Novel Technique for Producing Ultracold ^{4}He Beams

Eric S. Meyer, John C. Mester, and Isaac F. Silvera
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 3 August 1992)

We have developed a technique for producing ultracold beams of ground state ^{4}He atoms by evaporation from a film at subkelvin temperature in a dilution refrigerator. Our analysis shows that we have cooled atoms to below 700 μK and that the cooling process can be continued to below 100 μK. This new technique has great promise for determining the He-He interaction potential to high precision and searching for ^{4}He dimer formation. It might also be used to study quantum reflection off surfaces and to search for Bose-Einstein condensation in a dilute gas of ^{4}He.

PACS numbers: 34.40.+n, 34.20.Gj, 67.40.−w

We have demonstrated and analyzed a novel method for creating a beam of ultracold ^{4}He atoms. The beam is pulse evaporated from a film of liquid ^{4}He at subkelvin temperature in a dilution refrigerator. The beam cools as it expands isentropically, and a fast bolometer detects very narrow time-of-flight (TOF) distributions indicating temperatures orders of magnitude lower than the evaporation temperature. Careful analyses imply that the temperature is less than 700 μK, and that beams with temperatures below 100 μK can be created and studied.

In a conventional supersonic expansion, a gaseous species is forced to expand through an orifice into a vacuum. Substantial cooling results from the isentropic expansion, as the random thermal energy of the gas is converted into motion directed axially from the source. This phenomenon has been exploited to create atomic and molecular beams of high intensity with extremely narrow velocity distributions, i.e., low internal temperatures. Cooling in an expansion slows and eventually halts because of the $1/r^2$ reduction in the gas density of the beam. As the intrabeam collision rate falls, the transverse velocity distribution continues to cool because of the geometric effect of the expansion, but the longitudinal velocity distribution, which is the experimentally significant quantity, decouples and remains at higher temperature. When the collision rate becomes negligible, the beam is said to have entered the freezing zone; the longitudinal velocity distribution is frozen and experiences no further cooling [1,2].

^{4}He is exceptional in that at low but accessible temperatures, its scattering cross section is very large [3–5]. This allows the collision rate to remain high, and it means continued cooling of the longitudinal velocity distribution of a ^{4}He expansion beam, even at very large distances from the source where the density is small. This fortuitous property of ^{4}He was pointed out by Toennies and Winkelmann [2] in 1977, who adapted an analytical theory of supersonic expansions by Knuth and Fisher [6] and Miller and Andres [7] to include quantum mechanical scattering and realistic interatomic potentials. Campargue and Brusdeylins *et al.* have reported cooling ^{4}He beams to the millikelvin range [8], and Wang *et al.* have reported ^{4}He beams cooled to below 1 mK [9]. These groups used expansions over very long distances from room-temperature nozzle sources. Under their experimental conditions, cooling continued to axial distances exceeding $1000d$, where d is the orifice diameter.

A major difficulty of conventional supersonic expansions is that high vacuum must be maintained in the expansion chamber by large, high-speed vacuum pumps. This problem has led to the use and study of pulsed ^{4}He beam sources by several groups [10,11]. Wang *et al.* were able to avoid the pumping speed problems which limited the efficiency of previous ^{4}He expansions by developing a fast valve for pulsing beams [9]. In our low-temperature experiments, we use electrical heating pulses to create pulsed beams, and spent beam atoms are automatically cryopumped by the cold cell walls. We observed no buildup of a background gas during the operation of the beam source.

We conducted an experiment which demonstrates that the heat pulse technique can be used to generate ultracold beams of ^{4}He. Our beam chamber is a 10 cm diam, 5 cm high cylindrical copper cell that is cooled by the mixing chamber of a dilution refrigerator. The cell is temperature controlled at 250 mK, and ^{4}He is added to form a saturated, superfluid film covering all surfaces. The vapor density of ^{4}He at 250 mK is less than 1.0×10^8 atoms/cm^3, so that we do not have problems with scattering off of background gas [5].

The heater beam source and detector are identical bolometers made from $750\times750\times275$ μm^3 chips of neutron transmutation doped germanium which were silver epoxied to a 50 μm thick, 1 cm$\times$1.5 cm plate of ground sapphire. Their construction follows the recipe provided by Lange *et al.* [12] and is detailed elsewhere [13]. The heater and detector are separated by 8.3 cm, and they are oriented so that each Ge chip is on the back side of its sapphire plate, shielded from the other bolometer. The Ge chip resistance is calibrated versus temperature. In our experiment, the detector is current biased and the voltage drop amplified and recorded on an oscilloscope. The changing voltage drop results from heat deposited in the detector by beam atoms that strike and condense on

the film coating it. The detector response time is less than 40 μs, so that the signal can be resolved into a clean TOF distribution. About 1.3×10^9 incident atoms can be resolved in a single pulse, and the detector signal is averaged 100 times to give a resolution of 1.3×10^8 atoms per pulse.

Electrical pulses of fixed current and 200 μs duration are applied to the heater at a 19 Hz rate. During a pulse the heater chip becomes bare of ^{4}He film, so that its temperature rises and its resistance drops. Though the total power dissipation decreases during the pulse due to this effect, the power transmission to the ^{4}He film on the sapphire plate increases, and most of the beam is evaporated in the last 30–60 μs of the pulse. The TOF distributions and the average powers of the pulses we studied are shown in Fig. 1. According to a straightforward thermal model of the bolometer, the ^{4}He film in a central region of the sapphire plate heats to about 0.60 K during the lowest power pulses and to about 0.85 K during the highest power pulses. Because of thermal gradients in the sapphire plate and film, the central region from which more than half of the ^{4}He atoms evaporate shrinks from a diameter of 5 mm for the lowest power pulses to a diameter of 1 mm for the highest power pulses. As the pulse power and ^{4}He film temperature increases, the integrated intensity of the signals increase, the relative widths of the peaks decrease, and the positions of the peaks move to shorter times. Determinations of the temperature of the heater film and the diameter of the central region of evaporation from the positions of the peaks and integrated intensities of the peaks, respectively, are consistent with the thermal model. The diameter of the central evaporation region is an important quantity in determining the efficiency of the cooling effect, and in explaining why the expansion cooling effect is dramatically enhanced at higher pulse powers. For comparison in Fig. 1, we have plotted a Maxwell-Boltzmann TOF distribution for a beam at 0.67 K, scaled to the height of the highest power signal peak. Much lower power pulses (below 20 μW) were also tried. No cooling effect was observed, and the TOF distributions could be fitted assuming a Maxwell-Boltzmann distribution in the beam. For all pulse powers, there was no evidence of clustering in the beam, which we would expect to appear as structure in the TOF distributions or a cessation of cooling due to the heat of condensation.

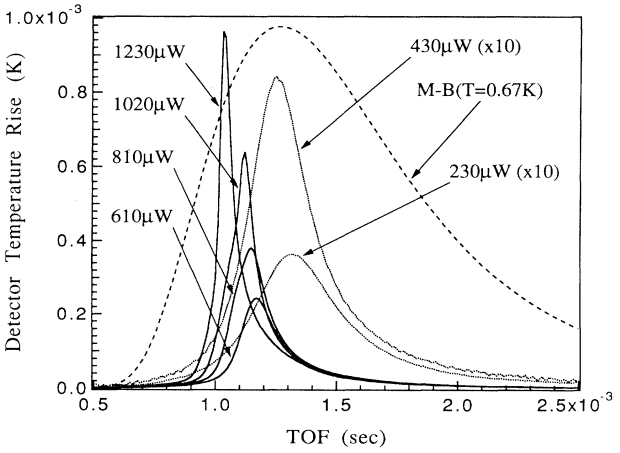

FIG. 1. TOF distributions for various electrical heating pulses applied to the heater. The average power of the pulses are 230, 430, 610, 810, 1020, and 1230 μW. The two lowest power pulses are scaled up in height by a factor of 10. A conventional simulation of the TOF distribution, assuming a film temperature of 0.67 K and no cooling of the beam, is shown scaled to the height of the highest peak.

We have analyzed the characteristics of ^{4}He film-evaporated beams, applying work done previously for conventional expansions [2,6,7]. In the latter stages of an expansion, when the speed ratio ($v/\Delta v$, where v is the mean beam velocity and Δv is the velocity spread) is high, the cooling rate for the longitudinal temperature is $dT_l^*(r)/dr = -2\mathcal{F}$, where r is the distance from the source in units of the source diameter d, $T_l^*(r)$ is the reduced longitudinal temperature T_l/T_0, and T_0 is the initial temperature. Following Toennies and Winkelmann [4], $\mathcal{F}$ is given by

$$\mathcal{F} = 2\left(\frac{m}{5k_B}\right)^{1/2} n_0 d \frac{n^*}{u^*}\frac{(T_t^*)^2}{(T_l^*)^{1/2}} \times \int_0^1 \frac{3\zeta^2-1}{(1-a\zeta^2)^3}\frac{1}{T_{\rm eff}^{1/2}}\Omega^{(2,1)}(T_{\rm eff})d\zeta, \quad (1)$$

where m is the ^{4}He mass, n_0 is the beam density at the source, d is the source diameter, n^* is the reduced density $n(r)/n_0$, u^* is the reduced stream velocity $u(r)/u_{\max}$, where $u_{\max}=(5k_BT_0/m)^{1/2}$, $T_t^*(r)$ is the reduced transverse temperature T_t/T_0, $a=(T_l-T_t)/T_l$, and $T_{\rm eff}(r) = T_t/(1-a\zeta^2)$. The collision integral $\Omega^{(2,1)}(T_{\rm eff})$ is a function of the quantum mechanical viscosity cross section $Q^{(2)}(g)$ (g is the relative velocity in a collision), which depends on the scattering partial wave phase shifts. Expressions for these quantities are given in the article by Toennies and Winklemann. $\mathcal{F}$ is proportional to n_0d, so that the source diameter d plays as important a role as the initial density n_0 in determining the cooling rate and thus the asymptotic temperature. This factor of d results from the conversion of distance into reduced units. If one wants the cooling to continue to large values of the reduced distance, one must have both a large source and a high source density.

In Eq. (1), Toennies and Winkelmann used $Q^{(2)}$ for ^{4}He calculated from a Lennard-Jones-type potential for ^{4}He-^{4}He [14]. We have recomputed $Q^{(2)}$ using the latest ^{4}He-^{4}He potential from Aziz, McCourt, and Wong [3]. Use of this potential leads to larger values of $Q^{(2)}$ at low relative collision velocity and therefore implies more efficient cooling.

We have used the theory to model ^{4}He supersonic ex-

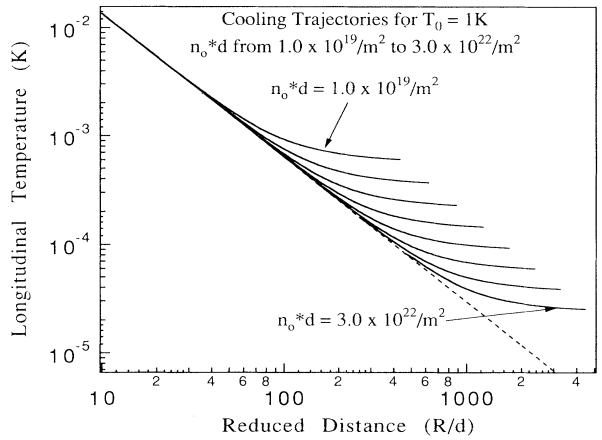

FIG. 2. Temperature vs reduced distance (R/d) trajectories for heat pulses with initial temperature $T_0=1$ K and varying n_0d. From top to bottom, $n_0d=1.0\times10^{19}$, 3.0×10^{19}, 1.0×10^{20}, 3.0×10^{20}, 1.0×10^{21}, 3.0×10^{21}, 1.0×10^{22}, and 3.0×10^{22} m^{-2}. The simulations are run until the ratio of transverse temperature to longitudinal temperature drops below 0.1.

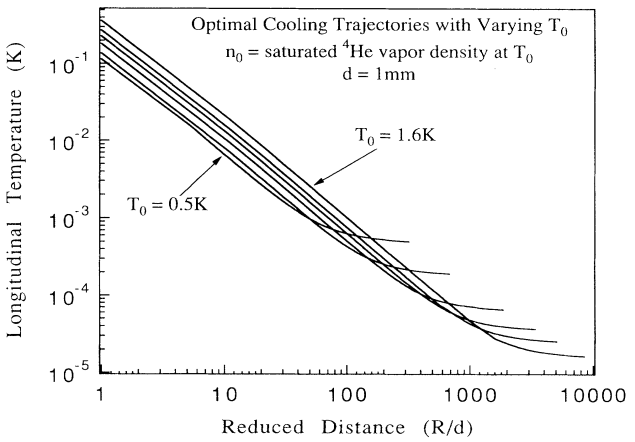

FIG. 3. Temperature vs reduced distance (R/d) trajectories for heat pulses with source diameter $d=1$ mm, and varying initial temperature T_0. n_0 is set equal to the vapor density of ^{4}He at T_0. From left top to left bottom, $T_0=1.6$, 1.2, 1.0, 0.8, 0.6, and 0.5 K. The calculations are extended until the ratio of transverse temperature to longitudinal temperature drops below 0.1.

pansions starting at temperatures, densities, and source diameters relevant to our technique. Longitudinal temperature trajectories at a fixed initial temperature and varying values of n_0d are shown in Fig. 2. The straight line represents a perfect isentropic expansion [1], in which the transverse and longitudinal velocity distributions are in thermal equilibrium at all distances. Clearly, the larger n_0d, the further this ideal line is followed, and the better the beam cools. In Fig. 3, we plot temperature trajectories for a number of different initial temperatures T_0 with the source diameter fixed at 1 mm. Since the beam is formed by evaporation, we have taken the initial density n_0 equal to the vapor density of ^{4}He at the initial temperature T_0. The graph shows that if the expansion goes out far enough, lower temperatures can be reached by increasing the heater pulse power and thus the initial temperature. Using the values $T_0=0.85$ K and $d=1.0$ mm from our thermal model for a 1230 μW pulse, Fig. 3 shows that the beam should be at 700 μK just before hitting the detector. In Fig. 4, we show the TOF distribution for this pulse along with Maxwell-Boltzmann distributions for delta function pulses at 4 mK and 700 μK, scaled to the same axial speed and same peak height. Since the pulsed beam cools dramatically as it travels to the detector, the TOF distribution is actually a complicated convolution of the pulse's spatial spread with its temperature trajectory. Thus the beam's temperature just before arriving at the detector is substantially lower than the signal width would indicate if a constant temperature flight were assumed.

For the pulse powers used in our experiment, the cooling was limited by the source diameter, or, equivalently, the source-detector reduced distance. The thermal gradients that developed in the sapphire plate and the ^{4}He film at such powers actually helped optimize the cooling process by reducing the effective source diameter well below 1.0 cm. We believe that this effect is responsible for most of the difference in widths between the highest and lowest powers in Fig. 1. By using a much smaller diameter source, we should be able to cool an order of magnitude lower in temperature, while keeping the same source-detector distance.

We have demonstrated supersonic expansion cooling of ^{4}He gas inside a dilution refrigerator. By contrast with a conventional nozzle expansion, the low starting tempera-

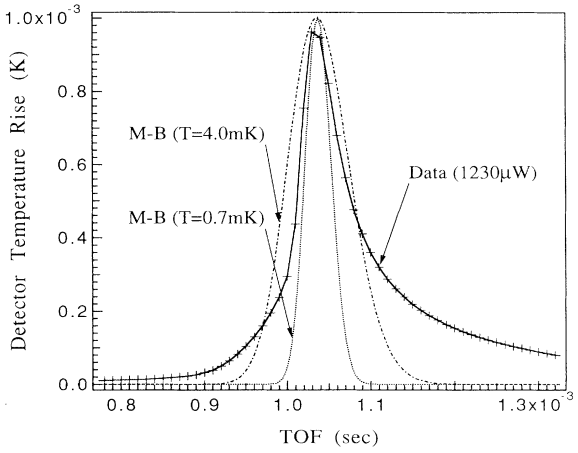

FIG. 4. TOF distribution of the highest power heat pulse (1230 μW) compared with Maxwell-Boltzmann TOF distributions for delta function pulses with constant internal temperature. The broad distribution is at 4 mK; the narrow one at 700 μK.

ture means that we do not need such large speed ratios or long distances to achieve ultracold temperatures. Furthermore, the benefits of the enormous low-temperature ^{4}He-^{4}He scattering cross section are reaped immediately, from the beginning of the expansion. We note that our initial densities are orders of magnitude lower than those of conventional low-temperature sources [15] so that massive clustering is unlikely. Finally, the beam chamber vacuum is near perfect and is maintained automatically.

Referring to Fig. 2 or Fig. 3, we note that if a 1.0 mm diam source is heated to 1 K, the generated helium beam would reach 100 μK in less than 40 cm. This source has exciting possible applications. If high initial ^{4}He densities can be attained so that the beam starts on the proper side of the Bose-Einstein condensation (BEC) phase line, it might be possible to expand and cool the beam until it enters the weakly interacting regime where BEC is manifested. The supersonic expansion process itself could be used to fit a new interatomic potential for He-He, since the efficiency of the cooling depends strongly on the elastic scattering cross section at low temperatures. At submillikelvin temperatures in the beam, ^{4}He$_2$ dimers might be created and observed by the heating such dimerization would cause. Finally, the monochromaticity of these ^{4}He beams could be used for the study of quantum reflection of ^{4}He off of surfaces.

We thank Z. Zhao, B. Freedman, and J. Kim for help with some of the measurements. The computer code for calculating $Q^{(2)}$ was developed by M. Reynolds. This work has been supported by Department of Energy Grant No. DE-FG02-85ER45190.

[1] J. B. Anderson, in *Molecular Beams and Low Density Gasdynamics*, edited by P. P. Wegener (Dekker, New York, 1974); J. B. Anderson and J. B. Fenn, Phys. Fluids **8**, 780 (1965).

[2] J. P. Toennies and K. Winkelmann, J. Chem. Phys. **66**, 3965 (1977).

[3] R. A. Aziz, F. R. W. McCourt, and C. C. K. Wong, Mol. Phys. **61**, 1487 (1987).

[4] R. A. Aziz, V. P. S. Nain, J. S. Carley, W. L. Taylor, and G. T. McConville, J. Chem. Phys. **70**, 4330 (1979); Y. H. Uang and W. C. Stwalley, J. Chem. Phys. **76**, 5069 (1982).

[5] J. C. Mester, E. S. Meyer, T. E. Huber, M. W. Reynolds, and I. F. Silvera, J. Low Temp. Phys. (to be published).

[6] E. L. Knuth and S. S. Fisher, J. Chem. Phys. **48**, 1674 (1968).

[7] D. R. Miller and R. P. Andres, in *Proceedings of the Sixth Symposium of Rarefied Gas Dynamics*, edited by L. Trilling and H. Y. Wachman (Academic, New York, 1969), Vol. 2, p. 1385.

[8] R. Campargue, Prog. Astronaut. Aeronaut. Pt. 2, **51**, 1033 (1977); B. Brusdeylins, H. D. Meyer, J. P. Toennies, and K. Winkelmann, Prog. Astronaut. Aeronaut. Pt. 2, **51**, 1047 (1977).

[9] J. Wang, V. A. Shamamian, B. R. Thomas, J. M. Wilkinson, J. Riley, C. F. Giese, and W. R. Gentry, Phys. Rev. Lett. **60**, 696 (1988).

[10] J. P. Bucher, D. C. Douglass, P. Xia, and L. A. Bloomfield, Rev. Sci. Instrum. **61**, 2374 (1990); O. F. Hagena, Z. Angew. Phys. **17**, 542 (1964); W. R. Gentry and C. F. Giese, Rev. Sci. Instrum. **49**, 595 (1978).

[11] B. D. Kay, T. D. Raymond, and J. K. Rice, Rev. Sci. Instrum. **57**, 2266 (1986); K. L. Saenger and J. B. Fenn, J. Chem. Phys. **79**, 6043 (1983); M. Izawa, S. Kita, and H. Inouye, J. Appl. Phys. **53**, 4688 (1982).

[12] A. E. Lange, E. Kreysa, S. E. McBride, P. L. Richards, and E. E. Haller, Int. J. Infrared Millimeter Waves **4**, 689 (1983).

[13] J. C. Mester, thesis, Harvard University, 1992 (unpublished).

[14] J. P. Toennies, Chem. Phys. Lett. **20**, 238 (1973).

[15] H. Buchenau, E. L. Knuth, J. Northby, J. P. Toennies, and C. Winkler, J. Chem. Phys. **92**, 6875 (1990).