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Progress Report

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"Relativistic Atomic Beam Spectroscopy"

covering the period

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PROGRESS IN RELATIVISTIC ATOMIC BEAM SPECTROSCOPY

With the HIRAB (High Resolution Atomic Beam) building now operational, the series of photodetachment experiments at LAMPF was able to continue in the dedicated facility. The 1988 runs, experiments 1075 and 1076, provided definitive data to complement that of 1986 on the effects of electric fields on the photodetachment cross section of H^- and the interaction of thin foils with relativistic H^- ions. In addition, the way was opened to an exciting new area in atomic physics: the first multiphoton detachment of H^- was observed.

In each of these experiments, a high-powered laser beam was allowed to intersect the relativistic ion beam; the photon energy in the barycentric system is Doppler shifted, and the laser may thus effectively be tuned (through up to a decade) by changing the angle of intersection of the two beams.

The HIRAB facility was designed specifically for photon-ion colliding beam physics. It provides a high-quality H^- beam with a low divergence and energy spread, thereby increasing the resolution in relativistic ion beam spectroscopy. In addition, as a dedicated facility, it allows optics to be set up and aligned precisely well in advance of the experiment itself, which was not previously possible. The building also contains a massive vibration isolation slab on which the entire optical system may be mounted. Beamline diagnostics are also considerably improved, simplifying especially beam tuning and location.

Following the demonstration in 1986 of electric field induced structure on the H^- photodetachment threshold cross section, further investigations of the effect were undertaken. The earlier experiment made use of the transformations of relativistic electrodynamics, whereby a small magnetic field in the lab frame is seen as a large electric field in the barycentric frame of the ion. Near-threshold photodetachment in such a field, with the incident light polarized parallel to the field, produced a ripple-like interference pattern on the cross section itself. The results were of great interest to theorists; they may, however,

be understood in terms of a simple model in which the wave packet of the photo-ejected electron, spreading preferentially in the direction of polarization of the incident light, will for a π polarized laser beam spread "upstream" and "downstream" in the electric field; the wave spreading "upstream" will then, upon reflection from the potential barrier, interfere coherently with the wave moving "downstream". The process may be regarded as an atomic analogue to a Michelson interferometer. Indeed the reciprocal of the electric field strength is analogous to the length of the interferometer arm since the ripples are equally spaced when plotted vs. the reciprocal field strength.

In order to test the theoretical models to the fullest, it was decided to look at both low and high fields, and to investigate in particular the region in which electron tunneling, brought into play by the lowering of the atomic potential barrier, was important; it is here the any effects due to the atom itself should manifest themselves. Further, it was important to verify that the structure seen so far was in fact due to the electric field and not to magnetic effects. A pair of polished electric plates, designed to be held accurately 1 cm apart and at a potential difference of up to 60 kV, was therefore inserted around the laser-particle beam interaction region, to provide an electric field of up to 96 kV/cm in the barycentric frame. Once again, the ripple-like structure was seen in these low fields. Data from this experiment are currently being analyzed.

Unfortunately, because of problems during the "shakedown" run in July 88, time did not permit any experimental studies under high field conditions, although extensive equipment, including a large magnet capable of providing a barycentric electric field of up to 5 MV/cm, was prepared and tested.

Experiment 1075 measured the yield of some excited states of neutral hydrogen atoms produced by the passage of relativistic H⁺ ions through thin foils as a function of foil thickness, composition, and beam energy. In particular, we used carbon, Formvar, and aluminum foils at beam energies of 500, 581, and 226 MeV.

This experiment consisted of two segments. The first segment was the laserless study of the distribution of high Rydberg hydrogen atoms ($n > 10$) by field-ionizing the excited H° atoms in a magnetic electron spectrometer which also separated different excited states. The motional electric field seen in the rest frame of the relativistic H° atoms caused them to split into Stark states, each having a lifetime depending on the strength of the gradually rising field. Hence, different Rydberg states decayed in different positions within the spectrometer, and their liberated electrons followed different trajectories. By gradually changing the magnetic field of the spectrometer the signal electrons were brought to a focus where they were detected by a scintillator. A spectrum was formed by counting the number of electrons detected versus the magnetic field value.

In order to extract information about the initial distribution of the excited H° atoms, a Monte Carlo program was developed which followed a given distribution of excited H° atoms through the beam line and the spectrometer. A qualitative comparison of a portion of the experimental data with the Monte Carlo spectra suggested a $1/n$ distribution of the excited atoms as opposed to the $1/n^3$ distribution observed at low energies where n is the principal quantum number of the excited atoms. In addition, a bending magnet downstream of the spectrometer separated the H^- , H° , and H^+ beams which were then observed with a fluorescent screen. The light from the screen was digitized with a CCD camera which provided data on the production of the three charge states as a function of foil thickness. An extensive study of the experimental data is currently underway which should give more detailed information about the distribution of high Rydberg atoms produced by the passage of relativistic H^- ions through thin foils.

In the second segment of the experiment a Nd:YAG laser pulse was made to intersect the excited H° atoms, and was Doppler tuned to induce transitions from $n = 2, 3, 4$ to $n = 13$ and 15 . These laser excited Rydberg atoms were then field-ionized in the electron spectrometer, which gave us information about the yield of the lower lying states as a

function of foil thickness. In one measurement the thickness of a Formvar foil was continuously changed by rotating the foil along an axis perpendicular to the beam direction. A preliminary analysis of the experimental data shows oscillations in the yield of excited H° atoms with principal quantum numbers of $n=2$ and $n=3$ suggesting a coherent excitation mechanism. A complete analysis of the experimental data is underway and further data will be gathered in July 1989.

Multiphoton ionization (MPI) of the negative hydrogen ion has recently attracted much attention. H^{-} has several characteristics that make it an especially interesting system with which to investigate multiphoton absorption physics. It has a very low electron affinity (0.754 eV) and no excited states below the detachment threshold. A low electron affinity means that MPI can take place with photons of much lower frequency than typical MPI experiments with neutral atoms; thus ponderomotive forces (which are proportional to intensity/frequency²) can lead to potential energies larger than not only the photon energy being used but also the electron affinity. There being no intermediate states has the consequence of simplifying the absorption process in one-electron MPI, as there are no resonance-induced effects. Furthermore, because the departing electron is not subject to a long coulombic tail but rather to a short range potential, the above threshold ionization (ATI) process will probably be significantly altered. Finally, electron correlation is important in the description of H^{-} electronic states, thus allowing the possibility of examining electron correlation effects on the MPI process.

We have observed nonresonant multiphoton electron detachment of H^{-} ions in moderately intense (a few tens of GW/cm^2) laser fields. The 581 MeV H^{-} beam was intersected by focused 10.6μ radiation from a pulsed CO_2 laser (Fig. 1). Once again using the relativistic Doppler shift to tune the barycentric photon energy, the minimum number of simultaneous photons required for electron detachment was varied from three up to sixteen. Definite signals were observed for the minimum photon number ranging from

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three to eight. Both the H° atoms and detached electrons were observed in coincidence with the laser pulse. Our preliminary results show evidence for structure in the relative total cross section; it is hoped that next year we may expand the experiment significantly, to provide important new data in this exciting area.

PUBLICATIONS (Referred)

"Stability of the $1p^0$ Shape resonance in H^- in moderate electric fields," G. Comtet, C.J. Harvey, J.E. Stewart, H.C. Bryant, K.B. Butterfield, D.A. Clark, J.B. Donahue, P.A.M. Gram, D.W. MacArthur, V. Yuan, W.W. Smith, Stanley Cohen, Phys. Rev. A 30, 1547 (1987).

"Observation of Motional-Field-Induced Ripples in the Photodetachment Cross Section of H^- ," H.C. Bryant, A. Mohagheghi, J.E. Stewart, J.B. Donahue, C.R. Quick, R.A. Reeder, V. Yuan, C.R. Hummer, W.P. Reinhardt, L. Overman, Phys. Rev. Letters, 58, 2412 (1987).

"Response of the $1p^0$ resonance near $n=3$ in the H^- continuum to External Electric Fields," Stanley Cohen, H.C. Bryant, C.J. Harvey, J.E. Stewart, K.B. Butterfield, D.A. Clark, J.B. Donahue, D.W. MacArthur, G. Comtet, W.W. Smith, Phys. Rev. A 36, 4728-4736 (1987).

"Effects of Electric Fields on the Photodetachment Cross Section of the H^- Ion Near Threshold," J.E. Stewart, H.C. Bryant, P.G. Harris, A.H. Mohagheghi, J.B. Donahue, C.R. Quick, R.A. Reeder, V. Yuan, C.R. Hummer, W.W. Smith, S. Cohen, Phys. Rev. A 38, 5628 (1988).

"Observation of Multiphoton Detachment of the H^- Ion," C.Y. Tang, P.G. Harris, A.H. Mohagheghi, H.C. Bryant, C.R. Quick, J.B. Donahue, R.A. Reeder, Stanley Cohen, W.W. Smith, J.E. Stewart, Phys. Rev. A. 39, 6068 (1989).

"Further Studies of H^- Photodetachment in Electric Fields," P.G. Harris, H.C. Bryant, A.H. Mohagheghi, C. Tang, J.B. Donahue, C.R. Quick, R.A. Reeder, S. Cohen, W.W. Smith, J.E. Stewart, C. Johnstone. To be submitted to Phys. Rev. A. Available as Los Alamos National Lab Preprint LA-UR-89-322.

INVITED PAPERS

"Near Luminal H^- in Strong Fields," Invited Lecture, International Symposium Atoms in Strong Fields, Hotel Am Badersee, Grainau, FRG, September 5-9, 1988. H.C. Bryant.

"The Physics of the H^- Ion" 40 minute lecture at the workshop on Long Range Forces in Few Body Systems, Vancouver, BC, Canada 28-30 June 1989. H.C. Bryant.

Ph.D. DISSERTATION

"Field Induced Oscillations in the Photodetachment Cross Section of the H^- Ion", J.E. Stewart, UNM, December, 1987.

CONTRIBUTED PAPERS

"Field Induced Oscillations in the H^- Photodetachment Cross-section," J.E. Stewart, H.C. Bryant, A. Mohagheghi, J.B. Donahue, C.R. Quick, R.A. Reeder, V. Yuan, C.R. Hummer, W.W. Smith, S. Cohen. Post deadline paper for annual DEAP meeting, Boston 18-20 May 1987.

"Stability of the $1p^{\circ}$ Shape resonance in H^{-} in moderate electric fields," G. Comtet, C.J. Harvey, J.E. Stewart, H.C. Bryant, K.B. Butterfield, D.A. Clark, J.B. Donahue, P.A.M. Gram, D.W. MacArthur, V. Yuan, W.W. Smith, Stanley Cohen. Interfering resonances and stabilized states in the continuum, Gif sur Yvette, 6-8 April 1987.

"An Atomic Interferometer," H.C. Bryant. Contributed paper to Atomic Spectra and Collisions in External Fields II, Royal Holloway and Bedford New College, Egham Hill, Egham, Surrey, TW200EX, UK, 30-31 July 1987. (Should appear in proceedings volume.)

"Double Photodetachment and High-Lying Resonances in the H^{-} Ion" P.G. Harris, J.B. Donahue, H.C. Bryant, S. Cohen, A.H. Modhagheghi, C.R. Quick, R.A. Reeder, W.W. Smith, J.E. Stewart, and C.Y. Tang. XVI International Conference on the Physics of Electronic and Atomic Collision 26 July - 17 August, 1989, New York, NY.

"Observation of Excited H° atoms Produced by Relativistic H^{-} Ions in Carbon and Formvar Foils," A.H. Modhagheghi, H.C. Bryant, P.G. Harris, C.Y. Tang, C.R. Quick, S. Cohen, R.A. Reeder, W.W. Smith, J.E. Stewart. XVI International Conference on the Physics of Electronic and Atomic Collisions. 26 July - 1 August, New York, NY.

COLLOQUIA AND TALKS

Colloquium, Department of Physics and Atmospheric Science, Drexel University, Philadelphia, 1 pm, May 4, 1987, Disque Hall, Room 12-919, "Experimental Verifications of Special Relativity." H.C. Bryant.

Bag Lunch Seminar, MP Division Auditorium, 12 noon June 8, 1987, "A New Test of Special Relativity." H.C. Bryant.

Seminar, "Relativity Tests at LAMPF" Rutherford Laboratory, Chilton, Didcot England 29 July 1987. H.C. Bryant.

Talk, "Photon Interactions with H^{-} ," Los Alamos National Lab, TA 35-127, A101, 2:30 pm, February 3, 1988. H.C. Bryant.

Series of 5 Lectures given at the Los Alamos Summer School in Atomic Physics: (H.C. Bryant)

July 25-29, 1988: 10:30-12 UNM Campus, Los Alamos

1. What good is relativity?
2. The Structure of the H^{-} Ion.
3. Photodetachment of H^{-} .
4. Effects of Fields: The Tale of Two Resonances.
5. The Atomic Interferometer and Beam Me Up, Scotty!

Colloquium, Department of Physics and JILA, University of Colorado, Boulder, CO, October 5, 1988, "Atomic Physics Near the Speed of Light." H.C. Bryant.

Talk, " H^{-} Physics at HIRAB," to Neutral Particle Beam Sensing and Control Panel, (SDI), J.A. Schafer and Associates, Albuquerque, NM, April 17, 1989. H.C. Bryant.