PHOTOEJECTION OF ELECTRONS FROM BUBBLE STATES IN LIQUID HELIUM*

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We have observed changes in the drift properties of negative ions in liquid helium when they are exposed to near-infrared radiation. The existence of this effect strongly supports the bubble model of the ion's structure. The results imply a bubble radius of 21.2 ± 0.5 Å and a well depth of 1.0 ± 0.2 eV.

Since the original suggestions, in connection with positronium[1] and electrons[2] in liquid helium, that these light particles might distort the surrounding medium and enter a state in which the light-particle wave function is concentrated in a region of very low helium density (the bubble), a good deal of evidence tending to support the model has appeared.[3-7] There has not, however, been any experiment which probed in detail the state of the electron, or provided the kind of microscopic information typically available after spectroscopic study. We report here such an experiment.[8] It provides a very detailed test of the model, and the most direct evidence yet available of the essential correctness of the bubble picture.

The apparatus is shown schematically in Fig. 1. It consists of a transit-time measuring device,[9] in which we observe a change in electron drift velocity when the cell is exposed to electromagnetic radiation. A dc electric field is applied between the Po^{210} α source and the first grid, a square-wave field between the two grids, and another dc field between the second grid and the collector. The Dewar is provided with optical windows, and an image of the exit slit of the grating monochromator is placed in the intergrid region. A 2500-W xenon arc lamp illuminates the monochromator entrance slit. The light leaves the Dewar through another window, and is monitored with a thermopile.

The square-wave frequency is adjusted so that for normal ions the transit time between the grids is slightly greater than one half-period. No current will reach the collector unless charges of higher than normal mobility, such as electrons out of bubbles, appear. Thus, if electrons are ejected from bubbles when the light is turned on, collector current should appear. In practice, the light is mechanically modulated, and the component of the collected current synchronous with the chopped light is detected using a phase-sensitive detector. The output of the detector, S, should be given by

$$S = \sigma(\lambda)P(\lambda)f(\lambda),$$

where $\sigma(\lambda)$ is the cross section[10] for ejection of electrons from bubbles (in cm^2/J) by radiation of wavelength λ, $P(\lambda)$ the light flux (in $\mathrm{W/cm}^2$), and $f(\lambda)$ a weighting function related to the collection efficiency. We have determined experimentally that at constant λ, S is indeed proportional to P (as measured by the thermopile). Consequently, we have adopted as a normalized signal the ratio S/P. The best argument in favor of this procedure is that it generates a curve which is insensitive to variations in the light spectrum. The ratio is evaluated at each wavelength by converting S and P to digital form with voltage-to-frequency converters, and counting the number of cycles of S in a standard number of cycles of P. The resulting values of S/P are plotted as a function of λ on an X-Y recorder, as shown in Fig. 2(a).

The most significant feature of this curve is its existence, which is predicted by the bubble model, but not by alternative models[2] of the ion's structure. We find no such signal when studying positive-ion currents. The amplitude of the entire curve decreases with in-

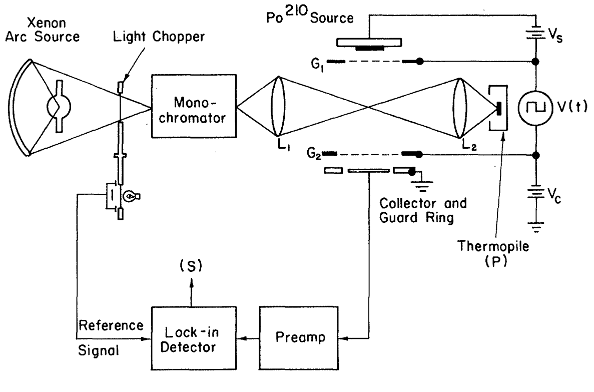

FIG. 1. Schematic diagram of the apparatus. The grid structure at the right is immersed in the helium bath.

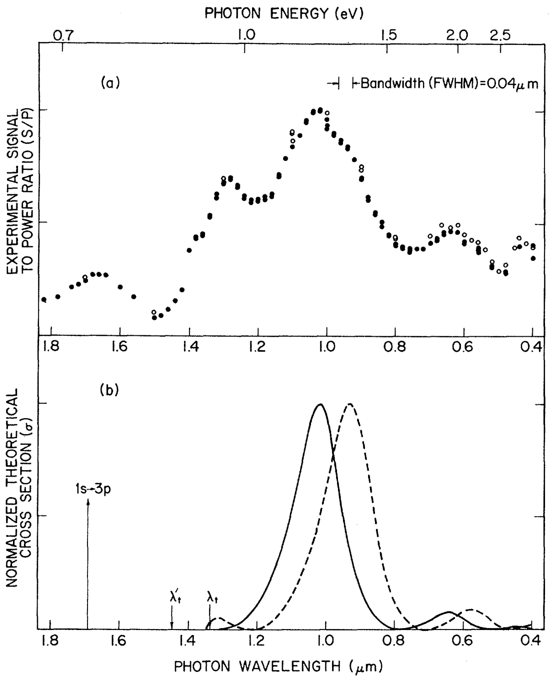

FIG. 2. (a) The experimental signal-to-power ratio. Each point represents from 30 sec to 5 min of averaging. The closed circles are data taken sequentially from right to left. The open circles were taken on a return trace after a lapse of up to 5 h, and indicate the magnitude of instrumental drifts. (b) Theoretical cross sections computed for $V = 1.00$ eV, $R = 21.30$ Å (solid curve), and $R = 20.30$ Å (dashed curve). The positions of the higher energy maxima and minima of the solid curve agree quite well with experiment. The dashed curve is shown in order to illustrate the great sensitivity of the peak structure to the bubble radius. The thresholds and the $1s$-$3p$ transition are shown for the 21.30-Å curve only.

creasing temperature, becoming unobservable above roughly 1.7°K. The relative intensities of the peaks are independent of temperature, except for the peak at 1.28 μm, whose relative intensity decreases sharply with increasing temperature. The signal is observed only for source fields greater than about 1 kV/cm at 1.3°K.[11] If we assume that the weighting function $f(\lambda)$ is slowly varying function of λ, the maxima and minima of the experimental ratio curve should reflect similar features in the cross section, $\sigma(\lambda)$.

In Fig. 2(b) we show theoretical cross sections, calculated from a simple version of the bubble model. In the calculation the electron is assumed to be initially in the ground state of a spherical square-well potential, of radius R and depth V. The calculation[12] assumes electric-dipole coupling, and that the final state is a continuum p state in the same potential.[13] The theoretical curves are characterized by a threshold λ_t, followed by a sequence of diffractionlike peaks and zeroes. The peak positions are quite sensitive to the radius, but are less sensitive to the well depth. The cross section calculated for $R = 21.35$ Å and $V = 1.02$ eV exhibits quite good quantitative agreement with the observed primary (1.02 μm) maximum and all higher energy maxima and minima ($R = 21.05$ Å, $V = 1.02$ eV gives somewhat better agreement for the minima). This agreement is insensitive to changes in well depth near 1.0 eV, but is destroyed by small changes in the assumed radius.[14] In Table I we display this correspondence between the maxima and minima of the experimental curve and the peaks and zeroes of some theoretical cross sections. Although all features of the curve are consistent with a radius between 21.0 and 21.4 Å we prefer to quote a somewhat larger error because of uncertainties in interpretation, which we discuss below.

These theoretical cross sections do not account for three of the observed features: (1) the lowest energy peak near 1.75 μm; (2) the temperature-dependent peak near 1.28 μm; (3) the

Table I. Positions of maxima and minima (in eV).

		Theory		
	Experimental values	$R = 21.35$ Å $V = 1.02$ eV[a]	$R = 21.05$ Å $V = 1.02$ eV	$R = 15.50$ Å $V = 1.00$ eV
Primary maximum	1.21 ± 0.03	1.21	1.25	1.21
First minimum	1.66 ± 0.05	1.59	1.63	1.77
Second maximum	1.94 ± 0.06	1.94	1.99	2.26
Second minimum	2.48 ± 0.10	2.41	2.48	3.00
Third maximum	2.82 ± 0.13	2.83	2.92	>3.30
Bound p state	0.75 ± 0.01	0.73	0.75	0.59

[a] The value of the barrier for photoinjection of electrons (1.02 ± 0.08 eV) measured by Woolf and Rayfield (Ref. 4).

fact that the experimental curve has minima rather than zeroes. It is possible that these discrepancies indicate that the simple bubble model cannot give a complete account of the situation. However, we will discuss each feature within the spirit of the model.

We believe that the low-energy peak can be interpreted as a transition from the ground state to the highest bound p state in the well. The energy corresponding to this transition is also included in Table I. The agreement for the "best fit" well parameters is quite good. A serious objection to this interpretation is that, since the electron is not ejected, it is not clear how it reaches the collector. However, we have good experimental reasons for believing that the detection process for the entire effect is more complex than the simple model proposed above[11] and, in fact, can include a mechanism for detecting bound-state transitions.

The temperature-dependent peak at 1.28 μm is thought to involve a different type of ejection mechanism, in which the bubble collapes, delivering its surface energy to the electron. The transition leading to this type of final state, we believe, involves excitation of a high vibrational state of the bound p state discussed above. The energetic threshold for such an effect, λ_t', is shown for the "best fit" curve in Fig. 2(b). It agrees rather well with the rapid rise from the deep minimum at 1.5 μm.

There are several mechanisms which can lead to a signal curve which does not have true zeroes. Among these are a distribution of bubble sizes and shapes, contributions from higher multipole radiative processes, and instrumental distortions including the finite bandwidth of the monochromator and spurious thermal effects caused by absorption of radiation in the Dewar. At present we do not, however, have a quantitative understanding of this feature of the curves.

Finally we may mention that a study of the the effect of external pressure on this spectrum should help to illuminate some of the unsettled points we have mentioned. Such an experiment has been begun by Mrs. C. Zipfel, whose assistance in the later phases of the present work we gratefully acknowledge. We are also indebted to Dr. Shou-Yih Wang for calculating the theoretical cross sections and for permission to use them in this communication.

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[10] We use the symbol $\sigma(\lambda)$, and the term cross section, for the normal cross section divided by photon energy.

[11] This behavior suggests that the actual detection mechanism may involve the interaction of the ion with turbulence or vorticity present in the bath.

[12] S. Wang, thesis, University of Michigan, Ann Arbor, Michigan, 1967 (unpublished). The calculation is similar to one for the photodisintegration of the deuteron by G. Breit and E. U. Condon, Phys. Rev. 49, 904 (1936).

[13] The helium atoms are assumed fixed during the electronic transition.

[14] Any single feature of the experimental curve can be fit by a sequence of values of the radius. For example, the cross section for $R = 15.5$ Å fits the primary maximum, but is in marked disagreement with all other features of the experimental curve. This value is near the radius (15.96 Å) deduced from ion trapping on vortex lines (Ref. 7). However, a recent analysis of the same phenomenon by W. P. Pratt, Jr., and W. Zimmermann, Jr. [Bull. Am. Phys. Soc. 12, 551 (1967), and private communication], indicates a larger radius.