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High-Performance Sodium Bose–Einstein Condensate Apparatus with a Hybrid Trap and Long-Distance Magnetic Transfer *

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We report on the production of large sodium Bose–Einstein condensates in a hybrid of magnetic quadrupole and optical dipole trap. With an optimized spin-flip Zeeman slower, 2×10^{10} sodium atoms are captured in the magneto-optical trap (MOT). A long distance magnetic transfer setup moves the cold atom over 46 cm from the MOT chamber to the UHV science chamber, which provides great optical access and long conservative trap lifetime. After evaporative cooling in the hybrid trap, we produce nearly pure condensates of 1×10^7 atoms with lifetime of 80 s in the optical dipole trap.

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Cold atoms and cold molecules in the optical lattices, serving as quantum simulators, are very well suited for mimicking solid-state systems.[1,2] In comparison with ^{87}Rb, ^{23}Na has stronger and wider Feshbach resonances which are favorable for tuning the atomic interaction.[3–5] As for spinor condensate, ^{23}Na Bose–Einstein condensates (BECs) are antiferromagnetic,[6] while ^{87}Rb BECs are ferromagnetic.[7–9] Furthermore, ^{23}Na BEC is a very important ingredient in the ultracold dipolar molecule research. Ultracold gases of dipolar molecules are of an excellent quantum mechanical model that offers the prospect to create fundamentally new quantum phases of matter, has the potential to dramatically influence precision tests of fundamental physics, and also provides a promising platform for quantum information processing.[1] In the past decade, great progress has been achieved in the ultracold molecule research. The absolute rovibrational ground state ^{40}K^{87}Rb molecules were produced with the Feshbach resonance and stimulated Raman adiabatic passage.[10–12] Unfortunately, the ^{40}K^{87}Rb molecule is unstable against the exchange reaction KRb+KRb→K_2+Rb_2,[13] which makes further evaporative cooling unsuccessful. ^{23}Na^{40}K and ^{40}K^{133}Cs are the only two chemically stable fermionic alkali-metal dimers, which are expected to overcome the stability problem of the KRb molecule, and ^{23}Na^{40}K has the larger electric dipole moment of $d = 2.72$ D.[14,15]

The making of the ground-state molecules requires a large number of quantum degenerate atoms.[12,16,17] In this Letter, we report on the production of the large sodium BEC of 1×10^7 atoms in our ^{23}Na-^{40}K sympathetic cooling apparatus. A large number of cold atoms are achieved from a high performance Zeeman slower,[18,19] which provides high flux of slowed atoms for the 3D magneto-optical trap (MOT). In addition, a high efficiency, long distance magnetic transfer belt[20] of cold atoms is used to move the atoms from the MOT chamber to the UHV science chamber to achieve great optical access and long trap lifetime, which are important for further experiments with optical lattices and *in situ* imaging. Evaporative cooling of ^{23}Na atoms into BEC is carried out in a hybrid trap.[21]

The experimental setup is shown in Fig. 1. Two pre-cooling techniques, i.e., Zeeman slower for ^{23}Na atoms and 2D$^+$MOT[22] for ^{40}K atoms, are used in the apparatus. The slowed sodium beam is magneto-optically trapped at the center of the MOT chamber. The atom cloud is then transferred into the UHV glass cell over a distance of 46 cm. The background pressure in the glass cell is 1.2×10^{-9} Pa, measured by the ionization gauge (Agilent, UHV-24p) in the science chamber. Magnetic transport is chosen due to its large trap volume and deep trap depth. For atoms with a temperature of several hundreds of micro Kelvin, the Majorana loss due to spin flip close to the field zero of a magnetic quadrupole potential is negligible on the timescale of seconds.[23] Evaporative cooling into BEC is carried out in a hybrid trap with a magnetic quadruple trap and crossed optical dipole trap (ODT).

The experimental cycle to produce sodium BEC starts with the deceleration of sodium beams with a spin-flip Zeeman slower.[24,25] The deceleration rate of sodium atoms in the slower is given by $a_s = \eta\frac{\hbar k}{M}\frac{\Gamma}{2}$,[26] in which $\hbar k$ is the single-photon recoil momentum of 589 nm light, Γ is the natural line width of the sodium D_2 transition, and M is the sodium atomic mass, with the slowing factor $\eta = 0.7$ for our slower design. The theoretical field profile is a parabolic-shaped curve with a 22 cm long low field gap for spin repolarization. A MATLAB program was developed

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to optimize the winding pattern, as shown in Fig. 2(a). Both the simulated and measured values of magnetic field strengths are given in Fig. 2(b). For the fringing fields to decay quickly at the exiting end, we wound the increasing field section with a small outside diameter of only 46 mm. The slower solenoid was wound with 4×4 mm square copper wires. Cooling water through the 2.5 mm diameter center bore of the copper wire removes the 0.3 kW heat dissipation of the slower solenoids. The σ^+ polarized Gaussian slowing beam, with a total power of 75 mW, enters the Zeeman slower with a $1/e^2$ radius of 1 cm and reaches a focus in the oven nozzle. The slowing laser beam, generated from the main laser (Toptica, DLC TA-SHG pro, @589 nm) with frequency shift acousto-optic modulators (AOMs), is 483 MHz red detuned from the sodium D_2 line. To prepare the atoms in the cycling transition, the slowing beam has a sideband at 1712 MHz that is created with an electro-optic modulator, which contains 16% of the total intensity. The performance of the slower is stable with ±3 MHz change of the sideband detuning. Atoms with speed up to 900 m/s can be captured by the slower and slowed to the final speed of 30 m/s, measured by the absorption spectra of the slowed atom beam at the center of the MOT chamber.

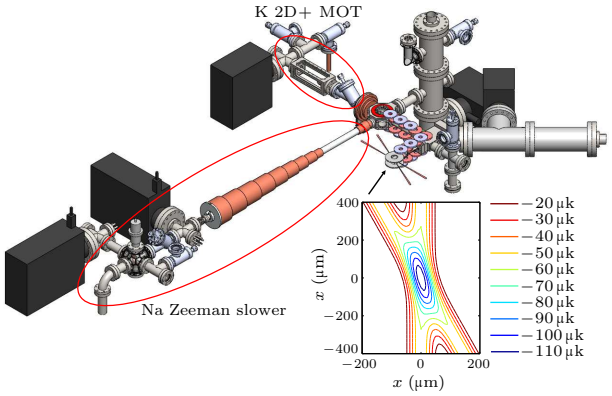


Fig. 1. Schematic diagram of the experimental setup. A spin-flip Zeeman slower and a $2D^+$ transverse cooling system provide high flux of ^{23}Na and ^{40}K atoms, respectively. Cold atoms trapped in the MOT chamber are transferred into the UHV glass cell. Each transfer coil consists of 69 windings, with an outer diameter of $d_o = 60$ mm, an inside diameter of $d_i = 18.6$ mm and a height of $h = 6.6$ mm. Evaporative cooling of cold atoms into BEC is carried out in a hybrid trap located in the glass cell. The inset shows the profile of the ODT potential for sodium in the horizontal plane with full laser power.

Slowed atoms exiting the Zeeman slower are then captured by a dark spontaneous-force optical trap.[27] The MOT runs at an axial magnetic field gradient of 12.5 G/cm. The cooling beam is 19 MHz red detuned from the $F = 2$ to $F' = 3$ cycling transition with the peak beam intensity of 5.3 mW/cm^2 for each of the six MOT beams. Opaque circles with diameter of 11 mm block light in the middle of repumping beams, which are 16 MHz red detuned from $F = 1$ to $F' = 2$ transition, creating a region at the center of the MOT where trapped atoms are optically pumped into the $F = 1$ state which does not interact with the cooling beams. The dark spot can reduce the light-induced loss in the MOT which makes the MOT trap more atoms. The typical atom number in the ^{23}Na MOT is around 2×10^{10}. However, after 18 months of operation, the oven nozzle is partially clogged by the sodium deposition, and now we typically have 7.5×10^9 atoms to start for our BEC experiment. At the end of the MOT loading, another set of repumping beams with total peak intensity of 3 mW/cm^2 and 8 MHz red detuning are shined onto the atoms for 10 ms, which causes stronger MOT forces for the atoms and a thirty-fold increase in the atom density to 9×10^{11}/cm^3. Then a 5 ms polarization gradient cooling (PGC)[28,29] is used to cool the atoms to 100 μK, during which we turn off the magnetic quadrupole field and increase the cooling beam detuning from −19 MHz to −28 MHz. At the end of the PGC, the cooling beam is switched off after the repumping beam is switched off for 50 μs, which will send most of the atoms to the $F = 1$ state.

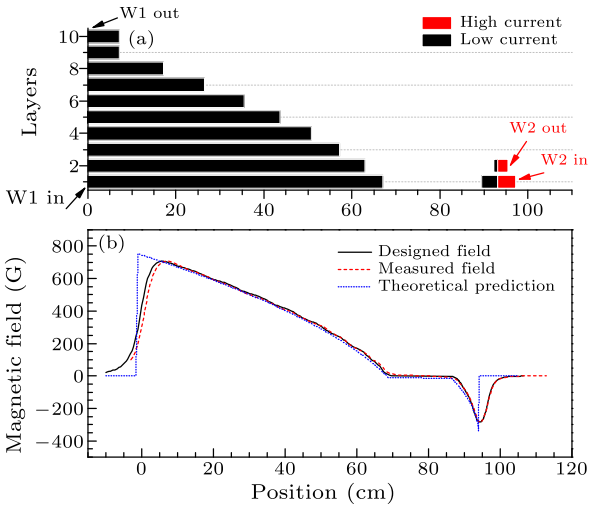


Fig. 2. (a) Half cross section of the slower solenoids. The solenoids are divided into two sections: a decreasing field solenoid and an increasing field solenoid. A current of 29 A flow through the large part of the coils (black) and a current of 82 A flow through the coils (red) next to the exiting end of the slower. Cooling water is running through the inner bore of the copper coils in a direction labeled by the arrows. (b) Magnetic field produced by the slower solenoids as a function of position. The designed field data is our simulation result and the measured field data is obtained using a Gauss meter.

A quadrupole field with $B' = 80$ G/cm is turned on in 0.5 ms to transfer the atoms from the optical molasses to the quadrupole trap. The field gradient is then adiabatically ramped up to 180 G/cm in 300 ms to compress the atom cloud, which is important for the high efficiency magnetic transfer. Typically 1/3 atoms are trapped in the magnetic trap in the $|1, -1\rangle$ state and the temperature of the atoms after the magnetic compression is 200 μK. Subsequently, the center of the trapping field is moved over a distance of 46 cm

into the UHV glass cell, with a 90° corner turn in the middle of the transfer path, which provides better optical access. The transfer time is 3 s, and the transfer efficiency is 60%. Typically 1.4×10^9 atoms are transferred into the final magnetic trap. A total of fifteen pairs of quadrupole coils and a tapered push coil are used in the transfer, and the last pair of coils also serves as the quadrupole coils for the hybrid trap, as shown in Fig. 1.

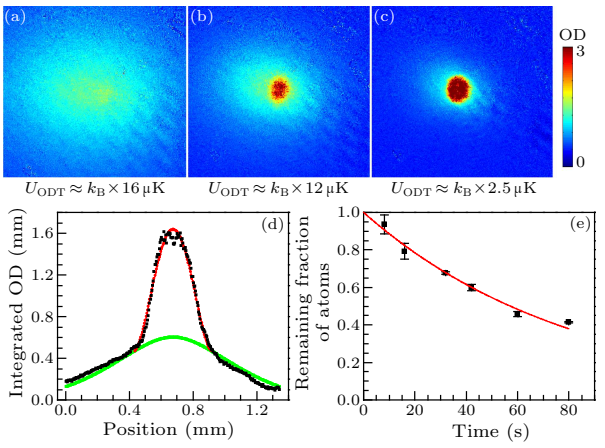


Fig. 3. Bose–Einstein condensation: (a)–(c) Optical density distributions determined from absorption images taken after time-of-flight 28 ms for different final trap depths of the ODT. With decreasing the final trap depth, a spatially small peak with increasing optical density forms at the center of the thermal cloud. (d) Projections of the optical column densities along with corresponding bimodal fit (lines). (e) Lifetime of ultracold sodium atoms in the hybrid trap. The red line is the exponential fitting to the measurement, which gives a $1/e$ lifetime of 80 s.

Evaporative cooling in a hybrid trap is desirable for the following reasons. Firstly, the deep trap depth and large trap volume of the quadrupole magnetic traps are ideally suited for creating a large number of cold atoms. Secondly, evaporative cooling in the linear traps is more efficient compared with that in the harmonic traps before the Majorana loss becomes significant at low temperature.[30] Finally, the ^{23}Na $|2,2\rangle$+^{40}K $|9/2,9/2\rangle$ state, which is used in the magnetic trap to avoid spin exchange losses, suffers severe three-body loss in the last stage of evaporative cooling when atom density is approaching quantum degeneracy, thus transferring ^{23}Na atoms into the $|1,1\rangle$ state is required to reduce the three-body loss.[31] This can only be carried out in the ODT due to the fact that the Na $|1,1\rangle$ state cannot be magnetically trapped. In our experiment, the crossed ODT is produced by a 1064 nm fiber laser. The two arms are intensity stabilized by two independent PID controlled AOMs and intersect at an angle of 20°. The beam waists are 65 μm, and the beam foci are 60 μm vertically below the magnetic field zero. The total power of the two beams is 14.2 W, which produces a trap depth of 118 μK.

After the magnetic transfer of the atom cloud to the last pair of quadrupole coils, the field gradient is ramped from 180 to 400 G/cm in 1 s to enhance the initial elastic-collision rate. Simultaneously with the adiabatic compression of quadrupole trap, the intensity of the crossed ODT beams is also ramped up in 200 ms. We then turn on the rf and apply a sweep of the frequency from 65 MHz down to 4 MHz in 4.4 s. After this rf-forced evaporation, the temperature of the atoms drops to 30 μK and 8×10^7 atoms remain in the trap. Next, we adiabatically ramp down the quadrupole field gradient from 400 to 8.0 G/cm in 0.5 s and transfer the atoms into the ODT. Here 5×10^7 atoms with a temperature of 10 μK are transferred into the crossed ODT, forced evaporation by lowering the dipole trap intensity is then performed. The evaporative cooling process is optimized with several segments in both the magnetic quadrupole trap and the crossed ODT.

Phase transition from the thermal cloud to BEC is shown in Figs. 3(a)–3(c) by varying the final trap depth of the ODT. The characteristic bimodal distribution signature,[25] as shown in Fig. 3(d), occurs with around 2×10^7 atoms in the trap. By reducing the trap depth to 2 μK, we are able to produce pure condensates with 1×10^7 atoms. The lifetime of BEC in the ODT, as shown in Fig. 3(e), is 80 s, which indicates a very good vacuum level and agrees with the result measured by the ionization gauge.

In conclusion, we have produced a large sodium BEC with 1×10^7 atoms in our ^{23}Na-^{40}K sympathetic cooling apparatus. To our best knowledge, this is the largest BEC with a hybrid trap in the world. A high performance spin-flip Zeeman slower is the key to the large BEC. In addition, long distance magnetic transfer with low heating brings the atoms to a separate science chamber, which is important for future quantum manipulation of the atomic and molecular states. Quantum degeneracy with a large atom number is the key to the success of achieving quantum degeneracy of the dipolar molecules, due to the fact that the conversion efficiency to molecules is only 15% in the MIT experiments.[31] With a potassium $2D^+$ cooling stage already set up in the apparatus, this BEC machine is ready for the sympathetic cooling of ^{40}K and ^{23}Na and the creation of ultracold ^{23}Na^{40}K molecules in the near future.

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