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Citation: [Review of Scientific Instruments](#) **71**, 3342 (2000); doi: 10.1063/1.1288261

View online: <http://dx.doi.org/10.1063/1.1288261>

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Candlestick rubidium beam source

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(Received 15 March 2000; accepted for publication 9 June 2000)

We describe a long-lived, bright and intense rubidium atomic beam source based on a previously published recirculating candlestick design for sodium, with several modifications and enhancements. The device operates for thousands of hours without maintenance, with brightness of $1.9 \times 10^{22} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$. © 2000 American Institute of Physics. [S0034-6748(00)05009-7]

I. INTRODUCTION

Many atomic physics laboratories rely on beams of alkali atoms for their experiments, for example in the atom optics and laser cooling communities. Rubidium is commonly used, due to the fortunate coincidence of the dipole resonant transition with the optimum output wavelength of low-cost AlGaAs semiconductor lasers.¹ Suitable rubidium beams can easily be produced with effusive ovens, but many experiments require high flux, and with conventional sources this leads to short lifetimes. Recharging of alkali ovens is messy, time consuming, and often dangerous.

Recirculating designs, which use some mechanism to recycle those atoms not emitted in the desired beam, have been published for other alkalis such as cesium² and sodium.³ More recently, Vestergaard Hau *et al.*⁴ have developed an elegant recirculating sodium design using capillary action, which they call a “candlestick.” It is compact, and provides high brightness, high flux, good energy efficiency, and long life. In this article we describe a version of the candlestick source developed for rubidium, with several modifications and enhancements, including a cooling system which is needed to maintain the required temperature gradient across the candlestick, improved heating elements, and details of the cleaning procedure and operating conditions which were critical to successful operation.

II. DESIGN

The oven is shown schematically in Fig. 1. It consists of a high-temperature emitting source called the candlestick, supplied with Rb via capillary action through a tightly wound stainless steel mesh “wick.” A copper crucible surrounds the candlestick, to collect most of the emitted Rb into a cool reservoir maintained at just above the Rb melting point. Additional wire mesh lining the crucible encourages migration of the collected Rb into the reservoir. A 1 mm diam aperture in the candlestick and another in the crucible, separated by 17.75 mm, allow a small fraction of the atoms to escape in a collimated Rb beam. For our experiments, we use an additional 1 mm aperture 30 cm from the candlestick.

The candlestick concept relies on a temperature gradient between the hot emissive region at the top of the candlestick

and the Rb reservoir. This gradient is maintained by heating the candlestick with a resistive heating element, and cooling the crucible. The crucible temperature is kept at 70–90 °C, well above the 40 °C melting point, to prevent clogging of the capillaries. Higher crucible temperatures are avoided, to minimize Rb loss, and to maintain a low vapor pressure in the reservoir to reduce contamination of the surrounding vacuum chamber. The candlestick temperature is varied, depending on the desired flux, in our case up to 200 °C.

With these temperatures we can estimate the required heating power needed in the candlestick heater and the cooling capacity for the reservoir. To maintain this temperature difference, the heat flow down the candlestick will be

$$\frac{\Delta Q}{\Delta t} = kA \frac{\Delta T}{\Delta l}, \quad (1)$$

where $\Delta Q/\Delta t$ is the energy per unit time, k is the thermal conductivity, A is the cross-sectional area, and $\Delta T/\Delta l$ is the temperature gradient along length Δl . For a maximum temperature difference of $200 - 70 = 130$ °C across a 6.35 mm diam stainless steel (where⁵ $k = 30 \text{ W m}^{-1} \text{ K}^{-1}$) candlestick of length 40 mm, the heat flow will be ≈ 3 W. Of course, the candlestick is only partly stainless steel; it also includes stainless steel mesh and liquid Rb, which may have higher or lower thermal conductivity depending on convection, capillary action, filling fraction, and other ill-determined parameters; in practice we have used up to 7 W.

To dissipate this heat from the reservoir and out of the vacuum chamber, Ref. 4 used a 6.35 mm copper rod. We use direct water cooling of the crucible to maintain the lower reservoir temperature needed for Rb. The water is supplied through a 3 mm nylon tube, coaxially inside a hollow copper feedthrough (MDC MMCT-150) of 6.35 mm outer diameter, and back around the nylon supply tube to a T piece where the supply and exhaust are separated. The copper tube is capped and soldered to the crucible with a silver–tin–copper alloy. A second heater was added around the crucible and connected to a temperature controller to improve the temperature stability.

The heating elements are type-*K* thermocouple wire, mineral insulated, and sheathed in stainless steel, with an overall diameter of 1.5 mm (Pyrotenax type 15 321K). This material is commonly used in large quantities industrially for temperature measurement in harsh environments, but also

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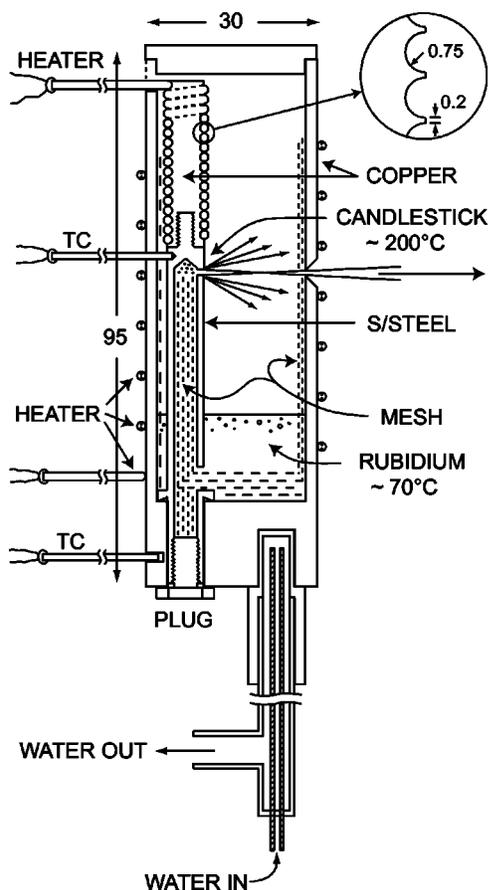


FIG. 1. Schematic of the rubidium oven (to scale). The candlestick and plug are made from 316 stainless steel, the crucible and candlestick heater form are copper. The capillary mesh is gold-plated 310 stainless steel, $40\ \mu\text{m}$ diam wire spaced at $0.1\ \text{mm}$. The heating elements and thermocouples (TCs) are stainless steel sheathed type-K thermocouples (diameter 1.5 and $1.0\ \text{mm}$, respectively). Dimensions are in millimeters.

works well for heating up to temperatures of $\approx 800\ ^\circ\text{C}$. We purchased ready-made thermocouples, with the sheath closed at one end, and with the two conductors welded inside the closed end. Low vapor pressure epoxy was used to seal the terminating end, which ordinarily remains cold. These heating elements have several advantages over the tungsten wire used by Ref. 4. They are much less brittle, and because they have two parallel conductors with opposing currents, magnetic fields are minimized, and it is unnecessary to use the oven itself as a conductor.

The candlestick was made in two parts, with a separate copper form at the top, cut with a spiral groove to accommodate the heater, as shown in Fig. 1. A knife edge seals against the bottom of the crucible to prevent leakage of the molten Rb around the outside of the candlestick.

The Rb delivery rate to the emission region, which must be sufficient to balance the emission rate from the candlestick, can be estimated following Ref. 4. For capillary height of $40\ \text{mm}$, Rb surface tension of $\xi = 0.084\ \text{N m}^{-1}$ and viscosity of $\mu = 5.0 \times 10^{-4}\ \text{Pa s}$, the delivery rate should be $\approx 1\ \text{kg/h}$, which is four orders of magnitude greater than the calculated emission rate (see Sec. III).

III. OPERATION

Before assembling the oven, all components were thoroughly cleaned in an ultrasonic bath in several stages: detergent and water, distilled water, acetone, isopropanol, and finally ethanol. This was insufficient to ensure good wetting of the Rb onto the mesh. As for sodium,⁴ surface oxides prevent good wetting at low temperatures, and so the mesh was commercially electroplated with nickel and gold. We found that the normal cleaning procedure used by commercial electroplating companies was insufficient to ensure reliable wetting of the final plated wick. Vigorous precleaning using the method described above, followed by commercial electroplating, and then postcleaning as above, was successful.

After the beam source was assembled, the oven was installed in the vacuum chamber, pumped down, and baked empty. The candlestick and the copper cavity temperatures were kept at 250 and $80\ ^\circ\text{C}$ for $2\ \text{h}$, then allowed to cool under vacuum.

The oven was then loaded with Rb inside an argon-filled plastic glove box constructed around the oven chamber loading port. A glass ampoule of Rb was broken, heated to $\approx 60\ ^\circ\text{C}$, and the liquid Rb poured into the oven cavity.

The vacuum system was pumped down and the whole oven heated to $82\ ^\circ\text{C}$ for $4\ \text{d}$ to allow for degassing and wetting. While maintaining the crucible at $82\ ^\circ\text{C}$, the candlestick temperature was increased to $150\ ^\circ\text{C}$ for $36\ \text{h}$, and then to $200\ ^\circ\text{C}$. Strong laser-induced fluorescence was observed within $12\ \text{h}$. The oven was left operating at these temperatures for $2\ \text{d}$ to ensure good wetting.

The candlestick heater current was typically $0.9\ \text{A}$ at $8\ \text{V}$ ($7\ \text{W}$), but about one third of the heating element is outside the oven and so the candlestick heating power is approximately $5\ \text{W}$. The cooling water flow was adjusted such that the cavity temperature stabilized at 80 – $90\ ^\circ\text{C}$, with a flow rate below $50\ \text{ml/min}$, and with the crucible heater running at $0.25\ \text{A}$ and $18\ \text{V}$ ($4\ \text{W}$). Under these conditions, the temperature was stabilized to $\pm 1\ ^\circ\text{C}$ over a few hours.

The oven has not been opened to atmosphere in over 18 months. It is frequently switched off, and gradually reheated when needed, first by heating the crucible until it is stable at $70\ ^\circ\text{C}$ for about $15\ \text{min}$, and then gradually heating the candlestick until fluorescence is observed ($\approx 1\ \text{h}$).

IV. CHARACTERISTICS

Absolute beam densities ρ were obtained as a function of the candlestick temperature by measuring the frequency dependence of laser absorption near resonance,⁷ at a distance of $35\ \text{cm}$ from the candlestick (Fig. 2). The absorption measurements detect only the ^{85}Rb isotope (72% abundance), and only those atoms in the $F=3$ ground state. The total Rb density as plotted is adjusted for this factor of 2.4 .

The atomic beam intensity I can be estimated from the density $I = \rho \bar{v}$, where \bar{v} is the mean velocity inside the source, $\bar{v} = \sqrt{8k_B T / M \pi}$, k_B is Boltzmann's constant, and M is the mass of a Rb atom. The intensity was insensitive to changes in the oven cavity temperature between 60 and $90\ ^\circ\text{C}$. For a candlestick temperature of $200\ ^\circ\text{C}$, the oven produced a beam with density of $(1.1 \pm 0.1) \times 10^{15}\ \text{m}^{-3}$ and

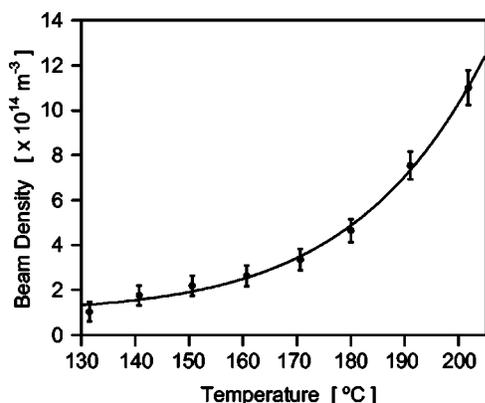


FIG. 2. Rubidium beam density measured by frequency-dependent laser absorption of the ^{85}Rb $F=3$ atoms (see Ref. 7) 35 cm from the candlestick, as a function of the candlestick temperature. The data have been scaled to account for isotopic abundance and atoms initially in the $F=2$ ground state. The solid line is a best fit to the experimental data, using $\rho \propto \exp(-\text{const}/T)/T$. The uncertainties are 1 sd, calculated from the uncertainty in measuring the fluorescence variation as the laser is swept across the resonance.

calculated intensity and brightness of $(3.8 \pm 0.3) \times 10^{17} \text{ m}^{-2} \text{ s}^{-1}$ and $(1.9 \pm 0.2) \times 10^{22} \text{ m}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$, 35 cm from the candlestick.

There is no indication that the oven is limited to this output, and both higher temperatures and larger output apertures could be expected to increase the final flux significantly.

Classical kinetic theory can be used to calculate the beam parameters for various temperatures.⁸ The vapor pressure p for liquid Rb is given by⁹ $\log p = 9.318 - (4040/T)$, where T is in Kelvin, and p is in Pascals. At 80 and 200 °C, $p = 7.5 \text{ mPa}$ and 6.0 Pa . At 200 °C, the on-axis intensity is $4.9 \times 10^{17} \text{ m}^{-2} \text{ s}^{-1}$ and the density is $\rho = 1.4 \times 10^{15} \text{ m}^{-3}$, at a distance of 35 cm. The small difference with respect to the measured beam density may be due to reduction of the effective aperture sizes from contamination or blocking with liquid Rb. Another group¹⁰ has constructed an almost iden-

tical oven for cesium, but found that enlargement of the candlestick exit aperture to 2 mm diameter was necessary to prevent clogging.

The total candlestick emission rate is given by $p\bar{v}A_S/(k_B T)$, and so at 200 °C the consumption of Rb is 0.03 g/h. The useable Rb charge would be depleted in a few days, but with recirculation only those atoms emitted into the solid angle of the exit beam (i.e., 1/100 sr) escape the crucible, and so the net consumption is approximately 50 $\mu\text{g/h}$ (2 yr per gram).

ACKNOWLEDGMENTS

The authors would like to thank M. M. Burns for detailed information on the original candlestick source, and T. R. Mackin for helpful discussions. They gratefully acknowledge the support of the Australian Research Council, and the Australian Postgraduate Research Awards scheme (MRW, PJF).

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