field of view and a high throughput radiometer carried above the earth's atmospheric water vapor, and (b) a partial survey of the sky near 50 μ with a telescope capable of resolving and detecting large numbers of individual infrared galaxies. Method (b) is basically easier since it is much less sensitive to extraneous background radiation and deals with larger signals.

Once the spectral energy distribution is well determined for a representative sample of infrared galaxies, it should be possible to use the observations of method (a) as a sensitive test of cosmological models involving evolution.

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PARTIAL PHOTOPRODUCTION CROSS SECTIONS UP TO 12 GeV*

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The Stanford Linear Accelerator Center 40-in. hydrogen bubble chamber has been exposed to positron-electron annihilation radiation at 5 and 7.5 GeV, which was superimposed upon a background of bremsstrahlung radiation with 12-GeV maximum energy. Reaction cross sections for events with no neutral particles are presented for all energies up to 12 GeV, for one neutral at 5 and 7.5 GeV, and for multineutral production at 7.5 GeV.

We report here the results obtained from a study of γp interactions produced by the Stanford Linear Accelerator Center (SLAC) annihilation beam in the SLAC 40-in. hydrogen bubble chamber. The special feature of this experiment is that the use of positron annihilation radiation allows a clean separation of events with a single neutral particle from multineutral events.

The experimental arrangement, and details of the analysis, have been given in another paper.[1] So far 10^6 pictures have been taken with this beam setup under various conditions and 180 000 have been analyzed to date: (I) 60 000 pictures with 10-GeV e^+, 5.2-GeV annihilation energy; (II) 60 000 pictures with 12-GeV e^+, 7.5-GeV annihilation energy; (III) 60 000 pictures with 12-GeV e^-, bremsstrahlung.

We present combined results from these three different exposures on the following reactions which can be completely analyzed:

$$\gamma p \to p\pi^+\pi^-, \quad (1)$$

$$\to p\pi^+\pi^-\pi^0, \quad (2)$$

$$\to n2\pi^+\pi^-, \quad (3)$$

$$\to p2\pi^+2\pi^-, \quad (4)$$

$$\to p2\pi^+2\pi^-\pi^0, \quad (5)$$

$$\to n3\pi^+2\pi^-. \quad (6)$$

The separation of reactions with a single neutral particle from those with more than one is made possible at 5 and 7.5 GeV by the small energy uncertainty of the annihilation peak in the photon-beam energy spectrum. For reactions with no missing neutrals in these topologies we are further able to obtain cross sections up to 12 GeV. Reactions with one charged secondary will not be analyzed; those with ≥7 charged secondaries and those with strange-particle secondaries have not as yet been fully analyzed and are not included. Topological cross sections were given previously.[1]

Annihilation spectrum. – The photon spectrum produced by high-energy positrons on hydrogen at a given production angle consists of an annihilation peak superimposed upon a bremsstrahlung spectrum. The relation between annihilation photon energy E_γ, production angle θ, and positron energy E_+ is

$$E_\gamma = \frac{E_+}{1+(E_+/2m)\theta^2}, \tag{7}$$

where m is the electron mass and $E_+ \gg m$.

Owing to the finite acceptance $\Delta\theta$ in photon-production angle, the annihilation photons have an energy spread about the nominal value. However, by measuring the position of the interaction point in the chamber, the photon-production angle could be determined with a precision independent of the angular acceptance, using formula (7). The parameters were $E_+ = 10.0 \pm 0.05$ GeV, $\theta = 9.4$ mrad, $\Delta\theta = \pm 0.65$ mrad, $E_\gamma = 5.2 \pm 0.3$ GeV for exposure I, and $E_\pm = 12.0 \pm 0.06$ GeV, $\theta = 7.15$ mrad, $\Delta\theta = \pm 0.45$ mrad, for exposures II and III ($E_\gamma = 7.5 \pm 0.4$ GeV for II). The uncertainty in the calculated energy arising from finite positron spot size, positron beam divergence, and multiple scattering in the hydrogen radiator is ±1.6%.

In exposure I, one-prong events were not recorded. Otherwise, the scanning and measuring procedures for pairs and events were the same for all three exposures and have been described in another paper.[1] Geometrical reconstruction and kinematic analysis were performed using the TVGP-SQUAW system, and fits inconsistent with ionization were rejected by visual inspection. The number and energy distribution of photons traversing the chamber was determined by counting and measuring a sample of the e^+e^- pairs produced within the event volume, and using the known pair-production cross sections. The pair spectra found for exposures II and III were presented in Ref. 1.

The cross sections given in Table I are based upon 1413, 1690, and 1290 3-prong, and 183, 266, and 82 5-prong events found in exposures I, II, and III, respectively, not including strange particles. Of these, 93.4% gave a successful geometrical reconstruction. Kinematic fits were made to determine their cross sections.

Table I. Partial cross sections in the 3- and 5-prong topologies.

	$E_\gamma = 5.2$ GeV	$E_\gamma = 7.5$ GeV
$\gamma p \to p\pi^+\pi^-$	19.8 ±2.8	16.0 ±2.0
$\to p\pi^+\pi^-\pi^0$	20.8 ±3.6	10.9 ±2.3
$\to n2\pi^+\pi^-$	11.2 ±2.4	7.3 ±1.7
$\to p\pi^+\pi^-\pi^0\pi^0\cdots$ [a]		30 ±7
$\to n2\pi^+\pi^-\pi^0\cdots$ [a]		14 ±6
$\to p2\pi^+2\pi^-$	5.5 ±1.5	4.2 ±1.1
$\to p2\pi^+2\pi^-\pi^0$	8.6 ±2.6	13.2 ±3.8
$\to n3\pi^+2\pi^-$	3.3 ±1.2	3.4 ±1.3
$\to \begin{pmatrix} p2\pi^+2\pi^-2\pi^0\cdots \\ n3\pi^+2\pi^-\pi^0\cdots \end{pmatrix}$ [a]		18.2 ±3.1

[a] More than one neutral particle.

Separation of reactions. – For Reactions (1) and (4), where there is no missing neutral particle, the photon energy can be determined uniquely through a 3-constraint fit (3C). Any event fitting to Reaction (1) or (4), and satisfying the ionization criterion, was accepted as a genuine 3C event. Fake calculations[2] have shown that (a) no 3- or 5-prong events involving neutrons will fit the 3C hypothesis, (b) the contamination of Reaction (1) by single and multiple π^0 events is less than 5%, and (c) the contamination of Reaction (4) is negligible.

In separating single π^0 events produced by annihilation photons, one is faced with two problems. The first is the same as encountered in charged-particle beam experiments, namely contamination from multineutral particle production by the annihilation photons owing to finite measuring accuracy. The second is the elimination of false fits coming from events due to bremsstrahlung photons. The procedure used to effect the separation was to compare the hypothesis with one constraint (1C) and zero constraints (0C). The 1C fit assumes production by an annihilation photon, while the 0C fit allows any photon energy. For genuine events, the photon energies from 1C and 0C fits must agree. Figure 1 shows the distribution of the differences between 1C and 0C determinations of photon energy for the Reactions (2), (3), (5), and (6) from the 5 and 7.5-GeV exposures. As can be seen, the distributions peak sharply at zero, indicating a clean separation of single neutral production. The arrows indicate cutoffs used for determining the corresponding cross sections. After use of the ionization criterion, less than 15% of these

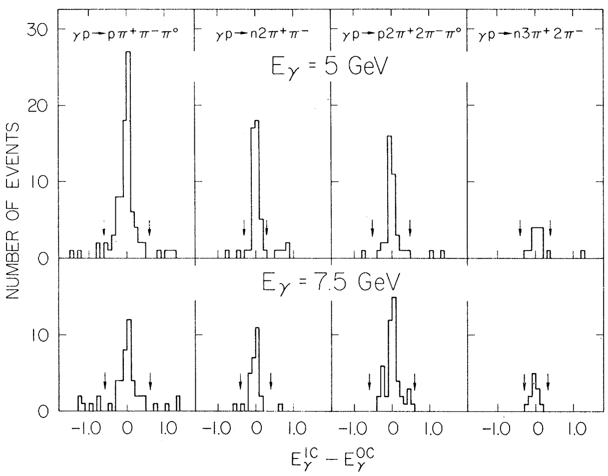

FIG. 1. Difference between photon energy found in 1C and 0C fits to reactions with missing neutral particles at 5.2 and 7.5 GeV. The arrows indicate the cutoffs used in calculations of cross sections. Events with |difference| > 1.4 GeV are not shown. They were rejected as 1C events.

events were ambiguous between single neutron and π^0 production. These were divided on the basis of χ^2.

Cross section for reactions.—(a) $\gamma p \to p\pi^+\pi^-$. Figure 2(a) shows the cross section for this reaction as a function of photon energy. From 4 to 12 GeV the cross section remains rather constant. Below 5.8 GeV the cross section values are in agreement with those found in the Cambridge Electron Accelerator[3] and DESY[4] experiments, and are consistent over our range with the more recent SLAC streamer chamber results.[5]

Figure 2(b) shows the $\pi^+\pi^-$ mass distribution for photon energies between 5 and 8 GeV, in which ρ^0 production clearly predominates. Averaged over the annihilation peak regions the ρ^0 production cross section is 16 ± 2.5 μb at 5.2 GeV and 14 ± 2.5 μb at 7.5 GeV.

(b) $\gamma p \to p2\pi^+2\pi^-$. Figure 2(c) shows the cross section for this reaction as a function of photon energy. It reaches a roughly constant value ~5 μb above 3 GeV. Also shown in Fig. 2(c) are cross-section values as predicted by Satz who relates this reaction to the analogous πp and pp reactions using the vector-dominance model and a quark model.[6] The theoretical cross sections agree with the measured values.

(c) Single neutral production. For these reactions we can report cross sections only at the annihilation peaks. These are presented in Table I. The ratio between π^0 and neutron-associated events is about 2, reminiscent of πp interactions. The cross section for Reactions (2)

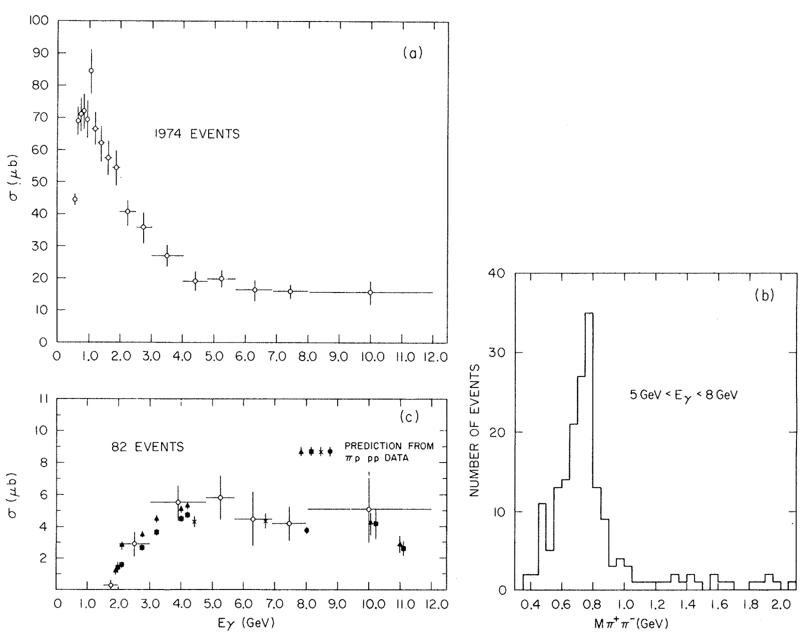

FIG. 2. (a) Cross section for Reaction (1) as a function of photon energy. Data are compiled from exposures I, II, and III. (b) Mass spectrum of $\pi^+\pi^-$ pairs from Reaction (1) for photon energies 5-8 GeV. Data are combined from all exposures. (c) Cross section for Reaction (4) as a function of photon energy, data combined from all exposures. Open circles: our data; triangles: predicted from $\pi^-p \to p\pi^+2\pi^-\pi^0$; filled circles: predicted from $\pi^+p \to p2\pi^+2\pi^-$; squares: predicted from $\pi^-p \to n2\pi^+2\pi^-$; crosses: predicted from $pp \to pn2\pi^+2\pi^-$.

and (3) decrease substantially between 5 and 7.5 GeV, in contrast to those of Reactions (5) and (6).

(d) Multineutral production. At 7.5 GeV, the cross section for multineutral events may be deduced by counting the numbers of 3- and 5-prong events not assigned a 1C or 3C interpretation, and subtracting those of the e^- exposure from those of the e^+ exposure. The technique, and corrections applied, are as described in another paper,[1] except that the events have been divided as far as possible into proton and neutron associated events on the basis of track ionization (ambiguous events were divided equally). The resulting cross sections are shown in Table I.

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γ-p TOTAL HADRONIC CROSS SECTIONS AT 7.5 GeV*

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The total hadronic γp cross section has been measured using 7.5-GeV positron-electron annihilation radiation in a hydrogen bubble chamber. A value of 126 ± 17 μb is found, excluding reactions with only one charged particle (~3 μb).

We report a measurement of the total hadronic γp cross section $\sigma_{\gamma p}^{\text{tot}}$ at 7.5 GeV. The method used was to expose the Stanford Linear Accelerator Center 40-in. hydrogen bubble chamber to high energy positron-electron annihilation radiation (plus a background of wide-angle bremsstrahlung) and to subtract out the bremsstrahlung contribution by making an identical exposure using electron-induced radiation instead of that from positrons. We find $\sigma_{\gamma p}^{\text{tot}} = 126 \pm 17$ μb if we neglect reactions with one charged particle.

Beam. – The layout of the beam is shown in Fig. 1. A positron or electron beam of 12 GeV/c momentum with a spread of ±0.5% traverses a 15-cm liquid-hydrogen target and is dumped into a shielding mass. At the target cell the spot was about 3 mm in diameter. The e^+ or e^- beam position and direction were kept to $<10^{-4}$ rad by checking the toroid position monitors $P36$ and $2P1$. Photons produced at an angle of 7.15 mrad pass through the collimators $C0$, $C1$, and $C2$ (altogether 140 radiation lengths) and enter the 40-in. hydrogen bubble chamber. Charged particles are removed by three sweeping magnets, and the low-energy photon component is suppressed by 1 radiation length of lithium hydride placed in a magnetic field. The beam cross section at the bubble chamber was 42×6.5 cm^2.

Bubble Chamber. – The Stanford Linear Accelerator Center 40-in. hydrogen bubble chamber has a visible volume 1 m in diameter and 0.5 m in depth, and a magnetic field of 26 kG. A Scotchlite-lined piston provides bright field illumination. A study of a zero-field exposure to charged