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RESPONSE TO THE PSCC QUESTIONS ON PROPOSAL P-94, A MEASUREMENT OF THE GRAVITATIONAL ACCELERATION OF THE ANTIPROTON

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In this note the collaboration responds to the PSCC questions that were raised after the presentation of our proposal to measure the gravitational acceleration of antiprotons at the February PSCC meeting. For the reader's convenience we list all the questions first followed by the responses.

QUESTIONS ON THE GRAVITY EXPERIMENT

1. What is your experimental schedule? When will you actually want floor space?

2. Will an MCP work at 4K and 6T?

3. Is background a serious problem?

4. With its low Q, how will the first collection trap cool particles?

5. Because of the extremely small value of the gravitational force:
   A. Will the "Coulomb explosion" invalidate the TOF spectra?
   B. Will "near neighbor" coulomb forces in the drift tube invalidate the TOF spectra?

6. Will the TOF results be seriously affected by:
   A. Single charges (from annihilation products for instance) resting on an insulating layer on the inner surface of the drift tube surface?
   B. The "Patch" effect on the tube wall and/or the exit hole in the launch trap?

ANSWER TO QUESTION 1.

We expect to complete the program of testing using the RFQ to decelerate 2 MeV H^- ions from the LANL Van de Graaff accelerator to 20 keV and their injection into the trap system in early 1988. The RFQ system, including vacuum isolation systems, power supplies and beam diagnostics would be shipped to LEAR after these tests are completed. The shutdown period during January and February 1988 should be used to install the necessary beam line connections and vacuum isolation valves onto the experimental beam line in order not to interfere with the LEAR operations at a later date. After the RFQ installation some time running with H^- would be required for testing and tuning of the system.

We project that final tests of the actual gravity experiment at LANL using H^- ions and protons from a low energy ion source would continue into 1989. After the techniques of catching, cooling, transferring, and launching have been established and time-of-flight spectra suitable for a measurement of the gravitational effect on H^- and antiprotons have been obtained, the experimental set-up will be transferred to LEAR around mid-1989 for installation. Actual running with antiprotons is expected in the 1990 experimental period. The RFQ will therefore be available for studies of beam parameters and for preliminary tests of particle trapping by us and afterwards for other LEAR experiments requiring a low energy pulsed antiproton beam during the 1988/1989 cycle.

ANSWER TO QUESTION 2.

We will only operate our detector under proven conditions. Figure III-1 in our proposal (P-94) only represented a very schematic view of our experiment. We do not anticipate operating our detector, an electron multiplier device (EMD) possibly a MCP, in the highest magnetic field nor at the 4K temperature unless our studies show that this is possible. A recent study[1] shows the successful operation of an MCP at 77K and in 1T field strengths. The figure below shows a more detailed view of the upper end of the drift tube in one possible scenario where an MCP is removed from the high magnetic field and the lowest temperature environment. The detector

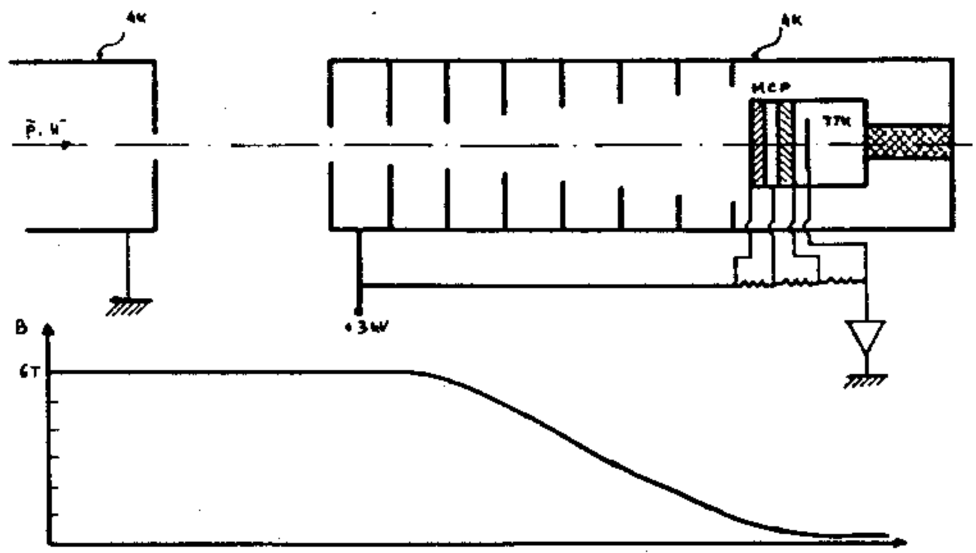

Fig. 1. The MCP detector and upper end of the drift tube is schematically shown. Note the post-acceleration stage and thermal isolation baffles.

package is thermally insulated from the 4 K shield and can be heated to a higher temperature.

After particles have been drifting along the axis of the drift tube at extremely low energy, spending up to 0.45 seconds per meter in the drift tube, they have to be post accelerated up to 3 keV kinetic energy to be detected by an MCP with significant efficiency. This is accomplished by applying an electric field between the exit of the drift tube and the front end of a second baffled tube which serves mainly as a heat shield, but also provides again an electrostatic field free region to transport particles from the high magnetic field region to a region of moderate magnetic field strength where the MCP can be operated with well known characteristics. Because the acceleration is taking place in a region of high magnetic field, the radius of the trajectories is small, enabling the use of small apertures without having particles strike the aperture edges and thus be lost or produce background due to annihilation.

The time needed for a particle to travel the distance from the drift tube exit to the MCP in this scenario is only of the order of 85 μsec and therefore insignificant compared to the proposed bin width of ~1 msec in the TOF spectra.

At the same time this system allows for the MCP to be physically removed from the drift tube assembly and to operate at a higher temperature (e.g. 77K). Cold baffles on the inside of this second tube will provide the necessary heat shielding to avoid interference with the low temperature operation of the drift tube.

Experiments using H^- ions and protons will be carried out to investigate the properties of this scenario and to establish the efficiency, background properties, and TOF distribution using this system. In parallel, an investigation has been started to search for alternative detectors, sensitive to both H^- ions and antiprotons with known characteristics.

ANSWER TO QUESTION 3.

We do not expect background signals to be a serious problem. From our studies we predict that only signals from external events will be of concern.

1. External Events. These are actual penetrating particles from other LEAR experiments, LEAR beam spill, PS beam spill, and Cosmic Rays. Our detector will be 2 meters or more above or below the plane of the beams. We will be using a detector that is small (1-2 cm^2) and is less sensitive to neutrons (an MCP or other electron multiplier).

From the Monte-Carlo study of the TOF end point analysis, we conclude that 20 background counts per 2 millisecond data bin over a run of 2×10^4 launches would be a preferable upper limit. This corresponds to a steady background rate of 0.5 counts/second. Depending on the sensitivity of an MCP to fast muons, this rate indicates that Cosmic Rays might begin to be a problem. Although expected to be small, machine caused background rates are unknown.

Therefore, especially since background rates provide sometimes nasty surprises, two collaborators (Scuri and Torelli) will operate a typical detector in the environment of the LEAR experimental hall. They expect to have results in April 1986 or sooner. Should an unexpected high rate be discovered, we would plan to use passive (bulk shielding) or active (anticoincidence counters) to reduce the background to an acceptable level. In this case, the antiproton annihilation "signature" could be useful to distinguish between background and real events.

2. Internal Events: From antiprotons or H^- ions not part of the regular launch and detection pattern. These would come from:

A. Our beam line: The beam is off long before the launching begins.

B. The half of the released antiprotons going opposite to a launch or those being rejected at the entrance to the drift tube: All of these events will be prompt. A small solid angle factor $\lesssim 10^{-5}$, will eliminate the few late time events from secondary processes.

C. Antiprotons striking the output aperture of the top end cap because of imperfect transmision: These again are all prompt; and we expect very good transmission since we intend to use the sideband centering technique to reduce the magnetron motion radii to a value smaller than the radius of the exit hole.

D. Antiprotons annihilating with residual gas atoms in the ion traps: If the trap contains 10^7 antiprotons, and as at the vacuum expected we will have an annihilation rate of 10^{-6}/particle/second, there would be 20 disintegrations/second. Because there are about 4 or 5 pions per disintegration and with a geometry factor of $\leq 10^{-5}$ (a 1 cm^2 detector at 1 m), the resulting background rate would be about 5×10^{-4}/second. Thus a background from this source is negligible.

E. Antiprotons annihilating in the drift tube: Only 100 particles at a time will be launched. Because of the above mentioned annihilation rate at the vacuum expected, the background during the total time of flight of .5 seconds would be less than 5×10^{-5} counts for each launch and therefore negligible.

Extending the TOF measurement beyond the end point up to the next launch will help establish the amount and nature of the background.

ANSWER TO QUESTION 4.

The cooling in the collection trap will be produced by a one time adiabatic well depth reduction and by resistive damping in the axial and radial directions.

With its elongated design, the collection trap gives the appearance of being highly anharmonic. However, this need not be the case. By choosing a basic harmonic trap design, but selecting equipotential surfaces for the ring and endcap electrodes having different parameters, proper biasing of the electrodes will provide harmonic confinement. The requirement of truncation in the radial direction will re-introduce anharmonicities, but these can be minimized by the proper choice of compensation electrodes. We expect that field mapping and/or relaxation calculations will be necessary to establish the proper electrode configuration to achieve the desired harmonic properties. Nevertheless anharmonicities will exist. Experience with anharmonic traps with more conventional dimensions show that the ion oscillation Q in the trap remains high (~2000), but the resonant frequency of the axial oscillation is shifted from the theoretical (harmonic) value. Similar shifts are observed when trapped space charge distorts the potentials. The requirement for effective resistive damping is that the ion oscillation Q exceeds the Q of the damping tuned circuit -- this latter Q is of order of 200. Past experience indicates that only severe anharmonicities might reduce the ion oscillation Q to this low value.

A second requirement of resistive damping is that as the ions cool, an axial frequency shift due to anharmonicities not detune the ion oscillation frequency from the tuned circuit resonance. This can be accomplished by small adjustments in the tuned circuit frequency (electronic capacitor tuning) or in the confining potential. These required adjustments can be determined from experience, and programmed into the cooling cycle.

To increase the cooling rate over the axial cooling rate (which is slow due to the large endcap electrode separation) the ring and compensation electrodes will be split into quadrants to permit radial cooling of the cyclotron motion at the frequency ω_+. This cooling becomes more effective as the ions lose energy, and spend more time in the vicinity of the ring electrode quadrants.

A second possibility of cooling in this first structure is the method of stochastic cooling. At present no experimental evidence is available but theoretical estimates are very promising. This possibility is currently being investigated experimentally by us. If the experimental results from this effort support the theoretical predictions, then this method will be superior in a large structure to all other techniques, and will be employed in our collection trap. A third cooling method under discussion is the electron cooling well known from storage rings, but not yet established in ion traps. We recognize the strong need of detailed experimental studies and therefore started investigations in different areas by parts of our collaboration in parallel: While at Los Alamos National Laboratory the main emphasis is directed towards tests of adiabatic and resistive cooling from energies of several kilo electron volts down to 10-100 eV, Texas A&M has started to develop the techniques for the final cooling to 4 K. The study of stochastic cooling is carried out at the University of Genova and results are expected to be available in the near future. Tests simulating electron cooling of antiprotons in a penning trap are planned at Rice University using positrons and protons.

Only after the different possibilities have been studied carefully can a decision on the final design be made. But even at this time it must be noted that the well established method of resistive cooling will be fast enough to carry out the experiment.

ANSWER TO QUESTIONS 5A & 6.

Parts of questions 5A and 6 address the launching technique and are best answered together. A more detailed study of the launch technique than presented in the proposal should help in clearing up these questions. Figure 2 shows a conceptual view of the drift tube, the launch trap, and related potentials. Also shown are the potentials Φ along the z-axis and the energy distribution dN/dE of the particles in the trap. Inside the drift tube we assume, for the moment, that the potential is perfectly flat and arbitrarily set to zero. At the edge of the drift tube entrance and the trap exit aperture there exist uncontrollable variations due to imperfections and contact potentials. In the gap between the trap and drift tube entrance, the imperfections of the surrounding vacuum shell will introduce potential variations of unknown character as well. The effect of these potential variations can be overcome by using the same launching technique as used by F. Witteborn in his work on the gravitational force on freely falling electrons.[2] For measurements on antiprotons and H^- ions the

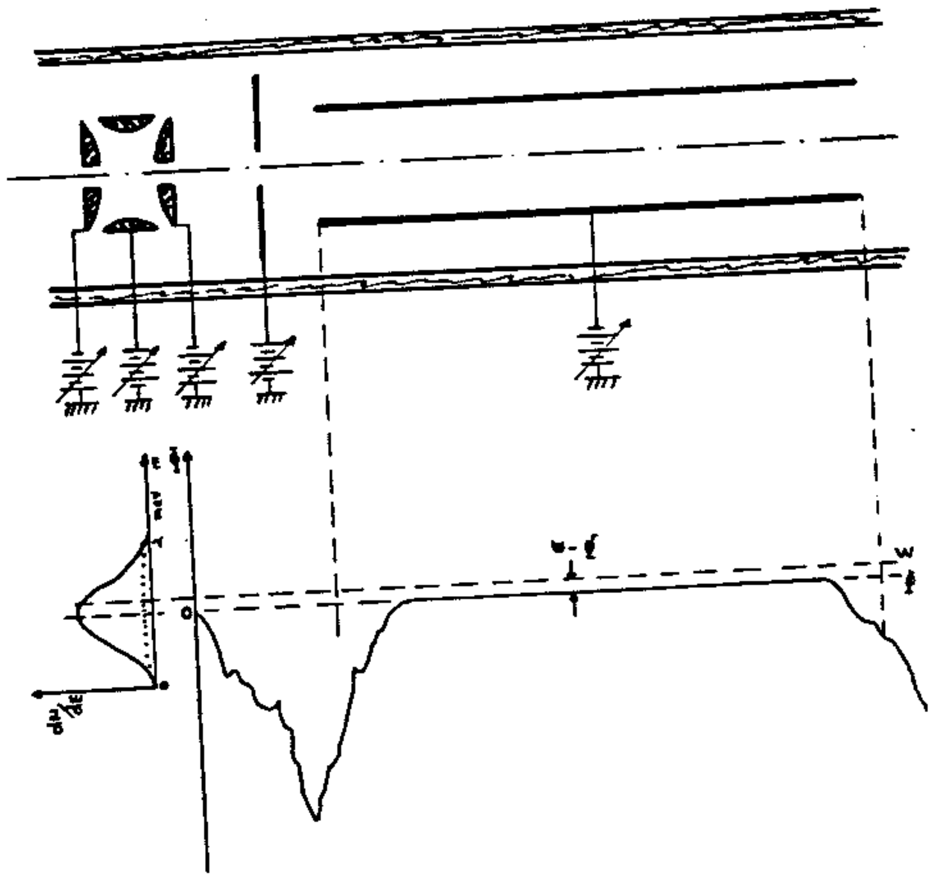

Fig. 2. Ion trap and drift tube system showing the potential variation along the z-axis and the energy distribution of the stored particles.

drift tube and ion trap will be biased negatively to a potential significantly higher than the variations in potential between these two components. The relative bias between these two structures will be adjusted so that the effective potential on the drift tube approximately coincides with the maximum of the energy distribution of the particles in the trap. Because only a few particles will be launched at a time this distribution has to be interpreted as the probability to find a particle with a specific energy in the individual ensemble which is indicated by the dots at the bottom of this part of the figure. After launching (i.e. by opening the downstream endcap) the particles will traverse the gap in a relatively short time compared to the time spent by a slow particle in the effective drift length. Particles with a total energy larger than Φ will be able to enter the drift tube. The density in the energy distribution can be chosen appropriately to have a probability of less than 1 to have a particle with kinetic energy $W-\Phi \leq 1 \times 10^{-7}$ eV. Particles with a total energy W less than Φ will be rejected at the drift tube entrance. The total number of particles in the drift tube at any one time will be small enough not to affect the TOF spectra by the Coulomb force between "near neighbor" particles (see answer to question 5B).

It is important to note that this scenario requires that the potential at the drift tube and ion trap be controlled at a value somewhat smaller than the energy spread of the ensemble of stored particles (10^{-3} eV at 4K). The number of particles entering the effective drift length with a kinetic energy less than 10^{-7} eV is established statistically by the probability distribution. This technique of extraction from a source prior to the drift tube has been used successfully by F. Witteborn and W. M. Fairbank in the experiment on freely falling electrons[3] where they launched electrons from a tunnel diode with an axial energy spread between 0.1 and 1.0 eV. In this work they were able to observe the gravitational force on electrons which is equivalent to a potential of order 10^{-11} eV.

The effect of contact potentials, the exit hole "patch" effect, and the potential variations between trap and drift tube are thus overcome. The effect of the "Coulomb explosion" of a number of particles leaving the trap as a dense package has also become unimportant because the critical comparison is no longer the gravitational potential equivalent to 10^{-7}eV but the width of the energy distribution of the released particles which is of order 10^{-3} eV for 4 K. Because the Coulomb interaction of the particles in the trap is at most in equilibrium with the temperature of 4 K the extreme case would be a broadening of the distribution by a factor of 2. This would reduce the probability to obtain a "slow" particle by 50%. But detailed Monte-Carlo studies show that the actual effect is much less.

In his work on the gravitational acceleration of the electron, F. C. Witteborn saw no effects from isolated charges trapped on the inside surface of the drift tube. Surface trapping of charges does not occur because, even though there are atomic layers of metal oxides and other gases and contaminants on the drift tube's surface, these layers are much too thin to act an insulators; the strong image attraction to the tube's surface simply pulls any nearby charge through this layer and into the metal. Even if a charge would be able to reside on a surface layer of sufficient thickness it and its image charge would represent an electric dipole. The net field seen by the particle traveling along the axis of the drift tube would be very small.

The influence of the patch effect on the tube walls on the particle trajectories in the drift tube can be enormously reduced by using an amorphous conducting coating on the interior surface of the drift tube. Recent advances in surface coating techniques have allowed for conducting coatings with grain sizes of the order of 10-100 Å.[4,5] With this small grain size the patch effect is well below the gravitational effect.

ANSWER TO QUESTION 5B.

The original proposal did not develop the details of the launch geometry (see figure 2 in answer to question 5A - 6). We will choose a number of H^- ions or antiprotons per launch of approximately 100. Assuming for simplicity a Maxwell-Boltzmann distribution of width 10^{-3} eV (equivalent to a temperature of approximately 4 K) only a 1% fraction of the particles will occupy the energy range of interest (10^{-6} eV). Most particles will either be rejected at the drift tube entrance or reach the detector very promptly. Monte-Carlo simulations show that the 100 particle cloud will be dispersed at the entrance to the drift tube to a density where the Coulomb force between neighboring particles is below 1% of the gravitational force within 1 msec, a small time compared to the .4 seconds transit time for the particles making up the end point of the TOF spectrum.

Currently we are in the process of performing a more detailed Monte-Carlo study incorporating the accel-decel region between the trap and the drift tube. Preliminary results indicate that near neighbor interactions do not present a serious problem. Results of these simulations will be available for the next PSCC meeting in April.

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