Measurement of the Rate of Formation of Pi-Mu Atoms in K_L^0 Decay

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Hydrogenlike atoms consisting of a pion and a muon can be formed in $K_L{}^0 \to \pi\mu\nu$ decays. In an intense, high-energy $K_L{}^0$ beam, 320 pi-mu atoms were detected and simultaneously the $K_L{}^0$ flux was monitored by recording ordinary $K_L{}^0 \to \pi\mu\nu$ decays. The first measurement is reported of the branching ratio $R = \Gamma(K_L{}^0 \to \text{pi-mu atom} + \nu)/\Gamma(K_L{}^0 \to \pi\mu\nu) = (3.88 \pm 0.41)\times 10^{-7}$, using a subset of 155 atoms. This ratio may be sensitive to anomalous interactions between the pion and the muon. In the absence of such interactions, theory predicts $R = (4.43 \pm 0.12)\times 10^{-7}$.

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In a rare decay mode first predicted by Nemenov[1] and observed by Coombes *et al.*,[2] the $K_L{}^0$ can decay into a neutrino and a hydrogenlike atom consisting of a pion and a muon.[3] We report herewith a measurement carried out with an intense, high-energy neutral beam at Fermilab in which we observed 320 pi-mu atoms and measured the branching ratio $R = \Gamma(K_L{}^0 \to \text{pi-mu atom} + \nu)/\Gamma(K_L{}^0 \to \pi\mu\nu)$, using a subset of 155 atoms.

This ratio may be calculated straightforwardly by regarding the decay $K_L{}^0 \to$ pi-mu atom $+\nu$ as a weak two-body process. Because of the pointlike nature of the weak interaction, the decay rate depends directly upon the square of the pi-mu atom wave function at zero separation, $|\psi(0)|^2$. The decay mode $K_L{}^0 \to \pi\mu\nu$ ($K_{\mu 3}$) provides a convenient normalization. The predicted value of R depends somewhat upon the form factors involved in $K_L{}^0$ decay and has been determined to be $R_{\text{theor}} = (4.43 \pm 0.12)\times 10^{-7}$.[4,5]

In calculating this branching ratio, it was assumed that only the Coulomb interaction is significant in determining $|\psi(0)|^2$. If an anomalous interaction were present, it might lead to a change in the wave function at small distances and affect the anticipated $K_L{}^0$ decay rate into pi-mu atoms.

To implement the experiment, we constructed an intense, high-energy $K_L{}^0$ beam at Fermilab. After the 400-GeV/c proton beam struck a beryllium target, a series of collimators and magnets defined the beam and swept charged particles from the flux of secondaries emerging in the forward direction. The beam then entered a 250-m-long evacuated pipe. Our detector was sensitive to decays that occurred in this pipe. A block of lead placed upstream of the collimators and sweeping magnets reduced the photon component of the beam. The average $K_L{}^0$ momentum was about 75 GeV/c, and typical intensities were about 10^7 $K_L{}^0$'s and 10^9 neutrons per accelerator pulse.

The arrangement of various elements of the detector is shown schematically in Fig. 1. The $K_L{}^0$ decay products of interest to us were those which rose sufficiently out of the beam region to clear the bottom of the detector system. The remainder of the beam passed underneath the detector, in vacuum, to a concrete dump considerably downstream.

A characteristic of pi-mu atoms basic to our method of detection is that they are neutral ob-

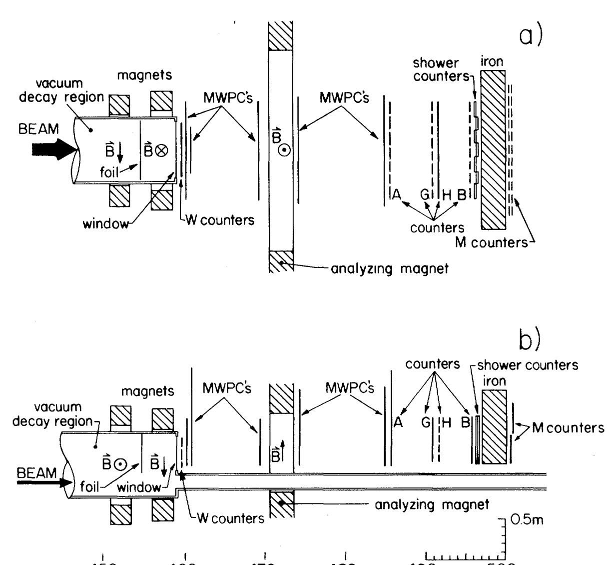

FIG. 1. Plan (a) and elevation (b) views of the detection apparatus. Also shown in the elevation view is the vacuum system in which the beam traveled. The scale is in meters from the target.

jects which are readily dissociated when passed through a thin foil. It has been calculated that approximately 0.01 in. of aluminum is sufficient to ionize a pi-mu atom.[6] We collected roughly half of our data with a 0.020-in. aluminum foil and the remainder with a 0.035-in. aluminum foil to allow verification that in each sample all the atoms were dissociated. The foil was mounted within the evacuated decay region, but above the K_L^0 beam itself. After ionization, the two charged particles traveled essentially collinearly and with the same velocity, since they originated in a bound state and the impulse required to separate them was negligible compared to the laboratory momentum.

In order to distinguish a pi-mu atom from a pion and muon (from ordinary $K_{\mu 3}$ decay) that happened to be nearly collinear and traveling with the same velocity, we introduced a horizontal magnetic field prior to the foil. This magnet caused the pion and the muon from $K_{\mu 3}$ decay always to have vertically separated trajectories as seen in the elevation view. Neutral objects, such as pi-mu atoms and photons, passed through this magnet unperturbed. Hence the pion and the muon from an atom that dissociated in the foil followed nearly identical trajectories in the elevation view.

The components of the apparatus downstream of the foil performed several functions. The fact that the pion and muon from dissociated pi-mu atoms traveled parallel paths was exploited by use of two dipole magnets with vertical fields. The first separated the particles horizontally, and the second, by providing an equal but opposite 165-MeV/c impulse, restored the parallelism of the particles' trajectories, thereby simplifying the trigger requirements (described below). The second magnet (the analyzing magnet), in conjunction with ten multiwire proportional-chamber planes, was used to measure the momenta of charged particles. A thin window separated the vacuum system from this magnetic spectrometer, which also contained scintillation counters for triggering the acquisition of data. Upstream of the analyzing magnet, a plane of thin horizontal counters (W) just overlapped the vacuum window. Downstream were four planes of vertical counters (A,G,B, and M), and one of horizontal counters (H). The M counters, located behind a 3-m-thick steel wall, were used to identify penetrating muons. In addition, an array of lead-lucite shower counters enabled us to distinguish electrons cleanly from pions and muons.

The trigger requirements for the two types of events used in the present analysis were as follows[7]:

(1) Pi-mu atoms.—We demanded that three pairs of counts appear in the A, B, and G counters, and that the distance between the struck counters in the A and B banks be nearly equal.[8] In addition, we required that exactly one counter in each of the H and W banks and at least one in the M bank be hit.

(2) $K_{\mu 3}$ decays.—This trigger was identical to the pi-mu atom trigger except that we accepted events in which more than one H or more than one W counter was hit. We chose to record only one in 32 $K_{\mu 3}$ triggers, since these decays were plentiful in comparison to pi-mu atom events.

In the analysis of the data,[5] we separated $K_{\mu 3}$ decays from pi-mu atoms using only the geometry of the pion and muon trajectories through the apparatus, as reconstructed from the pattern of hits in the proportional chambers. For example, the pion and muon from an atom formed an apparent "V" with its vertex at the center of the magnetic field region following the foil, while those from $K_{\mu 3}$ decays did not. Also, the projection of the trajectories onto a vertical plane showed two well separated tracks for $K_{\mu 3}$ decays, whereas the pion and muon tracks from an atom coalesced into an apparent single track.

Electron-positron pairs from photons that converted in the foil geometrically resembled pi-mu atoms in their passage through the apparatus. The separation of pi-mu atoms from e^+e^- events accidentally accompanied by a muon was effected by a study of the pulse height in the shower counters. The 17-radiation-length thickness of a shower counter was enough to contain the electromagnetic shower of an electron, making the pulse height in the counter proportional to the energy of the electron. By discarding all events in which more than 70% of either particles's energy appeared in the shower counters, we eliminated this background with a negligible loss of pi-mu atoms.

Figure 2 shows a histogram of the quantity $\alpha = (p_\pi - p_\mu)/(p_\pi + p_\mu)$ for those events which met the pi-mu atom criteria, where p_π and p_μ are, respectively, the pion and muon momenta. For atoms, the pion and muon have the same velocity, and hence α should be the difference over the sum of the pion and muon masses, equal to 0.14. Figure 2 shows a pi-mu atom peak at $\alpha = 0.14$ containing 355 events in the range $0.08 < \alpha < 0.20$, with an interpolated background of 35 ± 7 events.

A total of 109 469 events, collected concurrent-

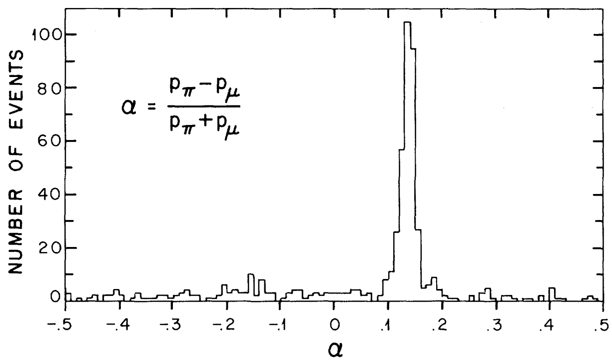

FIG. 2. Histogram of the variable α, defined in the text, showing a pi-mu atom signal at $\alpha = 0.14$.

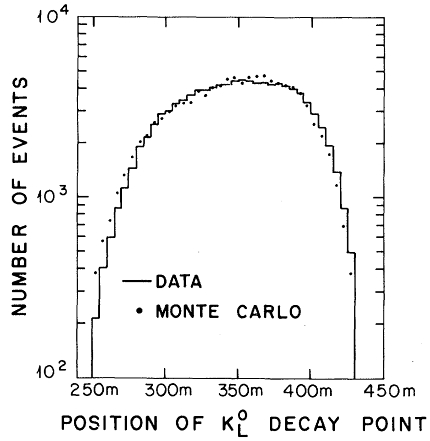

FIG. 3. A comparison of data to the Monte Carlo prediction for the position of the $K_L{}^0$ decay point, in meters from the target, for $K_L{}^0 \to \pi\mu\nu$ events.

ly, satisfied all the $K_{\mu 3}$ criteria. Subtracting a measured background of $(5.2 \pm 0.6)\%$ left 103 734 $K_{\mu 3}$ decays with which to normalize the sample of pi-mu atoms. Neutron interactions and accidental coincidences of random particles accounted for most of this background. The variety of track configurations for $K_{\mu 3}$ decays demanded that more stringent requirements be imposed in reconstructing particle trajectories than were necessary for atoms. To minimize systematic errors in the comparison of pi-mu atoms and $K_{\mu 3}$ decays, we imposed these requirements on atoms. This reduced our atom signal to 163 events with a measured background of 8.2 ± 2.1 events.

We calculated the efficiency of our apparatus for observing $K_{\mu 3}$ decays and pi-mu atoms by making a detailed Monte Carlo simulation of the experiment. The simulation included a $K_L{}^0$ momentum spectrum and $K_{\mu 3}$ decay parametrization consistent with previous measurements,[9] as well as the geometry of the beam and detection apparatus. The Monte Carlo simulation reproduced the data well. For example, in Fig. 3 we display a histogram of the position of the reconstructed $K_L{}^0$ decay point, measured in meters from the target, for $K_{\mu 3}$ decays. The ratio of our detection efficiencies for pi-mu atoms and $K_{\mu 3}$ decays was found to be 120.3 ± 8.0. The uncertainty in this ratio was obtained by adding in quadrature estimated systematic errors from a variety of sources.[10]

The above figures yield a branching ratio $R = (3.88 \pm 0.41) \times 10^{-7}$, where the error includes a statistical part (8.4%) and a systematic part (6.6%) added in quadrature. This is to be compared with the theoretical prediction $R_{\text{theor}} = (4.43 \pm 0.12) \times 10^{-7}$. Using the $K_{\mu 3}$ branching fraction $(27.0 \pm 0.5)\%$, we obtain a branching fraction for $K_L{}^0$ decay into pi-mu atoms of $(1.05 \pm 0.11) \times 10^{-7}$. The results for our samples of data collected with the 0.020-in. foil and the 0.035-in. foil are $R_{20} = (4.18 \pm 0.53) \times 10^{-7}$ and $R_{35} = (3.52 \pm 0.52) \times 10^{-7}$, demonstrating that the dissociation probability was consistent with 100% for both samples.

A property of pi-mu atoms that affects somewhat the present determination of the branching ratio is the lifetime. In our Monte Carlo simulation we assumed that the atom lifetime equals the pion lifetime. If we allow the lifetime to vary, then the only measurable effect is to alter the number of pi-mu atoms we would expect to detect. The effect is small because atoms typically lived only 8% of a pion lifetime before they were dissociated in the foil. We note, for example, that if the atom lifetime were one third the expected value, our measured branching ratio would increase to 4.6×10^{-7}.

In conclusion, we have collected 320 examples of the rare decay $K_L{}^0 \to$ pi-mu atom $+\nu$ and have measured the decay rate relative to the decay $K_L{}^0 \to \pi\mu\nu$. The theoretical prediction for this ratio, calculated on the assumption that the interaction between the muon and the pion at small distances is just the Coulomb interaction, is in agreement with our experimental result.

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[5]Derivations of the value quoted and detailed descriptions of the experiment appear in R. D. Cousins, Jr., Ph.D. thesis, Stanford University, 1981 (unpublished); J. F. Greenhalgh, Ph.D. thesis, Stanford University, 1981 (unpublished); D. Hedin, Ph.D. thesis, University of Wisconsin, 1980 (unpublished).

[6]Prasad, Ref. 4.

[7]We collected a third type of event in the experiment, e^+e^- pairs from photons that converted in the foil. The trigger was identical to the pi-mu atom trigger, except that instead of requiring an M counter to be hit, we required a pulse height above a prescribed minimum in the shower-counter band. These photons arose principally from $K_L{}^0$ decays. The results of the analysis of this data sample will be published elsewhere.

[8]The circuit used to effect this requirement is described in D. Porat and D. Ouimette, IEEE Trans. Nucl. Sci. 26, 209 (1979).

[9]R. T. Edwards *et al.*, Phys. Rev. D 18, 76 (1978); R. L. Kelly *et al.* (Particle Data Group), Rev. Mod. Phys. 52, S1 (1980).

[10]The largest systematic errors were due to the uncertainty in the $K_{\mu 3}$ form factors, uncertainties in the magnetic field strengths and the locations of the beam and detector elements, and the particle trajectory reconstruction.