Measurement of the K^0 Charge Radius and a CP-Violating Asymmetry and a Search for CP-Violating $E1$ Direct Photon Emission in the Rare Decay $K_L \to \pi^+\pi^-e^+e^-$

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Using the complete KTeV data set of 5241 candidate $K_L \to \pi^+\pi^-e^+e^-$ decays (including an estimated background of 204 ± 14 events), we have measured the coupling $g_{\rm CR} = 0.163 \pm 0.014({\rm stat}) \pm 0.023({\rm syst})$ of the CP conserving charge radius process and from it determined a K^0 charge radius of $\langle r^2_{K^0}\rangle = [-0.077 \pm 0.007({\rm stat}) \pm 0.011({\rm syst})] fm^2$. We have determined a first experimental upper limit of 0.04 (90% C.L.) for the ratio $\frac{|g_{E1}|}{|g_{M1}|}$ of the couplings for the $E1$ and $M1$ direct photon emission processes. We also report the measurement of $|g_{M1}|$ including a vector form factor $|\tilde{g}_{M1}|(1 + \frac{a_1/a_2}{(M_\rho^2 - M_K^2) + 2M_K E_{\gamma^*}})$, where $|\tilde{g}_{M1}| = 1.11 \pm 0.12({\rm stat}) \pm 0.08({\rm syst})$ and $a_1/a_2 = [-0.744 \pm 0.027({\rm stat}) \pm 0.032({\rm syst})]\ {\rm GeV}^2/c^2$. Finally, a CP-violating asymmetry of $[13.6 \pm 1.4({\rm stat}) \pm 1.5({\rm syst})]\%$ in the CP and T odd angle ϕ between the decay planes of the e^+e^- and $\pi^+\pi^-$ pairs in the K_L center of mass is reported.

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The presence of a virtual photon in the rare decay $K_L \to \pi^+\pi^-e^+e^-$ allows the measurement of the K^0 charge radius and CP violation using this decay. The emission of the virtual photon proceeds via the processes [1] [see Fig. 1: (a) bremsstrahlung, (b) $M1$ and $E1$ direct photon emission, and (c) the charge radius process]. The bremsstrahlung process takes place via the CP-violating decay $K_L \to \pi^+\pi^-$ followed by emission of an electric dipole ($E1$) photon by bremsstrahlung from one of the π's. The direct emission process involves either the CP conserving or CP-violating direct emission at the primary decay vertex of a magnetic dipole ($M1$) or an electric dipole ($E1$) photon, respectively. The CP conserving charge radius process is the transformation of a $K_L \to K_S$ by emission of a virtual photon in a $J = 0$ transition (forbidden in real photon emission) followed by the CP conserving decay of the K_S into $\pi^+\pi^-$. The charge radius coupling $g_{\rm CR}$ is related to the charge radius of the neutral kaon by $\langle r^2_{K^0}\rangle = -3|g_{\rm CR}|/M_K^2$ since the virtual photon acts as a probe of the K^0 in a way similar to the virtual photon in K^0-atomic electron scattering.

An indirect CP-violating asymmetry in the CP and T-odd angle ϕ between the decay planes of the e^+e^- and $\pi^+\pi^-$ pairs in the K_L center of mass system arises from the interference of the CP-violating bremsstrahlung

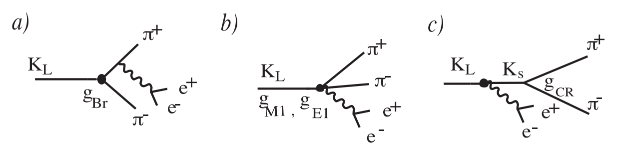

FIG. 1. Processes by which $K_L \to \pi^+\pi^-e^+e^-$ takes place; (a) bremsstrahlung, (b) $M1$ and $E1$ direct photon emission, (c) charge radius process.

photon emission process and the dominant CP conserving $M1$ photon emission process [1,2]. The asymmetry appears in the distribution of the quantity $\sin\phi\cos\phi$ [given by $(\hat{n}_{ee} \times \hat{n}_{\pi\pi}) \cdot \hat{z}(\hat{n}_{ee} \cdot \hat{n}_{\pi\pi})$, where the $\hat{n}$'s are the unit normals to the ee and $\pi\pi$ planes, and $\hat{z}$ is the unit vector in the $\pi\pi$ direction in the K_L center of mass] and is given by

$$A = \frac{N_{\sin\phi\cos\phi>0.0} - N_{\sin\phi\cos\phi<0.0}}{N_{\sin\phi\cos\phi>0.0} + N_{\sin\phi\cos\phi<0.0}}. \quad (1)$$

The matrix elements [1] for the bremsstrahlung, $M1$, $E1$, and charge radius processes are

$$M_{\rm br} \sim \eta_{+-} e^{i\delta_0(M_K^2)} \left[\frac{p_{+\mu}}{p_+ \cdot k} - \frac{p_{-\mu}}{p_- \cdot k}\right] \frac{\bar{u}(k_-)\gamma^\mu v(k_+)}{k^2}$$

$$M_{M1} \sim i|g_{M1}| e^{i\delta_1(M_{\pi\pi}^2)} \epsilon_{\mu\nu\rho\sigma} k^\nu p_+^{\rm rho} p_-^\sigma \frac{\bar{u}(k_-)\gamma^\mu v(k_+)}{k^2}$$

$$M_{E1} \sim |g_{E1}| e^{i[\phi_{+-} + \delta_1(M_{\pi\pi}^2)]} [(p_- \cdot k) p_{+\mu} - (p_+ \cdot k) p_{-\mu}] \times \frac{\bar{u}(k_-)\gamma^\mu v(k_+)}{k^2}$$

$$M_{\rm CR} \sim |g_{\rm CR}| e^{i\delta_0(M_{\pi\pi}^2)} \frac{k^2 P_\mu - (P \cdot k) k_\mu}{M_{\pi\pi}^2 - M_K^2} \frac{\bar{u}(k_-)\gamma^\mu v(k_+)}{k^2}, \quad (2)$$

where p_+, p_-, k_+, k_-, k, P are the π^+, π^-, positron, electron, virtual photon, and K_L four momenta. The $\delta_{0,1}$ are the isospin $I = 0, 1$ $\pi^+\pi^-$ strong interaction phase shifts. η_{+-} is the coupling of the $K_L \to \pi^+\pi^-$ decay and the $E1$ and $M1$ direct emission and charge radius couplings are g_{E1}, g_{M1}, and $g_{\rm CR}$.

The KTeV E799-II experiment at Fermi National Accelerator Laboratory previously reported the first observation [3] of the rare four body decay mode $K_L \to \pi^+\pi^-e^+e^-$ based on 1% of the KTeV data. We have also made an initial measurement [4] based on 36% of the KTeV $K_L \to \pi^+\pi^-e^+e^-$ data of a CP-violating asymmetry in the variable $\sin\phi\cos\phi$ (where ϕ is the CP- and T-odd angle between the e^+e^- and $\pi^+\pi^-$ planes in the K_L center of mass). In addition, the measurement of the $M1$ direct photon emission coupling $|g_{M1}|$, including a vector form factor, was reported in Ref. [4]. In this Letter we report a measurement of the charge radius of the K^0 obtained from the coupling $|g_{\rm CR}|$ of the charge radius process of the $K_L \to \pi^+\pi^-e^+e^-$ decay. We also determined an upper limit for the $E1$ direct photon emission in this decay. Finally, we present the measurements of the $M1$ direct emission process coupling and its form factor and the CP-violating asymmetry in $\sin\phi\cos\phi$.

The $K_L \to \pi^+\pi^-e^+e^-$ data were accumulated during the 1997 and 1999 runs of the KTeV E799-II experiment. A total of 5241 $K_L \to \pi^+\pi^-e^+e^-$ candidate events, including an estimated background of 204 ± 14 events, obtained after the analysis cuts described below, is shown in the $\pi^+\pi^-e^+e^-$ mass plot of Fig. 2. Note that data have been separately plotted for $\sin\phi\cos\phi > 0$ and $\sin\phi\cos\phi < 0$. The CP violation is seen directly in the different sizes of the two peaks.

The KTeV four track trigger [4] selected 3.9×10^8 events from the 1997 and 1999 runs. Candidates for the rare decay $K_L \to \pi^+\pi^-e^+e^-$ [BR $= (3.11 \pm 0.19) \times 10^{-7}$ [5]] were extracted from these triggers by requiring events to have four tracks that passed track quality cuts and had a common vertex with a good vertex χ^2. To be designated as $e^\pm$, two of the tracks were required to have opposite charges and $0.95 \le E/p \le 1.05$, where E was the energy deposited by the track in the calorimeter and p was the momentum obtained from magnetic deflection. To be consistent with a $\pi^\pm$ pair, the other two tracks were required to have $E/p \le 0.90$ and opposite charges. To reduce backgrounds arising from other types of K_L decays in which decay products have been missed, the candidates $\pi^+\pi^-e^+e^-$ were required to have transverse momentum P_t^2 of the four tracks relative to the direction of the K_L be less than 0.6×10^{-4} GeV$^2/c^2$. This cut was 94% efficient for retaining $K_L \to \pi^+\pi^-e^+e^-$.

The major background to the $K_L \to \pi^+\pi^-e^+e^-$ mode was $K_L \to \pi^+\pi^-\pi_D^0$ where π_D^0 was a Dalitz decay, $\pi^0 \to \gamma e^+e^-$, in which the photon was not observed in the CsI calorimeter or the photon vetoes. To reduce this background, all $K_L \to \pi^+\pi^-e^+e^-$ candidate events were interpreted as $K_L \to \pi^+\pi^-\pi_D^0$ decays. Under this assumption, the longitudinal momentum squared $(P_L^2)_{\pi^0}$ of the assumed π^0 can be calculated in the frame in which the momentum of $\pi^+\pi^-$ is transverse to the K_L direction. $(P_L^2)_{\pi^0}$ was greater than zero for $K_L \to \pi^+\pi^-\pi_D^0$ decays except for cases where finite detector resolution resulted in a $(P_L^2)_{\pi^0} \le 0$. In contrast, most of the $K_L \to \pi^+\pi^-e^+e^-$ decays had $(P_L^2)_{\pi^0} \le 0$. The requirement that all $\pi^+\pi^-e^+e^-$ had $(P_L^2)_{\pi^0} \le -0.025$ GeV$^2/c^2$ reduced the

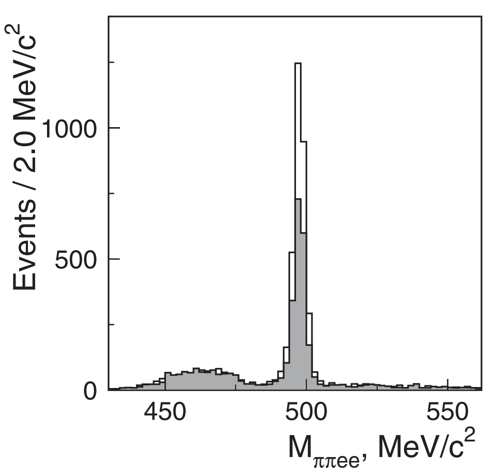

FIG. 2. $M_{\pi^+\pi^-e^+e^-}$ invariant mass for events passing all $K_L \to \pi^+\pi^-e^+e^-$ physics cuts. The superimposed K_L mass peaks for $\sin\phi\cos\phi > 0$ (white histogram) and <0 (gray histogram) directly demonstrate the large CP-violating asymmetry. There is no asymmetry in the backgrounds outside the K_L peaks.

$K_L \to \pi^+\pi^-\pi^0_D$ background under the K_L peak to 177 events while retaining 94% of the signal.

A second significant background was due to $\Xi^0 \to \Lambda\pi^0 \to p\pi^- e^+e^-\gamma$ where the photon was missed and the proton was misidentified as a π^+. There were 22 events of this type estimated by using the ratio of Ξ^0/K_L in the beam determined by various studies and the acceptances from the simulation and branching ratios for the decay chain. All other backgrounds were relatively minor. The largest was due to $K_L \to \pi^0\pi^0\pi^0$ with $\pi^0 \to e^+e^-e^+e^-$. This mode contributed approximately four events to the background after cuts. In addition, a potentially large background due to $K_L \to \pi^+\pi^-\gamma$ decays in which the photon converted in the material of the spectrometer producing an e^+e^- pair was eliminated by requiring $M_{e^+e^-} \geq 2.0\ \mathrm{MeV}/c^2$. The $M_{e^+e^-}$ cut retained 95% of the $K_L \to \pi^+\pi^-e^+e^-$ events with only one event contributing to the background.

The final requirement of the $K_L \to \pi^+\pi^-e^+e^-$ events was that $492\ \mathrm{MeV}/c^2 \leq M_{\pi\pi ee} \leq 504\ \mathrm{MeV}/c^2$. The magnitude of the background under the K_L peak was determined by a fit of the sum of the mass distributions of the various backgrounds to the sidebands of the signal region. From this fit, a $K_L \to \pi^+\pi^-e^+e^-$ signal of 5037 events above a background of 204 ± 14 events was obtained. The magnitude of the background obtained in this way was consistent with the background estimated directly from the Monte Carlo simulations.

We analyzed the $K_L \to \pi^+\pi^-e^+e^-$ decays in a likelihood fit that used the matrix elements [Eq. (1)] of the model of [1] with additional radiative corrections applied to the final state particles using the PHOTOS program [6]. We also found it necessary to include a dependence on the virtual photon energy in the $M1$ virtual photon emission coupling in order to obtain agreement with the virtual photon energy spectrum $E_{\gamma^*} = E_{e^+} + E_{e^-}$ of the data [Fig. 3(f)]. The $M1$ coupling $|g_{M1}|$ was modified by a vector form factor

$$|g_{M1}| = |\tilde{g}_{M1}|\left[1 + \frac{a_1/a_2}{(M_\rho^2 - M_K^2) + 2M_K E_{\gamma^*}}\right] \quad (3)$$

suggested by the chiral perturbation model of Ref. [7] and similar to that used in Ref. [8] to describe $K_L \to \pi^+\pi^-\gamma$. Here M_ρ is the mass of the ρ meson ($770\ \mathrm{MeV}/c^2$) and the $E_{\gamma^*} = E_{e^+} + E_{e^-}$, where E_{e^+} and E_{e^-} are the e^+ and e^- energies in the K_L center of mass.

The likelihood of a given event [see Eq. (4) below], based on the matrix elements $\mu(\vec{x}_i, \vec{\alpha})$ of the model of Ref. [1], is a function of the five independent variables $\vec{x}_i$: ϕ, θ_{e^+} (the angle between the e^+ and the $\pi^+\pi^-$ direction in the e^+e^- center of mass), θ_{π^+} (the angle between the π^+ and the e^+e^- direction in the $\pi^+\pi^-$ center of mass), $M_{\pi^+\pi^-}$, and $M_{e^+e^-}$. It also depends on the values of the fit parameters $\vec{\alpha}$: a_1/a_2 and $|\tilde{g}_{M1}|$, $\frac{|g_{E1}|}{|g_{M1}|}$,

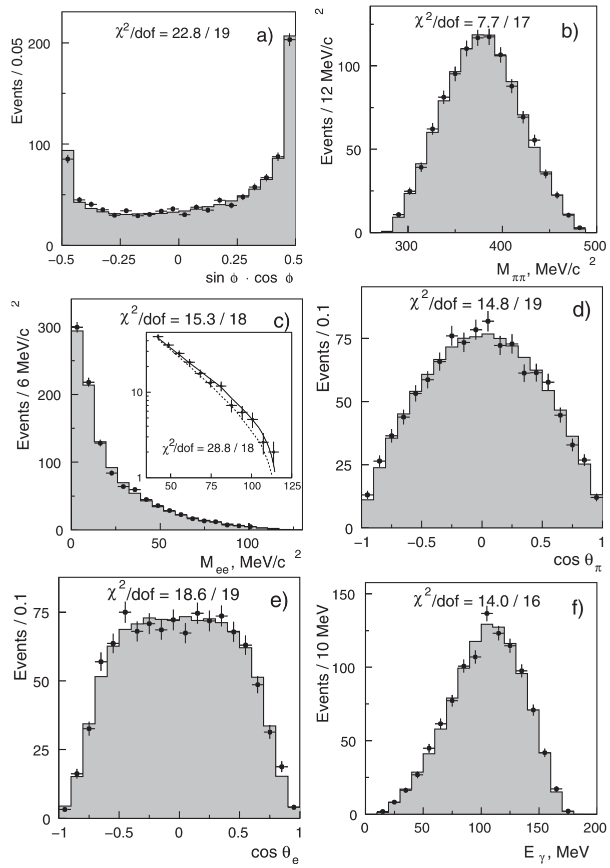

FIG. 3. Likelihood fit to the five independent variables (a) $\sin\phi\cos\phi$, (b) $M_{\pi^+\pi^-}$, (c) $M_{e^+e^-}$ (the dotted curve in the inset in this figure shows the deficit of e^+e^- pairs at high M_{ee} if the charge radius process is ignored. The χ^2/d.o.f. for the fit of the model to the data increases from 0.85 to 1.6 if the charge radius process is left out), (d) θ_{π^+}, and (e) θ_{e^+} of the $K_L \to \pi^+\pi^-e^+e^-$ decay; (f) E_{γ^*} defined as $E_{e^+} + E_{e^-}$.

$|g_{\mathrm{CR}}|$ and nominal values for other model parameters such as $\eta_{+-} = (2.286 \pm 0.017) \times 10^{-3}$ and $\Phi_{+-} = 43.51^0 \pm 0.06^0$. The measured strong interaction phase shifts of the $\pi^+\pi^-$ were taken from Ref. [9]. The likelihood used the selected $K_L \to \pi^+\pi^-e^+e^-$ data sample of N_D events and a large Monte Carlo event sample N_{MC} generated with nominal values of the fit parameters $\vec{\alpha}_0$, passed through the spectrometer and reconstructed, and then reweighted with a new set of fit parameters $\vec{\alpha}$ using the matrix elements $\mu(\vec{x}_i, \vec{\alpha})$. The likelihood fit to the five independent variables is shown in Fig. 3 along with the fit to E_{γ^*}. The charge radius process contributes to the higher mass M_{ee} [see the inset of Fig. 3(c)] while the $M1$ direct emission is determined by the shape of the $M_{\pi^+\pi^-}$ spectrum.

The likelihood function used to perform the fit is

$$\ln L(\vec{\alpha}) = \sum_{i=1}^{N_D} \ln\mu(\vec{x}_i, \vec{\alpha}) - N_D \ln \sum_{j=1}^{N_{MC}} \frac{\mu(\vec{x}_j, \vec{\alpha})}{\mu(\vec{x}_j, \vec{\alpha}_0)}. \quad (4)$$

TABLE I. Systematic errors of a_1/a_2, $|\tilde{g}_{M1}|$, $|g_{\rm CR}|$, $\frac{|g_{E1}|}{|g_{M1}|}$, and $A =$ the CP-violating ϕ asymmetry.

Source	Uncertainty in a_1/a_2	$\lvert\tilde{g}_{M1}\rvert$	$\lvert g_{\rm CR}\rvert$	$\frac{\lvert g_{E1}\rvert}{\lvert g_{M1}\rvert}$	A (%)
Monte Carlo Statistics	0.002	0.01	0.001	0.001	⋯
Initial MC parameters	0.005	0.02	0.001	0.001	⋯
Skewing due to MC values	0.000	0.028	0.002	0.010	⋯
Physics cut variations	0.022	0.041	0.021	0.018	0.71
Background	0.022	0.05	0.010	0.008	0.30
η_{+-} uncertainty	0.0001	0.01	0.002	0.0002	0.163
Φ_{+-} uncertainty	0.0003	0.002	0.0002	0.0005	0.111
$\delta_{0,1}$ uncertainty	0.001	0.004	0.001	0.0003	0.325
$\frac{\lvert g_{E1}\rvert}{\lvert g_{M1}\rvert}$	⋯	⋯	⋯	⋯	0.326
$\lvert g_{M1}\rvert$, a_1/a_2	⋯	⋯	⋯	⋯	0.335
$\lvert g_{\rm CR}\rvert$	⋯	⋯	⋯	⋯	0.335
Total systematic error	0.032	0.08	0.023	0.023	1.46

The best fit values were $a_1/a_2 = [-0.744 \pm 0.027(\text{stat})]$ GeV$^2/c^2$, $|\tilde{g}_{M1}| = 1.11 \pm 0.12(\text{stat})$, $|g_{\rm CR}| = 0.163 \pm 0.014(\text{stat})$, and $\frac{|g_{E1}|}{|g_{M1}|} \le 0.028$ (upper limit due to statistical uncertainty only). The correlation ($\rho = 0.924$) between a_1/a_2 and $|\tilde{g}_{M1}|$ was allowed for in the errors.

The asymmetry in the $\sin\phi\cos\phi$ distribution shown in Fig. 3(a) was determined to be $[23.8 \pm 1.4(\text{stat})]\%$ before acceptance corrections. Using the fit of the model of Ref. [1] to the data to determine the acceptance, an asymmetry integrated over the entire $K_L \to \pi^+\pi^-e^+e^-$ phase space of $[13.6 \pm 1.4(\text{stat})]\%$ was obtained, the largest such CP-violating effect yet observed in kaon decay. Possible sources of false asymmetries were considered including those due to backgrounds and asymmetries in the detector. To check for detector asymmetries, a sample of 15×10^6 $K_L \to \pi^+\pi^-\pi^0_D$ decays (which are expected to have no ϕ asymmetry and which have similar topology to $K_L \to \pi^+\pi^-e^+e^-$ except for the presence of an extra photon in the CsI) was examined, and an asymmetry of $(3.3 \pm 2.6) \times 10^{-4}$ was measured.

Systematic errors on a_1/a_2, $|\tilde{g}_{M1}|$, $|g_{\rm CR}|$, and $\frac{|g_{E1}|}{|g_{M1}|}$ due to several sources are shown in Table I. The dominant systematic error is due to the variation of the fitted parameters resulting from varying the physics cuts used to select the $K_L \to \pi^+\pi^-e^+e^-$ data and Monte Carlo events and repeating the fit procedure. Some analysis cut variations significantly increased the level of backgrounds to the $K_L \to \pi^+\pi^-e^+e^-$ mass peak. These cuts were separated from the other physics cuts and are labeled as "background" in Table I. Finally, input parameters to the Monte Carlo such as η_{+-}, Φ_{+-} and the strong interaction $\pi^+\pi^-$ phases shifts $\delta_{0,1}$ that were not included in the likelihood fit were varied by $\pm 1\sigma$ of their published values to determine the uncertainty in the fit parameters due to their uncertainties. The systematic errors in the ϕ asymmetry due to several sources are given in Table I below. The physics cut variations and background systematics of the ϕ angle asymmetry have been determined as discussed above. The η_{+-}, Φ_{+-}, and $\delta_{0,1}$ systematics were obtained using the $\pm 1\sigma$ uncertainties in these parameters. Additional uncertainties of the asymmetry due to the one σ uncertainties of the fitted parameters were included. Individual systematic errors were added in quadrature to get the total systematic errors.

In conclusion, the KTeV Collaboration measured a charge radius coupling $|g_{\rm CR}| = 0.163 \pm 0.014(\text{stat}) \pm 0.023(\text{syst})$ which was used to obtain, in a novel way [1], a K^0 charge radius of $[-0.077 \pm 0.007(\text{stat}) \pm 0.011(\text{syst})](fm^2)$, consistent with measurements of the K^0 charge radius [10–12] obtained in K^0 electron scattering and from a similar measurement by NA48 [5]. We set the first experimental upper limit on the presence of $E1$ direct photon emission in $K_L \to \pi^+\pi^-e^+e^-$ decays of $\frac{|g_{E1}|}{|g_{M1}|} < 0.04$ (90% C.L.). In addition, the $M1$ photon emission coupling was measured to be $|\tilde{g}_{M1}| = 1.11 \pm 0.12(\text{stat}) \pm 0.08(\text{syst})$ plus a vector form factor as given in Eq. (2) with $a_1/a_2 = [-0.744 \pm 0.027(\text{stat}) \pm 0.032(\text{syst})]$ GeV$^2/c^2$. Using a_1/a_2 and $|\tilde{g}_{M1}|$, an average $|g_{M1}|$ over the range of E_{γ^*} was calculated to be 0.74 ± 0.04. Finally, we measured a large CP-violating asymmetry in T-odd angle ϕ of $[13.6 \pm 1.4(\text{stat}) \pm 1.5(\text{syst})]\%$ consistent with the theoretically expected asymmetry of Refs. [1,2] and with our original result [4] and a later measurement by NA48 [5].

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