RAPID COMMUNICATIONS

PHYSICAL REVIEW A VOLUME 32, NUMBER 3 SEPTEMBER 1985

Energy measurement of the lowest $^1P^0$ Feshbach resonance in H^-

D. W. MacArthur, K. B. Butterfield, D. A. Clark, J. B. Donahue, and P. A. M. Gram
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

H. C. Bryant and C. J. Harvey
University of New Mexico, Albuquerque, New Mexcio 87131

W. W. Smith
University of Connecticut, Storrs, Connecticut 06268

G. Comtet
Université Paris-Sud, 91400 Orsay, France

(Received 28 June 1985)

We use the 800-MeV LAMPF H^- beam to Doppler-shift the energies of photons from a Nd:YAG laser (where YAG denotes yttrium aluminum garnet) up to the 10–13-eV range. Using these Doppler-shifted photons and calibrating our apparatus by observing the Lyman resonances in H^0, we find that the energy of the first Feshbach resonance below $n=2$ in the H^- ion is 10.9264(6) eV. This energy is in good agreement with predictions and appears to indicate that the one-electron reduced-mass rydberg, rather than the infinite-mass rydberg, is appropriate to use for this Feshbach resonance.

Although there appear to be no singly excited states in the H^- ion,[1] there are many doubly excited states,[2] of which only the $^1P^0$ states can be excited in zero electric field by single-photon absorption from the $^1S^e$ H^- ground state. In the photodetachment process on H^-, which is the inverse of the e^--H^0 scattering described in Ref. 3, two prominent $^1P^0$ resonances have been observed in the photodetachment spectrum of the H^- ion at photon energies just below 11 eV. The lower of these states, first predicted from the Feshbach projection-operator formalism,[4] is commonly called the Feshbach resonance (see Table I). The higher-energy $^1P^0$ state, much broader than the Feshbach resonance, is usually called the shape resonance.[5] The method of laser photodetachment is a precise probe of these resonances in the H^- ion. Figure 1 shows a comparison of the theoretical prediction of Broad and Reinhardt[6] for the Feshbach and shape resonances with experimental data from an early version of our experiment.[7]

Our method depends on the intersection of the 800-MeV H^- beam at the Clinton P. Anderson Meson Physics Facility at Los Alamos laser (LAMPF), with photon beams derived from a Nd:YAG laser (where YAG denotes yttrium aluminum garnet). The apparatus used in this measurement, discussed in more detail in Ref. 8, is shown in Fig. 2.

TABLE I. Theoretical predictions for the first Feshbach resonance energy E_F. For purposes of comparison we take our value of $E_F = 10.9264(6)$ eV and subtract the accurately known H^0 electron affinity of 0.7542 eV given by Pekeris (Ref. 9), which gives a value of 10.1722(6) eV.

Feshbach resonance energy (eV)	Authors	Date	Ref.
10.173	O'Malley and Geltman	1965	12
10.258	Bhatia, Temkin, and Perkins	1967	13
10.172	Burke	1968	14
10.180	Seiler, Oberoi, and Callaway	1971	15
10.170	Matese and Oberoi	1971	16
10.1692	Broad and Reinhardt	1974	6
10.1699	Ajmera and Chung	1976	17
10.1685	Wendoloski and Reinhardt	1978	18
10.1729	Wishart	1979	11

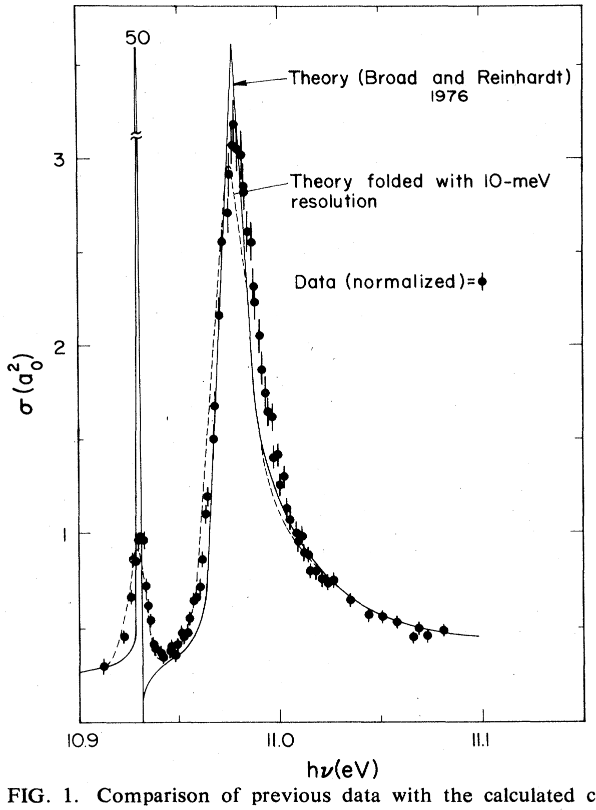
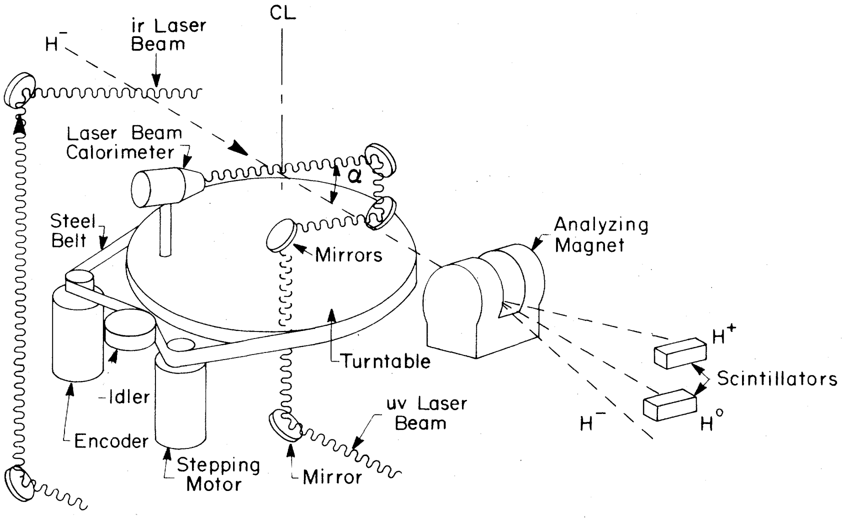


FIG. 1. Comparison of previous data with the calculated cross sections of Broad and Reinhardt (Ref. 6). Error bars reflect counting statistics only. The set of experimental points is normalized to fit the theoretical prediction in the continuum.



Schematic of LAMPF Photodetachment Apparatus

FIG. 2. Schematic of the photodetachment apparatus. The uv laser beam crosses the ion beam at the center of the chamber; the pulsed laser beam is aligned to enter the chamber along the vertical axis of the rotating optical bench and is directed across the interaction region by mirrors mounted on the optical bench. A calorimeter monitors the laser-beam intensity, the downstream analyzing magnet directs the reaction fragments into their respective detectors, where they are observed in coincidence with the laser pulses, and a stepping motor turns the optical bench with a minimum increment of 30.2 μrad through 360°. The intersection angle α of the two beams is monitored by a 14-bit shaft angle encoder (CL stands for the turntable center line). The infrared (ir) laser beam can be used as needed to create H^0's from H^-'s in the particle beam by photodetachment.

Two photon beams are derived from the Nd:YAG laser—the fundamental, of energy 1.164 87 eV, and the fourth harmonic, of energy 4.659 48 eV. The fundamental infrared (ir) beam can be directed to intersect the H^- beam upstream of the principal interaction region. The ir beam photodetaches some of the H^- ions to form a beam of neutral H^0 atoms with essentially unchanged velocity, and the ultraviolet (uv) beam intersects the H^- (or H^0) beam in the principal interaction region. Changing the angle between the uv laser beam and the particle beam varies the Doppler-shifted energy, in the range from 1.4 to 15.8 eV, of the fourth-harmonic photons seen in the particle rest frame. A magnet downstream along the path of the particles separates the positive and neutral reaction products from the residual H^- beam so that the products may be detected by scintillation counters.

With the upstream infrared beam turned off, a photodetachment spectrum such as the one shown in Fig. 1 is produced by the reaction

$$H^- + \gamma \rightarrow (H^-)^* \rightarrow H^0 + e \ .$$

In our experiment we detect the H^0 atoms. When the infrared beam is turned on, the H^0 atoms produced are excited to states in the atomic hydrogen Lyman series by varying the angle of intersection between the H^0 beam and the uv photon beam. Any H^0 atoms in states of $n=4$ or higher are ionized by passing through the field of the analyzing magnet, producing protons that are detected by the appropriate counter. Measurement of the angles corresponding to excitations of the very-well-known states in the hydrogen atom establishes an absolute relationship between the collision angle and the photon energy seen in the rest frame of the particle. The photon energy is dependent on the angle α between the beams and is given by $E = E_0\gamma(1+\beta\cos\alpha)$, where $\beta = v/c$, with v the velocity of the beam and $\gamma = (1-\beta^2)^{-1/2}$.

Data are taken at the same angle α on both sides of the particle beam so that the exact angle of the beam can be interpolated from the data. The Lyman series is shown schematically for both sides in Fig. 3. Figure 4 shows an example of resonance line data taken with small energy steps. The entire equation for the Doppler-shifted energy of the photons is

$$E = \gamma E_0 \left[1 + \beta \cos\left(\frac{\theta_{\text{enc}} - \theta_0}{K} \right) \right] \ .$$

Here θ_{enc} is the angle of the resonance peak measured with an optical encoder, θ_0 is the particle-beam position inferred from the data, and K is a conversion factor. The experiment was run twice. The first time K was measured directly

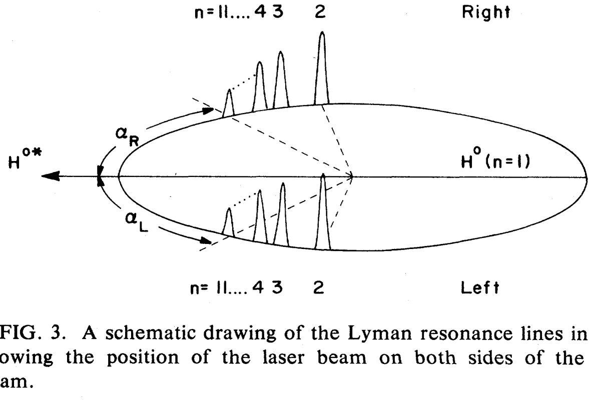


FIG. 3. A schematic drawing of the Lyman resonance lines in H^0 showing the position of the laser beam on both sides of the H^0 beam.

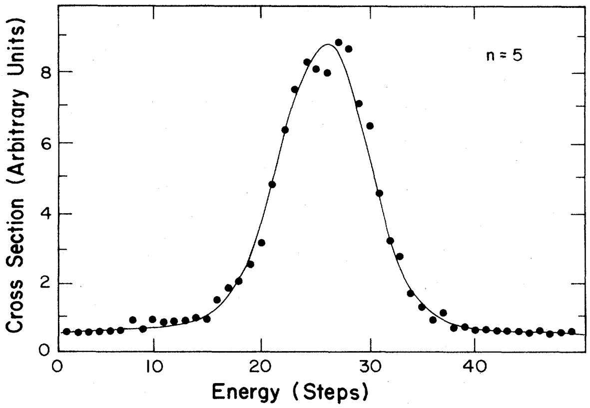


FIG. 4. Sample of the H^0 ($n = 5$) Lyman resonance data. Each point represents one angle where data were taken for ~ 30 s. Then the angle between the uv laser beam and the particle beam was changed mechanically. The solid line is a χ^2 minimization fit of a Gaussian line shape to the data. Each energy step represents ~ 0.85 meV.

using a theodolite, and the result was $E_F = 10.9265(7)$ eV (with E_F the Feshbach energy); the second time K was calculated from a fit to the H^0 data, with the result $E_F = 10.9259(14)$ eV. A weighted average of our two measured values gives 10.9264(6) eV as the Feshbach resonance energy. Restating this result in terms of the energy above the H^0 electron affinity (given by Pekeris[9] as 0.7542 eV), our result becomes $E_F = 10.1722(6)$ eV. In both experiments the β for the particle beam was calculated from the positions and well-known energies[10] of the Lyman resonance lines in H^0.

Theoretical predictions for the energy of the Feshbach resonance are given in Table I. All of these are corrected for the use of the one-electron reduced-mass rydberg $R_e = R_\infty(1 - M_e/M_p)$. The units had to be changed on some of the values using the conversion factors

$$R_\infty = 13.6058 \text{ eV and } R_e = 13.5984 \text{ eV} .$$

Our result rules out very large values of E_F and gives evidence that Wishart's calculation[11] is correct. The two-electron reduced-mass rydberg is defined as $R_{2e} = R_\infty \times (1 - 2M_e/M_p)$. Using either the infinite-mass rydberg or the two-electron reduced-mass rydberg would change the predicted Feshbach resonance energy by ~ 5.5 meV. These rydbergs would be required if the correlation between the two electrons were completely positive or negative, respectively. We see no evidence of a 5.5-meV effect and conclude that the one-electron reduced-mass rydberg is the correct one to use in this case.

We have measured the energy of the Feshbach resonance in the H^- ion to be 10.9264(6) eV, in good agreement with recent theoretical predictions. This value suggests that the one-electron reduced-mass rydberg is the correct one to use with the first Feshbach resonance in the H^- system. This measurement of the Feshbach resonance energy provides a calibration for all of our other experiments that used this resonance as a reference point. A new experiment we are now preparing to measure the Feshbach resonance energy to 0.1 meV at LAMPF may further resolve the theoretical discrepancies.

This work was supported by the U. S. Department of Energy in part under Contract No. DE-A50477ER03998. One of us (G.C.) was supported by NATO and Centre National de la Recherches Scientifique.

---

[1] R. N. Hill, Phys. Rev. Lett. **38**, 643 (1977).

[2] J. S. Risley, *Atomic Physics 4,* edited by G. zu Putlitz, E. W. Weber, and A. Winaker (Plenum, New York, 1975), pp. 487–528.

[3] See, e.g., G. J. Shultz, Rev. Mod. Phys. **45**, 378 (1973).

[4] H. Feshbach, Ann. Phys. (N.Y.) **5**, 357 (1958); **19**, 287 (1962).

[5] The Feshbach operator formalism can also be used to describe the shape resonance.

[6] J. T. Broad and W. P. Reinhardt, Phys. Rev. A **14**, 2159 (1976).

[7] P. A. M. Gram, J. C. Pratt, M. A. Yates-Williams, H. C. Bryant, J. Donahue, H. Sharifian, and H. Tootoonchi, Phys. Rev. Lett. **40**, 107 (1978).

[8] H. C. Bryant *et al.,* Phys. Rev. A **27**, 2889 (1983).

[9] C. L. Pekeris, Phys. Rev. **126**, 1470 (1962).

[10] R. L. Kelly, University of California Research Laboratory (Stanford Research Institute, Menlo Park, California) Report No. 5612, 1959 (unpublished), p. 1.

[11] A. W. Wishart, J. Phys. B **12**, 3511 (1979).

[12] T. F. O'Malley and S. Geltman, Phys. Rev. **137**, A1344 (1965).

[13] A. K. Bhatia, A. Temkin, and J. F. Perkins, Phys. Rev. **153**, 177 (1967).

[14] P. G. Burke, Adv. At. Mol. Phys. **4**, 173 (1968).

[15] G. J. Seiler, R. S. Oberoi, and J. Callaway, Phys. Rev. A **3**, 2006 (1971).

[16] J. J. Matese and R. S. Oberoi, Phys. Rev. A **4**, 569 (1971).

[17] M. P. Ajmera and K. T. Chung, Phys. Rev. A **12**, 475 (1975).

[18] J. J. Wendoloski and W. P. Reinhardt, Phys. Rev. A **17**, 195 (1978).