Radiative Decay Width Measurements of Neutral Kaon Excitations Using the Primakoff Effect

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We use K_L's in the 100–200 GeV energy range to produce 147 candidate events of the axial vector pair $K_1(1270)$-$K_1(1400)$ in the nuclear Coulomb field of a Pb target and determine the radiative widths $\Gamma(K_1(1400) \to K^0 + \gamma) = 280.8 \pm 23.2(\text{stat}) \pm 40.4(\text{syst})$ keV and $\Gamma(K_1(1270) \to K^0 + \gamma) = 73.2 \pm 6.1(\text{stat}) \pm 28.3(\text{syst})$ keV. These first measurements appear to be lower than the quark-model predictions. We also place upper limits on the radiative widths for $K^*(1410)$ and $K_2^*(1430)$ and find that the latter is vanishingly small in accord with SU(3) invariance in the naive quark model.

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The rates of radiative transitions between mesons are sensitive to the magnetic moments of the constituent quarks [1]. The radiative decay widths of mesonic excitations, $\Gamma_r(M^*) = \Gamma(M^* \to M + \gamma)$, have been calculated using both a dynamic quark model [2] and a relativistic quark model [3,4]. Figure 1 is a schematic representation of the spin-parity and mass assignments [5] of the low-lying excitations of the neutral kaon. Only $\Gamma_r(K^*(892))$ has been measured thus far [6].

Since the radiative decay widths of strange mesons are much smaller than the total widths, direct observation of decays such as $K^* \to K + \gamma$ is difficult. However, the inverse reaction $K + \gamma \to K^*$ is experimentally accessible as a subreaction of the process $K_L + \text{Nucleus} \to K^* + \text{Nucleus}$ and can be used to measure the radiative width. This Coulomb process is also known as Primakoff production [7].

In this Letter, we describe the observation of 147 Primakoff-produced candidate events of the mixed axial vector pair $K_1(1270)$-$K_1(1400)$ by reconstructing the decay sequence [5,6] $K_1(1270/1400) \to K^*(892)\pi^0 \to [K_S\pi^0]\pi^0 \to [(\pi^+\pi^-)(\gamma\gamma)](\gamma\gamma)$. We call this six-body channel the $K^*(892)\pi^0$ channel. The 147 event sample is used to measure the radiative widths $\Gamma_r(K_1(1400))$ and $\Gamma_r(K_1(1270))$ for the first time. We also place upper limits on the radiative widths for the vector $K^*(1410)$ and the tensor $K_2^*(1430)$ by studying the four-body $K_S\pi^0$ channel [5,6]: $K^*(1410)/K_2^*(1430) \to K_S\pi^0 \to (\pi^+\pi^-)(\gamma\gamma)$.

For high particle energies and small production angles, the rate of exciting a K_L in the Coulomb field of a nucleus

A is given by [8]

$$\frac{d\sigma}{dt}(K_L + A \rightarrow K^* + A) = \pi \alpha Z^2 \left(\frac{2S_{K^*} + 1}{2S_K + 1} \right) \frac{\Gamma(K^* \rightarrow K + \gamma)}{k^3} \frac{t'}{t^2} |f_{\mathrm{EM}}|^2, \tag{1}$$

where α is the fine structure constant, Z is the atomic number of the nucleus, S_K and S_{K^*} are the spins of K_L and the generic excited state K^*, respectively, $k = (m_{K^*}^2 - m_K^2)/2m_{K^*}$, t is the magnitude of the square of the momentum transfer, and $t' = t - t_{\min}$, $\sqrt{t_{\min}} = (m_{K^*}^2 - m_K^2)/2P_K$, where P_K is the laboratory momentum of the K_L. Finally, f_{EM} is the nuclear electric form factor corrected for absorption and has an approximate form $f_{\mathrm{EM}} \approx e^{(-R^2/4)t'}$, where R is the nuclear radius ($= 33.6\ \mathrm{GeV}^{-1}$ for lead [6]). Thus, the rate of Primakoff production is directly proportional to the radiative width. Since $t_{\min}$ is very small for $P_K \sim 100$ GeV, the production has an approximate t^{-1} dependence; i.e., the excitations are produced predominantly in the forward direction and are thus readily isolated from other modes of production.

We use the full data set collected during the 1996–1997 run of the KTeV experiment at Fermilab in this analysis. KTeV utilized an 800 GeV/c proton beam to generate two neutral beams consisting of kaons, neutrons, and some hyperons. In the E832 configuration [9], one of the beams passed through a regenerator which was located ~124 m from the target. The regenerator consisted of 84 modules of 2 cm thick plastic scintillator followed by a module composed of two 6 mm lead pieces alternating with two 4 mm scintillator pieces. While Primakoff production took place all through the regenerator, more than 98% of the observed decays were produced in the final lead pieces because photons from upstream decays were mostly lost to conversion in the regenerator. The regenerator was instrumented with photomultiplier tubes which enabled us to tag and reject backgrounds from inelastic interactions.

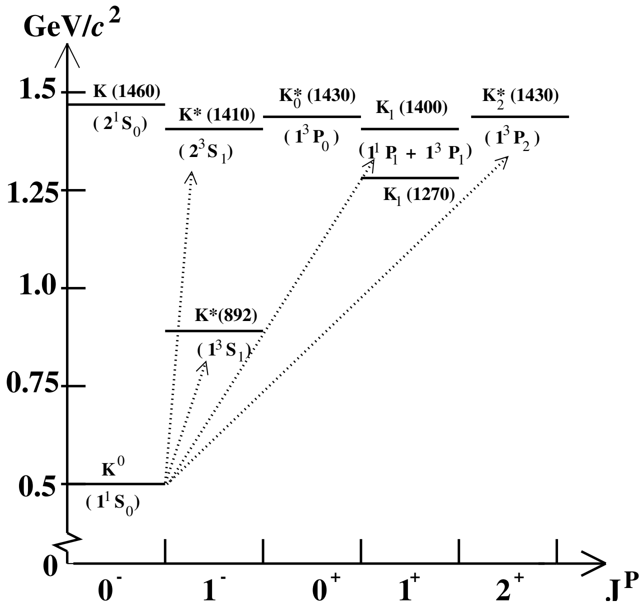

FIG. 1. Mass vs angular momentum and parity (J^P) for neutral kaon resonances. Arrows indicate resonances accessible by Primakoff excitation.

We detected $\pi^+\pi^-$ tracks from K_S decays using a drift chamber spectrometer system and photons from π^0 decays using a pure CsI electromagnetic calorimeter. The event trigger was initiated by signals from two scintillator hodoscopes located downstream of the spectrometer and required hits in the drift chambers consistent with two oppositely charged tracks. The decay volume was surrounded by a near-hermetic set of devices to veto photons.

In the offline analysis, the fiducial volume for the decay vertex of $K_S \rightarrow \pi^+\pi^-$ is restricted to a 15 m region downstream of the regenerator. We reconstruct π^0's using pairs of energy clusters in the calorimeter. The clusters are required to have energies greater than 1 GeV and photon-like spatial distributions. To reject electrons, we require that the ratio of energy deposited in the calorimeter to the particle momentum as measured by the spectrometer be <0.8. The π^0 and K_S decays are reconstructed by requiring the $\gamma\gamma$ and the $\pi^+\pi^-$ invariant masses to be within 10 MeV/c^2 of the π^0 and K_S nominal masses, respectively.

After reconstructing the π^0's and the K_S's, we are in a position to inspect the four-body $K_S\pi^0$ channel for the $K^*(892)$ and other excitations. We isolate forward production by demanding that the square of the transverse momentum (p_t^2) of the $\pi^+\pi^-\gamma\gamma$ with respect to a line connecting the target and the decay vertex of $K^*(892)$ be less than 0.001 (GeV/c)^2. We further require $\pi^+\pi^- p_t^2 >$ 0.010 (GeV/c)^2 because the daughter K_S recoils against the π^0. The resulting sample of 29 399 $K^*(892) \rightarrow K_S\pi^0$ decays with K_S energy between 30 and 210 GeV and the $K^*(892)$ energy between 55 and 225 GeV is shown in Fig. 2(a). We use this large sample of $K^*(892)$ decays for normalization purposes in measuring radiative widths of higher excitations.

The requirements for the six-body $K^*(892)\pi^0$ channel are similar, except for changes to account for the extra π^0 and differences in kinematics. The photon pairings for the two π^0's are determined using a χ^2 formed by comparing $M_{\gamma\gamma}$ and $M_{\pi^+\pi^-\gamma\gamma}$ to the known masses of π^0 and $K^*(892)$, respectively. The $K_S\pi^0$ mass for the daughter $K^*(892)$ is required to be within 101 MeV/c^2 (twice the Breit-Wigner width) of the $K^*(892)$ mass and its p_t^2 to be >0.030 (GeV/c)^2. To eliminate events in which two kaons decay to a charged and a neutral pion pair, we remove events for which the four-photon invariant mass is within 20 MeV of the K_L mass. The resulting sample of $(K_S\pi^0)\pi^0$

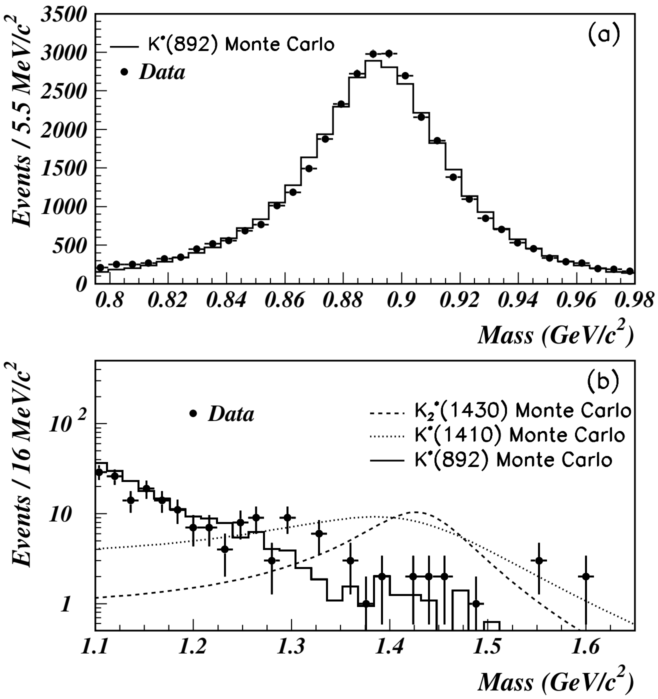

FIG. 2. (a) $K_S\pi^0$ invariant mass in the four-body channel showing $K^*(892) \to K_S\pi^0$ decays. (b) The same $K_S\pi^0$ invariant mass in the 1.4 GeV/c^2 region. $K_2^*(1430)$ and $K^*(1410)$ Monte Carlo simulations are also shown to arbitrary scale. No $K_2^*(1430)$ or $K^*(1410)$ resonance is apparent.

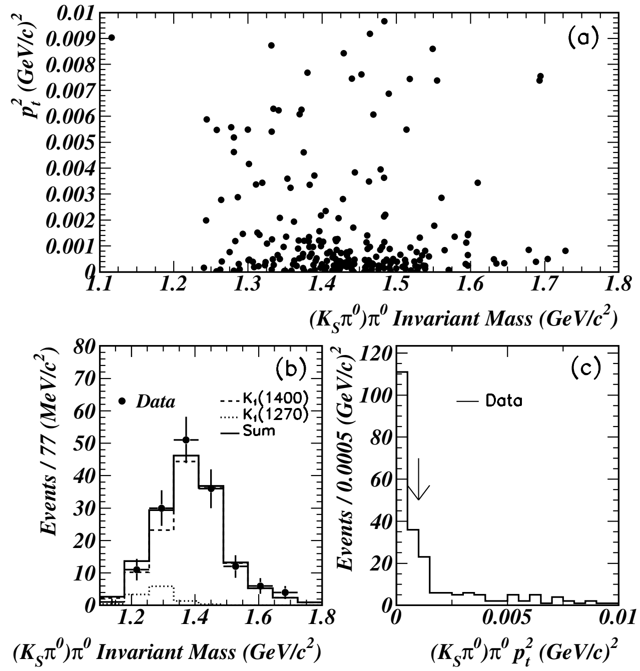

FIG. 3. (a) $[K^*(892)\pi^0]$ p_t^2 vs invariant mass after all other cuts. (b) Projection onto the abscissa after the p_t^2 cut. Decomposition of the observed signal into $K_1(1270)$ and $K_1(1400)$ is also shown. (c) Projection onto the ordinate after the mass cut. Note the sharply forward nature of Primakoff production. We discard events to the right of the arrow.

decays with total energy greater than 90 GeV is depicted in Fig. 3 and shows a clustering near 1.4 GeV/c^2. The mass projection shows the resonant signature exhibited by events with $p_t^2 < 0.001$ $(\mathrm{GeV}/c)^2$ and the p_t^2 projection shows the sharp falloff away from the forward direction confirming Primakoff production. There are 147 events within the mass fiducial region (1.10–1.64 GeV/c^2). Figure 4 shows the invariant mass and p_t^2 of the daughter $K^*(892)$ where the p_t^2 displays a Jacobian distribution expected of a daughter particle in a two-body decay.

We now turn to the identification of the observed $K^*(892)\pi^0$ resonance. Of the six possible candidates (see Fig. 1), $K_0^*(1430)$ and $K(1460)$ are ruled out because of spin-parity conservation and the $J = 0 \not\to J = 0$ selection rule, respectively. Contributions from the vector $K^*(1410)$ and tensor $K_2^*(1430)$ can be eliminated because both have significant branching fractions to $K_S\pi^0$ [5], yet we see no evidence for their presence in the $K_S\pi^0$ channel; note the lack of resonance near 1.4 GeV/c^2 in Fig. 2(b). We fit a combination of $K^*(892)$ and $K^*(1410)$ or $K_2^*(1430)$ simulations to the data and confirm that the signal from $K^*(1410)$ and $K_2^*(1430)$ in the $K_S\pi^0$ channel is consistent with zero and, using the known branching fractions [5] of the two excitations to the two channels, infer a negligible 2.4 ± 3.6 $[0.0 \pm 0.7]$ event contribution of $K^*(1410)$ $[K_2^*(1430)]$ to the observed signal in the $K^*(892)\pi^0$ channel. With all other possibilities thus eliminated, we conclude that the observed resonant signal in the $K^*(892)\pi^0$ channel is from the axial vector pair $K_1(1270)$-$K_1(1400)$.

We now discuss the potential sources of backgrounds in the signal. Primakoff production is characterized by a sharp ($\sim t^{-1}$) forward production [Eq. (1)] allowing a strict $p_t^2 < 0.001$ $(\mathrm{GeV}/c)^2$ cut which virtually eliminates all potential backgrounds; see Fig. 3. Based on an extrapolation from the large p_t^2 $[> 0.100$ $(\mathrm{GeV}/c)^2]$ region, we estimate 1.2 events out of 147 signal candidate events to be due to incoherent production and other possible backgrounds such as those from the decay products of the Λ's and ϕ's produced when neutrons in the beam interact with the regenerator. Coherent strong production and its interference with Primakoff production are expected to be small at our energies [6]. Indeed, a maximum likelihood fit in the p_t^2 variable for the strong production and the strength of the strong-Coulomb interference using the prescription given in [6,10] indicates that the strength of interference preferred by our data is consistent with zero. The mean change in our estimate of Primakoff production corresponding to 1 standard deviation variation in the interference strength is 8.7%, which we take to be the uncertainty due to strong production.

Finally, it is necessary to decompose the observed signal into the individual components of the mixed vector pair before the radiative widths can be computed. This task is

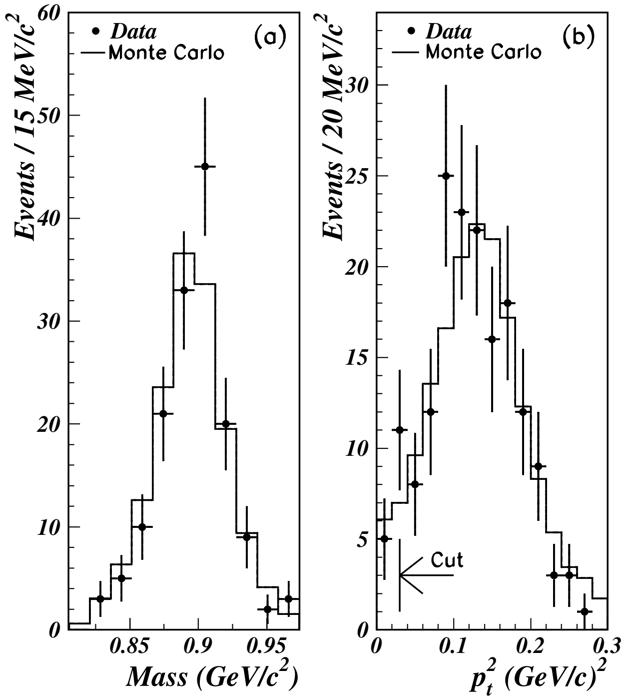

FIG. 4. Data/MC comparisons for the $K_S\pi^0$ invariant mass (a) and the p_t^2 for the observed $K_1(1270) - K_1(1400) \to K^*(892)\pi^0$ signal (b). A Jacobian distribution in p_t^2 indicates the recoil of the daughter $K^*(892)$ against the π^0. We discard events to the left of the arrow.

difficult because the $K_1(1270)$-$K_1(1400)$ mass separation is comparable to their widths and our event sample is relatively small. Nonetheless, mass information alone tells us that there are only 8.8 ± 8.6 $K_1(1270)$ events in the sample. However, a more precise decomposition is possible indirectly. The vector pair is a mixture (see Fig. 1) of the singlet ${}^1P_1$ and the triplet ${}^3P_1$ states [11], parametrized by the mixing angle Θ: $K_1(1270) = -{}^3P_1 \sin\Theta + {}^1P_1 \cos\Theta$ and $K_1(1400) = {}^3P_1 \cos\Theta + {}^1P_1 \sin\Theta$. The Coulomb field excites only the singlet component [12] and the mixing angle has been measured to be $56° \pm 3°$ [13]. Using this value and the known branching ratios of $K_1(1270)$ and $K_1(1400)$, we resolve the observed signal into $11.4 \pm 1.0(\text{stat}) \pm 4.1(\text{ext syst})$ $K_1(1270)$ events and $134.4 \pm 11.1(\text{stat}) \mp 4.1(\text{ext syst})$ $K_1(1400)$ events, where the (external) systematic error is due to the measurement uncertainties in the mixing angle and the $K_1(1270)$ and $K_1(1400)$ branching fractions to the $K^*(892)\pi^0$ channel. This decomposition is depicted in Fig. 3.

We now compute the radiative widths using the large $K^*(892)$ sample (Fig. 2) for normalization since $\Gamma_r(K^*(892))$ is known [6]. We separately integrate Eq. (1) for the signal and normalization states, allowing for the dependence of $t_{\min}$ on the kaon laboratory momentum P_K. The detector acceptance is evaluated using a detailed Monte Carlo simulation that incorporates the resonant line shapes of the excited states and the dependence of the Primakoff production on kaon momentum via the momentum dependence of $t_{\min}$. We use the relativistic Breit-Wigner form identical to the one used for the $K^*(892)$ radiative width measurement [6] to allow for the varying mass of the excited states. The results of the simulation overlayed with data histograms in Figs. 2 and 3 show satisfactory agreement. Finally, since the signal and normalization modes have a different number of photons in the final state, a correction is made for the difference in event loss to photon conversion in the regenerator. This correction factor (1.97) is very close to the ratio of the number of photons in the two final states because the regenerator is thick in terms of radiation lengths. After accounting for these differences in the signal and normalization modes, we obtain $\Gamma_r(K_1(1270)) = 73.2 \pm 6.1(\text{stat}) \pm 8.2(\text{int syst}) \pm 27.0(\text{ext syst})$ keV and $\Gamma_r(K_1(1400)) = 280.8 \pm 23.2(\text{stat}) \pm 31.4(\text{int syst}) \pm 25.4(\text{ext syst})$ keV, where the measurements share internal systematic errors of 8.7% due to the strong production uncertainty, 6.6% due to detector acceptance effects, and 2.4% due to the 3.6 event uncertainty in the possible contributions from $K^*(1410)$ and $K_2^*(1430)$, as discussed earlier. The uncertainty in the $K^*(892)$ radiative width (normalization) measurement [6] causes an additional 8.5% (external) systematic error.

Earlier, we used the absence of a resonance in the $K_S\pi^0$ channel near 1.4 GeV$/c^2$ (Fig. 2) to limit the $K^*(1410)$ and $K_2^*(1430)$ contributions to the observed $K_1(1270)$-$K_1(1400)$ signal. A further benefit of this finding is that we are able to limit the radiative widths $\Gamma_r(K^*(1410))$ and $\Gamma_r(K_2^*(1430))$ to 52.9 and 5.4 keV, respectively, at 90% C.L. $\Gamma_r(K^*(1410))$ has not been examined experimentally before, whereas $\Gamma_r(K_2^*(1430))$ was previously limited to 84 keV at 90% C.L. [6].

The predicted radiative widths for the axial vector mesons [14] are 538 keV for $K_1(1400)$ and 175 keV for $K_1(1270)$; compare to our results, 280.8 ± 46.6 keV and 73.2 ± 28.9 keV, respectively. While the measured values appear to be on the smaller side, it should be noted that the predictions [14] are given without uncertainties. Our 90% C.L. upper limit on the vector $K^*(1410)$ radiative width is 52.9 keV. There is no prediction for the radiative width of this state. In the naive quark model, $K^*(1410)$ is the first radial excitation of $K^*(892)$, for which $\Gamma_r(K^*(892)) = 116.5 \pm 9.9$ keV [6]. Finally, we have substantially improved the upper limit on the radiative width of the tensor $K_2^*(1430)$ from 84 keV [6] to 5.4 keV (at 90% C.L.). Babcock and Rosner [12] used SU(3) invariance to predict that excitations with $J^{PC} = 1^{++}$ or 2^{++} would have vanishing radiative widths. In the limit of SU(3), $K_2^*(1430)$ has $C = +1$; thus, our limit lends support to Babcock and Rosner's prediction and serves as a direct test of the naive quark model and SU(3)-breaking.

In conclusion, we have used the Primakoff effect to measure the radiative widths for the mixed axial vector pair $K_1(1270)$-$K_1(1400)$ and placed an upper limit on the radiative width for $K^*(1410)$. These radiative widths have been studied for the first time. We also find that the radiative width for $K_2^*(1430)$ is vanishingly small, as anticipated on the basis of SU(3) invariance in the naive quark model.

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