Experiments to Study Photoemission of Electron Bubbles from Quantized Vortices

Denis Konstantinov, Matthew Hirsch and Humphrey J. Maris

Department of Physics, Brown University, Providence, Rhode Island 02912, USA

Abstract. At sufficiently low temperatures, electron bubbles (negative ions) can become trapped on quantized vortices in superfluid helium. Previously, the escape of electron bubbles from vortices by thermal excitation and through quantum tunneling has been studied. In this paper, we report on an experiment in which light is used to release bubbles from quantized vortices (photoemission). A CO_2 laser is used to excite the electron from the 1S to the 1P state, and it is found that each time a photon is absorbed there is a small probability that the bubble containing the electron escapes from the vortex.

Keywords: electrons, bubbles, helium, photons.
PACS: 67.40, 78.20c

Electrons injected into liquid helium create a cavity in the liquid from which helium atoms are excluded. These so called "electron bubbles" have been studied in many low temperature experiments, mainly through measurements of their mobility.[1] If an electron bubble moves above a critical velocity, a vortex ring forms and the bubble helium can become trapped on the vortex with a binding energy U_0.[2] Electrons can escape from a vortex as a result of thermal excitation or by quantum tunneling. In this paper, we investigate another mechanism by which electrons can escape from a vortex, namely via optical excitation.

The apparatus is shown schematically in Fig. 1. A sharp tungsten tip is used to introduce electrons into a region of liquid between a metal perforated disk (PD) and a collector plate. The disk is located 5 mm below the point of the tip and has a number of holes in it to allow ions to pass through. The disk is separated from the collector by a cylindrical nylon spacer of height 5 mm and with holes at either side to allow light into the liquid that is between the PD and the collector. A constant voltage of -2 kV is applied to the tip to inject negative ions into the liquid, the voltage on the perforated disk is -100 V, and the collector plate is connected to ground through a 100 kΩ resistor.

Because of the high electric field in the region above the PD, electrons emitted from the tungsten tip quickly become trapped on vortices. Some of these vortex rings pass through the PD into the region of lower electric field between the PD and the collector. A light pulse from a CO_2 laser is applied to the region between the PD and the collector. Some fraction of the trapped electrons escape from the vortices, and give a pulse of current arriving at the collector a few hundred μs later. Through an analysis of the variation of the size of the current pulse with the energy in the light pulse the probability that the absorption of a photon leads to electron escape can be determined as described below.

The laser beam has a Gaussian profile with a waist diameter of about 3.6 mm. Typically a series of 1000 light pulses at intervals of 1 s were applied, and the average signal at the collector was measured using a digital oscilloscope. All of the measurements were

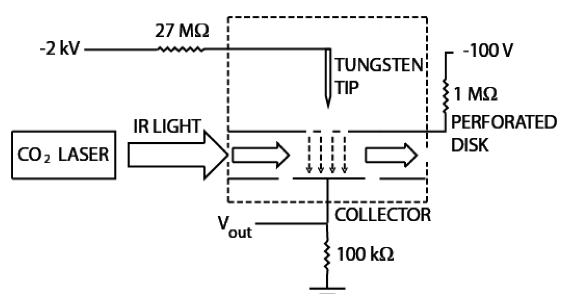

FIGURE 1. Schematic diagram of the apparatus.

CP850, *Low Temperature Physics: 24th International Conference on Low Temperature Physics;*
edited by Y. Takano, S. P. Hershfield, S. O. Hill, P. J. Hirschfeld, and A. M. Goldman

conducted at a static pressure of 1 bar where the cross-section for light absorption[3] has its maximum value of 4.6×10^{-15} cm^{-2}, and at 1 K where almost all ions should be trapped on vortices.

Let σ be the absorption cross-section for the 1S→1P transition at the CO_2 wavelength, and p be the escape probability. Then the rate at which ions escape from vortices due to a light pulse is given by

$$\frac{dN}{dt} = (N_0 - N)\, I\, \sigma\, p \qquad (1)$$

where N is the number of untrapped ions, N_0 is the total number of ions in the volume illuminated by the light, and I is the flux of photons per unit area per unit time. If a light pulse of length τ is introduced, the number of liberated ions is

$$N(I,\tau) = N_0[1 - \exp(-I\sigma\,\tau\, p)]\,. \qquad (2)$$

These released electrons give a pulse of current $J(t)$ at the collector, which is much larger than the current without illumination. The integral Q of the detector signal over the pulse is proportional to $N(I,\tau)$, and hence a measurement of Q for a series of values of I or τ can be used to find the probability p. In this analysis we use the calculated absorption cross-section for the 1S→1P transition.

In Fig. 2 we show examples of the collector signal as a function of time when the length of the light pulse and the intensity were varied. From these data, we calculate Q and then determine the value of p that gives the best fit to the data when Eq. 2 is used. An example of this fit is shown in Fig. 3.

This procedure gives a value for p of 1.3×10^{-4}. As far as we are aware, there is no theory with which to compare this result. Immediately after the light is absorbed, the shape of the bubble undergoes a dramatic change because of the change in the form of the electron wave function. Calculations[4] show that the bubble may break into two smaller bubbles which could be ejected away from the vortex line. In addition, the motion of the bubble wall results in energy dissipation in the surrounding liquid, and it is possible that this energy enables the bubble to escape from the confining potential. To attempt to distinguish between these possibilities we are currently making measurements of the escape probability as a function of temperature and electric field.

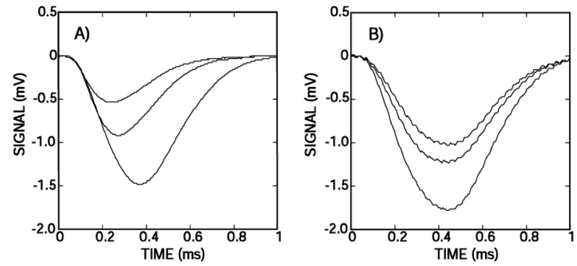

FIGURE 2. Signal at the collector as a function of time resulting from the application of a light pulse. A) Results for pulses of the same intensity length and length 50, 100 and 300 µs. B) Results for 400 µs pulses of intensity 35 %, 50 % and 100 % of the maximum laser output power.

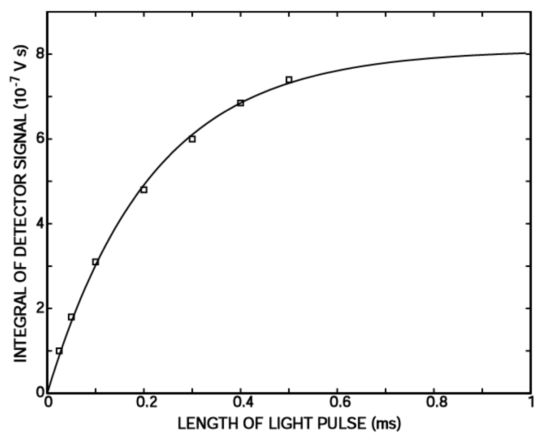

FIGURE 3. Plot of the integral of the detector signal as a function of the length of the light pulse to illustrate the fitting procedure. The signal saturates when all electrons have escaped from vortices.

We thank A. Ghosh, W. Guo, and G.M. Seidel for helpful discussions. This work was supported in part by the National Science Foundation through Grant No. DMR-0305115.

REFERENCES

1. For a review, see A.L. Fetter, in *The Physics of Liquid and Solid Helium*, edited by K.H. Benneman and J.B. Ketterson, New York: Wiley, 1960.
2. See R.J. Donnelly, *Quantized Vortices in Helium II*, London: Cambridge, 1991.
3. H.J. Maris and W. Guo, *J. Low Temp. Phys.* **137**, 491 (2004).
4. H.J. Maris, *J. Low Temp. Phys.* **120**, 173 (2000).