GAMMA-RAY PROTON INTERACTIONS BETWEEN 0.5 AND 4.8 BeV*†

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This Letter, and the following one, constitute a first report on a detailed study of meson and hyperon production initiated by photons of energies between 0.5 and 4.8 BeV. This study includes a wide new photon-energy range made accessible by the Cambridge Electron Accelerator.

A 12-in. hydrogen bubble chamber, located in a magnetic field of 13.2 kG, has been exposed to a well-collimated, hardened, 4.8-BeV bremsstrahlung beam. A double-conversion method ($\gamma \rightarrow e^+ \rightarrow \gamma$) was used to achieve the low-intensity beam necessary for the bubble chamber. This permitted maintaining a high-intensity circulating beam in the accelerator which insured stable operation and compatibility with simultaneous beam users. The intensity of our beam could be controlled by varying the energy selected by the e^+ transport system or the thickness of the two conversion targets; it was designed to yield an average of 40 equivalent quanta (about four electron-positron conversion pairs in the chamber) per picture. This intensity resulted in about one nuclear event (defined as having three or more visible prongs, or one prong plus V^0's) per 100 pictures. The neutron contamination in the beam was negligible. This report is based upon approximately 120 000 pictures analyzed, and represents about 15% of our total sample.

The separation between the various classes of events was achieved by using the CERN kinematical fitting program GRIND. The correct hypothesis was selected on the basis of the χ^2 value and by requiring agreement between the observed and predicted bubble density for each track. Since the incident photon energy for a particular event was unknown, we normally had three degrees of freedom (3C) for events with no neutral missing (e.g., $\gamma + p \rightarrow p + \pi^+ + \pi^-$), and zero degrees of freedom (0C) if an additional neutral particle was produced (e.g., $\gamma + p \rightarrow n + \pi^+ + \pi^- + \pi^+$). The direction of the incident photons was known to $\pm\frac{1}{2}°$ from measurements on the electron-positron pairs produced in the hydrogen. Initially, a 3C fit was made to all events. The χ^2 distribution obtained indicated a clear-cut separation between the true 3C events ($\chi^2 < 10$) and the remainder. These remaining events were all consistent with 0C events, i.e., with one missing neutral particle. It is probable that some of these events involved two or more missing neutrals since, in practice, at high energies such an event will almost always fit as a 0C configuration. This is discussed in greater detail below.

A summary of the observed events is given in Table I, and the resulting cross sections are shown in Fig. 1. A count of electron-positron pairs produced in the hydrogen, and

Table I. Reaction types and number of events.

Reaction	Threshold (BeV)	Number of events
$\gamma+p\to p+\pi^++\pi^-$	0.32	588
$\to p+\pi^++\pi^-+\pi^0$	0.51	192
$\to n+\pi^++\pi^-+\pi^+$	0.51	119
$\to p+2\pi^++2\pi^-$	0.73	24
$\to p+2\pi^++2\pi^-+\pi^0$	0.96	11
$\to n+3\pi^++2\pi^-$	0.96	3
$\to$ Strange particles	0.91	51

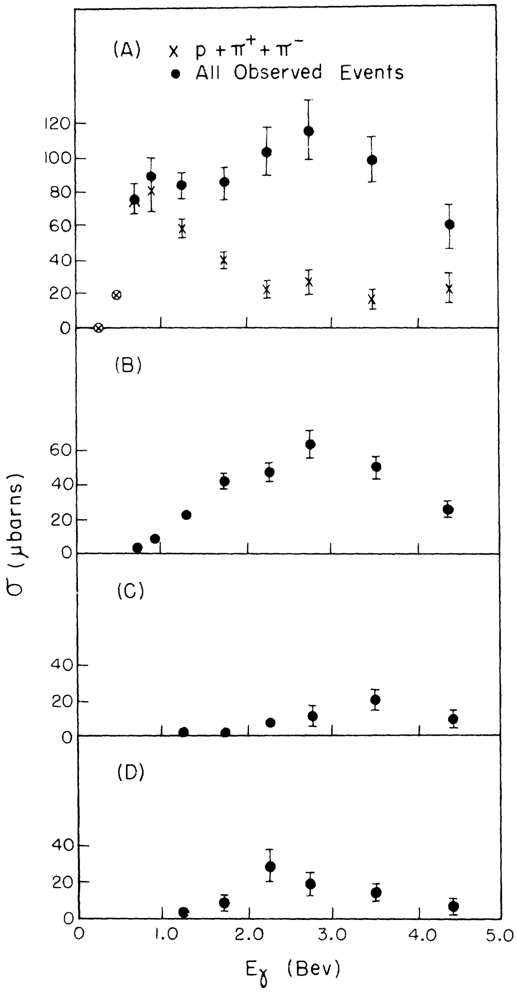

FIG. 1. Cross sections for (a) $\gamma+p\to p+\pi^++\pi^-$, and the sum of these with the cross sections of (b), (c), and (d); (b) $\gamma+p\to p+\pi^++\pi^-+\pi^0+(y\pi^0)$ and $\gamma+p\to n+2\pi^++\pi^-+(y\pi^0)$, where $y\geq 0$; (c) $\gamma+p\to p+2\pi^++2\pi^-+y\pi^0$ $(y\geq 0)$ and $\gamma+p\to n+3\pi^++2\pi^-$; (d) all reactions resulting in strange particles (corrected for potential paths and neutral branching ratios). Note that each point is plotted at the center of the corresponding bremsstrahlung energy range.

measurements of their energy, yielded the photon-beam intensity and overall energy spectrum necessary for cross-section calculations. The two-pion-production cross section rises rapidly to a maximum near $E_\gamma=1.0$ BeV, and then falls off. This is in agreement with the cloud-chamber data of Chasan et al.[1] below 1 BeV. At photon energies above 1.0 BeV, three- and four-pion production and strange-particle production become increasingly important, so that the total observed cross section remains approximately constant. Note that these cross sections are for observed nuclear events as defined above; for instance, they do not include events with only one charged particle, e.g., π^+n, $p\pi^0$, $p\pi^0\pi^0$. The observed strange-particle cross sections have been corrected for potential paths,[2] and for the neutral decay modes.

As discussed above, the three-pion sample probably contains some four-pion events where two of the particles are neutral. We can estimate the number of these events by considering the cross section for four-pion events where all particles are charged (i.e., five-prong events). It is seen that this cross section, and hence the contamination of the three-pion sample, is negligible below a photon energy of 2 BeV. If we assume equal population of the charged and neutral states for the four-pion events, the possible contamination of the three-pion sample could be as large as 40% for photon energies between 2 and 3 BeV, and 100% above 3 BeV. With an increased sample of five-prong events it should be possible to make a more exact, model-dependent, estimation of this correction.

We first discuss the strange-particle events. These are summarized in Table II. Even with this limited sample there is good evidence for Y^* production. Excluding the $K^+\Lambda^0$ events in which no known resonances can be formed, we notice that in almost all events there exists one combination of the secondary particles the mass of which agrees with one of two known Y^*'s: $Y_1^*(1385)$ or $Y_0^*(1520)$. The situation is illustrated in Figs. 2(a) and (b). Both plots include all possible hyperon-meson mass combinations; the shaded regions contain those combinations (one for each event) which fall closest to the Y^* mass. The smooth curves show the expected phase-space mass distri-

Table II. Strange-particle event types and number of events.

Strange-particle reaction	Threshold (BeV)	Number	Corrected number[a]
$\gamma+p\to p+K^++K^-$	1.52	10	10
$\to p+K^++K^-+\pi^0$	1.72	1	1
$\to p+K^++K^-+\pi^++\pi^-$	2.11	1	1
$\to K^++\Lambda^0$	0.91	7	21
$\to K^0+\Lambda^0+\pi^+$	1.15	5	15
$\to K^++\Lambda^0+\pi^0$	1.15	4	12
$\to K^++\Lambda^0+\pi^++\pi^-$	1.41	13	13
$\to \Sigma^++K^0$	1.07	1	3
$\to \Sigma^++K^0+\pi^0$	1.29	1	3
$\to \Sigma^++K^++\pi^-$	1.29	2	2
$\to \Sigma^-+K^++\pi^+$	1.29	2	2
$\to \Sigma^-+K^0+2\pi^+$	1.57	3	3
$\to \Xi^-+K^++K^+$	2.37	1	1

[a]Corrected for potential path and neutral modes of decay.

bution normalized to the total number of events. Within our limited statistics we see no evidence for K^* or φ production.

Using all possible mass combinations, appropriately normalized, the average total cross sections (corrected for potential path and for neutral decay modes) for Y^* production in the energy range 2-4.8 BeV are found to be

$$Y_0^*(1520) = 6.3 \pm 2.2\ \mu\text{b},$$

$$Y_1^*(1385) = 4.9 \pm 2.5\ \mu\text{b}.$$

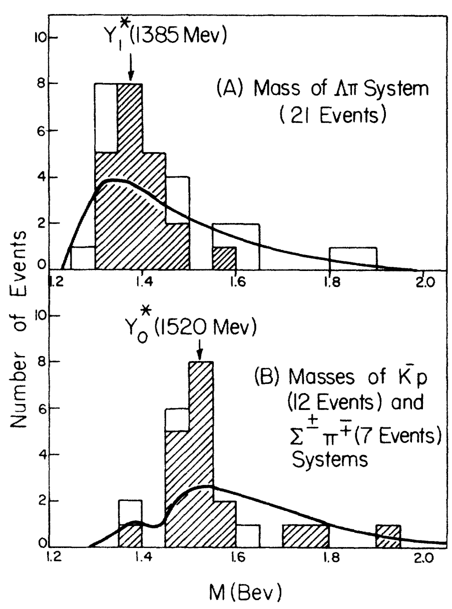

FIG. 2. Invariant-mass distributions for $\Lambda\pi$ and K^-p or $\Sigma^{\pm}\pi^{\mp}$ systems, respectively. The shaded areas show the masses closest to the Y^* mass for each event. The total area shows the masses for all combinations. The smooth curves are phase space normalized to all events.

A detailed discussion of the $p\pi^+\pi^-$ (3C) events will be presented in the following paper.[3] Due to the smallness of our samples of three- and four-pion events, we can expect to see only dominating features, if any, of these reactions. Some of the mass plots are shown in Fig. 3. We see clear evidence for production of $N^{*++}(1238)$ in the reaction $\gamma+p\to p+\pi^++\pi^-+\pi^0$ [Fig. 3(a)] and, similarly, N^{*-} in the final state $n\pi^+\pi^+\pi^-$ [Fig. 3(b)]. This is of particular interest in view of the fact that the latter reaction cannot be produced via the exchange of one singly charged particle. It should be noted that the reaction $\gamma+p\to p+\pi^++\pi^-+\pi^0$ is not dominated by ω^0 production as shown by the mass plot of the $\pi^+\pi^-\pi^0$ system [Fig. 3(c)]. This point will be further discussed in the following paper.

SU(3) symmetry[4] predicts the following ratios between (3,3) isobar and $Y_1^*(1385)$ production matrix elements:

$$\frac{|M(\gamma+p\to N^{*-}+\pi^++\pi^+)|^2}{|M(\gamma+p\to Y_1^{*-}+K^++\pi^+)|^2}=\frac{3}{2}, \tag{i}$$

$$\frac{|M(\gamma+p\to N^{*0}+\pi^+)|^2}{|M(\gamma+p\to Y_1^{*0}+K^+)|^2}=2. \tag{ii}$$

The observed cross sections must be corrected by the usual kinematical factors[5] in order to compare them with these ratios. As may be seen in Fig. 3(b), there is distinct evidence for $N^{*-}(1238)$ production in the three-pion

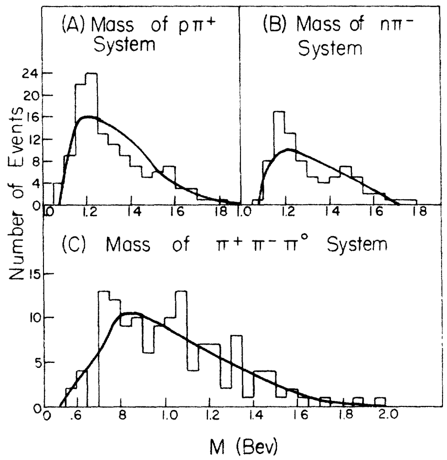

FIG. 3. Invariant-mass distributions of the $p\pi^+$ and $\pi^+\pi^-\pi^0$ systems from the reaction $\gamma+p\rightarrow p+\pi^+ +\pi^- +\pi^0$, and the $n\pi^-$ system from the reaction $\gamma+p\rightarrow n+2\pi^+ +\pi^-$, all for $E_\gamma \geq 1.1$ BeV. The smooth curves are phase space normalized to all events.

events. After applying an average kinematical correction we obtain a value of 0.8 ± 0.5 for relation (i). Similarly, using the results on N^{*++} production to be described in the following Letter,[3] coupled with the assumption of a 3:1 ratio for N^{*++}:N^{*0} production, we obtain 2.0 ± 1.7 for relation (ii).[6] Considering the uncertainties in these estimates due to the limited sample, we can conclude only that the data are not inconsistent with the SU(3) prediction.

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[1]B. M. Chasan, G. Cocconi, V. T. Cocconi, R. M. Schectman, and D. H. White, Phys. Rev. 119, 811 (1960).

[2]Those strange-particle events which could only be identified if the decay of the Λ^0 was observed were corrected for potential path by increasing the number by a factor of 2.0 ± 0.7. This factor is an estimate based on the observed Λ^0 momenta.

[3]H. R. Crouch, Jr., et al., following Letter [Phys. Rev. Letters 13, 640 (1964)].

[4]C. A. Levinson, H. J. Lipkin, and S. Meshkov, Proceedings of the International Conference on Nucleon Structure at Stanford University, 1963, edited by R. Hofstadter and L. I. Schiff (Stanford University Press, Stanford, California, 1964).

[5]S. Meshkov, G. A. Snow, and G. Yodh, Phys. Rev. Letters 12, 87 (1964).

[6]A direct estimate of this ratio using the $p\pi^-$ invariant-mass distribution is consistent with this conclusion.