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A MEASUREMENT OF THE GRAVITATIONAL ACCELERATION OF THE ANTIPROTON: AN EXPERIMENTAL OVERVIEW

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ABSTRACT

An ambitious experiment is being developed to measure the force on the antiproton due to the gravitational field of the earth. The technique consists in obtaining antiprotons of the lowest energy possible from the LEAR facility at CERN, decelerating them further in an external beam line, trapping and cooling them to ultralow energy, and measuring their gravitational acceleration by time-of-flight methods. The experiment has been granted CERN approval (PS-200). Present plans and initial development efforts are described.

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1. Introduction

An adventurous and difficult experiment to measure the gravitational interaction of antimatter (an antiproton) with matter (the earth) is being planned. The effect of earth's gravity on other fundamental particles has been measured (3), but no measurement of the gravitational interaction of antimatter with either matter or antimatter has ever been made. Recent theory (1,2,3) suggest that the antimatter-matter gravitational interaction could be significantly different than the matter-matter interaction with which we are so familiar. One typical estimate is that the antimatter-matter interaction could be a factor of 3 stronger (4). In keeping with the nature of this conference I will not detail the theoretical background, but I shall first outline the basic experiment as planned by our scientific collaboration developing the project (5), then discuss some of the more challenging aspects of the work, and finally comment on our current progress.

2. The Basic Experiment

A simple schematic of the experiment is shown in figure 1. Antiprotons in a thermal (statistical) distribution in an electromagnetic trap are released to traverse upwards through a 1-m shielded drift tube to a detector, most likely a multichannel plate detector (MCP). The time of flight (TOF) of the particles from release to detection is recorded. At some slow velocity, because of the gravitational attraction, the particles will fall back and not reach the detector. This cutoff time, $T_C=(2L/g)^{1/2}$, about 0.45 seconds, (for normal gravity) allows the determination of g if the drift length L is known.

3. The Real Experiment

Transforming the basic experiment into reality introduces numerous and challenging complications.

a. For a 1-m drift tube, the release energy of the particle with the cutoff TOF is about 10^{-7} eV (5 m/s); gravity is weak! Supplying sufficient numbers of antiprotons to map out the TOF spectrum in the region of the cutoff is a problem. If the antiproton cluster in the launch trap has been cooled to liquid helium temperature, 4 K, the mean energy of the particles is about 10^{-3} eV (1 meV), and few particles have a low enough energy to be useful. Monte Carlo studies indicate that roughly 10^7 particles will have to be launched from a trap at 4 K to measure g to 1%. In order to obtain sufficient numbers of antiprotons, we plan to perform the experiment at the Low Energy Antiproton Ring (LEAR) facility at CERN in Genova, Switzerland, where our proposal (6) has been accepted as experiment PS-200. Details of this experiment have been discussed previously (7-11).

b. In order not to compete with gravitation, electromagnetic forces must be extremely small in the drift tube region: less than 10^{-7} V/m and 1 part in 10^{-5} variation in the magnetic guide field needed for such low energy particles.

c. The drift length L will not be known well because of electric field penetration into the drift tube. An H^- ion has the same electric charge and very nearly the same inertial mass and magnetic moment as an antiproton. An essential part of the experiment will be to repeat the measurements using H^- ions for a calibration and comparison. Thus H^- ion sources will be needed: at 20 keV for tests and development, at 2 MeV for checkout of the deceleration and final experiment setup at Los Alamos, and at 2 MeV from LEAR for beam alignment and tuning. D^- and O^- beams will provide different mass ions to test and help understand the time-of-flight experiment.

d. Extremely low vacuums will be needed, on the order of 10^{-14} Torr, to avoid antiproton annihilation and H^- neutralization by the residual gas atoms.

e. The antiprotons created at the CERN facility at about 3.6 GeV/c (2.7 GeV) must be decelerated, (trapped) and cooled by 16 orders of magnitude in energy to obtain 10^{-7} eV particles, and this must be done without undue losses.

4. Filling the Antiproton Reservoir

A more complete schematic of the experiment is shown in figure 2. The antiprotons produced at CERN are collected, decelerated to 600 MeV/c and injected into LEAR for further deceleration and cooling. We hope to receive from LEAR a 200 ns burst of about 10^8 or more 2 MeV antiprotons. We will then decelerate this bunch to 20 keV using a radiofrequency quadrupole (RFQ). A design study of the use of the RFQ as a *decelerator* has been given by J.H. Billen et al.(12). Transverse currents in the RFQ pole structure provide alternating electric polarities resulting in a transverse electric quadrupole field. This field produces focusing in one transverse plane and defocusing in the other. The fields reverse direction one half an RF period later to produce a net strong focusing effect. The pole tips are machined with an oscillatory variation in radius to produce longitudinal accelerating (or decelerating) fields as well as transverse focusing fields. The strong focusing in an RFQ permits the preservation of good beam quality during deceleration. The RFQ frequently offers the advantage of reduced size over an electostatic system. A current design (13) gives an RFQ length of less than 2 meters. An RF buncher 8 m upstream is necessary to create the initial 200 MHz structure that the RFQ requires. Beam tuning and steering to insure that the single LEAR antiproton pulse will properly strike the first trap is critical, and development of such an ability for the 2 MeV and 20 keV beam lines is underway. The necessary timing for the LEAR beam bunch, chopped H^- beam, trap electrode voltage changes will be handled by a small computer; which will also analyze the experimental time-of-flight data as it is taken.

The 20 keV particles are then further decelerated to 5 keV by electrostatic forces, and then caught in an electomagnetic Penning trap (9,14,15). Here an important transistion takes place from the particles having a directed energy of a beam to a thermal distribution of a cluster held in the center of a trap. Particle confinement in a Penning trap is achieved by a combination of static electric and magnetic fields, with the electic field being that of an axially symmetric quadrupole, the magnetic field being uniform and in the axial direction (the symmetry axis being the beam direction.) Cooling the thermal particle bunch is possible by several means. Stochastic cooling is being studied by collaborators at the University of Genoa and Pisa in Italy, electron cooling at Rice University, and resistive cooling at Texas A&M University and Los Alamos. Information on trapping and cooling processes is reported by Kenefick (16) and Church (17) at this conference.

The catching trap must be long in order to contain a large fraction of the antiproton burst. This length interferes with the harmonicity of the trap and thus its ability to cool the thermal distribution. An example of a design of a catching trap that also has some cooling ability is shown in figure 3. Here the shaping of the electric field with additional electrodes will allow efficient catching of the bunch and still retain enough resonant harmonicity to allow resistive cooling to be used to bring the temperature down to about 10-100 eV on the order of I hour or less. A 6-T magnet provides the axial field necessary for trap operation and for guiding the entering and exiting particles. "Closing the door" to catch the incoming particles is not a routine matter. 10 to 20 kilovolts in 10's of ns must be applied with careful timing to the front electrode of the catching trap. A programmed high-voltage level shifter is under development which will provide the various potential changes in the trap electrode.

The now-small particle bunch is transfered to one or more smaller highly-compensated harmonic traps for additional and fast cooling (to a few Kelvin, $\sim 10^{-3}$ eV) and launching. Even after such cooling, the particles of interest are far down on the slow part of the velocity distribution at 10^{-7} eV.

Successful development of a source of a large number of cold thermal antiprotons may open the door to a number of interesting experiments using antiptrotons or antihydrogen in addition to the gravity experiment.

5. Vacuums and Cryostat Technology

The annihilation cross section rises rapidly as the velocity of the antiproton falls (18). Vacuums of 10^{-10} to 10^{-12} Torr should suffice in the first catching trap. Such vacuums require painstaking but known techniques. In the launch-drift region where the energies are very low, the vacuums must be 10^{-14} Torr or better for adequate antiproton survival. This will necessitate complete enclosure at a temperature of 4 K or colder (19). The design of a system to provide all the voltage and signal leads, as well as a beam "trap door" (see Fig. 1), all to fit in the bore of a superconducting magnet, will be a stimulating challenge.

6. The Gravity Experiment Itself

Launching and detecting such slow particles in an understandable way will be difficult. The pioneering experiment by Witteborn and Fairbank (20) with electrons has and will be a great help in investigating some of the possible systematic effects and errors. Table I lists some of the effects that must be considered. I shall discuss several of these effects. See Ref. (3) for more details.

Table II. Sources of systematic errors.

1. End effects	7. Magnetic field uniformity
2. The patch effect	8. Alignment and tube uniformity
3. Thompson emf	9. Off-axis orbits
4. Electron sag	10. Collisions with residual gas atoms
5. Lattice compression	11. Neighbor interactions
6. Thermal fluctuations	

The patch effect occurs because the surface of even the best of conductors is not at a uniform potential because it consists of many crystal faces (patches) that can have differing work functions (21). The rms axial electric field produced by a random patch distribution on the surface of a typical conductor is estimated to be considerably larger than the gravitational equivalent (22). However, we expect to coat (23) the inner surface with an amorphous but still conducting material to reduce this field significantly. Furthermore, it has been discovered (22) that the patch field is strongly reduced at liquid-helium temperatures, although the reason for this suppression is not understood.

A temperature gradient along the drift tube will cause a potential variation (Thompson emf) of a few μV/K. In our experiment we will need a temperature difference less than 10^{-2} K. Immersing the entire tube in liquid helium cannot accomplish this, because the change in boiling point with pressure causes a temperature gradient of 0.3 K/m. However, it is possible (20) to reduce the gradient to $<10^{-5}$ K/m by having the tube in contact with the helium bath at only one location (see Fig. 1 "Thermal Support Link").

The gravitational force on an antiproton at the earth's surface is equal to the electrostatic force between two antiprotons 12 cm apart. Thus the interaction of neighbor particles in the launch might seriously deplete the number of very low-energy particles. However, in a conducting tube the antiprotons are partially shielded from each other. One finds that the effect is small compared to gravity if the antiprotons are separated by at least two to three times the tube's radius. The effect of such Coulomb forces on the velocity distribution of the launched particles is currently being studied by computer simulation. First results indicate that the number of particles per launch should be in the range of 10-100 to avoid a serious problem. This question will be studied experimentally in tests with H^- ions.

7. Present Status

We have constructed at Los Alamos a test beam line to begin developing the apparatus for the antiproton gravity experiment. A 20 keV H^- beam, chopped to resemble an antiproton bunch is sent through a horizontal section consisting of valves, cold traps, four-way slits, vacuum pumps, magnetic steerers, and electrostatic lenses. The beam is then turned into the vertical direction by a 90° magnet mounted in a large vertical support stand. Above the 90° magnet, the beam is steered and focused into a Penning trap situated in the 6-T field of a superconducting solenoid magnet.

Our ongoing tests with this apparatus will allow us to study vacuum isolation and bakeout procedures, ultimate vacuum capability with a room-temperature ion trap, trap pulsing to capture protons or H^- ions, the features needed in subsequent trap designs, and the type of H^- source to be taken to LEAR. To date, we have succeeded in passing a 10 μA beam of 20 keV H^- ions through the trap's 3 mm diameter apertures in a 6-T magnetic field. We have also demonstrated simple trapping of NNN ions for TTT seconds by a fast raise of the voltages on the appropriate traps caps, followed by release and detection with an MCP. This is an important step: capture of in-flight ions has only recently been demonstrated (24).

In the future, an improved system with a new 20 keV H^- source, buncher and RFQ decelerator will be constructed and installed at Los Alamos to receive a 2 MeV H^- beam from the Los Alamos Vertical Van-de-Graaff. Research with this system will lead to a final choice of traps and drift tube assembly, which in turn will be proof tested with H^- ions before shipment to CERN for the antiproton experiment.

8. Acknowledgements

Besides expressing appreciation to my colleagues (5) for discussions and help, I would like to thank D. C. Lizon, R. Martinez, R. R. Showalter, and C. B. Webb for their expert help in constructing and operating the present test system at the Los Alamos Ion Beam Facility.

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Figure Captions.

1. Schematic of an apparatus design for the time-of-flight antiproton gravity experiment. Ten eV antiprotons coming from below are trapped and cooled in the final Penning "launch" trap to a temperature of roughly 10 K. The antiprotons would be extracted, a few at a time, to drift up the shield tube; and, if not pulled back by gravity, accelerated to strike the detector. A rough scale is given by the 1-m tall drift tube.

2. A possible schematic diagram for the Antiproton Gravity Experiment. The layout is a plan view except for the section after the electrostatic mirror which is a side view. The diagram is not to scale. The region inside the dotted lines represents a "thermal source" of low to very-low energy antiprotons that would be available for a variety of experiments.

3. Schematic cross section of a design for a first stage catching trap. The device is azimuthally symmetric about the horizontal axis. The entrance electrode is elongated to accomodate the beam burst length after some electrostatic deceleration. The Penning trap proper centers at the torus of circular cross section, and has a extended array of electrodes to provide a long trap that still has sufficient harmonicity for cooling. The entire trap length in this design is 50 cm.

9.REFERENCES

1. T. Goldman and M. M. Nieto, Phys. Lett. 112B, (l982) 437.
2. T. Goldman, R. J. Hughes, and M. M. Nieto, Phys. Lett. B171, (1986) 217; see also Ref. 10.
3. R.E. Brown, in *2nd Conference on the Intersections between Particle and Nuclear Physics,* Lake Louise, Canada, May, 1986.
4. R.J. Hughes, private commincation.
5. A recent list of collaboration members is given in ref. 3.
6. N. Beverini, *et al.*, CERN proposal P-94 (Los Alamos National Laboratory report LA-UR-86-260).
7. M. V. Hynes, in *Physics with Antiprotons at LEAR in the ACOL Era,* Proc. Third LEAR Workshop, Tignes, Savoie, France, January, 1985, edited by U. Gastaldi, R. Klapisch, J. M. Richard, and J. Tran Thanh Van (éditions Frontières, Gif sur Yvette, 1985), p. 657.
8. R. E. Brown, in *Workshop on the Design of a Low Energy Antimatter Facility in the USA,* Madison, Wisconsin, October, 1985 (American Institute of Physics).
9. M. H. Holzscheiter, in the Workshop of Ref. 8.
10. T. Goldman, in *Antimatter Physics at Low Energy,* Fermilab Low Energy Antiproton Facility Workshop, April, 1986 (to be published by the Fermi National Accelerator Laboratory).
11. M. V. Hynes, in the Workshop of Ref. 6.
12. J. H. Billen, K. R. Crandall, T. P. Wangler, and M. Weiss, in *Physics with Antiprotons at LEAR in the ACOL Era,* Proc. Third LEAR Workshop, Tignes, Savoie, France, January, 1985, edited by U. Gastaldi, R. Klapisch, J. M. Richard, and J. Tran Thanh Van (éditions Frontières, Gif sur Yvette, 1985), p. 107.
13. F. Iazzourene and K. Crandell, Private communication
14. J. Byrne and P. S. Farago, Proc. Phys. Soc. (London) 86, (1965) 801.
15. L.S. Brown and G. Gabrielse, Rev Mod. Phys. 58, (1986) 233.
16. R.A. Kenefick, *Considerations for Electromagnetic Antiproton Traps,* this conference.
17. D.A. Church, *Highly-charged Ions at Electron-Volt Energies and Below: Production, Storage and Measurements,* this conference.
18. L. Bracci, G. Fiorentini, and O. Pitzurra, Phys. Lett. 85B, (l979) 280. See also ref. 6.
19. W. Thompson, and S. Hanrahan, J. Vac. Sci. Technol. 14, (1977) 643.
20. F. C. Witteborn and W. M. Fairbank, Phys. Rev. Lett. 19, (1967) 1049; Rev. Sci. Instrum. 48, (1977) 1, this ref. discusses the design criteria and sources of error for the electron gravity experiment; F. C. Witteborn, Ph.D. thesis, Stanford University (1965).
21. C. Herring and M. H. Nichols, Rev. Mod. Phys. 21, (1949) 185.
22. J. M. Lockhart, F. C. Witteborn, and W. M. Fairbank, Phys. Rev. Lett. 38, (1977) 1220.
23. R. Mah, private communication; S. Takayama, J. Mat. Sci. 11, (1976) 164.
24. H. Schnatz et al., *In-Flight Capture of Ions into a Penning Trap,* Submitted to Nucl. Instr. and Methods.; H.-J. Kluge, private communication. Also: G. Gabrielse and collaborators, Science, 233, 1383, (1986).

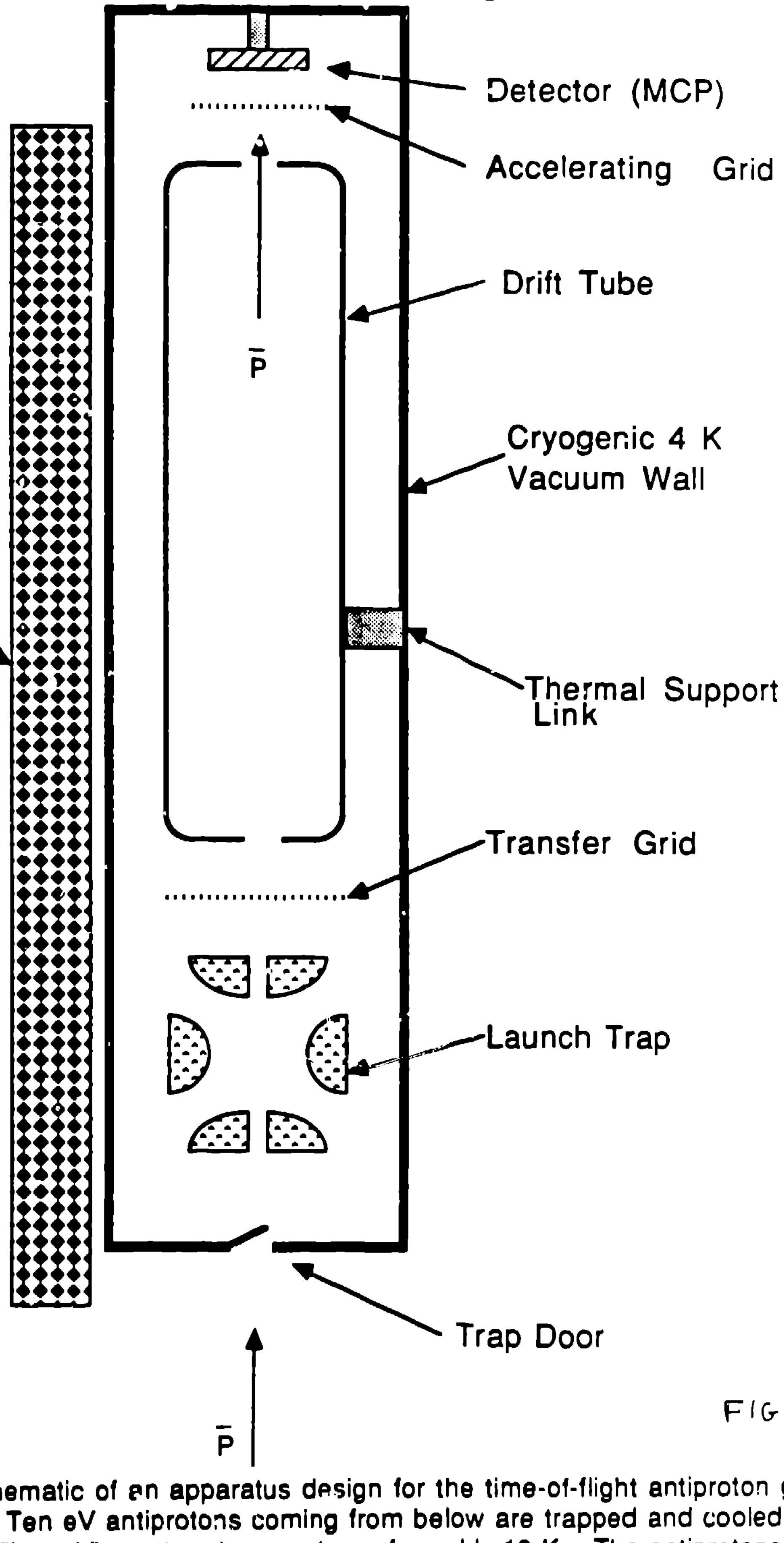


FIG. 1

1. Schematic of an apparatus design for the time-of-flight antiproton gravity experiment. Ten eV antiprotons coming from below are trapped and cooled in the final Penning "launch" trap to a temperature of roughly 10 K. The antiprotons would be extracted, a few at a time, to drift up the shield tube; and, if not pulled back by gravity, accelerated to strike the detector. A rough scale is given by the l-m tall drift tube.

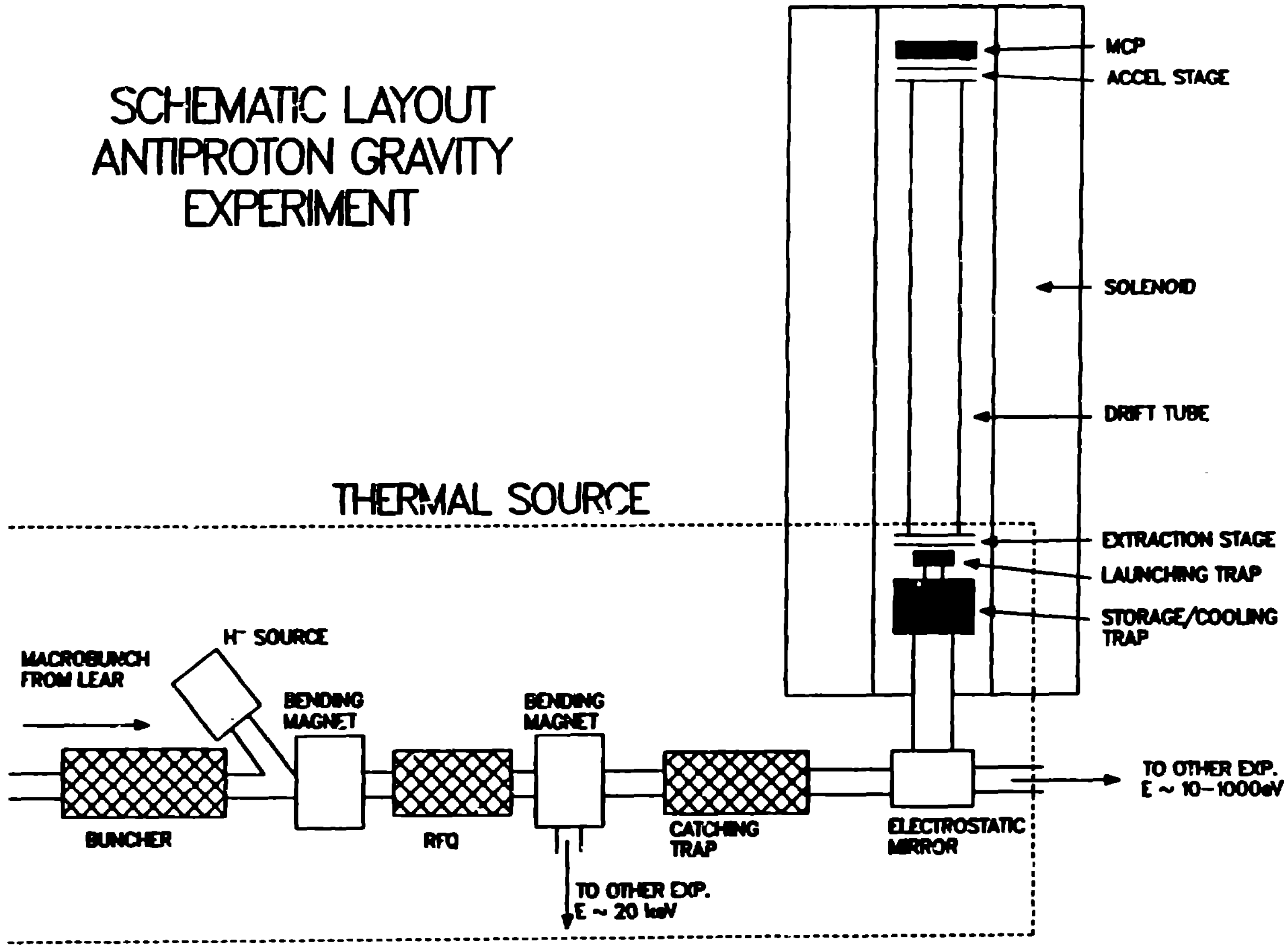
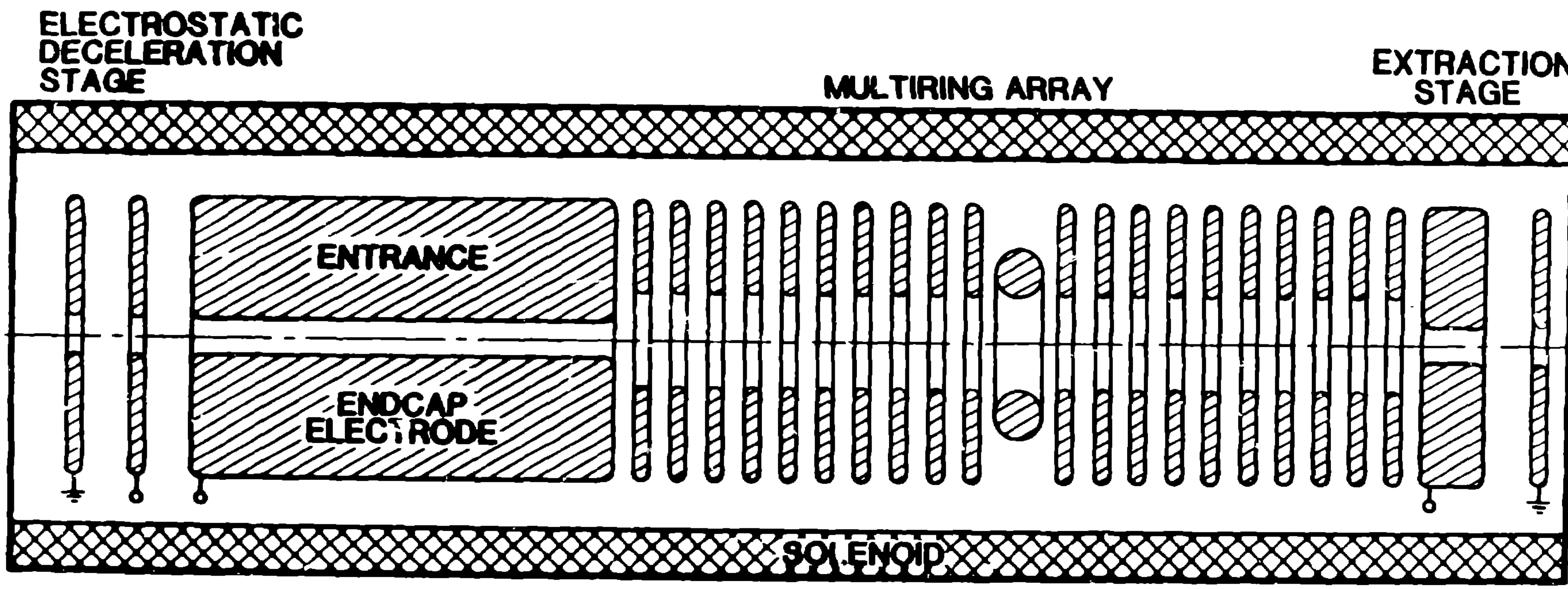


FIG 2.

2. A possible schematic diagram for the Antiproton Gravity Experiment. The layout is a plan view except for the section after the electrostatic mirror which is a side view. The diagram is not to scale. The region inside the dotted lines represents a "thermal source" of low to very-low energy antiprotons that would be available for a variety of experiments.



3. Schematic cross section of a design for a first stage catching trap. The device is azimuthally symmetric about the horizontal axis. The entrance electrode is elongated to accomodate the beam burst length after some electrostatic deceleration. The Penning trap proper centers at the torus of circular cross section, and has a extended array of electrodes to provide a long trap that still has sufficient harmonicity for cooling. The entire trap length in this design is 50 cm.

FIG 3