Trapping of Negative Kaons by Metastable States during the Atomic Cascade in Liquid Helium

T. Yamazaki and M. Aoki
Institute for Nuclear Study, University of Tokyo, Tokyo 188, Japan

M. Iwasaki, R. S. Hayano, T. Ishikawa, H. Outa, E. Takada, and H. Tamura
Department of Physics and Meson Science Laboratory, Faculty of Science, University of Tokyo, Tokyo 113, Japan

A. Sakaguchi
Department of Physics, Faculty of Science, Hiroshima University, Hiroshima 730, Japan
(Received 5 July 1989)

We observed two distinct peaks, 205-MeV/c π^- and 235-MeV/c μ^-, associated with $K_{\pi 2}^-$ and $K_{\mu 2}^-$ decays at rest, respectively, from negative kaons stopped in liquid helium. These peaks were found to be delayed with respect to the stopping K^-, showing that about a 2% fraction of the stopped K^- mesons are trapped in metastable states with an overall lifetime of about 40 nsec. This observation provides direct evidence for Condo's trapping hypothesis for the at-rest decay components of K^- and π^- in liquid helium.

PACS numbers: 36.10.−k

In this Letter we report on the first direct observation of possible trapping times during the atomic cascade of negative kaons in liquid He. This has become possible as a result of the high-resolution spectroscopy of decay and reaction products from K^- mesons stopped in a liquid-He target;[1] we were able to isolate the $K_{\mu 2}^-$ and $K_{\pi 2}^-$ monoenergetic peaks as signatures of at-rest decays and to measure their time distributions.

In early experiments using He bubble chambers it was observed that at-rest decays of negative pions[2,3] and negative kaons[4,5] occur with significant fractions. They were well characterized by the unique μ^- range at large decay angles in the case of π^- and by the zero center-of-mass momentum of the K^- in the 3π decay mode. The observed at-rest fractions,

$$f = \frac{N(\text{decay at rest})}{N_{\text{stop}}}, \tag{1}$$

are given in Table I. At-rest decays of Σ^- particles in liquid He were also observed,[6,7] but they can be understood in terms of the slower stopping time of Σ^- which is of the order of the Σ^- lifetime (1.48×10^{-10} sec). On the other hand, since the stopping times of π^- and K^- mesons are shorter and the lifetimes are much longer, the presence of such large at-rest decay components appeared to be surprising.

In the early days these at-rest decay fractions were ascribed to "average cascade times" as defined by

$$T_{\text{av}} = \frac{f}{1-f} \times \tau^{\text{free}}. \tag{2}$$

The average cascade times thus deduced were in the range of 2×10^{-10} sec and turned out to be 2 orders of magnitude larger than the theoretical values of Day[8] (around 10^{-12} sec), who showed that the cascade of a mesonic He ion is enhanced by the external Auger effect, the molecular Stark effect, and the polarization absorption. To remove this discrepancy, questions were raised as to the absence of the Stark-effect mixing.

At that time Condo[9] proposed an entirely different interpretation, asserting that negative mesons of fraction f_K are trapped into long-lived states ($\tau^{\text{tr}} \gtrsim \tau^{\text{free}}$) during the cascade, where they are destined to decay with the free lifetime. He pointed out that the mesons captured in circular orbits ($l = n-1$) of large principal quantum numbers ($n \gtrsim 30$) cannot emit an additional internal Auger electron and hence stay in a neutral mesic atom (e^-K^-He), because the electron binding energy ($\sim$25 eV) is too large to allow fast enough Auger processes ($\Delta l \leq 3$). This neutral mesic atom is unaffected by external Auger and molecular Stark effects and deexcitation to lower states proceeds only by a radiative process. Thus, circular orbits of large l are expected to have lifetimes around 10^{-8} sec, which is comparable to or longer than the free-decay lifetime. Although the hypothesis of Condo was supported by further theoretical arguments,[10,11] it has not been examined in a direct way simply because no time information was obtained from

TABLE I. Fraction of at-rest decays of π^- and K^- in liquid He.

Particle	Fraction f (%)	Reference
π^-	1.0 ± 0.5	Fetkovich and Pewitt (Ref. 2)
	1.2 ± 0.1	Block *et al.* (Ref. 3)
K^-	2.0 ± 0.43	Block, Kopelman, and Sun (Ref. 4)
	2.6 ± 0.44	Fetkovich *et al.* (Ref. 5)
	2.5 ± 0.4	Comber *et al.* (Ref. 6)
	1.9 ± 0.3	Present work

bubble-chamber experiments. It should be straightforward to examine experimentally whether the at-rest decay particles are really delayed or not with respect to the stopped mesons.

The present experiment was a byproduct of an experiment to search for Σ hypernuclei produced in ^{4}He (stopped K^-, π) reactions.[1] The K^- mesons from the K3 beam line of the KEK 12-GeV proton synchrotron were stopped in a liquid-He target. The incoming K^- beam trajectory as well as the trajectory of each charged-particle event in the magnetic spectrometer was recorded to obtain information about the reaction or decay vertex and the particle momentum. The particle identification was made by using range and time-of-flight (TOF) information. After particle identification as π or μ, the TOF information with respect to the timing of the incoming kaon was used to deduce the total cascade time.

Figure 1 shows a gross momentum spectrum of all negative particles emitted from K^- stopped in liquid He. Surprisingly, the most dominant peaks are the 235-MeV/c μ^- and the 205-MeV/c π^-, which provide unique signatures of $K_{\mu 2}^-$ and $K_{\pi 2}^-$ decays at rest, respectively. The total fraction of K^- decay at rest was obtained in two ways: (1) from comparison of the decay peak in the stopped-K^- spectrum with that in the stopped-K^+ spectrum, and (2) from comparison of the decay peak with the total $\pi^- + \mu^-$ in the same spectrum. The final value thus obtained is $f_K = 0.019 \pm 0.003$ which is in good agreement with the earlier values of f_K deduced from the 3π decay in He bubble chambers (see Table I).

Figure 1 also shows a delayed spectrum ($3.5 < t < 30$ nsec), which clearly indicates that the $K_{\mu 2}^-$ and $K_{\pi 2}^-$ peaks are indeed delayed. Now let us look at the time distribution of these at-rest decay peaks, as shown in Fig. 2. For comparison, Fig. 2 also includes the time distribution of K^+ decays measured with the same experimental setup, showing a lifetime of 12.6 ± 0.2 nsec, in good agreement with the K^+ lifetime of 12.37 nsec. In contrast, the time distribution of the K^- decay in liquid helium shows a faster exponential decay with an effective lifetime of 9.5 ± 0.3 nsec. The reason for the shorter lifetime in liquid helium is that a fraction $f = f_K \tau^{\text{free}} / \tau(K^-)$ of K^- mesons are trapped in metastable states, and the fraction f of trapped mesons is also depleted by the decay of the metastable states (which results in the nuclear absorption of the K^- rather than its decay). From the measured effective K^- lifetime and the free K^- lifetime, the lifetime of the metastable state is $\tau_{\text{trap}} = 41 \pm 6$ nsec.

The spectra also show unambiguously that the "prompt" fraction is negligibly small ($f^{\text{prompt}} \leq 1.2 \times 10^{-3}$). If the average cascade time were around 10^{-10} sec, then a significant fraction of the prompt component would be seen. The present experiment thus excludes the "slow cascade time" conjecture and indicates that the average cascade time for the majority of K^- mesons (which do not undergo trapping) is

$$T_{\text{av}} = \frac{f^{\text{prompt}}}{1 - f^{\text{prompt}}} \times \tau^{\text{free}} \leq 1.4 \times 10^{-11} \text{ sec}, \tag{3}$$

which supports the theoretical estimates of Day including the molecular Stark effect.[8]

In conclusion, we have demonstrated for the first time that the at-rest decay peaks of K^- mesons stopped in liquid He are delayed and that a significant fraction of the K^- mesons are trapped in metastable states and then mostly decay with the free lifetime, as asserted by Condo.[9] This also means that the majority of the K^-

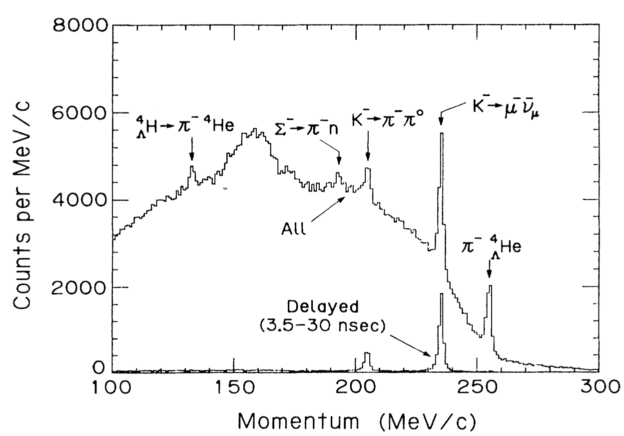

FIG. 1. Momentum spectra of all the negative particles emitted from K^- mesons stopped in liquid He, exhibiting well-standing $K_{\mu 2}^-$ and $K_{\pi 2}^-$ peaks from at-rest decays; with no time selection, and with a time gate $3.5 < t < 30$ nsec.

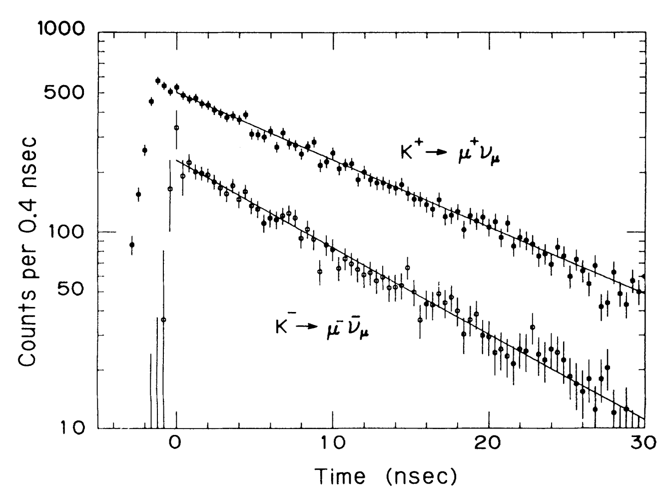

FIG. 2. Time distributions of the 235-MeV/c $K_{\mu 2}^-$ decay peak (open circles) together with the $K_{\mu 2}^+$ peak (closed circles). The data points are fitted by a single exponential function, showing $\tau(K^+) = 12.6 \pm 0.2$ nsec and $\tau(K^-) = 9.5 \pm 0.3$ nsec.

mesons undergo rapid nuclear absorption as theoretically predicted by Day. Furthermore it means that most of the K^- will undergo nuclear absorption from S states of large n, which is caused by molecular Stark mixing. This implication appears to be consistent with the fact that the total L x-ray intensity of the K^-He atom is only $(13 \pm 6)\%$.[12,13] This phenomenon may also have some relevance to the fact that the μ^- polarization in liquid He is largely lost,[14,15] and also to the problem related to the metastable $2S$ state of the μ^-He atom.[16]

The present experiment may have an interesting impact; it infers a similar mechanism for the pion cascade in liquid He. If the observed pion-decay fraction at rest (about 1%)[2,3] in liquid He is also delayed due to trapping, this free-decay component may be used as a source of bright and highly polarized negative muons of 4 MeV similar to surface muons from stopped π^+.[17] This monoenergetic μ^- component can be filtered by acquiring timing with the primary beam phase in the case of cyclotrons such as those at TRIUMF and SIN. This possibility is open to further investigation.

The trapping lifetime and the shape of the time distribution that we have measured are subject to a more quantitative theoretical investigation. The present observation has a bearing on the metastable states of similar character observed in single-electron atoms formed in heavy-ion reactions, where a fully stripped ion captures a single electron in a large-n orbital.[18]

Finally, we point out that metastable states should also exist for antiprotonic atoms. In this case, there is no limitation on the time window because antiprotons do not decay and thus the delayed annihilation of antiprotons in liquid (and also gaseous) helium will provide a powerful probe to study such metastable states.

The authors are grateful to Professor D. H. Davis for stimulating discussions, to T. Motoki for his contribution in target preparation, and to the KEK Proton Synchrotron staff in the execution of this experiment. This work is supported in part by the Grant-in-Aid for Special Project Research on Meson Science of the Japan Ministry of Education, Science and Culture. One of the authors (H.T.) acknowledges the support of a Grant-in-Aid for Encouragement of Young Scientists.

[1]R. S. Hayano, T. Ishikawa, M. Iwasaki, H. Outa, E. Takada, H. Tamura, A. Sakaguchi, M. Aoki, and T. Yamazaki, Phys. Lett. B (to be published).

[2]J. G. Fetkovich and E. G. Pewitt, Phys. Rev. Lett. **11**, 290 (1963).

[3]M. M. Block, T. Kikuchi, D. Koetke, J. Kopelman, C. R. Sun, R. Walker, G. Culligan, V. L. Telegdi, and R. Winston, Phys. Rev. Lett. **11**, 301 (1963).

[4]M. M. Block, J. B. Kopelman, and C. R. Sun, Phys. Rev. **140**, B143 (1965).

[5]J. G. Fetkovich, J. McKenzie, B. R. Riley, I.-T. Wang, K. O. Bunnel, M. Derrick, T. Fields, G. S. Keyes, and L. G. Hyman, Phys. Rev. D **2**, 1803 (1970).

[6]C. Comber, D. H. Davis, J. Gordon, D. N. Tovee, R. Roosen, C. Vander Velde-Wilquet, and J. H. Wickens, Nuovo Cimento **24A**, 294 (1974).

[7]J. G. Fetkovich, J. Mckenzie, B. R. Riley, and I.-T. Wang, Nucl. Phys. A **240**, 485 (1975).

[8]T. B. Day, Nuovo Cimento **18**, 381 (1960).

[9]G. T. Condo, Phys. Lett. **9**, 65 (1964).

[10]J. E. Russel, Phys. Rev. Lett. **23**, 63 (1969); Phys. Rev. **188**, 187 (1969).

[11]J. G. Fetkovich, B. R. Riley, and I.-T. Wang, Phys. Lett. **35B**, 178 (1971).

[12]C. E. Wiegand and R. H. Pehl, Phys. Rev. Lett. **27**, 1410 (1971).

[13]S. Baird, C. J. Batty, F. M. Russel, P. Sherman, P. M. Bird, A. S. Clough, K. R. Parker, G. J. Pyle, and T. A. Squier, Nucl. Phys. **A392**, 297 (1983).

[14]D. C. Buckle, J. R. Kane, R. T. Siegel, and R. J. Wetmore, Phys. Rev. Lett. **20**, 705 (1968).

[15]P. A. Souder *et al.*, Phys. Rev. A **22**, 33 (1980).

[16]See, for instance, L. Bracci and E. Zavattini (to be published).

[17]A. E. Pfifer, T. Bowen, and K. R. Kendall, Nucl. Instrum. Methods **135**, 39 (1976).

[18]P. Kienle (private communication).