Combined Trap with the Potential for Antihydrogen Production

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We present the first experimental demonstration of simultaneous trapping of electrons and ions in the same spatial region. Confinement of particles with opposite charges and very different mass in the combined trap represents an important step towards the synthesis of antihydrogen.

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The laboratory production of antimatter atoms will provide the physics community with an unexplored and fascinating testing ground. Possible experiments, both on the symmetry between matter and antimatter and on the gravitational acceleration of antimatter, are issues of considerable interest and controversy [1–4]. When the challenging task of antihydrogen production at low energies is completed, the same powerful experimental techniques of high-resolution optical spectroscopy of hydrogen and deuterium, which have been used to test quantum electrodynamics [5], to measure fundamental constants [6], and even to investigate hadronic structure [7], can be applied to antihydrogen. Work essential to the production of antihydrogen has been recently advanced by several groups. To begin with, its constituents, dense clouds of up to 10^6 antiprotons [8,9] and 2×10^4 positrons [10], have been accumulated in Penning traps and cooled to 4.2 K. However, the spatial overlap, and hence the recombination of antiprotons and positrons, remains a problem. The spontaneous rate for radiative recombination of positrons and antiprotons is small, since photon emission is a slow process on the time scale of a collision. However, the reaction rate can be increased substantially, if this free-bound transition is stimulated with laser radiation. The predicted large enhancement factors have been observed recently in experiments on merged electron and proton beams [11–14]. We point out that progress in the cooling and spectroscopy of magnetically trapped atomic hydrogen [15,16] provides potential means for the isolated storage of cold antihydrogen.

In this Letter we report the first demonstration of simultaneous confinement of electrons and ions in the same spatial volume, by means of a combined trap [17,18]. Such a trap employs a homogeneous static magnetic field and a static electric quadrupole field for ion confinement (Penning trap). For electrons, the repelling character of this static electric quadrupole field in axial direction is overcompensated by an electric quadrupole field, which oscillates at microwave frequencies (Paul trap).

A competing approach to the experimental problem of a trap that is suitable for recombination employs cryogenic nested Penning traps [19]. A stack of cylindrical electrodes is used to create a potential well for positrons, which is surrounded by two neighboring potential wells for antiprotons. The antiprotons would then be moved through the cloud of trapped positrons. This approach relies not on spontaneous recombination or laser-stimulated recombination, but rather on three-body recombination [20], which is expected to occur with a dramatically high rate for temperatures of a few kelvins [19]. In a test experiment, electrons and protons were used. A space-charge effect was clearly observed, but recombination has not been reported [21]. A possible reason for the failure to observe recombination is that the electrons did not spend enough time [20] in the proton cloud. Our combined trap has the distinct advantage over nested Penning traps that positrons and antiprotons can be kept together in the same volume for an indefinitely long time.

A diagram of our apparatus is shown in Fig. 1. Both the static electric quadrupole field and the quadrupole field oscillating at microwave frequencies are generated by semispherical electrodes. The separation of the end caps is 3.0 mm and the inner diameter of the ring electrode is 4.0 mm. A magnetron at 2.42 GHz is used as a microwave source. Only a small fraction of its output power is needed for the experiment, typically less than 900 mW. The microwave voltage between the quadrupole electrodes is enhanced by employing a resonant quarter wavelength coaxial line with rectangular cross section [22]. As is shown in Fig. 1, the ring electrode is machined into the inner conductor and the end caps are capacitively connected to the outer conductor. The addition of the tuning capacitor to the system decreases the electrical length of the resonator, thus lowering the resonant frequency to the desired value. The tuning capacitor is mounted on a piezoelectric transducer, providing an electrical tuning range of about 30 MHz. To compensate for thermal frequency drift, the resonator is FM locked to the emission frequency of the magnetron. The resonator is driven by a coupling loop on a coaxial cable. The quality factor of the capacitively loaded resonator with coupling circuit is about 500. The amplitude of the oscillating quadrupole potential has been calibrated vs the microwave power using the observed shift of the axial frequency of electrons in the Penning trap due to ponderomotive forces. The homogeneous magnetic field, necessary for the Penning trap, is produced by two rare-earth

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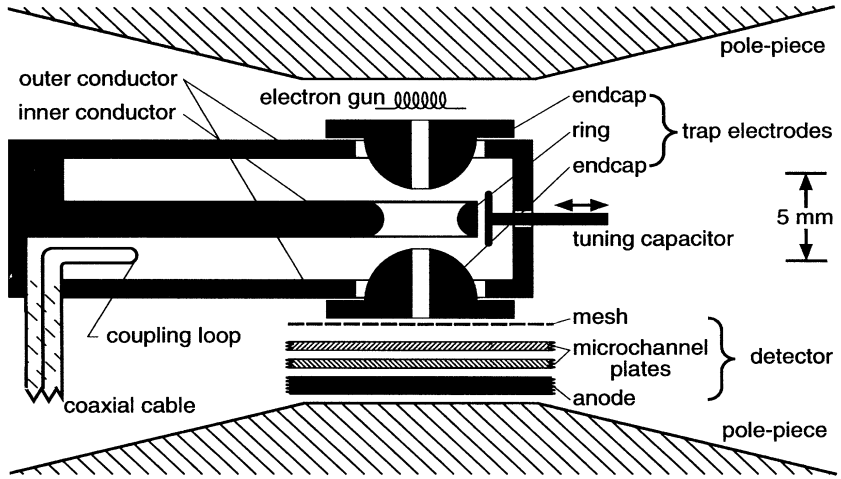

FIG. 1. Schematic of the combined trap, the detector, and the electron gun. Semispherical electrodes connected to a resonant coaxial line generate dc and microwave quadrupole fields. The magnetic field is produced by permanent magnets whose pole pieces are displayed. Optical access to the trap's center is not shown in the figure.

permanent magnets. The magnets are supported by a soft-iron yoke that recycles the magnetic flux [23]. The strength of the magnetic field is 0.57 T, as has been determined from observed cyclotron and magnetron frequencies of trapped protons. Ions and secondary electrons are created in the trap by collisional ionization of residual gas with an electron beam. Trapped electrons and ions are detected destructively with a chevron-type microchannel plate detector. The particles are extracted from the trap by applying suitable voltages on the lower end cap and then accelerated by biasing the mesh at high voltage. The pulses are then amplified, discriminated, and counted. The entire trap is placed in a UHV chamber maintained at less than 10^{-8} Torr by an ion-getter pump. Details of the apparatus will be published elsewhere [24].

To obtain the results presented below, the following timing sequence was used at a repetition rate of 0.2 Hz. During a trap loading time of 1.2 s, the filament bias voltage of the electron gun is set to -200 V and the filament heating current is turned on. The bias voltage of the mesh is set to -300 V to prevent the direct electron beam from reaching the microchannel plates. The electron gun is then turned off. Electrons and ions are stored for 400 ms. Electrons are then extracted by ramping the voltage of the lower end cap from 0 to $+10$ V in 30 ms and biasing the mesh voltage to $+300$ V, which accelerates electrons towards the microchannel plates. Pulses detected during the time of the voltage ramp are counted. Ions are then extracted and detected using the same procedure but with opposite voltages.

In Fig. 2 the number of detected electrons and ions is displayed as a function of time for varying experimental conditions. Each pair of data points is the result of one loading-trapping-detection cycle. First the trap is operated in the Penning mode, without microwave power. For 11 cycles a bias voltage of $+10$ V is applied to the ring electrode with respect to the end caps, trapping electrons. The observed average electron count is 22, and the average ion count is at a background level of 1.3. For the next 3 cycles the trap is operated with a ring electrode voltage of -2.2 V, now trapping ions. The average ion count is 58 while the average electron count is at a background level of 1.0. This demonstrates our ability to detect both electrons and ions separately. Then, the trap is operated

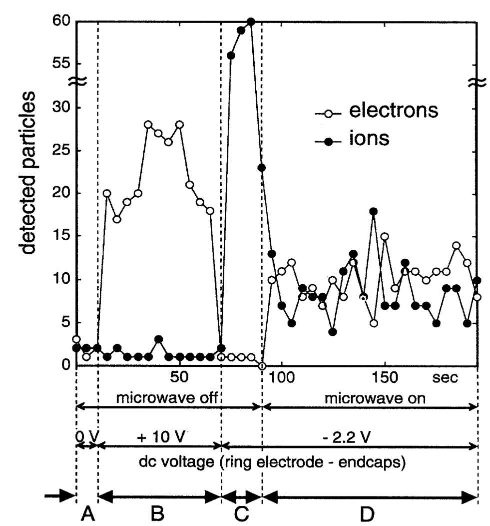

FIG. 2. Number of detected electrons and ions vs time. Each pair of points is the result of one loading-trapping-detection cycle. Section A shows the background level. The trap is operated as a Penning trap for electrons in section B and as a Penning trap for ions in section C, showing the independence of the electron and ion signal. Section D demonstrates that ions and electrons can be trapped simultaneously in the combined trap.

as a combined trap by adding the microwave quadrupole field with an amplitude of 280 V (peak to peak) to the bias voltage of the ring electrode of -2.2 V. The average count is 10 for electrons and 8.7 for ions. Electrons and ions are now trapped simultaneously in the same spatial volume.

The efficiency of extraction and detection is roughly 1%. This was determined by comparison with a measurement of the number of electrons [25] stored in a Penning trap of the same size in our apparatus. Hence, the data shown in Fig. 2 correspond to several thousand trapped electrons and ions. The spatial extent of the trapped cloud is estimated to be 1/4 of the trap's dimensions, corresponding to the diameter of the extraction hole in the lower end cap. We can then estimate the number densities of both ions and electrons to be about 10^7 cm^{-3}, which is about 1/100 of the space-charge limited value [26]. The difference in ion number between the Penning and combined mode is interpreted to be a consequence of sympathetic heating of the ions due to rf heating of the electrons [26]. Earlier observation of axial resonances in our apparatus indicates that the ion signal shown in Fig. 2 consists of $H_2{}^+$ ions and protons with a ratio of about 7:1. In the future, we plan to produce pure proton clouds by heating out the heavier ions.

In experiments on a cold two-species ion plasma, centrifugal separation [27] has been observed [28]. The heavier ions form a torus around the lighter ions, which stay close to the center. For the combined trap, we do not expect centrifugal separation, since the electrons and ions attract each other.

Because of the rf heating of particles in a Paul trap [26], it is expected that the temperatures of electrons and protons in a combined trap are somewhat higher than in nested Penning traps, which use only static fields. The three-body recombination rate decreases with temperature as $T^{-9/2}$ [20] and will be low in a combined trap. However, three-body recombination may not be the best process for antihydrogen synthesis, since it produces preferentially Rydberg atoms [9], which are not immediately accessible to precision optical experiments. Laser-stimulated recombination not only populates low-lying levels, but is also less sensitive to the higher temperatures in a combined trap, since its rate [13] decreases with temperature only as $T^{-3/2}$.

Spontaneous radiative recombination into all n levels is expected to occur at a rate per proton of $R^{\mathrm{spon}} = (1.92 \times 10^{-13}\ \mathrm{cm^3\,s^{-1}})\, n_e\, (kT/\mathrm{eV})^{-1/2}[1.73 - 0.5\ln(kT/\mathrm{eV})]$ where n_e denotes the density and kT denotes the temperature of trapped electrons [14]. If we assume 5000 protons and electrons in a combined trap at a density of 10^7 cm^{-3} and an average energy of 0.1 eV, only one hydrogen atom is produced every 11 s. However, this recombination rate may be enhanced by stimulation with laser radiation [11,12]. Enhancement factors of roughly 400 have been achieved, where the enhancement is defined as the ratio of the stimulated rate into one n level to the sum of spontaneous rates to all possible n levels [13]. The trap has been designed with optical access and experiments to stimulate recombination are under way.

In conclusion, several thousand electrons and ions are confined in an electromagnetic field configuration that combines a Penning trap with a microwave frequency Paul trap, spatially overlapping the clouds. In the future, we plan to generate hydrogen inside our trap by stimulated recombination using a cw CO_2 laser [12,14]. This technique may solve one of the cardinal problems of antihydrogen production.

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