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THE UNIVERSITY OF ROCHESTER

DEPARTMENT OF PHYSICS AND ASTRONOMY

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Fermi National Accelerator Laboratory, Batavia, Illinois 60510  
 University of Minnesota, Minneapolis, Minnesota 55455  
 University of Rochester, Rochester, New York 14627

Abstract

Coherent production of  $K^0$  systems observed in the excitation of 200 GeV/c positive kaons on nuclear targets has been analyzed, including both electromagnetic and strong contributions, to yield a new value for the radiative width for the process  $K^{*+}(890) \rightarrow K^+\gamma$  of  $51 \pm 5$  keV. This measurement is consistent with a prediction of 46 keV from non-relativistic quark models that include no SU(3) symmetry breaking.

Radiative decays of vector mesons present one of the simplest regimes for testing unitary symmetry schemes and quark models of hadrons. In particular, the decay: vector meson  $\rightarrow$  pseudoscalar meson +  $\gamma$ , which can be interpreted as a magnetic dipole transition between two quark levels, provides a rather sensitive probe of the symmetry of quark-antiquark systems. Much theoretical work has been devoted to the phenomenology of such decays from the viewpoint of unitary symmetry<sup>1</sup>, simple quark models<sup>2</sup>, and vector dominance ideas<sup>3</sup>.

Predictions for the rates  $K^{*+}(890) \rightarrow K^+\gamma$  and  $K^{*0} \rightarrow K^0\gamma$  are independent of octet-singlet mixing within the vector or pseudoscalar nonets. Also, due to the near equality of the  $K^{*+}(K^+)$  and  $K^{*0}(K^0)$  masses, predictions for the ratio of widths  $\Gamma(K^{*0} \rightarrow K^0\gamma)/\Gamma(K^{*+} \rightarrow K^+\gamma)$  are insensitive to final-state phase space factors. Assuming that quark magnetic moments are simply proportional to the quark charges yields a value of 4.0 for this ratio. If we take the quark moments, instead, to be given by values extracted from measurements of baryon magnetic moments<sup>4,5</sup> (i.e. allowing a phenomenological SU(3) symmetry breaking), the ratio becomes 1.64. The absolute predictions for  $K^{*+} \rightarrow K^+\gamma$  range between 46 keV (non-relativistic phase space and exact SU(3)) and 122 keV (for relativistic phase space with SU(3) breaking)<sup>6</sup>.

We have studied the coherent reactions

$$K^+Z \rightarrow K^+\pi^0 Z \quad (1)$$

$$K^+Z \rightarrow K^0\pi^+ Z \quad (2)$$

using 200 GeV/c kaons incident on copper and lead targets. We have extracted the partial width for the decay  $K^{*+}(890) \rightarrow K^+\gamma$  by means of a Primakoff analysis of the inverse reaction  $K^+ + \gamma \rightarrow K^{*+}(890)$ ,<sup>7</sup> where the photon is

supplied by the Coulomb field of the target nucleus. We used copper and lead targets (0.44 and 0.22 radiation lengths thick, respectively) to ensure that we understood the scaling behavior of the Coulomb production of the  $K^+(890)$ , as well as that of the competing strong production mechanism ( $\omega$ -exchange), with nuclear charge  $Z$  and nucleon number  $A$ . Data were also taken without a target in position for performing background (empty-target) subtractions.

We were motivated to study radiative decays through the Primakoff reaction at high energies because the cross section for the coherent excitation of vector mesons in the nuclear Coulomb field (one-photon exchange) grows with incident beam momentum, and that of the background mechanism ( $\omega$ -exchange) falls at least as rapidly as the inverse power of the beam momentum. Consequently, at high energies, the extraction of radiative widths becomes less sensitive to the phenomenology of the nuclear models employed in the analysis<sup>8</sup>.

The total coherent differential cross section can be written as:

$$d\sigma/dt = |T_c + e^{i\phi} T_s|^2$$
, where  $T_c$  and  $T_s$  represent, respectively, the electromagnetic and strong amplitudes, and  $\phi$  is the relative phase. The formalism for calculating  $T_c$  and  $T_s$ , which depend on nuclear form factors, is presented elsewhere<sup>9,10</sup>. For our purposes, we need only say that  $\Gamma(K^+(890) \rightarrow K^+\gamma)$  is proportional to  $|T_c|^2$ , and that  $|T_s|^2$  is proportional to  $C_s$ , a normalization factor for strong coherent production on single nucleons.

The experiment was carried out in a secondary beam at the Meson Detector Building of Fermilab. Three Cherenkov counters were used to tag the pion, kaon and proton fractions of the beam. The kaon fraction was enriched through sequential hadron filtration, using a beryllium absorber<sup>11</sup>, from a nominal value of 2.5% to ~15%. The kaon flux at the experimental target was typically  $4-5 \times 10^4$  K

We utilized a forward high-resolution spectrometer optimized for precision charged-particle tracking and momentum determination, as well as for accurate position and energy measurements of high energy photons.

The detailed lay-out of our spectrometer is presented elsewhere<sup>12</sup>. Two modules of MWPC's, and several small scintillator counters, defined the incident beam. Trajectories of charged particles were determined using two modules of drift chambers in front of, and two modules downstream of, an analyzing magnet. The spatial resolutions of the drift chambers were 200  $\mu$ m and 250  $\mu$ m for the modules upstream and downstream of the analyzing magnet, respectively.<sup>13</sup> Six planes of MWPC's were utilized in a fast track-counting circuit (TC)<sup>14</sup> to count the number of bunches of contiguous hits in each chamber. (The TC information was part of the event trigger.) A veto matrix (NBV) was also formed from signals from the beam MWPC's, and one doublet of the spectrometer MWPC's. If a charged particle did not scatter by more than 0.3 mrad from the incident beam particle trajectory, the event was vetoed. This eliminated contamination from interactions in the spectrometer that occurred downstream of the target.

A decay tank, 6 meters long, immediately downstream of the target, provided an evacuated volume for sampling beam  $K^+$  and neutral Vee decays (e.g.  $K_S^0 \rightarrow \pi^+\pi^-$ ). The former events were used to study details of spectrometer resolutions (comparing data to Monte Carlo expectations), as well as for final normalization of the topologically similar  $K^+(890)$  decay channels.

A liquid argon photon calorimeter<sup>15</sup> (LAC;  $\sim 25$  radiation lengths of material) was used to detect high energy photons from the decay of  $\pi^0$ 's in Reaction (1), as well as from beam  $K^+ \rightarrow \pi^+ \pi^0$  ( $K_{\pi 2}$ ) decays.

Veto counters surrounding the target were used to select coherently produced events such as  $K^{*+}(890)$  final states of Reactions (1) and (2). Concurrently, with these events, beam  $K_{\pi 2}$  and  $K^+ \rightarrow \pi^+ \pi^+ \pi^-$  ( $K_{\pi 3}$ ) decays were collected.

The trigger for Reaction (1) required that only one charged track leave the target and only one charged track be counted by the TC circuit. Also, a minimum energy ( $\sim 10$  GeV) was required to be deposited in either the upper or lower half of the LAC, with no same-half accompanying charged particle.

The latter restriction eliminated small-angle elastic scatters that deposited energy above threshold in the LAC. The trigger for Reaction (2) required one charged particle to leave the target, and three charged tracks to be detected in the TC circuitry. Both triggers required that the beam particle be tagged by at least one of the Cherenkov counters, and that the MBV veto not be activated.

A Monte Carlo analysis was used to determine the acceptance of the spectrometer through a comparison of generated  $K_{\pi 2}$  and  $K_{\pi 3}$  decays with the data. In the Monte Carlo, the  $K_{\pi 2}$  events were allowed to decay isotropically in the rest frame of the  $K^+$ , while the  $K_{\pi 3}$  decays were generated uniformly over the Dalitz plot. The Monte Carlo results agreed well with the data distributions.<sup>16</sup> This gave us confidence in our modeling of the spectrometer for subsequent use in studying resolutions and acceptances for  $K^{*+}(890)$  events.

For decays occurring near the target, the transverse momentum ( $p_T$ ) resolution for  $K_{\pi 2}$  decays was found to be 7 MeV/c, 12 MeV/c, and 10 MeV/c (and for  $K_{\pi 3}$  decays 11 MeV/c, 15 MeV/c, and 13 MeV/c) for the empty, copper, and lead targets, respectively. Monte Carlo simulations of Reactions (1) and (2) indicated that the  $p_T$  resolutions for the two  $K^{*+}(890)$  decay modes were essentially the same; namely, 14 MeV/c and 12 MeV/c, respectively, for the copper and lead targets. This information was used to account for resolution-smearing of the experimental t-distributions for  $K^{*+}(890)$  production.

The most important use of the beam  $K^+$  decays was to normalize the topologically similar  $K^{*+}(890)$  yields to the observed yields of beam  $K^+$  decays. This procedure obviated the need for relying on absolute trigger, reconstruction, and analysis efficiencies.

To isolate  $K^{*+}(890)$  events produced in Reactions (1) and (2), the following criteria were applied in data analysis: (i) that there be a single incident beam particle per event and that it be tagged as a kaon, (ii) that there be one charged track and two photons (or three charged tracks) reconstructed in the final state, (iii) that the total reconstructed event energy be consistent with the incident beam energy, and (iv) that the reconstructed interaction point be in a small range centered on the target. (Because there was no particle identification downstream of the target, in calculating the invariant mass we assumed the charged particles were kaons for Reaction (1), and pions for Reaction (2).)

For Reaction (1), we also required: (v) that the 2- $\gamma$  invariant mass be in accord with that expected for a  $\pi^0$ , and (vi) that the invariant mass for the final state, assuming a  $\pi^+$  interpretation for the charged track, be greater than 0.580 GeV. This last cut was needed to diminish the background from

$K_{\pi 2}$  decays that contaminated Reaction (1). This restriction reduced the  $K^*$  yield by ~25% and cut out primarily low-mass  $K\pi$  events. The effects of this cut can be seen in the sharp drop in acceptance at low masses in Fig. 1a.

For Reaction (2), we imposed the further constraint that two oppositely charged particles form a neutral  $Vee$  in the decay tank, and have an invariant mass (assuming both to be pions) consistent with that of a  $K^0_S$ . This  $K^*$  decay channel was free of any beam  $K^+$  decay contamination.

Figures 1a and 1b show the  $K\pi$  invariant mass distributions for events produced on the lead target for  $t < 0.004 \text{ GeV}^2$ . These data have been corrected for branching ratios and acceptance (including analysis cuts), normalized to beam  $K^+$  decays, and corrected by an empty target subtraction. The distributions show clear  $K^{*+}(890)$  signals. The superimposed curves are fits to the data, in the range between the arrows, assuming a relativistic p-wave Breit-Wigner line-shape distorted by the coherent production processes. These fits give resonant parameters consistent with world averages. The solid curves above the distributions show the acceptance as a function of mass.

Plots of the polar-angle distributions in the Gottfried-Jackson frame for the final state  $K^+$  in Reaction (1) and the prompt  $\pi^+$  in Reaction (2), summed over data from both targets (after an empty-target subtraction), and corrected for acceptance, are shown in Figs. 2a and 2b. The data are for events with an invariant  $K\pi$  mass in the range 0.790 GeV to 0.990 GeV, and with  $t < 0.004 \text{ GeV}^2$ . The superimposed  $\sin^2\theta$  curves, expected for the decay of coherently excited spin-1 objects, fit the data well, and indicate convincingly that we have isolated coherently produced  $K^{*+}(890)$  signals.

Figures 3a, and 3b show the differential cross sections in  $t$  for  $K^{*+}(890)$  events found in Reactions (1), and (2), respectively. The data are fully

corrected for acceptance, and empty-target subtractions and are properly normalized. The sharp forward peaks characterize Primakoff production, which scales as the square of the nuclear charge; the weaker dependence at larger  $t$ -values is due to coherent strong production. The superimposed curves are the results of three-parameter fits, based on an optical model for the nucleus. Results of the parameterizations are given in Table I. Results of a global fit to the four data sets for  $t < 0.01 \text{ GeV}^2$ , assuming  $\Gamma_\gamma$ ,  $C_S$  and  $\phi$  to be independent of target material, are also given in Table I.

The sensitivity of the extracted values of  $\Gamma(K^{*+}(890) \rightarrow K^+\gamma)$  to the fitting procedure was investigated by separately fixing  $C_S$ , and  $\phi$  in the ranges 1-4 mb/GeV<sup>4</sup> and 0-2 $\pi$ , respectively, and repeating the fits. In no case did  $\Gamma_\gamma$  vary by more than two standard deviations from the values quoted in Table I. Single-parameter fits with  $C_S$  constrained at 0 (i.e. assuming pure Coulomb production), yielded an average value for  $\Gamma_\gamma$  of  $62 \pm 2 \text{ keV}$ , where the quoted error is purely statistical.

Systematic effects on the fitted results for  $\Gamma_\gamma$  include contributions from uncertainties in the normalization to  $K^+$  decays (estimated to be 5% for Reaction (1), 10% for Reaction (2)), and from uncertainty in the  $P_T$  resolution, which is an input to the fitting formalism. Changing the  $P_T$  resolution by  $\pm 10\%$  resulted in variations in  $\Gamma_\gamma$  of  $\sim \pm 8\%$ . Because we believe that we know the  $P_T$  resolution to  $\pm 5\%$ , we estimate a  $\pm 4\%$  systematic error due to this uncertainty.

Taking a weighted average of the fitted values for  $\Gamma_\gamma$  (weighted by the inverse squares of the statistical errors) yields  $\Gamma(K^{*+}(890) \rightarrow K^+\gamma) = 51 \pm 3 \text{ keV}$ , where the errors represent overall statistical and systematic uncertainties, respectively. If we add these sources of error in quadrature, we have the result  $\Gamma(K^{*+}(890) \rightarrow K^+\gamma) = 51 \pm 5 \text{ keV}$ , which implies a radiative

branching ratio for the  $K^{*+}(890)$  of  $0.10 \pm 0.01\%$ .

This measurement is in agreement with the upper limit of 80 keV first reported for the  $K^{*+}(890)$ .<sup>10</sup> It also agrees with the first, but statistically poorer, measurement by our group (for the charge conjugate  $K^{*-}(890)$ ; Berg et al., Ref. 8).

If we compute the ratio of the rate for  $K^{*0} \rightarrow \bar{K}^0 \gamma$  decay<sup>17</sup> to the rate we have measured for  $K^{*+} \rightarrow K^+ \gamma$ , we obtain  $1.47 \pm 0.70$ . This is in excellent agreement with expectations from broken SU(3) symmetry, where the effective magnetic moments of quarks are deduced from baryon magnetic moments.<sup>18</sup> However, the absolute rate for  $K^{*+}(890) \rightarrow K^+ \gamma$  agrees best with predictions of non-relativistic quark models—that do not provide phenomenological SU(3) symmetry breaking.<sup>6</sup> Clearly, in addition to an improved measurement of the radiative width of the  $K^{*0}$ , a complete theoretical reappraisal of vector meson radiative decays is in order.

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TABLE I

Results of the parameterization of the  $K^{*+}(890)$  data  
(all errors are statistical)

Reaction type (a)	Target	$\Gamma_\gamma$ (keV)	$C^S$ (mb/GeV <sup>4</sup> )	$\phi$ (degrees)	$\chi^2/DF$
(1)	Cu	62 ± 6	2.9 ± 1.0	85 ± 26	6.1/6
(2)	Cu	51 ± 7	2.8 ± 1.1	85 ± 32	4.4/6
(1)	Pb	48 ± 4	4.2 ± 2.0	84 ± 28	8.6/6
(2)	Pb	47 ± 6	4.9 ± 2.2	82 ± 30	5.8/6
Global fit (b)		51 ± 3	2.4 ± 0.8	64 ± 26	31/33

(a) There are, respectively, 333 events, 177 events, 486 events, and 256 events with  $\tau < 0.01$  GeV<sup>2</sup> in the individual data samples.  
(b) Fit to all data constraining  $\Gamma_\gamma$ ,  $C^S$ , and  $\phi$  to be independent of target material.

Footnotes and References

- (a) Presently at University of Illinois at Urbana-Champaign, Urbana, Illinois 61801.  
 (b) Presently at EP Division, CERN, 1211 Geneva 23, Switzerland.  
 (c) Presently at Brookhaven National Laboratory, Upton, New York 11973.  
 (d) Presently at Institute for Nuclear Study, University of Tokyo, Tanashi City, Tokyo 188, Japan.

1. S. Okubo, *Physics Letters* **4**, 14 (1963).
2. C. Becchi and G. Morpurgo, *Phys. Rev.* **140**, 687 (1965); P. Van Royen and V. F. Weisskoff, *Nuovo Cimento* **A50**, 617 (1967).
3. G. Grunberg and F. M. Renard, *Nuovo Cimento* **33A**, 617 (1976); P. J. O'Donnell, *Rev. Mod. Phys.* **53**, 673 (1981).
4. J. Franklin, *Phys. Rev.* **172**, 1807 (1968) gives the procedure for extracting quark magnetic moments from measurements of the baryon magnetic moments  $\mu_p$ ,  $\mu_n$ , and  $\mu_\Lambda$ .
5. The most recent experimental values for  $\mu_p$ ,  $\mu_n$ , and  $\mu_\Lambda$  are given, respectively, in: E. R. Cohen and B. N. Taylor, Jr. *Phys. Chem. Ref. Data* **2**, 633 (1973); G. L. Greene et al., *Phys. Rev.* **D20**, 2139 (1979); L. Schachinger et al., *Phys. Rev. Lett.* **41**, 1348 (1978).
6. P. J. O'Donnell, *Can. J. Phys.* **55**, 1301 (1977). We have updated some of the predictions using newer results for the magnetic moment of the strange quark as deduced from measurements of  $\mu_\Lambda$  (Schachinger et al., Ref. 5).
7. H. Primakoff, *Phys. Rev.* **91**, 899 (1951); A. Halprin, C. M. Andersen, and H. Primakoff, *Phys. Rev.* **152**, 1295 (1966).
8. D. Berg et al., *Phys. Rev. Lett.* **44**, 706 (1980); *Phys. Letts.* **98B**, 119 (1981); S. Cihangir et al., *Phys. Letts.* **117B**, 119 (1982); *Phys. Letts.* **117B**, 123 (1982); T. Jensen et al., *Phys. Rev.* **D27**, 26 (1983).
9. G. Fäldt, *Nucl. Phys.* **B43**, 591 (1972); see also T. Jensen et al., Ref. 8.

10. C. Bemporad et al., *Nucl. Phys.* **B51**, 1 (1973).
11. A. Jonckheere et al., *Nucl. Instru. & Methods* **180**, 25 (1981).
12. A description of the spectrometer can be found in Berg et al., Ref. 8 and Jensen et al., Ref. 8. For this data run, the experiment was implemented with a second MWPC doublet in the upstream half of the spectrometer (see ref. 13).
13. C. Chandlee et al., (to be submitted to *Nucl. Instru. and Methods*).
14. A description of this circuit is given in C. Kearns, Fermilab Report TM-819 2510.0 (1978).
15. Details of the construction and operational performance of the LAC can be found in C. Nelson et al., (to appear in *Nucl. Instru. & Methods*).
16. For further details see C. Chandlee, Ph.D. Thesis, University of Rochester Report No. UR-842, 1982 (unpublished).
17. W. C. Carithers, P. Mühleemann, D. Underwood, and D. G. Ryan, *Phys. Rev. Lett.* **35**, 349 (1975).
18. R. B. Teese and R. Settles, *Phys. Lett.* **87B**, 111 (1979).

Figure Captions

1. Fully corrected mass distributions for  $K\pi$  events produced coherently on the lead target with  $t < 0.004 \text{ GeV}^2$ . The superimposed curves are the results of fits assuming p-wave decay of coherently excited  $K\pi$  systems. The total acceptances as a function of mass are given by the smooth curves above the data.
2. Acceptance corrected polar angle decay distributions (Gottfried-Jackson frame), summed over  $K^+(890)$  events with  $t < 0.004 \text{ GeV}^2$  produced on copper and lead targets. The superimposed curves are the  $\sin^2\theta$  forms expected for the decay of coherently excited spin-1 objects.
3. Fully corrected t-distributions for  $K^+(890)$  events with fits to the data.

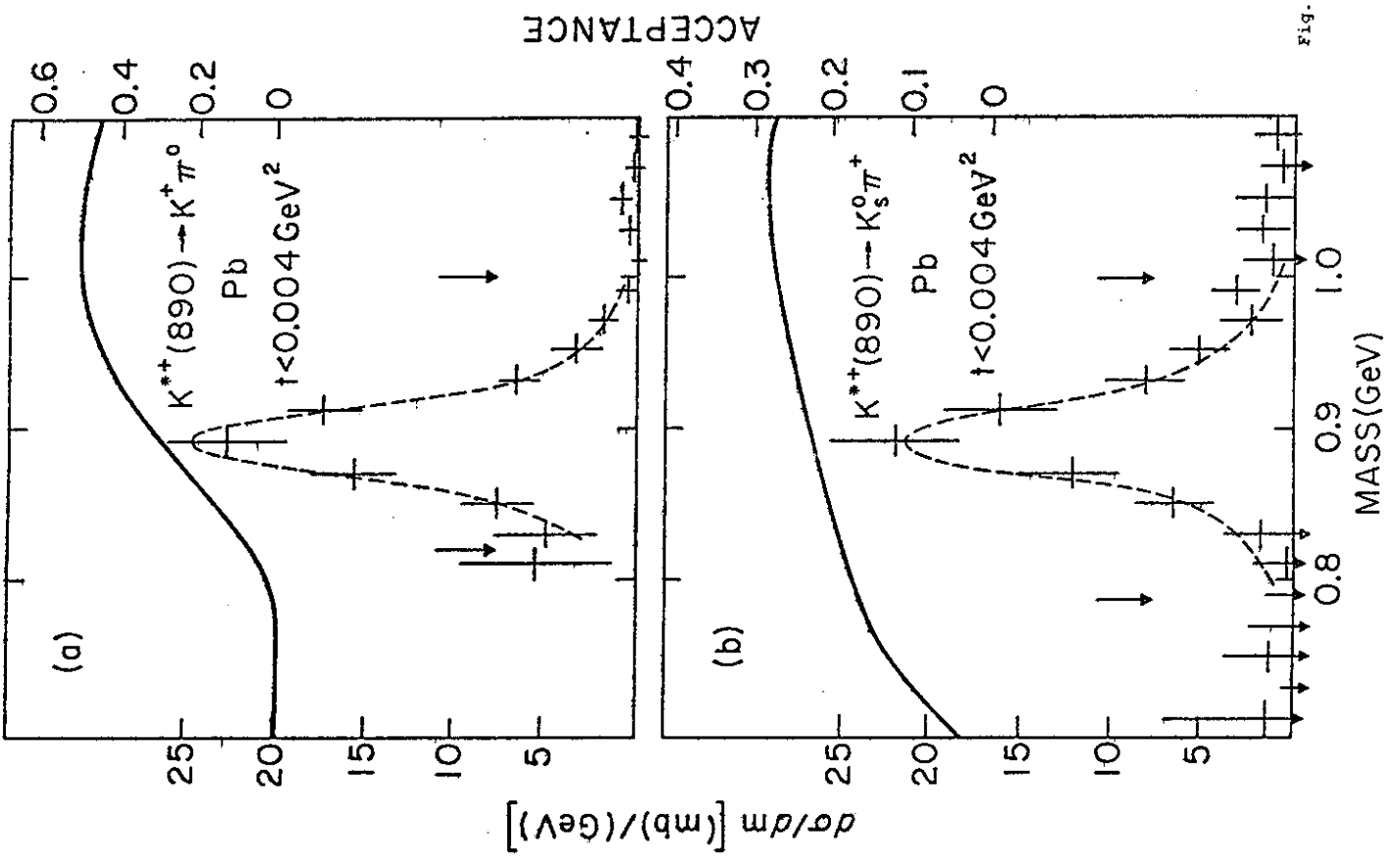


Fig. 1

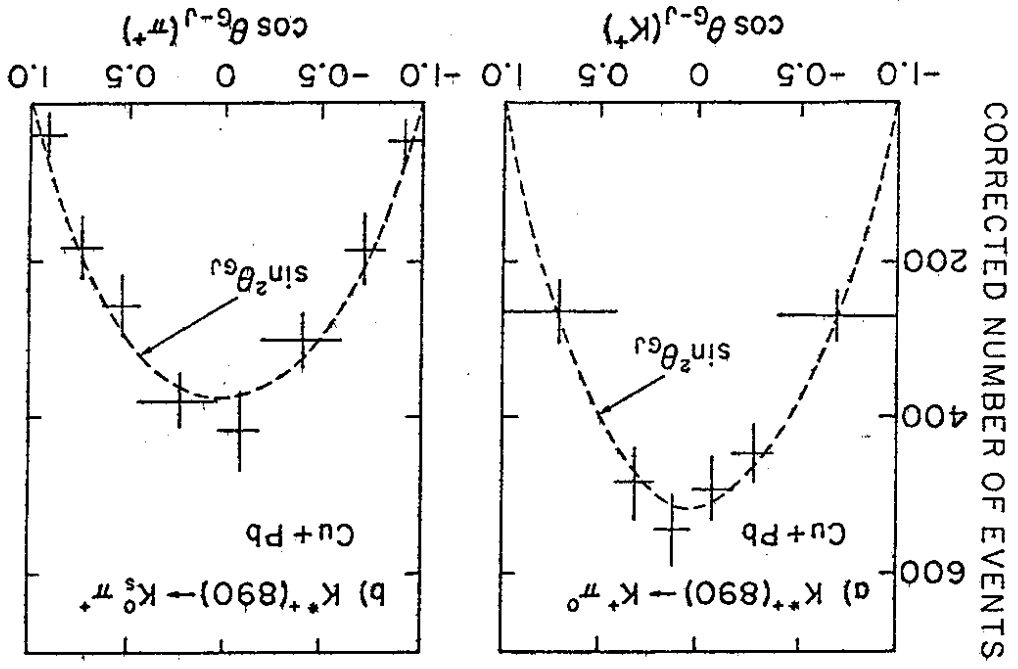


Fig. 2



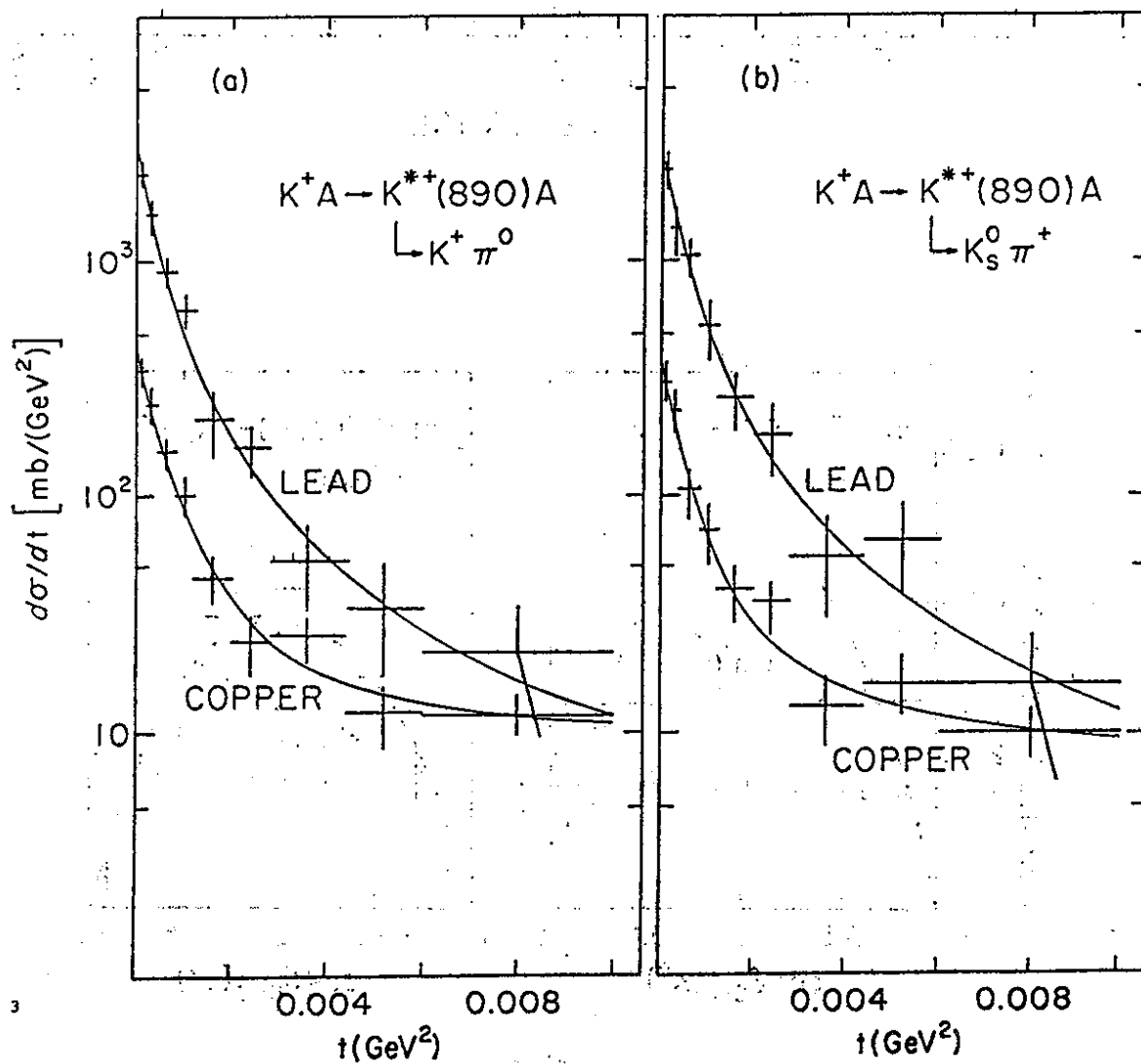


Fig. 3