Abstract

This document presents an overview of the results of the DOE's support of experimental research into the structure and interactions of the negative ion of hydrogen conducted by the Department of Physics and Astronomy of the University of New Mexico at the Los Alamos National Laboratory. The work involves many collaborations with scientists from both institutions, as well as others. Although official DOE support for this work began in 1977, the experiment that led to it was done in 1971, near the time the 800 MeV linear accelerator at Los Alamos (LAMPF) first came on line. Until the mid nineties, the work was performed using the relativistic beam at LAMPF. The most recent results were obtained using the 35 keV injector beam for the Ground Test Accelerator at Los Alamos. A list of all published results from this work is presented.
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noncommittal as to which electron is which. Nowadays, it is fashionable to refer to such a description as a case of "entangled states".

The above discussion of the quantum mechanics of two electrons falls under the rubric of the Pauli exclusion principle. Early in my career I had dreams of testing this principle for small violations, and had looked briefly into the spectrum of He for possibilities that the ground state of He could ever be in a triplet state. Triplet states are strictly forbidden by the Pauli principle when the two electrons are in the same spatial state. Although this idea was abandoned, and I published nothing on it, I was primed to jump into a study of the other fundamental two-electron system, the negative ion of hydrogen, when the opportunity arose.

The opportunity began to arise in 1970 when the linear accelerator at Los Alamos, LAMPF, Los Alamos Meson Physics Facility, came on line. This accelerator produced beams, on alternate halves of its rf cycle, of protons and H\(^{-}\) ions at kinetic energies up to 800 MeV. At the time I was working with a group\(^2\) interested in producing pulsed neutron beams at up to 800 MeV to do time-of flight studies of n on p production of pions. The energy of the neutron was measured by its time of flight, using scintillators viewed with photomultipliers. The best time resolution one could get was about a nanosecond, with such a system, and, for this reason it was necessary to know the "birth-time" of the neutron that well. Neutrons produced in short (nanosecond) bursts separated by hundreds of nanoseconds were therefore required, and we were faced with the problem of how this could best be done.

It occurred to me that with a pulsed laser fired into the H\(^{-}\) beam, which consisted of 1/4 nanosecond pulses separated by 5 nanosecond intervals, we ought to be able photodetach all the ions in a single micropulse. The resulting isolated H\(^{0}\) pulse could be directed onto a neutron-producing target, e.g. a liquid deuterium target, giving us our desired isolated burst of neutrons with a very narrow pulse duration.

Since I knew very little about atomic physics, I asked my colleague, Charles Beckel, what he thought the cross section for photodetachment from H\(^{-}\) was. He thought \(10^{-17}\) cm\(^2\) would be about right. After a brief back of the envelope calculation, I concluded that with a pulsed Nd:glass laser we could do the trick, and we submitted a proposal to the LAMPF Program Advisory Committee to make such a beam.\(^3\) We were thinking in terms of what we called a "photon target", in which we filled the region between two parallel mirrors with a photon pulse by multiple reflections, and directed an H\(^{-}\) beam through it.

\(^2\) Under the sponsorship of the predecessor of the DOE, ERDA, H. C. Bryant, B. D. Dieterle, C. P. Leavitt, and D. Wolfe, E (29-2)-3347, 7/73-9/76.

\(^3\) Our research proposal, "Solitary Micropulses by Photodetachment of the H\(^{-}\) Beam" (LAMPF proposal 52) by H. C. Bryant, spokesman, C. P. Leavitt, B. D. Dieterle, John Doe (we were planning to hire another UNM faculty member who turned out to be David Wolfe), Alan Paxton, and Paul Lovoi, was acknowledged received by Louis Rosen, Director of LAMPF, April 1, 1971, approved for accelerator development on July 28, 1971, and approved as a LAMPF experiment on May 9, 1973.
The Program Advisory Committee, evidently a conservative group, was not convinced from the calculations in our proposal that it would work, and instead of giving us valuable beam time at LAMPF to try it, recommended that we do a proof of principle at the vertical Van de Graaff at Los Alamos, which produced a DC 4 MeV H- beam of 4 microamps. With student, Paul Lovoi, and colleague Gerald Ohlsen, we set up a demonstration experiment which bore out our predictions very well.

Unfortunately, by the time we had proven our method would work, another way of producing solitary pulses, although not as cleanly, was invented using a pulsed electrostatic deflector. Our method was never used for its intended purpose, although it did give us our first paper on the subject. Furthermore, I began to think about the possible atomic physics that might be done with this method.

It was not widely understood that the negative hydrogen ion had any structure in its photodetachment continuum, although theoretical evidence of the doubly-excited shape resonance associated with the first excited state of hydrogen had already been advanced. So in 1972 when we turned in a proposal to LAMPF for beam time to study H-, resonances were not mentioned. Our principal goal was to make a precision measurement of the H$^-$ binding energy some ten times better than existing measurements. A research proposal to the NSF to fund this effort, was, like the one for beam time, declined. It is interesting to note that unlike our first proposal to make a pulsed neutron beam, the referees felt the experiment would work; they just did not think it was worth the effort. Calculations of ground state energies of two-electron systems were universally thought to be more precise and reliable than any feasible measurement. With the wind thus taken out of our sails we turned to other things.

In the Spring of 1974, spurred by the remarkable dips demonstrated in the photodetachment from negative alkali ions by Lineberger et al, we realized that we had a unique technique that would allow us to look for resonances in the vacuum ultraviolet photodetachment continuum of the H$^-$ ion.

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8 "This proposal is an example of an individual who realizes that an amusing experiment is possible but fails to ask the question, 'Will we learn anything?'" Anonymous referee for NSF.
10 Discussions with D. Norcross, C. Lineberger, J. Slater and J. Cooper at JILA were most helpful and encouraging at this point.
submitted to the LAMPF PAC\textsuperscript{15} and a proposal for funding was submitted to ERDA.\textsuperscript{16} Our experimental run in March 1977 revealed much richer structure than had been anticipated, and so on June 3, 1977, we submitted a proposal for beam time to increase the energy range of our measurements.\textsuperscript{17} In October 1978, we submitted a proposal to look above the two-electron threshold\textsuperscript{18}. Over the years the list of proposals and the subsequent experiments continued to grow.\textsuperscript{19} as we expanded the scope of our research using the relativistic beam. There seemed to be no end of new ideas for experiments.\textsuperscript{20}

\textsuperscript{16} "The Photodetachment Spectrum of H-", Submitted to the U. S. Energy Research and Development Administration, January 28, 1977. Requested starting date: June 1, 1977. Amount requested $82,727. The proposal was awarded $60,000 for the first year May 18, 1977.


YAG harmonic with a tunable dye beam. We also did fixed frequency multiphoton measurements.

Our most striking results in these low energy beam measurements were the observations of the singlet D resonance in both negative hydrogen and negative deuterium. We were able to observe an isotope shift whose magnitude we could attribute directly to electron momentum correlation. Our result is 2.1 standard deviations from what is expected from theory. The ball is now in the theorists' court\(^2\), although the laws of statistics do not signal an irreconcilable discrepancy. As far as we know, this is the first measurement of electron correlation, explicitly. This work also demonstrated that with the use of multiphoton techniques, essentially all of the singlet resonances are experimentally assessable.

Finally, most recently we have returned to an earlier mystery, which, in part, has motivated our work. Why is not the shape resonance seen in stellar spectra? With my colleague and former student, Stanley Cohen, we have been searching through astrophysical archives, available on the internet, with spectra in the appropriate vacuum ultraviolet wavelength region. A report of our search so far was given at the APS Centennial Meeting in Atlanta and is cited among the list of publications.\(^2\)

We tried to publish all of our results over the years. These publications are attached, and we urge the reader to consult them for the details. Of course, not all significant work was published, sometimes because of some fatal flaw that made it scientifically unreliable, and sometimes because it got left behind in our zeal to uncover new results. My students, collaborators and I still carry much in their heads from this experience, and hopefully more will be written in the future.

The dissertations written by the students supported by these grants, a list of which also attached, give perhaps the best perspective, as well as the "nitty gritty", on this work for they speak with many voices, and often give a very clear idea of the human as well as scientific aspects of this endeavor. I dedicate this report to my students with the sincerest of thanks for coming along with me with courage, energy and enthusiasm on our various adventures into the unknown. My other coworkers are legion; to these capable colleagues, whose names I leave to be discerned as authors on the list of publications appended, I offer heartfelt thanks. Finally I thank the Division of Chemical Sciences, Office of Basic Energy Sciences, Office of Energy Research of the U. S. Department of Energy\(^2\) for their support, and especially I wish to thank Dr. J. V. Martinez, Fundamental Interactions Branch, who with his wise counsel and even-handed encouragement, has been along for the entire journey. Mi gracias, Joe!

\(^2\) In a recent (June 17, 1999) email Prof. Shi-I Chu at the University of Kansas writes "Dr. K.T. Chung and I have performed some precision two-electron calculations for the case of two-photon detachment of H\(^+\) through the singlet D state etc. It appears that the results are in excellent agreement with your experimental data published in PRL 75, 2924 (1995)\(^3\). We have just sent him our isotopic shift data from PRA 58,1889 (1998) with erratum PRA 59,906 (1999), and it remains to be seen if he will confirm the discrepancy.


\(^2\) Georgia McClelland, Oakland Operations, thank you for your help and patience.
Publications Resulting from this Work

Publications in Refereed Journals


"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,

"Response of the $^1p^0$ resonance near n=3 in the H$^-$ Continuum to External Electric Fields,"

"Effects of Electric Fields on the Photodetachment Cross Section of the H$^-$ Ion Near Threshold,"


"Excitations of atoms passing through a TEM$^{00}$ Gaussian laser beam at relativistic velocities,"


Comments


Invited Papers


"Transverse diffusion of mass-identified ions in their parent gases," Invited paper presented by H. C. Bryant, published in Proceedings of the 3rd International Swarm Seminar, Innsbruck, Aug. 5-6, 1983 (Editors: W. Lindinger, H. Villinger and W. Federer). H. C. Bryant, G. Sejkora, P. Girstmair, M. Hesche, N. Duric, T. D. Mark. See also dissertation by Martin Hesche, "Experimental Untersuchungen und Theoretische Analysen Diffusionskoeffizienten von Ionen in Gasen." 1985. I was one of his mentors at the University of Innsbruck, Austria. His advisor was Prof. Dr. T. Märk.

"Atomic Physics Near the Speed of Light," Invited Lecture (45 minutes) at Symposium on Atomic and Surface Physics, Maria Alm, Salzburg Jan. 29-Feb. 4, 1984 (not published). H. C. Bryant.


"H⁻ as Quantum Mechanical Interferometer," invited talk at the Foundations of Quantum Mechanics Workshop, Santa Fe, NM, May 29, 1990.

"Recent Results from HIRAB," invited talk at the 24th LAMPF Users Group Meeting, Los Alamos National Laboratory, August 14, 1990.


"Atomic Physics at Fermilab," H.C. Bryant, (40 minutes) Proceedings 400 MeV Beam International Conference, Fermilab, October 24-27, 1993, Carol Johnstone, Editor. FNAL, Batavia, IL

"Modeling Multiphoton Measurements on H-", H. C. Bryant, Invited Lecture at the Fourth U.S.-Mexico Atomic and Molecular Physics Symposium, Hotel Antigua Hacienda de Galindo, San Juan del Rio, Queretaro, Mexico. December 7-10, 1994,. Published with coauthor E. P.


**BOOK CHAPTERS**


"H- Spectroscopy", H. C. Bryant and M. Halka, Chapter 4, p.221-280, in **Coulomb Interactions**


ABSTRACTS OF CONTRIBUTED PAPERS


"Excess-Photon Ionization of Atoms at 1064 nm," T. David Nichols and H. C. Bryant, Post deadline talk at 1993 annual meeting of DAMOP, May 16-19, 1993, Reno, NV (We 5, 19 May,


"Stripping Yields and Production of Stark States Through Interaction of 800 MeV H- Ions with


TECHNICAL REPORTS


Report of Committee on Relativistic Atomic Collisions, U.S. Department of Energy Workshop on Future Opportunities in Atomic, Molecular and Optical Physics, Berkeley, November 7, 1989. Panel Members: Prof. Walter Meyerhof (Chair), Dr. Chris Bottcher, Prof. Howard Bryant, Dr. Harvey Gould, Dr. Peter Mohr, Prof. Winthrop Smith.


"High Excitations and Double Escape in the Negative Hydrogen Atom," op cit p. 41-45, P. G. Harris, H. C. Bryant et al.


POPULAR ARTICLES


"A Brief Report on the 'Physics of the H\textsuperscript{-} Ion' Workshop," Honglie Fang and H. C. Bryant, submitted to Acta Optica Sinica. (Do not have reference)


"Hooked on Resonances," by Sherry Robinson (Profile interview, with drawings by HCB), Quantum 13, 1, Spring 1996, Research and Scholarship at the University of New Mexico,
TALKS AND COLLOQUIA SINCE 1980


Colloquium: Max-Planck-Institut fur Quanten Optik, Garching, West Germany, Dec. 8, 1982. "Experimental Spectroscopic Studies of the H- Ion at Relativistic Velocities."

Colloquium for the Institut fur Experimental Physik, Canisianum, U. of Innsbruck, Innsbruck, Austria, March 10, 1983, "Outdoor drift tube: the physics of the salt-gradient solar pond."

Colloquium for the Physics Department, University of Kragujevac, Kragujevac, Yugoslavia, March 31, 1983, "The origin of the electromagnetic force."

Colloquium for the Physics Department, University of Belgrade, Belgrade, Yugoslavia, April 1, 1983, "Atomic Physics near the speed of light."

Colloquium for the Institut fur Experimental Physik, University of Freiburg, Germany, April 23, 1983, "Atomic Physics near the speed of light."

Seminar for the Physics Department at the Universite Degli Studi, Povo, Trient, Italy, May 7, 1983, "Atomic Physics near the speed of light."

Colloquium for UNM Physics and Astronomy Department, March 2, 1984, "Atomic Spectroscopy Near the Speed of Light."

"Atomic Physics with Relativistic Beams," talk to Physics Division (1 hour), Los Alamos National Lab, MP 215, Nov. 8, 1984.
Colloquium for UNM Physics and Astronomy Department, January 25, 1985 "Progress in Understanding Simple Atoms."

The University of New Mexico 30th Annual Faculty Research Lecture
April 1, 1985, Physics Lecture Hall, The University of New Mexico, 8p.m.
"A Physicist's Journal: from the Glory to the Two-electron Ion."


Sandia Colloquium, Sandia National Laboratory, Albuquerque, N.M., 9-10 a.m. 13 Sept., 1985, "Tweedle Dee and Tweedle Dum Near the Speed of Light," (on film, transcript also available).

Seminar: Los Alamos National Laboratory, Conference Room TA3, Bldg. 215, Rm 281, 1 pm, July 16, 1986, "Photodetachment Study of H ions at Relativistic Velocities."

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

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


Series of 5 Lectures given at The Los Alamos Summer School in Atomic Physics:
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: Dept. of Physics and JILA, University of Colorado,Boulder, CO, Oct 5, 1988, "Atomic Physics Near the Speed of Light."

Series of 3 Lectures given at the 1989 Los Alamos Theoretical Atomic Physics Summer School, July 18, 19, 20, 1989:
1. What good is relativity?
2. The Structure of the H⁻ Ion.
3. Effects of Fields.


Colloquium: Department of Physics, University of Wyoming, Laramie "Recent advances in the Physics of the H⁻ Ion," February 27, 1990.


Seminar: Tungsram Factory, Budapest, "Atomic Physics at the Linear Accelerator at Los Alamos," June 6, 1990, 10:00 am.


Colloquium: UNM, Department of Physics, "Relativistic Atomic Physics," December 7, 1990.
Colloquium: New Mexico State University, Department of Physics, "Relativistic Atomic Physics," January 31, 1991.

Colloquium: Rice University, Department of Physics, Houston; "Atomic Physics Near the Speed of Light," February 7, 1991.

Presentation of Expression of Interest, Super-Conducting Super Collider Laboratory, "Relativistic Atomic Physics at the SSC," EOI-17, June 14, 1991, Dallas, TX.


Series of 4 Lectures given at the Los Alamos AMO Summer School, July 27-31, 1992
1. Relativistic Beams.
2. The H⁻ Ion.
3. The effects of electric fields.

Native American Science Teachers, August 10, 1992, Regener Hall, UNM, "Physics Demonstration Equipment."


Tulane University Quantum Group and Physics Colloquium, November 16, 1992, New Orleans, LA, "Experiments with H⁻ at LAMPF and around the World".

General Seminar, Louisiana State University, November 17, 1992, Baton Rouge, LA, "The Photoabsorption Spectrum of H⁻."

Colloquium: Department of Physics, University of Nevada, Reno, "The Spectroscopy of H⁻", February 11, 1993


"Research on the Physics and Technology of Hydrogen Beams at Los Alamos," H.C. Bryant, Brief Topics session of IDEA DAY #1, LAMPF Auditorium, LANL 6/10/93.

Guest Lecturer: Science and Math Summer School for Navajo Children, Fort Defiance Middle School, Sohatso, AZ, July 17, 18 1993.


Talk: Sertoma Club, Fiesta Restaurant, Montgomery and Carlisle, March 2, 1995 12-1 pm. "Tweedle Dee and Tweedle Dum at near the speed of light".

Guest Lecturer: Science and Math Summer School for Navajo Children, Fort Defiance Middle School, Sohatso, AZ, June 13, 1995.


Seminar: "The spectroscopy of the H− ion", H. C. Bryant, Dec 10, 1996, 10 am, room 120, bldg 400, Phillips Lab, Albuquerque, NM
Colloquium: "Recent Advances in H- Spectroscopy", July 15, 1997, Max Born Institute, Berlin, Germany.

Colloquium: "Recent Advances in H- Spectroscopy", July 17, 1997, Technical University of Munich, Garching, Germany

Seminar: "Color Vision in Birds", November 4, 1997, Department of Physics, Brigham Young University, Provo, Utah

Colloquium: "Recent Advances in H- Spectroscopy", November 5, 1997, Department of Physics, Brigham Young University, Provo, Utah

Colloquium: "Experimental Studies of a Quantum-Mechanical Three-Body Problem", August 28, 1998, Room 184, Physics and Astronomy Bldg., 4:00 pm, UNM

Ph.D. DISSERTATIONS Completed under the DOE auspices

Chokun-Hossein Tootoonchi Sarraf, 1977
"Study of resonances Near 11 eV in the Photodetachment Cross Section of H- Ion."

Mohamad Hassan Sharifian-Attar, 1977
"Measurement of the H- Photodetachment Cross Section in the Continuum Region from 1.5 to 10.5 eV."

Charles Alan Frost, 1981
"Measurements of Threshold Behavior for One- and Two-Electron Photodetachment from the H- Ion."

Kenneth B. Butterfield, 1984
"Stark Broadening of H- Resonances in Large Electric Fields."
LA-10149-T UC-34, June 1984

Stanley Cohen, 1986
"The Response of the 1Po Resonance Near n = 3 in the H- Continuum to External Electric Fields."
LA-10726-T UC-34a. May 1986

James Edward Stewart, 1987
"Effects of Electric Fields on the Photodetachment Cross Section of the H- Ion Near Threshold."
LA-11152-T UC-34 Dec. 1987

Philip G. Harris, 1990
"Observations of High-Lying Resonances in the H- Ion."
LA-11843-T UC-413 May 1990
Amir H. Mohagheghi, 1990
"Interaction of Relativistic H\textsuperscript{-} Ions with Thin Foils."
LA-11925-T UC-411 Sept. 1990

Thomas David Nichols, 1991
"Measurement of Intensity-Dependent Rates of Above-Threshold Ionization (ATI) of Atomic Hydrogen at 248 nm."
LA-12060-T UC-700, April, 1991 (Dr. George Kyrala was his Los Alamos advisor)

Chen Yau Tang, 1992
"Multiquanta Photodetachment from the H\textsuperscript{-} Ion."
LA-12254-T UC-414 March 1992

Monica Halka, 1993
"Partial Cross Sections in H\textsuperscript{-} Photodetachment."
LA-12533-T UC-410 April 1993

Edward P. MacKerrow, 1995
"Measurement of Two and Three Photon Absorption by the H\textsuperscript{-} Ion", May 1995

Philip Brian Keating, 1996
"Interactions of Relativisitic H\textsuperscript{-} Ions with Matter and Fields", May 1996

Mark Shannon Gulley, 1997
"Non-resonant Two-photon Detachment of H\textsuperscript{-} Ions with 1.165 eV Photons", July, 1997

Daniel Rislove, 1997