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A LIMIT ON THE $K^+ \to \pi^+ + \nu + \bar{\nu}$ DECAY RATE*

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ABSTRACT

The branching ratio for the process $K^+ \to \pi^+ + \nu + \bar{\nu}$ is shown by a counter-spark chamber experiment to be less than 1.2×10^{-6} of all decay modes, assuming a pion energy spectrum like that of $K^+ \to \pi^0 + e^+ + \nu$. Our apparatus was sensitive to pions in the kinetic energy range 117 - 127 MeV.

In 1964 Camerini, Cline, Fry, and Powell[1] reported the results of a search for the reaction $K^+ \to \pi^+ + e^+ + e^-$. They set an upper limit of 2.5×10^{-6} on the branching ratio for this decay mode. Other experiments[2] have been made to search for $K_L^0 \to e^+e^-$, $K_{L,S}^0 \to \mu^+\mu^-$, and $K^+ \to \pi^+\mu^+\mu^-$. These decays have not been observed. In the experiment described here, we have searched for the decay

$$K^+ \to \pi^+ + \nu + \bar{\nu} \; . \qquad (1)$$

We have observed no examples of this decay. If we assume that the energy spectrum of the π^+ is the same as that of the π^0 in the observed reaction[3] $K^+ \to \pi^0 + e^+ + \nu$, we can set an upper limit on the branching ratio[4] for the K^+ to decay in this manner of 1.2×10^{-6} (90% C. L.).

The significance of our result depends upon the manner in which we account for the absence of the reactions discussed above. We may suppose that $K^+ \rightarrow \pi^+ + \nu + \bar{\nu}$ should result from the same interaction that gives rise to $K^+ \rightarrow \pi^0 + e^+ + \nu$. The matrix element for this latter decay is known to be of the form:[5]

$$\frac{G}{\sqrt{2}} (\bar{U}_\nu \, \gamma_\lambda (1 + \gamma_5) U_e) \langle \pi^0 | J_\lambda | K^+ \rangle \ . \qquad (2)$$

If we substitute $\langle \pi^+ | J_\lambda | K^+ \rangle$ for $\langle \pi^0 | J_\lambda | K^+ \rangle$ and $\bar{U}_\nu \, \gamma_\lambda (1 + \gamma_5) U_\nu$ for $\bar{U}_\nu \gamma_\lambda (1 + \gamma_5) U_e$, and if $\langle \pi^0 | J_\lambda | K^+ \rangle = \langle \pi^+ | J_\lambda | K^+ \rangle$, the above expression for the matrix element is practically unchanged. The energy release in the decay is so high that the electron mass is negligible. The fact that our upper limit on the branching ratio for $K^+ \rightarrow \pi^+ + \nu + \bar{\nu}$ is at most very small in comparison with the branching ratio for $K^+ \rightarrow \pi^0 + e^+ + \nu$ (which is 0.05) can be accounted for by assuming either that $\langle \pi^+ | J_\lambda | K^+ \rangle$ vanishes or that some lepton selection rule is violated by a current $\bar{U}_\nu \, \gamma_\lambda (1 + \gamma_5) U_\nu$.

The current J_λ is known empirically to obey the $\Delta I = 1/2$ rule. If we assume that the $\langle \pi^+ | J_\lambda | K^+ \rangle$ component of this current vanishes, it is impossible to account for the $\Delta I = 1/2$ selection rule of non-leptonic strange particle decays in the usual fashion as the result of a current-current interaction where one current carries $\Delta I = 1/2$, $\Delta S = 1$, and the other carries $\Delta I = 1$, $\Delta S = 0$. Thus it is necessary to abandon the hypothesis that all weak interactions occur as the self-interaction of a current made up of many parts. Our experiment is consistent with the assumption that the matrix element $\langle \pi^+ | J_\lambda | K^+ \rangle$ vanishes since both $K^+ \rightarrow \pi^+ + e^+ + e^-$ and $K^+ \rightarrow \pi^+ + \nu + \bar{\nu}$ would then vanish. On the other hand, if $\langle \pi^+ | J_\lambda | K^+ \rangle \neq 0$

there must be a selection rule among leptons which prohibits currents of the form $\bar{U}_e \gamma_\lambda (1 + \gamma_5) U_e$. Our experiment then shows that the combination $\bar{U}_\nu \gamma_\lambda (1 + \gamma_5) U_\nu$ is also forbidden. It is impossible to decide at present whether it is this leptonic current or the hadronic current matrix element $\langle \pi^+ | J_\lambda | K^+ \rangle$ that vanishes.

Oakes[6] has suggested that although $K^+ \rightarrow \pi^+ + \nu + \bar{\nu}$ may not occur in the framework of conventional weak interaction theory for one of the reasons discussed above, there may be an additional type of weak interaction current which violates CP and gives rise to $K_2^0 \rightarrow 2\pi$ decay. The branching ratio[7] for $K^+ \rightarrow \pi^+ + \nu + \bar{\nu}$ in the theory of Oakes is 1.8×10^{-5}. Our result is inconsistent with this prediction. Other authors[8] have calculated $K^+ \rightarrow \pi^+ + \nu + \bar{\nu}$ on the basis of higher order weak interaction theories. A simple second order application of weak interaction theory as it is now known leads to a divergent result for the $K^+ \rightarrow \pi^+ + \nu + \bar{\nu}$ decay rate. Various models have been made to ameliorate the difficulties caused by this divergence.[8] The interpretation of our result hinges then on details of the model employed.

The experiment depends on the fact that no observed K^+ decay at rest produces a π^+ with an energy greater than that from $K^+ \rightarrow \pi^+ \pi^0$ ($T_\pi = 109$ MeV; b.r. = 0.21). In order to produce a π^+ of higher energy the K^+ must decay into a π^+ and a neutral system with rest mass less than that of the π^0. If we neglect decays into four or more particles, the only possibilities are $K^+ \rightarrow \pi^+ e^+ e^-$ (b.r. $< 2.5 \times 10^{-6}$),[1] $K^+ \rightarrow \pi^+ \gamma\gamma$ (b.r. $< 1.1 \times 10^{-4}$),[9] and reaction (1). The last two reactions may give pions with energies up to 127 MeV. Hence the fact that we observe no π^+

emitted with energy between 117 and 127 MeV unaccompanied by high energy γ's or charged particles in the opposite hemisphere is sufficient to exclude the $\pi^+\nu\bar{\nu}$ decay.

The experimental arrangement is shown in Fig. 1. Kaons in the incoming beam from the Bevatron are brought to rest in the "K-stop" counters KS1 and KS2. Scattered and transmitted particles are suppressed by the anti-coincidence counters K4 and K5. Those scattered toward the π counters are suppressed by the requirement that the pulses from counters π1 and π2 must be delayed $\gtrsim$ 6ns after the pulse from the stopping K. Pions in the beam are excluded by i) a water Cerenkov counter KC [actually consisting of two counters connected in parallel: $\beta(K) < \beta(\text{threshold}) < \beta(\pi)$], ii) two dE/dX counters $[(dE/dX)_K > 1.5(dE/dX)_\pi]$, and iii) range ($R_\pi \gg R_K$ for same initial momentum). In summary the K^+ signal is $[K1, K2, K3, KS1 \text{ and/or } KS2, \overline{KC}, \overline{K4}, \overline{K5}]$. We require that a subsequent π signal occur between 6 and 54 ns after the K^+ signal, and we denote the K^+ signal together with this additional timing requirement as the "K decay" signal.

The triggering system of the π^+ detector ($\pi1, \overline{\pi C}, \pi2, \pi3, \overline{\pi8}, \overline{KC}, \overline{K4}, \overline{K5}$) does not distinguish between stopping π's and stopping μ's, but high velocity μ's from $K_{\mu2}$ are vetoed by the water Cerenkov counter πC and by the maximum-range counter π8. A large counter, K0, which completely covers the incoming beam (not shown in Fig. 1) is used to detect events in which more than one beam particle enters the apparatus during the $K \to \pi \to \mu \to e$ decay sequence. These events are excluded if a beam particle enters in coincidence with the π, μ, or e. The requirement

$\overline{KC}$ in the π^+ triggering system further insures against detecting scattered beam pions.

Whenever the whole triggering system ("K decay", π, and γ) indicates that a K^+ has stopped in the target, that later a slow charged particle has passed through the π telescope and stopped in one of the decay counters $\pi4$ to $\pi7$, and that no high energy γ has entered the lead-glass Cerenkov counters $\gamma C1$ or $\gamma C2$, then the spark chambers are pulsed and the signals from the decay counters are displayed on each of two four-beam oscilloscopes. One of the oscilloscopes has a sweep range of 200 ns. The four traces on this oscilloscope are examined for the stopping π^+ and the $\pi^+ \to \mu^+$ decay. The μ^+ energy loss is determined by measuring the μ^+ pulse height. Since the μ^+ in $\pi^+ \to \mu^+ + \nu$ decay has an energy of 4.4 MeV, this measurement is helpful in eliminating accidental backgrounds. The other oscilloscope has a sweep range of 3 μs. The traces on this oscilloscope are examined for the $\mu^+ \to e^+$ decay. We require that an e^+ pulse occur in the counter in which the π^+ stopped, and that either the e^+ have an energy loss of > 4.5 MeV in that counter or that it make a pulse in at least one adjacent counter.

The pion range is computed using the absorber thickness (which is varied according to the portion of the spectrum to be examined), the pion trajectory as seen in the spark gaps, and the positions of the counters showing the K-stop and the π-decay.

The $K^+ \to \pi^+\pi^0$ decays are used to calibrate the apparatus. The measured pion mean life using pions from $K^+ \to \pi^+\pi^0$ is 26.4 ± 1.0 ns in good agreement with the accepted value. The inefficiency of the γC anti-coincidence counters (determined by comparing the $K^+ \to \pi^+\pi^0$ event rates with γ's vetoed versus the rate with γ's required) is 6×10^{-4}. The branching ratio $(K^+ \to \pi^+\pi^0)/(K^+ \to \mu^+\nu)$ is found to be 0.36 ± 0.03 in satisfactory agreement with the accepted value 0.33. This agreement checks the assumed value for π^+ absorption.

Events with an apparent $\pi^+ \to \mu^+ \to e^+$ decay sequence and with a π^+ range of at least 50 g cm^{-2} were considered "$K^+ \to \pi^+\nu\bar{\nu}$" events. The most important source of background was $K^+ \to \mu^+\nu\gamma$ events where an accidental particle struck the decay counters causing the $\mu \to e$ decay to be mistaken for a $\pi \to \mu \to e$ decay sequence. The probability of this was determined by examining a sample of 30,000 stopping μ^+ from $K^+ \to \mu^+\nu$ for apparent $\pi \to \mu \to e$ decays. The range of the stopping particles ($R > 70$ g cm^{-2}) guaranteed that they could not be pions. Most of the spurious "π" → "μ" → e events were found to have low "μ" pulse heights. The same probability for spurious events was assumed for the 32,000 stopping μ^+ (from $K^+ \to \mu^+\nu\gamma$) seen during the search for $K^+ \to \pi^+\nu\bar{\nu}$ ($50 \leq R \leq 59$ g cm^{-2}). Another source of background was due to pions in the K beam which the KC counter failed to veto.

The numbers of "$K^+ \to \pi^+\nu\bar{\nu}$" events and the expected background events were considered for various cut-off values of the K life-time, the π life-time, and the "μ" pulse height. The numbers of "$K^+ \to \pi^+\nu\bar{\nu}$" were consistent with the expected background for a wide variety of cut-off values. In the final sample of "$K^+ \to \pi^+\nu\bar{\nu}$" events "$\mu$" pulses were required to have between 0.5 and 1.5 times the mean pulse height of muons from $\pi \to \mu$ decays.

The π and K life-times were required to be within two mean lives after our detection thresholds. Measurement with $K^+ \rightarrow \pi^+\pi^0$ events showed that these cuts excluded 33% of the pions. After the cuts the expected background is 0.8 events. There were no "$K^+ \rightarrow \pi^+\nu\bar{\nu}$" events in the final sample.

Our detector efficiency for $\pi^+\nu\bar{\nu}$ events is shown in curve II of Fig. 2A. The meaning of observing one event in our experiment depends on the convolution of this efficiency and an assumed pion spectrum. We denote this convolution by $\epsilon_{\pi^+\nu\bar{\nu}}$. We have considered the possibilities shown in Table I.

Assuming a vector interaction if one event had been found the branching ratio would have been

$$\frac{\Gamma(K^+ \rightarrow \pi^+\nu\bar{\nu})}{\Gamma(\text{all modes})} = \frac{(\pi^+\nu\bar{\nu})/K^+}{(\pi^+\pi^0)/K^+} \cdot \frac{\epsilon_{\pi^+\pi^0}}{\epsilon_{\pi^+\nu\bar{\nu}}} \cdot \frac{T_I}{T_{II}} \cdot \frac{\Gamma(\pi^+\pi^0)}{\Gamma(\text{all modes})} = 5.3 \times 10^{-7}. \quad (3)$$

Here $\pi^+\nu\bar{\nu}/K^+$ stands for the ratio of the number of "$K^+ \rightarrow \pi^+\nu\bar{\nu}$" events found to the number of K^+ signals examined by the triggering system (7.2×10^{-10} assuming 1 event); $\pi^+\pi^0/K^+$ is the ratio of the number of $\pi^+\pi^0$ events found to the number of K^+ signals examined when the apparatus was used to detect $K^+ \rightarrow \pi^+\pi^0$ (1.5×10^{-3}); $\epsilon_{\pi^+\pi^0}$ (0.054) is the detection efficiency for $\pi^+\pi^0$ (the convolution of curve I with curve (i) in Fig. 2A); $\epsilon_{\pi^+\nu\bar{\nu}}$ (0.0105) is the detection efficiency for $\pi^+\nu\bar{\nu}$ assuming a vector spectrum (the convolution of curve II with curve (ii) in Fig. 2A); and T_I/T_{II} (1.05) is the ratio of π^+ transmissions for the absorbers corresponding to curves I and II in Fig. 2A (44 and 52 g cm^{-2} Cu equivalent, respectively).

Table I contains the branching ratios which we infer from (3).

By the 90% confidence level we mean the rate which we would compute had we found 2.3 events.

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Table I. Effective detection efficiency $\epsilon_{\pi^+\nu\bar{\nu}}$ (117 MeV $\leq T_\pi \leq$ 127 MeV) and resultant branching ratio (90% C. L.) for several assumed π^+ spectra. p_π and T_π are the momentum and kinetic energy, respectively, of the π^+. T_{MAX} = 127 MeV is the kinematic upper limit for $K^+ \to \pi^+\nu\bar{\nu}$. The spectra were normalized to have unit area between 0 and T_{MAX}.

$\frac{dN}{dT_\pi}$ assumed	Type of first-order interaction	$\epsilon_{\pi^+\nu\bar{\nu}}$	Branching Ratio
p_π^3	vector	0.0105	1.2×10^{-6}
$p_\pi^3\ (T_{MAX}-T_\pi)$	tensor	0.0034	3.8×10^{-6}
$p_\pi\ (T_{MAX}-T_\pi)$	scalar	0.00072	1.8×10^{-5}

FOOTNOTES AND REFERENCES

* Research supported by the U. S. Atomic Energy Commission and by the National Science Foundation (Grant Gp 14521).

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2. Branching ratio limits (90% CL.): $K_L^0 \rightarrow e^+e^- < 1.5 \times 10^{-7}$, $K_L^0 \rightarrow \mu^+\mu^- < 2.1 \times 10^{-7}$, H. Foeth et al., Phys. Letters 30B, 282 (1969); $K_S^0 \rightarrow \mu^+\mu^- < 7.3 \times 10^{-6}$, B. D. Hyams et al., Phys. Letters 29B, 521 (1969); $K^+ \rightarrow \pi^+\mu^+\mu^- < 2.4 \times 10^{-6}$, V. Bisi et al., Phys. Letters 25B, 572 (1967). See also D. W. Carpenter et al., Phys. Rev. 142, 871 (1966), C. Alf-Steinberger et al., Phys. Letters 21, 595 (1966), and References 1 and 4.

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FIGURE CAPTIONS

Fig. 1. Apparatus. Kaons stopping in the target scintillators KS1 and KS2 are selected from the incoming beam by signals K1, $\overline{KC}$, K2, K3, KS1 and/or KS2, $\overline{K4}$, $\overline{K5}$ where K2 and K3 have pulse heights $\geq$ 1.5 × pion pulse height. Low velocity decay particles are selected by signals $\pi 1$, $\overline{\pi C}$, $\pi 2$, $\pi 3$, $\overline{\pi 8}$, $\overline{KC}$, $\overline{K4}$, $\overline{K5}$ where $\pi 1$ is delayed $\geq$ 6 ns after K3. Events which emit gammas into the opposite hemisphere are eliminated by signals $\overline{\gamma C1}$ and/or $\overline{\gamma C2}$. Pions are distinguished from stopping muons by 'scope displays of the π-μ-e decay pulses in counters $\pi 4$-$\pi 7$

Fig. 2. Range Distributions. 2A: Calculated distributions for K^+ decays into $\pi^+\pi^0$, $\pi^+\nu\bar{\nu}$ (vector), and $\mu^+\nu$ with straggling and small angle multiple scattering taken into account. Dashed curves I, II, and III show detector efficiencies for different absorber thicknesses (curve II is weighted sum of curves corresponding to two nearly equal thicknesses). 2B: Expected event distributions for $\pi^+\pi^0$ and $\mu^+\nu$ (curves I and III folded into i and iii) and corresponding observed distributions (histograms). 2C: Expected and observed $\pi^+\pi^0$ and "$\pi^+\nu\bar{\nu}$" distributions for absorber corresponding to curve II, Fig. 2A. [$\gamma C1$ and/or $\gamma C2$ required in coincidence for $\pi^+\pi^0$ (open histogram) and in anticoincidence for "$\pi^+\nu\bar{\nu}$" (shaded histogram)].

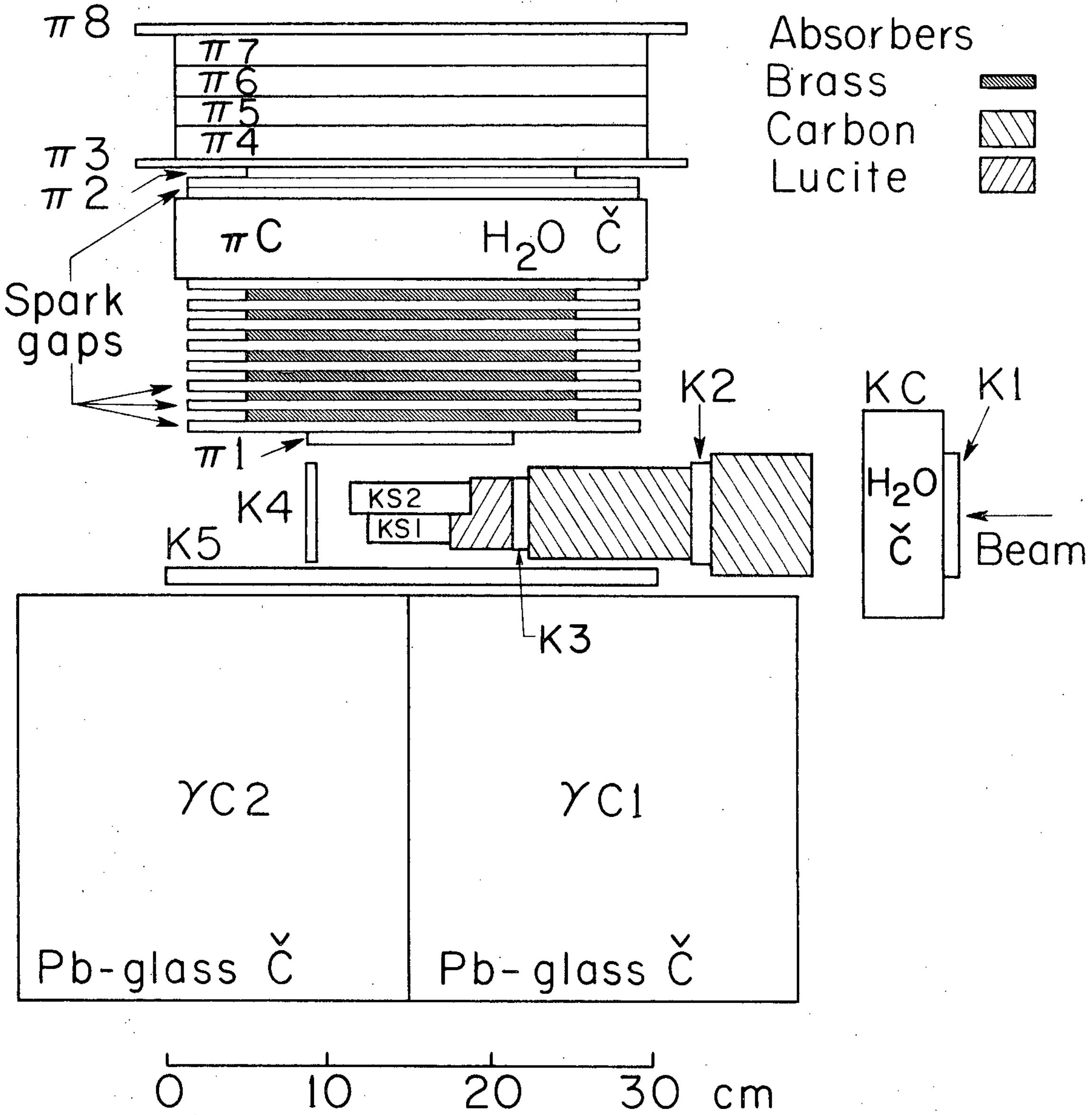

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Fig. 1

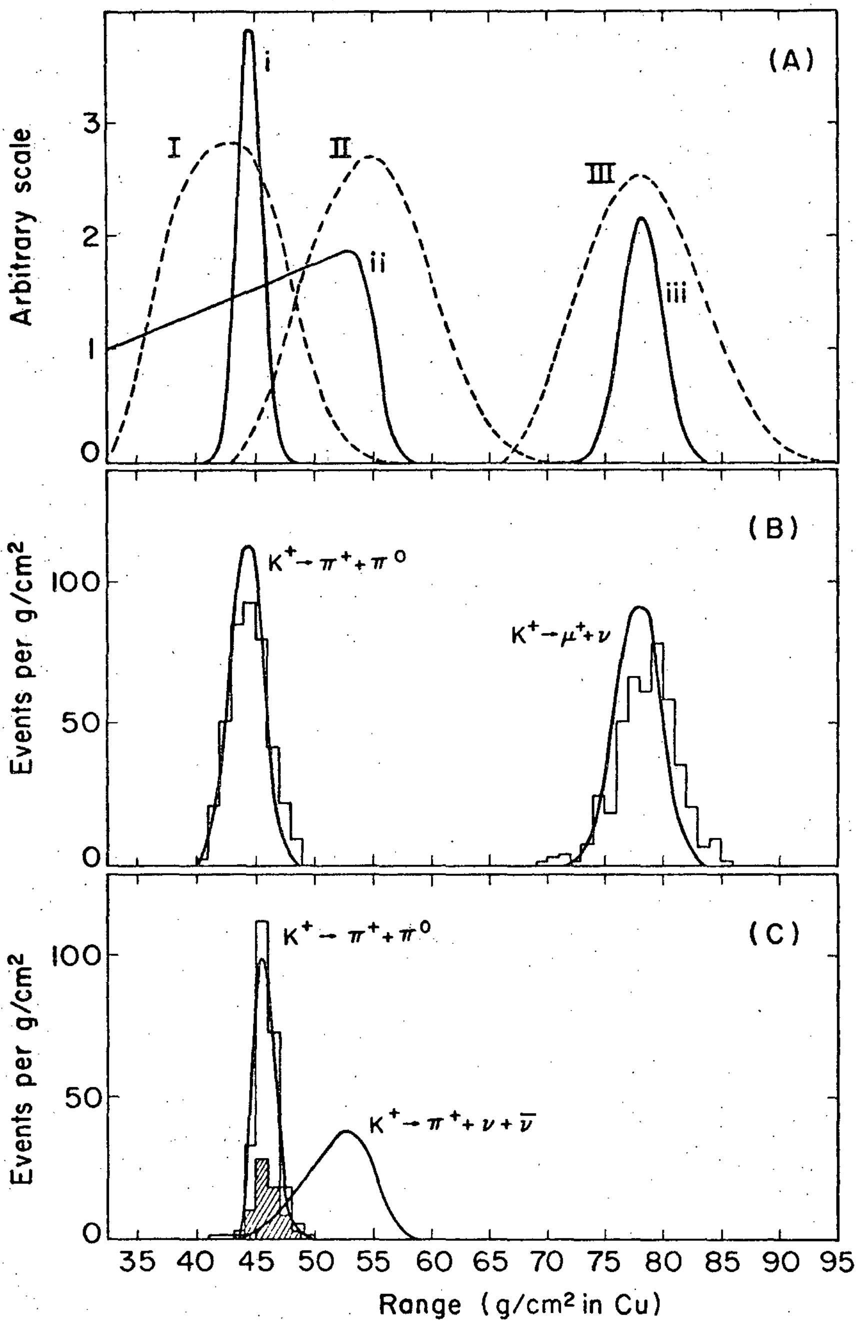

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Fig. 2

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