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Portable trap carries particles 5000 kilometers

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Electrons suspended in a Penning trap were transported more than 5000 km, all the way across the continental United States. The magnetic field was provided by a persistent superconducting solenoid at 4.7 T which was not connected to any source of power during travel. The electric field was produced using ordinary 9 V batteries. A good vacuum, expected to be sufficient to keep antiprotons stored indefinitely, was maintained within the trap by keeping it at 4 K. Portable traps are of interest for experiments which require small numbers of antiprotons for precise studies, for acceleration to energies not available at the LEAR antiproton source, for experiments with large immovable detectors, and for possible medical applications. The portable apparatus is so similar to that used to contain low energy antiprotons, that the trip demonstrates the feasibility of transporting cold antiprotons over large distances in portable traps.

In the last several years, antiprotons have been slowed from 5.9 MeV to below 3 keV via collisions in matter [1,2], captured in a Penning trap [1] and cooled via collisions with cold electrons in the trap [3] to below 1 meV. Antiprotons are now regularly studied at this low energy which is more than 10^{10} times lower than the previous low storage energy for antiprotons attained in the Low Energy Antiproton Ring (LEAR) at CERN. No loss of antiprotons has been observed over a confinement time of two months. The inertial mass of the antiprotons has been shown to be the same as that of protons to better than 4 parts in 10^8 [4], an improvement in accuracy by more than a factor of 1000 over previous measurements.

The possibility to transport antiprotons within a trap is of some interest. First, the increasing accuracy being achieved in the comparison of the antiproton and proton masses may require moving the trapped antiprotons away from the magnetic disturbances at the location near LEAR where the antiprotons are loaded into the Penning trap. Any such precision experiment could be performed in a more suitable location if antiprotons could be transported from the antiproton source. Second, antiprotons transported to the location of a large, expensive and immovable detector could be used for experiments (e.g., hadron spectroscopy experiments) with more resolution than is possible with the detectors already located at LEAR or which could be fitted into the available space. Third, trapped antiprotons could be reaccelerated to energies not available at LEAR in an accelerator located at an-other location. Fourth, medical applications for imaging and therapy have been studied [5–7].

The occasion for the portable trap demonstration was the completion of a new superconducting solenoid and dewar manufactured by the Nalorac Cryogenics Corporation in Martinez, California. The new solenoid had to be transported across the United States, to Cambridge, Massachusetts. We decided to transport the solenoid with a substantial persistent current flowing and to locate a Penning trap containing particles suspended inside.

Charged particles in a Penning trap are regularly stored for long times. For example, a single electron has been trapped continuously for over ten months [8]. The confinement is maintained through a combination of a strong, homogeneous magnetic field and an electrostatic quadrupole potential [9]. For the portable trap, the magnetic field was created by an NMR grade superconducting solenoid. This solenoid was energized to 4.7 T, about 80% of its maximum rated field, and shimmed to a homogeneity of about 25 ppb/cm^3. The Penning trap was then installed and cooled to the liquid helium boiling temperature (4 K). This cryogenic vacuum system was essentially identical to that used to store trapped antiprotons long enough to establish a pressure better than 5×10^{-17} Torr [4]. The quadrupole electric field was created by a group of carefully shaped copper electrodes (in an orthogonalized hyperbolic geometry [10]) held at various potentials. For the portable trap, two ordinary 9 V radio batteries provided the trapping potentials. The electrons oscillated along the magnetic field direction at a frequency of 63.4 MHz. With the magnetic field provided by the persistent superconducting solenoid and the electric field by the small batteries, the apparatus required no source of power to confine particles.

Electrons are loaded in the trap by applying about 800 V to a field emission point (a sharpened tungsten wire) to make an electron beam which follows a field line of the strong magnetic field through the center of the trap. The electrons dislodge atoms from a surface they strike. Other electrons subsequently ionize some of the atoms. Electrons scattered from the atoms and electrons from ionization are trapped. Approximately 6×10^4 electrons were loaded and held for 51 h before the apparatus was hoisted into the truck. (Many more electrons could have been carried, but this number of electrons was convenient for monitoring.) Minimal detection electronics sufficed to measure the number of trapped electrons. The motion of electrons in the trap induced a signal current in a tuned circuit attached to one of the electrodes. This signal was picked up by a GaAs FET preamplifier (kept near 4 K) and then sent to a series of low noise broadband amplifiers. The resultant signal as detected on a Hewlett-Packard spectrum analyzer (model 8593A) was a dip in the noise voltage across a tuned circuit. Fig. 3a shows the electron signal before the trip began, followed by corresponding signals at other times during the trip. The width of the dip measures the number of electrons in the trap [11], which number can be easily determined to approximately 10%.

We were the sole occupants of a 15 m long air-ride trailer. The magnet was loaded on a 25 cm thick wooden pallet and 20 cm of high density styrofoam within the trailor, along with the detection electronics and other supporting equipment. This included back-up storage containers of liquid helium, liquid nitrogen, and helium gas. During each of 23 stops (requiring a minimum of 10 min), a diesel ac generator was turned on to provide power for the monitoring electronics. Cryogen levels and boiloff rates were also monitored at each of the stops. The total distance for the trip was 4984 km and took 88.4 h (3.68 days, average speed 56 km/h). The route (fig. 1) followed Interstate 80 from Sacramento to Chicago, and then Interstate 90 into Cambridge. The Sierra Nevada mountains were crossed beginning at Donner Pass (elevation 2203 m) and the Rocky Mountains near Laramie, Wyoming (elevation 2179 m).

The trip was uneventful except for one unfortunate (and completely avoidable) incident which occurred while stopped in Grand Island, Nebraska. As is evident from fig. 2, the boiloff of the cryogen reservoirs increased and then decreased dramatically as the helium boiling temperature changed with changing altitude (i.e. changing atmospheric pressure). The sustained period of low boiloff after descending from the mountain passes allowed moisture laden air to seep back through the exhaust hoses and flowmeters to form ice blockages in both the main helium reservoir around the solenoid and in the dewar for the Penning trap. The ice blockage was unplugged in Echo Reservoir, Utah by inserting a transfer line into the dewars and also by flowing helium gas across the ice. The exhaust lines were extended in hopes of reducing the moisture backflow. (A simple one way check valve which would have completely eliminated this problem was unfortunately not available

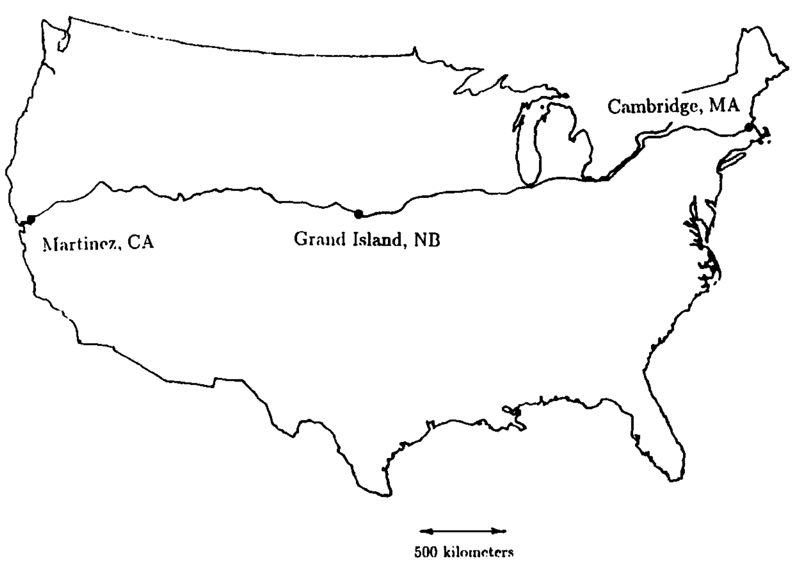

Fig. 1. The route followed Interstate 80 from Sacramento to Chicago, and then Interstate 90 into Cambridge.

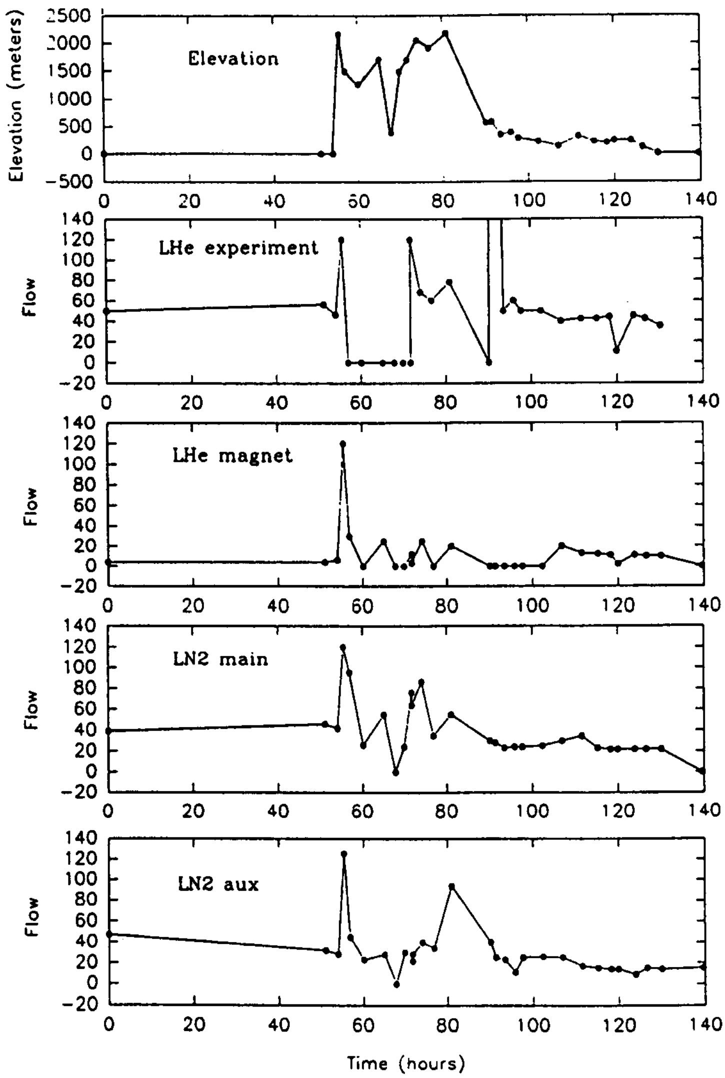

Fig. 2. Cryogen boiloff rates as a function of time show clearly the effect of altitude (i.e. pressure) changes.

owing to our earlier belief that the flowmeters were sufficient check valves.) After crossing the Rocky Mountains, the Penning trap dewar was again blocked with ice. When we stopped in Grand Island, Nebraska, the electrons were still present in the trap. However, to unplug the blockage we unfortunately warmed the dewar sufficiently to lose the cryogenic vacuum and hence the electrons. This occurred 2500 km into the trip. The dewar was refilled with liquid helium. While still stopped, approximately the same number of trapped electrons were loaded and then transported the remaining 2500 km to Cambridge, Massachusetts. The second leg of the

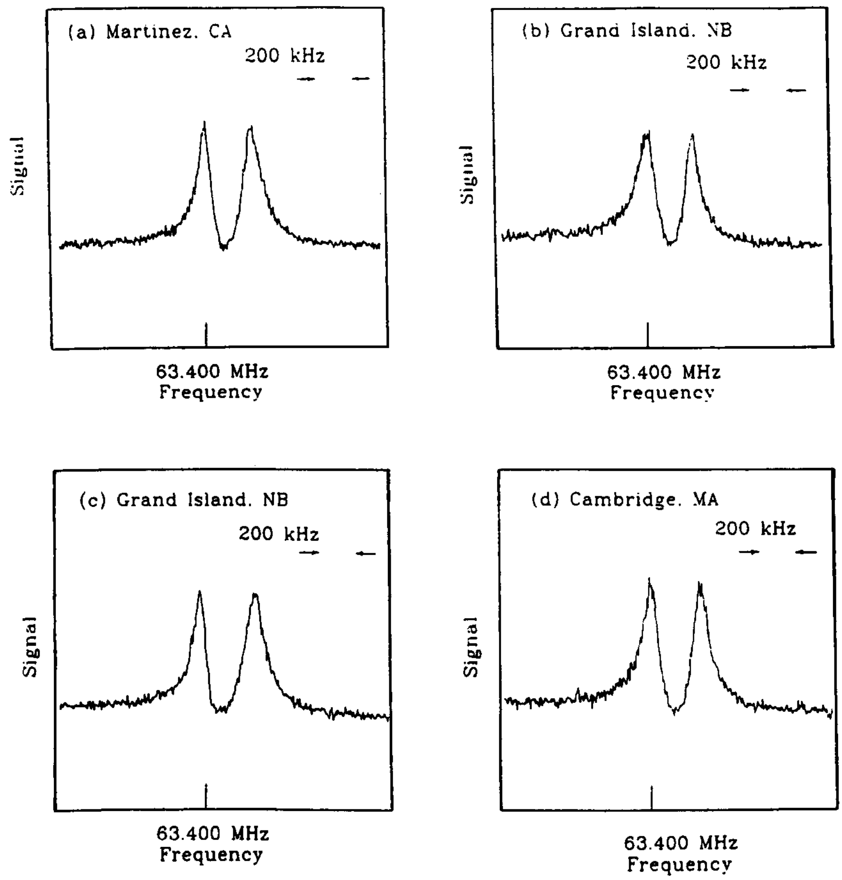

Fig. 3. Trapped electrons produce the central dip in the resonant noise peak from a tuned circuit attached to trap electrodes, with a dip width that indicates the number of trapped electrons. Electrons loaded in California are shown before departure (a) and while stopped in Nebraska (b). Electrons loaded during this stop in Nebraska (c) remain in the trap after arrival in Massachusetts (d).

trip had only small elevation changes, and the monitored flow rates did not vary much. Although the mishap illustrates that great care must be taken with low loss helium dewars, eliminating ice blockages in the future will be extremely easy. We thus regard the two successful 2500 km trips as a convincing demonstration of the feasibility of transporting charged particles in traps.

A portable trap apparatus could, of course, take many forms. As discussed earlier, transport of antiprotons in a trap seems to be of the greatest interest. We thus deliberately used an apparatus very similar to that used for the antiproton experiments mentioned. Of particular importance (for antiprotons rather than electrons) is a vacuum expected to be better than 5×10^{-17} Torr [4] obtained by cooling a sealed vacuum enclosure to 4 K. No vacuum pumps produce such a low pressure. Moreover, pumps would require power throughout the trip. Once liquid helium and liquid nitrogen were employed to produce high vacuum, it seemed sensible to use a persistent superconducting solenoid cooled by the same cryogenic liquids to produce the high magnetic field. A stable and strong field was maintained throughout the trip using only the cryogenic fluids stored in the low loss dewars, and no power source was required. Permanent magnets could have been used instead, but the magnetic field would necessarily have been lower. (Permanent magnets could be located within the higher field of a superconducting solenoid during antiproton loading and cooling and then removed for transport at a lower field when the solenoid field is turned off.) A high field is desirable for capturing, storing and transporting the largest possible number of particles.

In conclusion, we have moved trapped electrons over 5000 km across the United States, from California to Nebraska and then from Nebraska to Massachusetts. We deliberately used an apparatus which is very similar to that used with trapped antiprotons, so we regard the trip as a convincing demonstration that antiprotons can be transported over similar large distances.

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