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### MEASUREMENT OF THE BRANCHING RATIO

$$K_L \rightarrow \gamma\gamma/K_L \rightarrow 3\pi^0 \text{ *}\dagger$$

**MASTER**

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MEASUREMENT OF THE BRANCHING RATIO  $K_L \rightarrow \gamma\gamma/K_L \rightarrow 3\pi^0$  <sup>\*†</sup>

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ABSTRACT

We have measured the branching ratio  $(K_L \rightarrow \gamma\gamma)/(K_L \rightarrow 3\pi^0)$  to be  $(2.24 \pm 0.28) \times 10^{-3}$ . Combined with a recently reported branching ratio  $(K_L \rightarrow 3\pi^0)/(K_L \rightarrow \text{all modes}) = 0.209 \pm 0.011$ , we find  $(K_L \rightarrow \gamma\gamma)/(K_L \rightarrow \text{all modes})$  to be  $(4.68 \pm 0.64) \times 10^{-4}$ .

An experiment to measure  $K_L \rightarrow \pi^0 \pi^0$  and  $K_L \rightarrow \gamma\gamma$ , previously reported in preliminary form,<sup>(1)</sup> has been repeated with an improved apparatus. We report here the results obtained for the decay rate  $K_L \rightarrow \gamma\gamma$ .

The apparatus consisted of a pair spectrometer placed parallel to a  $K_L$  beam at the Princeton-Pennsylvania Accelerator. The spectrometer has been described in reference 1. In principle, a measurement of the energy spectrum of single  $\gamma$ -rays in the center of mass allows one to distinguish between the decay modes  $K_L \rightarrow \gamma\gamma$ ,  $K_L \rightarrow \pi^0 \pi^0$  and  $K_L \rightarrow 3\pi^0$ . However, no kinematic check that the  $\gamma$ -rays came from  $K_L$  is possible. To provide such a check, steel-plate spark chambers have been added to convert the additional  $\gamma$ -rays.

Figure 1b shows a view of the apparatus looking upstream along the beam line. We have surrounded the remaining three sides of the beam with spark chambers. Each chamber consists of three  $0.86 \text{ gm/cm}^2$  aluminum plates nearest the beam, followed by twenty  $2.5 \text{ gm/cm}^2$  stainless steel plates. The total thickness of each chamber, as measured along its normal, is 3.6 radiation lengths. The spark chambers extend along the beam for 10 feet, as is shown in the plan view of Fig. 1a, and were viewed in small angle stereo. The precision of spark location was 0.1 in. perpendicular to the beam, and 0.5 in. parallel to the beam.

These spark chambers were triggered along with the spectrometer every time the logic indicated a  $\gamma$ -ray had been detected in the spectrometer. We did not demand in the trigger that a  $\gamma$ -ray convert in the steel chambers. The velocity of the decay particle was measured using the 67.3 nsec. time structure present in the

accelerator beam. A helium bag in the beam reduced problems of neutron and  $K_L$  interactions in the decay volume.

In the experiment reported here, we observed 7351 converted  $\gamma$ -rays in the spectrometer. For these events we verified that the efficiency per gap of each steel chamber was always greater than 90%. In addition, the spatial reconstruction was verified by measurement of cosmic ray tracks that passed through both the spectrometer and the steel chambers. The correspondence between the two coordinate systems was within 0.1 in.

Of the 7351 good events, 643 were found to have a transverse momentum greater than 165 MeV/c. The cut in transverse momentum was chosen to eliminate almost all the  $3\pi^0$  decays. A cut in center-of-mass energy was not made since about 1% of the  $3\pi^0$  events were expected to have an apparent energy greater than 165 MeV because of time of flight ambiguities.

The 643 selected events were scanned and measured twice by physicists. The criterion for a converted  $\gamma$ -ray in a steel chamber was the presence of at least two contiguous sparks, even though the expected  $\gamma$ -ray energy was  $> 240$  MeV. A fit to  $K_L \rightarrow \gamma\gamma$  was attempted for each such  $\gamma$ -ray, providing it did not convert in the first two gaps. Occasionally a fit was found for two separate  $\gamma$ -rays, but in each case these could be traced to the same shower.

In the fitting of events, only the conversion points were used for those  $\gamma$ -rays converting in the steel chambers. The  $K_L$  decay point was assumed to lie along the line of the spectrometer  $\gamma$ -ray projected back into the beam. Points were chosen along this trajectory at 0.5 in. intervals across the beam volume. For each point, the

direction of a  $\gamma$ -ray in a steel chamber was taken to be along the line drawn from this point to its conversion point. The decay point was chosen to give the best collinearity in the center-of-mass system with the restriction that the point be no more than 2 in. outside the beam volume. The resulting collinearity distribution is shown in Fig. 2a. The spectrometer momentum measurement has not been used in the fitting. Figure 2b shows the transverse momentum distribution of those events which show a collinearity  $-1.00 \leq \cos \theta_{\gamma\gamma} < -0.99$ . Figure 2c shows the energy distribution of these events in the center-of-mass system using the time of flight information for each event.

For the branching ratio calculation, we used events with  $215 < E_{\text{cm}} < 270$  MeV,  $P_{\perp} > 165$  MeV/c, and  $-1.00 \leq \cos \theta_{\gamma\gamma} < 0.99$ . Here  $E_{\text{cm}}$  and  $P_{\perp}$  refer to the center-of-mass energy and transverse momentum of the spectrometer gamma ray respectively. There were 116 events which satisfied these conditions. A Monte Carlo study using the observed number of  $\pi^0\pi^0$  decays indicated that we can expect to find one  $K_L \rightarrow \pi^0\pi^0$  event in this region. The decay  $K_L \rightarrow \pi^0\pi^0$  is discussed in the following paper. The final number of  $\gamma\gamma$  events is then found to be  $115 \pm 11$ .

Monte Carlo calculations have shown that  $0.828 \pm 0.032$  of all  $K_L \rightarrow \gamma\gamma$  events detected in the spectrometer with  $215 < E_{\text{cm}} < 270$  MeV will show a materialized  $\gamma$  in a steel chamber and satisfy the fitting criteria. The 17% inefficiency is due to 10% of the events with no conversion in a steel chamber, and 7% with a conversion in one of the first two plates. Less than 1% of all events fail to fit. The fraction of all  $K_L \rightarrow \gamma\gamma$  events which are detected in the spectrometer with  $215 < E_{\text{cm}} < 270$  MeV, and  $P_{\perp} > 165$  MeV/c is calculated to be  $0.884 \pm 0.019$ . The total number of  $K_L \rightarrow \gamma\gamma$  events observed in the

spectrometer is then  $N_{\gamma\gamma} = 157 \pm 16$ .

We wish to emphasize that the Monte Carlo calculations referred to above made use of geometrical quantities and the absolute pair-production cross section;<sup>(2)</sup> they did not require application of shower theory.

The solid curves in Fig. 2b and 2c are the distributions from the Monte Carlo calculations normalized to 116 events for  $E_{cm} > 215$  MeV. This calculation for the spectrometer  $\gamma$ -ray took into account the incident  $K_L$  momentum spectrum, the bremsstrahlung loss in the converter, scattering in the converter and foils of the spark chambers, and the relative pair-production cross section in the thin radiator as a function of  $\gamma$ -energy. It also included our estimate of measurement errors. It did not include the fact that at steep angles the sparks do not necessarily follow the trajectory of the particle, nor could it account for unknown errors of reconstruction. Therefore the data itself was used to determine the actual resolution. The full width at half maximum of the  $K_L \rightarrow \gamma\gamma$  peak was observed to be 20 MeV, whereas the calculation had predicted 14 MeV. In addition, the centers of the experimental  $E_{cm}$  and  $P_L$  peaks were shifted down by 1% from their expected positions. We attribute these facts to a fault in the reconstruction calculation, as evidenced by the fact that cosmic rays passing through the spectrometer under zero field conditions had an 8 mrad. shift between their directions in the two spectrometer spark chambers. This error has no significant effect on our conclusions. The measured resolution has been used in all subsequent calculations. It is important to note that the distributions in  $P_L$  and  $E_{cm}$  do not show any evidence of a tail on the high energy side. The good agreement between the calculated and observed distributions for



both  $P_{\perp}$  and  $E_{cm}$  indicates that our measured time of flight resolution (2 nsec. FWHM) does not have to be increased.

Figure 3a shows the  $P_{\perp}$  distribution for all events measured in the spectrometer. Among these are approximately 157  $K_L \rightarrow \gamma\gamma$  events; in the paper that follows, we find approximately 100  $K_L \rightarrow \pi^0\pi^0$  events with  $P_{\perp} > 165$  MeV. We have established that the remaining 386 events with  $P_{\perp} > 165$  MeV are mainly background from interactions of  $K_L$  or neutrons in the helium gas and in the walls of the steel chambers. A distribution of  $P_{\perp}$  typical of interactions was obtained by the insertion of a tungsten target in the beam volume. This distribution has been used, along with the distributions expected for  $K_L \rightarrow \pi^0\pi^0$  and  $K_L \rightarrow \gamma\gamma$  events, to compute the dashed curve, which has been normalized for  $P_{\perp} > 165$  MeV. Figure 3b shows the subtracted spectrum, and the solid dots are the Monte Carlo predictions. From this curve we find that a total of  $6077 \pm 85$   $3\pi^0$  and  $\pi^+\pi^-\pi^0$  decays (designated  $N_{3\pi}$ ) were observed.

Once the number of  $\gamma\gamma$  and  $3\pi$  events has been established, the branching ratio  $R = (K_L \rightarrow \gamma\gamma)/(K_L \rightarrow 3\pi^0)$  depends only on the relative detection efficiency for the two processes. It does not depend on the absolute conversion efficiency in the thin radiator of the spectrometer. By Monte Carlo, the efficiency ratio  $\bar{\epsilon}/\epsilon_{\gamma\gamma}$  is found to be  $0.0241 \pm 0.0007$ . Here  $\bar{\epsilon}$  is the weighted efficiency to observe a single  $\gamma$ -ray in the spectrometer from either  $K_L \rightarrow \pi^+\pi^-\pi^0$  or  $K_L \rightarrow 3\pi^0$ , and  $\epsilon_{\gamma\gamma}$  is the corresponding efficiency for  $K_L \rightarrow \gamma\gamma$ . The former is defined by

$$\bar{\epsilon} = [6 \epsilon_{3\pi^0} + 2R' \epsilon_{\pi^+\pi^-\pi^0}]/(6 + 2R'),$$

where  $R' = 0.60 \pm 0.03$  is the branching ratio  $(K_L \rightarrow \pi^+\pi^-\pi^0)/(K_L \rightarrow 3\pi^0)$  recently reported by the CERN-Orsay-Ecole Polytechnique collaboration. (3)

The integers 6 and 2 correspond to the fact that  $3\pi^0$  and  $\pi^+\pi^-\pi^0$  yield 6 and 2  $\gamma$ -rays respectively.

We have studied the dependence of  $\bar{\epsilon}/\epsilon_{\gamma\gamma}$  upon a number of variables. These included: 1) an observed variation in efficiency of the wide gap chamber for angles of incidence greater than 0.5 radians, 2) a slight deviation of the observed  $K_L$  momentum spectrum from that used in the calculation, and 3) variation with respect to the magnetic field of the spectrometer. The latter effect is the only significant one and must be taken into account. If the 2.5 MeV shift of the  $E_{cm}$  and  $P_{\perp}$  peaks were due to a 1% increase in the magnetic field, there would be a 6% decrease in the value of  $\bar{\epsilon}/\epsilon_{\gamma\gamma}$ . Accordingly, we have included an additional 6% error in this efficiency ratio.

The branching ratio R is given by:

$$R = \frac{N}{N} \frac{\gamma\gamma}{3\pi} \times \frac{\bar{\epsilon}}{\epsilon_{\gamma\gamma}} \times \frac{(6 + 2R)}{2} .$$

The integer 2 corresponds to the fact that one has 2  $\gamma$ -rays per  $\gamma\gamma$  decay. We thus find:

$$\frac{K_L \rightarrow \gamma\gamma}{K_L \rightarrow 3\pi^0} = (2.24 \pm 0.28) \times 10^{-3} .$$

Using the recently measured branching ratio  $(K_L \rightarrow 3\pi^0)/(K_L \rightarrow \text{all modes}) = 0.209 \pm 0.011^{(3)}$ , we find

$$\frac{K_L \rightarrow \gamma\gamma}{K_L \rightarrow \text{all modes}} = (4.68 \pm 0.64) \times 10^{-4} .$$

This result is to be compared with  $(7.4 \pm 1.6) \times 10^{-4}$  reported previously,<sup>(1)</sup> and  $(1.3 \pm 0.6) \times 10^{-4}$  reported by Creigee et al.<sup>(4)</sup>

The possibility of experiments to detect direct interference between  $K_L \rightarrow \gamma\gamma$  and  $K_S \rightarrow \gamma\gamma$  has been discussed.<sup>(5)</sup> The realistic possibilities depend strongly on the rate  $K_S \rightarrow \gamma\gamma$  which remains to be observed.

ACKNOWLEDGEMENTS

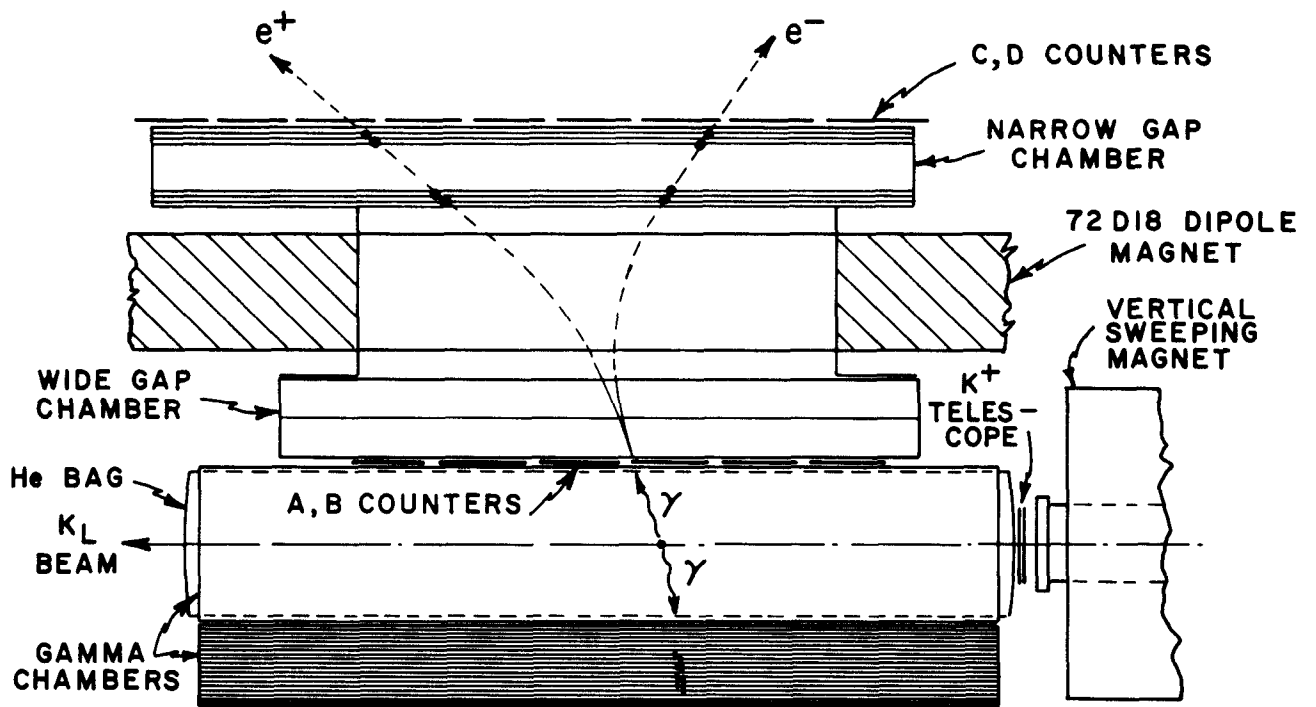
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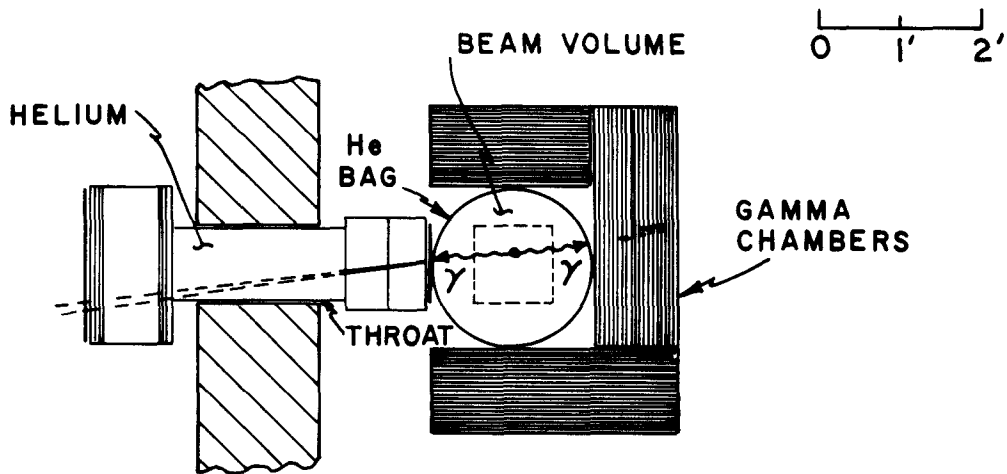
- \* Work supported by the U. S. Office of Naval Research, Contract No. NO014-67-A-0151-0001 and by the U. S. Atomic Energy Commission Contract No. AT(30-1) - 2137.
- † This work made use of computer facilities supported in part by a National Science Foundation grant, No. NSF-Gp 579.
- †† On leave from Département de Physique des Particules Elementaires, Centre d'Etudes Nucléaires, Saclay, France.
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FIGURE CAPTIONS

- Figure 1a Plan view of apparatus .
- 1b End view of apparatus .
- Figure 2a Collinearity distribution of  $K_L \rightarrow \gamma\gamma$  events. The solid dots are the result of a Monte Carlo calculation for the expected distribution. The experiment indicates an angular resolution of  $\pm 0.030$  radians while the Monte Carlo predicts  $\pm 0.025$ .
- 2b Distribution of transverse momentum of spectrometer  $\gamma$ -ray for the  $K_L \rightarrow \gamma\gamma$  events. The solid curve is the Monte Carlo prediction.
- 2c Distribution of energy in the center of mass of the spectrometer  $\gamma$ -ray. The solid curve is the Monte Carlo prediction adjusted to match the experimental resolution, the dashed curve is the background expected from  $K_L \rightarrow \pi^0\pi^0$  decays.
- Figure 3a Distribution of transverse momentum of the spectrometer  $\gamma$ -ray for the entire experiment. The dashed curve is the composite spectrum of  $K_L \rightarrow \pi^0\pi^0$ ,  $K_L \rightarrow \gamma\gamma$  and background.
- 3b Distribution of transverse momentum with the dashed curve of a) subtracted. The solid dots show the Monte Carlo prediction of the distribution for  $K_L \rightarrow 3\pi^0$  and  $K_L \rightarrow \pi^+\pi^-\pi^0$ .



(A) TOP VIEW



(B) FRONT VIEW

FIG. 1

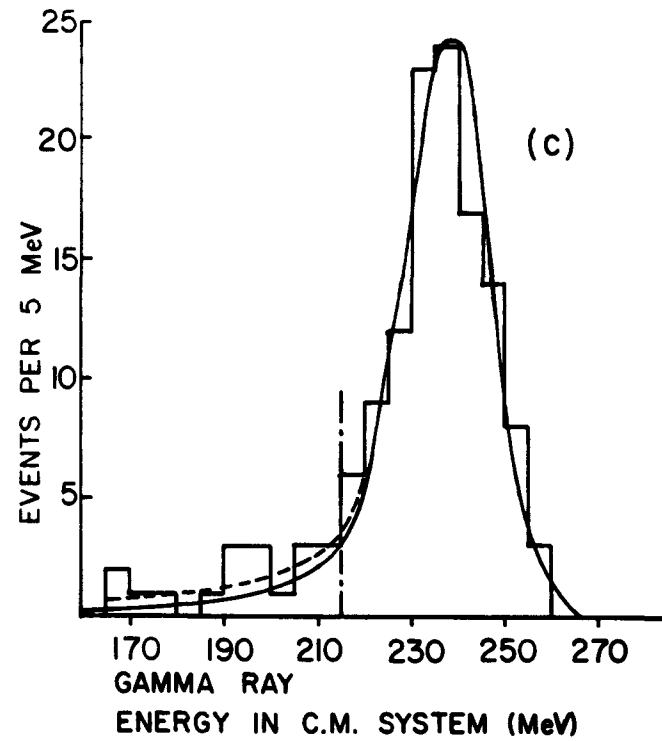
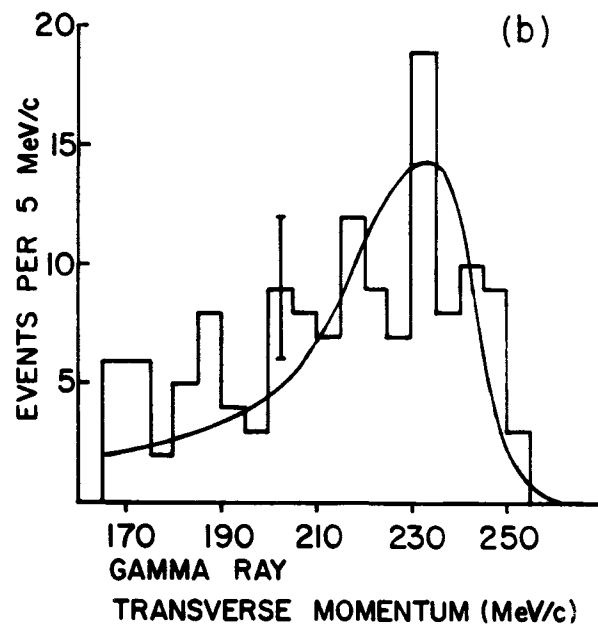
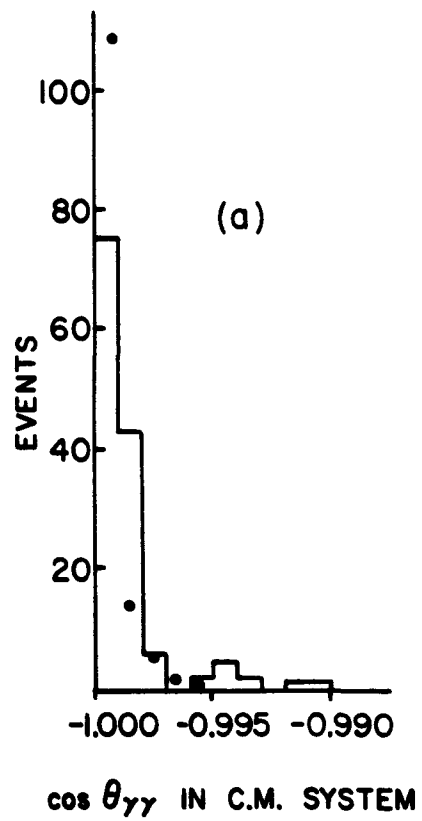


FIG. 2

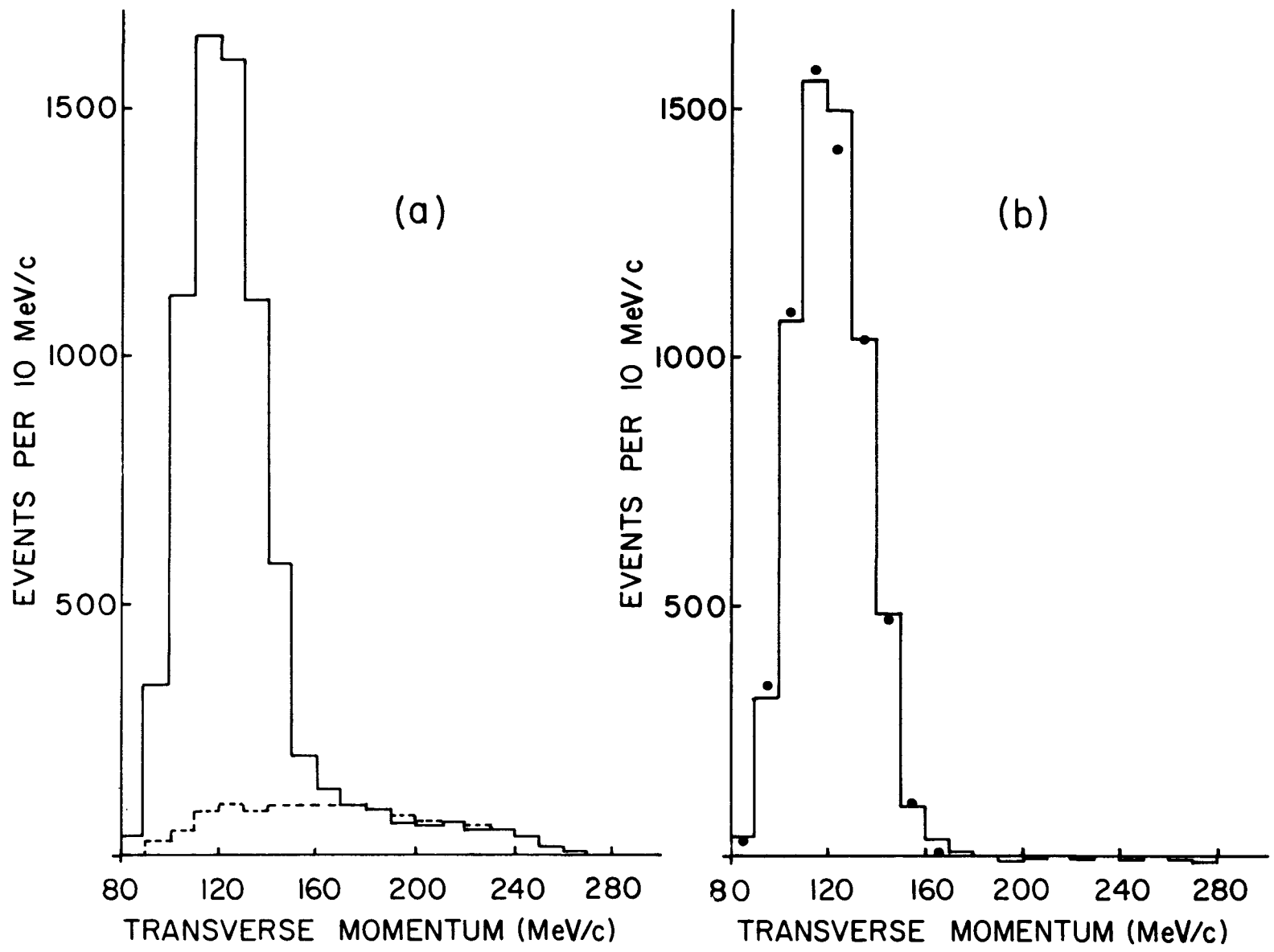


FIG. 3