nuclei.

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[1]M. Gell-Mann, D. Sharp, and W. G. Wagner, Phys. Rev. Letters 8, 261 (1962); S. L. Glashow, Phys. Rev. Letters 7, 469 (1961); Y. Nambu and J. J. Sakurai, Phys. Rev. Letters 8, 79 (1962); N. M. Kroll, T. D. Lee, and B. Zumino, to be published; R. van Royan and V. F. Weisskopf, to be published; H. Joos, Phys. Letters 24B, 103 (1967).

[2]M. Ross and L. Stodolsky, Phys. Rev. 149, 1172 (1966); J. G. Asbury et al., Phys. Rev. Letters 19, 869 (1967).

[3]J. D. Jackson, Nuovo Cimento 34, 1644 (1964).

[4]A. H. Rosenfeld et al., Rev. Mod. Phys. 39, 1 (1967).

[5]L. J. Lanzerotti et al., Phys. Rev. Letters 15, 210 (1965); Aachen-Berlin-Bonn-Hamburg-Heidelberg-München Collaboration, Nuovo Cimento 41A, 270 (1966).

[6]S. D. Drell and J. S. Trefil, Phys. Rev. Letters 16, 552, 832(E) (1966).

[7]S. C. C. Ting, Report to 1967 International Conference on Photons and Electrons, Stanford University, September, 1967 (unpublished).

[8]J. G. Asbury et al., Phys. Rev. Letters 18, 65 (1967).

[9]J. G. Asbury et al., Phys. Rev. Letters 19, 865 (1967).

PHOTOPRODUCTION OF π^0 IN THE BACKWARD DIRECTION*

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The photoproduction of neutral pions in the reaction $\gamma p \to \pi^0 p$ has been investigated in the backward direction ($\theta_{\pi^0}{}^{\mathrm{c.m.}} \approx 180°$) at photon energies E_γ from 0.8 to 5.5 GeV, using a bremsstrahlung beam from the Deutsches Elektronen-Synchrotron (DESY) electron accelerator. Only the recoil proton was detected and its momentum determined with a magnetic spectrometer. Since the lab momentum of the recoil protons is 300-400 MeV/c higher than the momentum of light particles, it was possible to detect the protons in the forward direction without serious troubles from the high positron background.

The minimum energetic separation between single and multiple pion production processes is of the order of 40 MeV. Therefore, a good momentum resolution of the spectrometer was required.

The experimental setup is shown in Fig. 1. The photon beam was produced in a tungsten target of 0.06 radiation lengths and defined by three lead collimators. The flux was measured with a gas-filled quantameter. The liquid hydrogen target had a length of 30 cm.

The spectrometer produced an angular focus

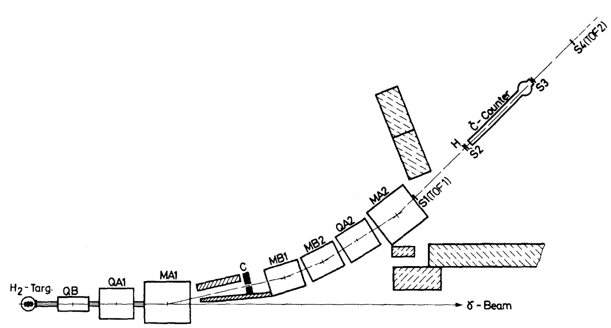

FIG. 1. Experimental setup: QB and QA, quadrupoles; MA and MB, bending magnets; C, lead collimator; $S1,\cdots,S4$ scintillation counters; H, hodoscope; $S1$ and $S4$, time-of-flight (TOF) counters.

at a lead collimator C which defined the angular acceptance. A scintillator counter hodoscope H placed in the target image plane served to measure the particle momentum.

For photon energies below 3.4 GeV a "low-momentum" version of the spectrometer was used which had a momentum dispersion at H of $(\Delta p/p_0)/\Delta x = 0.33\,\%/\mathrm{cm}$ and an angular acceptance of ±5 mrad horizontally and ±9 mrad vertically, corresponding to a mean π^0-production angle $\theta_{\pi^0}{}^{\mathrm{c.m.}} \approx 179°$. Above 3.4 GeV a slightly different version of the spectrometer with a momentum dispersion of 0.41 %/cm was used. In this case, a central stopper in the collimator C turned out to be necessary to reduce the background caused by positrons. Thus, the angular acceptance was restricted to vertical angles between 4 and 18 mrad and horizontal angles between 0 and 5 mrad, corresponding to $\theta_{\pi^0}{}^{\mathrm{c.m.}} \approx 178°$.

The acceptance of the spectrometer was determined by a Monte Carlo calculation which took into account multiple scattering and dE/dx losses in the hydrogen target and all counters. The momentum resolution ranged from 1% full width at half-maximum at 1 GeV/c (mainly due to varying dE/dx losses in the target) to 0.3 % at 5.5 GeV/c.

Events were defined by a coincidence between four scintillation counters $S1, \cdots, S4$. Background positrons and pions were rejected by a gas threshold Čerenkov counter and a time-of-flight system. Whereas at lower momenta ($p < 3.4$ GeV/c) there was practically no background, a 5% background resulted at higher momenta mainly from positrons hitting magnet pole tips and shielding.

The photon density distribution was computed from the Bethe-Heitler formula taking into account the finite thickness of the converter target, the collimation angle, and radiative corrections. The intercalibration of the synchrotron energy and the spectrometer momentum was determined by fitting the calculated photon density distribution, corrected for the spectrometer resolution, to the proton yields.

For $E_\gamma < 3.4$ GeV, the π^0 cross sections were calculated from the proton yields using a photon energy interval of 15 MeV $< E_\gamma{}^{\max} - E_\gamma < 60$ MeV. The contribution of double-pion production in this interval was less than a few percent of the single-π^0 yield. Empty-target corrections were typically 10 %.

For $E_\gamma > 3.4$ GeV, subtraction runs with a step of $\Delta E_\gamma = 40$ MeV were taken in order to eliminate the di-pion contribution and the background from secondary particles. The peaks in the subtracted proton momentum spectra were fitted with the calculated photon density distribution and the cross section computed from this fit.

The cross sections are shown in Fig. 2 together with results at lower energies.[1] The error bars include statistical errors and errors due to the energy intercalibration. Not included is an overall systematic error of about 10 % which is mainly due to uncertainties in the acceptance and bremsstrahlung-spectrum calculations, the nuclear absorption cross sections, and the quantameter calibration. An additional error is introduced by the contribution from backward Compton scattering which is presumably small.

The structure observed in the cross section implies that resonance contributions, if not dominant, are at least comparable with nonresonant contributions. Only $I = \frac{3}{2}$ resonances seem to contribute strongly. We notice a shift in the

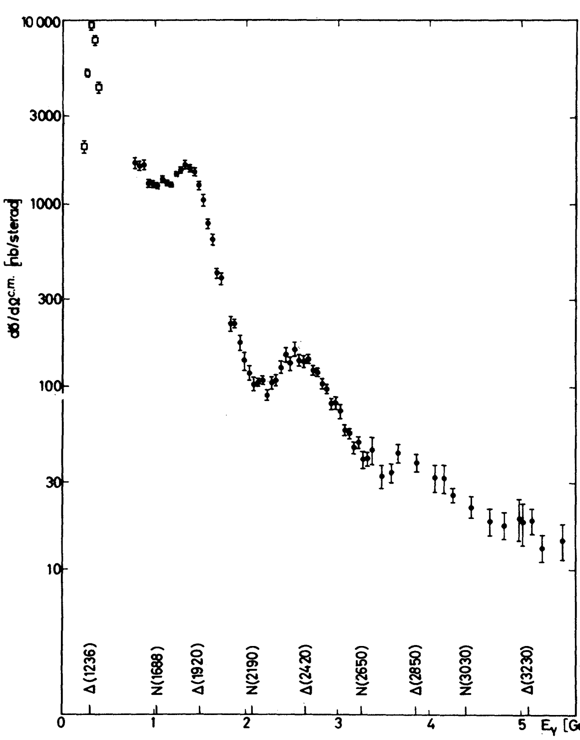

FIG. 2. Dependence of $d\sigma/d\Omega^{\mathrm{c.m.}}$ for $\gamma p \to \pi^0 p$ on the photon energy E_γ. Solid circles, this experiment; squares, Orsay (Croissiaux et al., Ref. 1). For convenience, some resonance positions are labeled on the graph.

position of the $\Delta(1920)$ and the $\Delta(2420)$ resonances which is of the order of $\Delta E = 50$ MeV. Similar shifts have previously been observed in the photoproduction of the $\Delta(1236)$, $N(1525)$, and $N(1688)$.[2] The sharp dip near the $N(2190)$ seen in backward π^-p scattering[3] is not present in backward π^0 photoproduction.

According to a quark model,[4] the $\Delta(2420)$ resonance may be excited only by magnetic photon interaction.[5] Assuming that the $\Delta(2420)$ dominates the backward cross section around 2.5 GeV, an estimate of the total cross section due to this resonance is possible. A Breit-Wigner fit then implies that the radiative width $\Gamma_\gamma(2420)$ is of the order of 100 keV, whereas Fujimura et al.,[4] assuming a special quark wave function, obtain $\Gamma_\gamma(2420) = 0.3$ keV.

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[1]M. Croissiaux, E. B. Dally, R. Morand, J. P. Pahin, and W. Schmidt. Phys. Rev, 164, 1623 (1967).

[2]G. Höhler, Nuovo Cimento Suppl. III, 3, 651 (1965).

[3]S. W. Kormanyos, A. D. Krisch, J. R. O'Fallon, K. Ruddick, and L. G. Ratner, Phys. Rev. Letters 16, 709 (1966).

[4]K. Fujimura, T. Kobayashi, T. Kobayashi, and M. Namiki, Progr. Theoret. Phys. 37, 916 (1967).

[5]Using data of Bolon et al. [G. C. Bolon, D. Garelick, S. Homma, R. Lewis, W. Lobar, D. Lucky, L. S. Osborne, R. Schwitters, and J. Uglum, Phys. Rev. Letters 18, 926 (1967)] and our 180° point, one obtains a π^0 angular distribution at $E_\gamma = 2.5$ GeV and $\theta_{\pi^0}{}^{\text{c.m.}} > 90°$, which is roughly compatible with $M5$ photoexcitation of a $J = 11/2$ resonance.

CALCULATION OF THE n-p MASS DIFFERENCE*

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Assuming that the Regge asymptotic behavior prevails and using a generalized superconvergence relation, we compute the first-order electromagnetic nucleon mass difference. We find $M_p - M_n \approx -1.4$ MeV compared with the experimental value -1.3 MeV.

It is well known that the first-order electromagnetic calculation of the neutron-proton mass difference using conventional techniques (i.e., the nucleon pole term with known form factors) gives the wrong sign. (Experimentally, $M_p - M_n \approx -1.3$ MeV; theoretically, $M_p - M_n \approx 1.0$-1.4 MeV.)[1] One way out is to add a "tadpole" contribution to this mass difference as proposed by Coleman and Glashow.[2] Harari[3] then pointed out that such unknown subtraction constants are necessitated by the bad asymptotic behavior of the dispersion integrals.

It is the purpose of this note to show that indeed, if we take the usual Regge asymptotic behavior for the amplitudes, we can calculate this term. Under what we believe to be reasonable assumptions, we obtain a correction term of ≈ -2.4 MeV to be added to the old number of $+1.0$-$+1.4$ MeV, thus obtaining a mass difference lying between -1.4 and -1.0 MeV, which is in good agreement with experiment.

As shown by Cottingham,[4] the mass difference to first order in e^2 can be written as

$$dM \equiv M_p - M_n = -\frac{1}{2\pi}\int_0^\infty \frac{dq^2}{q^2}\int_0^q d\nu\,(q^2-\nu^2)^{1/2}\left[3q^2 t_1(q^2, i\nu) - (2\nu^2+q^2)t_2(q^2, i\nu)\right], \tag{1}$$

where $t_i(q^2, \nu)$ are a linear combination of the (two gauge-invariant parts of the) forward Compton amplitudes for scattering a virtual photon of mass q^2 and energy $q^0 = \nu$ off a proton or neutron. It has also been shown in Ref. 4 that for a fixed q^2, $t_i(q^2, \nu)$ satisfy dispersion relations in the ν variable.