Discovery of Antiproton Trapping by Long-Lived Metastable States in Liquid Helium

M. Iwasaki, S. N. Nakamura, K. Shigaki, Y. Shimizu, H. Tamura, T. Ishikawa, and R. S. Hayano
Department of Physics and Meson Science Laboratory, Faculty of Science, University of Tokyo, Tokyo 113, Japan

E. Takada
National Institute of Radiological Sciences, Chiba 260, Japan

E. Widmann, H. Outa, M. Aoki, P. Kitching,[a] and T. Yamazaki
Institute for Nuclear Study, University of Tokyo, Tokyo 188, Japan
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Delayed annihilation of antiprotons stopped in liquid helium has been observed, revealing that about 3.6% of stopped antiprotons are trapped in long-lived metastable states. No delayed component was found either in liquid nitrogen or in liquid argon. The observed time distribution of delayed annihilation shows fast-decaying components followed by a major part with a decay time constant of 3 μsec.

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Negative hadrons such as π^-, K^-, and $\bar{p}$, when stopped in material, are believed to vanish immediately by nuclear absorption after forming hadronic atoms. Recently we found that a few percent of the K^- mesons stopped in liquid helium show free decay with a lifetime around 10 nsec, indicating the presence of long-lived trapping states of about 50 nsec lifetime (trapping time), while there are no such delayed K^- decays observed in other materials (Li, Be, C, and Ca) [1]. This experiment definitely supported Condo's interpretation in terms of a trapping hypothesis [2] of earlier data showing at-rest decays of π^- [3] and K^- [4] in helium bubble chambers, which had been ascribed to slow "average cascade times" in the range of 10^{-10} sec without justification. Condo asserted a model for trapping states, that is, circular orbits of large principal quantum numbers in a neutral exotic helium atom $e^-X^-\mathrm{He}^{++}$, where X^- is a negatively charged hadron. More recently, we have studied experimentally π^- absorption in liquid helium at TRIUMF, finding that a similar fraction of π^-'s are also trapped in liquid helium, but with a much shorter trapping time ($\sim$10 nsec) [5]. A more spectacular case is expected for antiprotons in liquid helium, where much longer trapping times were predicted by Russell [6]. Since antiprotons are stable, there is in principle no limitation on the observable time window. So, we attempted to search for this interesting phenomenon at KEK, and have discovered that antiprotons do survive in liquid helium up to 15 μsec.

In the present experiment we measured the time distribution of the annihilation products (mostly pions) with respect to $\bar{p}$ stopping. A separated $\bar{p}$ beam from the K3 beam line at the KEK 12-GeV proton synchrotron was stopped in liquid helium. We used a liquid-helium target of cylindrical shape with 23 cm diam. The present $\bar{p}$ intensity at beam momentum of 519 MeV/c was 28/sec, but the beam contained 1000 times more π^-'s. Since these beam pions are scattered and absorbed by the target material or elsewhere, they fire the detector system for annihilation products independently of the $\bar{p}$ stop, and may produce fake "delayed-annihilation" events. To discriminate genuine $\bar{p}$ annihilation from scattering or reaction of background pions, we used 128 pieces of $6.5\times6.5\times25$ cm^3 NaI(Tl) scintillator, which covered about 30% of the total solid angle.

We identified particles from the beam line by using four sets of plastic scintillators and one Lucite Čerenkov counter (LC). The $\bar{p}$'s were well separated from pions and kaons by time of flight and the LC. The in-flight reactions within these beam-line counters were clearly recognizable in the pulse-height spectra of the counters. The trajectories of the $\bar{p}$'s were measured by two sets of two-dimensional multiwire proportional chambers. The $\bar{p}$ annihilation products were detected by two plastic scintillators (T counters) and two chambers, which were placed at 90° with respect to the beam. This detector assembly covered about 10% of the total solid angle. The vertex at the $\bar{p}$ annihilation point was reconstructed with a spatial resolution of 5 mm (FWHM) in the horizontal plane and 15 mm (FWHM) in the vertical axis by using the information from the chambers. This vertex point was used to identify the $\bar{p}$ stopping point, and to calculate the range in helium and the flight time between the beam-defining counter and the $\bar{p}$ stopping point.

We measured $\bar{p}$ annihilation products in the time window from -120 nsec to 30 μsec, with respect to the $\bar{p}$ stopping time in the target. The negative time window was set to see the accidental background level. We monitored the particles from the beam line and rejected events which recorded "second $\bar{p}$ hit" or "K^- hit" in the beam-line counters in the time range from -12 to 30 μsec. Since pions coming from the beam line every 20 μsec on average cause a number of fake delayed events, it was vitally important to eliminate the pion scattering and reaction events from the $\bar{p}$ annihilation events by other means.

To do this, we rejected (1) events which have a large discrepancy in the annihilation vertex (>12 mm in vertical axis), and (2) events in which a beam pion hits the beam-line counters at the same time as one of the "annihilation products" hits the T counters (within 40 nsec). After application of these cuts, the accidental background

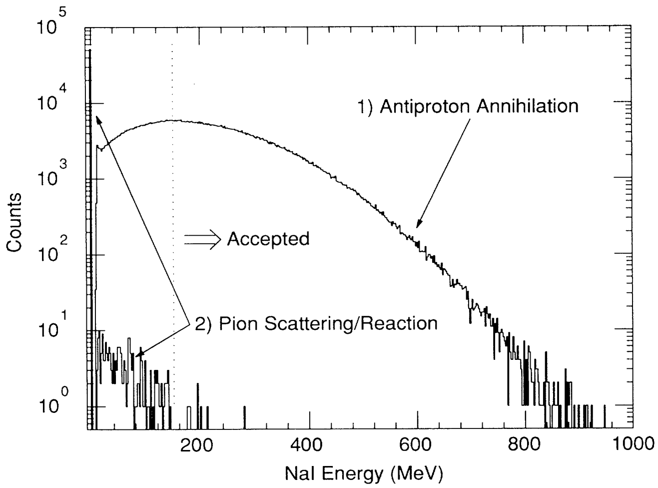

FIG. 1. Energy-sum spectra of the NaI counters corresponding to (1) $\bar{p}$ annihilation events and (2) pion scattering and reaction events.

dropped down by a factor of 200, but this background reduction was still insufficient to eliminate background due to the beam pions which did not hit the beam-line counters (pion halo).

We were able to improve another factor of 200 by using the information of the NaI counters. When $\bar{p}$ annihilates in liquid helium, it produces several particles and some of them were detected in the NaI counters. The energy sum of the NaI counters for $\bar{p}$ annihilation was found to be distributed up to ~ 1000 MeV, as shown in Fig. 1. On the other hand, the energy sum for π^- scattering and reaction in helium was found to be distributed only up to ~ 150 MeV, as also shown in Fig. 1. Thus we selected events with a large energy deposit in the NaI counters (> 150 MeV). Increasing the discrimination energy threshold does not alter the quality of the selected events.

In this way, we obtained a final time spectrum of annihilation products with respect to the $\bar{p}$ stopping time. It is shown in three different time ranges [Figs. 2(a)-2(c)]. As shown in the figures, delayed annihilation is clearly observed with almost no background. It survives up to 15 μsec.

The prompt peak corresponds to prompt annihilation following $\bar{p}$-atom formation, but it should also involve in-flight reactions. To estimate the fraction of in-flight reaction in the helium target before forming the $\bar{p}$ atom, we performed a Monte Carlo simulation extrapolating the $\bar{p}$ cross section to lower momenta using the formula given in [7] and the data from the higher-momentum run at 550 MeV/c. It was found that $(20 \pm 5)\%$ (systematic error) of the observed events in the helium target came from in-flight reaction.

The observed time spectrum is not a single exponential function; it has several different time components. The time spectrum can be conveniently approximated by a sum of four exponential functions as shown in Figs. 2(a)-2(c) and in Table I, although this does not neces-

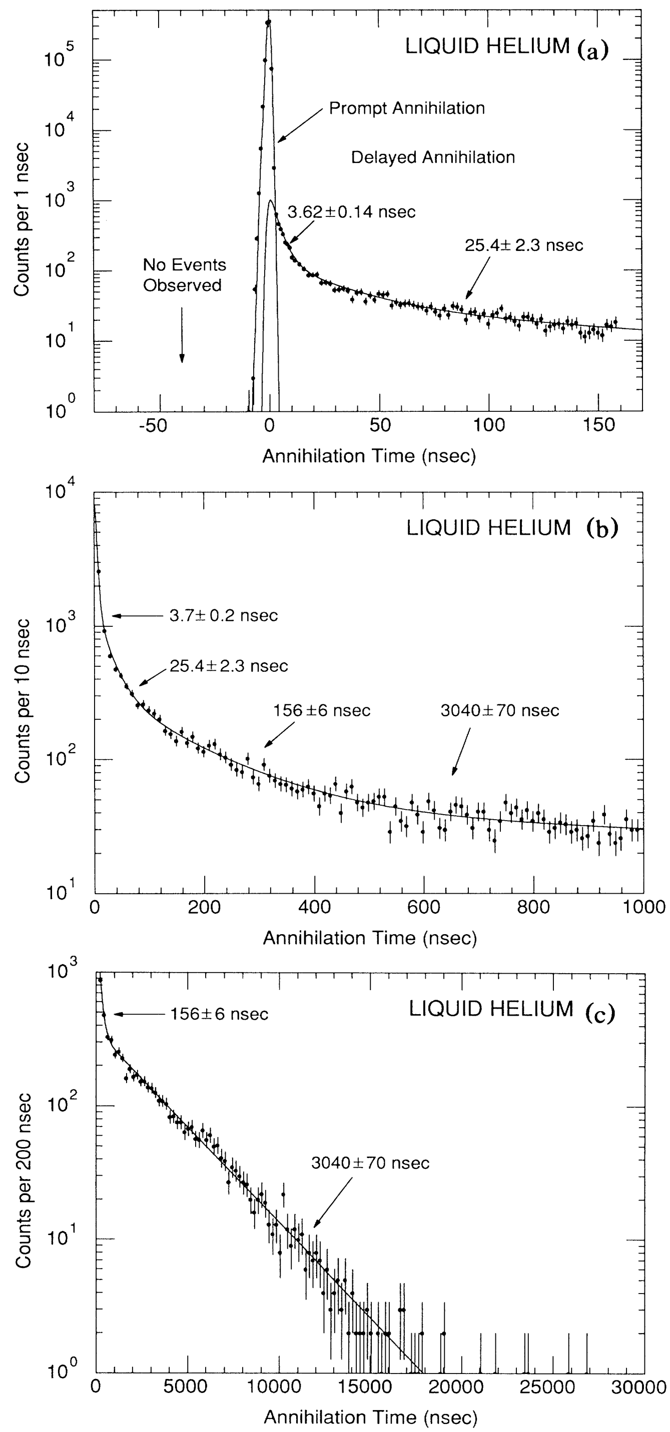

FIG. 2. Time spectra of $\bar{p}$ annihilation in liquid helium in different time ranges. (a) -80 to 170 nsec, (b) 0-1000 nsec, and (c) 0-30 μsec (only 43% of all the data are in this time range).

TABLE I. Trapping times and trapping fractions of delayed annihilation of $\bar{p}$ in liquid helium, deduced by assuming a sum of four-exponential functions.

Component (delayed)	Trapping time	Trapping fraction[a] (%)
1st	3.62 ± 0.14 nsec	0.60 ± 0.03 (0.03)
2nd	25.4 ± 2.3 nsec	0.43 ± 0.06 (0.02)
3rd	156 ± 6 nsec	0.71 ± 0.03 (0.04)
4th	3.04 ± 0.07 μsec	1.92 ± 0.05 (0.10)
Total		3.63 ± 0.13 (0.21)

[a]Systematic error in parentheses.

sarily mean that such decomposition is unique. The spectrum might be a sum of more complicated time spectra including growth decays.

To check the background level, $\frac{1}{4}$ of the total events were taken with a low-intensity beam (reduced to $\frac{1}{10}$), but there was no difference in the trapping time and the branching ratio of the delayed components. We also took data on superfluid helium at 1.8 K ($\frac{1}{4}$ of the total data), and found there is no significant difference from the data with normal liquid helium at 4 K. The time spectra given in Figs. 2(a)–2(c) are the sum of all the data. The background level in the time spectrum was $2\times10^{-6}/\mu$sec per stopped $\bar{p}$.

We made additional runs on different target materials, accumulating 5.1×10^4 $\bar{p}$ annihilation events on liquid N_2 and 2.7×10^4 events on liquid Ar. They exhibited only the prompt component, as shown in Fig. 3. There were several events observed in the delayed time range, but they are consistent with the background level. In Table II we evaluated the upper limits of 90% confidence level for the branching ratio of delayed annihilation assuming that the trapping time is less than 10 μsec. These runs confirmed that the presence of delayed annihilation of an-

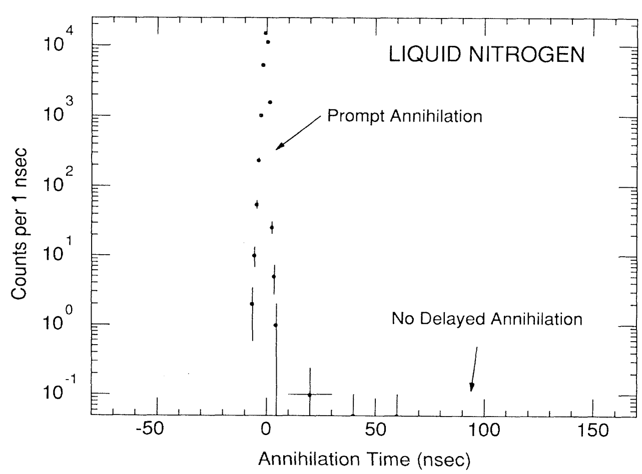

FIG. 3. Time spectrum of $\bar{p}$ annihilation in liquid N_2.

TABLE II. Upper limit for delayed annihilation of $\bar{p}$ in liquid N_2 and liquid Ar.

Target	Delayed component
Liquid N_2	$<5\times10^{-4}$ (90% C.L.)
Liquid Ar	$<5\times10^{-4}$ (90% C.L.)

tiprotons is characteristic of liquid helium.

In summary, we have discovered that about 3.6% of the antiprotons stopped in liquid helium undergo delayed annihilation, indicating the presence of long-lived trapping states. The observed time distribution of annihilation products shows several components with different lifetimes. The fact that the time distribution of the delayed $\bar{p}$ annihilation involves many components infers that the observed trapping phenomenon results from many metastable states, as expected in the case of the neutral exotic helium atoms $e^-\bar{p}\alpha$ proposed by Condo [2]. Here, particles in high-lying circular orbits of large principal quantum numbers deexcite slowly by radiating low-energy photons, since the transition energy ($\sim$2 eV) is not large enough to cause fast Auger transitions. The neutrality of these atoms involving one electron protects them from prompt nuclear absorption through Stark effects or polarization capture. This model was extensively studied by Russell [6]. A more comprehensive calculation, taking into account the configuration interactions of both e^- and $\bar{p}$, is in progress [8]. There may be some other mechanisms for trapping; for instance, shallow metastable states of the same composition but with totally different atomic quantum numbers are discussed in [9].

Experimentally it is very important to study the dependence of the trapping lifetime and fraction on the various phases of stopping substance. Whether the time distribution and its fraction change from liquid to gas helium or not is an extremely intriguing question, to be answered experimentally in the near future.

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(a)Visiting Professor from TRIUMF, 4004 Wesbrook Mall, Vancouver, British Columbia, Canada V6T 2A3.

[1] T. Yamazaki *et al.*, Phys. Rev. Lett. **63**, 1590 (1989); H. Outa *et al.* (private communication).
[2] G. T. Condo, Phys. Lett. **9**, 65 (1964).
[3] M. M. Block *et al.*, Phys. Rev. Lett. **11**, 301 (1963); J. G. Fetkovich and E. G. Pewitt, Phys. Rev. Lett. **11**, 290

(1963).

[4] M. M. Block, J. B. Kopelman, and C. R. Sun, Phys. Rev. **143**, B140 (1965); J. G. Fetkovich *et al.*, Phys. Rev. D **2**, 1803 (1970); C. Comber *et al.*, Nuovo Cimento **24A**, 294 (1975).

[5] S. N. Nakamura *et al.* (to be published).

[6] J. E. Russell, Phys. Rev. Lett. **23**, 63 (1969); Phys. Rev. **188**, 187 (1969); Phys. Rev. A **1**, 721 (1970); **1**, 735 (1970); **1**, 742 (1970).

[7] P. R. Hamilton *et al.*, Phys. Rev. Lett. **44**, 1182 (1980).

[8] K. Ohtsuki (private communication).

[9] K. Richter *et al.*, Phys. Rev. Lett. **66**, 149 (1991).