New Measurement of the Rate for Pion Beta Decay

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The conserved-vector-current hypothesis, together with measured nuclear-beta-decay rates, predicts a value of the rate for the decay $\pi^+ \rightarrow \pi^0 e^+ \nu$ of $0.4027 \pm 0.0018\ \mathrm{s}^{-1}$. With use of a decay-in-flight technique the authors have made the most precise measurement to date of this rate, obtaining the value $0.398 \pm 0.015\ \mathrm{s}^{-1}$, in good agreement with the prediction.

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We present here a measurement of the rate for pion beta decay ($\pi\beta$), $\pi^+ \rightarrow \pi^0 e^+ \nu$, made with the use of a new technique at the Clinton P. Anderson Meson Physics Facility (LAMPF), which is substantially more precise than previous measurements. The conserved-vector-current (CVC) hypothesis,[1] a cornerstone of the unified theory of electromagnetic and weak interactions, relates the rate for $\pi\beta$ directly to the ft value for nuclear β decays:

$$R = \frac{\ln 2}{30(ft)} \left(\frac{\Delta}{m_e} \right)^5 F(m_e, m_+, \Delta),$$

where R is the predicted rate, Δ the π^+-π^0 mass difference, m_e the electron mass, m_+ the π^+ mass, and the function F is close to unity. With the use of recent values[2,3] of ft and of the other constants,[4] and following Sirlin[5] and Källén,[6] R is $0.4027 \pm 0.0018\ \mathrm{s}^{-1}$, where the uncertainty is primarily due to the uncertainty in Δ. In the Weinberg-Salam model[7] as applied by Sirlin[5] the electroweak corrections are the same for pion and nuclear β decays, except for a small energy-release-dependent correction.[8] The most precise previous experiment was that of Depommier *et al.*[9] who found a branching ratio $[\pi\beta/(\pi^+ \rightarrow \mu^+ + \nu)]$ of $(1.00^{+0.08}_{-0.10}) \times 10^{-8}$, corresponding to a decay rate of $0.38^{+0.03}_{-0.04}\ \mathrm{s}^{-1}$. Though this result is consistent with the theory it is very desirable to improve the experimental precision since the $\pi\beta$ rate is the most direct test of the CVC hypothesis.

In contrast to the previous experiments, which used stopped pions, this one used decays in flight of a π^+ beam, of momentum 522.1 ± 0.8 MeV/c and intensity $2 \times 10^8\ \pi/\mathrm{s}$. The π^0 from the π^+ decay had transverse momentum less than 5 MeV/c and nearly the same momentum in the laboratory as the π^+; we detected the γ rays from the π^0 decay. Figure 1 shows our apparatus, in which a decay region was defined by the minimum opening angle between the γ's and the geometrical limits of two γ detectors. The π^0 had a mean total energy of about 523 MeV and geometrically detectable coincident γ's ranged in energy from 175 to 350 MeV. To avoid background from pion charge exchange, the decay region was in a vacuum tank at 3×10^{-7} Torr. The beam was collimated twice and the γ detectors were located outside the 5° cone filled by the intense flux of

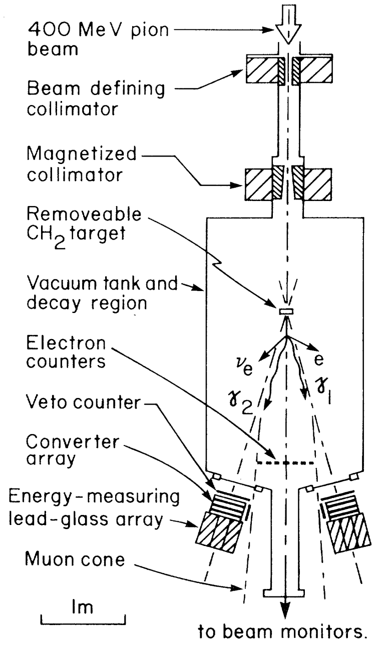

FIG. 1. Diagram of pion-beta-decay detection apparatus.

muons from decay of the charged pions. The second collimator was toroidally magnetized to reduce μ scattering into the detectors. A system of beam monitors was placed downstream.

The two γ detectors were modifications of the LAMPF π^0 spectrometer.[10] Each detector had three successive lead-glass counters as γ converters [0.56 radiation length (r.l.) each], with lead-glass blocks (14 r.l.) for total energy measurement. Each converter was followed by scintillation hodoscopes for position and time measurement. On each side, the hodoscopes defined a fiducial area with a surrounding guard ring. Veto counters rejected events with charged particles entering either detector. The trigger required a coincidence between neutral particles converting in the two detectors, and a minimum energy deposit of 40 MeV in each detector.

Besides normal running we also took calibration data with a 1.3-cm CH_2 target near the center of the decay region with π^+ and π^- beams, and with a π^- beam and hydrogen gas at atmospheric pressure filling the tank. The π^0's produced by charge exchange in these runs were used to calibrate the energy scale, conversion efficiency, and absolute timing of the detectors. By subtracting the π^+-CH_2 spectrum from the π^--CH_2 spectrum we obtained energy-response curves for the almost monoenergetic π^0's from $\pi^- p$, which showed the long tail to low apparent energies usual for total-absorption γ detectors.

The final $\pi\beta$ data consisted of 667 000 events recorded via a CAMAC system. In the first stage of analysis we computed the times of conversion of each γ and the total energy E detected; loose cuts on these two variables reduced the data samples to 7 000 events. Further analysis reduced the sample to about 1 600 events. Figure 2 gives the spectrum of the sum of the energies of the two γ's for events which comprise the majority of our final sample. The clear, well-defined peak has the apparent energy and width (543 ± 43 MeV) expected from $\pi\beta$ events. The increase above the true mean energy was due to random background pulses equivalent to 20 ± 20 MeV in the detectors; this is one of several effects of the high beam intensity used.

The decay rate R is found from

$$N_\beta = R N_\pi P(\beta\gamma c)^{-1} \int \eta(z) dz \prod_{i=1}^{4} F_i ,$$

where N_β is the number of good events, N_π is the number of beam pions entering the apparatus, P is the joint γ-ray conversion probability, $(\beta\gamma c)^{-1}$ is the pion proper time per unit flight path, $\eta(z)$ is the geometric efficiency of detection as a function of position z along the beam, and the four factors F_i are corrections. The combination

$$T = (\beta\gamma c)^{-1} \int \eta(z) dz$$

is the effective proper time spent by a beam pion in the decay region, and was determined by a Monte Carlo program which simulated the beam as measured experimentally, the fiducial geometry of each detector, and the pion β decay with use of standard weak interaction theory; it includes a correction of (16.1 ± 0.5)% for the positron from $\pi\beta$ hitting the veto counters. T is given in Table I, along with the other factors entering into the decay-rate calculation.

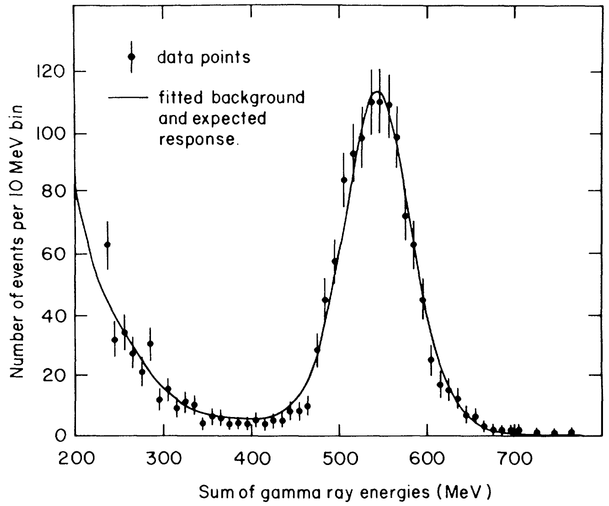

FIG. 2. Distribution of the sum of energies of coincident pairs of photons for class-A events after final event selection. Fitted curve is the expected energy-response function plus a background shape based on the distribution of events selected only on the transverse momentum parameters C and D.

N_π was determined by three separate monitors: two ionization chambers and a set of scintillation telescopes to detect $\pi \rightarrow \mu\nu$ decays.[11] These were calibrated at a beam intensity low enough for counters in the beam to count pions directly, and corrected for the measured contamination of the beam by protons, muons, and electrons, and for attenuation and decays between the decay region and the monitors. N_π was also corrected for data-acquisition dead time.

P was determined from calibration data and is the product of the conversion efficiencies of each of the detectors, with small (0.1%) corrections for variation in efficiency with energy sharing

TABLE I. Parameters entering into decay rate.

Symbol	Description	Value
N_β	Number of good events[a]	1235.4 ± 35.9
T	Time in decay region (s)[b]	$(3.534 \pm 0.031) \times 10^{-11}$
N_π	Number of beam pions[b]	$(2.144 \pm 0.022) \times 10^{14}$
P	Conversion efficiency[a]	0.5151 ± 0.0062
F_1	Dalitz, early conversions[b]	0.9423 ± 0.0050
F_2	Trigger efficiency[b]	0.8917 ± 0.0090
F_3	Software efficiency[b]	0.9581 ± 0.0050
F_4	Event selection efficiency[b]	0.9880 ± 0.0073

[a] Error is primarily statistical.

[b] Error is primarily systematic.

between the two detected γ's and position of the decay vertex.

To estimate N_β we divided the events into classes according to whether they registered only in the fiducial area (class A) or also in the guard ring. Our final sample had 1144 events in class A between 420 and 800 MeV and 114 events in the other class. Real background processes were estimated to contribute less than 10^{-4} of the $\pi\beta$ rate; we corrected only for random background, by fitting the distribution of total energy for each of the classes with the expected pulse-height response plus a curve based on the energy distribution of random events. Figure 2 shows the fit for events of class A, from which we found a background subtraction of 13.0 ± 2.2 events with energy in the range given. Three corrections were applied to the number of class-A events remaining: the fraction of $\pi\beta$ events expected in the apparent-energy interval 420 to 800 MeV (0.974 ± 0.003), the probability of leakage of the shower to veto counters on the beam side of the detectors causing the event to be vetoed (0.992 ± 0.001), and a weight which took account of transverse spreading of the shower from conversions near the edge of the fiducial area. A Monte Carlo shower calculation was used to calculate this weight for events according to class and gave a weight of 0.9983 ± 0.001 for class A. The overall correction factor for class A was thus 1.033 ± 0.003. The use of the same procedure for the other class and application of the appropriate factors gave N_β.

The factors F_i arose in three ways: from physical processes, from trigger inefficiences, and from losses in analysis. Dalitz decays of the π^0 and γ conversion in the tank windows and the front veto counters could cause the event to be vetoed, leading to the correction F_1. The trigger electronics had three inefficiencies: the effect of the finite resolving time of the left-right coincidence circuit, the dead time of the discriminators which defined a minimum γ energy for the trigger, and the inefficiency due to random pulses from the veto counters which accidentally vetoed good events; these are all combined in F_2. Random backgrounds caused otherwise good events to be lost from the sample in the first stage of analysis, resulting in a software efficiency F_3.

Finally, there was an efficiency associated with the cuts other than on energy applied in producing a final sample. This was estimated by studying the distribution of each parameter used and matching it to a Monte Carlo distribution; the overall result is F_4. Three parameters were cut on: two measures (C, D) of the momentum transverse to the beam, and timing. The cuts on C and D corresponded to requiring the transverse momentum to be less than about 20 MeV/c. The most effective criterion for event selection was timing. The π beam preserved the primary proton-beam time structure so that the pions passed through the apparatus in bunches 5 ns apart and less than 0.25 ns wide. We defined a variable

$$\chi_T^2 = (t_1/\sigma)^2 + (t_2/\sigma)^2,$$

where t_1 and t_2 are the conversion times of the γ's relative to the beam bunches and σ is the intrinsic standard deviation (~270 ps). The effect of our final cut of $\chi_T^2 \leq 10$ for $\pi\beta$ events was estimated by folding this time resolution with the time spread (~71 ps) due to the distribution of the decays over the decay region.

The final result for the pion-beta-decay rate is

$$R = 0.398 \pm 0.015 \text{ s}^{-1},$$

where the error includes statistical (3.1%) and systematic (2.0%) errors. Our result is in good agreement with the standard weak interaction theory, the difference being (− 1.2 ± 3.7)%, giving the best existing confirmation of the CVC hypothesis at low momentum transfer. Combining R with 26.030 ± 0.026 ns for the pion lifetime[4] gives a partial decay fraction of $(1.036 \pm 0.039) \times 10^{-8}$. The model of Kobayashi and Maskawa[12] implies that the original Cabibbo approach[13] of using a single mixing angle for all β decays is no longer appropriate,[14] and instead two angles are needed to parametrize $\Delta S = 1$ decays, with one of these used for $\Delta S = 0$ decays. If we use the coupling constant for muon decay and assume the validity of CVC and the radiative correction calculation,[5] we obtain a ratio of 0.937 ± 0.035 between our result and the rate calculated without use of a mixing angle. The $\Delta S = 0$ mixing angle is then $\theta = 0.25^{+0.07}_{-0.09}$ (68% C.L.) radians; in the context of the Weinberg-Salam–Kobayashi-Maskawa model this is the first direct measurement of this angle in a particle β decay as opposed to a nuclear β decay.

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