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Note: A 3D-printed alkali metal dispenser

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We demonstrate and characterize a source of Li atoms made from direct metal laser sintered titanium. The source's outgassing rate is measured to be $5(2) \times 10^{-7}$ Pa L s^{-1} at a temperature $T = 330\,^{\circ}$C, which optimizes the number of atoms loaded into a magneto-optical trap. The source loads $\approx 10^7$ ^{7}Li atoms in the trap in ≈ 1 s. The loaded source weighs 700 mg and is suitable for a number of deployable sensors based on cold atoms. https://doi.org/10.1063/1.5023906

Numerous emerging quantum technologies are being adapted from laboratory-scale experiments to deployable real-world sensors and space-based missions.[1–4] Cold atoms are at the heart of many of these applications, including interferometers[3] and ultra-precise atomic clocks.[5,6] Recently, we have begun a program to develop a device based on trapped cold atoms, which is simultaneously a primary standard and an absolute sensor of vacuum.[7,8]

Translating these cold atom-based technologies into deployable sensors requires an atomic source which is scalable, lightweight, and suitable for ultra-high vacuum (UHV, $<10^{-6}$ Pa). Miniature vapor cells are well suited for sensors using atoms which have substantial vapor pressure at room temperature (such as Rb).[9,10] However, many applications use atoms which must be heated to several hundred degrees Celsius to produce a substantial vapor pressure, including Li, Sr, and Yb.[2,5,6]

Several groups have reported direct loading of a magneto-optical trap (MOT) from effusive sources[2,11–13] such as ovens or alkali metal dispensers (AMDs). Some commercial AMDs are known to outgas at levels not suitable for ultra-high vacuum[12] when operating. This can be mitigated by including a reducing agent, but these typically limit the alkali yield to ≈ 10 mg. Alternatively, the small features and thin walls (for high electrical resistance) of an AMD makes additive manufacturing an attractive construction technique. Direct metal laser sintered (DMLS) titanium has recently been demonstrated to be low outgassing and suitable for in-vacuum components[14] and vacuum flanges[15] for ultimate pressures of $\lesssim 10^{-8}$ Pa.

In this note, we report on a lithium AMD made from DMLS grade 5 titanium (6% Al, 4% V by weight). The AMD holds ≈ 100 mg of Li and is used to directly load a MOT suitable for use in cold atom experiments. The measured outgassing rate is $5(2) \times 10^{-7}$ Pa L s^{-1} for optimal MOT loading conditions (uncertainties in this paper are the uncorrelated combination of 1σ statistical and systematic uncertainties), limited by contaminants outgassing from the loaded lithium metal.

Figure 1 shows the 3D-printed AMD which consists of two parts: a tube (5.1 mm diameter, 13.8 mm long, 0.13 mm wall) and a plug (1.2 mm thick) which snugly fits into the open end of the tube. Both the tube and plug have 0.25 mm thick, 5.1 mm wide tabs with a 2.4 mm diameter clearance hole for mounting and electrical connections. A 5.1 mm long, 0.25 mm wide slit in the tube directs the output of the (approximately) effusive source orthogonal to the plane of the tabs. The combined tube and plug have a measured mass of 584 (2) mg and a designed total surface area (not including surface roughness) of 6.8 cm^2.

The AMD is loaded with seven pellets of natural-isotopic-abundance metallic lithium, which we estimate to total 100 mg. The plug fits tightly into the tube to secure the Li. It is loaded and inserted into the vacuum chamber while under an argon-purged atmosphere. The vacuum chamber consists of a Kimball spherical cube[16] with four viewports around the equator for optical access. A four-way cross off the bottom connects the vacuum chamber to an ion pump, an ion gauge, and a viewport for optical access from below. The chamber is topped by a custom flange consisting of a viewport and high-conductivity Cu feedthroughs which hold and electrically connect the AMD. The six viewports' common axes define the MOT center, which is 35 mm from the AMD.

The AMD is resistively heated by a current of typically 10 A–15 A. Upon initial warm-up, the resistance of the AMD dropped by nearly a factor of two, presumably as the (relatively conductive) Li melted and came into better electrical contact with the tube. We therefore characterize the AMD in terms of the power P dissipated across the AMD. With subsequent operations, we have noticed further decreases in the
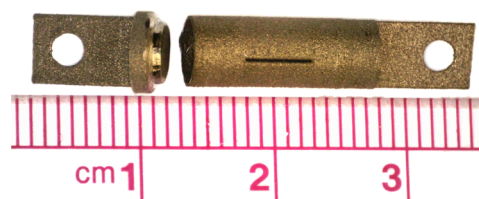

FIG. 1. Photograph of the 3D-printed titanium cap (left) and tube (right).

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AMD resistance at the 1% level and noticed a small accumulation of Li outside the slit of the tube. A thin Ni mesh inside the tube could be used to wick the Li in a future design.[17]

A laser beam counterpropagating to the Li emerging from the source allows the temperature T of the Li to be determined spectroscopically. We monitor the laser induced fluorescence collected on a charge-coupled device (CCD) camera from a spatial region along the laser beam. The frequency-dependent fluorescence is fit to a Maxwell-Boltzmann distribution for a 1D beam. The temperature was measured for a number of dissipated powers P. In thermal equilibrium, the power dissipated is equal to the thermal power transported away from the source by conductive and radiative processes, $P = a(T - T_r) + b(T^4 - T_r^4)$, where $T_r = 20(1)\,°C$ is the measured room temperature and a and b are fit coefficients. In the experiments discussed below, the power P was measured and the AMD temperatures were inferred from the best fit to the empirical model.

All stainless steel components of the vacuum chamber were baked at 450 °C for 21 days prior to assembly to reduce hydrogen outgassing.[18,19] All vacuum components, including the 3D-printed titanium AMD, were cleaned in alkaline detergent, followed by acetone and then ethanol. No cleaning procedure was performed on the Li beyond selecting pellets with minimal black nitride coating.

The chamber was pumped by using an ion pump (nominal pumping speed $S = 50\,L\,s^{-1}$ for N_2, with an estimated conductance-limited pumping speed $S = 10\,L\,s^{-1}$ at the AMD) and monitored by using a mass spectrometer (Granville-Phillips Vacuum Quality Monitor, with an ion gauge mounted nearby measuring total pressure[16]). The AMD was degassed for 3 days by dissipating $P = 2.0\,W$ ($T \approx 240\,°C$). We did not otherwise bake the vacuum chamber to remove water. Upon initial degassing, the pressure increased to $3 \times 10^{-5}\,Pa$, dominated by water. After degassing, the mass spectrometer recorded a significant decrease in all gasses, except for $m = 28\,u$. Outgassing that is not a strong function of time is likely due to species that are chemically bound or are diffusing from bulk material. Because Li forms a nitride layer in the presence of air, we suspect the $m = 28$ peak to be N_2 originating from the Li pellets.

Figure 2 shows the increase in background gas composition recorded on the mass spectrometer when operating the AMD under typical conditions ($P = 3.0\,W$, $T \approx 330\,°C$, total pressure $3.3(6) \times 10^{-7}\,Pa$). The presence of a $m = 14\,u$ peak roughly 1/10 the intensity of the $m = 28\,u$ peak is consistent with the cracking fraction of N_2 in most mass spectrometers. The lack of a visible $m = 12\,u$ peak indicates that the possible contribution of CO to the $m = 28\,u$ peak is small. The magnitude of the observed $m = 44\,u$ peak indicates a negligible contribution to the $m = 28\,u$ peak from cracking of CO_2 into CO (28 u) and O (16 u). In addition, the partial pressure of O_2 (32 u) is observed to increase. This too may originate from the Li pellets because Li forms hydroxides and carbonates upon exposure to air.

We investigated the outgassing rate of the AMD by the throughput method, wherein the pressure p in a vacuum chamber is determined by the total gas flow q from all sources into
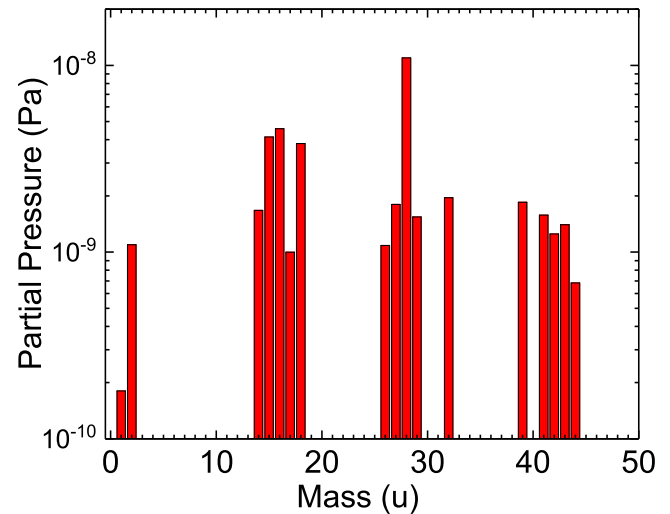

FIG. 2. Background-subtracted (i.e., source on minus source off): the mass spectrum of gas composition with $T = 330\,°C$. The total pressure including background is $3.3(6) \times 10^{-7}\,Pa$.

the chamber and effective pumping speed S, $q = pS$. The AMD was tested in a small stainless-steel vacuum chamber evacuated by using a turbomolecular pump. The effective pumping speed S was limited by the conductance of the vacuum components between the AMD and the turbomolecular pump; we roughly estimate $S \approx 7\,L\,s^{-1}$ for N_2 at $T_{rm} = 20\,°C$. The outgassing rate for the AMD q_{AMD} is determined by the measured pressure rise p_{AMD} above the background when the source is turned on. We obtain an N_2 outgassing rate of $q_{AMD} = 5(2) \times 10^{-7}\,Pa\,L\,s^{-1}$ for the source operating at 330 °C. Our estimate of q_{AMD} does not take into account possible outgassing of the chamber due to heating from the AMD and therefore represents an upper limit.

The MOT consists of six independent, circularly polarized laser beams, detuned −18 MHz from the $F = 2 \rightarrow F' = 3$ transition of the Li D_2 line. Each beam has Gaussian rms width 3.6(2) mm and power 40(1) mW. An electro-optic modulator adds 814 MHz RF sidebands ($\approx$20% in each of the ±1 order sidebands) to the beams in order to drive the $F = 1 \rightarrow F' = 2$ repump transition. A quadrupole magnetic field with axial gradient $\frac{\partial B}{\partial z} = 3$ mT/cm is formed by two arrays of grade N52 permanent magnet bars held in 3D-printed acrylonitrile butadiene styrene mounts around the vacuum chamber.

The number of atoms N in the MOT is determined by fluorescence imaging on a CCD camera. We estimate the measured atom number to be accurate to within a factor of 2. The load dynamics of the MOT are well described by the differential equation

$$\frac{dN}{dt} = R - \gamma N - \beta \int n^2 d^3x, \tag{1}$$

where n is the atomic density, R is the trap loading rate, and γ and β are the one- and two-body loss rate coefficients, respectively. Equation (1) has solution

$$N(t) = N_S \frac{1 - e^{-\gamma_0 t}}{1 + \frac{N_S^2 \beta}{VR} e^{-\gamma_0 t}}, \tag{2}$$
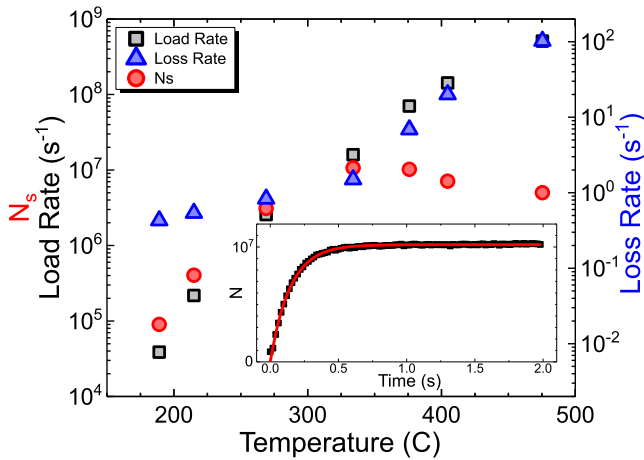
FIG. 3. Loading rate R (black squares), steady-state atom number N_S (red circles), and one-body loss rate γ (blue triangles) as a function of temperature T. The inset shows a typical MOT loading curve with $T = 330\ ^\circ$C. The red line is a fit to Eq. (2).

$$\gamma_0 = \gamma \sqrt{1 + \frac{4\beta R}{V\gamma^2}}, \qquad (3)$$

where N_S is the steady-state atom number, and we assume that the MOT occupies a fixed volume V determined by the fitted Gaussian widths on the CCD camera, such that $n = N/V$.

Figure 3 shows the loading rate R and steady-state atom number N_S as a function of AMD temperature T. We observe loading rates as high as 5×10^8 s^{-1}, comparable to that of many Zeeman slowers.[20] The steady state atom number initially increases as T is increased, reaching a maximum $N_S \approx 10^7$. For temperatures in excess of 330 $^\circ$C, the increase in background pressure due to contaminant outgassing exceeds the increase in Li production, and the trapped atom number decreases marginally. At the optimal $T = 330\ ^\circ$C, we measure an equilibrium N_2-equivalent pressure of $1.8(4) \times 10^{-7}$ Pa on an ion gauge attached to the vacuum chamber.

AMDs have proven to be useful for a variety of cold atom experiments. The 3D-printed AMD presented here loads a Li MOT with comparable atom number, load rate, and background pressure to other MOTs directly loaded from effusive sources.[2,11–13] We note that with a 100 L s^{-1} pumping speed and negligible other outgassing sources, the pressure in the chamber would be $\approx 10^{-9}$ Pa, which is useful for a wide range of cold atom experiments. It is possible that with better preparation of the Li,[17] contaminant outgassing can be made even lower. The pressures obtained with the limited Li preparation procedure presented here are more than sufficient for typical Li vapor deposition environments, e.g., for organic light-emitting diodes.[21,22] We plan to use this 3D-printed AMD in designing a cold atom vacuum standard based on Li.[7,8] Our design is generic to a number of atomic species; specifically, Sr, Yb, Mg, and Ca all have negligible vapor pressure at room temperature but can achieve vapor pressures comparable to Li at comparable (± 50 K) operating temperatures.

Thus, this source warrants consideration for other deployable technologies based on cold atoms, including clocks and accelerometers.

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