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TOTAL AND PARTIAL PHOTOPRODUCTION CROSS SECTIONS AT 1.44, 2.8, AND 4.7 GeV *

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A nearly monochromatic high-energy photon beam produced by Compton backscattering of ruby laser light has been used to study photoproduction in a hydrogen bubble chamber. The total hadronic γp cross sections at 1.44, 2.8, and 4.7 GeV are found to be 145.1 ± 5.7, 131.3 ± 4.3, and 124.2 ± 3.9 μb, respectively. Partial cross sections are presented also.

In 1963 R. Milburn[1] concurrently with Arutyunian, Goldman, and Tumanian[2] pointed out that Compton backscattering of an intense polarized light beam by high-energy electrons would produce useful yields of monoenergetic polarized photons. Such a beam has been realized at the Stanford Linear Accelerator Center (SLAC)[3] and used together with the 82-in. Lawrence Radiation Laboratory–SLAC hydrogen bubble chamber for a study of γp interactions with linearly polarized photons. About 800 000 pictures have been taken at photon energies of 1.44, 2.8, and 4.7 GeV, 10% of which have been used for the present study. Because the energy spread is small and because the bubble chamber permits a clear separation of electromagnetic and hadronic interactions, the exposures allow a straightforward measurement of the total hadronic γp cross section. Thus this measurement is free of the usual background and detection biases caused by the 150-times more copious pair production.

Beam.—The beam results from Compton backscattering of light by high-energy electrons. This is a two-body process; hence for given incident photon and electron energies k_i and E, the energy k of the scattered photon depends only on the laboratory angle θ as measured with respect to the incident electron beam:

$$k = \frac{E(1-a)}{1+a(\gamma^\theta)^2}, \quad \theta \ll 1, \tag{1}$$

where m = electron mass, $\gamma = E/m$, and $a = [(1+4\gamma)k_i/m]^{-1}$.

To limit the scattered-photon energies to the top 10% of the Compton spectrum at our energies requires angular definition of the order of 10^{-5} rad about $\theta = 0°$ for both the incident-electron and the backscattered-photon beam. A special fea-

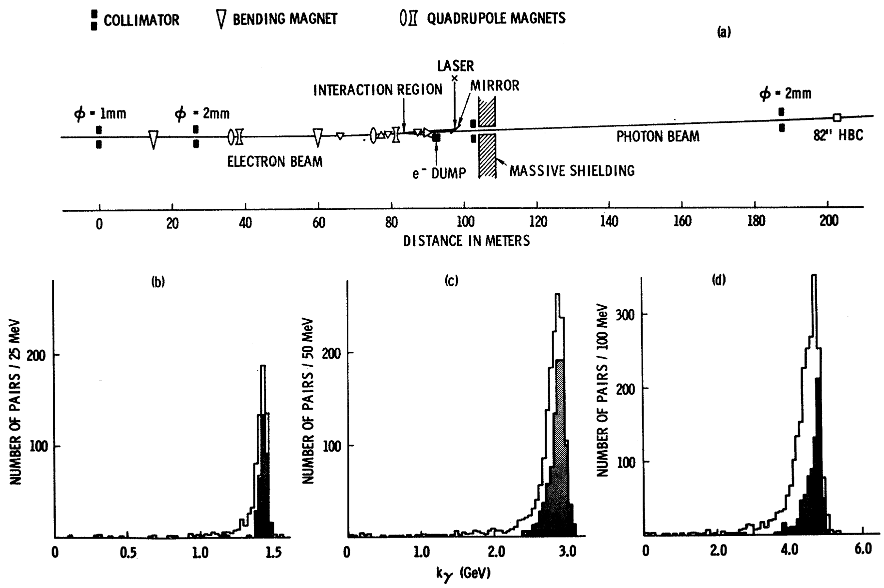

FIG. 1. (a) Experimental layout of the beam. (b)-(d) The pair-energy spectra at 1.4, 2.8, and 4.7 GeV. The solid histograms show the energy spectra of events fitting the reaction $\gamma p \rightarrow p\pi^+\pi^-$ (168 events at 1.4, 758 events at 2.8, and 293 events at 4.7 GeV). In Figs. 1(c) and 1(d), $p\pi^+\pi^-$ events with photon energy below 2 GeV are not shown.

ture of the Compton process is that if the incident light is polarized, the high-energy part of the Compton spectrum is almost completely polarized in the same way.

Figure 1(a) shows the beam schematic layout. Since 10^{11} electrons in a 1-μsec pulse pass through the 5-m-long interaction region. The electron beam is a few millimeters in diameter with about 10^{-5}-rad divergence. The linearly polarized light beam is generated by a Q-switched ruby laser ($\lambda = 6934$ Å, $k_l = 1.786$ eV, maximum output = 2 J, and pulse length = 50 nsec). The polarization mode can be changed from pulse to pulse by a set of quarter- and half-wave plates. The two beams clash at a relative angle of 3 mrad in the interaction region. The accepted range of scattered photon angles is defined by a 2-mm-diam hole in the final collimator 100 m downstream of the interaction region. Scintillators embedded in this collimator are used to control the beam steering to 10^{-6} rad. The optimal flux for the analysis of the photographs turned out to be 100 photons per pulse; actually, several hundred were obtainable at the higher energies.

In Fig. 1(b)-1(d), the pair energy spectra are shown for the three different energies. In addition to the peak there is a small tail (of a few %) extending towards low energies. Also shown in Fig. 1(b)-1(d) are the distributions of the photon energy obtained from events which satisfy a three-constraint (3C) fit to the reaction $\gamma p \rightarrow p\pi^+\pi^-$ and provide a more accurate measurement of the photon energy than do the pairs. Table I gives the full width at half-maximum of these distributions. The energy determination was checked to 0.2 % by measuring K^0 decays in the chamber.

Scanning and Measuring. – Film was taken at the energies shown in Table I. For the total-cross-section measurement film with low photon flux was selected. All pictures were independently scanned twice and discrepancies were resolved in a third pass. The combined double-scan efficiency ϵ was better than 99 % for all topologies including e^+e^- pairs except that events with one changed particle have $\epsilon = 94\text{-}97\,\%$. The scanning efficiencies were checked by scanning part of the film a third time. The photon flux was determined by counting the number of e^+e^- pairs produced in the fiducial volume. The events were measured in order to make sure that the event vertex was located in the beam volume. This volume is well-defined because the diameter of the photon beam is less than 3 mm in the chamber. Geometrical reconstruction and kinematical analysis were done using the programs TVGP and SQUAW.

Results. – The photoproduction cross section is obtained from the number of events N_{ev} and the number of e^+e^- pairs N_{pair} produced in the same chamber volume using the known[4] e^+e^- pair-production cross section σ_{pair}:

$$\sigma(\gamma p \rightarrow \text{hadrons}) = (N_{\mathrm{ev}}/N_{\mathrm{pair}})\sigma_{\mathrm{pair}}. \qquad (2)$$

Table I. Numbers of events observed and corrected, and their cross sections, by topology. Average photon energies (GeV) are 1.443 ±0.003, 2.84 ±0.01, and 4.66 ±0.01. Full widths at half-maximum (GeV) are 0.050, 0.150, and 0.300.

Topology	Number of Events Found for k(GeV)			Corrections[a] in Percent for k(GeV)			Cross Sections in μb for k(GeV)		
	1.44	2.84	4.66	1.44	2.84	4.66	1.44	2.84	4.66
1 prong[b]	356	293	200	α) 2.5	5.1	6.1	54.9±3.2	22.7±1.5	15.6±1.2
				β)	- 9.8	-12.5			
				γ)-7.1	-14.2	-14.0			
3 prong	536	986	877	β)	- 1.0	- 0.9	85.6±3.7	91.5±3.2	81.6±2.8
				γ)-1.4	- 2.0	- 4.2			
5 prong	1	96	190	γ)		- 1.0	0.2±0.2	9.2±1.0	18.4±1.3
7 prong		2	8					0.2±0.2	0.8±0.3
With strange particle decay	27	82	82	γ)	- 0.8	- 2.8	4.4±0.9	7.7±0.9	7.8±0.9
Total	920	1,459	1,357	α) 1.0	1.0	0.9	145.1±5.7	131.3±4.3	124.2±3.9
				β)	- 2.7	- 2.5			
				γ)-3.6	- 4.5	- 5.1			

[a]The entries α, β, γ, denote corrections for scanning efficiency, for events out of beam volume, and for low-energy photons, respectively. The low-energy cutoffs were 1.0, 2.25, and 3.0 GeV for the three different energies.

[b]An n-prong event has n-charged particles without detected strange-particle decay.

In Table I the relevant numbers, such as the number of events found in the various topologies, are summarized together with the corrections applied. The low-energy correction removes events produced by photons in the low-energy tail. For photon energies below 1 GeV, we used the published cross sections on single[5]- and multiple[4]-pion production. For energies above 1 GeV, the cross-section values measured in this experiment were interpolated. The uncertainties in the cross sections from the low-energy photon flux contribute errors of the order of 1.0-1.9 μb to the total-cross-section errors. The loss of events of the type $\gamma p \to p\pi^+\pi^-$ produced at very small momentum transfers to the proton was found to be negligible. The errors given for the cross sections include the statistical uncertainty in the number of events and in the photon flux, and the uncertainties in the pair-production cross section and in the corrections for low-energy photons.

In Fig. 2 the total hadronic γp cross section as measured in this experiment is shown as a function of the photon energy together with the results of previous experiments.[6,7] The cross-section values of Ref. 6 are lower than ours at 2.8 and 4.7 GeV. Our values are in agreement with the

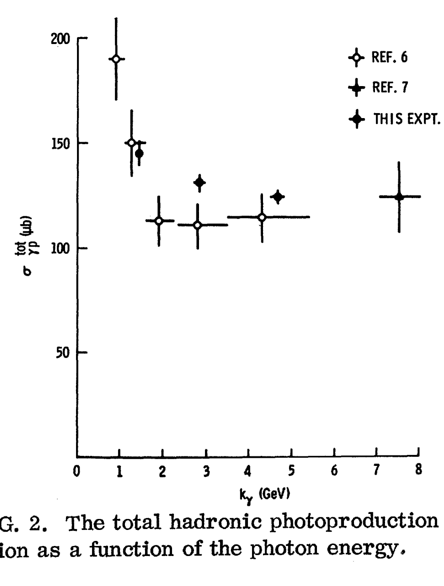

FIG. 2. The total hadronic photoproduction cross section as a function of the photon energy.

preliminary results of a counter measurement[8] and of an electron-proton inelastic-scattering experiment.[9]

In the framework of the vector-dominance model, the total γp cross section can be related to the forward cross sections for photoproduction of ρ^0, ω, and φ. Using the assumptions of Guiragossián and Levy,[10] our measurements at 2.8 and 4.7 GeV lead to $\gamma_\rho^2/4\pi = 0.4 \pm 0.05$ for the square of the γ-ρ coupling constant.

Table I presents a breakdown of the photoproduction total cross sections into contributions from various topologies. The contribution from reactions with one charged outgoing particle decreases rapidly between 1.4 and 4.7 GeV. The dominant topology is that with three charged outgoing particles. However, with increasing photon energy reactions with higher multiplicities gain importance. (See also Refs. 4, 7, 11, and 12.) In this respect, photoproduction behaves in the same way as πN, KN, or NN interactions.

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POSSIBLE RELATION BETWEEN LEPTON NONCONSERVATION AND *CP* NONCONSERVATION*

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A weak-interaction Hamiltonian is presented which can account in a unified way for the CP nonconservation observed in K_L decay and for a possible lepton nonconservation associated with nuclear double-beta decay.

If the lepton weak current which enters into the weak-interaction Hamiltonian is of the form[1]

$$l_\lambda = \sum_{l=e,\mu} (\bar{\psi}_l \gamma_\lambda \{(1+\gamma_5) + \eta(1-\gamma_5)\} \psi_{\nu_l}) \tag{1}$$