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Sympathetic cooling of Rb^+ ions by cold Rb atoms in an ion-neutral hybrid trap*

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Abstract Sympathetic cooling of Rb^+ ions by cold Rb atoms is studied in an ion-neutral hybrid trap. The effect of a linear Paul trap (LPT) parameter $q_{1,2}$ on the sympathetic cooling is studied by measuring the changes in ion number N_i and temperature T_i after interaction with cold atoms. The sympathetic cooling effect is observed with $0.3 \leqslant |q_{1,2}| \leqslant 0.8$. At the $|q_{1,2}|$ value of 0.32, ions are cooled from initial (2 010 ± 380) K to (325 ± 35) K and the lifetime of ions is extended from 7 s to 15 s via sympathetic cooling. These findings are very useful for cooling of atomic and molecular ions, especially for the ions without available optical channels.

Keywords sympathetic cooling; ion-atom collisions; ion-neutral hybrid trap

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离子－原子混合阱中冷 Rb 原子对 Rb^+ 离子的协同冷却

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摘　要　研究在离子－原子混合阱中冷 Rb 原子对 Rb^+ 离子的协同冷却效应。通过对与原子相互作用之后离子温度和数目的测量研究离子阱参数 $q_{1,2}$ 对协同冷却的影响。发现在 $0.3 \leqslant |q_{1,2}| \leqslant 0.8$ 时冷原子对离子具有明显的协同冷却效果。选取 $|q_{1,2}| = 0.32$,测量到离子可以从初始温度(2 010 ± 380) K 冷却至(325 ± 35) K,寿命从 7 s 延长至 15 s。这对于冷却原子离子或者分子离子,尤其是没有合适光学通道的离子将是非常有意义的。

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关键词 协同冷却;离子-原子碰撞;离子-原子混合阱

Sympathetic cooling provides an efficient cooling of particles that are difficult to cool, especially for those particles which do not have optically accessible transitions[1-3]. Sympathetic cooling has achieved great success in many fields. In neutral-neutral sympathetic cooling, sympathetic cooling of an atomic Fermi gas by a Bose gas is a standard technology to study degenerate atomic Fermi gases and Boson-Fermion mixtures in many laboratories[4-6]. In ion-ion sympathetic cooling, usually one of the ionic species is directly laser cooled first and then cools the other ionic species by elastic collisions. Due to the strong Coulomb interaction $V \propto 1/r$, this is a highly effective method for cooling ions to cold and ultracold temperatures[7-9]. Recently, ion-ion sympathetic cooling was used to cool the molecular ion external degrees of freedom to ultracold temperature[10-11]. However, the long range ion-ion interaction does not couple to the molecular ion internal degrees of freedom and therefore the rovibrational temperature is unmodified by the ion-ion sympathetic cooling. Precise control over the internal motion of the molecular ions is required and useful in the study of ultrahigh-precision molecular spectroscopy[12], quantum control reactions[13], and ultracold chemistry[14-15].

Since the ion-neutral hybrid trap was originally proposed[3], which consists of two separate but spatially concentric traps (a magneto-optical trap (MOT) for the neutral species and a mass-selective linear Paul trap (LPT) for the ionic species), it becomes an ideal apparatus for ion-neutral sympathetic cooling[16-20]. In ion-neutral sympathetic cooling, collisions are dominated by the long range polarization potential, which can be described by $-C_4/r^4$, where $C_4 = \alpha e^2/(8\pi\varepsilon_0)$, with α the static electric polarizability of the neutral spices and r the ion-neutral separation. Such long-range polarization forces between ions and neutral atoms result in large elastic scattering cross sections, as well as inelastic collision sections. Therefore, the ion-neutral sympathetic cooling offers a unique advantage to simultaneously cool both the internal and external degrees of freedom for molecular ions[21].

Before the invention of MOT, the ion-neutral sympathetic cooling was widely studied in the neutral buffer gas[22-24], in which the neutral buffer gas is usually dispersed throughout the whole experimental chamber. In those cases, the technique works best for ions (with mass m_i) and neutral atoms (with mass m_n) whose masses meet the criterion $m_i/m_n > 1$, or else the ion trap's inherent atom-ion rf heating mechanism overwhelms the collisional cooling[22-24]. Unlike the buffer gas cooling, the cold neutral species is directly laser cooled and localized in a small volume compared to the volume of ions cloud in a LPT. Goodman et al.[19] have theoretically studied the ion-neutral sympathetic cooling in an ion-neutral hybrid trap, and shown that a MOT efficiently cools ions. Very recently, equal mass ion-neutral sympathetic cooling was observed experimentally within ion-neutral hybrid traps (See Refs. [17,20]). They first reported evidence of sympathetic cooling of Rb^+ by a Rb MOT and Na^+ by a Na MOT, respectively.

In this paper, sympathetic cooling of Rb^+ by cold Rb atoms is investigated in an ion-neutral hybrid trap. By directly mesruing the temperature of ions, the effect of LPT parameter $q_{1,2}$ on the sympathetic cooling of Rb^+ is studied. Then an appropriate $q_{1,2}$ value is selected for further study of sympathetic cooling.

1 Experimental method

The dynamic of a LPT will be introduced firstly to help us understanding the ion-atom collisions in the ion-neutral hybrid trap. The confining potential of a LPT is not conservative as it is based on oscillating electric fields, the trapped ions can be heated due to trap imperfections and rf heating caused by ion-ion repulsion[17,19]. Even in a mixed systems of co-trapped ions and cold atoms, the collisions between ions and cold atoms can cause atom-ion rf heating mechanism[17-19]. The only available cooling channel for Rb^+ ions in such an ion-neutral hybrid trap is collisions with cold Rb atoms. The heating and cooling of ions are simultaneous and competitive, therefore appropriate parameters of LPT must be selected to make sure that the collisional cooling can overwhelm many heating mechanisms[18-22].

The potential of the LPT is of the form

$$\Phi(x,y,z,t) \approx \frac{V_{\mathrm{rf}}}{r_0^2}\cos(\Omega t)(x^2-y^2) + \frac{\eta V_{\mathrm{ec}}}{z_0^2}\left[z^2-\frac{1}{2}(x^2+y^2)\right], \quad (1)$$

where V_{rf} and Ω is amplitude and frequency of the rf voltage respectively, V_{ec} the electrostatic voltage on the end-cap, r_0 the radial distance of the rf electrode from the centre of the LPT, and η the efficiency factor depends on the geometry of the end-cap electrode. The equation of motion for a single ion in the LPT can be described by the well-known Mathieu equation.

For a single ion with charge e and mass m_{i}, the ranges of the so-called stability parameters a_i and q_i in which the ion can be trapped in the LPT are $a_1 < 0$ and $0 < q_1 < 0.9$[8,22]. The parameters a_i and q_i are defined as

$$a_1 = a_2 = -\frac{a_3}{2} = \frac{-4e\eta V_{\mathrm{ec}}}{m_{\mathrm{i}} z_0^2 \Omega^2},$$

$$q_1 = -q_2 = \frac{4eV_{\mathrm{rf}}}{m_{\mathrm{f}} r_0^2 \Omega^2}, (q_3 = 0), \quad (2)$$

And the total time-averaged kinetic energy $\langle E_k \rangle$ of the ion is defined as

$$\langle E_k \rangle = \frac{1}{2} m_{\mathrm{i}} \langle v_i^2 \rangle = \frac{m_{\mathrm{i}} x_{0i}^2}{4}\left(\omega_i^2 + \frac{q_i^2 \Omega^2}{8}\right), \quad (3)$$

where $\omega_i \approx \frac{\Omega}{2}\sqrt{a_i + \frac{q_i^2}{2}}$ is the secular motion frequency.

Our ion-neutral hybrid trap and processes of sympathetic cooling will be described as following. The detail description of our ion-neutral hybrid apparatus can be found in our previous work[25]. Here we will briefly describe the apparatus and experiments processes for the convenience of the reader. Figure 1 shows the schematic of our ion-neutral hybrid trap. The typical MOT is used to cool and trap cold ^{87}Rb atoms with a maximum atom density up to $n_a \sim 1 \times 10^{10}$ cm^{-3}, with atom temperature 100 ~ 1 000 μK. Note that, the total number and the temperature of the cold atoms are directly measured by the time-of-flight (TOF) method[26]. The $^{87}Rb^+$ ions are generated by two-step photoionization of cold ^{87}Rb atoms and then trapped by a LPT, which is comprised of four radio frequency (rf) central parallel rods arranged in a quadrupole configuration and two dc hollow end-cap ring electrodes along the cylindrical axis. The microchannel plate (MCP) is used to detect the trapped ions by appropriately switching off the voltage on the hollow end-cap electrode closer to the MCP. The maximum number of ions is calculated by an equation $N_i^0 = N_a \zeta \frac{1}{\gamma_{\mathrm{ia}} \kappa}$, where N_{a} is the number of cold atoms, $\zeta = \frac{\sigma_{PI} \lambda_{PI} f_e}{hc}$, γ_{ia} the loss rate of atoms due to ion-atom collisions, and κ the intensity-loss coefficient with units of inverse intensity due to the finite potential depth of the ion trap[25]. Then the ion signals from microchannel plate MCP can be calculated by N_i^0 to obtain the N_i in each experimental cycle. In this paper, the initial ion number is deduced approximately 2×10^4. The temperature of ion T_i can be obtained by fitting of the ion TOF signal detected by MCP to the Maxwell-Boltzmann distribution. Although some Refs. have shown that the measured ion's energy distribution deviates obviously from the Maxwell-Boltzmann distribution with a single ion in the hybrid traps[27],

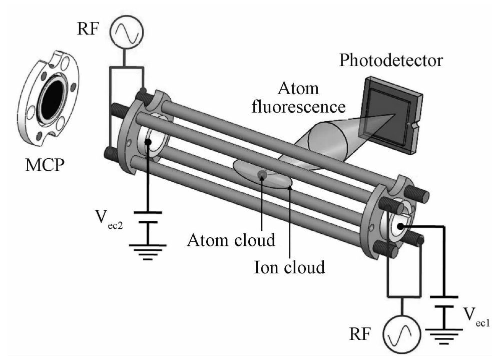

Fig. 1 Schematic of the ion-neutral hybrid trap in this work

the TOF signal of a large number of ions basically meets the Maxwell-Boltzmann distribution[17,20,25].

Both the cold atom cloud and ion cloud are located at center represented by the red sphere and blue cigar shape, respectively. The MCP is used to detect the ions. The MOT fluorescence is detected by a homemade photodetector.

The sympathetic cooling of Rb^+ ions is studied by measuring the changes of ion number N_i and temperature T_i after interaction with cold Rb atoms. Figure 2 (a) shows the temporal sequence for one experimental cycle. In the first step, from 0 to T_1, the MOT is turned on and loaded for as long as 42 s until saturation. In the second step, a blue diode continuous-wave laser at 473 nm is introduced to photoionize a small fraction of the cold atoms, and the LPT is turned on simultaneously to trap the ions. The duration of the ionizing laser is 500 ms from T_1 to T_2, with the laser intensity $I_{PI} = 6.2\ \mathrm{mW/cm^2}$. Then, the LPT is kept on and the MOT is kept on for a duration T_{sc} from T_2 to T_3 (MOT on) or turned off at T_2 (MOT off), i. e., the ions collide with the MOT atoms in the hybrid trap or freely evolve in the LPT. At last the ions are released by switching off the electrostatic voltage V_{ec2} on the end-cap electrode close to the MCP rapidly at T_3 (the MOT is turned off simultaneously if it works during T_{sc}). The rf voltage and electrostatic voltage on the other end-cap electrode V_{ec1} lag a little while (~5 ms) for the fully export of the ions. Figure 2(b) is a typical loading curve of the cold atoms with MOT on (dark line) and MOT off (grey line) from T_2 to T_3.

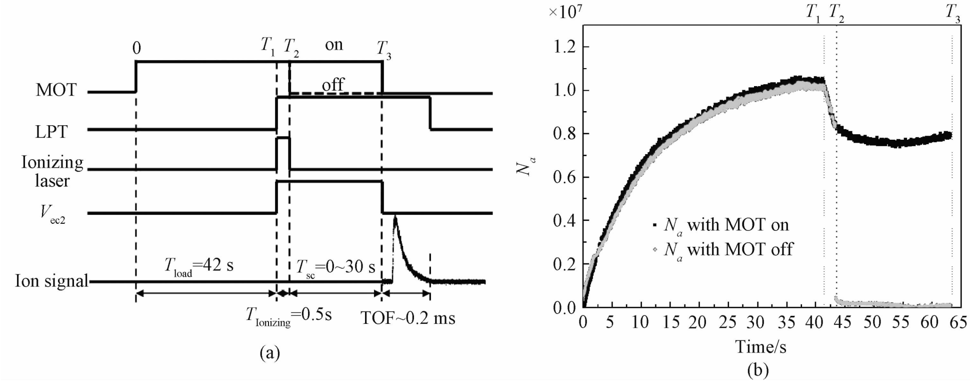

Fig. 2　Temporal sequence for one experimental cycle (a) and corresponding cold atom number in one experimental cycle (b)

2　Experimental results and analysis

Goodman et al.[19] have theoretically studied the ion-neutral sympathetic cooling in an ion-neutral hybrid trap, and shown that sympathetic cooling effect is related to the ion-atom mass ratio and the parameters $q_{1,2}$ of the LPT. Here, we experimentally studied the effect of $q_{1,2}$ on the sympathetic cooling of Rb^+ by cold Rb atoms in our ion-neutral hybrid trap. We fixed $\Omega = 470$ kHz and $V_{ec1} = V_{ec2} = 60$ V, and changed $|q_{1,2}|$ in the range of 0.18 to 0.90 by changing the V_{rf} based on equation (2), and the effect of $q_{1,2}$ on sympathetic cooling is studied by measuring the changes of T_i with MOT on and MOT off. Figure 3 shows that with MOT off a relationship of $T_i \propto q_{1,2}^2$ which is expected by the equation (3). Such relationship is broken with MOT on and shows T_i with MOT on is lower than MOT off when $0.3 \leqslant |q_{1,2}| \leqslant 0.8$. For further study, $|q_{1,2}| = 0.32$ is selected with an lower initial T_i by setting the experimental parameters of the LPT as $\Omega = 470$ kHz, $V_{rf} = 70$ V and $V_{ec1} = V_{ec2} = 60$ V.

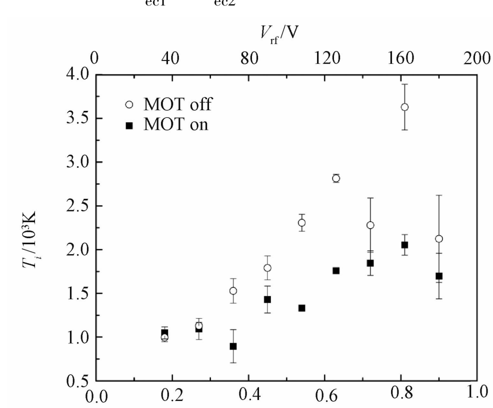

Fig. 3　Ion temperatures at different $|q_{1,2}|$ values in the presence and absence of an overlapping MOT

The solid squares are obtained with sympathetic cooling time of 20 s, and the hollow circles are obtained by only hold LPT 20 s. The LPT parameters are as following: $\Omega=470$ kHz, $V_{ec1}=V_{ec2}=60$ V.

Figure 4 shows two typical TOF of ion signals with different sympathetic cooling time $T_{sc}=5.20$ s, respectively. T_i is estimated by fitting the TOF signal with a Maxwell-Boltzmann distribution as $T_i \approx$ (1 380 ± 135) K and (598 ± 55) K, correspondingly. Figure 4 also shows that the TOF signal follows a more well Maxwell-Boltzmann distribution with longer sympathetic cooling time T_{sc}, and this behavior indicates that the combined ion-atom system is intrinsically stable with longer sympathetic cooling time T_{sc}.

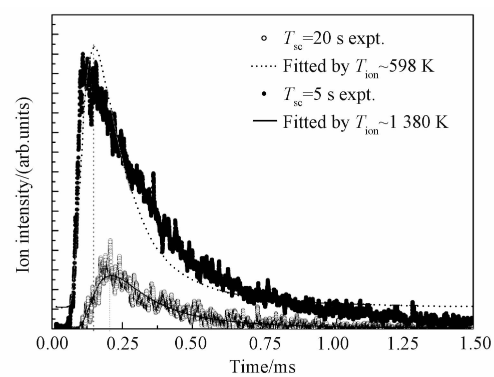

Fig. 4 Measured TOF profiles of ions with different sympathetic cooling time of 5 s and 20 s, and the corresponding fitting results by the Maxwell-Boltzmann distribution

Figure 5 shows the number of ions N_i with different hold time of LPT with MOT off and MOT on, and the N_i decay curves shows the difference in trap loss with MOT on and MOT off. The lifetime of ions in LPT is extended via sympathetic cooling from 7 s to 15 s. Note that, the TOF ion signal becomes very weak after LPT hold 15 s with MOT off, we can not get exact the value of N_i and T_i. The error bar of N_i becomes smaller after LPT hold 15 s with MOT on and also indicates that the combined ion-atom system becomes more stable. This is very important for future cold chemistry experiments.

Figure 6 shows the temperature of ions T_i with different hold time in the LPT with MOT off and MOT on. The experimental results with MOT off show that T_i decreases with hold time of LPT in the

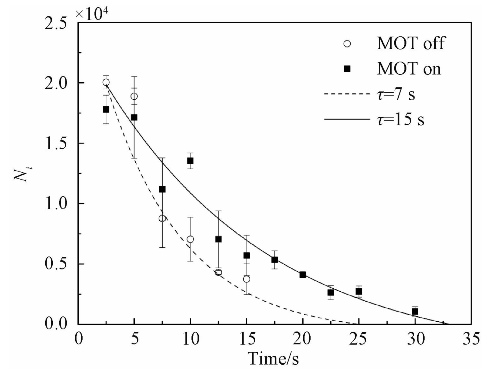

Fig. 5 Number of ions N_i vs. the hold time of LPT with MOT off and MOT on

first 12.5 s, and then does not decrease until the ion signal is too weak to be measured. In the case of MOT on, T_i decreases with hold time of LPT after the first 12.5 s which confirmed that ions are sympathetically cooled by cold atoms. More interestingly, T_i can be obtained as lower as $T_i=$ (325 ± 35) K with a relatively large number $N \approx$ 1 500.

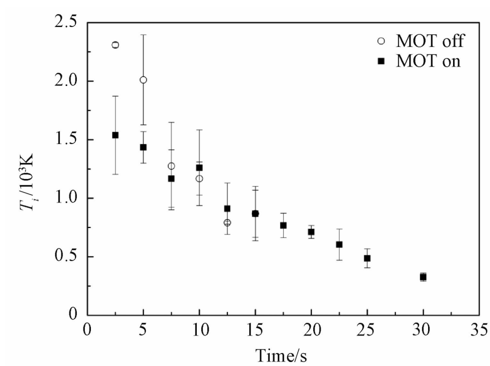

Fig. 6 Temperature of ions T_i vs. the hold time of LPT with MOT off and MOT on

3 Conclusion

In summary, we studied the effect of LPT parameter $q_{1,2}$ on the sympathetic cooling of Rb^+ ions by cold Rb atoms in an ion-neutral hybrid trap. By directly measuring the changes in ion number N_i and temperature T_i after interaction with cold atoms, we found obvious sympathetic cooling behavior with $0.3 \leqslant |q_{1,2}| \leqslant 0.8$. At the $|q_{1,2}|$ value of 0.32, sympathetic cooling was further investigated by two methods. The temperature of ions was cooled from the initial (2010 ± 380) K to (325 ± 35) K and the lifetime of ions in LPT was extended from 7 s to 15 s via sympathetic cooling. These findings are very useful for sympathetic cooling of atomic and molecular ions, especially for the ions without available optical channels.

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