A Quick Survey of the Physics of the Negative Ion of Hydrogen

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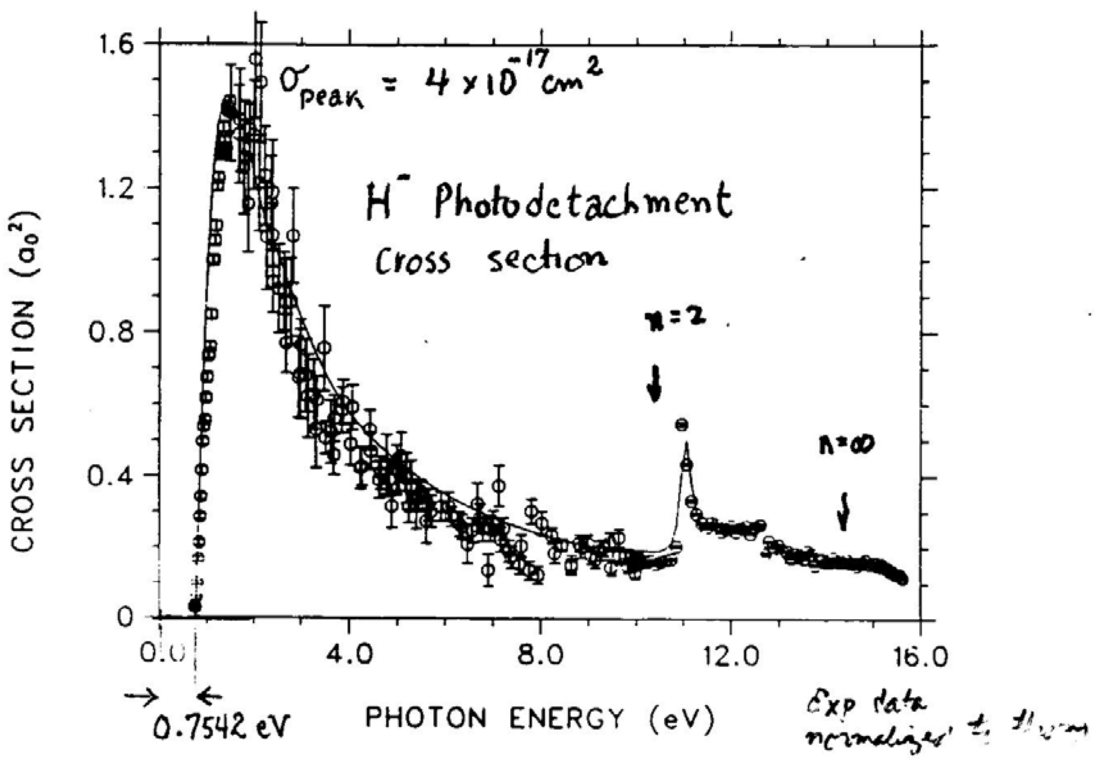
We are here today to discuss ways we can use H- to enhance the performance of the Main Injector. But besides being a useful tool in accelerator physics, H- has an intrinsic interest of its own as a relatively simple quantum mechanical three-body problem. Therefore, before we start discussing applications, I will present a short review of what is known about the ion, from an experimental point of view. Some of its properties, that I'd like to briefly describe, may also turn out to be useful for practical applications.

First something very general about H-. If it were not for the high correlation between the motions and positions of the two electrons, it would not be bound. After all why would a neutral object attract another charge? Like most negative atomic ions, H- has only one bound stable state. There is also a state sometimes termed "the second bound state". (The ground state is $1s^2\ {}^1S^e$ and this state is $2p^2\ {}^3P^e$). This state is forbidden to just fall apart into a hydrogen atom and an electron ("autodetach"), but it can decay into three bodies: a H atom, an electron and a photon. In this sense, it is unique in atomic physics. It cannot be excited by single photon absorption and its lifetime is 1.73 nano-second, so it presents no problems in a H- beam, even if it emerges from the source. The H- lacks, completely, singly excited states in which only one electron is excited and the other remains in the ground state. Compared with He, another simple two-electron system, with all kinds of spectral lines, H- seems quite dull. However, don't give up on H-, as it has an infinite series of manifolds of doubly excited states. H- is not singly exciting, but it's doubly exciting! More about those shortly.



Here is the photodetachment spectrum of H-. The threshold is at 0.7542 eV, because that is the binding energy of an electron to H atom, the so called "electron affinity" of hydrogen. Note that the slope rises as the excess energy to the 3/2 power at first (the Wigner threshold law), levels out and peaks at 1.5 eV, then declines like the cube of the reciprocal of the photon energy. A very simple and useful function. If there had been any singly excited states, they would have been seen as bumps below 0.75 eV. If we follow the curve out to around 10.9 eV, we start to see structure in the continuum. This structure persists until we reach the two electron continuum at 14.35 eV (13.6 +.75). After that the continuum is featureless.

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

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(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.

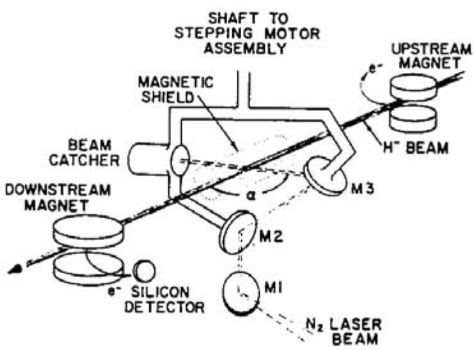

FIG. 1. Schematic diagram of the apparatus.

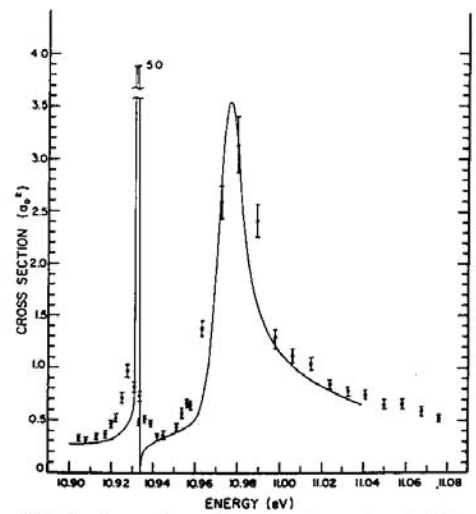

FIG. 2. Comparison of theory and experiment. The solid curve is from a calculation by Broad and Reinhardt (Ref. 1). The data points are from this experiment, normalized to theory at 10.90 eV. The error bars are statistical only.

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

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

The tale of two resonances. The first structure we encounter, as we raise the photon energy, is the lowest-lying

PHYSICAL REVIEW A, VOLUME 61, 022702

High-resolution VUV spectroscopy of H^- in the region near the $H(n=2)$ threshold

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(Received 23 July 1999; published 5 January 2000)

Experimental investigations of the photodetachment cross section for the negative hydrogen ion in the region near the $H(n=2)$ threshold are discussed. Doppler-tuned spectroscopy in a collinear geometry is used to obtain a comparatively high resolution in this photon-energy range. The ions are accelerated in the ASTRID storage ring, which allows an accurate velocity measurement and further enables the application of momentum-spread reduction techniques. The fixed-frequency vacuum-ultraviolet laser beam (118 nm) is generated by sum-frequency mixing in a xenon gas cell. The photodetachment cross section exhibits pronounced resonances that correspond to the rich spectrum of doubly excited ^1P states near the $H(n=2)$ threshold. The position of the resonances is determined with an accuracy that challenges the current theoretical developments. The experimental observations are used to predict the behavior of a dipole series below $H(n=2)$. The measurement on both hydrogen and deuterium facilitates a study of isotope effects. By means of momentum-spread-reduction techniques it should be possible to resolve the natural linewidth of the narrow dipole resonances. Preliminary studies show that improvements in electron cooling of the H^- beam promise to reach this limit. Finally, the feasibility of extending the high-resolution work to higher-lying ($n=3$) resonances is briefly discussed.

PACS number(s): 32.80.Gc, 39.30.+w

I. INTRODUCTION

Investigations of the neutral hydrogen atom are at the heart of the development of atomic theory. The Coulomb potential is one of the few tractable problems in non relativistic quantum mechanics. It is a remarkable fact that when trying to describe systems with more than a single electron, serious approximations have to be made. Guidance in developing a description of multielectron systems must then come from comparison with experiments. Although the independent electron approximation is generally quite good for systems in singly excited states, the description of multiply excited states is more complicated, since the interaction between two (or more) electrons of similar excitation is strong and their repulsion is poorly described by a single-particle potential. In this case the independent electron approximation may fail even in assigning meaningful quantum numbers to the excited states. In the development of alternative theoretical descriptions of these highly correlated systems, it can be useful to draw on studies of fundamental few-electron systems as, e.g., helium [1].

Over the last 20 years, experimental studies of the negative hydrogen ion have provided a testing ground for the development of the theory of correlated multielectron systems (see, e.g., [2–4] and references therein). Compared to the helium atom, the structure of the negative hydrogen ion is even more strongly influenced by interelectron repulsion, since the nuclear attraction is smaller for this system. In fact,

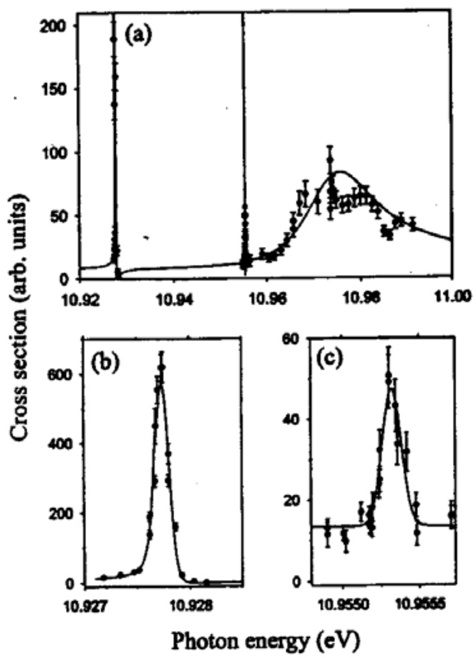

FIG. 2. Relative photodetachment cross section (measured neutral atom yield corrected for collisional background) vs. effective photon energy. The error bars indicate a statistical uncertainty of one standard deviation. (a) The full energy range. The data have been normalized to the theoretical results of Lindroth [32] (solid curve). Some of the measured points on the $_2\{0\}_3^-$ resonance at 10.9277 eV exceed the vertical scale of the plot. (b) Blow-up of the region near the $_2\{0\}_3^-$ resonance. The solid curve shows a fit to a Fano profile convolved with the photon energy resolution as discussed in the text. (c) Blow-up of the region near the $_2\{0\}_4^-$ resonance. The solid curve shows a fit to a Gaussian profile.

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1050-2947/2000/61(2)/022702(11)/$15.00

Feshbach resonance. This is a major enhancement in the photodetachment rate, but unfortunately for our purposes it is only about 30 microvolts wide. It can be thought of as a (2s3p-2p3s) $^1P^o$ state. There is also a second, much narrower Feshbach state, (2s4p-2p4s) $^1P^o$ discovered in the late 90's in Denmark, some 40 millivolts above it. These resonances are converging on an energy of the photon that corresponds to the liberation of one electron from H-, leaving behind a H atom excited to n=2. The photon energy is thus 10.2 eV+.75 eV = 10.95 eV. Then comes a relatively broad resonance, the so-called "shape resonance" 2s2p $^1P^o$. This is a very durable resonance, as we shall see later, that actually gets stronger when you put it in an electric field. The shapes of the resonances, embedded in the single electron continua as functions of energy are called "Fano profiles" and are a quantum mechanical consequence of the interference of essentially two processes involved in the production of the detachment.

The importance of the correlations between the two electrons cannot be stressed too highly. H- would not exist without correlations. The independent particle model of a state $|n_1l\ ,n_2l_2,L,S,\pi\rangle$ is replaced by $|nmKTAS\pi\rangle$. The two electrons form essentially a quasiparticle specified by the correlation quantum numbers KTA.

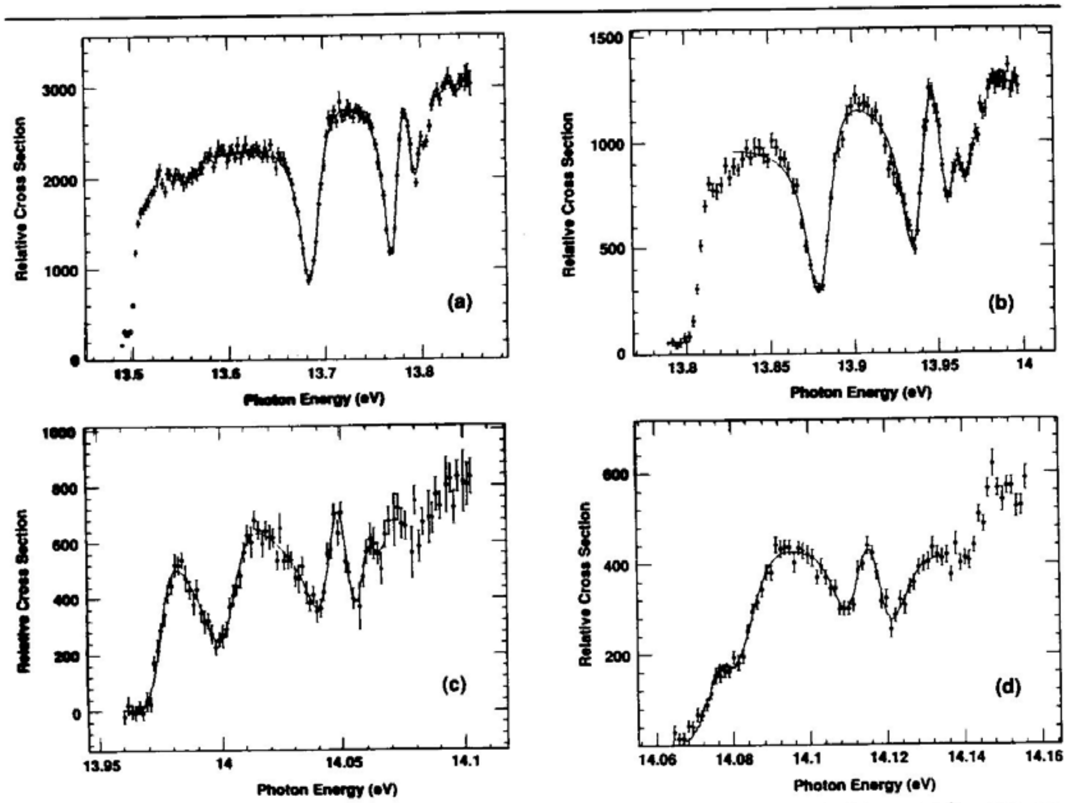


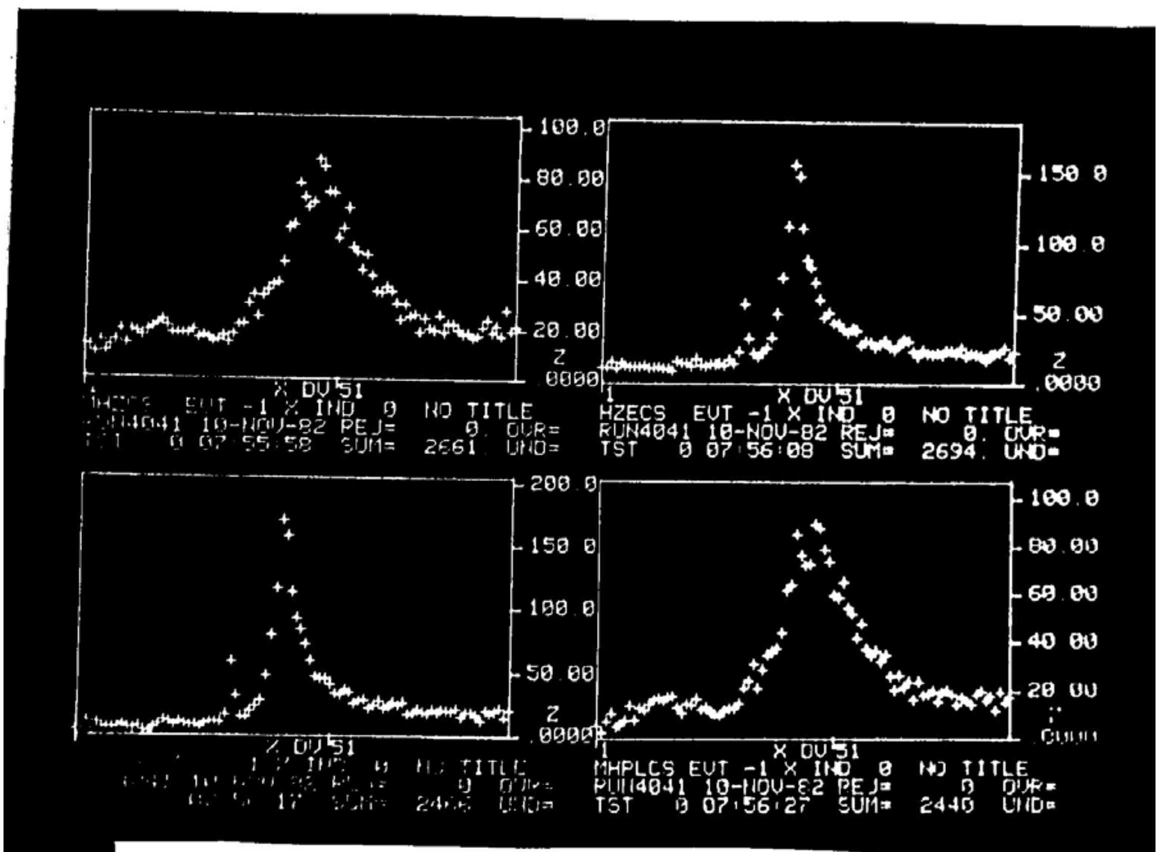
FIG. 1. Partial photodetachment cross sections of H^-, showing production of neutral hydrogen in (a) $n \geq 4$ ($\chi^2/\nu=0.97$, 55% C.L.), (b) $n \geq 5$ ($\chi^2/\nu=1.85$, 0.01% C.L.), (c) $n \geq 6$ ($\chi^2/\nu=0.88$, 73% C.L.), and (d) $n \geq 7$ ($\chi^2/\nu=0.98$, 50% C.L.). Instrumental resolution is 8.3 meV. Threshold energies are $n=4$, 13.5054 eV; $n=5$, 13.8084 eV; $n=6$, 13.9746 eV; $n=7$, 14.0748 eV; $n=8$, 14.1398 eV.

The manifolds of window resonances. Starting with the threshold for detachment of an electron from H- leaving the residual core hydrogen atom in n=3, we find successive series of "window", or as you say, "notch" resonances, converging first on n=3, then n=4, etc. The same sort of thing can be seen in He.

Other resonances. Photodetachment from the H- ground state using a single photon is limited by the selection rules to singlet P continua, so that only states with singlet P even parity are accessible directly. However, there are many other states in H-, and we have been able to see them in our experiments. There are two ways they may be studied in an

H- beam, in multiphoton absorption and by mixing with allowed states in the presence of an electric field. We shall discuss these cases later.

The double detachment. Finally when the energy of the photon is at 14.35 eV we can leave the residual H atom in n=∞, that is, both electrons can be detached. Here there is theoretical interest in the nature of the threshold law, which we have tried to elucidate, but I shall not go further here. Some people think the Wannier threshold law describes the situation pretty well; others do not.



Raw spectra in the Shape-Feshbach region taken under high fields alternating at 5 Hz with zero field as displayed on line on cathode ray screen.
a.) Run 4041: top left trace, electron rate vs. intersection angle of the laser beam with the ion beam in 2.6 MV/cm (5.6 kG in the lab); top right, electron rate zero field; bottom left, proton rate zero field; bottom right, proton rate in 2.6 MV/cm. The proton and electron data were taken simultaneously, and the angular scale is the same in all.

The effects of electric fields. We have studied the effects of electric fields on the structures of the ion mostly using the very strong motional electric fields one can induce in the ion's rest frame using modest laboratory magnetic fields transverse to the ion beam. The lowest Feshbach resonance splits into a triplet when it finds itself in a weak electric field and then quenches; the shape resonance on the other hand requires much stronger fields to show an effect, and in fact becomes stronger in strong electric fields. It appears that the shape mixes with an underlying singlet D state, just as the Feshbach mixes with an underlying single S state. The effects are laser-polarization dependent.

Threshold region. Effects of electric fields. The dual beam interferometer. If even the tiniest electric field is applied to a negative ion, in principle it becomes stable, as the wave-function is free asymptotically. It just may take a long time to tunnel out. That lifetime τ in an electric field F can be expressed quite well by the formula

$$\tau = \frac{a}{F}\exp\left(\frac{b}{F}\right),$$

where $a = 3.073(10)\times 10^{-6}$ sV/m and $b = 4.414(10)\times 10^{9}$ V/m , all evaluated in the ion's rest frame. This behavior is of great interest in designing the proposed beam line, of course, but we will defer such discussions now. What happens if one tries to photodetach this asymptotically free electron? Consider the case where the laser beam is polarized along the direction of the applied electric, which can be arranged as shown in the illustration. The electron is lifted up above the energy barrier by absorbing a photon and the makes its way out preferentially along the electric field lines. The

VOLUME 58, NUMBER 23 PHYSICAL REVIEW LETTERS 8 JUNE 1987

Observation of Motional-Field–Induced Ripples in the Photodetachment Cross Section of H^-

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A ripplelike structure in the photodetachment cross section of H^- near threshold, arising from autocorrelation in the wave function of the photoelectron in the presence of motional electric fields, is observed.

PACS numbers: 32.80.Fb, 32.60.+i

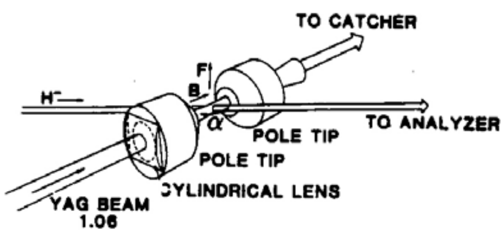


FIG. 1. Schematic representation of the interaction region. The magnetic field **B** is kept parallel to the laser direction so that states for which the laser light is pure π and σ in the center-of-mass system can be prepared.

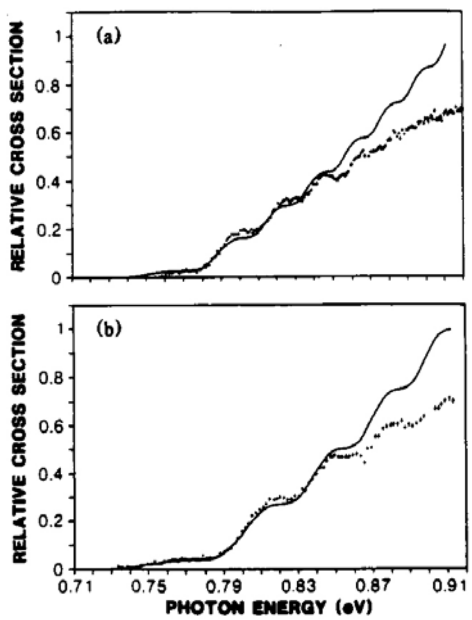


FIG. 2. Relative cross sections for π polarization compared with the theory of Reinhardt and Overman (solid curve). (a) Laboratory field of 300 G. (b) Laboratory field of 470 G.

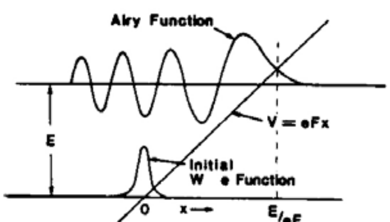
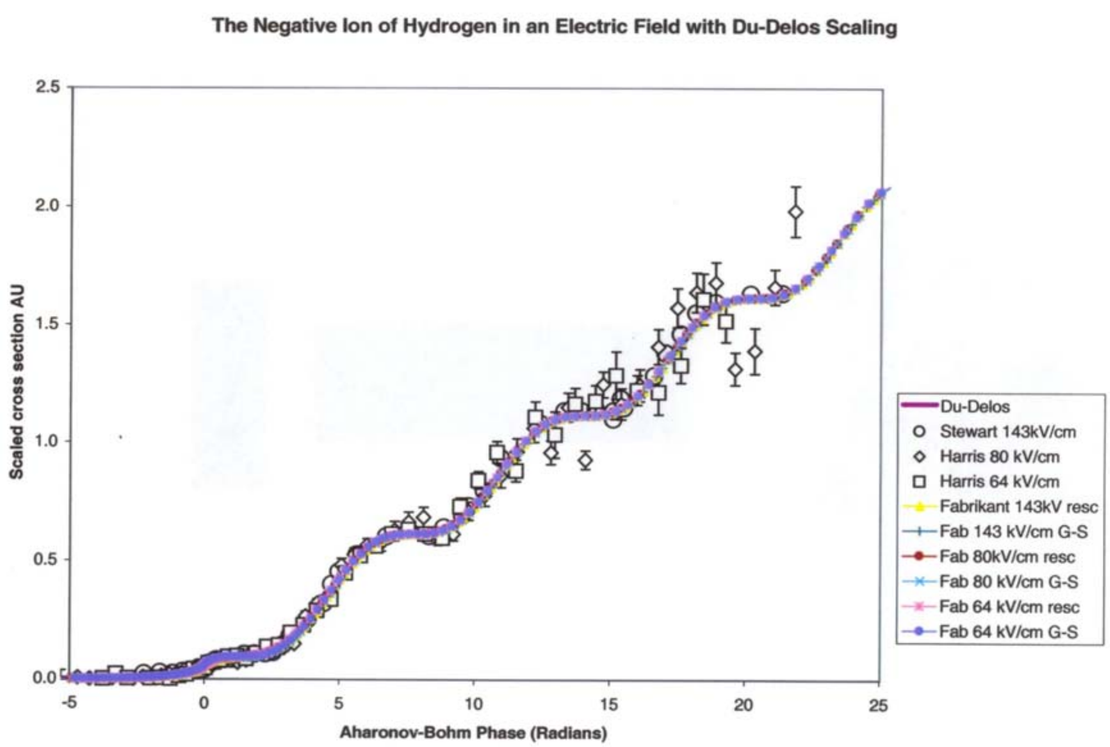


FIG. 3. The absorbed photon causes transitions from the initial bound wave function to that of an electron in a constant electric field. E is the energy above zero-field threshold. The classical turning point for the ejected electron in the constant field F is a distance E/eF from the center of the atom.

I.I. Fabrikant JETP 52 1045 (1980)

wave function of the detaching electron divides into two lobes, one going along the field direction and the other going "upstream", against the field. Think of two coherent electron waves traveling in opposite directions. Well, the one going upstream will eventually run out of steam and fall back toward the atom from which it was ejected. It is essentially reflected by the rising potential wall. Now assuming the process of ejection is still going on, the reflected wave will then lap back over the lobe which is heading down stream. The total wavefunction of the ejected wave is the sum of the two lobes which can interfere, just as in a two beam interferometer, the Michelson, for example. As one increases the photon energy the phase between the two lobes varies between constructive and destructive, so that the cross section develops ripples.



Du-Delos Formulas

M.L. Du & J.B. Delos, Phys Rev A 38, 5609 (1988)
Phys Lett A 134, 476 (1989)

$H^- + h\nu \rightarrow H^0(1) + e$ in electric field F

$$\boxed{\sigma(E,F) = 0.3604 \frac{F}{(h\nu)^3} D(\phi) \qquad \text{a.u.}}$$

where F is the field strength, $h\nu$ is the photon energy, E is the detached electron energy $= h\nu - E_0$, where E_0 is the electron affinity of hydrogen. ϕ is the Aharonov-Bohm phase shift for the reflected electron $\oint v\,dt = \phi = \frac{4\sqrt{2}}{3} \frac{E}{F}^{3/2}$

for π polarization (laser linearly polarized along applied electric field)

$$D_{\parallel}(\phi) = \frac{1}{4\pi}\left[\phi + \cos\phi\right], \quad \phi \gtrsim 11$$

below threshold,

$$\phi = -\frac{4\sqrt{2}}{3}\left(\frac{-E}{F}\right)^{3/2}$$

$$D(\phi) = \frac{1}{8\pi} e^{-\phi}, \quad \phi \lesssim -14$$

Disagree by factor of 2 @ $\phi = 0$

for σ polarization (laser linearly polarized perpendicular to the applied electric field)

$$D_{\perp}(\phi) = \frac{1}{4\pi}\left[\phi - \frac{1}{12\pi}\frac{\sin\phi}{\phi}\right]$$

Multiphoton processes. Observation of the singlet D state.

VOLUME 75, NUMBER 16 PHYSICAL REVIEW LETTERS 16 OCTOBER 1995

Resonant Two-Photon Detachment through the Lowest Singlet *D* State in H^-

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(Received 6 June 1995)

We report the measurement of the two-photon detachment spectrum of the $^1D^e$ resonance of H^- just below the $n = 2$ threshold. The excess photon detachment resonance fits a Fano profile with energy 10.872(2) eV (relative to H^- ground state), a width of 0.0105(10) eV, and a shape parameter of −8(2). To our knowledge, this describes the first time direct multiphoton excitation of a resonance has been observed in any negative atomic ion.

PACS numbers: 31.50.+w, 32.80.Fb, 32.80.Wr

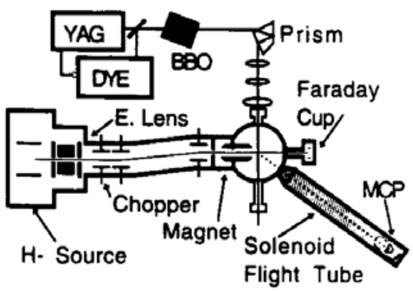


FIG. 1. A schematic of the experimental arrangement. The magnetic bottle is an adaptation of a Kruit-Read design modified by Kyrala [13,14].

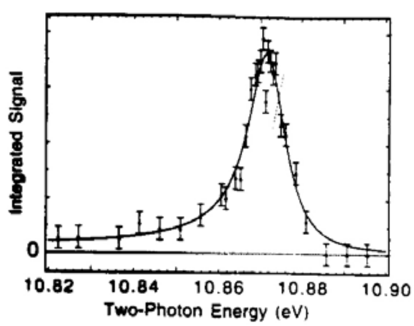


FIG. 3. The yield of electrons in the two-photon detachment continuum in the region of the $^1D^e$ resonance as a function of energy. Shown also is the fit to a Fano line profile (solid) and the theoretical prediction of Proulx and Shakeshaft (dashed) [17].

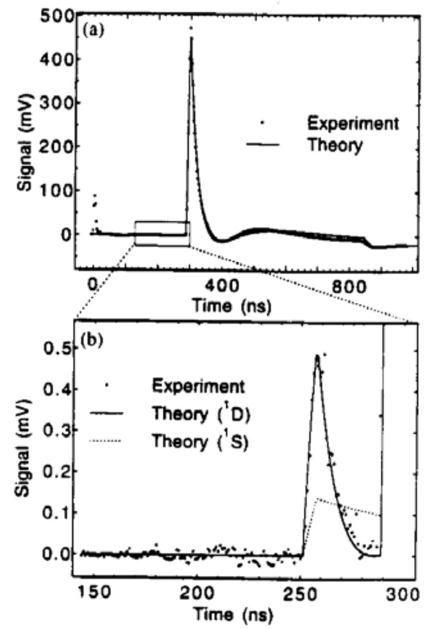
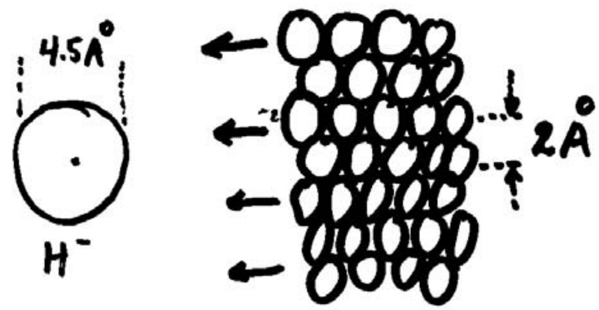


FIG. 2. (a) A typical time-of-flight electron spectrum for the one-photon detachment process. The temporal distribution reflects the angular distribution for a given center of mass electron energy. (b) An enlarged view (~1000×) of the rectangular area of (a) shows the portion of the two-photon signal that we observe in these experiments.

Work with foils.

How does it feel to be an H^- ion passing through a carbon foil?



for a 20μg/cm² foil, time to pass through is $\frac{900\text{Å}}{\gamma\beta c}$
$\simeq$ 0.2 femtoseconds

the crowd of carbon atoms is a chaotic electromagnetic pulse of intensity ~ 10^{18} W/cm² (F ~ 10^{10} V/cm)

central frequency of disturbance ~ 2×10^{18} Hz
or $\hbar\omega$ ~ 9 keV

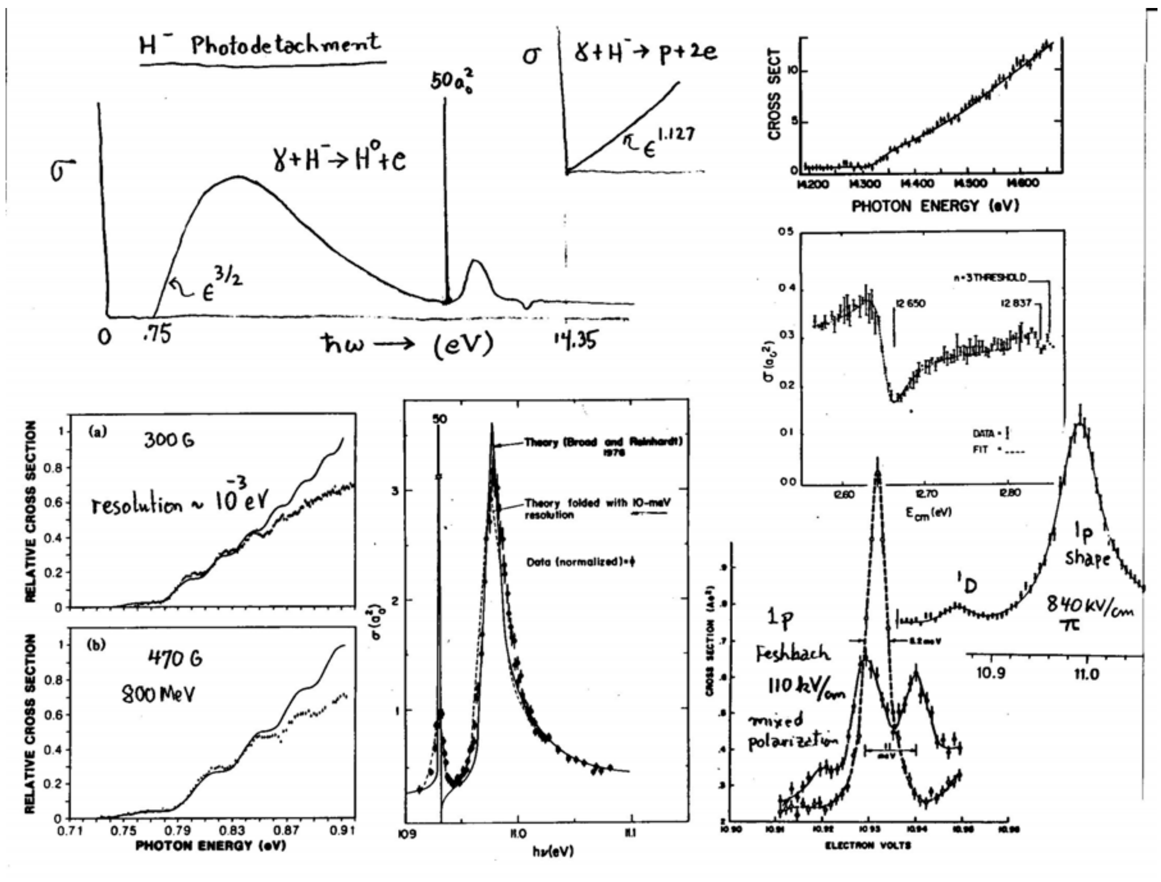
But ponderomotive shift is only

$$E_p = \frac{1}{4}\,\frac{e^2 F_0^2 \gamma^2}{m\omega^2} = 0.73 \text{ meV !}$$

and KE loss of electron relative to proton is 10 meV!

.

Summary



The availability of the 8 GeV H- beam for atomic physics would be a bonanza

One of our collaborators in her postdoc days: Carol Harvey Johnstone