does not vanish at $t = 0$ shows that there are problems associated with evasive extrapolations to the pion pole (i.e., extrapolations which assume that the amplitudes vanish at $t = 0$). The effect of this on the results for pion-pion scattering will be discussed elsewhere.

These curves exhibit a forward peak for transverse rho production.[19] This is in agreement with the conclusion of Cho and Sakurai[7] and in disagreement with that of Avni and Harari,[6] even though $\rho_{11}(d\sigma/dt)$ in the OPE frame (not shown) is relatively flat.

One of us (L.G.) would like to thank G. Kane for his criticism of the extrapolation procedure previously used in Refs. 9 and 10. Part of this work was initiated to answer his criticism. A discussion with J. J. Sakurai drew our attention to the importance of the $t = 0$ region.

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PHOTOPRODUCTION OF 8-GeV RHO MESONS FROM NUCLEI*

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We present results on measurements of photoproduction of ρ^0 mesons from seven different nuclei. The forward cross sections are analyzed in terms of the ρ-nucleon total cross section and the γ-ρ coupling constant, giving $\sigma(\rho, N) = 26.8 \pm 2.4$ mb and $\gamma_\rho^2/4\pi = 0.62 \pm 0.12$.

By measuring production cross sections of unstable particles in different nuclei it is possible to deduce the particle-nucleon cross sections.[1] Along these lines, there recently have been several ρ^0 photoproduction experiments[2-4] which give in addition information about the γ-ρ^0 coupling constant. Unfortunately, the published ρ^0 photoproduction cross sections differ by up to a factor of 2.[2,4]

We have performed a ρ^0 photoproduction experiment in conjunction with an ω photoproduction experiment (which will be reported later). As the goal of the latter experiment is a comparison of the γ-ω and γ-ρ^0 couplings, and of the ω-N and ρ^0-N cross sections, it is first essential to clarify the ρ^0 photoproduction picture. This is the aim of the present article.

A bremsstrahlung beam with 9.15-GeV endpoint energy was produced inside the Cornell 10-GeV electron synchrotron on a thin copper target. The beam traversed a 1-m LiH beam hardener and was collimated to a diameter of 5 mm. The target was located 20 cm upstream of a 100-cm-long, 75-cm-wide homogenous magnet with 25-cm gap. The following targets were used: beryllium, 0.02 radiation length (r.l.); carbon, 0.02 r.l.; aluminum, 0.03 r.l.; copper, 0.04 r.l.; tin, 0.04 r.l.; tungsten, 0.07 r.l.; and lead, 0.08 r.l. Charged particles emerging from the target were bent by the magnetic field and their tracks were recorded in a magnetostrictive wire-spark-chamber array behind the magnet extending over 85 cm in the beam direction. Six spark chambers of 1-m^2 area were used, each capable of measuring both coordinates with an accuracy of ±0.5 mm. In the first two chambers one of the wire directions was tilted by 15° in order to separate the coordinates of multiple tracks. The events were fed into an IBM-1800 computer which wrote them onto magnetic tape and performed on-line stability checks of the apparatus. One vertical plane of scintillation counters in front of the chambers and two in back served for triggering. Each plane was divided into four separate counters in order to trigger selectively.

The primary γ beam as well as electron pairs produced in the target passed through the material of the spark chambers which had an ineffective region of about 5-cm height in the median plane. The intensity of the γ beam was monitored by a quantameter; it was typically 10^6 effective quanta/sec.

Because of the time needed for recharging the spark capacitors, only one event per machine pulse could be handled. A second event too close to the first one was prevented by gating off the fast counter electronics and the linac trigger (inhibiting the next three machine pulses). The quantameter reading was corrected for the charge from the rest of the pulse after an event by comparing counting rates gated off as described and not gated off.

A Monte Carlo program was used to calculate the detection efficiency for different masses of the final state, different angles of the decay pions with respect to the recoiling nucleus, different energies, and different production angles. The computation took into account multiple scattering, finite size of the target, and finite accuracy of determining the track coordinates.

The detection efficiency for a forward-produced, 8-GeV ρ^0 meson of 760-MeV mass decaying symmetrically to the incident γ direction was typically 55% averaged over the azimuth of the decay angle. The inefficiency was due to particles going into the dead center region of the chambers. The efficiency was fairly constant over the forward diffraction peak, and a factor of 2 lower at a momentum transfer of 0.1 (GeV/c)^2. The efficiency versus mass of the $\pi^+\pi^-$ state in the region between 400 and 1000 MeV was high enough to measure the effective-mass spectrum between $t=0$ and 0.1 (GeV/c)^2 in one spectrometer setting.

An off-line program reconstructed the event configuration from the tracks and determined the kinematical variables. The accuracy was 150 MeV for the γ energy, 0.002 (GeV/c)^2 for the square of the momentum transfer, t, and 20 MeV for the $\pi\pi$ mass.

The apparatus was thoroughly checked (i) by taking data for ρ^0 photoproduction at different energies, intensities, and target positions, and (ii) by taking electron-pair data. The second series of tests was made possible by changing the vertical position of the spark chambers so that the electron pairs hit them within their sensitive part. The γ-beam intensity had to be reduced to a few pairs per second. A large number of experimental distributions in real and momentum space was checked against the Monte Carlo computations. In particular the reconstruction of events coming from different regions of the chambers was compared. Also the reconstruction assuming an effective homogenous field was compared with the results from a program which took the measured field at each particle position along the track. From these tests small corrections to the effective magnetic field and the track coordinates were derived.

The event distributions were corrected for their geometric detection efficiency. Further overall corrections were applied for absorption and decay of the pions (11%), absorption of the γ beam in the target (~2%), and inefficiency of the chambers and counters (8 %).

The normalization was based on the number of effective quanta measured by the quantameter. The correct number of γ quanta in the energy bin used for the analysis (7-9.2 GeV), relative to all quanta, was taken from a precise measurement of the γ spectrum by detecting electron pairs emerging from a very thin target.

The effective-mass distribution $d^2\sigma/dt\, dm$ of the pion pairs is shown for carbon in Fig. 1(a). This mass spectrum is deduced from a summation over t up to 0.1 $(\mathrm{GeV}/c)^2$, corrected for the differences in the minimum momentum transfer. The spectral shape, however, does not depend on the t region taken for this, in agreement with findings in Ref. 2. Comparing with a Breit-Wigner of suitable width one notices a suppression of masses higher than 800 MeV as well as a too high rate at very small masses. There is no general theory for this line shape available. Ross and Stodolsky[5] (i) proposed to modify the Breit-Wigner shape by a factor $(m_\rho/m_{\pi\pi})^4$, whereas (ii) Söding[6] explained the shape by an interference of the ρ^0 meson with a p-wave two-pion background, in which one of the pions is diffractively scattered off the nucleus. Both functions plus a polynomial background in $m_{\pi\pi}$ were tried in separate fits, and in either case the measured distribution could be fitted with about equal qualities. The first method gave $m_\rho = 760 \pm 10$ MeV and $\Gamma_\rho = 144 \pm 10$ MeV; the second, a 10-MeV higher mass with about the same width. It should be noted, however, that the cross sections were about 5 % lower by using method (ii). For further analysis method (i) was chosen for easier comparison with other experiments. The total number of counts between 500 and 1000 MeV, corrected for resonant events outside this region and the polynomial background inside, was taken for the mass-integrated $d\sigma/dt$.

One example for $d\sigma/dt$ is shown in Fig. 1(b). From these distributions the cross sections at 0° production angle were obtained[7,8]; they are given in Table I. For further analysis, the optical-model formula for the coherent production amplitude has been used:

$$A_{\gamma\rho} = A_0 \int_0^\infty d^2b \int_{-\infty}^{+\infty} dz\, \rho(b,z) e^{iq_{11}z} e^{i\vec{q}\cdot\vec{b}} \times \exp[-\tfrac{1}{2}\sigma_{\rho n}(1-i\alpha)\int_z^\infty \rho(b,z')dz']. \quad (1)$$

Here A_0 is the production amplitude of a ρ_0 meson on a single nucleon, $\vec{b}$ the impact-parameter vector, z the coordinate in forward direction, $q_{11} = m\rho^2/2E_\gamma$, $\rho(b,z)$ the nuclear density distribution, $\sigma_{\rho n}$ the ρ_0-nucleon total section, and α the ratio of the real to the imaginary parts of the

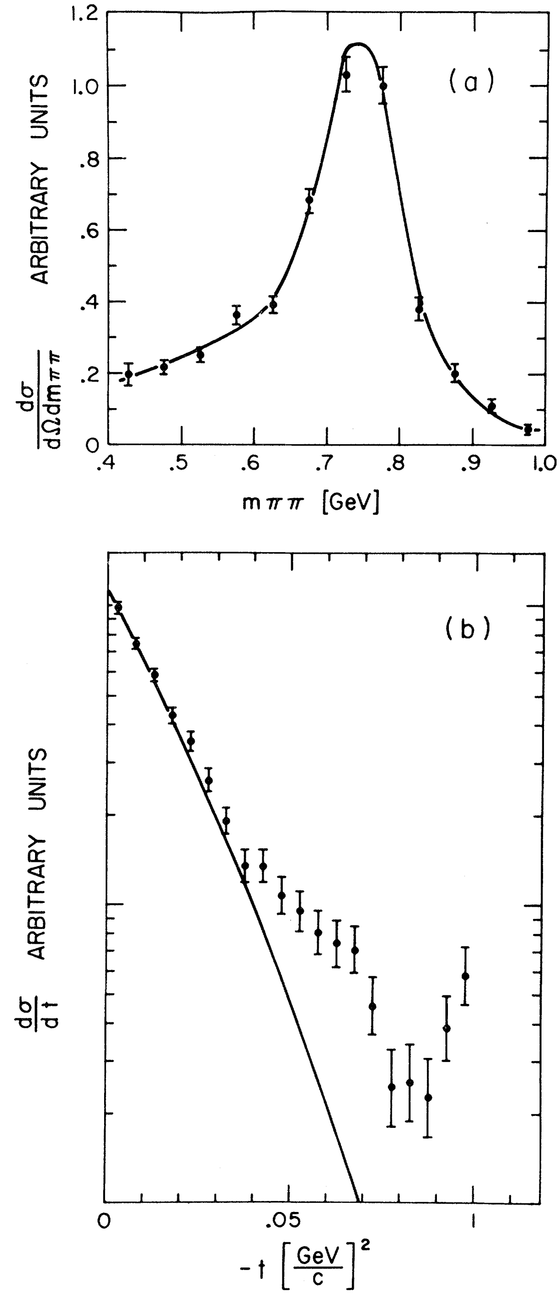

FIG. 1. (a) Distribution of the effective mass of the $\pi^+\pi^-$ pair for carbon summed between $t=0$ and 0.1 $(\mathrm{GeV}/c)^2$. The curve is a Breit-Wigner fit plus polynomial background. The Breit-Wigner shape is corrected by the Ross-Stodolsky factor $(m_\rho/m_{\pi\pi})^4$. (b) Differential cross section $d\sigma/dt$ for carbon. The line represents the optical-model calculation with harmonic-well density distribution and $r = 2.35$ F.

Table I. Table of cross sections [$p = 8$ GeV, $t_{\|} = 0.0013\ (\mathrm{GeV}/c)^2$].

Nucleus	$(d\sigma/dt)_{\theta=0}$ and total error (mb/GeV^2)
Be	5.27 ±0.30
C	8.15 ±0.41
Al	35.3 ±2.6
Cu	125 ±8
Sn	348 ±25
W	610 ±51
Pb	675 ±44

one-nucleon amplitude.

The slope of the coherent peak $d\sigma/dt$ at small t is sensitive only to the assumed density model and the nuclear radius. In a recent experiment Alvensleben et al.[2] measured these slopes with high statistics. They found that the nuclear radii are well described by $R = r_0 A^{1/3}$ with $r_0 = 1.12$ F using the Wood-Saxon density distribution

$$\rho(r) = \rho_0 / 1 + \exp[(r-R)/\alpha] \tag{2}$$

with $\alpha = 0.545$ F and R being the nuclear half-density radius. For Al, Cu, Sn, W, and Pb the slopes of our t distributions agree well with these results. Therefore our analysis for $A \geqslant 27$ is carried out along these lines. For beryllium and carbon, however, the calculated t distributions are much steeper than our t distributions,[9] thus giving rise to an unreasonably high incoherent contribution at small t (which should be suppressed according to the exclusion principle).

For the light nuclei we therefore preferred to use the harmonic-well density distribution

$$\rho(r) = \rho_0(1 + aK^2r^2/R^2)\exp(-K^2r^2/R^2) \tag{3}$$

which describes the electron-scattering data from carbon quite well.[10,11] With radii 2.35 and 2.15 F for carbon and beryllium, respectively, we achieved a good representation of the data as shown in Fig. 1(b). The ratio of the real to the imaginary parts was taken as $\alpha = -0.2$ as deduced from γp total-cross-section measurements[12] and from a quark-model prediction.[13,14]

Using $d\sigma/dt = |A_{\gamma\rho}|^2$, the cross sections at $t_{\min}$ were fitted by formula (1) leaving $|A_0|^2$ and $\sigma_{\rho n}$ as free parameters [see Fig. 2(a)]. The values deduced were $|A_0|^2 = 117 \pm 8\ \mu\mathrm{b/GeV}^2$ and $\sigma_{\rho n} = 29.2 \pm 2.5$ mb with $\chi^2 = 6$ for five degrees of freedom.[15,16] Since $\sigma_{\rho n}$ derived in this way depends only on the relative A dependence of the cross sections, only statistical errors and the uncertainty for subtracting the mass background were taken into account.

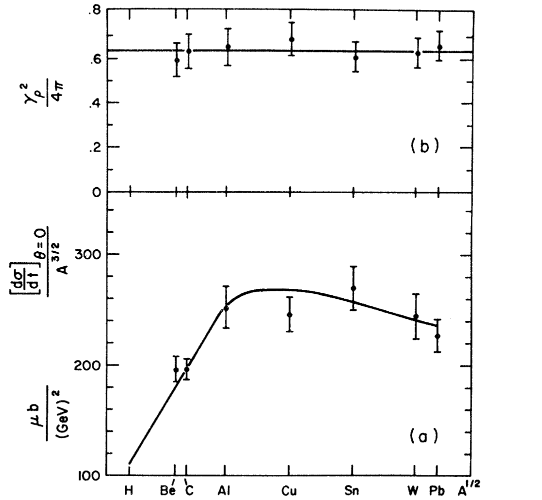

FIG. 2. (a) Measured forward cross sections compared with the optical-model calculations (solid curve) as described in the text for $\sigma_{\rho n} = 26.8$ mb. (b) The γ-ρ coupling constant $\gamma_\rho^2/4\pi$ as deduced from each element. The line shows the average.

Our forward cross sections for the light nuclei (Be, C, Al) are on the average 8% lower than those reported by Alvensleben et al.,[2] corrected for the differences in $t_{\min}$ for the two experiments. They have also measured[17] the cross section of ρ photoproduction on protons with different γ energies up to 6.5 GeV using a background subtraction similar to that used here. They found a cross section decreasing with energy which should account for most of the difference between their light-nuclei cross sections and ours. Using their published cross section at 6.5 GeV corrected for the reported energy dependence, we can $|A_0|^2 = 110 \pm 8\ \mu\mathrm{b/GeV}^2$ as an additional constraint on our fit. The error is mainly due to the uncertainty in this normalization. In this way we are left with a one-parameter fit, and uncertainties in the theory of the optical model for light nuclei are avoided because now they play only a minor role. Thus a probably better value for the ρ-nucleon total cross section,

$$\sigma_{\rho n} = 26.8 \pm 2.4 \text{ mb},$$

was derived. The χ^2 went up to 7.5 mainly because of the beryllium point.

Vector dominance relates the $t=0$ cross section to the total ρ_0-nucleus cross section. Extrapolating the data to $t=0$ by setting $q_{11}=0$ in Eq.

(1) and averaging over all nuclei [see Fig. 2(b)] gave $\gamma_\rho^2/4\pi = 0.62 \pm 0.12$ for the γ-ρ coupling constant. The error includes the statistical and systematical errors of the cross sections used for the analysis. The value changes by ±5% for variations of α by ±0.1.

Because the analysis is somewhat dependent on the nuclear radii, it should be mentioned that the value for $\sigma_{\rho n}$ increases only by 0.9 mb if one uses $r = 1.2A^{1/3}$ for the nuclear radii as done by McClellan et al.[18]

Our final results agree reasonably well with the recent ones by Alvensleben et al.[2] Our forward cross sections are between 5 and 10% lower than theirs and agree within the statistics with McClellan et al.[3] The disagreement between our value for $\sigma_{\rho n}$ and that of Ref. 3 is mainly due to the following: (1) Introducing a real-to-imaginary part for the production amplitude of $\alpha = -0.2$ lowers $\sigma_{\rho n}$ by about 4 mb. (2) The hydrogen cross section of 110 μb/GeV^2 used here compared with the value of 124 μb/GeV^2 used by McClellan et al. lowers the cross section by another 5 mb. The difference in the γ-ρ coupling constant follows mainly from the different $\sigma_{\rho n}$ derived from the two experiments.

Comparison of the cross sections here reported with data of Bulos et al.[4] at a similar energy shows bad disagreement. Their cross sections are about 30% lower than ours, giving rise to their higher $\gamma_\rho^2/4\pi$. Their A dependence of the forward cross sections is similar to ours, and the difference in $\sigma_{\rho n}$ is mainly due to including $\alpha = -0.2$ in the analysis here.

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[8]For all elements except W and Pb a fit to Trefil's theory (Ref. 7) with suitable parameters was used. This theory describes the sum of coherent and incoherent processes and should therefore well represent the data especially for the light elements. For W and Pb the forward cross sections were gained by integrating over the coherent peak assuming nuclear radii as described in the text.

[9]Approximating $d\sigma/dt$ by ae^{bt} the calculated t distributions gave for carbon ($r = 2.35$ F) $b = 78$ (GeV/c)$^{-2}$, whereas the fit to the measured t distribution gave $b = 54$ (GeV/c)$^{-2}$. The radius was taken from R. J. Glauber and G. Matthiae, Laboratori di Fisica, Istituto superiore di Sanità, Report No. ISS 67116, 1967 (unpublished), which agrees well with the electron-scattering radius [R. Hofstadter, Ann. Rev. Nucl. Sci. 7, 231 (1957)]. Using $R = 1.12A^{1/3}$ would increase the discrepancy further.

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[11]McClellan et al. (Ref. 3) also used the harmonic-well distribution for C and Be.

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[15]Results using our computer program were compared against those computed with the programs of McClellan et al. (Ref. 3) and of Alvensleben et al. (Ref. 2). There was excellent agreement in both cases.

[16]The sensitivity of the ρ-nucleon cross section with respect to α can be seen by the following result: Setting $\alpha = 0$ gave $\sigma_{\rho n} = 33.2 \pm 2.5$ mb.

[17]H. Alvensleben et al., Phys. Rev. Letters 23, 1058 (1969).

[18]This is mainly because cross sections integrated over t were used for deducing the $\theta = 0$ cross section from the data for W and Pb. A larger radius increases the theoretical slope and therefore the $\theta = 0$ cross section as well as the value calculated by Eq. (1).