Measurement of Direct Photon Emission in the $K_L \to \pi^+\pi^-\gamma$ Decay Mode

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In this paper the KTeV collaboration reports the analysis of 112.1×10^3 candidate $K_L \to \pi^+\pi^-\gamma$ decays including a background of 671±41 events with the objective of determining the photon production mechanisms intrinsic to the decay process. These decays have been analyzed to extract the relative contributions of the CP violating bremsstrahlung process and the CP conserving M1 and CP violating E1 direct photon emission processes. The M1 direct photon emission amplitude and its associated vector form factor parameterized as $|\tilde{g}_{M1}|(1 + \frac{a_1/a_2}{(M_\rho^2 - M_K^2) + 2M_K E_\gamma})$ have been measured to be $|\tilde{g}_{M1}| = 1.198 \pm 0.035(\text{stat}) \pm 0.086(\text{syst})$ and $a_1/a_2 = -0.738 \pm 0.007(\text{stat}) \pm 0.018(\text{syst})\ \text{GeV}^2/c^2$ respectively. An upper limit for the CP violating E1 direct emission amplitude $|g_{E1}| \leq 0.21$ (90%CL) has been found. The overall ratio of direct photon emission (DE) to total photon emission including the bremsstrahlung process (IB) has been determined to be DE/(DE +IB) $= 0.689 \pm 0.021$ for $E_\gamma \geq 20$ MeV.

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The study of the direct photon emission in $K_L \to \pi^+\pi^-\gamma$ decays gives insight into both the structure of the kaon and the sources of CP violation in this mode. This decay proceeds via two main processes [1,2]. The first of these is the inner bremsstrahlung process (IB) in which one of the charged pions from a CP violating $K_L \to \pi^+\pi^-$ decay emits an E1 electric dipole photon by bremsstrahlung. The second process is the emission of a CP violating E1 electric dipole photon or a CP conserving M1 magnetic dipole photon together with the $\pi^+\pi^-$ pair directly from the primary decay vertex. The photons produced by the IB process have a typical bremsstrahlung spectrum with E_γ in the K_L center of mass peaking toward zero and falling off like $1/E_\gamma$, while the direct photon emission produces an energy spectrum peaked toward larger E_γ. The M1 amplitude is expected to require a form factor $(1 + \frac{a_1/a_2}{(M_\rho^2 - M_K^2) + 2M_K E_\gamma})$ according to chiral perturbation theory [4] in order to incorporate the effects of the structure of the K_L on photons emitted at the primary decay vertex (as opposed to the photons of the bremsstrahlung process emitted from the charged pions). In this form factor M_ρ^2 and M_K^2 are the mass squared of the ρ (770 MeV/c^2) and K (497 MeV/c^2) mesons..

The KTeV collaboration previously reported a measurement [3] using 8669 candidate $K_L \to \pi^+\pi^-\gamma$ decays accumulated in the 1996 KTeV E832 run at Fermi National Accelerator Laboratory which indicated clearly the presence of the M1 process and the need for the associated form factor. In addition, the presence of M1 photon emission and the need for a form factor have also been demonstrated by the KTeV E799 experiment [5,6] and NA48 [7] measurement of the $K_L \to \pi^+\pi^- e^+e^-$ mode. While this mode differs from the $K_L \to \pi^+\pi^-\gamma$ since the photon is virtual converting internally to a e^+e^-

Dalitz pair in the $K_L \to \pi^+\pi^-e^+e^-$ decay, both modes have the same amplitudes contributing except for the presence of an extra "charge radius" amplitude in the $K_L \to \pi^+\pi^-e^+e^-$ decay. Thus we expect the same g_{M1} amplitude and associated form factor to be present in the $K_L \to \pi^+\pi^-e^+e^-$ decay. This has been demonstrated by the measurements detailed in Refs [5–7].

Values of $|g_{M1}|$, its form factor, and the ratio DE/(DE+IB) presented in this paper were determined by using the much larger, complete KTeV E832 1997 $K_L \to \pi^+\pi^-\gamma$ data set containing 112.1×10^3 candidate $K_L \to \pi^+\pi^-\gamma$ decays. We have analyzed the $K_L \to \pi^+\pi^-\gamma$ decay mode using the double differential decay rate

$$\frac{d\Gamma}{dE_\gamma d\cos\theta} = (\frac{E_\gamma}{8\pi M_K})^3(1-\frac{4m_{\pi^2}}{M^2_{\pi\pi}})^{\frac{3}{2}}(1-\frac{2E_\gamma}{M_K}) \quad (1)$$
$$\times \sin^2\theta[|E1_{BR}+E1_{direct}|^2+|M1_{direct}|^2]$$

from the model of Ref. [8]. In this expression, θ is the angle of the photon with respect to the π^+ in the $\pi^+\pi^-$ center of mass system, E_γ is the photon energy in the K_L rest frame, and

$$E1_{BR} = (\frac{2M_K}{E_\gamma})^2 \frac{|\eta_{+-}|e^{i\Phi_{+-}}e^{i\delta_0}}{1-(1-\frac{4m^2_\pi}{M^2_{\pi\pi}})\cos^2\theta}$$
$$E1_{direct} = |g_{E1}|e^{i\delta_1} \quad (2)$$
$$|M1_{direct}| = |\tilde{g}_{M1}|(1+\frac{a_1/a_2}{(M^2_\rho - M^2_K)+2M_K E_\gamma})e^{i\delta_1}$$

where $\delta_0(s = M^2_K)$ and $\delta_1(s = M^2_{\pi\pi})$ are the isospin = 0,1 strong interaction $\pi^+\pi^-$ phase shifts evaluated at the kaon mass and at the particular $\pi^+\pi^-$ mass of a given $K_L \to \pi^+\pi^-\gamma$ decay. $|\eta_{+-}|e^{i\Phi_{+-}}$ is the amplitude for the CP violating $K_L \to \pi^+\pi^-$ decay.

Note that there is no interference term between the E1 and M1 amplitudes. However, there can still be an interference term in the differential decay rate between the $E1_{BR}$ and $E1_{direct}$ amplitudes. The interference will generate a contribution to the E_γ energy spectrum intermediate in energy between the lower energy bremsstrahlung photons and the higher energy M1 photons.

The $K_L \to \pi^+\pi^-\gamma$ signal of 111.4×10^3 events above a background of 671± 41 events, obtained after the analysis cuts described below, is shown in Fig. 1. Details of the detector and beam can be found in Ref. [10] so we only give a brief overview here. A proton beam with a typical intensity of 3×10^{12} delivered in a 20 second spill every minute was incident at an angle of 4.8 mr on a BeO target producing two nearly parallel K_L beams, one of which intercepted a K_S regenerator and the other of which remained a "vacuum" beam. The data for the $K_L \to \pi^+\pi^-\gamma$ measurement were obtained from the "vacuum" beam decays. The configuration of the KTeV E832 vacuum beam and detector consisted of a vacuum decay tube, a magnetic spectrometer with four drift chambers, photon vetoes, a Cesium Iodide (CsI) electromagnetic calorimeter, and a muon detector.

Approximately 4.3×10^8 events were extracted from two track triggers [10] by requiring that the two tracks to pass track quality cuts and form a vertex with a good vertex χ^2. These tracks were also required to have opposite charges and E/p $\leq$ 0.85, where E was the energy deposited by the track in the CsI, and p was the momentum obtained from magnetic deflection. Showers chosen as photons are required to be far from pion showers and to have a transverse shower shape consistent with electromagnetic showers. Only photons with $E_\gamma \geq 20$ MeV in the $\pi^+\pi^-\gamma$ rest frame were included in this analysis.

To reduce backgrounds arising from other types of K_L decays in which decay products have been missed, the candidate $\pi^+\pi^-\gamma$'s were required to have transverse momentum P_t^2 relative to the direction of the K_L be less than 2.5×10^{-4} GeV$^2/c^2$ and $M_{\pi^+\pi^+\gamma}$, the invariant mass of the $\pi^+\pi^-\gamma$ system, to be 490 MeV/c^2 $\leq M_{\pi\pi\gamma} \leq$ 506 MeV/c^2.

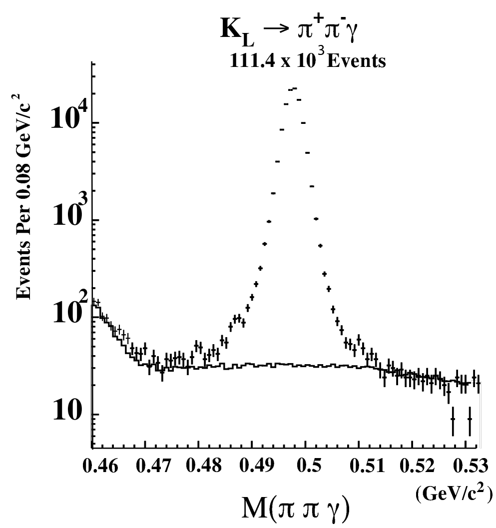

FIG. 1. $\pi^+\pi^-\gamma$ invariant mass for events passing all $K_L \to \pi^+\pi^-\gamma$ physics cuts except for the $M_{\pi^+\pi^-\gamma}$ cut. Crosses are data and the solid line is the fit to the background components

The major background to the $K_L \to \pi^+\pi^-\gamma$ mode was due to an accidental calorimeter cluster in coincidence with a $K_L \to \pi^\pm\mu^\mp\nu$ decay in which the muon was misidentified as a pion. This background was suppressed by the muon detector identification as well as the P_t^2 and $M_{\pi\pi\gamma}$ cuts. A smaller background was due to $K_L \to \pi^\pm e^\mp\nu$ decays in which there was an accidental photon, and the electron was misidentified as a pion. This background was suppressed by electron E/p identification and P_t^2 and $M_{\pi\pi\gamma}$ cuts. The $M_{\pi^+\pi^-\gamma}$ spectrum shapes due to the K_{e3} and $K_{\mu3}$ backgrounds were similar.

A still smaller background to the $K_L \to \pi^+\pi^-\gamma$ mode was $K_L \to \pi^+\pi^-\pi^0$ in which one of the photons from the π^0 decay was not detected in the CsI calorimeter or the photon vetos. To reduce the $K_L \to \pi^+\pi^-\pi^0$ background, the longitudinal momentum $(P_L^2)_{\pi^0}$ of all candidate $K_L \to \pi^+\pi^-\gamma$ events was calculated (under the assumption that the events were really $K_L \to \pi^+\pi^-\pi^0$) in the frame where the $\pi^+\pi^-$ momentum was transverse to the K_L direction. In this frame,$(P_L^2)_{\pi^0}$ is ≥ 0.0 (except for resolution effects) for $K_L \to \pi^+\pi^-\pi^0$ decays. In contrast, the $K_L \to \pi^+\pi^-\gamma$ decays should have $(P_L^2)_{\pi^0} \leq 0$. The requirement $-0.10 \leq (P_L^2)_{\pi^0} \leq -0.0055$ GeV$^2/c^2$, together with the P_t^2 and $M_{\pi\pi\gamma}$ mass cut, suppressed the $K_L \to \pi^+\pi^-\pi^0$ background.

Hyperon decays such as $\Lambda \to p\pi^-$ plus an accidental photon with the proton misidentified as a π^+, or $\Xi \to \Lambda\pi^0$ with a misidentified proton and one of the π^0 photons missed, were determined to contribute a few events. Other sources of background such as $K_L \to \pi^+\pi^-$ coincident with an accidental photon or $K_S \to \pi^+\pi^-\gamma$ produced in the neutral beam production target were completely negligible.

The magnitude of the remnant background after all cuts was determined by a fit (see Fig. 1) of the sideband regions above and below the K_L mass peak to shapes obtained from a Monte Carlo of the backgrounds leading to an estimated total background of 671 ± 41 events. The best estimate of the composition of this background is 9% $K_L \to \pi^+\pi^-\pi^0$, 30% $K_L \to \pi^\pm e^\mp\nu$, 60% $K_L \to \pi^\pm\mu^\mp\nu$, and the remainder due to the other minor backgrounds mentioned above. The 112.1×10^3 candidate events, including the estimated 671 events of background, were analyzed in a likelihood fit based on equations 1 and 2. The likelihood was a function of the two independent variables θ and E_γ, the values of the fit parameters a_1/a_2, $|\tilde{g}_{M1}|$ and $|g_{E1}|$ and nominal values from the PDG [11] for the other model parameters such as η_{+-}. The strong interaction phase shifts of the $\pi^+\pi^-$ system are taken from Ref. [12]. The likelihood was calculated using a Monte Carlo event sample generated with nominal values of the fit parameters, traced through the spectrometer undergoing multiple scattering, bremsstrahlung, and secondary decays. The resulting events are then reconstructed using the same reconstruction code as was used on data. These reconstructed Monte Carlo events are then reweighted with a new set of fit parameters using the $K_L \to \pi^+\pi^-\gamma$ matrix element of Ref. [8] and a likelihood is calculate for the new parameters. The maximum likelihood fits to the two independent variables cosθ and E_γ are shown in Fig. 2a) and Fig.2b) respectively.

Possible systematic uncertainties in a_1/a_2, $|\tilde{g}_{M1}|$ and $|g_{E1}|$ due to disagreements between data and Monte Carlo simulations were investigated by varying analysis cuts and observing variations in these fit parameters. In addition, the momentum spectrum of the $\pi^+\pi^-\gamma$ system observed in the $K_L \to \pi^+\pi^-$ decays has been adjusted to agree with the K_L momentum spectrum observed in $K_L^0 \to \pi^+\pi^-$ mode and the data has been refit after the adjustment. Any differences between a_1/a_2, $|\tilde{g}_{M1}|$ and $|g_{E1}|$ before and after the final adjustments were taken to be a systematic error due to uncertainty in the kaon beam momentum spectrum. Systematics due to uncertainties of parameters such as η_{+-}, and the strong interaction phase shifts $\delta_{0,1}$ that were not determined by the fit were studied by varying each parameter over $\pm 1\sigma$ of their published values and observing the variation of a_1/a_2, $|\tilde{g}_{M1}|$, and $|g_{E1}|$. Bremsstrahlung radiation from the pions was studied using the PHOTOS program [13]. This radiation could lead to $\pi^+\pi^-\gamma\gamma$ final states in which one of the photons is not observed causing shifts of the kinematics of the original $\pi\pi\gamma$ decay. Possible systematic effects due to the non-orthogonality of drift chamber planes were also studied. Final overall systematic errors in a_1/a_2, $|\tilde{g}_{M1}|$, and $|g_{E1}|$ were obtained by adding the individual errors in quadrature. Table I lists the non-zero systematic uncertainties of a_1/a_2 and $|\tilde{g}_{M1}|$, and $|g_{E1}|$.

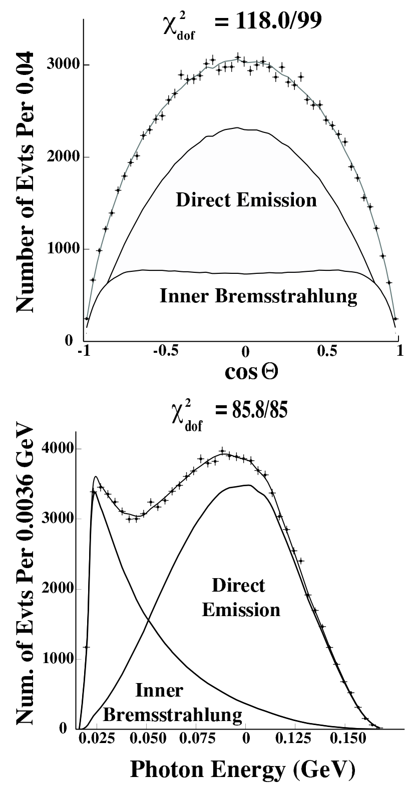

FIG. 2. Likelihood fit to the two independent variables in the K_L rest frame: a) the angle θ between the π^+ and the γ in the $\pi^+\pi^-$ center of mass and b) the photon energy spectrum E_γ in the K_L rest frame. The components of the photon energy spectrum and the cosθ spectrum due to the bremsstrahlung and M1 direct emission processes are shown.

The results, including systematic errors of the measurement of the M1 direct photon emission amplitude and the attendant vector form factor, are $a_1/a_2 = (-0.738 \pm 0.007(\text{stat}) \pm 0.018(\text{syst}))$ GeV$^2/c^2$ and $|\tilde{g}_{M1}| =$

1.198±0.035(stat)±0.086(syst). These measurements are in good agreement with the measurements of Ref. [3,5–7] (see Fig. 3). After incorporating the systematic errors, an upper limit of $|g_{E1}| \leq 0.21$ (90% CL) was obtained.

Using the result for $|\tilde{g}_{M1}|$ and its associated form factor and taking $|g_{E1}|$ to be equal to zero, the ratio of direct to total photon emission in $K_L \to \pi^+\pi^-\gamma$ decay was determined by integrating the M1 and bremsstrahlung processes over θ and E_γ (for $E_\gamma \geq 20$ MeV) to be DE/(DE+IB)= 0.689 ± 0.021. This result is in good agreement with Ref. [3].

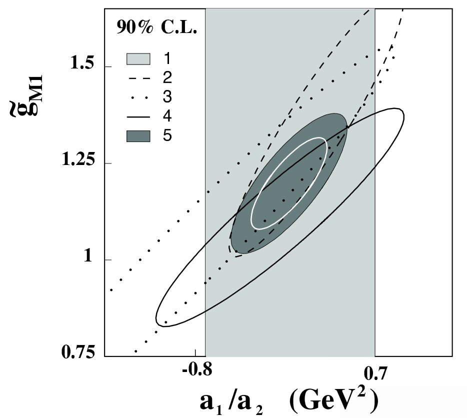

FIG. 3. 90% CL contours of $\tilde{g}_{M1}$ vs. a_1/a_2 for various experimental measurements; 90% CL results from the $K_L \to \pi^+\pi^-\gamma$ mode from this paper (5-shaded contour) with the 68% CL contour also shown (white contour); For comparison, we show the results from the $K_L \to \pi^+\pi^-e^+e^-$ mode for NA48 data (3-dotted contour) of Ref. [7], for KTeV 1997 data (2-dashed contour) in Ref. [5], and for KTeV 1997+1999 data (4-solid contour) of Ref. [6], and for a_1/a_2 from earlier KTeV 96 $K_L \to \pi^+\pi^-\gamma$ data (1-light gray vertical region) of Ref. [3].

In conclusion, this paper presents the best measurements achieved to date for the M1 direct photon emission form factor parameters $|\tilde{g}_{M1}| = 1.198 \pm 0.035(\text{stat}) \pm 0.086(\text{syst})$ and $a_1/a_2 - 0.738 \pm 0.007(\text{stat}) \pm 0.018(\text{syst})$ GeV$^2/c^2$ in the $K_L \to \pi^+\pi^-\gamma$ and $K_L \to \pi^+\pi^-e^+e^-$ decay modes. These measurements are in good agreement with our previous measurement of a_1/a_2 using the 1996 KTeV $K_L \to \pi^+\pi^-\gamma$ data [3] and with our measurements of $|\tilde{g}_{M1}|$ and a_1/a_2 using the 1997 and 1999 KTeV $K_L \to \pi^+\pi^-e^+e^-$ data [5,6] and with NA48 results [7] from $K_L \to \pi^+\pi^-e^+e^-$. We have also determined an upper limit $|g_{E1}| \leq 0.21$ (90%CL) for CP violating E1 direct photon emission in the $K_L \to \pi^+\pi^-\gamma$ mode consistent with that measured using $K_L \to \pi^+\pi^-e^+e^-$ decays [6].

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Source	$\lvert\tilde{g}_{M1}\rvert$	a_1/a_2	$\lvert g_{E1}\rvert$
Differing initial MC parameters	0.0093	0.0021	0.013
Kaon Beam Momentum Uncertainty	0.0031	0.0004	0.005
Background uncertainty	0.0355	0.0067	0.045
Pion bremsstrahlung	0.0326	0.0140	0.097
Non-Orthogonality of chambers	0.0402	0.0013	0.009
Physics cut variations	0.0463	0.0056	-
Fitting resolution	0.014	0.0056	0.024
E_γ,cosθ resolution	0.023	0.0042	0.038
η_{+-} uncertainty	0.0171	0.0014	-
δ_0 phase uncertainty	0.0111	0.0021	-
δ_1 phase uncertainty	0.0053	-	-
Total Systematic Error	0.086	0.018	0.117

TABLE I. Contributions to the systematic errors (67% CL) for a_1/a_2, $|\tilde{g}_{M1}|$, and $|g_{E1}|$.