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Generation of an Intense Low-Velocity Metastable-Neon Atomic Beam

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Abstract. A metastable neon ($1S_5$) atomic beam with a velocity of 394 m/s (373 K) and an intensity of $1.1 \times 10^{15}\,s^{-1}\,sr^{-1}$ is produced with a novel construction using a dc glow discharge.

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Metastable atomic beams have been used in various research works as a source of neutral particles having well defined high internal energy which is released at various kinds of targets through the Penning ionization process [1, 2]. High detection efficiency of metastable rare-gas atoms is also an attractive feature in many experiments. Recently metastable rare-gas beams were used in laser cooling [3], interferometry [4] and atom optics [5]. In these experiments, reduction of the atomic velocity is important to increase the manoeuverability of atoms because the kinetic energy is proportional to the square of atomic velocity.

1 Concept and Design

The standard technique to produce a high intensity metastable beam is electron-impact excitation of a supersonic ground state atomic beam [6, 7]. A magnetic field is applied to increase the mean free path of electrons in the interaction area, thus to increase the efficiency of excitation. More recently a glow discharge between the nozzle and the skimmer is preferred, because this is easier to implement and yet produces a metastable beam with higher intensity [8]. Although the second method is simpler, it tends to heat the atomic beam due to the discharge.

Our new technique tries to minimize this heating of translational motion of atoms by spatially separating the discharge and excitation region.

Figure 1 shows the arrangement of our source. Neon atoms flew toward the nozzle through a narrow gap between a pyrex glass tube and a liquid nitrogen cooler. The nozzle was a pinhole of 0.5 mm in diameter in a 1 mm thick aluminum plate. The glass tube had an opening of 1.5 mm in diameter. The gap between the nitrogen cooler and the glass tube was further narrowed near the nozzle with a teflon spacer. The atoms were released into the small space behind the nozzle. A part of the cooled atoms flew into the pyrex glass tube and the rest was released into the vacuum chamber through the nozzle. A dc glow discharge was produced between a cathode of tungsten wire of 0.8 mm in diameter inside the glass tube and the nozzle. The atoms

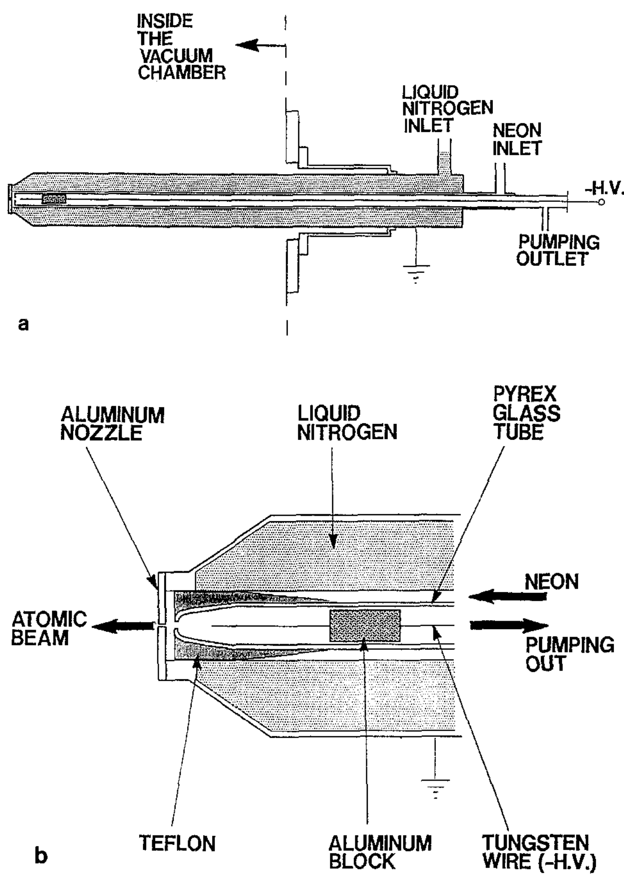
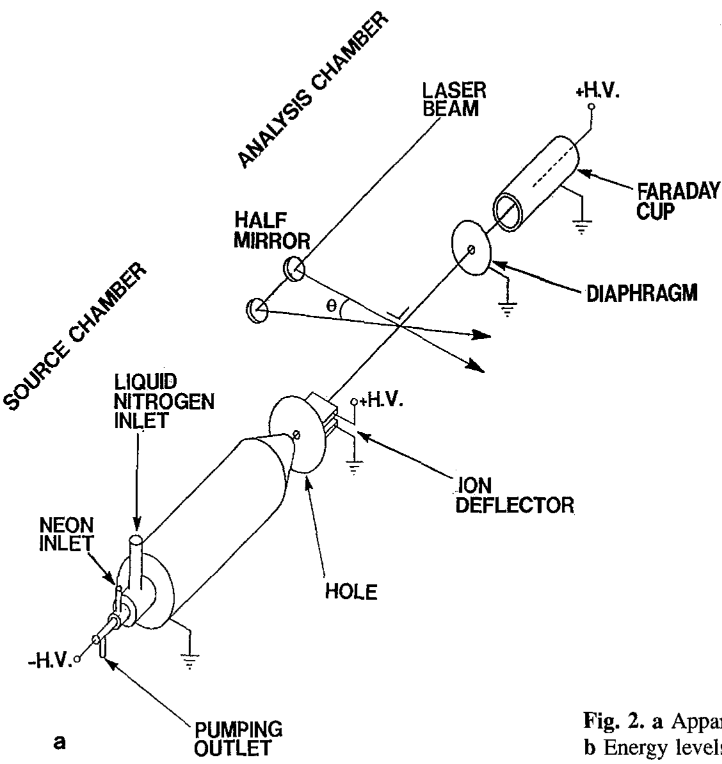


Fig. 1. **a** Schematic of the metastable-neon source. **b** Details of the tip of the source



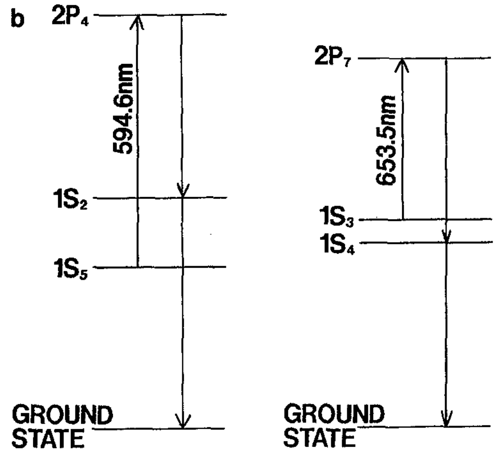


Fig. 2. a Apparatus for measuring the intensity and the velocity of the neon beam. **b** Energy levels relevant to the measurement

inside the glass tube were pumped from the other end of the tube with a rotary pump. Its pumping speed was adjusted to obtain optimum discharge conditions. The diameter of the glass tube and the inner diameter of the liquid nitrogen cooler were 12 mm and 14 mm, respectively. The width of the small space between the aluminum nozzle and the teflon spacer was 1.5 mm. The discharge inside the glass tube produced metastable neon atoms, neon ions and electrons. Neutral and ionized neon atoms were pulled toward the pump, but electrons are pulled toward the anode (nozzle) and pass through the hole of the glass tube. They excited atoms behind the nozzle, which flew through the nozzle without passing the main discharge region. Therefore, the heating of the atoms was kept minimal.

The atomic beam was led from the source chamber into the analysis chamber through a hole with a diameter of 3.0 mm. The pressure (P_S) in the source chamber was kept below 4×10^{-4} Torr during operation. The neon pressure at the inlet was between 0 Torr and 100 Torr. Typical discharge voltage was 500 V and its current was varied between 0 mA and 16 mA.

2 Intensity and Velocity Measurement

The schematics of the intensity and velocity measurement are shown in Fig. 2a. The atomic beam hit a Faraday cup made of stainless steel, while ions and electrons were removed by an ion deflector. The atomic beam, after the deflector, consisted mainly of $1S_3$ and $1S_5$ metastable neon atoms. The atomic beam was intersected by two laser beams before it reached the Faraday cup. One beam was sent perpendicular to the atomic beam, and the other at an angle $\theta = 30°$.

The intensity of the metastable atoms was determined from the dip of the current through the Faraday cup when the perpendicular laser beam was at resonance (Fig. 3a). The wavelength of the laser was 594.6 nm for the measurement of $1S_5$ atoms, and 653.5 nm for $1S_3$ atoms. In each case, the metastable atoms were quenched by the resonant pumping

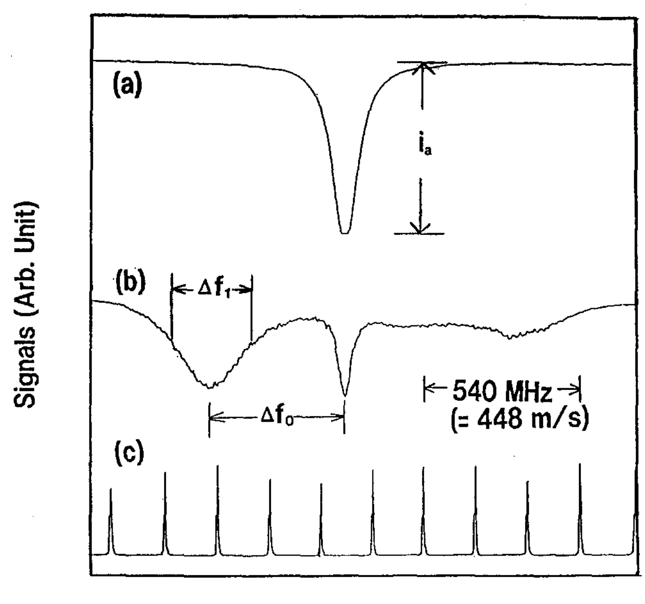


Fig. 3. a Current signal from the Faraday cup as a function of the laser frequency for the intensity measurement. **b** Current signal from the measurement of the velocity distribution. A small broad dip at the right-hand side of this curve is caused by the reflection of the laser inside the chamber. **c** Frequency marker of the scanning laser with a reference cavity of FSR = 180 MHz

to a higher $2P$ state. The flux intensity I_M of metastable atoms was determined from the dip of the current i_a

$$I_M = i_a/(\Delta\omega\eta e)\,, \tag{1}$$

where e is the electron charge, η the quantum efficiency of the Faraday cup and $\Delta\omega$ is the solid angle of the diaphragm in front of the Faraday cup. In the following discussion, $\eta = 0.61$, which was obtained by Dunning et al. [9] was used.

The velocity distribution was measured using the laser beam which crossed the neon beam at an angle $\theta = 30°$. The Doppler effect of the atomic velocity caused a shift of the dip spectrum by

$$\Delta f = V \cdot \sin\theta/\lambda\,, \tag{2}$$

where λ is the wavelength of the laser (Fig. 3b). The sharp peak caused by the perpendicular laser beam was used as a reference point of zero Doppler shift. The most probable velocity V_M was defined as the velocity corresponding to the peak f_0 of the spectrum in Fig. 3b. The width ΔV of the velocity distribution was defined as the width Δf_1 at the half maximum point of the spectrum.

Since the pressure behind the nozzle was difficult to measure, the pressure in the source chamber was used as a parameter, which was proportional to the nozzle pressure, in the following discussion.

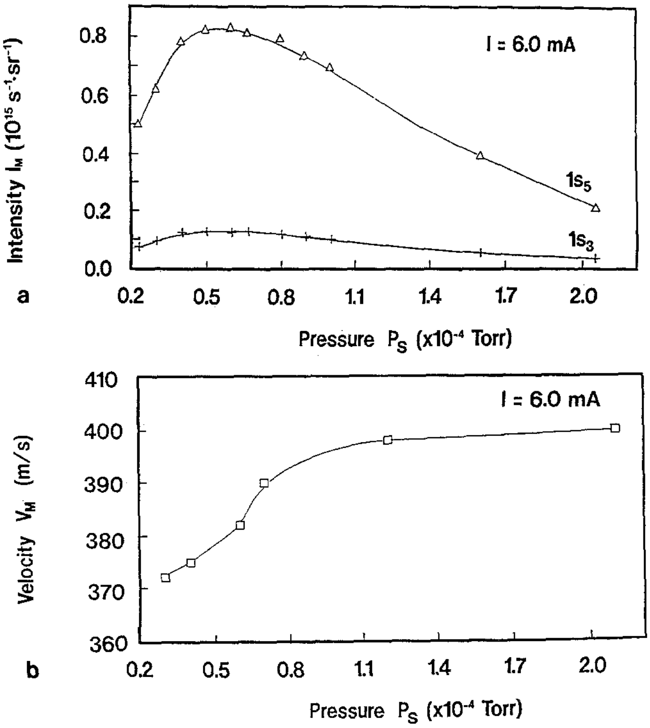


Fig. 4. **a** Intensity I_M of the neon beam as a function of the pressure P_S of the source chamber at $I = 6\,\text{mA}$; Δ: $1S_5$ state metastable neon; $+$: $1S_3$ state. **b** Translational velocity V_M of $1S_5$ metastable-state neon atoms as a function of P_S at $I = 6\,\text{mA}$

3 Results and Discussion

Figure 4a shows the beam intensity as a function of the pressure P_S in the source chamber at a discharge current of $I = 6\,\text{mA}$. The flux intensity was maximum at a pressure of approximately 6×10^{-5} Torr for any discharge current. The intensity ratio between the $1S_5$ and $1S_3$ atoms was approximately constant (6.5 : 1) at any pressure and discharge current. Figure 4b shows the most probable velocity V_M of $1S_5$ neon atoms as a function of P_S. The velocity curve rose rapidly with P_S at 6×10^{-5} Torr. The solid lines in Fig. 5 show V_M and I_M of $1S_5$ atoms as a function of the discharge current when the intensity was maximum at $P_S = 6.1 \times 10^{-5}$ Torr. With increasing discharge current, the velocity increased linearly with increasing flux intensity. We could obtain intensities higher than $1 \times 10^{15}\,\text{s}^{-1}\,\text{sr}^{-1}$ with velocities slower than 400 m/s, as shown in Fig. 5. The narrowest velocity width was $\Delta V = 170\,\text{m/s}$. We believe that the slow velocity and narrow velocity width was due to the pre-cooling with liquid nitrogen and the spatial separation of the discharge and excitation region. To test these effects, we repeated the experiment with different arrangements of the source.

First, the pumping direction of the neon was reversed so that atoms pass through the discharge region. The intensity was maximum at $P_S = 6.4 \times 10^{-5}$ Torr (broken lines in Fig. 5), and the velocity was almost 100 m/s faster than in the case of standard configuration. The width ΔV also increased to 290 m/s, while the intensity dropped to $I_M = 4.6 \times 10^{14}\,\text{s}^{-1}\,\text{sr}^{-1}$. Stopping the pumping inside the discharge tube in the standard configuration also resulted in a lower intensity (dot-dashed line in Fig. 5a). The above result clearly

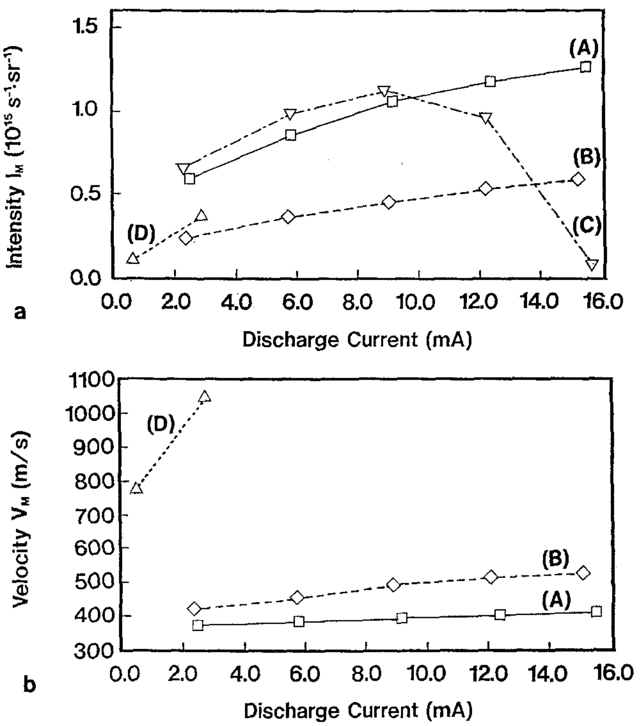


Fig. 5. **a** Intensity I_M of the $1S_5$ neon beam as a function of the discharge current. **b** Translational velocity V_M of a $1S_5$ neon beam as a function of the discharge current. *Solid line* (A): standard configuration ($P_S = 6.1 \times 10^{-5}$ Torr); *broken line* (B): direction of the neon flow reversed ($P_S = 6.4 \times 10^{-5}$ Torr); *dot-dashed line* (C): no pumping inside the pyrex-glass tube ($P_S = 4.0 \times 10^{-5}$ Torr); and *dotted line* (D): positive voltage applied to the tungsten wire with standard gas flow ($P_S = 8.0 \times 10^{-5}$ Torr). The pressure P_S was optimized for maximum intensity for each operating condition

shows the effect of heating of the atoms in the discharge region.

Secondly, the sign of the voltage supplied to the tungsten wire was reversed, that is, the tungsten wire served as anode. In this case, the intensity I_M decreased to below $3.8 \times 10^{14}\,s^{-1}\,sr^{-1}$, while the velocity V_M increased to above 800 m/s (1539 K) (dotted lines in Fig. 5). The velocity width ΔV was also broadened over 800 m/s. Electron recombination with ionized atoms is one of the important processes which produce metastable atoms. So ionized atoms must have been accelerated to the nozzle (cathode).

We usually operated this source at $I = 9\,mA$. At a higher discharge current $I = 16\,mA$, the tungsten cathode wore out after about 20 h of operation. By increasing the number of the tungsten wires to four, the lifetime of the cathode drastically improved without changing the atomic velocity and intensity as compared to the case of a single wire.

4 Conclusions

Our novel neon-beam source produces beams of metastable neon atoms with a low translational velocity, a narrow velocity-distribution width and a high intensity. These characteristics are preferable to the laser cooling of metastable neon atoms with the Zeeman tuning technique. The same technique can be applied to other rare gas metastable atoms.

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