

hep-ex/9506015  
LA-UR-95-1604

# <sup>1</sup>ARE ANTIPROTONS FOREVER?

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## ABSTRACT

Up to one million antiprotons from a single LEAR spill have been captured in a large Penning trap. Surprisingly, when the antiprotons are cooled to energies significantly below 1 eV, the annihilation rate falls below background. Thus, very long storage times for antiprotons have been demonstrated in the trap, even at the compromised vacuum conditions imposed by the experimental set up. The significance for future ultra-low energy experiments, including portable antiproton traps, is discussed.

PACS: 39.10.+j, 25.43.+t, 35.80.+s, 07.30.-t

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An experiment to measure the gravitational acceleration of antiprotons is under preparation at the Low Energy Antiproton Ring (LEAR) at CERN [1]. The experiment proposes to use a time-of-flight technique [2], as pioneered in an experiment which measured the gravitational acceleration of electrons [3]. A critical requirement for such an experiment is a sufficiently large number of antiprotons at sub-eV energies in order to assemble a time-of-flight spectrum with sufficient statistics.

The lowest-energy antiprotons currently available are produced at LEAR. Here antiprotons are delivered at energies as low as 5.9 MeV. A gap of at least 10 orders of magnitude in energy has to be bridged before a meaningful measurement of the gravitational acceleration of antiprotons can be attempted.

To achieve this energy reduction we have developed a large Penning trap system which is matched to the output phase space of the LEAR facility. An antiproton bunch of 200 ns duration, containing up to  $10^9$  antiprotons, is transmitted through a thin foil in which the energy of the individual particles is reduced by multiple collisions. With a properly chosen foil thickness up to 0.6 % of the incident antiprotons emerge from the foil with less than 12.5 keV kinetic energy.

These particles are dynamically captured in the Penning trap by rapidly switching the entrance electrode potential while the bunch is inside the trap volume. Once captured, the antiprotons are cooled by an electron cloud which has been stored in the trap in preparation for the capture. During recent tests of this system we have succeeded in the capture of up to one million antiprotons from a single bunch from LEAR. Up to 65 % of the captured particles were cooled to sub-eV energies and collected in a  $1 \text{ cm}^3$  region at the center of the trap.

Using a set of scintillators mounted externally to the vacuum system we are able to monitor the annihilation of the antiprotons on the residual gas molecules during the cool-down period. When all particles have been collected in the central well and have been cooled below 1 eV, no annihilation can be observed above the ambient

background of approximately 1-2 counts per second.

This result is, at first glance, in contradiction to what one would expect to happen since the annihilation cross section at low energy is generally assumed to have a  $1/v$  dependence. As a result of this effect, antiprotons were stored for significantly long periods of time, even though the residual gas pressure in the system was estimated to be equal to or greater than  $10^{-11}$  Torr. Note that our result is of different origin than the long storage times obtained by the PS196 collaboration [4]. There a fully cryogenic vacuum system was used. Their long storage time was simply attributed to an extremely-low residual gas density. Effects discussed here were not considered.

We now describe our results in detail and comment on their significance. Charged particles may be confined in vacuum by a superposition of an electric quadrupole field and a strong, axial, magnetic field, a combination typically referred to as a Penning trap [5]. One needs to ensure that all the antiprotons emerging from the degrading foil during a single LEAR pulse and having a kinetic energy of less than 12.5 keV are still within the trap volume when the potential at the entrance electrode is ramped up. This requires an axial dimension of the trap of about 50 cm.

To meet this requirement we have constructed an ‘open-end-cap’ Penning trap [6]. It contains 5 cylindrical electrodes of inside diameters 2.8 cm and with other dimensions carefully chosen to form a harmonic potential at the center. Additionally there are two high-voltage electrodes, located at the entrance and the exit of the trap. The entrance electrode consists of a 5 mil, gold-coated, aluminum foil of diameter 0.6 cm, which also serves as the degrading foil. The exit electrode was chosen to be an open cylinder (of inside diameter 2.8 cm) to allow ejection of the antiprotons from the trap subsequent to their capture and cooling.

This trap is located in the bore of a superconducting magnet capable of producing an axial magnetic field of up to 6 Tesla. Figure 1 displays a schematic lay-out of the entire set-up, including the location of the external scintillators used to monitor

antiproton annihilations.

The following is a brief description of a normal measurement cycle. The central, harmonic well of the trap is preloaded with typically  $10^9$  electrons from an electron gun located in the fringe field of the magnet. These electrons quickly cool by synchrotron radiation to equilibrium with the ambient temperature of the system ( $\approx 10$  K). Initially the entrance foil potential is held at ground while the exit electrode is at full potential. Antiprotons from LEAR traverse the beam profile monitor, generating a trigger for the high-voltage switch to the entrance foil. The antiprotons are slowed down in the foil. Those emerging from it at kinetic energies below the exit electrode potential are reflected back towards the entrance. The potential at the entrance electrode is ramped up to the desired potential in less than 100 ns by a commercial switch [7]. This captures the antiprotons in the 50 cm long (non-harmonic) well of this “catching trap.” Due to scattering on the cold electrons the antiprotons lose energy and eventually collect in the inner, harmonic region of the trap.

Antiprotons stored in either the the long, non-harmonic well or the inner, harmonic well of the trap can be detected by lowering the respective electrical potentials. Escaping antiprotons will follow the magnetic field lines, strike the surface of the down-stream radiation baffle, and annihilate. External scintillators S5-S8 (see figure 1) detect the annihilations and the information is stored in a multichannel analyzer. If the time constant for reducing the potential is chosen to be much longer than the oscillation period in the trap, the resulting ‘time of arrival’ spectrum directly reflects the energy distribution of the particles in the trap before the release.

In Figure 2 we show the total number of antiprotons detected in the inner, harmonic well (normalized to the number of antiprotons initially captured) vs. the cooling time. We find that after approximately 600 seconds as much as 65 % of the initially captured antiprotons were cooled into the inner well. The solid line shows the result of a fit to a cooling time constant of 175 sec.

Figure 3 shows the energy spectrum of those antiprotons released from the inner, harmonic trap after 1500 sec of storage time. The energy scale is deduced from the time of arrival of the particles after the release, with high energy particles escaping first. Due to the capacitance of the trap electrodes the relation between well depth and release time is not linear and has been obtained by digitizing the exit electrode potential vs. time. We find the width of the peak to be less than 800 meV, with the centroid located below 1 eV. Due to unknown contact potentials on the trap structure it is impossible to determine the absolute value of the energy, and the width of the distribution must be attributed mostly to the Coulomb interactions amongst the charged particles (electrons and antiprotons) during their release. Therefore, our results are fully compatible with 65 % of the antiprotons having been cooled to the ambient temperature of the trap ( $< 15$  K) after 600 seconds.

During the entire time between the initial capture of the antiproton pulse and the final release from the inner trap, the counts in the external scintillators are recorded. Scintillators S1 - S3 are located closest to the center of the trap and are therefore mostly sensitive to annihilations occurring on the residual gas in the trap (see Figure 1). For background suppression these scintillators are connected in a two-fold coincidence set-up and the detection efficiency is determined to be 4 %. Since the number of stored antiprotons may vary in time, the observed annihilation rate needs to be normalized to the number of particles present in the trap at any given time  $t$ . Such a normalized annihilation rate, for a specific run, is shown in Figure 4.

At the beginning of the cool-down we see an increase in the probability for annihilation on the residual gas. The annihilation rate reaches a maximum at approximately 150 seconds, but afterwards decreases strikingly. At  $t = 600$  seconds the long, non-harmonic section of the trap is opened and a small, but sharp, drop in the annihilation rate is seen. This indicates the ejection of the few higher-energy antiprotons remaining in this section of the trap. Subsequently, the observed rate is not distinguishable

above the cosmic-ray background. This is so even though, in this specific example, approximately 12 % of the initially captured antiprotons were determined to be still present in the inner trap at  $t = 1500$  sec.

This observation is in contradiction to the generally held belief that the annihilation cross section at low energy should exhibit a  $1/v$  dependence [8]. (This adiabatic calculation was done, it should be noted, for hydrogen targets.) Such a  $1/v$  behavior would result in a normalized annihilation rate which would be independent of the antiproton energy, which in turn implies that we should observe a constant rate vs. time. Thus, with a  $1/v$  behaviour, neither the initial rise of the observed rate nor the decay at times larger than 200 seconds could be explained. (The initial increase may be consistent with a  $1/v^n$ ,  $n > 1$ , dependence as given, for instance, by Morgan and Hughes [9], who had  $n = 2$ .) The upper bound of the observed annihilation rate is  $8 \times 10^{-3} \text{ sec}^{-1}$ . However, the final annihilation rate at  $t = 1500$  sec is significantly lower than this. To our knowledge no theoretical model exists that predicts such a striking (or indeed, any) decrease of the rate with temperature. An approach [10] different than that of Ref. [8] uses a coupled-channel, non-adiabatic procedure. Although this produces a low rate at low energies, that model underpredicts our measured results at times less than 200 sec.

The chemical composition of the residual gas in the trap is of critical importance. Since the outer wall of the vacuum vessel is in direct contact with the liquid helium in the cryostat, all gases except hydrogen and helium should be frozen out. Furthermore, because of the liquid helium environment and the fact that helium is poorly pumped by the external ion-getter pumps, the remaining gas should be predominantly helium.

Now we can consider the actual gas pressure in the trap. In fact, the observed maximum annihilation rate,  $8 \times 10^{-3} \text{ sec}^{-1}$ , can be used to verify a rough estimate for the residual gas pressure. Assume that (1) the cross-section estimates given by Bracci et al. [8] (which has a  $1/v$  dependence) are valid as an upper bound for our

observed annihilation rate even through the calculation was for a hydrogen target, and (2) the measured temperature of the trap structure, 10 K, is the temperature of the residual gas. Using these parameters one obtains  $4 \times 10^{-12}$  Torr for the residual gas pressure. This is in good agreement with our expectation that the gas pressure in the trap is bounded from above by the lower limit of the residual gas pressure in the cryogenic section,  $10^{-11}$  Torr.

In those runs where no electrons were preloaded so no cooling of the antiprotons was taking place, the observed annihilation rate was constant over comparable time intervals. This shows the importance of the temperature of the antiprotons and proves the stability of the antiproton cloud against dynamical effects.

Experimental data for the annihilation of antiprotons on neutral particles at low energy does not exist. We are investigating the possibility that there exists a small repulsive potential at short range [11]. Strong binding/antibinding effects on antiprotons penetrating the electron cloud of helium atoms have been observed by the PS194 collaboration [12] in a study of the double-ionization cross section for antiprotons and protons impacting on a helium gas target at energies of 13 keV and above. Recently, the formation of metastable systems in antiproton-helium collisions have been observed [13] and theoretical predictions of repulsive potentials in excited-state systems have been discussed [14]. Possibly related effects have been seen in positronium formation from positron impact on large molecules [15]. ( Elsewhere we will comment in more detail on these points [16].)

The observed reduction of the annihilation rate at ultra-low energies would have a significant impact on a number of experiments planned with cold antiprotons. For these experiments antiprotons, once captured and cooled in the PS200 catching trap, need to be extracted as a beam and transported to either a scattering chamber or a second trap system for recapture. Such transport would be made technically much easier if a room temperature vacuum system can be used instead of enclosing the

entire apparatus in a cryogenic environment.

The construction of portable trap systems has also been proposed [17]. Antiprotons could then be delivered to laboratories around the world, allowing many different kinds of experiments to be done. Such experiments could vary from ultra- low-energy antiproton physics *per se* to scattering of several hundred MeV/c pions and kaons (produced by low-energy antiproton annihilation on a production target).

Portable traps will have to include a vacuum section which can be coupled first to the PS 200 catching trap (or a similar system) for filling and which can also be coupled to an experiment at a remote site. Again, this is easier to do if ultra-low pressures are not needed. To summarize, because of the reduced antiproton annihilation rate at low energies that we have observed, the long storage times needed for both transport of and also experimentation with antiprotons can realistically be achieved.

Future work will include the controlled reheating of the cooled antiprotons. This will be done by using resonance excitation of the axial motion with radio-frequency fields. The energy dependence of the annihilation cross section will be studied. We also will use different target gases to investigate the possible effect of the polarization potential of the target atom.

The work described here has been performed within the framework of the PS200 experimental development and we wish to thank the entire PS200 collaboration for their support. We especially wish to thank P. L. Dyer for the development of the data acquisition system used for these measurements, J. Rochet for his assistance in constructing and operating the experimental apparatus, and M. Charlton and Y. Yamazaki for their support during data taking. We appreciate the helpful comments by S. Barlow on the positron annihilation data. None of the results presented here would have been obtainable without the support and help from the entire LEAR operating team. A very special ‘thank you’ goes to J.-Y. Hemery, M. Michel, and M. Giovannozzi for delivering the very best beam spot possible to the entrance of our



apparatus. This work was in part supported by the US Department of Energy under contract no. W7405 ENG-36 (Los Alamos), the U.S. Air Force Office of Scientific Research under grant no. F49620-94-1-0223 (Pennsylvania State University) and the Alexander von Humboldt Stiftung (M.M.N. at Ulm).

## References

- [1] M. H. Holzscheiter, *Hyperfine Int.* 81 (1993) 71; M. M. Nieto and M. H. Holzscheiter, *Appl. Phys. B* 60 (1995) 103; M. H. Holzscheiter, et al., *Phys. Atom. Nucl.* 57 (1994) 1799; M. H. Holzscheiter, *Physica Scripta* (to be published).
- [2] T. Goldman and M. M. Nieto, *Phys. Lett. B* 112 (1982) 437.
- [3] F. S. Witteborn and W. M. Fairbank, *Phys. Rev. Lett.* 19 (1967) 1049.
- [4] G. Gabrielse, X. Fei, L. A. Orozco, R. L. Tjoelker, J. Haas, H. Kalinowsky, t. a. Trainor, and W. Kells, *Phys. Rev. Lett.* 65 (1990) 1317.
- [5] J. R. Pierce, *Theory and Design of Electron Beams* (D. van Nostrand, NY, 1949), chapter 3; H. G. Dehmelt, *Adv. At. Mol. Phys.* 3 (1967) 53; *ibid.* 5 (1969) 109.
- [6] G. Gabrielse, L. Haarsma, and S. L. Rolston, *Int. J. Mass Spec. Ion Processes* 88 (1989) 319.
- [7] Solid state switch Model HTS301 from Behlke Electronics GmbH, Frankfurt, Germany, with maximum operating voltage of 30 keV and a rated rise time of 20 ns under optimum load conditions.
- [8] L. Bracci, G. Fiorentini, and O. Pitzurras, *Phys. Lett. B* 85 (1979) 280.
- [9] D. L. Morgan, Jr. and V. W. Hughes, *Phys. Rev. A* 7 (1973) 1811.
- [10] A. Yu. Voronin, *Zh. Eksp. Teor. Fiz.* 102 (1992) 760. [*Sov. Phys. JETP* 75 (1992) 416.]
- [11] We wish to especially thank T. Kinoshita and T. Ziegler, private communications, for insightful comments on this matter.

- [12] P. Hvelplund, H. Knudsen, U. Mikkelsen, E. Morenzoni, S. P. Moller, E. Uggerhoj, and T. Worm, *J. Phys. B* 27 (1994) 925.
- [13] T. Yamazaki, R. S. Hayano, T. Ishikawa, H. Onta, E. Takada, H. Tamura, and A. Sakaguchi, *Phys. Rev. Lett.* 63 (1989) 1590.
- [14] K. Richter, J.-M. Rost, R. Thurwächter, J. S. Briggs, D. Wintgen, and E. A. Solov'ev, *Phys. Rev. Lett.* 66 (1991) 149.
- [15] C. M. Surko, R. G. Greaves, and M. Leventhal, *Hyperfine Int.* 81 (1993) 239.
- [16] M. H. Holzscheiter et al., *Hyperfine Int.* (in preparation).
- [17] H. G. Dehmelt, R. Van Dyck, P. Schwinberg and G. Gabrielse, *Bull. Am. Phys. Soc.* 24 (1979) 757, abstract D 3; S. D. Howe, M. V. Hynes, and A. Picklesimer; in *Antiproton Science and Technology*, eds. B. W. Augenstein, B. E. Bonner, F. E. Mills, and M. N. Nieto (World Scientific Singapore, 1988), p. 481; G. A. Smith, *Hyperfine Int.* 81 (1993) 189.

Figure Captions:

**Fig.1** Schematic layout of the experimental set-up. Shown is the superconducting magnet system (length 2 meter), the PS200 catching trap, all beam monitors, and the scintillators used to trigger the voltage switch and to monitor the antiproton annihilations during storage and upon release.

**Fig.2** Accumulation of ultra-low energy antiprotons in the harmonic well in the center of the PS200 catching trap. The solid line is calculated for a cooling time constant of 175 seconds and a maximum transfer efficiency of 65 %.

**Fig.3** Energy spectrum of cold antiprotons released from the inner trap. Note that the energy scale is in the reverse direction and is quite nonlinear towards the low-energy end. The centroid of the distribution is at  $\leq 1$  eV, the FWHM is  $\leq 800$  meV.

**Fig.4** Rate of annihilation during storage and cooling of antiprotons in the PS200 catching trap. The observed rate has been normalized to the number of antiprotons in the trap at any given time  $t$ . The sharp drop between 600 and 700 seconds is due to the loss of antiprotons when the outer trap is opened completely.

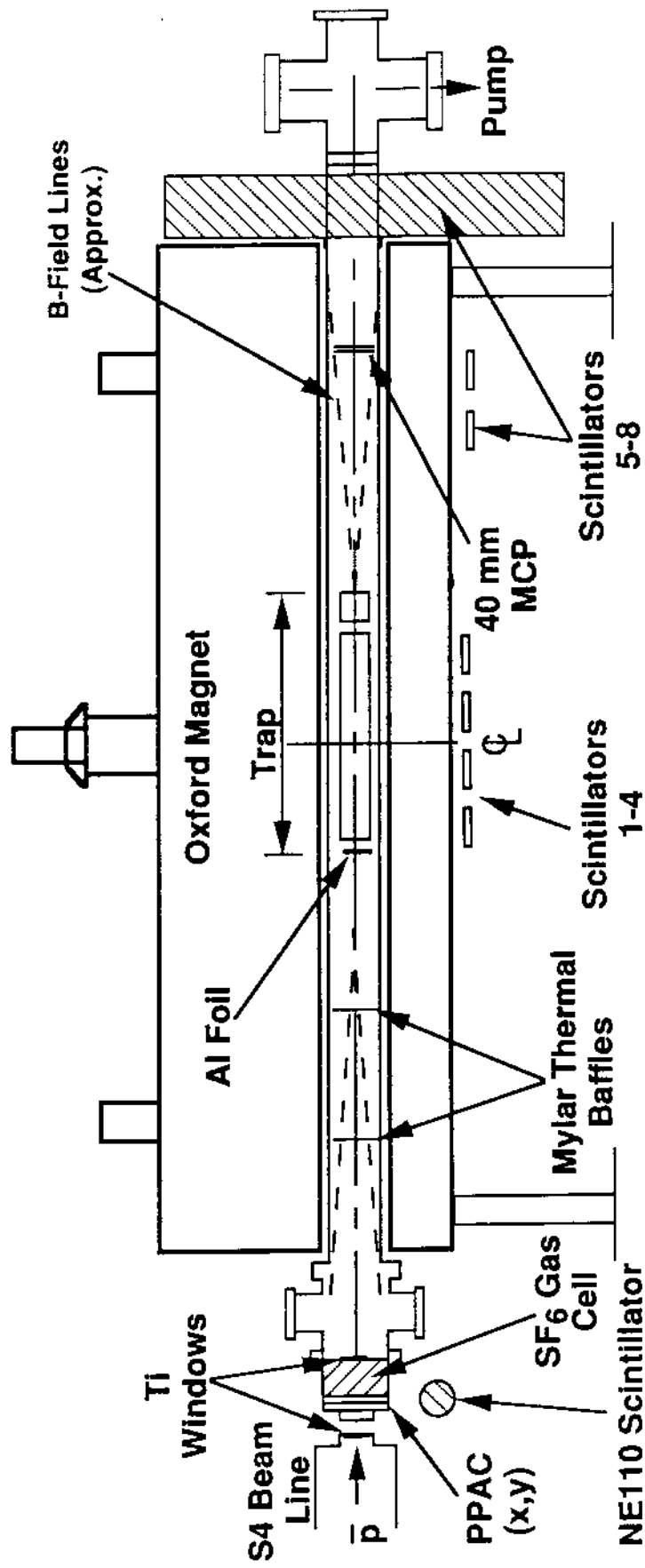


Figure 1

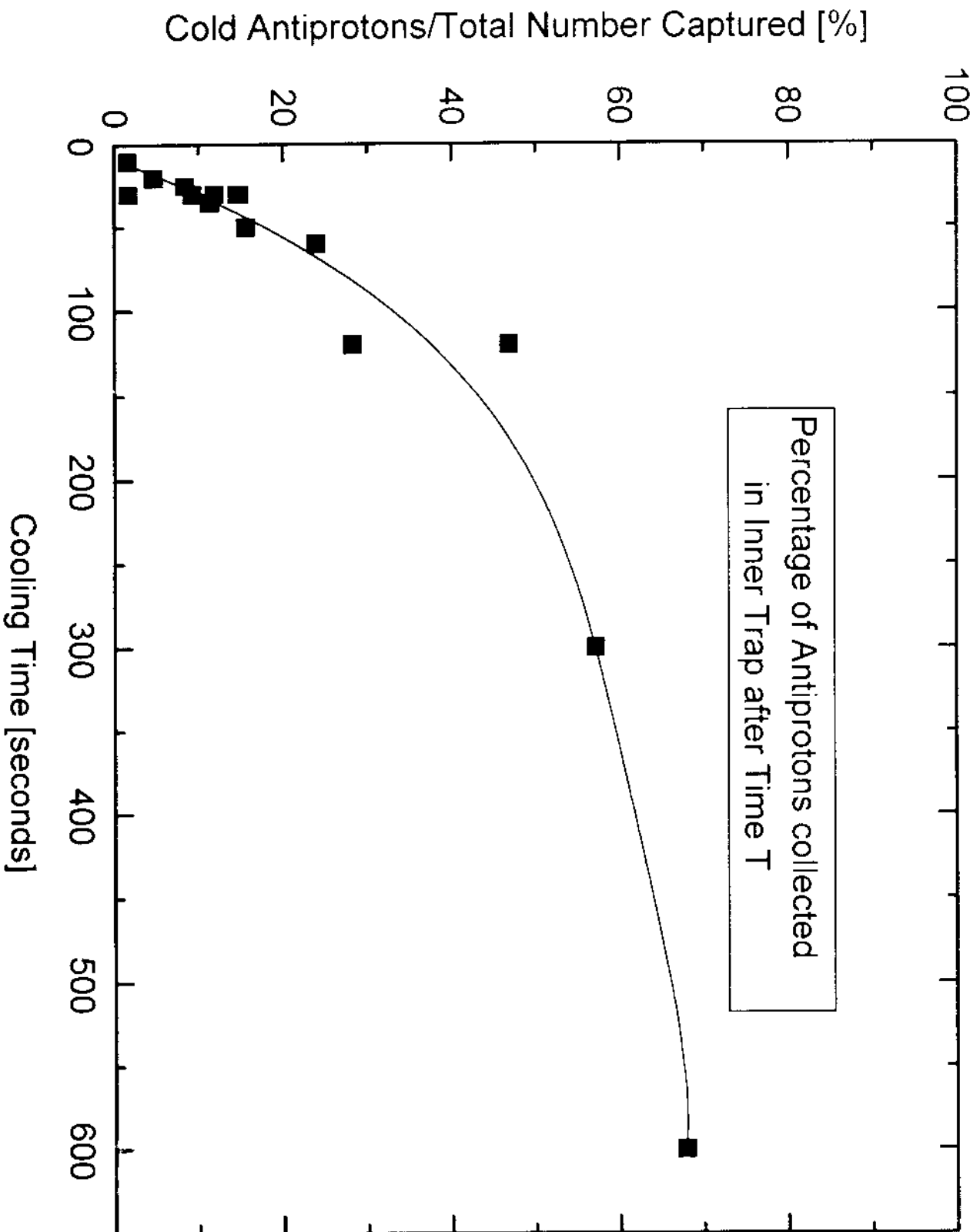


Figure 2

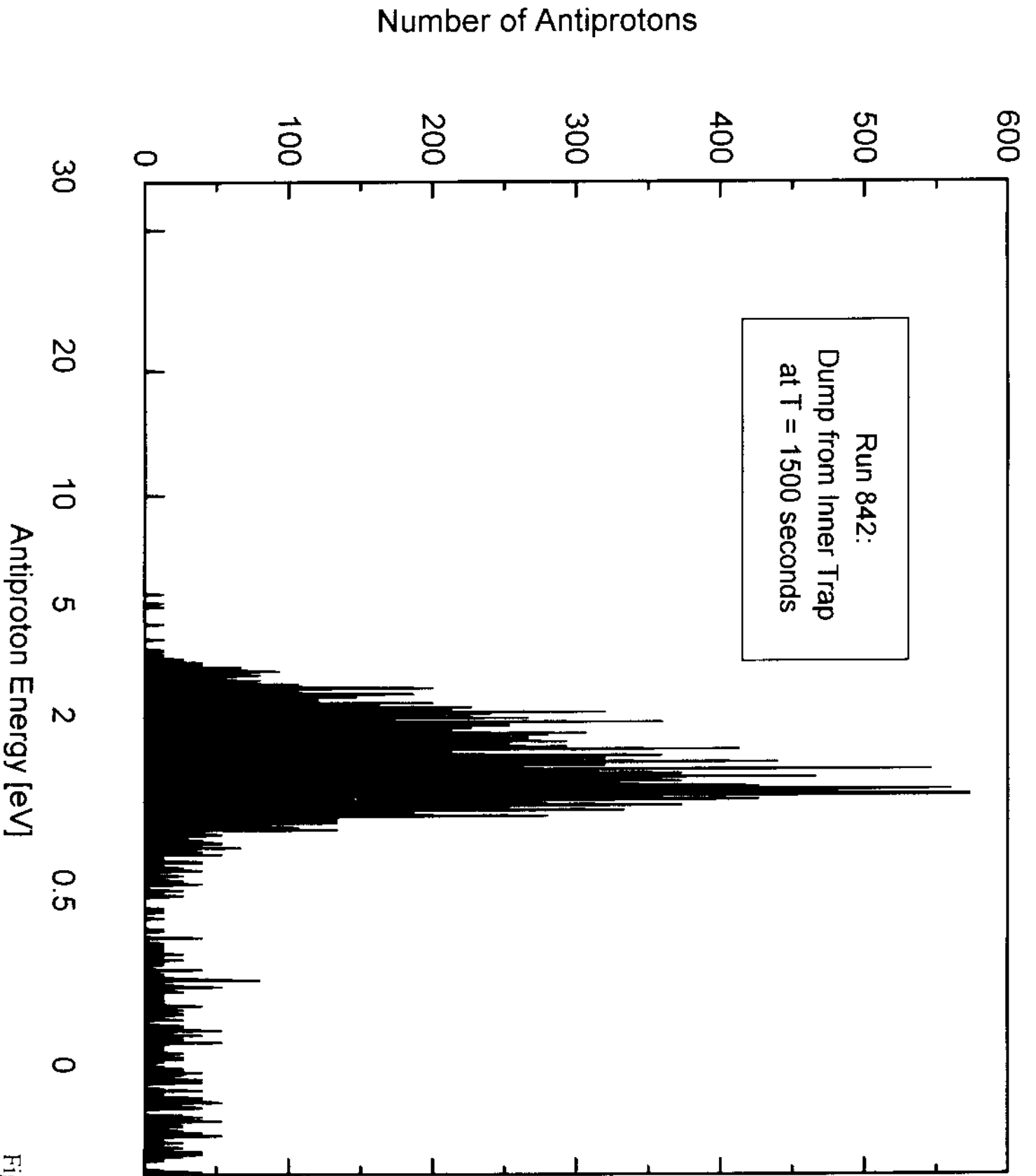


Figure 3

Normalized Antiproton Annihilation Rate  
(1/N) dN/dt [1/sec]

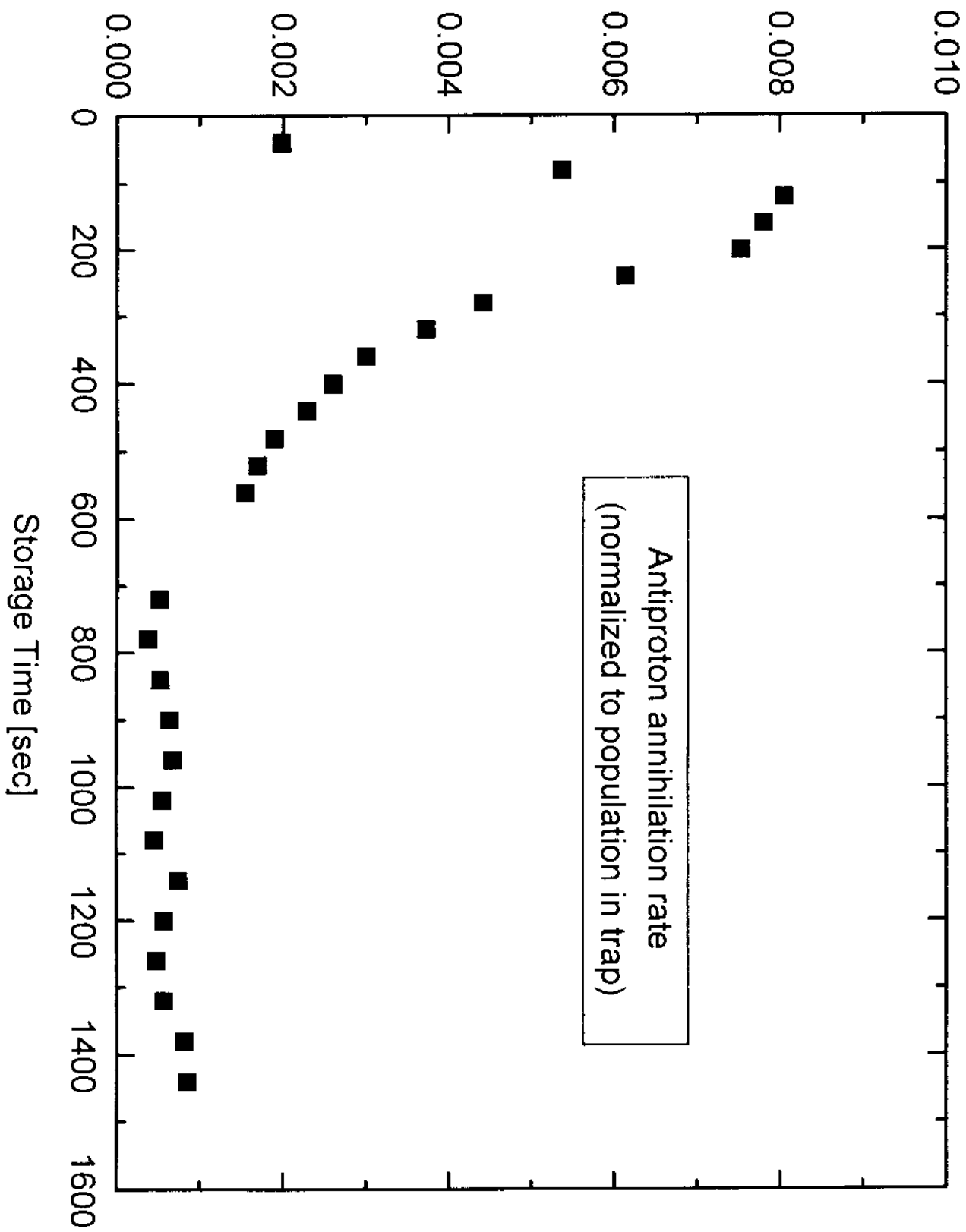


Figure 4