

$K_{\ell 3}^{\pm}$ AND $K_{\ell 3}^0$ FORM FACTORS

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Assuming that only the vector current contributes to $K \rightarrow \pi \ell \nu$ decays, we write the matrix element as

$$M \propto f_+(t) [(P_K + P_\pi)_\mu \bar{\ell} \gamma_\mu (1 + \gamma_5) \nu] + f_-(t) [m_\ell \bar{\ell} (1 + \gamma_5) \nu] , \quad (1)$$

where P_K and P_π are the four-momenta of the K and π mesons, m_ℓ is the lepton mass, and f_+ and f_- are dimensionless form factors which can depend only on $t = (P_K - P_\pi)^2$, the square of the four-momentum transfer to the leptons. If time-reversal invariance holds, f_+ and f_- are relatively real. $K_{\mu 3}$ experiments, discussed immediately below, measure f_+ and f_- , while $K_{e 3}$ experiments, discussed further below, are sensitive only to f_+ because the small electron mass makes the f_- term negligible.

For this edition, fits to the form factor data have been made with and without the assumption of μ - e universality, as described near the end of the note.

$K_{\mu 3}$ Experiments. Analyses of $K_{\mu 3}$ data frequently assume a linear dependence of f_+ and f_- on t , *i.e.*,

$$f_\pm(t) = f_\pm(0) [1 + \lambda_\pm(t/m_\pi^2)] \quad (2)$$

Most $K_{\mu 3}$ data are adequately described by Eq. (2) for f_+ and a constant f_- (*i.e.*, $\lambda_- = 0$). There are two equivalent parametrizations commonly used in these analyses:

(1) λ_+ , $\xi(0)$ parametrization. Analyses of $K_{\mu 3}$ data often introduce the ratio of the two form factors

$$\xi(t) = f_-(t)/f_+(t) . \quad (3)$$

The $K_{\mu 3}$ decay distribution is then described by the two parameters λ_+ and $\xi(0)$ (assuming time reversal invariance and $\lambda_- = 0$). These parameters can be determined by three different methods:

Method A. By studying the Dalitz plot or the pion spectrum of $K_{\mu 3}$ decay. The Dalitz plot density is (see, *e.g.*, Chounet *et al.* [1]):

$$\rho(E_\pi, E_\mu) \propto f_+^2(t) [A + B\xi(t) + C\xi(t)^2] ,$$

where

$$A = m_K (2E_\mu E_\nu - m_K E'_\pi) + m_\mu^2 \left(\frac{1}{4} E'_\pi - E_\nu \right) ,$$

$$B = m_\mu^2 \left(E_\nu - \frac{1}{2} E'_\pi \right) ,$$

$$C = \frac{1}{4} m_\mu^2 E'_\pi ,$$

$$E'_\pi = E_\pi^{\max} - E_\pi = (m_K^2 + m_\pi^2 - m_\mu^2) / 2m_K - E_\pi . \quad (4)$$

Here E_π , E_μ , and E_ν are, respectively, the pion, muon, and neutrino energies in the kaon center of mass. The density ρ is fit to the data to determine the values of λ_+ , $\xi(0)$, and their correlation.

Method B. By measuring the $K_{\mu 3}/K_{e 3}$ branching ratio and comparing it with the theoretical ratio (see, *e.g.*, Fearing *et al.* [2]) as given in terms of λ_+ and $\xi(0)$, assuming μ - e universality:

$$\begin{aligned} \Gamma(K_{\mu 3}^\pm) / \Gamma(K_{e 3}^\pm) &= 0.6457 + 1.4115\lambda_+ + 0.1264\xi(0) \\ &\quad + 0.0192\xi(0)^2 + 0.0080\lambda_+\xi(0) , \\ \Gamma(K_{\mu 3}^0) / \Gamma(K_{e 3}^0) &= 0.6452 + 1.3162\lambda_+ + 0.1264\xi(0) \\ &\quad + 0.0186\xi(0)^2 + 0.0064\lambda_+\xi(0) . \end{aligned} \quad (5)$$

This cannot determine λ_+ and $\xi(0)$ simultaneously but simply fixes a relationship between them.

Method C. By measuring the muon polarization in $K_{\mu 3}$ decay. In the rest frame of the K , the μ is expected to be polarized in the direction \mathbf{A} with $\mathbf{P} = \mathbf{A} / |\mathbf{A}|$, where \mathbf{A} is given (Cabibbo

and Maksymowicz [3]) by

$$\begin{aligned} \mathbf{A} = & a_1(\xi)\mathbf{p}_\mu \\ & - a_2(\xi) \left[\frac{\mathbf{p}_\mu}{m_\mu} \left(m_K - E_\pi + \frac{\mathbf{p}_\pi \cdot \mathbf{p}_\mu}{|\mathbf{p}_\mu|^2} (E_\mu - m_\mu) \right) + \mathbf{p}_\pi \right] \\ & + m_K \text{Im}\xi(t)(\mathbf{p}_\pi \times \mathbf{p}_\mu) . \end{aligned} \quad (6)$$

If time-reversal invariance holds, ξ is real, and thus there is no polarization perpendicular to the K -decay plane. Polarization experiments measure the weighted average of $\xi(t)$ over the t range of the experiment, where the weighting accounts for the variation with t of the sensitivity to $\xi(t)$.

(2) λ_+ , λ_0 parametrization. Most of the more recent $K_{\mu 3}$ analyses have parameterized in terms of the form factors f_+ and f_0 which are associated with vector and scalar exchange, respectively, to the lepton pair. f_0 is related to f_+ and f_- by

$$f_0(t) = f_+(t) + [t/(m_K^2 - m_\pi^2)] f_-(t) . \quad (7)$$

Here $f_0(0)$ must equal $f_+(0)$ unless $f_-(t)$ diverges at $t = 0$. The earlier assumption that f_+ is linear in t and f_- is constant leads to f_0 linear in t :

$$f_0(t) = f_0(0) [1 + \lambda_0(t/m_\pi^2)] . \quad (8)$$

With the assumption that $f_0(0) = f_+(0)$, the two parametrizations, $(\lambda_+, \xi(0))$ and (λ_+, λ_0) are equivalent as long as correlation information is retained. (λ_+, λ_0) correlations tend to be less strong than $(\lambda_+, \xi(0))$ correlations.

The experimental results for $\xi(0)$ and its correlation with λ_+ are listed in the K^\pm and K_L^0 sections of the Particle Listings in section ξ_A , ξ_B , or ξ_C depending on whether method A, B, or C discussed above was used. The corresponding values of λ_+ are also listed.

Because recent experiments tend to use the (λ_+, λ_0) parametrization, we include a subsection for λ_0 results. Wherever possible we have converted $\xi(0)$ results into λ_0 results and vice versa.

See the 1982 version of this note [4] for additional discussion of the $K_{\mu 3}^0$ parameters, correlations, and conversion between parametrizations.

K_{e3} Experiments. Analysis of K_{e3} data is simpler than that of $K_{\mu 3}$ because the second term of the matrix element assuming a pure vector current [Eq. (1) above] can be neglected. Here f_+ is usually assumed to be linear in t , and the linear coefficient λ_+ of Eq. (2) is determined.

If we remove the assumption of a pure vector current, then the matrix element for the decay, in addition to the terms in Eq. (1), would contain

$$\begin{aligned}
 &+2m_K f_S \bar{\ell}(1 + \gamma_5)\nu \\
 &+(2f_T/m_K)(P_K)_\lambda(P_\pi)_\mu \bar{\ell} \sigma_{\lambda\mu}(1 + \gamma_5)\nu , \quad (9)
 \end{aligned}$$

where f_S is the scalar form factor, and f_T is the tensor form factor. In the case of the K_{e3} decays where the f_- term can be neglected, experiments have yielded limits on $|f_S/f_+|$ and $|f_T/f_+|$.

Fits for $K_{\ell 3}$ Form Factors. Fits are made for the two parameters λ_+ and λ_0 and their correlation, or equivalently for λ_+ and $\xi(0)$ and their correlation. The fits are done both with and without assuming μ - e universality. This assumption sets $\lambda_+(K_{\mu 3}) = \lambda_+(K_{e3})$ so that the more precise λ_+ values from K_{e3} can be included with the $K_{\mu 3}$ data in the fit. In addition it allows the $K_{\mu 3}/K_{e3}$ branching ratio to be used in the determination of $\xi(0)$ or λ_0 as a function of λ_+ . Without this assumption, $\lambda_+(K_{e3})$ values are averaged separately and excluded from the fit to $K_{\mu 3}$ data, and branching ratio data are not used. The Kaon Particle Listings show the results with and without assuming μ - e universality.

References

1. L.M. Chounet, J.M. Gaillard, and M.K. Gaillard, Phys. Reports **4C**, 199 (1972).
2. H.W. Fearing, E. Fischbach, and J. Smith, Phys. Rev. **D2**, 542 (1970).
3. N. Cabibbo and A. Maksymowicz, Phys. Lett. **9**, 352 (1964).
4. Particle Data Group, Phys. Lett. **111B**, 73 (1982).