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PHOTODETACHMENT OF RELATIVISTIC IONS*

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Summary

A series of fundamental laser ion beam experiments has been made feasible by the high-quality, relativistic ($\beta = 0.842$) H^- ion beam available at the Clinton P. Anderson Meson Physics Facility (LAMPF). The relativistic Doppler shift of the light from an ordinary ultraviolet laser provides what is, in effect, a continuously tunable vacuum-ultraviolet laser in the rest frame of the moving ions. The Lorentz transformation of a modest laboratory magnetic field provides an electric field of several megavolts/centimeter. The latest results of our photodetachment work with H^- beams and our spectroscopic work with H^0 beams are presented. Our plans for future work are discussed.

Introduction

The H^- ion is the simplest two-electron system to describe quantum mechanically and has therefore attracted much theoretical attention as a proving ground for models and their extensions to more complicated systems. It also is of practical interest to astrophysics, to neutral beam injection for fusion and to accelerator design.

The structure of H^- is closely related to resonances in electron-atom scattering and in photodetachment. Unfortunately, the resonance region of H^- is difficult to study experimentally. The photon energies required for photodetachment lie in the vacuum ultraviolet region where no tunable lasers yet exist. The combination of establishing a monochromatic electron beam and a source of atomic hydrogen for scattering experiments has been a difficult problem. Stark studies of the lower lying states require electric fields on the order of megavolts/centimeter which are not available in the laboratory.

Method

We have overcome the experimental difficulties in the case of photodetachment by exploiting the large Doppler shift that results from colliding a relativistic H^- beam with the photon beam from an ordinary ultraviolet laser. The Doppler shift formula for the energy of the photons in the rest frame of the H^- ions is given by

$$E = \gamma E_L (1 + \beta \cos \alpha) \quad (1)$$

where E_L is the energy of the photons in the laboratory frame, $\beta = v/c$ for the ions, $\gamma = (1 - \beta^2)^{-1/2}$, and α is the angle of the intersection between the two beams. A Yttrium-Aluminum-Garnet (YAG) laser with accessories for producing the second, third, fourth,

and fifth harmonics allows us to produce continuously variable photon energies from 0.35 to 20 eV in the rest frame of the ions.

A magnetic field applied transverse to the velocity vector of the H^- beam is Lorentz transformed according to

$$E_{cm} = \gamma \beta c B_L \quad (2a)$$

$$B_{cm} = \gamma B_L \quad (2b)$$

where E_{cm} and B_{cm} are the magnitudes of the electric field and magnetic field in the rest frame of the ions and B_L is the magnetic field in the laboratory frame. A magnetic field of 2.2 kG in the laboratory results in an electric field of 1 MV/cm in the rest frame of the $\beta = 0.842$ ions.

The energy resolution that we have achieved is about 0.005 eV in the resonance region. The resolution varies somewhat due to the kinetic energy spread of the H^- beam and to the angular divergence of the beams. The contribution of these effects to the energy resolution can be determined by taking partial derivatives of Eq. (1):

$$\frac{\partial E}{\partial \alpha} = \gamma \beta E_L \sin \alpha \quad (3a)$$

$$\frac{\partial E}{\partial T} = \frac{E_L}{Mc^2} (1 + \frac{\cos \alpha}{\beta}) \quad (3b)$$

$$\frac{\partial E}{\partial E_L} = \gamma (1 + \beta \cos \alpha) \quad (3c)$$

where T and M are the kinetic energy and mass of the H^- ions. In practice, the contribution of the laser line width, Eq. (3c), and the contribution of the H^- beam angular divergence are negligible compared with the H^- kinetic energy spread and the laser angular divergence. Fortunately, nature has provided us with a delta-function in the form of the narrow Feibach resonance near $n = 2$ which allows us to constantly check on our energy resolution and scale calibration.

A schematic of the apparatus is shown in figure 1. The present apparatus features an improved rotating mirror system for Doppler tuning the laser beam and downstream scintillators for detecting the photodetached H^0 and H^+ as well as the electrons.

The scintillators were originally added to look for the H^+ signal from double photodetachment, but they will now be a regular feature. The improved time resolution of the scintillators (5 ns) has allowed us to increase the H^- ion current to 100 nA without significant backgrounds from residual gas stripping. The H^- beam is bent by the upstream magnet and then bent back into a Faraday cup by the downstream magnet.

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The H^+ , H^0 , and e^- , which are created by photodetachment or gas stripping between the two magnets are directed into their respective scintillators. This arrangement protects us from the situation where the beam suddenly becomes entirely H^+ due to the insertion of beam diagnostic devices upstream.

Results

We have reported our observations of the $1P$ "shape" and Feshbach resonances near the $n = 2$ region¹, the induction of the $1S$ by Stark mixing², and the observation of two resonances just below the $n = 3$ threshold³. We will only discuss our most recent results here.

1. Threshold Region for Single Photodetachment

A closeup of the threshold region near 0.75 eV is shown in figure 2. These data were taken with the fundamental frequency of the YAG laser ($E_L = 1.1649$ eV). They were fit to a power law of the form

$$\sigma(E) = A(E - E_0)^n + C; \quad E \geq E_0. \quad (4)$$

The nonlinear optimization routine MINUIT⁴ was used to minimize the χ^2 between the theoretical curve and the experimental data. The result of the fit for the four free parameters was

$$E_0 = 0.7528 \pm 0.0007$$

$$n = 1.279 \pm 0.026$$

$$C = 3.06 \pm 0.04$$

$$A = 800 \pm 10$$

The background term, C , is believed to be due to laser photons that are reflected backward from the photon beam stop. Both A and C are subject to an overall arbitrary normalization.

If the threshold dependence follows the Wigner law⁵, then the exponent n should be equal to $3/2$. This data, which ranges up to 0.060 eV above threshold, is clearly not consistent with the Wigner exponent. However, we know that the threshold law is only valid over a small energy range above threshold.

Figure 1. Schematic view of the crossed beam apparatus.

As we restrict the fit closer and closer to threshold, the exponent approaches $3/2$. The Wigner law appears to be applicable only over the first 0.025 eV above threshold.

The threshold, E_0 , is relatively insensitive to the energy range used in the fit. The error on E_0 of 0.0007 eV is statistical only; the possible systematic error is much greater. The zero of the angle measurement and the velocity of the beam must be known in order to fix the energy scale. In this particular case, the velocity of the beam is unimportant since we are working very near the Doppler free angle where Eq. (3b) goes to zero. Our possible systematic error of 0.005 eV comes entirely from the fact that we neglected to scan the threshold region on both sides of the H^- beam. If we simply do this in a future experiment, we can reduce the systematics to ≈ 0.001 eV. However, even with the large systematic uncertainty we can still quote the best experimental determination of the binding energy of the H^- ion. A comparison of several experimental and theoretical determinations is shown in Table I.

2. Threshold Region for Double Photodetachment

The threshold behavior for photoejection of both electrons from H^- and the related problem of electron impact ionization have been under study both theoretically⁶⁻¹⁰ and experimentally¹¹⁻¹² for some time. Near threshold, the two electrons must be almost perfectly correlated in energy and angle in order to escape. This high correlation makes the usual independent particle techniques difficult to apply. Experimental studies of the threshold region are therefore important tests of theoretical techniques for dealing with correlated systems.

The theoretical approaches have included classical and quantum mechanical treatments. Most theories predict a power law dependence of the form

$$\sigma(E) \sim (E - E_0)^n \quad (5)$$

where n ranges between 1.0 and 1.5 depending upon the degree of correlation. The best accepted theoretical

Figure 2. Photodetachment cross section near threshold. The curve is the result of the fit discussed in the text.

TABLE I
ENERGY OF THE GROUND STATE OF H^- . NUMBER IN PARENTHESIS
GIVES UNCERTAINTY IN LAST DIGITS.

E(eV)	Method	Investigator
<u>Theoretical</u>		
-0.754215(2)	Variational determination - 444 order	Pekeris (1962)
-0.754220(2)	Variational determination - 20 order	Aashamar (1976)
<u>Experimental</u>		
-0.5(1)	Surface ionization	Khvostenko and Bukarskii (1960)
-0.77(2)	Extrapolation of photodetachment cross section	Weisner and Armstrong (1964)
-0.756(13)	Stellar photodetachment spectrum	Berry (1969)
-0.776(20)	Crossed-beam, photodetachment threshold	Feldman (1970)
-0.753(5)	Crossed-beam, photodetachment threshold with Doppler-tuned laser source	This experiment

value for n is that of the classical Wannier theory⁶ which predicts $n = 1.12689...$ This value has also been supported by quantum mechanical treatments.

We have recently applied our colliding beam technique to this problem using the scheme shown in figure 1. The H^+ ion is the signal for double photodetachment and the H^0 ion is the signal for single photodetachment. The downstream magnet is used to separate them from the H^- beam which is much more intense. Unfortunately, this magnet also contributes a background to the H^+ channel due to motional electric field stripping of excited H^0 states produced in single photodetachment.

Since the bend angle of the ions in the magnet is proportional to the product of the field strength and the length, this problem has been largely eliminated by using a magnet which is both long and weak. Although the field stripping is a problem, it has uncovered new resonances in H^- below the $n = 6$ threshold which were previously obscured by the non-resonant states with lower n values. These structures are now being fit to a Fano line profile and will be reported at a later date. A new experimental proposal is being prepared to exploit this technique to search for new resonances and measure their branching ratios.

A sample of the threshold data for our lowest deflecting field of 22 G is shown in figure 3. The preliminary fits are consistent with the Wannier law if we restrict the data set to be within ~ 0.020 eV above threshold. However, the remaining data are so sparse that the fits cannot rule out even a linear law or predicted oscillations¹⁰ in the cross section. Our next scheduled experimental run in February, 1981, will be devoted to improving these statistics. This run will also feature an improved weak field magnet and improved scintillators to check for systematic effects.

Future Plans

Following our continuation of double detachment studies, we have proposals to search for long-lived states, to apply very strong fields to the H^- ions, and to begin exploratory work with neutral hydrogen

Figure 3. Ratio of cross section from H^+ signal to that from H^0 signal near the threshold for double photodetachment. The curve is the result of a fit discussed in the text.

atoms. These new proposals require only minor modification to the basic apparatus.

1. Search for Long-Lived States.¹³

This work will initially concentrate on a determination of the lifetime of the Feshbach resonance near $n = 2$. Theoretical predictions for the lifetime range from 6×10^{-13} s to 2.8×10^{-11} s. We already know that the width of this resonance is substantially less than our energy resolution so it must have a lifetime greater than 2×10^{-13} s. The relativistic velocity and the associated time dilation allow us to measure lifetimes through much of this range by observing the distance which an ion travels before decaying. The mean free path for decay is $\gamma \beta c t$ where βc is the velocity of the ion, t is the life-

time, and γ is the time dilation factor. For the 800-MeV ion beam at LAMPF: $\gamma\beta c = 46.7$ cm/ns.

In addition to the usual crossed beam apparatus, a weak magnet will be placed just downstream of the interaction region. The angle at which a detached electron emerges from the magnet will depend upon the position at which the decay occurred. An electron detector can measure the angular distribution with sufficient precision to determine lifetimes in the range 4.3×10^{-12} s to 6.4×10^{-11} s.

The next step will be to use the apparatus to search for the very narrow recursions of the Feshbach resonance which are now believed to be obscured by the short-lived continuum states.

2. H^- Ions in Very High Fields¹⁴

The shape resonance near the $n = 2$ threshold has resisted quenching by the strongest fields that we have yet been able to apply (~ 1.2 MV/cm). Our limitations on the field have not been due to the modest magnetic fields required but are due to the problems of mounting a more massive magnet in a confined space, cooling it in a vacuum, and its effect on the trajectories of the detached electrons.

These problems will be solved by detecting the H^0 atoms instead of the electrons since their trajectories are relatively unaffected by the field and by using a pulsed air-core magnet to provide the field. The magnet and its pulsing circuit have already been developed to fields of ~ 10 kG.

3. Exploratory Work with Atomic Hydrogen¹⁵

A relativistic atomic hydrogen beam is easily produced by stripping the H^- beam in a thin foil or in a strong magnet. The Lyman series is easily excited by a single Doppler-shifted photon. These excited states can then be detected by photoionization with a second photon or by stripping in the motional electric field due to a magnet. We have demonstrated the feasibility of both techniques. The data for the field-stripped atoms is shown in figure 4. The exploratory work will include high-field Stark studies of the low-lying states, an improved calibration of the H^- Feshbach resonance using the Lyman series, and high resolution (10^{-3} eV) threshold photoionization measurements in a higher electric field regime than ever before. These high electric field studies will require the further development of our pulsed magnet to ≥ 50 kG.

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Figure 4. Photoexcitation of Lyman series in atomic hydrogen followed by stripping in a motional electric field. The numbers next to the peaks identify the principal quantum number of the state. The amplitudes follow a $1/n^3$ dependence except for $n = 7$ and $n = 8$ which are saturated.

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