

## Measurement of the $K^{0*}(896)$ Radiative Width

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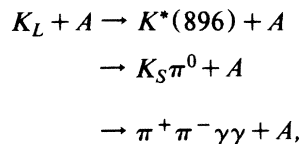
Primakoff production of the  $K^{0*}(896)$  by incident  $K_L$ 's was observed in the energy range 100–200 GeV. Production from Cu and Pb targets was measured simultaneously leading to a new value for the  $K^{0*}(896)$  radiative width  $\Gamma(K^{0*}(896) \rightarrow K^0 + \gamma)$  of  $116.5 \pm 9.9$  keV. The result agrees with a previous determination while being considerably more precise and allows for more stringent tests of quark-model relations among the radiative widths of the low-lying vector mesons.

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Becchi and Morpurgo,<sup>1</sup> in 1965, were the first to point out that the rates for magnetic dipole radiative decays of vector mesons to pseudoscalar mesons [ $(J^P=1^-) \rightarrow (J^P=0^-) + \gamma$ ] are sensitive to the magnetic moments of the constituent quarks and are accessible to experiment. The radiative widths of a number of low-lying vector mesons have since been measured and analyzed in terms of quark models in an effort to understand the nature of light-quark magnetic moments inside hadrons.<sup>2</sup> We report a new measurement of the radiative width  $\Gamma(K^{0*}(896) \rightarrow K^0 + \gamma)$ .

A previous experiment<sup>3</sup> which studied the angular distribution of  $K_S$  mesons produced in the coherent scattering of high-energy  $K_L$  mesons from a high- $Z$  target is relevant here. Although regeneration provides the largest source at small angles, Molzon<sup>4</sup> has shown that the dominant mechanism at large angles is actually the Primakoff production<sup>5</sup> of the  $K^{0*}(896)$  meson followed by its subsequent decay to  $K_S\pi^0$ . This observation provided the basis for the current work.

The radiative width was determined from the cross section for the process



where  $A$  denotes the nucleus. This reaction proceeds according to the Primakoff mechanism though the subreactions  $K^0 + \gamma \rightarrow K^{0*}(896)$  and  $\bar{K}^0 + \gamma \rightarrow \bar{K}^{0*}(896)$  in which the  $K^0$  and  $\bar{K}^0$  components of an incident  $K_L$  absorb a virtual photon from the electromagnetic field of the nucleus. The amplitudes for the production of the  $K^{0*}(896)$  and the  $\bar{K}^{0*}(896)$  have opposite sign and thus lead exclusively<sup>4</sup> to the

$K_S\pi^0$  final state, as opposed to  $K_L\pi^0$ .

The (single-photon exchange) differential production cross section is proportional to the radiative width and, in the narrow-resonance approximation, may be expressed<sup>6</sup> as

$$\begin{aligned} \frac{d\sigma}{dt}(K_L + A \rightarrow K^* + A) \\ = 3\pi\alpha Z^2 \frac{\Gamma(K^* \rightarrow K\gamma)}{k^3} \frac{t - t_{\min}}{t^2} |F_{\text{em}}(t)|^2, \end{aligned}$$

where  $\alpha$  is the fine-structure constant,  $Z$  is the atomic number of the target nucleus, and  $k$  is the rest-frame decay momentum in the transition  $K^* \rightarrow K\gamma$ . The four-momentum transfer,  $t$ , has a minimum value  $t_{\min} \simeq [(m^{*2} - m^2)/2P_{\text{lab}}]^2$ , where  $m$  and  $m^*$  are the masses of the  $K_L$  and  $K^{0*}$ , respectively, and  $P_{\text{lab}}$  is the beam momentum. The form factor  $F_{\text{em}}$  is the nuclear electric form factor corrected for absorption. Coherent strong production<sup>7</sup> contributes a background characterized by a differential cross section of the form

$$\frac{d\sigma}{dt}(K_L + A \rightarrow K^* + A) = C_{\text{str}}(t - t_{\min}) |F_{\text{str}}(t)|^2,$$

where  $F_{\text{str}}$  is a nuclear form factor and  $C_{\text{str}}$  is a normalization factor expected to fall roughly as  $1/P_{\text{lab}}$ . The electromagnetic and strong amplitudes add coherently and interference will occur. The radiative width was obtained by a fit to the observed differential cross section which exploited the difference in the momentum-transfer dependence of the two amplitudes. The analysis technique was similar to that used by Carithers *et al.*<sup>8</sup> in an earlier measurement of the  $K^{0*}(896)$  radiative width and will be described below. In contrast to this previous experiment, the strong-production background in our measurement was almost negligible, primarily as a result of the significantly higher beam

energy.

The experiment was performed in the M3 neutral beam line at Fermilab with a spectrometer which was developed to study  $CP$ -nonconserving  $K_L$  decays.<sup>9</sup> The  $K_L$  mesons were produced by 400-GeV protons incident upon a beryllium target. Collimators and sweeping magnets were used to produce two side-by-side neutral beams each subtending a solid angle of about  $4 \times 10^{-8}$  sr. At a distance of 406 m from the primary proton target, copper and lead targets (0.635 cm thick) were placed in the adjacent beams. The use of two target materials in dual beams provided a check of the atomic-number dependence of the Primakoff production cross section by a simultaneous measurement of the two cross sections. Thin scintillation veto counters, situated just downstream of the  $K^*$ -production targets, suppressed the interactions of neutrons in the beam. These counters were followed by a 13-m-long evacuated decay volume. The charged pions were detected with a drift-chamber spectrometer while the photons were detected in an 804-element lead-glass array. Simultaneous observation of beam decays of the type  $K_L \rightarrow \pi^+ \pi^- \pi^0$  provided the flux normalization.

Candidates for Primakoff production were isolated by applying kinematic constraints to events which contained two charged tracks in the drift chambers and two photon energy clusters in the lead-glass. Under the assumption that the charged particles were pions,

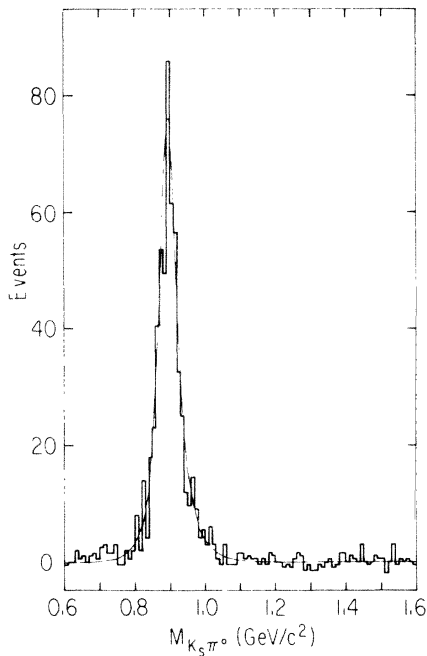


FIG. 1. Background-subtracted  $K_S \pi^0$  mass distribution for events with  $t' < 0.01$   $(\text{GeV}/c)^2$  from both the copper and lead targets. A fit by a distorted relativistic  $p$ -wave Breit-Wigner line shape is superimposed (solid curve).

the invariant mass of the pair was required to be within  $30 \text{ MeV}/c^2$  of the  $K_S$  mass. The three-momentum vector of the  $K_S$  was extrapolated through the reconstructed  $K_S$  decay vertex to the  $K^*$ -production target to determine the production point. The momentum vectors of the photons were constructed by use of this production point and the positions and energies of the photons at the lead-glass. The two-photon invariant mass was then calculated and required to be within  $15 \text{ MeV}/c^2$  of the  $\pi^0$  mass. The measured mass resolutions were  $4.2$  and  $3.8 \text{ MeV}/c^2$  for the  $K_S$  and  $\pi^0$ , respectively.

Primakoff production is characterized by a strong peak in the angular distribution close to the forward direction. In Fig. 1, the  $K_S \pi^0$  invariant-mass distribution is shown for  $K^*$  candidates with  $t' < 0.01$   $(\text{GeV}/c)^2$  from both targets, where  $t' = t - t_{\text{min}}$  is approximately equal to the square of the transverse component of the three-momentum transfer. A small ( $\sim 5\%$ ) smoothly varying background under the mass peak, resulting from neutron interactions, has been subtracted; it was estimated by use of events with  $\pi^+ \pi^-$  invariant mass outside the allowed  $K_S$  mass range. The event totals for the mass range  $0.8$ – $1.0 \text{ GeV}/c^2$  were 229 and 355 events for the copper and lead targets, respectively.

Superimposed on the mass distribution in the figure is the result of a fit by a relativistic  $p$ -wave Breit-Wigner line shape, distorted by the production process

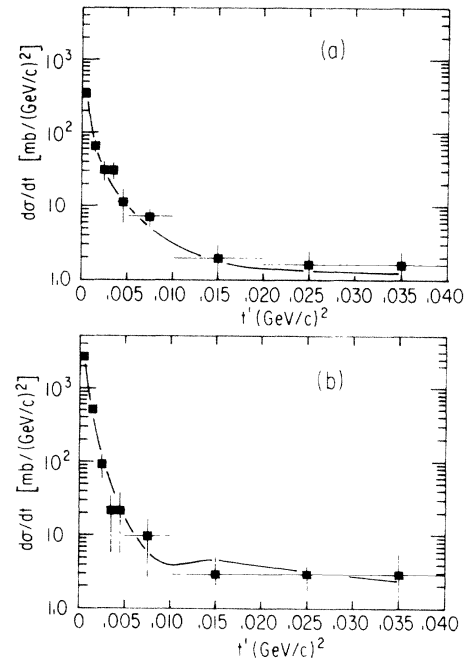


FIG. 2. Fully corrected  $t'$  distributions for the (a) copper and (b) lead targets for events with  $K_S \pi^0$  invariant mass in the range  $0.8$ – $1.0 \text{ GeV}/c^2$  with fits superimposed (solid curves).

and by the spectrometer resolution.<sup>10</sup> (An rms mass resolution of 10.6 MeV/c<sup>2</sup> was deduced from a Monte-Carlo simulation.) The fit gave a mass of  $896.4 \pm 0.6$  MeV/c<sup>2</sup> and a width of  $49.8 \pm 1.4$  MeV/c<sup>2</sup>, in good agreement with the world-average values.<sup>11</sup>

In order to extract the radiative width, the  $t'$  distributions for events in the  $K_S\pi^0$  mass range were corrected for empty-target background and acceptance, and then normalized by the measured incident flux to form energy-averaged differential cross sections. As shown in Fig. 2, the forward peak expected for Primakoff production was evident. When strong production is included, the differential cross section may be expressed as

$$d\sigma/dt' = |T_{\text{em}}(t) + e^{i\phi}T_{\text{str}}(t)|^2 + d\sigma_{\text{incoh}}/dt',$$

where  $T_{\text{em}}$  is the Primakoff amplitude [proportional to  $[\Gamma(K^{0*} \rightarrow K^0\gamma)]^{1/2}$ ],  $T_{\text{str}}$  is the coherent strong production amplitude [proportional to  $(C_{\text{str}})^{1/2}$ ], and  $\phi$  is their relative phase. The two amplitudes were expressed in an optical model to account for the effect of nuclear absorption.<sup>12</sup> The contribution of incoherent processes was assumed to have a weak  $t'$  dependence given by  $d\sigma_{\text{incoh}}/dt' = a_A e^{-bt'}$ , where  $a_A$  is a normalization constant and  $b = 8$  (GeV/c)<sup>-2</sup>.

Fits to the differential cross sections were performed with allowance for an rms  $t'$  resolution of 0.00010 (GeV/c)<sup>2</sup> as deduced from the Monte Carlo simulation. The result of a five-parameter simultaneous fit to the cross sections for the two targets is shown superimposed as curves on Fig. 2. The parameters of the fit were the radiative width  $\Gamma(K^{0*} \rightarrow K^0\gamma)$ , the strong-production normalization constant  $C_{\text{str}}$ , the phase  $\phi$ , and two independent normalizations for the incoherent contributions  $a_A$ . The radiative width as determined from this fit was  $116.5 \pm 5.7$  (statistical) keV. Similar fits to the data for the two targets separately resulted in the values  $110.5 \pm 8.8$  keV and  $120.7 \pm 7.2$  keV for the copper and lead targets, respectively. The other parameters were not well determined as a consequence of the limited statistical power of the data sample and of the relatively small size of the backgrounds. [The contribution of the terms other than the pure Coulomb term is  $< 3\%$  for  $t' < 0.01$  (GeV/c)<sup>2</sup>.] Fits were performed in which  $C_{\text{str}}$ , at an incident energy of 150 GeV, was varied from zero to the value 0.52 mb/GeV<sup>4</sup> given by extrapolation<sup>13</sup> from 12 GeV (Ref. 8). The phase was varied through all angles, and the incoherent contributions were varied from zero to the values necessary to reproduce the cross sections at large  $t'$ . In no case did the resulting value for the radiative width change by more than 4.5 keV. As the energy dependence of  $C_{\text{str}}$  is not well known, the extrapolation of the strong-production amplitude over an order of magnitude in energy may be unreliable. Moreover, only

odd-charge-conjugation-parity exchanges contribute to the  $K_S\pi^0$  channel while even-parity exchange may have contributed in Ref. 8 in which the charged decays  $K^{0*} \rightarrow K^+\pi^-$  and  $\bar{K}^{0*} \rightarrow K^-\pi^+$  were observed. The result of the unconstrained fit for the radiative width was therefore adopted. The final result was, however, quite insensitive to this choice.

The fits to the differential production cross sections confirmed our expectation that the strong-production contribution was relatively small. This was corroborated by the energy dependence of the total production cross section. In Fig. 3 the integral of the production cross section over the  $t'$  range 0.0–0.01 (GeV/c)<sup>2</sup> is shown as a function of energy for the two targets. The logarithmic energy dependence expected for Primakoff production is superimposed.

A number of possible sources of systematic error in the radiative width were considered. The systematic error was dominated by the uncertainty in the flux normalization (6%). A 3% error resulted from uncertainties in the optical-model parameters and was dominated by uncertainty in the neutron mean radius to which the absorption correction is sensitive. Smaller uncertainties were associated with the  $t'$  resolution and assumptions about the form of the mass line shape.

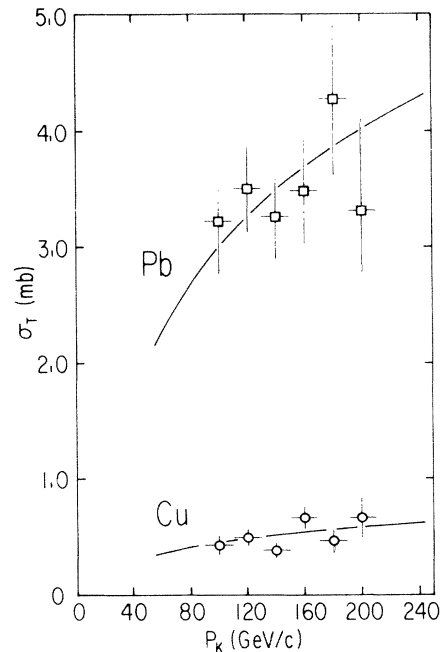


FIG. 3. Energy dependence of the  $K^*$  production cross section integrated from  $t'=0$  to 0.01 (GeV/c)<sup>2</sup> for the copper and lead targets. The logarithmic energy dependence expected for Primakoff production is shown by the solid curves. The relative normalization of the two curves is fixed by the atomic-number dependence of the Primakoff production cross section.

The combined systematic error in the radiative width was 8.1 keV. Adding systematic and statistical errors in quadrature gives a final result for the radiative width of the  $K^{0*}(896)$  of  $116.5 \pm 9.9$  keV. The result is in good agreement with the value  $75 \pm 35$  keV reported in Ref. 8.

In the naive quark model, the radiative width is given by<sup>14</sup>

$$\Gamma(K^{0*} \rightarrow K^0 \gamma) = \frac{4}{3} k^3 \frac{(m^2 + k^2)^{1/2}}{m^*} (\mu_s + \mu_d)^2 |I|^2,$$

where  $\mu_s$  and  $\mu_d$  are the magnetic moments of the strange and down quarks, respectively, and  $I$  is the overlap integral of the spatial wave functions of the  $K^0$  and  $K^{0*}$ . The quark moments may be deduced<sup>2</sup> from the measured proton, neutron, and lambda magnetic moments; the above expression then yields, with the assumption of  $I=1$ , the value of 126 keV for the radiative width. The good agreement with the experimental result reported here should be qualified since there exists a variety of predictions,<sup>14</sup> for  $\Gamma(K^{0*} \rightarrow K^0 \gamma)$  ranging between 50 and 250 keV, using different quark models and unitary symmetries. However, predictions for the *ratio* of the widths of the neutral and charged  $K^*$  mesons are less model dependent in that the relativistic phase space and spatial overlap factors should cancel to high order. The ratio can be expressed then in terms of the quark moments alone:

$$\frac{\Gamma(K^{0*} \rightarrow K^0 \gamma)}{\Gamma(K^{+*} \rightarrow K^+ \gamma)} = \left( \frac{\mu_s + \mu_d}{\mu_s + \mu_u} \right)^2.$$

If we define  $\mu_q = e_q/2m_q$ , where  $e_q$  and  $m_q$  are the quark charges and masses, respectively, the above ratio has the value 4.0 in the SU(3) limit (all quark masses equal). This is clearly different from the experimental value of  $2.28 \pm 0.29$ , where the recently measured<sup>15</sup>  $K^{+*}(892)$  radiative width has been used, strongly indicating that the magnetic moment of the strange quark should be reduced relative to that of the up and down quarks. If we again take the quark moments as deduced from the  $p$ ,  $n$ , and  $\Lambda$  moments, the value of 1.64 is predicted for the above ratio, where the effective quark masses are  $m_u = 337$  (MeV/c)<sup>2</sup>,  $m_d = 322$  (MeV/c)<sup>2</sup>, and  $m_s = 510$  (MeV/c)<sup>2</sup>. While the agreement with the experimental ratio is fair, the remaining discrepancy could in fact either signal configuration mixing<sup>16</sup> in the baryon wave functions or perhaps result from the neglect of the quark sea, or other simplifications<sup>17</sup> inherent in the model. A complete understanding of the vector-meson radiative widths and the baryon magnetic moments still awaits the development of a more refined theory of the static properties of hadronic matter.

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