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Magnetic Surface Microtraps for Two-Species Bose–Einstein Condensations *

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We propose a novel magnetic surface microtrap (i.e. a double Z-wire trap) for the study of two-species Bose–Einstein condensations. The spatial distributions of the magnetic fields from the double Z-wire configurations and their gradients and curvatures are calculated and analysed. The result shows that the proposed surface trap has double magnetic wells and can be continuously changed into a single-well trap by reducing the current in a straight wire, and the maximum field gradient greater than 5×10^4 G/cm and the maximum field curvature (at each trap centre) greater than 2.5×10^7 G/cm^2 can be generated in our double-well traps, which can be used to realize two-species Bose–Einstein condensations and to study the properties of double-well Bose–Einstein condensations and so on.

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In 1996, Ho *et al.*[1] first discussed the binary mixtures of alkali atomic Bose–Einstein condensations (BECs). Such two-species mixtures may consist of different alkali atoms such as ^{23}Na$-^{87}$Rb, or different isotopes such as ^{85}Rb$-^{87}$Rb and ^{39}K$-^{41}$K, or different hyperfine states of the same alkali such as the $|F = 2, m_F = 2\rangle$ and $|F = 1, m_F = -1\rangle$ spin states of ^{87}Rb atoms. Since then, a two-component ^{87}Rb atomic BEC in the $|F = 2, m_F = 2\rangle$ and $|F = 1, m_F = -1\rangle$ spin states has been produced in a macroscopic magnetic trap,[2] and the properties of two-species BECs in a single-well magnetic trap have been studied both theoretically and experimentally.[3−9] More recently, an ^{87}Rb atomic BEC in a single surface microtrap was observed by two groups,[10,11] and a real two-species BEC of ^{41}K and ^{87}Rb atoms in a single-well magnetic trap[12] was prepared by both rf evaporative cooling and sympathetic cooling. However, to date no real two-species BEC in a double-well magnetic trap has been realized. In fact, it may be more desirable to prepare a two-species BEC in a double-well magnetic trap and transfer them into a single-well trap, and then to experimentally study their properties.

In recent years, the theoretical study of atomic BECs confined in a symmetrical or asymmetrical double-well potential[13−18] has become an interesting hot topic in atomic physics and quantum optics. However, some questions have arisen: how to form a double-well magnetic trap with two independent but close microscopic wells, and how to split a larger BEC into two smaller BECs as well as how to load them into two magnetic wells. So far nobody has answered these questions. Thus, it would be interesting and worthwhile to design some double-well magnetic traps and to explore the possibility of realizing a two-species BEC. In this Letter, we use a double U-shaped current-carrying wire to construct a double-well magnetic surface microtrap for cold atoms and we discuss their applications in two-species atomic BECs and so on.

Recently, U-shaped and Z-shaped wire traps for cold atoms were studied theoretically by Cassettari *et al.*[20] and demonstrated experimentally by Reichal *et al.*[19] In particular, a Z-shaped wire microtrap was used to realize an ^{87}Rb atomic BEC on a microelectronic chip by the Hansch group.[10] Here we use a Z-shaped wire and a straight wire to construct a double Z-shaped wire trap (see Fig. 1), which can be used to form a new double-well magnetic surface microtrap. To form a double-well magnetic trap with nonzero B-values at each trap centre, a homogeneous bias field ($B_0 = 10$ G) along the z-axis is superposed with the magnetic fields from a double Z-shaped, current-carrying wire configuration. The spatial distribution of the magnetic field B from a double Z-shaped wire configuration can be calculated by

$$\begin{aligned}\boldsymbol{B} = \frac{\mu_0 I_1}{4\pi}\Big\{ &\int_{-b}^{0} \frac{-(y+a)\boldsymbol{i} + x\boldsymbol{j}}{[x^2+(y+a)^2+(z-z')^2]^{3/2}}\mathrm{d}z' \\ &+ \int_{0}^{b} \frac{-(y-a)\boldsymbol{i} + x\boldsymbol{j}}{[x^2+(y-a)^2+(z-z')^2]^{3/2}}\mathrm{d}z' \\ &+ \int_{-a}^{a} \frac{z\boldsymbol{i} - x\boldsymbol{k}}{[x^2+(y-y')^2+z^2]^{3/2}}\mathrm{d}y'\Big\} \\ &+ \frac{\mu_0 I_2}{4\pi} \times \int_{b}^{-b} \frac{y\boldsymbol{i} - x\boldsymbol{j}}{[x^2+y^2+(z-z')^2]^{3/2}}\mathrm{d}z'. \end{aligned} \quad (1)$$

From Eq. (1), the spatial distributions of the magnetic field B generated by both a double Z-shaped current-carrying wire layout and a bias field B_0 are calculated, and the results are shown in Figs. 2(a), 2(b) and 2(c) for $a = 200\,\mu$m, and $b = 300\,\mu$m, and the current I_2 in the straight wire is 200, 100 and 0 mA, respectively. It can be seen from Fig. 2 that when $I_1 = I_2 = 200$ mA, there are two microscopic

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magnetic wells with a minimal non-zero B-value at each well centre (see Fig. 2(a)), whereas there is only a microscopic well (see Fig.2(c)) above the wire surface as $I_1 = 200$ mA and $I_2 = 0$ mA. Obviously, when the current I_2 is decreased from 200 mA to 0 mA, a double-well magnetic trap becomes a single-well trap and the corresponding spacing between two trap centres in the y-axis is reduced from 150 μm to 0. In contrast, a single-well magnetic trap is split into two magnetic wells when the current I_2 is increased from 0 to 200 mA. When $I_1 = I_2 = 200$ mA, we obtained $B_{\min} = 2.5$ G at each trap centre, $B(x)_{\max} \geq 7$ G within $\Delta x = x - x_0 = -50\,\mu$m and $\Delta x = x - x_0 = -15\,\mu$m, $B(y)_{\max} \geq 9$ G within $\Delta y = y - y_0 = \pm 100\,\mu$m, and $B(z)_{\max} \geq 9$ G within $\Delta z = z - z_0 = \pm 50\,\mu$m, where (x_0, y_0, z_0) are the position coordinates of each trap centre and we have $x_0 = -36.2\,\mu$m, $y_0 = \pm 150\,\mu$m and $z_0 = 0$, respectively. Similarly, when $I_1 = 200$ mA and $I_2 = 0$ mA, we obtain $B_{\min} = 0.7$ G at the trap centre, $B(x)_{\max} \geq 5$ G within $\Delta x = x - x_0 = -50\,\mu$m and $\Delta x = x - x_0 = 15\,\mu$m, $B(y)_{\max} \geq 6$ G within $\Delta y = y - y_0 = \pm 200\,\mu$m, and $B(z)_{\max} \geq 8$ G within $\Delta z = z - z_0 = \pm 50\,\mu$m, having $x_0 = -39.2\,\mu$m, $y_0 = 0$ and $z_0 = 0$, respectively.

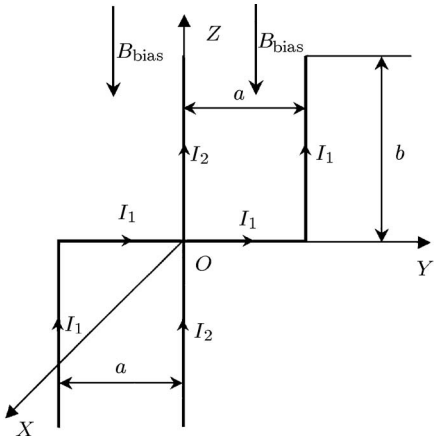


Fig. 1. Schematic diagram of double Z-shaped wire trap.

To know the characteristics of a single microscopic well in our double-well surface microtrap, we calculated the spatial distributions of the magnetic fields, gradients and their curvatures in the x-, y- and z-directions, and the results are shown in Figs. 3(a)–3(c), respectively. When $I_1 = I_2 = 200$ mA (i.e., the case of double-well trap), we obtained the maximal magnetic-well depth $\Delta B(x)_{\max} \geq 4.5$ G in the x-direction, $\Delta B(y)_{\max} \geq 7.5$ G in the y-direction and $\Delta B(z)_{\max} \geq 6.5$ G in the z-direction. The maximal magnetic-field gradients are $\left(\frac{\partial B}{\partial x}\right)_{\max} \approx 1.5 \times 10^3$ G/cm, $\left(\frac{\partial B}{\partial y}\right)_{\max} \approx 1.2 \times 10^3$ G/cm and $\left(\frac{\partial B}{\partial z}\right)_{\max} \approx 2 \times 10^3$ G/cm, respectively. We have the curvatures $\left(\frac{\partial^2 B}{\partial x^2}\right) \approx 5 \times 10^6$ G/cm^2, $\left(\frac{\partial^2 B}{\partial y^2}\right) \approx 1 \times 10^5$ G/cm^2 and $\left(\frac{\partial^2 B}{\partial z^2}\right)_{\max} \approx 3 \times 10^6$ G/cm^2 at each well centre, which are similar to that in the single-well BEC microtrap[10,11] and far larger than those of macroscopic BEC magnetic traps (usually the corresponding maximal gradient and curvature are $\sim$200 G/cm and 300 G/cm^2 respectively, whereas the typical currents I are about 25–100 A, even up to $\sim$1000 A[21]). However, when $I_1 = 200$ mA and $I_2 = 0$ mA (i.e., the case of single-well trap), we obtained the maximal magnetic-well depth $\Delta B(x)_{\max} \geq 7$ G, $\Delta B(y)_{\max} \geq 7$ G and $\Delta B(z)_{\max} \geq 8$ G. The maximal magnetic-field gradients are $\left(\frac{\partial B}{\partial x}\right)_{\max} \approx 2 \times 10^3$ G/cm, $\left(\frac{\partial B}{\partial y}\right)_{\max} \approx 1 \times 10^3$ G/cm and $\left(\frac{\partial B}{\partial z}\right)_{\max} \approx 2.5 \times 10^3$ G/cm, respectively. We have the curvatures $\left(\frac{\partial^2 B}{\partial x^2}\right)_{\max} \approx 2.2 \times 10^7$ G/cm^2, $\left(\frac{\partial^2 B}{\partial y^2}\right) \approx 1.1 \times 10^5$ G/cm^2, and $\left(\frac{\partial^2 B}{\partial z^2}\right)_{\max} \approx 2.1 \times 10^7$ G/cm^2 at the well centre, which are also larger than those of double-well traps.

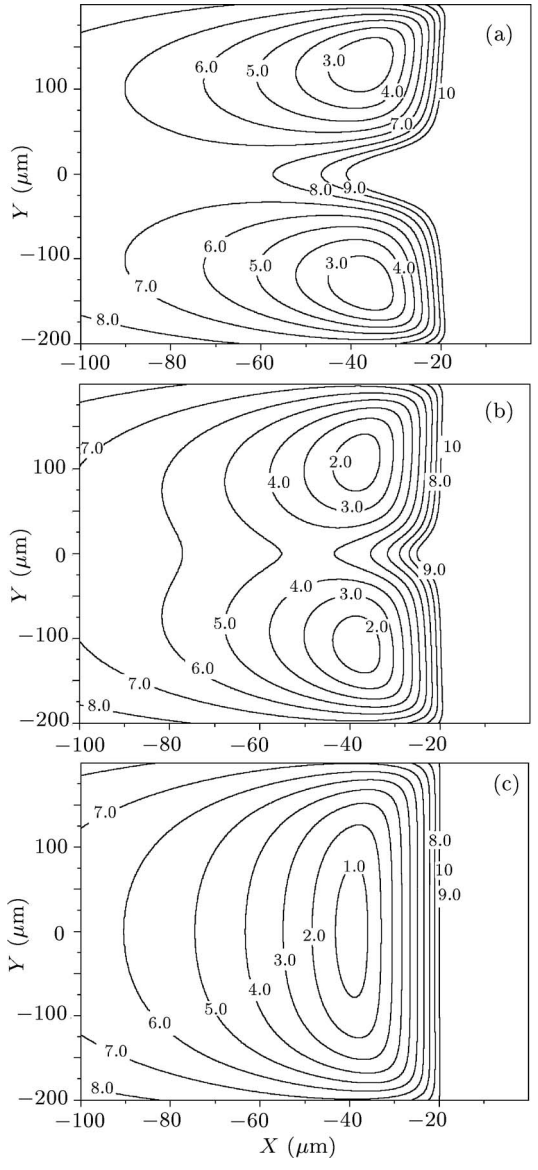


Fig. 2. Magnetic-field contours on the xoy plane by this layout with $a = 200\,\mu$m, and $b = 300\,\mu$m: (a) $I_1 = I_2 = 200$ mA; (b) $I_1 = 200$ mA, $I_2 = 100$ mA; (c) $I_1 = 200$ mA, $I_2 = 0$ mA.

From our calculations, we found that the magnetic field B at each well centre is non-zero, so the Majorana transitions of cold atoms in our double-well (including single-well) magnetic microtrap can be avoided. We also found that the magnetic field of each microscopic trap scales as I/s, the corresponding B-field gradient and curvature scale as I/s^2 and I/s^3, respectively, where s is the characteristic size of the trap system. This shows that one can obtain a tighter confinement for trapped cold atoms by using a magnetic microtrap composed of a smaller-sized wire layout, which is only limited by practical attainable current I in the wire.

In consideration of the interaction between a neutral atom with a magnetic dipole moment μ and a static inhomogeneous magnetic field B, the trapping potential for cold atoms is dependent on the position and is given by

$$U_{Mag} = -\boldsymbol{\mu} \cdot \boldsymbol{B} = g_F m \mu_B B, \qquad (2)$$

where m is the magnetic quantum number, g_F is the Lande G-factor, and μ_B is the Bohr magneton. When $\boldsymbol{\mu} \cdot \boldsymbol{B} < 0$, the potential is repulsive, and the atom in the weak-field-seeking state will be repulsed to the minimum of magnetic field. For ^{87}Rb atoms in the $|F = 2, m = 2\rangle$ state (or for ^{133}Cs atoms in the $|F = 3, m = -3\rangle$ state), the trapping potential is $U_{\rm Mag}^{\rm Rb} = 67.2\,B\ (\mu{\rm K})$ (or $U_{\rm Mag}^{\rm Cs} = 100.8\,B\ (\mu{\rm K})$). Here the magnetic field B is in units of Gauss. For our scheme, when $I_1 = I_2 = 200\,{\rm mA}$ and $\Delta B(x)_{\max} \leq 4.5\,{\rm G}$, we obtain $U_{\rm Mag}^{\rm Rb} \geq 302.4\,\mu{\rm K}$ (or $U_{\rm Mag}^{\rm Cs} \geq 453.6\,\mu{\rm K}$), which is far higher than the temperature $T_{\rm OM}$ of cold atoms in a three-dimensional (3D) optical molasses (such as $T_{\rm OM} \approx 20\,\mu{\rm K}$ for ^{87}Rb atoms and $\sim 10\,\mu{\rm K}$ for ^{133}Cs atoms).

Since our double-well magnetic microtrap is a surface microtrap, it can be fabricated by standard microfabrication techniques such as photolithography and electroplating[10,11,22,23] and fixed on a sapphire (or Al_2O_3) substrate. For example, a microstructure with a total width of $100\,\mu$m and a copper wire with a width of $3\,\mu$m were electroplated on an Al_2O_3 substrate in Ref. [11]. The widths of our microstructure and wire are 200 and 20 μm, respectively, so there is no problem with fabricating our microstructure wire trap in the experiment. Recently, the experiment of Pretiss's group shows that, due to heating dissipation, an Au wire on a sapphire substrate can support currents of several amperes with a current density of $\sim 10^8\ {\rm A/cm^2}$ and a power dissipation of $\sim 10\,{\rm kW/cm^2}$ at liquid nitrogen or helium temperatures in vacuum.[23] For our surface trap using a planar wire layout, we choose the wire diameter $d = 10\,\mu$m and the current $I = 0.2\,{\rm A}$, and the corresponding current density is $\sim 2.5 \times 10^5\ {\rm A/cm^2}$, which is far lower than $10^8\ {\rm A/cm^2}$.[23] Thus, Au wires on the surface of a sapphire substrate cooled by liquid nitrogen or helium can be used to form our double-well magnetic microtraps, and then to realize two-species BECs by rf evaporative cooling.

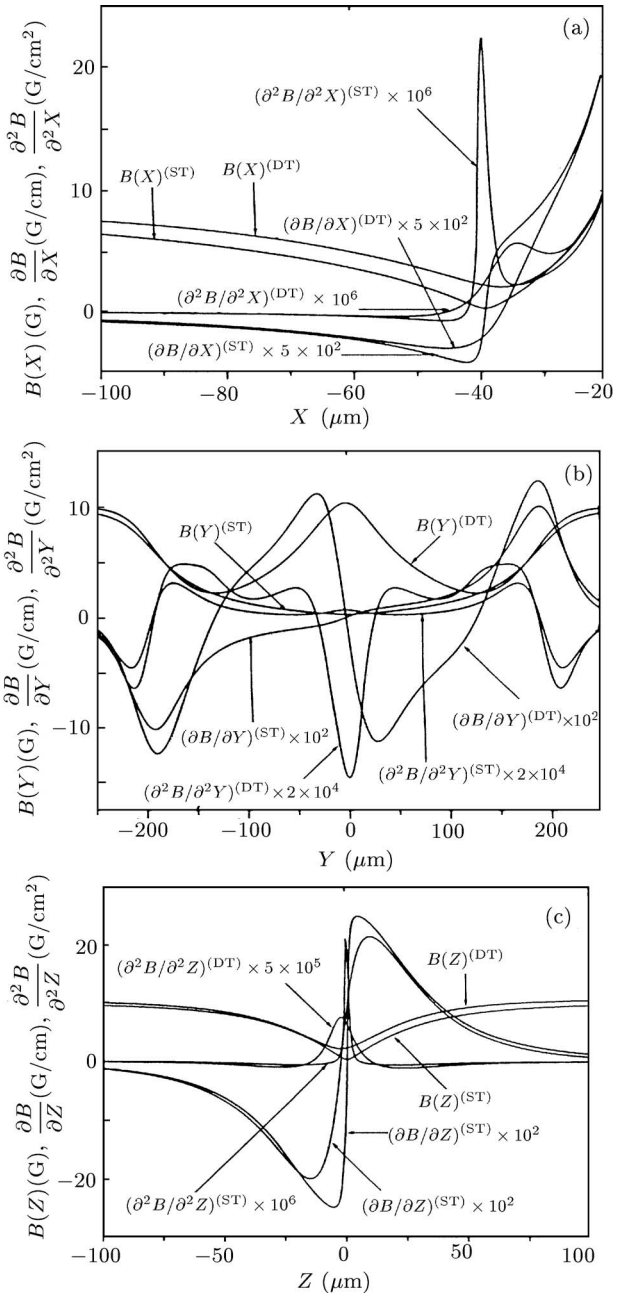


Fig. 3. Distributions of the magnetic fields with $a = 200\,\mu$m, and $b = 300\,\mu$m, $I_1 = 200\,{\rm mA}$, $I_2^{(DT)} = 200\,{\rm mA}$, $I_2^{(ST)} = 0\,{\rm mA}$ for our double Z-shaped wire trap: (a) $B(x)$, $\frac{\partial B}{\partial x}$, and $\frac{\partial^2 B}{\partial x^2}$ in the x-direction; (b) $B(y)$, $\frac{\partial B}{\partial y}$, and $\frac{\partial^2 B}{\partial y^2}$ in the y-direction; (c) $B(z)$, $\frac{\partial B}{\partial z}$, and $\frac{\partial^2 B}{\partial z^2}$ in the z-direction. The superscripts DT and ST denote double-well trap and single-well trap, respectively.

To load more cold atoms within a shorter time and to obtain a higher density in each microscopic trap, we have to use two cold atomic beams to load our double-well trap. For this, we must first prepare two different cold atomic beams with a rate of $\sim 10^{10}$ atoms/s in the lower-vacuum vapour cell by using the 3D MOT technique.[24,25] Secondly, we use two focused dark-hollow beams (DHB) as two atomic funnels,[26] to load two different atomic samples from

two lower-vacuum MOTs into two microscopic magnetic traps. We also use two 2D optical molasses beams together with our double magnetic well to cool and trap the cold atoms; then to build up two-species MOTs in an ultrahigh vacuum cell ($p \leq 10^{-11}$ Torr). After the 2D molasses beams (i.e., 2D polarization gradient cooling) are used to cool the trapped atoms in two-species MOTs and to obtain two ultracold and dense atomic samples with a temperature of $\sim 10\,\mu$K, by removing the 2D molasses beams and increasing the currents I_i ($i = 1$ and 2), one can realize the loading of cold atoms from two-species MOTs into a double-well magnetic trap. For ^{87}Rb atoms, when the atomic density in each MOT is $n \approx 10^{12}\,\mathrm{atoms/cm^3}$ and the trapping volume is $\sim 5 \times 10^{-6}\,\mathrm{cm^3}$, the corresponding atomic number in each microtrap is about 5×10^6 atoms, which is about equal to one in the first ^{87}Rb atomic BEC experiment[27] and in the first micro-BEC experiment.[10]

The collision mechanisms of cold atoms in the double-well magnetic trap are similar to those in a macroscopic magnetic trap. The adiabatic condition of atomic motion in our quadrupole Ioffe microtrap can be satisfied well, so when $p \approx 10^{-11}$ Torr and the atomic density n in each magnetic microtrap is higher (i.e., $n \approx 10^{12} \sim 10^{14}\,\mathrm{atoms/cm^3}$), the two-body spin relaxation and three-body recombination will become two dominant loss mechanisms. The corresponding loss rate is given by[28]

$$\gamma = \frac{1}{n}\frac{\mathrm{d}n}{\mathrm{d}t} \approx nG + Ln^2, \qquad (3)$$

where n is the density in each trap, and G and L are the two-body spin-relaxation and three-body-recombination rate coefficients, respectively. For ^{87}Rb atoms, $G < 10^{-15}\,\mathrm{cm^3/s}$[29] and $L = 4 \times 10^{-30}\,\mathrm{cm^6/s}$.[30] When $n = 10^{12} - 10^{14}\,\mathrm{atoms/cm^3}$ (which is usually the density range of alkali atomic BECs in magnetic traps[21]), we obtain $\gamma_{\mathrm{TBC}} < 10^{-3} \sim 10^{-1}\mathrm{s}^{-1}$, and the corresponding lifetime of atoms in each magnetic microtrap is longer than $10 - 1000\,\mathrm{s}$.

Similar to BEC experiments using a macroscopic magnetic trap (or a single magnetic microtrap[10,11]), after two ultracold atomic samples are loaded into the double-well magnetic trap, we can increase the currents in all wires so as to greatly enhance the magnetic-field gradient and its curvature of each microwell, and adiabatically compress cold atomic samples to a suitable density within $n = 10^{12}$-10^{14} atoms/cm^3. Then the cold atoms in each microwell can be further cooled to about the recoil temperature by rf evaporative cooling, which is the typical phase transition temperature in most BEC experiments.[21] Since the magnetic-field gradient of each magnetic microwell in our double-well trap and its curvature can be far larger than that of the macroscopic BEC traps and about equal to that of a micro-BEC trap,[10,11] an atomic density higher than the BEC density should be obtained in each microwell, and a real two-species BEC may be realized in our double-well magnetic microtrap.

Since our magnetic surface microtrap can be continuously changed from a double-well microtrap into a single-well microtrap, or vice versa, it can be used to experimentally study the properties of two-species BECs in a single-well magnetic trap,[2–9] and the sympathetic cooling between two different atomic samples, or to study the properties of double-well BECs[13–17] and so on.[18]

In conclusion, we have proposed a new scheme to form a double-well magnetic microtrap for cold atoms by using double Z-wire configuration. We have calculated the spatial distributions of magnetic fields, gradients and their curvatures from our double-well wire layout. Our study shows that the maximum magnetic-field gradient greater than 5×10^3 G/cm and the maximum field curvature (at each trap centre) greater than $2.5 \times 10^5\,\mathrm{G/cm^2}$ can be obtained in our double-well microtraps. These can be used to realize two-species BECs, and to study the properties of two-species and double-well BECs, and even to realize sympathetic cooling and so on.

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