Observation of Resonances near 11 eV in the Photodetachment Cross Section of the H^- Ion*

H. C. Bryant, B. D. Dieterle, J. Donahue, H. Sharifian, H. Tootoonchi, and D. M. Wolfe
Department of Physics and Astronomy, The University of New Mexico, Albuquerque, New Mexico 87131

and

P. A. M. Gram and M. A. Yates-Williams
Los Alamos Scientific Laboratory, Los Alamos, New Mexico 87545
(Received 17 November 1976)

We have used a colliding-beam method to find two resonances in the photodetachment of electrons from H^-. A nitrogen laser beam is directed at variable angle across the 800-meV H^- beam at the Clinton P. Anderson Meson Physics Facility (LAMPF), resulting in a center-of-mass photon beam wavelength which is continuously tunable from the visible to the vacuum ultraviolet. Our preliminary measurements of the two resonances observed near 11 eV agree well with theoretical predictions within our experimental resolution of 10 meV.

We have studied the photodetachment cross section of H^- by directing the light from a nitrogen laser ($h\nu = 3.678$ eV) to intersect a beam of 800-MeV H^- ions ($\gamma = 1.853$). This Letter reports the observation of two prominent features in the cross section near 11 eV which we identify with the Feshbach and shape resonances discussed by Broad and Reinhardt,[1] Macek,[2] Lin,[3] and others.[4]

By varying the angle of intersection between the beams, the Doppler-shifted energy seen by the ion can be tuned from 1.8 to 11.5 eV. Photodetached electrons occupy nearly the same small phase space (less than 0.1 mrad·mm) as the H^- beam and continue forward from the interaction region with the same velocity as the ions ($\beta = 0.842$). These electrons, which have an energy of 435 keV, are swept from the H^- beam by a magnetic field and brought to a solid-state detector.

Figure 1 is a schematic diagram of the apparatus. Variation of the beam intersection angle α is accomplished by a rotating-mirror system. Mirror $M1$ accepts light from the entrance port of the vacuum chamber, $M2$ is located on the axis of rotation, and, finally, $M3$ directs the light into collision with the H^- beam. The laser and beam-forming optics are in a fixed position outside the vacuum. The mirror assembly is driven by a stepping motor through a 100:1 antibacklash gearbox. A fourteen-bit shaft-angle encoder coupled to the axle telemeters the angle. A change of the least significant bit corresponds to 0.384 mrad or, near 11 eV, to a step of 1.5 meV. The assembly also has on it a bracket (not shown) with crossed wires that can be passed through the H^- beam so that a means is available within our apparatus to survey accurately the geometry of the interaction region.

The upstream magnet sweeps aside electrons stripped from H^- ions during their traversal of a long beam transport. The downstream magnet brings photodetached electrons to the detector, where they are identified both by their unique energy and their temporal relationship to the laser burst.

The interaction region is shielded from stray magnetic fields by a slotted high-permeability cylinder. At the beam intersection point the residual field is ~0.4 G, which at $v = 0.842c$ yields an electric field of 190 V/cm, considerably less than the field strength thought to be necessary to introduce Stark-effect broadening of the shape resonance.[5]

The laser burst is so short and intense (~50 kW, instantaneous power) that quite often two or more electrons are detached (from different ions to be

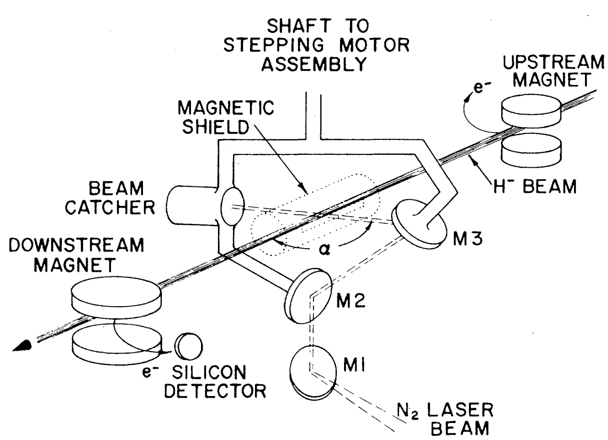

FIG. 1. Schematic diagram of the apparatus.

sure) during the same burst. The energy resolution of the detector enables us to correct the data for these occasions; peaks in the coincidence-gated pulse-height spectrum, corresponding to the arrival of up to six electrons at once, have been identified. However, this correction is rendered uncertain for some data points as a result of the statistics of the interaction between the two beams. The laser produces 4-ns-long bursts of light at 60 Hz. The H^- beam usually arrives in micropulses less than 1-ns long, separated by 40 ns.[6] This microstructure is modulated by 500-μs macropulses at 120 Hz. The laser is adjusted to fire once sometime during every other macropulse, but the overlap of the two microstructures is left to chance. One therefore expects a laser burst to overlap an H^- micropulse about 10% of the time. The multiplicity of electron events has been explicitly measured using the pulse-height spectra—but only for certain data points. For these points the distribution of two- and three-electron events can be seen to obey Poisson statistics. Unfortunately, values of $\bar{n}$, the average number of electrons, derived from (a) the multiplicity distribution and (b) the expectation based on a 10% chance of overlap between the photon and H^- pulses, are found to disagree by up to 15% for certain data runs. The disagreement can be treated to variation in laser-pulse width or in the H^--beam microstructure; occasionally, two micropulses 5-ns apart appear at the basic 40-ns separation instead of only one.

The intensity of the laser light is continuously measured by allowing stray light to reach a photodiode. Pulses from this diode are digitized, and the numbers are summed to provide an estimate of the integrated flux of photons during each data run. Periodic checks of the diode and "target-empty" runs are made by inserting a calorimeter in the light beam. The H^- current is measured by stopping the beam in a Faraday cup.

Knowledge of the energy alone does not suffice to identify the photodetached electrons because of the very high rate of electrons of the same energy produced by collisions with residual gas (10^{-7} Torr) in the interaction region. A coincidence requirement between the signal from the vacuum photodiode that looks at stray laser light and a signal from the electron detector sorts out the photodetached electrons. The coincidence resolving time is 80 nsec. Accidental coincidences are recorded by delaying one of the two signals before presenting them to another identical coincidence circuit. The ratio of reals to accidentals varies

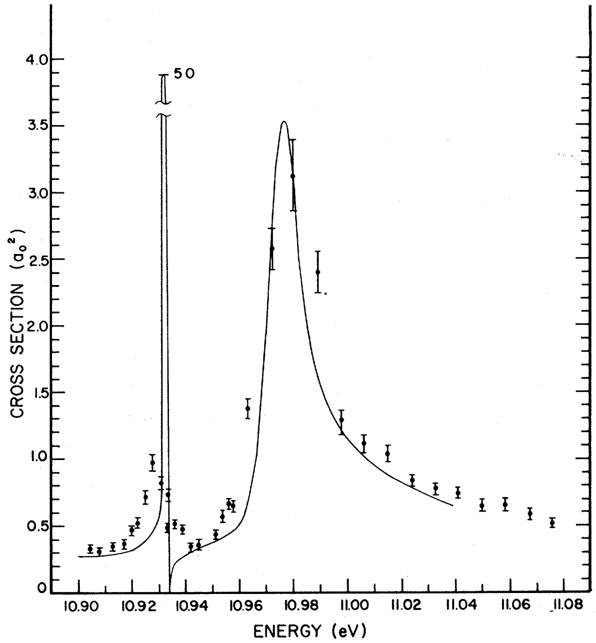

FIG. 2. Comparison of theory and experiment. The solid curve is from a calculation by Broad and Reinhardt (Ref. 1). The data points are from this experiment, normalized to theory at 10.90 eV. The error bars are statistical only.

between 20 to 1 in the peak of the shape resonance and 4 to 1 in the continuum. Count rates vary between 350 and 3500 counts per μC of H^- ions. To extract absolute cross sections the number of photons that traverse the H^- beam must also be known. We know relative values from run to run as described above, but do not report absolute values of the cross section here.

Figure 2 displays our data compared to the prediction of Broad and Reinhardt.[1] In this figure, the experimentally measured cross section is normalized to the low-energy continuum and the energy scale has been shifted by 33 meV, but not dilated, in order to align the low-energy peak with the Feshbach resonance. This shift is well within the error of our absolute energy calibration caused by uncertainty in the velocity of the H^- ions. The scale factor of the abscissa, which depends upon angle measurement, is relatively insensitive to variation in ion velocity.

The Feshbach resonance is thought to be much narrower than we can resolve: therefore, the shape it assumes in our data yields directly the resolution function of our apparatus. This width, 10 meV, when unfolded from the spectrum in the region of the shape resonance makes little change. We estimate the full width at half-maximum

(FWHM) of the shape resonance to be 23 ± 6 meV, consistent with the theoretical predictions which range from 15 to 28 meV.[1,3] The energy interval between the peaks is estimated to be 53 meV, compared to 46 meV in, for example, Broad and Reinhardt's[1] prediction. With normalization at low energy the data match the continuum at high energy.

Previous observations of the shape resonance in electron scattering from hydrogen have been reported,[7,8] but attempts to see it in the emission from an arc-discharge plasma,[9] and in a stellar spectrum,[10] have failed. The Feshbach resonance has, to our knowledge, so far gone unreported. We regard the observations reported here as persuasive evidence for the existence of these resonances in photoabsorption, but leave to future work the task of refining our preliminary measurement of cross sections and widths. The apparatus is also being modified to study the Stark-effect quenching of these structures.

We thank Dr. P. A. Lovoi for his contributions, Dr. W. A. Fitzsimmons for his advice, J. Hontas and J. Sanchez for their skilled workmanship, and Professor C. Leavitt for his support. We are indebted to the personnel of the LAMPF accelerator, especially J. van Dyke and Dr. R. Werbeck, for their large contribution to the success of this experiment.

*Work performed mostly under the auspices of the U. S. Energy Research and Development Administration.

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Observation of Parametric Instabilities in Lower-Hybrid Radio-Frequency Heating of Tokamaks*

M. Porkolab, S. Bernabei, W. M. Hooke, and R. W. Motley
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08540

and

T. Nagashima
Japan Atomic Energy Research Institute, Tokai Ibaraki-ken, Japan
(Received 29 November 1976)

Experimental data are presented which show that during lower-hybrid, radio-frequency heating of the Princeton University adiabatic toroidal compressor tokamak, parametric instabilities are excited, and the ion heating correlates with the presence of the parametric spectra. A theoretical interpretation of the parametric instabilities is presented.

Radio-frequency heating near the lower hybrid frequency may offer an attractive means to heat high-temperature plasmas toward thermonuclear conditions.[1] We wish to present experimental results which show that during lower-hybrid heating (LHH) of present day tokamaks, parametric instabilities play a fundamental role. In particular, our results show that the ion heating observed in the recent adiabatic toroidal compressor (ATC) tokamak LHH experiments is associated with the presence of parametric instabilities. Furthermore, the shape of the decay spectrum, when compared with theoretical calculations, allows us to estimate the position of the decay region, and this in turn gives us information about the radial location of the heating.

The experiments were performed on the Princeton University ATC tokamak.[2] An electrostatic probe was inserted in the plasma diagonally across the torus from the port where microwave power, up to 120 kW at 800 MHz, was injected through a single wave guide or a split wave guide.