background modes was even less apparent than in Fig. 1(a) insofar as only the $n=0$ point deviated visibly from the extrapolated Bose-Einstein distribution. This point fell at 84% [a factor of $\exp(-\bar{n}_b)$] of the straight-line extrapolation.

The authors believe that this experiment is the first observation of a (nearly) Bose-Einstein probability distribution of photoelectrons. Also, the results shown in Fig. 1(c) constitute the first experimental test of Eq. (3).

A determination of the probability distribution of photoelectron counts has been reported by Johnson, McLean, and Pike[9] using an incoherent light source and, therefore, counting intervals much longer than the inverse bandwidth. Their work provided the initial impetus for the measurements reported here.

The authors gratefully acknowledge many helpful discussions with Dr. R. J. Glauber, Dr. P. L. Kelley, Dr. R. H. Kingston, and Dr. E. R. Pike; and they are especially appreciative to P. Trent for the computer programing.

*Operated with support from the U. S. Air Force.

†This work was supported in part by the Joint Services Electronics Program under Contract No. DA36-039-AMC-03200(E).

[1]L. Mandel, Proc. Phys. Soc. (London) 72, 1037 (1959).

[2]E. Wolf, in Proceedings of the Symposium on Optical Masers at the Polytechnic Institute of Brooklyn, April, 1963 (Interscience Publishers, Inc., New York, 1963), Vol. 13, p. 29.

[3]R. J. Glauber, Phys. Rev. 130, 2529 (1963).

[4]R. J. Glauber, Phys. Rev. 131, 2766 (1963).

[5]P. L. Kelley and W. H. Kleiner, Phys. Rev. 136, A316 (1964).

[6]C. Freed and H. A. Haus, Appl. Phys. Letters 6, 85 (1965).

[7]C. Freed and H. A. Haus, Phys. Rev. (to be published).

[8]R. J. Glauber, in Physics of Quantum Electronics, edited by P. L. Kelley, B. Lax, and P. E. Tannenwald (to be published)

[9]F. A. Johnson, T. P. McLean, and E. R. Pike, in Physics of Quantum Electronics, edited by P. L. Kelley, B. Lax, and P. E. Tannenwald (to be published).

FORMATION OF H^- BY ELECTRON IMPACT ON H_2 AT LOW ENERGY*

G. J. Schulz and R. K. Asundi

Westinghouse Research Laboratories, Pittsburgh, Pennsylvania

(Received 15 November 1965)

This letter reports the formation of the atomic-hydrogen negative ion by electron impact on H_2 very close to the theoretical threshold for the production of H^- and H with zero kinetic energy, via the process $e+H_2 \rightarrow H^-+H$. We find H^- formation with a very sharp onset at an electron energy of 3.73 ± 0.07 eV and a very steeply rising, albeit small, cross section which peaks very close to its onset. This observation leads to a better understanding of the potential-energy curves of the H_2^- system and has a bearing on the interpretation of vibrational excitation in H_2.

Dissociative attachment by electron impact on H_2 has been the subject of repeated studies, both without[1,2] and with[3] mass spectrometry. The identity of the negative ions as well as the energy dependence of the cross section are rather well established[1,2] above electron energies of about 6 eV. One observes a broad peak in the energy range about 11 eV with a cross section in the range $(1.3 \text{ to } 1.5)\times 10^{-20}$ cm^2. The first value is from reference 1 and the second reference 2; the agreement in this energy range is therefore extremely good. A sharply rising peak in H^- formation at an energy 14.0-14.2 eV has a cross section[1,2] in the range $(2.1 \text{ to } 3.5)\times 10^{-20}$ cm^2. In the energy range 6 to 13.6 eV, the formation of H^- proceeds via a repulsive energy curve, leading to H^- ions and H atoms with kinetic energy. In the region of the peak near 14 eV, hydrogen atoms and H^- with low kinetic energy are produced, the hydrogen atoms being in the $n=2$ excited states.

In previous experiments on H^- formation in this[2] and in other laboratories,[4] a small negative signal was observed at an energy about 3.7 eV, but these results were not published because doubts persisted whether scattered electrons falsify the collected currents at these low energies. It should be noted that the early theory[5] predicted that no state of H_2^- could lie at these low energies. The predictions of this theory have recently been found to be in error.[6,7] Curran, working in this laboratory,[8] used a mass spectrometer to identify the 3.7-eV process as the formation of H^- from H_2 but was unable to establish that the H^- current

is proportional to gas pressure, as required for a two-body collision process.

Experiment.—An electron beam, aligned by a magnetic field of about 150 G, traverses a differentially pumped collision chamber where the ions are produced by dissociative attachment. The effective energy distribution of the electron beam is reduced by use of the retarding potential difference method.[9] The ions produced in the collision chamber are expelled by a repeller, which is usually operated about 2.7 V negative with respect to the collision chamber, and are analyzed by a 90-degree magnetic mass spectrometer equipped with an electron multiplier. Since the collision chamber, as well as the mass spectrometer, are differentially pumped, it is possible to reach pressures up to about 0.1 Torr in the collison chamber without appreciably scattering ions in the mass-spectrometer focusing and analyzer regions.

The pressure in the collision chamber is determined by measuring the total saturated ion current at an electron energy of 70 eV on the repeller electrode; the pressure is then calculated using the known ionization cross section.

Results in hydrogen.—Figure 1 shows a plot of the H^- ion current as a function of electron energy. A retarding curve on the electrons, shown by the dashed curve in Fig. 1, determines the energy scale.[10] The onset of the negative-ion current is determined from the high-energy tail of the retarding curve, and we obtain a value of 3.73 eV for the onset. The peak of the negative-ion curve is determined from the half-power point of the retarding curve and the mean of 10 determination gives a value 3.75 $\pm$ 0.07 eV. These results indicate that the H^- curve rises more steeply than can be determined from the presently available energy distribution, and the data, therefore, are not inconsistent with a much more steeply rising excitation function at threshold. Using accepted values for the dissociation energy D of H_2 and the electron affinity A for H, the onset of H^- with zero kinetic energy occurs at an energy $D-A = 4.48-0.75 = 3.73$ eV, in agreement with the onset observed in the present experiment.

The peak current at 3.75 eV is found to be 8% of the peak current at 14 eV. Since both these processes lead to H^- with essentially zero kinetic energy, kinetic-energy discrimination should be absent, and one can obtain a cross section for the 3.75-eV process by normalizing to the previously measured cross section at the 14.0-eV peak. Depending on the value one chooses to accept for the cross section[1,2] at 14 eV, one obtains a value of 1.6×10^{-21} or 2.8×10^{-21} cm^2 for the cross section at the 3.75-eV peak. It should be noted that, since the actual energy dependence near the peak could not be traced out in the present experiment because of insufficient energy resolution, the actual cross section at 3.75 eV is probably somewhat larger.

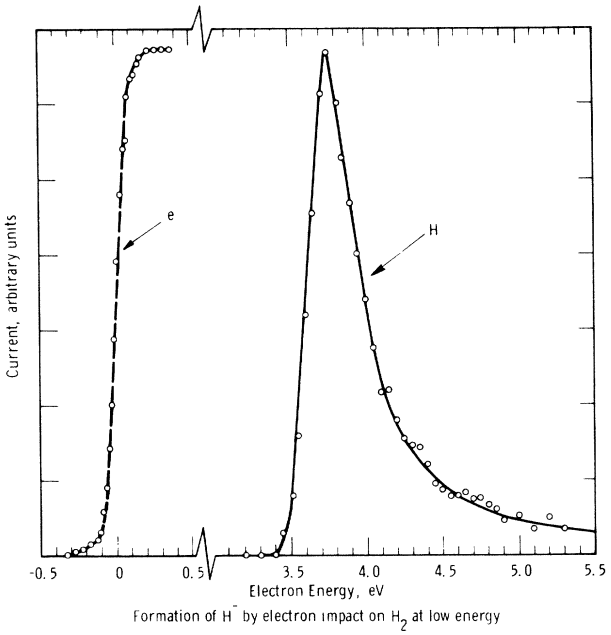

FIG. 1. Energy dependence of H^- formation from H_2 at low energies. The dashed curve is the electron retarding curve used to obtain the energy scale. The onset of H^- formation occurs at 3.73 ± 0.07 eV and the peak H^- current occurs at 3.75 ± 0.07 eV. The value of the cross section at 3.75 eV is about 2×10^{-21} cm^2. See text.

Figure 2 shows the pressure dependence of the ion currents at an electron energy W of 3.75 and 14.0 eV, showing that both processes are linear with pressure and thereby indicating that we are dealing with two-body processes.

Isotope effect.—We have attempted to observe the isotope effect by measuring the cross section of D^- formation from D_2 in the energy range of Fig. 1; in our experiments to date, we were unable to observe a D^- signal around 3.8 eV although we could observe a D^- signal at 14 eV (where the cross section[1] for D^- formation is 1×10^{-20} cm^2) with a signal-to-noise

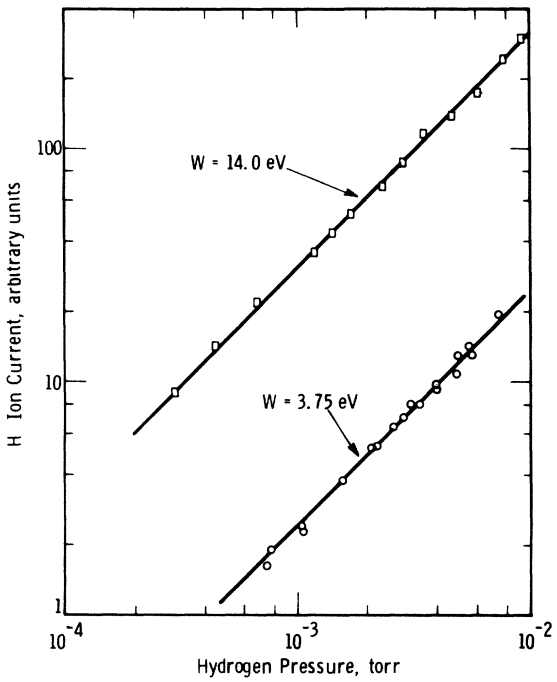

FIG. 2. Pressure dependence of two peaks involving H^- formation from H_2 with zero kinetic energy. The ratio of the ion peak at an electron energy, W, of 14 eV to that at $W=3.75$ eV is 12.5.

ratio of more than 100. This observation places an upper limit of 1×10^{-22} cm^2 on the D^- cross section in the 3.8-eV range. An expression for the negative-ion formation via a compound state, where "background decay" is present, is given[7,11] by $Q_- = Q_0 \exp(-2\bar{\Gamma}\tau/\hbar)$; here Q_- is the cross section for negative-ion formation, Q_0 is the cross section for formation of the compound state (H_2^-), $\bar{\Gamma}$ is the mean width of the potential energy curve, and τ is the time for the atoms to move to a distance where they are stabilized. This stabilization time for D^- is $\sqrt{2}$ times the stabilization time for H^-; from these considerations we arrive at a limit $2\bar{\Gamma}\tau \geq 3\times10^{-14}$ eV sec. Assuming τ to be of the order of a vibration time, $\tau\sim10^{-14}$ sec, we obtain $\bar{\Gamma}\geq1.5$ eV. Although this width seems large, it is not inconsistent with the hypothesis that the same compound state of H_2^- leads to vibrational excitation.[12] The large width of the H_2^- state causes the vibrational cross section to be broad and without appreciable structure, in agreement with previous experimental observations.[13,14] The large isotope effect observed in the present work at low energy (~3.8 eV) is in striking contrast with the small isotope effect previously reported[1] in the energy range 7-18 eV. It indicates that the level width $\bar{\Gamma}$ is considerably smaller for the high-energy process of negative-ion formation.

Conclusions.—The fact that we observe H^- negative-ion formation at 3.7 eV indicates that a potential energy curve traverses the Franck-Condon region at this energy. The large isotope effect observed in the present experiment leads us to the conclusion that the state involved here is short-lived and therefore the potential energy "curve" is broad. This state may be responsible[12] not only for the H^- production observed in this experiment but also for vibrational excitation of the H_2 molecule observed previously[13-15] as well as the peak in the elastic section[16] around 2 eV. These observations are substantially in agreement with the viewpoint of Taylor and Harris[6] and of Bardsley, Herzenberg, and Mandl[12] who point out that a short-lived state of H_2^- traverses the Franck-Condon region at energies below the $H^- + H$ dissociation limit and that a small portion of this curve extends above this limit.

The authors wish to express their thanks to A. V. Phelps and P. F. Chantry for many helpful comments.

---

*This work has been supported in part by the Advanced Research Projects Agency through the U. S. Office of Naval Research.

[1]D. Rapp, T. E. Sharp, and D. D. Briglia, Phys. Rev. Letters 14, 533 (1965).

[2]G. J. Schulz, Phys. Rev. 113, 816 (1959).

[3]V. I. Khvostenko and V. M. Dukel'skii, Zh. Eksperim. i Teor. Fiz. 33, 851 (1957) [translation: Soviet Phys.—JETP 6, 657 (1958)].

[4]D. Rapp and D. D. Briglia, Lockheed Missiles and Space Company Report No. LMSC6-74-64-40, state that the "peak at 3.9 eV in H_2 may possibly be caused by something other than negative ions."

[5]H. Eyring, J. O. Hirschfelder, and H. S. Taylor, J. Chem. Phys. 4, 479 (1936), found that the lowest lying potential energy curve of H_2 traverses the Franck-Condon region at an energy about 5 eV.

[6]H. S. Taylor and F. E. Harris, J. Chem. Phys. 39, 1012 (1963).

[7]Yu. N. Demkov, Zh. Eksperim. i Teor. Fiz. 46, 1126 (1964) [translation: Soviet Phys.—JETP 19, 762 (1964)]; Phys. Letters 15, 235 (1965).

[8]R. K. Curran, private communication.

[9]R. E. Fox, W. M. Hickam, D. J. Grove, and J. Kjeldaas, Rev. Sci. Instr. 26, 1101 (1955).

[10]When a negative potential with respect to the collision chamber is applied to the repeller—as is customary in negative-ion studies—then the retarding curve

on the electrons yields the correct energy scale calibration [G. J. Schulz, J. Appl. Phys. 31, 1134 (1960)].

[11]T. D. Holstein, Conference on Gaseous Electronics, Schenectady, New York, 1951 (unpublished).

[12]J. N. Bardsley, A. Herzenberg, and F. Mandl, in Abstracts of Papers of the Fourth International Conference on the Physics of Electronic and Atomic Collisions (Science Bookcrafters, Inc., Hastings-on-Hudson, New York, 1965), p. 359; and private communication.

[13]G. J. Schulz, Phys. Rev. 135, A988 (1964).

[14]A. G. Engelhardt and A. V. Phelps, Phys. Rev. 131, 2115 (1963).

[15]It should be noted, however, that K. Takayanagi, J. Phys. Soc. Japan 20, 562 (1965), calculates the vibrational excitation in H_2 without invoking a compound state and obtains agreement with experiment. The two viewpoints, namely, "direct" excitation of vibration with the polarization force dominant, and the "compound-state" viewpoint described above, may not be irreconcilable.

[16]R. Kollath, Physik. Z. 31, 985 (1930); and H. S. W. Massey and E. H. S. Burhop, Electronic and Ionic Impact Phenomena (Clarendon Press, Oxford, England, 1952), p. 215.

DIRECT MEASUREMENT OF THE SIZE OF CHARGED QUANTIZED VORTEX RINGS IN He II*

G. Gamota and T. M. Sanders, Jr.

The Harrison M. Randall Laboratory of Physics, University of Michigan, Ann Arbor, Michigan

(Received 15 November 1965)

A direct measurement has been made of the size of charged quantized vortex rings in liquid He^4 at about 0.3°K. The method consisted in studying the current-voltage characteristics of a tetrode tube, in which the size of holes in the last grid was varied. The data indicate a cutoff voltage which is determined by the size of the grid openings and implies that the size of these vortex rings can be correctly calculated by classical hydrodynamics.

Existence of charged vortex rings in liquid He^4 was first experimentally recognized by Rayfield and Reif.[1,2] They found an inverse relationship between the velocity, v, and the energy, E, of charged complexes at temperatures below about 0.6°K. In seeking an explanation for their data, they noted that classical vortex rings exhibit such a dependence of v on E. The following equations describe the behavior of vortices in a "perfect" fluid[3]:

$$E = \tfrac{1}{2}\rho\kappa^2 R\left[\ln\left(\frac{8R}{a}\right) - \frac{7}{4}\right], \tag{1}$$

$$v = \frac{\kappa}{4\pi R}\left[\ln\left(\frac{8R}{a}\right) - \frac{1}{4}\right], \tag{2}$$

where ρ is the density of the fluid, R the radius of the ring, a the core radius, and κ the circulation. Rayfield and Reif used these equations to eliminate R and obtain an equation relating v and E, which was then found to represent their data extremely well.

In our experiment, we have studied the dependence of R on E. The measurements are somewhat analogous to those of Parks, Mochel, and Surgent,[4] who have observed size effects of quantized vortices in a superconductor.

The apparatus used for this measurement is shown in Fig. 1. A Po^{210} alpha source, S, produces ionization between the source and grid G_1. The voltage V_S controls the current density. G_1 has large openings (170 μ), while the opening size in G_2 was varied from about 4 to 10 μ.[5] The voltage, V_{12}, applied between G_1 and G_2 was varied continuously. The total energy, E, of a vortex at G_2 is then $e(V_S + V_{12})$, where e is the charge of the ion (assumed to have the magnitude of the electronic charge). Throughout the temperature range in which data were taken (0.29-0.40°K), frictional energy losses can be neglected.[2] The current, I, was measured on a collector situated behind G_2. Some typical current-voltage curves are

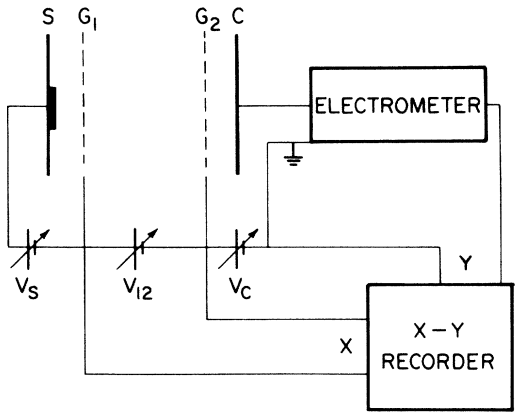

FIG. 1. Schematic diagram of the apparatus. The collector is actually guarded. Data were taken with both "attractive" and "repulsive" signs for V_C.