Jpn. J. Appl. Phys. Vol. 40 (2001) pp. 4221–4222
Part 1, No. 6A, June 2001

Short Note

Cryogenic Ion Trap for Minimization of Trapped Ion Loss

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(Received January 31, 2001; accepted for publication March 2, 2001)

A cryogenic linear ion trap was developed for the minimization of the loss of trapped Be^+ ions. Buffer gas cooling as well as laser cooling for light element ions was tested in the cryogenic trap. The lifetime for the He-gas-cooled Be^+ ions was longer than 15 min with a liquid-He-cooled trap, although they are known to be difficult to cool with a buffer gas in a conventional trap. A laser-cooled ion crystal was maintained for approximately 30 min without any ion loss.

KEYWORDS: Be, laser cooling, buffer gas cooling, cryogenic ion trap

Laser-microwave double resonance spectroscopy of trapped ions enables us to precisely measure the hyperfine structure splitting of alkali earth ions. In order to study the Bohr-Weisskopf effect of unstable Be isotopes, we have proposed systematic measurements of the hyperfine structures of unstable Be isotopes.[1)] Only a small amount of unstable isotopes can be produced at a time. Therefore, the loss of trapped ions should be minimized. Moreover, buffer gas cooling is essential for the trapping of such externally produced unstable isotope ions.[2,3)] The main causes of the ion loss are kinematic collisions with heavy residual gases and chemical reactions with impurities. Both problems can be solved by using a cryogenic trap whose electrodes can work as powerful cryopumps for such impurities in the trap region.[4)] In this paper, we report the construction of a cryogenic linear rf ion trap for the improvement of the ion storage time. An initial test of the new apparatus revealed successful trapping of He-buffer-gas-cooled Be^+ ions. Such light ions are known to be difficult to cool by a buffer gas. We have also tested the trap with laser-cooled Be^+ ions.

We used an experimental setup similar to that described in our previous paper.[5)] Modifications are as follows. The linear rf trap was enclosed in double cryogenic cylinders (Fig. 1). A cylindrical radiation shield in contact with a liquid helium (LHe) reservoir (1.6 l) was surrounded by an outer cylinder in contact with a liquid nitrogen (LN_2) reservoir (3.0 l). The coolant injection pipes were welded to the LHe reservoir and passed through the LN_2 reservoir to reduce evaporation of LHe by thermal inflow. The vacuum chamber was evacuated by a turbomolecular pump (300 l/s) backed by a rotary pump with a fore-line oil trap. The residual pressure was about 5×10^{-8} Pa at room temperature. The pressure in the cryogenic region was difficult to measure; thus, it was estimated from the pumping speed of the cryogenic parts and conductance calculations to be more than two orders of magnitude lower than the outside pressure of the cryogenic enclosure, which was about 1×10^{-8} Pa. The storage time of trapped Be^+ ions was measured by observation of the decay in the laser-induced fluorescence (LIF). The optical transition of Be^+ was excited by 313 nm UV laser light.[5)]

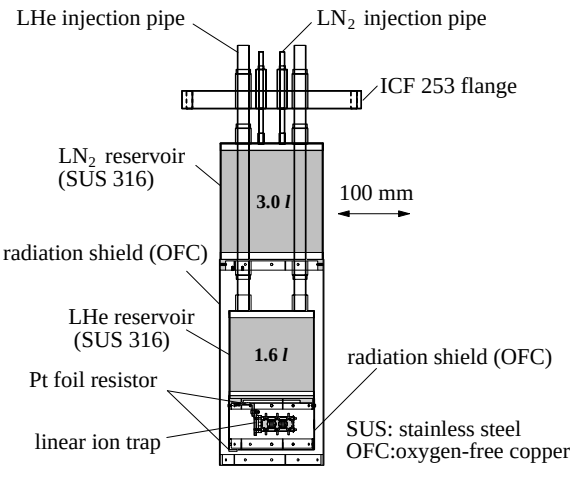

Fig. 1. Layout of the cryostat and the cryogenic linear trap.

We measured the storage time of He-gas-cooled Be^+ ions (Fig. 2). Typically, it was of the order of 10 s at room temperature, but extended to about 15 min with LHe cooling [Fig. 2(b)]. We also found that laser cooling assisted buffer gas cooling under cryogenic conditions. When the laser power was increased from 40 μW to 600 μW, the trap lifetime was prolonged to approximately 23 min even when the LN_2-cooled trap was used [Fig. 2(c)]. These results indicate that a difference in impurities of less than 10^{-9} Pa results in a considerably improved trap lifetime, i.e., the lifetime of trapped light Be^+ ions is very sensitive to the quality of He gas. We expect that prolongation of the storage time can also be achieved for other light ions in traps cooled by LN_2 or LHe. We also measured the trap lifetime of laser-cooled $^9Be^+$ ions under cryogenic conditions (Fig. 3). We obtained a lifetime of 178(3) min from the dominant time constant of the decay curve. This lifetime is approximately 18 times longer than the corresponding lifetime at room temperature.

With a small number of ions and a properly tuned laser frequency, we were able to observe crystallization of trapped Be^+ ions. In our previous experiment, the crystallized Be^+ ions decayed within ten minutes even under ultra high-vacuum conditions.[2)] However, we were able to achieve a longer confinement time for crystallized ions with the cryogenic linear ion trap. After observing crystallization, we fixed the laser frequency at about 100 MHz below the resonance frequency and monitored the intensity of the laser-induced fluorescence as a function of time (Fig. 4). The crystallized

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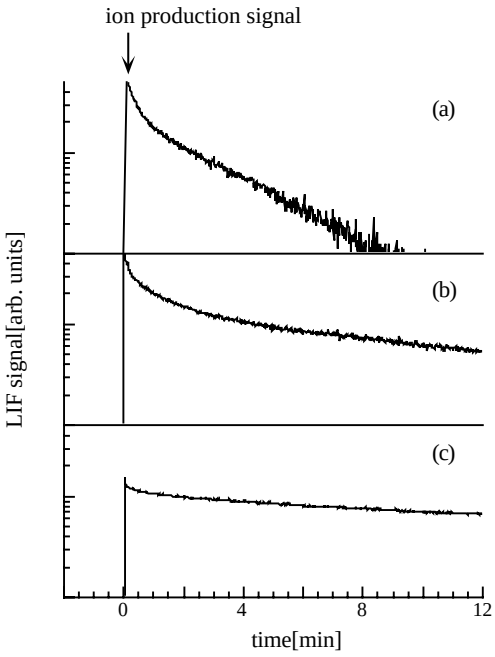

Fig. 2. Time spectra of the fluorescence signal from He-gas-cooled $^9Be^+$ ions. The data were normalized to an equal number of photon counts. The trap lifetimes are 2.37(5) min for the LN_2-cooled trap (a), 14.9(1) min for the LHe-cooled trap (b), and 22.9(1) min for the LN_2-cooled trap assisted by laser cooling (c). The laser power was 600 μW for (c), and 40 μW for (a) and (b). The stray light level lies below the axis in all three figures. $f_{rf} = 2.457$ MHz, $V_{ac} = 120\,V_{pp}$, He gas pressure $p = 4 \times 10^{-3}$ Pa.

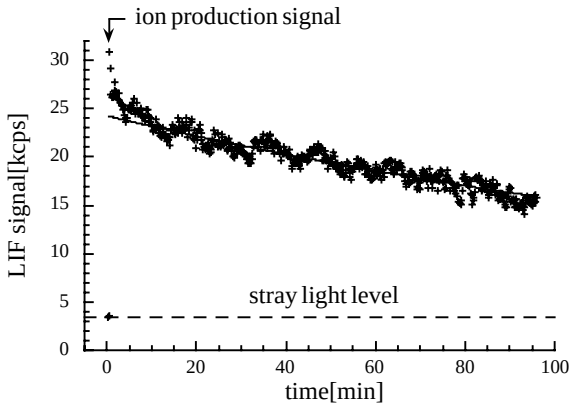

Fig. 3. Time spectrum of the fluorescence intensity from laser-cooled $^9Be^+$ ions in the cloud state under cryogenic, ultra high-vacuum conditions. The time constant of the decay curve is $\tau = 178(3)$ min. The laser power is 200 μW. $f_{rf} = 2.431$ MHz, $V_{ac} = 78\,V_{pp}$.

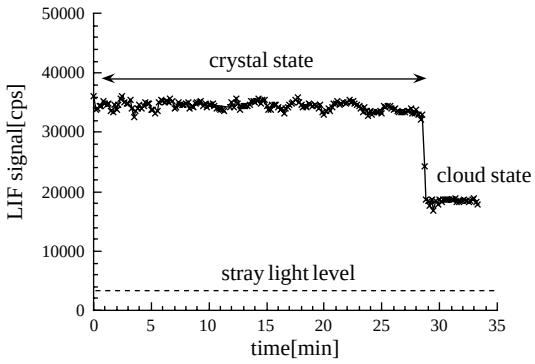

Fig. 4. Time spectrum of the fluorescence signal from laser-cooled crystallized Be^+ ions in the cryogenic linear ion trap. Parameters f_{rf} and V_{ac} are the same as those in Fig. 3.

state was maintained for about 30 min without any ion loss. The sudden decrease in fluorescence intensity was caused by a phase transition from the crystal to the cloud state. After retuning, the crystal reappeared. One possible reason for this undesirable phase transition was a small drift or a mode hop of the laser frequency.

Our experiments have shown the usefulness of a cryogenic linear rf ion trap for the minimization of ion loss and for long-term confinement of light Be^+ ions. Most of the ion-loss problems in ion trap experiments can be solved by using a cryogenic ion trap even if the buffer gas method is employed simultaneously. Such a cryogenic trap should also be useful for the accumulation of unstable isotope ions.

We would like to thank the staff of the Techno-Center of Sophia University for fabricating our linear ion trap. This work was supported by Grants-in-Aid for Encouragement of Young Scientists and for Scientific Research from the Ministry of Education, Culture, Sports, Science and Technology, and President's Special Grant of RIKEN.

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