^6 for lithium to 4×10^8 for cesium.

The cold atoms needed for BEC are generated first using laser cooling to produce a relatively large number of cold atoms. The atoms then undergo evaporative cooling due to elastic collisions that occur at a rate
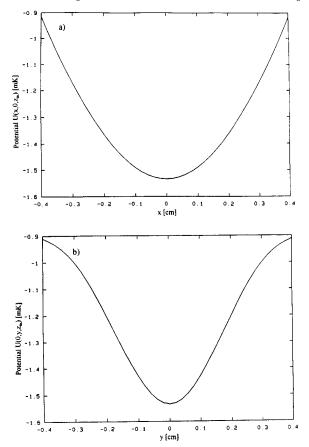
$$\frac{1}{\tau_{el}} = \frac{N}{V}\sigma_{el}v \tag{4}$$

Fig. 3. Trap potential vs. x and y. The atoms are well confined in the x and y directions.

where v is the relative speed and σ_{el} is the elastic scattering cross section which for sodium is 6×10^{-12} cm^2 [6]. Hence, for this trap, an initial 10^{10} sodium atoms at a temperature of 10 μK, will experience over 1000 collisions per second. This has been shown to yield a sufficient number of cold atoms such that (3) can be achieved [6]. The condensate lifetime is limited by collisions with background gas and hence ultra-high-vacuum chambers capable of 10^{-11} Torr (1 Torr = 133.3 Pa) are employed.

An important advantage of this trap is that it uses a simpler field configuration than is used by other existing traps. For example, the Ioffe Pritchard trap requires over a dozen separate coils to generate the necessary spatially inhomogeneous magnetic field [9–11]. The magnetic field is also obtained without the use of permanent magnets whose magnetic field cannot be tuned and can be affected by vacuum bakeout. One also does not need to reduce Majorana transitions using a tightly focussed laser beam that may inadvertently heat the atoms. The trap offers easy access in three dimensions for pairs of counterpropagating laser beams to create optical molasses. Evaporative cooling can be optimized by changing the electric field strength to vary the trap depth. Therefore, this trap offers an interesting complementary approach to existing traps for studying ultracold alkali atoms.

Acknowledgement

References

1. T. Walker and P. Feng. Adv. At. Mol. Opt. Phys. **34**, 125 (1994).
2. M.H. Anderson, J.R. Ensher, M.R. Matthews, C.E. Wieman, and E.A. Cornell. Science, **269**, 198 (1995).
3. K.B. Davis, M.O. Mewes, M.R. Andrews, N.J. van Druten, D.S. Durfee, D.M. Kurn, and W. Ketterle. Phys. Rev. Lett. **75**, 3969 (1995).
4. C.C. Bradley, C.A. Sackett, J.J. Tollett, and R.G. Hulet. Phys. Rev. Lett. **75**, 1687 (1995).
5. A. Griffin, D.W. Snoke, and S. Stringari (*Editors*). Bose–Einstein condensation. Cambridge University Press. 1995.
6. W. Ketterle and N.J. van Druten. Adv. At. Mol. Opt. Phys. **37**, 181 (1996).
7. W. Petrich, M.H. Anderson, J.R. Ensher, and E.A. Cornell. Phys. Rev. Lett. **74**, 3352 (1995).
8. J.J. Tollett, C.C. Bradley, C.A. Sackett, and R.G. Hulet. Phys. Rev. A: At. Mol. Opt. Phys. **51**, R22 (1995).
9. C.J. Myatt, E.A. Burt, R.W. Ghrist, E.A. Cornell, and C.E. Wieman. Phys. Rev. Lett. **78**, 586 (1997).
10. M.O. Mewes, M.R. Andrews, N.J. van Druten, D.M. Kurn, D.S. Durfee, and W. Ketterle. Phys. Rev. Lett. **77**, 416 (1996).
11. C. Townsend, W. Ketterle, and S. Stringari. Phys. World, **10**(3), 29 (1997).
12. M.O. Mewes, M.R. Andrews, D.M. Kurn, D.S. Durfee, C.G. Townsend ,and W. Ketterle. Phys. Rev. Lett. **78**, 582 (1997).
13. D.E. Pritchard. Phys. Rev. Lett. **71**, 1336 (1983).
14. D.S. Jin, J.R. Ensher, M.R. Matthews, C.E. Wieman, and E.A. Cornell. Phys. Rev. Lett. **77**, 420 (1996) ; D.S. Jin, M.R. Matthews, J.R. Ensher, C.E. Wieman, and E.A. Cornell. Phys. Rev. Lett. **78**, 764 (1997).
15. M.O. Mewes, M.R. Andrews, N.J. van Druten, D.M. Kurn, D.S. Durfee, C.G. Townsend, and W. Ketterle. Phys. Rev. Lett. **77**, 988 (1996).
16. A. Corney. Atomic and laser spectroscopy. Clarendon Press, Oxford. 1978.
17. A. Khadjavi, A. Lurio, and W. Happer. Phys. Rev. **167**, 128 (1968).
18. J. Li and W.A. van Wijngaarden. J. Phys. B: At. Mol. Opt. Phys. **28**, 2559 (1995).
19. L. Windholz et al. Phys. Rev. Lett. **77**, 2190 (1996).
20. C. Salomon, J. Dalibard, W.D. Phillips, A. Clairon, and S. Guellati. Europhys. Lett. **12**, 683 (1990).
21. A. Kastberg, W.D. Phillips, S. . Rolston, R.J.C. Spreeuw, and P.S. Jessen. Phys. Rev. Lett. **74**, 1542 (1995).
22. J. Reichel, F. Bardou, M. Ben Dahan, E. Peik, S. Rand, C. Salomon, and C. Cohen-Tannoudji. Phys. Rev. Lett. **75**, 4575 (1995).
23. H.J. Lee, C.S. Adams, M. Kasevich, and S. Chu. Phys. Rev. Lett. **76**, 2658 (1996).
24. R.W. Molof, H.L. Schwartz, T.M. Miller, and B. Bederson. Phys. Rev. A ; Gen. Phys. **10**, 1131 (1974).