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A bright metastable atom source at 80 K

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We describe a high flux source of cold (80 K) metastable helium atoms. The source employs a direct current nozzle discharge which produces in excess of 10^{15} atoms/steradian/s. Liquid nitrogen cooling of the discharge source yields atomic velocities below 900 ms^{-1} . Such a source has practical applications for experiments concerned with laser cooling and trapping of metastable helium atoms. © 2001 American Institute of Physics. [DOI: 10.1063/1.1372169]

I. INTRODUCTION

Recently, substantial interest has developed in the laser cooling and trapping of metastable noble gas atoms.¹ To achieve high metastable atom fluxes, the metastables are often generated in a direct current (dc) discharge that runs through a (mildly) supersonic gas expansion. However, even in the most efficient metastable atom sources, excitation fractions in the metastable state are usually very small (typically 10^{-4} – 10^{-5}).² For the lighter noble gas species, the atom source can also be cooled with liquid nitrogen,³ or for helium, with liquid helium,⁴ but at the further expense of atomic beam flux. A low temperature source is important as the cooling and stopping distances of neutral atoms are proportional to the source temperature. Hence, a reduction of the source temperature by a factor of 4, from room temperature to liquid nitrogen temperatures, immediately leads to a more compact apparatus. At the same beam flux, the atomic density is also increased by cooling the source.

For many applications, a large beam flux, as well as low source temperatures, are equally important. Here we will review some of the alternatives for creating a liquid nitrogen (LN_2) cooled metastable atom source, and describe the metastable atom source that is currently in use by us. This source provides reliable operation at very high beam fluxes, with the temperature of the generated metastable atomic beam close to liquid nitrogen temperature.

The LN_2 cooled metastable atom source has three functions:

- (1) to cool the gas down to LN_2 temperatures;
- (2) to excite the largest possible fraction of the gas to the metastable state; and
- (3) to form an atomic beam in a high vacuum environment.

One way to realize this is to create a cold atomic beam by expansion from a cooled nozzle source, and subsequently exciting the atoms to the metastable state using electron bombardment by an electron beam, as described in Ref. 5. An advantage of this method is that high pressures can be used for the gas expansion, and hence, the atomic beam can

be supersonically cooled to yield a narrow longitudinal and transverse velocity distribution. A disadvantage of this technique is that the metastable state fraction of the resulting beam is generally quite low (on the order of 10^{-7}).⁵

To obtain higher metastable beam fluxes, a dc discharge is often used in a gas expansion. This is the type of source used here, where the typical discharge current is a few milliamperes. The discharge can be drawn to an external anode, or the expansion nozzle can be used as the anode. The metastable atoms are now formed in the afterglow of the discharge. This is important as it ensures that many metastables are formed in the expanding, collision-free region outside the nozzle, after which they are less likely to suffer collisional de-excitation.⁶

A major design concern for a cold source is to remove the heat generated by this discharge as efficiently as possible. The most critical part of the source to keep cold is the expansion nozzle, as this is often the last surface that the atoms interact with before leaving the source. However, the discharge runs either to or through this nozzle plate, so that part of the afterglow of the discharge is in the low pressure region of the vacuum system. Hence, this part is strongly susceptible to heating, and it is advantageous for the nozzle to be manufactured from a good thermal conductor, such as a metal. Several groups have reported the use of a stainless steel nozzle plate, employing the nozzle plate as the discharge anode, and using the afterglow of the discharge in the low pressure area to generate the atomic beam.³ This technique depends very strongly on the exact shape and finish of the nozzle plate, indeed, some sharp edges near the nozzle orifice are essential to extend the afterglow to the low pressure region.

For the discharge to run through the nozzle, a metallic nozzle material is undesirable. The material most often used for the nozzle plate in this configuration is the ceramic boron nitride, which is a reasonable thermal conductor (thermal conductivity $\sim 30 \text{ W m}^{-1} \text{ K}^{-1}$) whilst still being an electric insulator. This is the technique used for the source described here, in which an anode is employed downstream of the nozzle (Fig. 1).

A major concern in obtaining a high metastable atom beam flux is the pumping speed from the area around the

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FIG. 1. Schematic diagram of the liquid nitrogen cooled, metastable helium source.

nozzle orifice. Hence, the cooling apparatus has to be kept as small as possible, so as not to limit the pumping speed from this region. Furthermore, the beam then has to be skimmed and differentially pumped.

II. SOURCE DESCRIPTION

Taking all this into consideration, at the Australian National University we constructed the metastable atom source illustrated in Fig. 1. It uses a dc discharge through the expansion nozzle, and liquid nitrogen cooling. Cooling is achieved with a coaxial, in-vacuum, stainless steel LN₂ reservoir, which surrounds the helium inlet line. The LN₂ reservoir is gravity fed from a large (~ 5 l) external Dewar.

The cathode of the discharge is contained in a glass tube that can be pumped by an additional rotary pump to remove the hot gas around the cathode.³ The cathode consists of a tungsten needle, as shown in Fig. 1. Its surface area can be increased by adding a nickel foil around the needle. During standard operation, the cathode is held at -400 V with respect to ground. Breakdown to the metal LN₂ reservoir, which is necessarily at ground potential, is prevented by a Macor sheath, in which a long spiral channel has been machined in the gas inlet path. This increases the path length to ground, and increases the surface area in contact with the LN₂ cooled jacket.

The anode is formed by a stainless steel ring, 5 mm from the nozzle, and is kept at $+400$ V. The discharge current is about 2 mA. To start the discharge, a -5 kV start pulse, with a duration of ~ 1 s, is added to the cathode voltage, and the source is allowed to run at a higher current (10 mA) for a few minutes. Then, to reduce the temperature, the current is reduced to its operational value. The source pressure at typical operating conditions is ~ 35 mbar, and the nozzle has a diameter of $300\text{ }\mu\text{m}$. This combination has been found to yield the lowest temperatures and axial velocities.

The source chamber is pumped by a 2000 l s^{-1} diffusion pump with a LN₂ cooled baffle (Varian type 184). The background helium pressure during operation is $\sim 10^{-5}$ mbar. The metastable beam then passes through a skimmer, located 5–10 mm from the nozzle, into the differentially pumped collimation chamber.

FIG. 2. Source intensity as a function of discharge current at a constant inlet pressure (30 mbar). The contribution to the detector current due to UV emission from the discharge has been subtracted.

III. SOURCE CHARACTERIZATION

The metastable atom beam flux obtained in typical conditions is $\sim 5 \times 10^{14}\text{ sr}^{-1}\text{ s}^{-1}$, at a temperature of 80 K. The average beam velocity is then $\sim 900\text{ ms}^{-1}$, with a spread of about $\sim 240\text{ ms}^{-1}$. However, the source can yield in excess of $10^{15}\text{ sr}^{-1}\text{ s}^{-1}$ when run at a higher (10 mA) discharge current and a higher pressure (100 mbar), but with higher average velocities ($>1100\text{ ms}^{-1}$). In Fig. 2 the measured beam intensity is displayed as a function of the discharge current at a constant pressure (30 mbar).

To determine the effective source temperature, a time-of-flight experiment is performed, as illustrated in Fig. 3. The atomic beam is chopped by an *in vacuo* mechanical chopper, with a slit width of 1 mm. The chopper wheel has a diameter of 100 mm and is driven by an inexpensive dc motor. It spins at about 50 revolutions/s. The atoms are detected using a channeltron electron multiplier, 400 mm downstream of the chopper, and the time-of-flight (TOF) distribution is recorded on a TRACOR TN7200 multichannel analyzer. The spectrum obtained, as shown in the top half of Fig. 4, contains two signal peaks: an instantaneous peak due to ultraviolet (UV) photons from the discharge and the atom peak, which occurs at a later time. The former is used to determine the zero of the time scale (t_0).

FIG. 3. Schematic of the apparatus used for the time-of-flight measurements. The flight length between the chopper and the detector is 380 mm. The chopper slit is ~ 1 mm wide, and the chopper disk is 100 mm diameter and rotates at ~ 50 Hz.

FIG. 4. A typical time-of-flight measurement (top). The left peak is due to photons generated in the discharge, that are also detected, and serve as a calibration of zero flight time. The right peak is caused by metastable atoms. The derived velocity distribution (bottom) indicates a source temperature of ~ 80 K.

A simple transformation $v = L_{\text{TOF}}/(t - t_0)$ then yields the velocity distribution (bottom half of Fig. 4), where L_{TOF} is the flight length. Also indicated in the figure is the capture velocity of the Zeeman slower used in our “bright beam” facility, which will be described elsewhere. As the slowing distance is proportional to the velocity squared, it is important to minimize the source velocity for such applications.

The velocity distribution is then least-squares fitted to a standard, displaced Gaussian, with an average velocity $\langle v \rangle$ and a spread u , as is usually obtained from a supersonic beam source.⁷ To obtain a better fit with the TOF data, this function is modified with a series of Hermite polynomials H_i as follows:

$$P(v) dv = A v \exp \left[-\frac{(v - \langle v \rangle)^2}{u} \right] \times \left[1 + \sum_{i=3}^N c_i H_i(v - \langle v \rangle) \right] dv. \quad (1)$$

The source temperature can then be extracted from⁷

$$\frac{5}{2} k_B T_{\text{source}} = \frac{3}{4} m u^2 + \frac{1}{2} m \langle v \rangle^2. \quad (2)$$

Deviations from the Gaussian velocity distribution is attributed to nonadiabatic effects in the expansion. However, at this stage no physical model is available to relate to the coefficients c_i .

In Fig. 5 the reservoir temperature as determined from the TOF measurements is shown as a function of both the discharge current and the helium inlet pressure. At low pressure (~ 30 mbar) and low discharge current (~ 2 mA) the

FIG. 5. The source temperature as a function of the driving pressure and the discharge current.

source temperature approaches the liquid nitrogen temperature. The average velocity $\langle v \rangle$ is then about 900 ms^{-1} . No further temperature reduction was found by pumping on the cathode region of the source to remove the hotter gas around the cathode. Consequently, this feature is not used at present.

A major issue when trying to achieve low source temperatures is the size of the nozzle orifice. A small size orifice seems beneficial at first, as, at a given pumping speed, the driving pressure can be higher, proportional to the area of the orifice. A more supersonic, and hence, narrower, velocity distribution may thus be obtained. However, experimentally we find that the achievable temperature is much lower for a large orifice size ($T \approx 80$ K for a $350 \mu\text{m}$ diameter orifice) than for a small orifice size ($T \approx 110$ K for a $100 \mu\text{m}$ diameter orifice). As can be seen from Fig. 5, the temperature also increases with increasing drive pressure. We believe that this is the main reason for the success of the source used in Refs. 3 and 14, which uses a very large orifice ($\sim 500 \mu\text{m}$) and reduces the drive pressure with additional pumping.

IV. DISCUSSION

A comparison of the performance of the present source and the other sources can be seen in Fig. 6. Here the meta-

FIG. 6. Comparison between our source and the metastable helium sources described in the numbered references (Refs. 8–14). Lines linking data points indicate the range of conditions achieved.

stable helium output (atoms/second/steradian) is plotted as a function of average atomic velocity. As can be seen, the present source produces the highest output at the lowest (liquid nitrogen) temperatures (80 K), yielding an average velocity $<900 \text{ ms}^{-1}$, which is important for laser cooling and trapping applications.

In summary, we demonstrate the operation of a highly efficient, liquid nitrogen cooled metastable atom source. The measured reservoir temperature approaches liquid nitrogen temperatures at low dc discharge currents. The source offers consistent and reliable operation and high metastable atom yields.

¹P. J. J. Tol, N. Herschbach, E. A. Hessels, W. Hogervorst, and W. Vassen, *Phys. Rev. A* **60**, R761 (1999).

²H. J. Metcalf and P. van der Straten, *Laser Cooling and Trapping* (Springer, New York, 1999), p. 43.

³J. Kawanaka, M. Hagiuda, K. Shimizu, F. Shimizu, and H. Takuma, *Appl. Phys. B: Photophys. Laser Chem.* **56**, 21 (1993).

⁴P. van der Straten (private communication).

⁵O. Carnal, M. Sigel, T. Sleator, H. Takuma, and J. Mlynek, *Phys. Rev. Lett.* **67**, 3231 (1991).

⁶K. G. H. Baldwin, R. P. Swift, and R. O. Watts, *Rev. Sci. Instrum.* **58**, 812 (1987).

⁷M. D. Morse, in *Atomic, Molecular, and Optical Physics: Atoms and Molecules*, edited by F. B. Dunning and R. G. Hulet (Academic, New York, 1996).

⁸D. W. Fahey, W. F. Parks, and L. D. Scheerer, *J. Phys. E* **13**, 381 (1980).

⁹K. Ohno, T. Takami, K. Mitsuke, and T. Ishida, *J. Chem. Phys.* **94**, 2675 (1991).

¹⁰N. Vansteenkiste, C. Gerz, R. Kaiser, L. Hollberg, C. Salomon, and A. Aspect, *J. Phys. II* **1**, 1407 (1991).

¹¹O. Carnal, M. Sigel, T. Sleator, H. Takuma, and J. Mlynek, *Phys. Rev. Lett.* **67**, 3231 (1991).

¹²M. Doery, M. Widmer, J. Bellanca, E. Vredenbrecht, T. Bergeman, and H. Metcalf, *Phys. Rev. Lett.* **72**, 2546 (1994).

¹³W. Rooijackers, W. Hogervorst, and W. Vassen, *Opt. Commun.* **123**, 321 (1996).

¹⁴H. C. Mastwijk, M. van Rijnbach, J. W. Thomsen, P. Van der Straten, and A. Niehaus, *Eur. Phys. J. D* **4**, 131 (1998).