Measurement of the $\pi^+ \to e^+\nu$ Branching Ratio

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A new measurement of the $\pi^+ \to e^+\nu$ branching ratio gives $R_{\pi e\nu}=\Gamma(\pi\to e\nu+\pi\to e\nu\gamma)/\Gamma(\pi\to\mu\nu+\pi\to\mu\nu\gamma)=[1.2265\pm0.0034(\text{stat})\pm0.0044(\text{syst})]\times10^{-4}$. This result is in agreement with standard model calculations and confirms the hypothesis of electron-muon universality at the 0.2% level.

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The electroweak couplings of the three lepton generations—the electron, muon, and tau—are equal in the standard model (SM). This lepton universality is studied with π, τ, and W leptonic decays; in particular, e-μ universality is tested precisely by a measurement of the branching ratio of the helicity-suppressed decay $\pi\to e\nu$ with respect to the common decay $\pi\to\mu\nu$. Within the context of the SM, radiative corrections to the ratio [1] are nearly independent of strong interaction effects and are explicitly calculable as discussed by Marciano and Sirlin [2]. The calculated value [3] of the $\pi\to e\nu$ branching ratio $R_{\pi e\nu}=\Gamma(\pi\to e\nu+\pi\to e\nu\gamma)/\Gamma(\pi\to\mu\nu+\pi\to\mu\nu\gamma)$ is $R^{\text{th}}_{\pi e\nu}=(1.234\pm0.001)\times10^{-4}$, where the uncertainty arises from uncalculated but bounded pion structure effects. A measurement in disagreement with this value could imply a deviation from universality, or indicate the existance of other physics beyond the SM. A relatively straightforward extension of the SM would involve the admixture of nonzero mass eigenstates in the neutrino [4]. The existence of new hypothetical particles such as massless Majorons [5] or charged Higgs scalars arising from extended symmetries [6] could also influence the observed branching ratio. A previous experiment found [7] $R_{\pi e\nu}=(1.218\pm0.014)\times10^{-4}$, consistent with the calculation at the 1% level. In this Letter we report on a new measurement of $R_{\pi e\nu}$ with improved precision.

The experiment [8] was carried out on the M13 channel at TRIUMF in a π^+ beam of momentum $P=83$ MeV/c and $\Delta P/P=1\%$ using the setup shown schematically in Fig. 1. The incoming beam was detected in scintillator B1 and stopped near the downstream side of the target counter B3 at a rate of 7×10^4 s^{-1}. Veto scintillators VL and VR confined the stopping region to the central 30% of B3 in order to contain the muons from $\pi\to\mu\nu$ decay, and V0 rejected penetrating particles. The LL, LR, and B4 counters also served a similar purpose. Positrons from stopped-pion decay in B3 were detected at 90° to the beam, passing through two planar 203 mm×203 mm wire chambers (WC) for position measurement, and trigger scintillators T1–T4, before being energy analyzed in a 460-mm-diam×510-mm-long NaI(Tl) crystal "TINA." The solid-angle acceptance of 2.9% was determined by the 152-mm-diam counter T4. The positron energy spectrum consisted of a peak at 70 MeV with $\sim1.2\times10^5$ $\pi\to e\nu$ decays and a distribution from 0 to 53 MeV from the decay $\mu\to e\nu\bar{\nu}$ following $\pi\to\mu\nu$ decay (the $\pi\to\mu\to e$ chain) as shown in Fig. 2(a) [9]. Timing of the incoming pion was obtained from scintillator B2, and decay-event time was defined by T4. Event time was measured using a time-to-amplitude converter (TAC) feeding an analog-to-digital converter (ADC). All events occurring within 30 ns following a pion stop, or having energy >50 MeV deposited in TINA, were recorded in order to favor $\pi\to e\nu$ events. The sample of $\pi\to\mu\to e$ and background events was obtained from (1:16)-prescaled triggers in the time range -120 to $+300$ ns with respect to a pion stop.

The measurement required the determination of the ratio of the positrons in the $\pi\to e\nu$ peak to those from the $\pi\to\mu\to e$ chain. The largest potential source of systematic uncertainty arose from the low-energy tail of the $\pi\to e\nu$ peak which extended under the $\pi\to\mu\to e$ distribution. The tail was due mostly to the response function of TINA; the component due to radiative processes was small (about 0.4%) since NaI is also sensitive to the forward-peaked bremsstrahlung gamma rays emitted in $\pi\to e\nu\gamma$ decay.

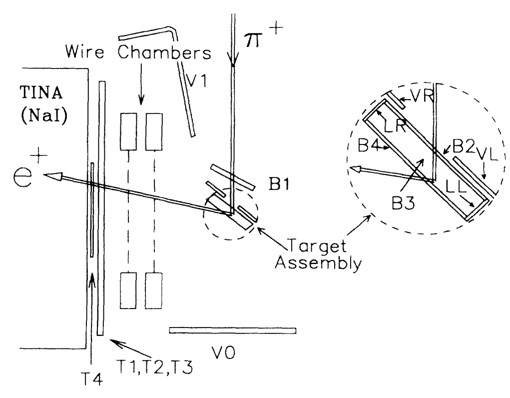

FIG. 1. Schematic view of the experimental setup.

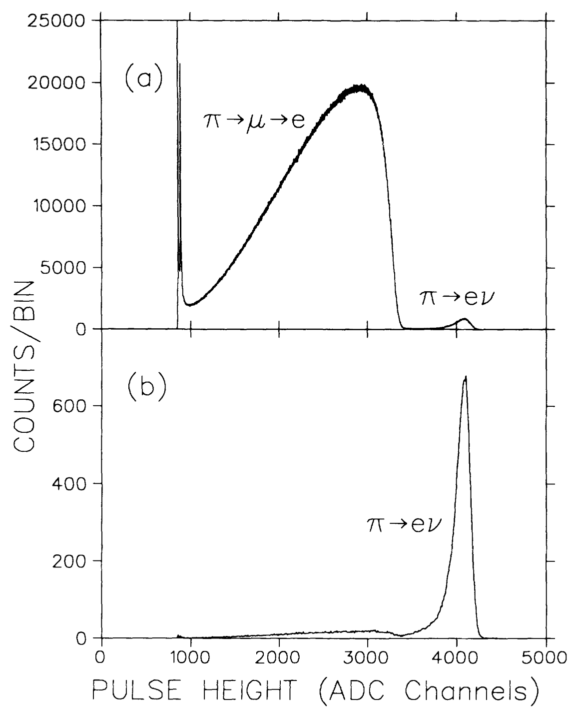

FIG. 2. (a) Positron energy spectrum for early time (<30 ns). The two peaks at low energy are due to the pedestal and the 0.511-MeV annihilation gammas from low-energy positrons which trigger, but do not penetrate, TINA. The two peaks account for 0.7% of the $\pi\rightarrow\mu\rightarrow e$ counts. (b) Positron spectrum after suppression technique described in the text.

In order to evaluate the response-function tail for $\pi\rightarrow e\nu$ events, it was necessary to suppress the dominant $\pi\rightarrow\mu\rightarrow e$ component. This was done by applying two techniques. First, by exploiting the short pion lifetime (26 ns) compared to the muon lifetime (2 μs), positrons accepted in the first 30 ns after the pion stop were enriched in $\pi\rightarrow e\nu$ events by a factor of ~ 100. The second technique used energy-loss and pulse-shape information from the B3 stopping counter [10]. For $\pi\rightarrow e\nu$ decay, the energy loss in B3 included the kinetic energy of the stopping pion plus a small contribution from the exiting decay positron. For events from the $\pi\rightarrow\mu\rightarrow e$ chain, there was an additional 4-MeV component from the kinetic energy of the decay muon, which stopped within the B3 counter. The latter events were identified by comparing the integrated charge from the B3 photomultiplier pulse as measured in two ADCs, one with a short time gate sensitive mostly to the stopping pion component, and the second with a long gate that contained the full energy including the subsequent pion decay. By applying suitable cuts on the two-dimensional distribution of long-gate versus short-gate ADC counts, an additional suppression of $\pi\rightarrow\mu\rightarrow e$ events by a factor of 1000 was obtained while retaining 73% of $\pi\rightarrow e\nu$ events as shown in Fig. 2(b). The residual background of $\pi\rightarrow\mu\rightarrow e$ events, due mostly to pion decays in flight, was subtracted using the spectrum shape for muon decay obtained from events with delayed positrons.

The suppression technique required several other factors to be taken into account. In eliminating events with 4-MeV muons, there was a bias against positrons with large energy deposition in B3. This effect led to a 170 ± 35 keV shift in the energy scale of the suppressed spectrum with respect to the unsuppressed spectrum representing a 0.08% difference in the tail fraction between the two. This shift was taken into account during the $\pi\rightarrow\mu\rightarrow e$ background subtraction, as well as in determining the tail contribution applicable to the full (unsuppressed) data set. Other effects that could distort the tail of the NaI response function were evaluated using Monte Carlo (MC) calculations. The major potential source of distortion arose from Bhabha (e^+,e^-) scattering within B3, where the scattered e^- was responsible for the trigger, while the e^+ passed through the wire chamber frames, thus losing energy and contributing to the tail. This process was most probable for events with long path lengths in B3, and, moreover, the presence of two exiting particles produced additional energy loss in B3. Such events were therefore preferentially rejected, leading to a 0.44% reduction of the tail in the suppressed spectrum. The various factors contributing to the overall (1.93 ± 0.25)% tail correction were tested for validity by observing that the branching ratio result was insensitive to the lower cutoff energy chosen for the $\pi\rightarrow e\nu$ peak, with the correction applied.

The branching ratio measurement could also be affected by distortions in the positron decay-time or energy measurements due to pulse pileup effects in the beam counters or in the positron detectors. The beam counters and the T1–T3 counters were inspected for additional charged particles with pileup logic within 6 μs of an event [7]. Pulse overlap within the resolving time of the signals in the pileup logic was detected in the analog pulses using dual ADCs with narrow and wide gates. The most effective pileup cut rejected events with additional beam particles up to 6 μs prior to a stop.

The raw branching ratio R' was determined by simultaneous fitting of the measured positron decay-time spectra shown in Fig. 3 for events above and below an energy threshold at 56.4 MeV (channel 3400) in the TINA energy spectrum, corresponding to $\pi\rightarrow e\nu$ and $\pi\rightarrow\mu\rightarrow e$ decays, respectively. Small distortions due to nonlinearity in the TAC-ADC time measurement were reduced by rebinning the data based on analysis of TAC-ADC nonlinearity test spectra taken during the beam-off periods.

The timing fit was done using MINUIT [11]. The equation for the high-energy ($\pi\rightarrow e\nu$) region is

$$F_{\pi e\nu}(t)=A_\pi[R'\lambda_\pi e^{-\lambda_\pi t}+\xi_{\pi\mu e}f(t)]\theta(t)+A_{\rm BG1}e^{-\lambda_\mu t}+\text{const}\,,$$

where $f(t)$ is the time spectrum for the decay $\pi\rightarrow\mu\rightarrow e$,

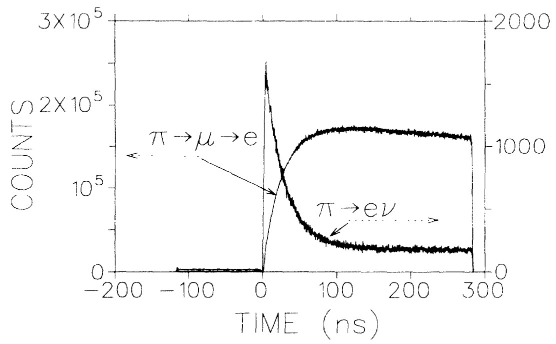

FIG. 3. Time spectra for the upper ($\pi \rightarrow e\nu$) and lower ($\pi \rightarrow \mu \rightarrow e$) parts of the energy spectrum. The dotted arrows indicate the appropriate vertical scale. The counts in the period before time zero are due to the $\pi \rightarrow \mu \rightarrow e$ spectrum.

$$f(t)=\frac{\lambda_\pi\lambda_\mu}{\lambda_\pi-\lambda_\mu}(e^{-\lambda_\mu t}-e^{-\lambda_\pi t}),$$

$t=t'-t_0$ for measured time t' and pion stop time t_0, and $\theta(t)=0$ for $t<0$ and $=1$ for $t>0$. A_π, R', $\xi_{\pi\mu e}$, and A_{BG1} are the total number of events, the raw $\pi \rightarrow e\nu$ branching ratio, the fraction of $\pi \rightarrow \mu \rightarrow e$ events above the cutoff energy (due to pileup), and a background amplitude with the muon lifetime, respectively; and λ_π and λ_μ are the pion and muon decay rates [12]. A Gaussian function was folded into the above equation to include timing resolution effects. (The branching ratio was found to be insensitive to the timing resolution which was measured to be 0.57 ± 0.02 ns.) The time spectrum for the low-energy ($\pi \rightarrow \mu \rightarrow e$) region is

$$F_{\pi\mu e}(t)=A_\pi[(1-\xi_{\pi\mu e})f(t)]\theta(t)+A_{\mathrm{BG2}}e^{-\lambda_\mu t}+\mathrm{const},$$

where A_{BG2} is a background amplitude with the muon lifetime. The constant background terms in both equations were used to estimate the potential component from a slowly decaying background (e.g., due to beam pileup inefficiency), if positive, or from short-lifetime background, if negative. The fitting ranges were -100 to -6.5 ns and 5.5 to 240 ns for both spectra. This avoided the lowest and highest channel regions which had large nonlinearities, and also the region around t_0 which was vulnerable to potential distortion from prompt π-nuclear reaction products. In the standard fitting procedure, A_π, R', $\xi_{\pi\mu e}$, t_0, and all background components were free parameters. The best combined fit, which occurred for a χ^2 per degree of freedom of 1.47, gave $R'=[1.1994 \pm 0.0034(\mathrm{stat}) \pm 0.0023(\mathrm{syst})]\times 10^{-4}$. Minor distortions in the timing spectra due to TAC-ADC nonlinearities, which were not fully eliminated by rebinning mentioned above, were responsible for the major part of the large χ^2. This effect also caused a small dependence on the fitting region, which is consistent with the systematic error indicated. However, the TAC-ADC nonlinearity correction changed the branching ratio by only 0.03%.

Other potential systematic effects were studied in the fitting procedure by introducing a component to account for possible distortion caused by the rate dependence of the pileup rejection, and by freeing fitting parameters such as the pion decay rate, the muon decay rate, and the timing resolution. Typically, these effects were at the 0.05% level. These variations were not added to the final error except for the pion decay-rate uncertainty [12]. The uncertainty in the time-spectrum calibration, 53.335 ± 0.020 ps channel^{-1}, obtained using the 23-MHz TRIUMF cyclotron radio frequency, implies an additional multiplicative uncertainty in the branching ratio of 1.0000 ± 0.00028.

MC calculations were used to test for systematic effects related to positron annihilation in flight and to multiple scattering of positrons and electrons leading to pathological triggers, false vetoes, and lost low-energy positrons. The MC calculations were also used to verify the effect of applying cuts on the acceptance using the wire chambers. The largest effects ($\sim 1\%$) were seen in annihilation and multiple scattering but $\pi \rightarrow e\nu$ and $\pi \rightarrow \mu \rightarrow e$ results canceled to the level of 0.1%. The fraction of low-energy $\pi \rightarrow \mu \rightarrow e$ positrons lost in the trigger was of the order of 0.2%. The combined multiplicative correction from the MC studies was 1.0027 ± 0.0011. Other small corrections—for backscattering into the veto counter V1, for wire chamber energy-dependent efficiency, and for a t_0 shift between $\pi \rightarrow e\nu$ and $\pi \rightarrow \mu \rightarrow e$ events—were determined empirically.

TABLE I. $\pi \rightarrow e\nu$ branching ratio summary.

Raw branching ratio R' (10^{-4})	$1.1994 \pm 0.0034(\mathrm{stat}) \pm 0.0023(\mathrm{syst})$
Multiplicative corrections:	
Tail correction	1.0193 ± 0.0025
Pion stop time t_0	0.9998 ± 0.0008
Time calibration	1.0000 ± 0.0003
Monte Carlo	1.0027 ± 0.0011
V1 veto	1.0009 ± 0.0005
WC inefficiency	0.9998 ± 0.0004
π lifetime	1.0000 ± 0.0009
Branching ratio $R_{\pi e\nu}$ (10^{-4})	$1.2265 \pm 0.0034(\mathrm{stat}) \pm 0.0044(\mathrm{syst})$

The corrections applied to the raw branching ratio are summarized in Table I where the uncertainties are combined in quadrature with the systematic error. The result is

$$R_{\pi e\nu}^{\text{expt}}=[1.2265\pm0.0034(\text{stat})\pm0.0044(\text{syst})]\times10^{-4},$$

in good agreement with the SM expectation $R_{\pi e\nu}^{\text{th}}$.

A quantitative comparison with the SM prediction can be obtained by writing $R_{\pi e\nu}^{\text{expt}}=(g_e/g_\mu)^2R_{\pi e\nu}^{\text{th}}$, where g_e and g_μ are the relative electroweak couplings of e and μ. The result is $g_e/g_\mu=0.9970\pm0.0023$ where unity corresponds to perfect e-μ universality. Alternatively, the result can be used to obtain a limit on a hypothetical pseudoscalar coupling $f_P=(-0.0030\pm0.0023)f_\pi m_e$, where f_π is the pion decay constant and m_e is the electron mass.

Other measures of charged-current universality are obtained from τ and W leptonic decays. Comparison of the measured [13] and predicted [14] ratios $\Gamma(\tau\to e\nu_e\nu_\tau)/\Gamma(\tau\to\mu\nu_\mu\nu_\tau)$ gives $g_e/g_\mu=0.998\pm0.010$. At the W scale, the UA1 collaboration found $g_e/g_\mu=0.95\pm0.07(\text{stat})\pm0.08(\text{syst})$ [15]. Measurements of the τ decay rate [13] and $W\to l\nu$ ($l=e,\mu,\tau$) decays [15-17] test τ-μ [18] and τ-e universality at the 3% and 7% levels, respectively. The ratio g_τ/g_e can also be deduced [19] using the decay $\tau\to\pi\nu_\tau$ and the $\pi\to e\nu_e$ branching ratio obtained in this work, to give $g_\tau/g_e=0.985\pm0.026$.

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