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13. ABSTRACT *(Maximum 200 words)*

The precise mass comparison of the antiproton and proton is a very important scientific test, being the most stringent test of CPT invariance for a baryon system. This scientific objective has led CERN, the nuclear and particle physics laboratory of Europe, to provide a unique access to the world's exceedingly limited supply of antiprotons. Pursuit of this scientific goal has made possible the development of techniques to slow and cool antiprotons, reducing their energy by a factor of 10,000,000,000 and also development of techniques for capturing, storing, and accumulating large numbers of antiprotons. The nondestructive containment of antimatter in a small volume has thus now been clearly demonstrated. Based on the many things learned in this series of experiments, the focus is now on increasing the number of trapped antiprotons. During this past year there has also been success in accumulating and storing positrons in much larger numbers, in a trap environment very similar to that used for storing antiprotons. The hope now is to combine the low energy antiprotons and the low energy positrons to make antimatter atoms for the first time. Test experiments with electrons and protons are encouraging.

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Harvard University
Cambridge, MA 02138

Progress Report to the Air Force Office for Scientific Research

ANTIPROTON STUDIES AND MASS SPECTROSCOPY
Grant Number: F49620-93-1-0243
Period: April 1, 1993 through September 1, 1995

From: Harvard University, Department of Physics, Cambridge, MA 02138

Principal Investigator: Gerald Gabrielse (351-44-0371)

Signature: Gerald Gabrielse

Phone: 617-495-4381

1. **OBJECTIVES - List the objectives of the research effort of the statement of work. This may be omitted if there has been no change. State new or revised objectives if they have changed and the reason why.**

   Objectives remain the same.

2. **STATUS OF EFFORT - A brief statement of progress towards achieving the research objectives. (Limit to 200 words.)**

   The precise mass comparison of the antiproton and proton is a very important scientific test, being the most stringent test of CPT invariance for a baryon system. This scientific objective has given us a unique access to the world's exceeding limited sup ply of antiprotons. Moreover, these antiprotons are provided to us free of charge by CERN, the nuclear and particle physics laboratory of Europe. In a pursuit of a pure science goal, we have been able to develop the techniques to slow and cool antiproton s, reducing their energy by a factor of 10,000,000,000, We also developed the techniques for capturing, storing, and accumulating large numbers of antiprotons. The nondestructive containment of antimatter in a small volume has thus now been clearly demo nstrated. Based on the many things we have learned in this series of experiments, we are now focusing on increasing the number of trapped antiprotons. During this past year we have also succeeded in accumulating and storing positrons in much larger numb ers, in a trap environment very similar to that used for storing antiprotons. (The positron experiments were not supported by AFOSR.) The hope now is to combine the low energy antiprotons and the low energy positrons to make antimatter atoms for the fir st time. Test experiments with electrons and protons are encouraging.

3. **ACCOMPLISHMENTS/NEW FINDINGS - Describe research highlights, their significance to the field, their relationship to the original goals, their relative to the AF's mission, and their potential applicants to AF and civilian technology challenge.**

   For some time, in and outside of the Air Force, there has been speculation about possible uses for confined antimatter. In the Star Trek television series,confined antimatter propelled the Enterprise. Speculations about the possible confinement of antim atter and about the uses of confined antimatter have been carried out by people with a dangerously wide range of expertise. Some have simply watched too much Star Trek, while others have carried out a more informed and thoughtful analysis.

   A major problem has always been an almost complete lack of hard experimental information and experience with antimatter confinement. The reason is that antiprotons are in extremely short supply. Right now, the only place where low energy antiprotons are available is the CERN Laboratory in Geneva, Switzerland. Obtaining antiprotons from this unique facility requires a scientific goal and a recognized experimental expertise, especially for Americans insofar as our government does not support the European CERN Laboratory. Access to antiprotons is awarded competitively and there are many more European groups requesting access to antiprotons than can possibly be accommodated.

   Our scientific goal of comparing the masses of the antiproton and proton, the most stringest test of CPT invariance with the baryon system, has required and allowed us to develop many antimatter cooling and confinement techniques. The number of antiproto ns cooled and captured in these initial experiments has been modest as one would expect for initial studies on a new frontier. However steady progress has been made and continues. We now know that heavy antimatter particles can be slowed and cooled tremendously, reducing their energy by a factor of 10,000,000,000. We now know that antiprotons can be confined and stored for months at a time. Although much more will be said about the new techniques and demonstratio ns arising from this antiproton research program, the point here is that a base of demonstrated techniques related to confinement of antimatter has been established and is growing. The slowing, cooling, and confinement which we now do routinely was considered by some to be outlandish and impossible at the outset of this antiproton research project.

   The base of understanding, expertise, and techniques related to antimatter confinement and use has been the payoff to the Air Force so far. In the future, the expectation is that this base will expand to include larger and larger numbers of confined anti protons and the production of the first antimatter atoms, antihydrogen. The scientific motivations for continued antiproton study are strong and are admired at the CERN Laboratory, as are the experimental accomplishments we have made while supported by A

FOSR. This will insure our unique access to antiprotons at CERN as long as CERN elects to continue antiproton production.

4. PERSONNEL SUPPORTED

(a) **Faculty**

Gerald Gabrielse

(b) **Post-Docs**

Kamal Abdullah
Wolfgang Quint
Gary Rouleau

(c) **Graduate Students**

Loren Haarsma
David Hall
Paul Janzen
Anton Khabbaz
Lisa Lapidus
Steven Peil
David Phillips
Ching-hua Tseng

5. PUBLICATIONS

1. "One Electron in a Cavity,"
G. Gabrielse and J. Tan
in *Cavity Quantum Electrodynamics*, edited by P. Berman, [Academic Press, New York, p. 267, 1994].
2. "Parametrically-Pumped Electron Oscillators"
J. Tan and G. Gabrielse
Phys. Rev. A., *48*, 3105 [1993].
3. "Extremely Cold Antiprotons, For Mass Measurements and Antihydrogen"
G. Gabrielse, W. Jhe, D. Phillips, W. Quint, C. Tseng, L. Haarsma, K. Abdullah, J. Gröbner, H. Kalinowsky
in *Atomic Physics 13. Thirteenth International Conference on Atomic Physics*, (American Institute of Physics, New York, NY), 85 [1993].
4. "The Magnetic Moment of the Antiproton",
W. Quint and G. Gabrielse
Hyperfine Interactions *76*, 379 [1993].
5. "(Anti)Hydrogen Recombination Studies in a Nested Penning Trap"
W. Quint, R. Kaiser, D. Hall, G. Gabrielse
Hyperfine Interactions *76*, 181 [1993].
6. "Extremely Cold Antiprotons for Antihydrogen Production"
G. Gabrielse, W. Jhe, D. Phillips, W. Quint, C. Tseng, L. Haarsma, K. Abdullah, J. Gröbner, H. Kalinowsky
Hyperfine Interactions *76*, 81 [1993].
7. "Portable Trap Carries Particles 5000 Kilometers"
C. Tseng and G. Gabrielse
Hyperfine Interactions *76*, 381 [1993].
8. "Extremely Cold Positrons for Antihydrogen Production"
L. Haarsma, K. Abdullah, G. Gabrielse
Hyperfine Interactions *76*, 143 [1993].

9. "Observing a Single Trapped Antiproton"
G. Gabrielse, W. Jhe, D. Phillips, W. Quint, H. Kalinowsky, J. Gröbner
Nuclear Physics A *558*, 701c [1993].

10. "A Single Trapped Antiproton and Antiprotons for Antihydrogen Production
G. Gabrielse, W. Jhe, D. Phillips, W. Quint, L. Haarsma, K. Abdullah, H. Kalinowsky, J. Gröbner
Hyperfine Interactions *81*, 5 [1993].

11. "Trapped Positrons for Antihydrogen
G. Gabrielse, L. Haarsma, K. Abdullah
Hyperfine Interactions *89*, 371 [1994].

12. "Extremely Cold Positrons Accumulated Electronically in High Vacuum"
L. Haarsma, K. Abdullah, G. Gabrielse
Phys. Rev. Lett. *75*, 806 [1995].

13. "One-Electron Parametric Oscillator"
C.H. Tseng and G. Gabrielse
Appl. Phys. B *60*, 95 [1995].

14. "Special Relativity and the Single Antiproton: Forty-fold Improved Comparison of $\bar{P}$ and P Charge-to-Mass Ratios"
G. Gabrielse, D. Phillips, W. Quint, H. Kalinowsky, G. Rouleau, W. Jhe
Phys. Rev. Lett. *74*, 3544 [1995].

15. "New Comparison of $\bar{P}$ and P Charge-to-Mass Ratios"
G. Gabrielse, D. Phillips, W. Quint, H. Kalinowsky, G. Rouleau, W. Jhe
to be published in *Proc. of LEAP '94 Conference* [February 1995].

16. "Extremely Cold Positrons for Antihydrogen"
G. Gabrielse, L. Haarsma, K. Abdullah
to be published in *Proc. of LEAP '94 Conference* [February 1995].

17. "Electronic Accumulation of Extremely Cold Positrons in Ultrahigh Vacuum"
K. Abdullah, L. Haarsma, G. Gabrielse
Physica Scripta [in press].

18. "Improved Comparison $\bar{P}$ and P Charge-to-Mass Ratios"
D. Phillips, W. Quint, G. Gabrielse
Physica Scripta [in press].

19. "Relativistic Mass Increase at Slow Speeds"
G. Gabrielse
Am. J. Phys. *63*, 568 [1995].

6. INTERACTIONS/TRANSITIONS

(a) **Participation at Meetings, Conferences, Seminars, etc.**

1993

Feb. 11 American Association for the Advancement of Science, Public Science Day, Cambridge Rindge and Latin School [invited lectures]

Feb. 12 American Association for the Advancement of Science, Boston [invited lecture]

Feb. 17 University of Delaware [physics colloquium]

Feb. 25 Workshop on Traps for Antimatter and Radioactive Nuclei [TRIUMF], University of British Columbia, Vancouver [invited lecture]

Mar. 12 McGill University, Montreal [physics colloquium]

Mar. 25 Society of Physics Students, Worcester Polytechnic Institute [invited lecture]

Apr. 13 Washington D.C. Meeting of the American Physical Society [undergraduate address]

Apr. 14 Washington D.C. Meeting of the American Physical Society [invited lecture]

Apr. 20 Brookhaven National Laboratory [physics colloquium]

May 4 Quantum Electronics Laser Science Conference, Baltimore [invited lecture]

May 17 Meeting of the Division of Atomic, Molecular, and Optical Physics of the American Physical Society [Reno, NV] [invited lecture]

June 3 California Institute of Technology physics colloquium

June 15 CSI [Darmstadt, Germany] [physics colloquium]

June 22 University of Bern, Switzerland [physics colloquium]

June 23 University of Geneva, Switzerland [physics colloquium]

July 5 Gordon Conference [New Hampshire] [invited lecture]

July 16 Positron Satellite Meeting to ICPEAC, Bielefeld, Germany [invited lecture]

Sept. 15 2nd Workshop on Nucleon-Antinucleon Physics [NAN '93], Institute of Theoretical Physics, Moscow

Oct. 27 McMaster University, Hamilton, Ontario, Canada [physics colloquium]

Oct. 28 University of Toronto, Toronto, Canada [physics colloquium]

Nov. 8 Harvard University [physics colloquium]

Nov. 17 Manne Siegbahn Memorial Lecture, Stockholm, Sweden [invited lecture]

1994

Jan. 6 American Association of Physics Teachers, San Diego [plenary lecture]

Jan. 31 North Carolina State University, Raleigh [Derieux Science Lecture]

Mar. 11 Harvard University [joint seminar for the History and Philosophy of 20th Century Science]

July 20 Nonneutral Plasma Workshop, University of California, Berkeley [invited lecture]

Aug. 24 Nobel Symposium 91 on Trapped Charged Particles and Fundamental Physics, Lysekil, Sweden [invited lecture]

Sept. 17 3rd Biennial Conference on Low-Energy Antiproton Physics [LEAP '94], Bled, Slovenia [invited lecture]

Nov. 7 University of Washington, Seattle [physics colloquium]

(b) **Consultative and Advisory functions to other laboratories and agencies, especially Air Force and other DoD laboratories. Provide factual information about the subject matter, institutions, locations, dates and name(s) of prinicipal individuals involved.**

This spring I spent a lot of time on the telephone responding to questions about the small business iniative which was related to our self-shielding solenoid invention. I provided information and answered questions to at least six or eight different comp anies. Very recently I have been approached by the Intermagnetics Corporations, which I believed was awarded the SBIR grant. I have provided additional information to them and may be working with them further.

(c) **Transitions. Describe cases where knowledge resulting from your effort is used, or will be used, in a technology application. Transitions can be to entities in the DoD, other federal agencies, or industry. Briefly list the enabling research, the laboratory or company, and an individual in that organization who made use of your research.**

Two of the most important research results summarized in the last section are technological developments which are having a wider impact.

The superconducting solenoid system was patented by Harvard University and has been licensed by several companies. Currently such systems are available from three different superconducting solenoid companies. They are being used by chemists and biologis ts doing ion cyclotron resonance (ICR), and they are being used for NMR experiments. When nearby elevators operate and the subway goes by, the magnetic field fluctuations which otherwise could perturb such measurements are reduced to negligible levels by a self-shielding superconducting solenoid system. Though it will take some more time, I expect that our invention will eventually be used for magnetic resonance imaging (MRI) insofar as it should make it possible to locate such facilities near hospital elevators, for example.

The open access Penning trap discussed in the last section is increasingly being used for ion cyclotron resonance applications. Its electrostatic properties are significantly better than the rectangular ICR cells which have been used most commonly for ch emical and biological studies. The large access to the trap center which we needed to get antiprotons in our trap is also useful for getting protein fragments and large molecules into the trap. These devices were not patented because the university was uncertain that it could recover the funds which would be expended to obtain patents. The d evices are being widely used nonetheless.

(d) **NEW DISCOVERIES, INVENTIONS, OR PATENT DISCLOSURES**

None

(e) **HONORS/AWARDS**

Fellow of the American Physical Society, 1992