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# Laser cooling and trapping of Ne metastable atoms

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A neon atomic beam in the metastable state $1s_5$ has been decelerated and trapped, by the spontaneous light force of a resonant laser in a quadrupole magnetic field. Trapping has been achieved in all isotopes $^{20}Ne$, $^{21}Ne$, and $^{22}Ne$ using a sample with natural abundance. For $^{20}Ne$, approximately $4\times10^7$ atoms are trapped.

In this Rapid Communication we report the first observation of the laser trapping of atomic species in the metastable state high above the ground state. The laser cooling and trapping of alkali metals, especially of sodium, have been studied extensively. The sodium beam has been decelerated and stopped by frequency chirping of the laser,[1–3] or by spatially varying Zeeman tuning.[4–6] Sodium atoms have been trapped at a minimum of Zeeman potential,[7,8] by the dipole force of the laser[9] and also by combinations of spontaneous light force, dipole force, and Zeeman field.[10,11] A temperature as low as 43 $\mu$K has been observed[12] in "molasses."[13] Collision mechanisms to limit the maximum density in the trap have been studied.[11,14] For atoms other than alkali metals few reports have been published.[15–17] Because of the unique characteristics of the laser-cooled atomic gas, it is of great interest to extend this technique to other atomic species.

Laser cooling usually requires an excited state with a large transition moment between the ground state in the wavelength region accessible by continuous coherent sources. Alkaline-earth, some group-III, and transition metals have such a transition. For rare gases and atoms on the right side of the Periodic Table, the lowest excited state is too energetic to be pumped by presently available continuous lasers. However, rare gases have a metastable state which can serve as the lower level of the cooling transition. We have demonstrated such a laser cooling scheme using Ne $1s_5$-$2p_9$ transition at 640 nm.[15] We show in this report an efficient trapping of a $1s_5$ metastable neon beam by combining the Zeeman-tuned deceleration stage and the Zeeman-field-assisted spontaneous-light-force trap.[10]

Figure 1 shows the experimental setup. The metastable neon source and the deceleration stage are essentially the same as the apparatus we have used for the previous cooling experiment.[15] Metastable atoms were generated by a weak dc discharge and extracted from a hole on the anode. The neon beam traveled approximately 60 cm, then entered the Doppler-tuning magnet with a length of 65 cm and a bore radius of 83 mm. The field intensity increased rapidly to the maximum value at approximately 10 cm from the entrance, and then decreased gradually towards the exit. The typical field intensity was 50 mT at its maximum. Then the neon beam passed through the extraction coil that was made of a single-layer coil of copper tube 35 mm in diameter and 20 cm long. Its field intensity was typically 10 mT. The second coil of the same structure with the opposite field direction was placed 35 mm further downstream of the neon beam to produce a zero-field point $Z$. The function of those coils was to guide all atoms decelerated in the Doppler-tuning magnet into the trap formed at $Z$. The first coil maintained the atomic velocity approximately constant to avoid loss due to transverse heating. The final stage of deceleration was done in the 18-mm gap between the first coil and $Z$.

The cooling laser beam was sent counter propagating against the neon beam. It was circularly polarized to induce $\Delta M=+1$ transitions. We used the same laser beam as a part of the longitudinal trapping laser. For this purpose the cooling beam was reflected back towards $Z$ using a reflector composed of a 90° quartz retardation plate with a 100% reflective coating on the backside. This reversed the polarization of the reflect beam. Two configurations were tried. In the first case, the reflector ($M_1$) was placed close to the neon beam source, approximately 35 cm upstream from the entrance of the magnet as shown in Fig. 1. The laser was sent slightly off axis and focused on the reflector. The beam diameter at $Z$ was approximately 1 cm. In the second configuration, two reflectors with the same structure were placed at the entrance of the extraction coil inside the magnet bore. A

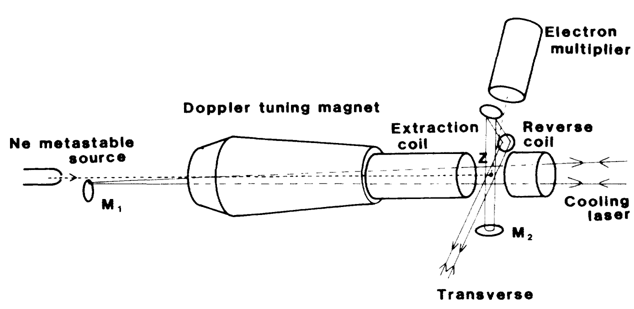


FIG. 1. Experimental configuration. $Z$ is the zero magnetic-field point, and $M_1$ and $M_2$ are the polarization reversing mirrors consisting of a $\frac{1}{4}$ wave plate with 100% reflection coating on the backside.

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part of the incoming laser beam was intercepted and reflected towards $Z$. In the first configuration the existence of an oppositely polarized copropagating laser in the Doppler tuning magnet modifies the deceleration process. While the incident laser pumps the atomic population to the maximum $M=2$ level and decelerates continuously along the magnet, the reflected beam pumps them to lower $M$ levels and throws outside the resonance by acceleration. The result of our numerical simulation shows that half of the atoms remain at $M=2$ level and are cooled, while the other half is lost, when the detuning of the laser frequency is small. Experimentally, both configurations worked as a trap. The second configuration was found more difficult to operate. The following data were taken with the first configuration.

Two orthogonal sets of standing waves for the transverse trapping were prepared using two dielectric mirrors and a polarization reversing mirror similar to $M_1$ as shown in the figure. The input beam was circularly polarized and was approximately 1 cm in diameter.

Trapping was monitored visually from the side window of the vacuum chamber and recorded on a video tape. Additional data were obtained from the electron multiplier placed 10 cm to the side of the trapping position. Since metastable neon atoms eventually collide with residual gas atoms, and then ionize them, the ion count received by the multiplier is proportional to the number of metastable atoms in the observation region. To detect only positive ions, a negative voltage of several hundred volts was applied to a mesh in front of the multiplier. When the trapping was observed visually, the count was found to burst up to 1000 times the untrapped situation.

The trapping was observed with several different laser configurations. In the standard arrangement for $^{20}$Ne trapping, the transverse and longitudinal confinements were achieved by two independent lasers. Their frequency was tuned slightly below the $1s_5$-$2p_9$ resonance, and the optimum condition was searched by adjusting the laser-beam angle, polarization, and magnetic field. The trapping was observed at a rather surprisingly wide range of condition. Figure 2 shows the ion-current intensity as a function of laser detuning when the transverse and longitudinal lasers are scanned independently. The capture range exceeds 50 MHz for the detuning of each laser. This was more than six times the full-half natural linewidth.[18] The spatial pattern of the trapped atoms varied widely depending on the laser frequency. On the best condition it was a spot with a diameter of slightly less than 1 mm. When the detuning was large the trapping size was generally larger and often showed a complicated pattern. The maximum number of atoms was approximately $4\times10^7$, which was determined from the fluorescence intensity at the trap. The maximum ion count rate of the electron multiplier was $6\times10^6\ \mathrm{s}^{-1}$. This means that the deexcitation of the metastable neon has a high ionization rate. The average trapping time was measured by gating the neon beam source, and by measuring the rise and fall times of the ion count. Both measurements gave approximately 0.15 s, which was limited by the collision with the residual gas. The background gas pressure was approximately $1\times10^{-7}$ Torr. Although we did not measure the flux of the metastable beam, the fraction of the trapped metastable atom can be roughly estimated from the background ion count, which results from the deexcitation of metastable atoms in the 4-cm observation range of the multiplier. The probability of the deexcitation at that distance is $\sim2\times10^{-4}$, determined from the measured pressure dependence of the quenching rate of the metastable state. Comparing this with the background-to-trap ion-count ratio of $10^{-3}$, the capture probability of the metastable atoms is 20% even without the correction for the solid angle. This verifies a very high efficiency of the present trapping configuration.

The characteristics of the trapping were also affected by the laser polarization, direction, and the magnetic-field intensity. The result shows that this trap is very stable against various parameter changes and sometimes works even in an unexpected condition. This scheme seems to be able to find new effective potential minimums against various modifications from the standard configuration. The allowance on the laser polarization was broad. The quarter-wave plate inserted in the trapping-laser passes could be rotated up to $\pm20°$ for the transverse direction, and $\pm30°$ for the longitudinal direction. They correspond to the intensity ratio of two circularly polarized lights of $I_-/I_+=0.13$ and 0.33, respectively. A weak trapping was found even without the transverse trapping laser. The trap size was large ($\sim1$ cm), and this trap was

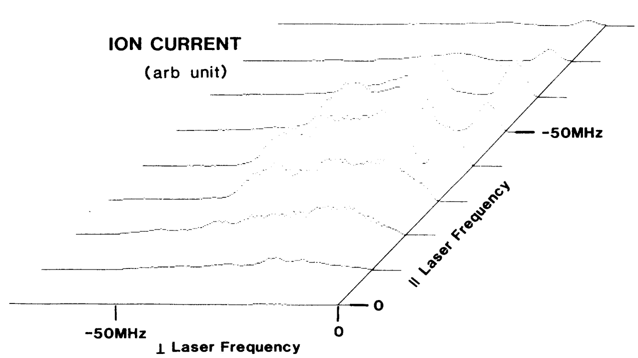


FIG. 2. Ion current vs laser detunings to measure the capture range of the trap.

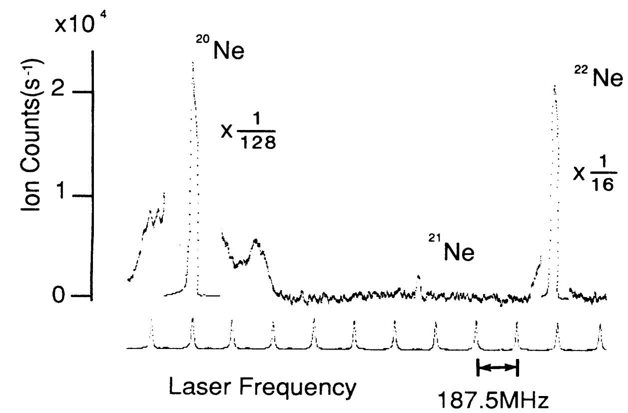


FIG. 3. Ion-current spectrum to demonstrate the trapping of three isotopes $^{20}$Ne, $^{21}$Ne, and $^{22}$Ne.

probably the magnetic trap demonstrated by Migdall *et al.* for Na.[7] Another configuration we found was the trap without the reverse field. By adjusting the direction of the longitudinal trapping laser we could form a bright spot outside the extraction coil.

In order to trap other isotopes, a single laser output was split into transverse and longitudinal beams, and its frequency was scanned. In addition, a laser field at the $F=\frac{5}{2}\rightarrow F'=\frac{7}{2}$ of $^{21}$Ne transition[19] and a weak field in the middle of closely spaced $F=\frac{1}{2}\rightarrow F'=\frac{3}{2}$ and $F=\frac{3}{2}\rightarrow F'=\frac{5}{2}$ transitions were prepared using a second laser and two acousto-optic modulators. They were mixed with the main laser through the beam splitter which separated the longitudinal and transverse beams. The intensity of the main laser was typically 100 and 50 mW for longitudinal and transverse lasers, respectively. Figure 3 shows the ion count spectrum. Visual patterns of $^{20}$Ne and $^{22}$Ne trappings were similar, and their intensity ratio was approximately 10 to 1, reflecting the abundance ratio. The trapping of $^{21}$Ne was observed at the $F=\frac{7}{2}\rightarrow F'=\frac{9}{2}$ transition frequency only when the second laser was on. The intensity of $^{21}$Ne signal was $\frac{1}{200}$ of that of $^{22}$Ne, whereas the abundance ratio was 1 to 34. The hyperfine splittings of $^{21}$Ne is of the same magnitude as the Doppler shift, and its Zeeman spectrum shows a complicated pattern. Therefore, the laser cooling by Zeeman tuning for $^{21}$Ne is not necessarily guaranteed. The present result indicates that $^{21}$Ne can be trapped in large quantity by Zeeman tuning if the vacuum or the intensity of the metastable source is improved.

In conclusion, we have demonstrated for the first time the laser trapping of metastable atoms with a high efficiency using the trap developed by Raab *et al.* for Na.[10] This result opens up the possibility for many applications of this technique for various kinds of atoms. The trapping of $^{21}$Ne has another interesting aspect because this is the first demonstration of the laser trapping of fermionlike particles. When a sufficient number of $^{21}$Ne are trapped so that $^{21}$Ne-$^{21}$Ne interaction becomes dominant, their collision characteristics may be found drastically different from the observation of Na trapping.[13]

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