to indicate the presence of higher waves than the S wave in Λ-p scattering at these momenta. At the momentum region 120-220 MeV/c the cutoff region is too large to enable a meaningful F/B ratio calculation. Finally, we looked at the up-down asymmetry $-\alpha P = 2(U-D)/(U+D)$ of the pion in the Λ decay. Only events with an incident Λ momentum between 220 and 320 MeV/c and for which $-0.5 < \cos\theta^* < 0.5$ have been considered. A value of $\alpha P = -0.22 \pm 0.47$ was obtained.

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[1]G. Alexander, J. A. Anderson, F. S. Crawford, Jr., W. Laskar, and L. J. Lloyd, Phys. Rev. Letters 7, 348 (1961).

[2]T. H. Groves, Phys. Rev. 129, 1372 (1963).

[3]B. Sechi-Zorn, R. A. Burnstein, T. B. Day, B. Kehoe, and G. A. Show, Phys. Rev. Letters 13, 282 (1964).

[4]B. Ram and B. W. Downs, Phys. Rev. 133, B420 (1964).

[5]B. W. Downs and R. J. N. Phillips, to be published.

TOTAL CROSS SECTIONS AND ANGULAR DISTRIBUTIONS FOR $\pi^- + p \to \eta^0 + n$ FROM THRESHOLD TO 1151 MeV*†

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In the experiment reported here we have measured the cross sections and angular distributions for the η^0 in the reaction

$$\pi^- + p \to \eta^0 + n, \tag{1}$$

where $\eta^0 \to 2\gamma$. This is a reaction in which η^0's are produced in a pure $T = \frac{1}{2}$ two-body final state. Unless explicitly stated otherwise, all results refer to the two-gamma decay mode of the η^0, since the experiment was designed to detect only gamma rays.

Data are presented for 10 incident π^- energies. These energies span the region of the second and third pion-nucleon resonances (600 and 900 MeV, respectively), and include the threshold energy for the above reaction. The cross section is found to rise rapidly above threshold reaching a maximum of 0.98 ± 0.08 mb at 659 MeV and then decreasing slowly to 0.38 ± 0.05 mb at 1151 MeV. The angular distributions are isotropic in the region of the 600-MeV resonance, but show forward peaking at 1003 MeV and above.

The two-gamma decay mode of the η^0 is detected in an experimental setup which consists of a small liquid hydrogen target, 5 cm in diameter transverse to the beam and 4 cm along the beam, surrounded by an anticoincidence shield and an array of four spark chambers composed of 50 2-mm thick steel plates (approximately 5.5 radiation lengths). This spark chamber system has been described elsewhere.[1] The system is suitably triggered by an electronic logic which

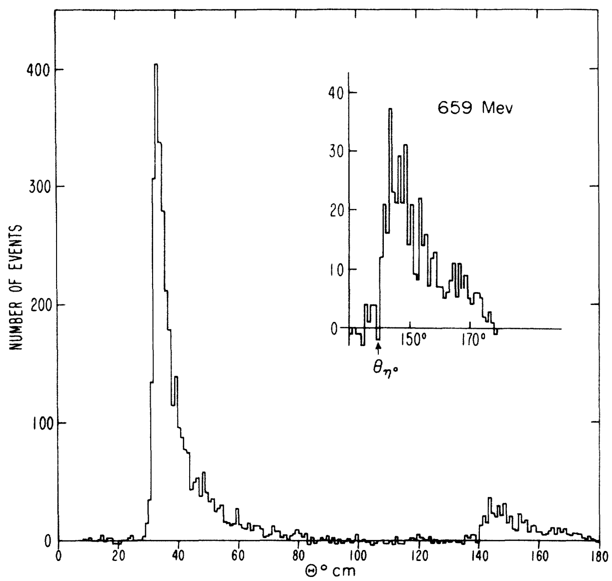

FIG. 1. Opening-angle distributions for 659 MeV (with η^0 region repeated in an inset), after background subtraction.

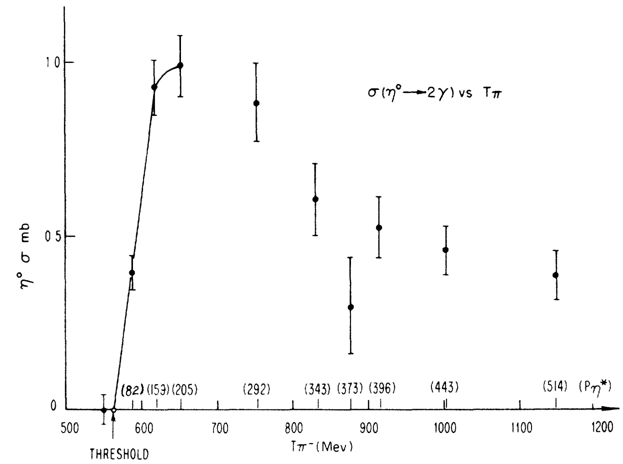

FIG. 2. The cross section of the reaction $\pi^- + p \to n + \eta^0$ (2γ decay mode).

is activated by the disappearance of an incident π^-. Photographs are taken of the chambers when so triggered and the resulting films are scanned for gamma-ray events.

Events found in these photographs have gamma-ray multiplicities ranging from zero to eight. Approximately 10% of the two-gamma-ray events are from the decay of the η^0 produced in Reaction (1), 80% are from π^- charge exchange, and 10% are from higher multiplicity events (e.g., $2\pi^0$, $3\pi^0$) from which only two gamma rays are seen because the detection solid angle is less than 4π. Reaction (1) can be easily distinguished from the π^- charge-exchange reaction by using the decay kinematics for a particle which decays into two gamma rays. The appropriate observed quantity for this technique is the opening angle between the two gamma rays in the $\pi^- + p$ center-of-mass system.[2] Figure 1 illustrates this separation technique for one of our energies.

The production cross section at each energy is determined from the electronic counting rate, the fraction of all events determined as η^0 (where $\eta^0 \to 2\gamma$), and the gamma-ray detection efficiencies calculated by Monte Carlo techniques[3] to account for the finite solid angle and energy dependence of the system. The results are shown in Fig. 2 and are tabulated in Table I. The energy which is below η^0 threshold has a cross section which is consistent with zero. At the four highest energies, it is possible to have contamination from the process $\pi^- + p \to \Lambda^0 + K^0$, where $\Lambda^0 \to \pi^0 + n \to 2\gamma + n$ and the K^0 decays as a $K_2^{\,1}$ outside of the chambers. This contamination, which is typically less than 0.2 mb,[4] has been subtracted out.

Table I. Summary of results; T_π is laboratory kinetic energy, while all other quantities are in the $\pi^- p$ center of mass.

T_π (MeV)	$P_\eta{}^*$ (MeV/c)	σ (mb)	A_0 (mb/sr)	A_1 (mb/sr)
545	Below threshold			
578	82.0 ± 9.8	0.39 ± 0.05	0.031 ± 0.002	
619	158 ± 10	0.92 ± 0.08	0.075 ± 0.005	
659	205 ± 8	0.98 ± 0.09	0.078 ± 0.005	
755	295 ± 7	0.88 ± 0.11	0.070 ± 0.006	
827	343 ± 7	0.60 ± 0.10	0.048 ± 0.003	
878	373 ± 6	0.30 ± 0.14	0.024 ± 0.014	
916	396 ± 6	0.52 ± 0.09	0.041 ± 0.003	
1003	443 ± 6	0.45 ± 0.07	0.037 ± 0.004	0.043 ± 0.009
1151	514 ± 6	0.38 ± 0.07	0.030 ± 0.003	0.030 ± 0.006

To study the momentum dependence of the production cross section near threshold, it is best to determine the center-of-mass momentum from the minimum angle between the two gamma rays in the experimental η^0 distribution. This is a more sensitive determination than the one made using wire orbits to obtain the primary beam momentum. We get 82.0 ± 9.8 MeV/c and 158.0 ± 10.0 MeV/c for the η^0 momenta in the $\pi^- $-$p$ center-of-mass system for incident pion energies of 578 MeV and 619 MeV, respectively. The ratio of these first two momenta above threshold is 1.9 ± 0.3 and the corresponding ratio of the cross sections is 2.4 ± 0.4 (see Table I). Assuming a center-of-mass momentum dependence, near threshold, of the form $\sigma \propto (ka)V_l(ka)$, where k and a are the η^0 wave number and the interaction radius, respectively, and the V_l are barrier-penetration factors,[5] we find that these ratios are consistent with η^0 production in s states for any radius of the interaction. For p-wave excitation the data require a radius of interaction $\geq \hbar/m_\pi c$; d-wave excitation requires much larger values of a.

We now proceed to a consideration of the angular distributions to obtain further evidence concerning these points. Since we do not determine the energies of the observed gamma rays, the direction of the parent η^0 which gives rise to each two gamma-ray event cannot be determined unambiguously. However, the distribution of the bisector of the angle between the two gamma rays can be related uniquely to the η^0 angular distribution by the relationship

$$n_B(x_B)dx_B = [\int P(x_B, x)n(x)dx]dx_B, \qquad (2)$$

where $x = \cos\theta_{\eta^0}$ and $x_B = \cos\theta_B$. θ_{η^0} is the angle made by the η^0 direction with the incident π^- direction in the $\pi^- p$ system and θ_B is the corresponding angle for the bisector. $n_B(x_B)$ is the number of events observed with x_B in dx_B, and $n(x)$ represents the η^0 angular distribution. The function $P(x_B, x)$, which is the probability of seeing a bisector angle θ_B from an η^0 emitted at θ_{η^0}, takes into account the detection efficiency in our particular geometry and the restriction of our sample to a limited opening-angle interval. $P(x_B, x)$ is determined by a Monte Carlo calculation. Since $n(x)$ is proportional to the η^0 differential cross section, which can be written as

$$\sum_{l=0}^{l_{\max}} A_l x^l,$$

one can use Eq. (2) to fit the experimental bisector distributions and so obtain directly the coefficients of the η^0 angular distribution.

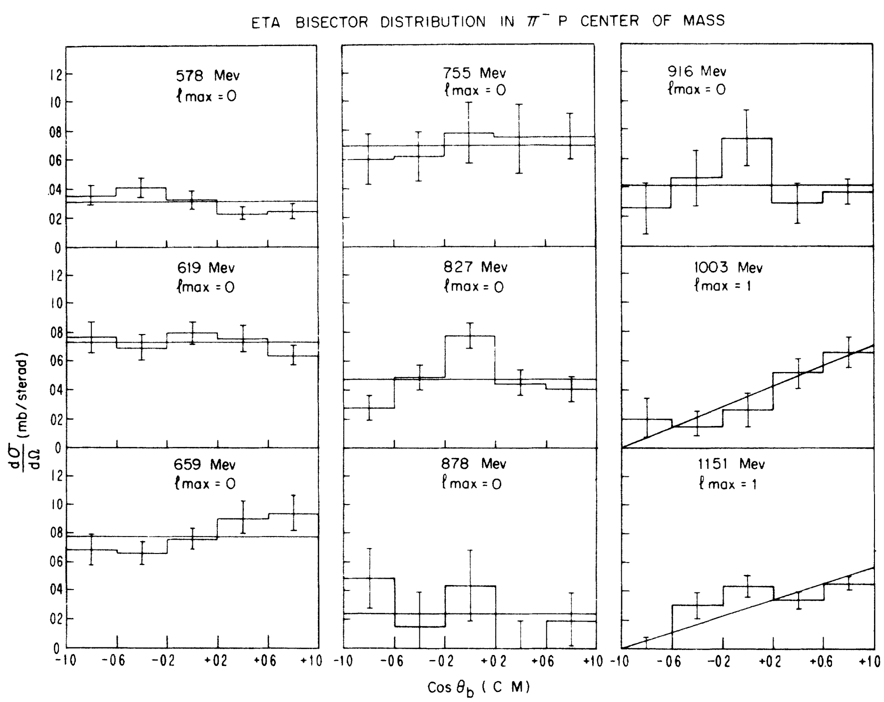

FIG. 3. Angular distribution of bisectors and bisector fits.

Before fitting the raw two-gamma bisector distribution we must subtract two background contaminations:

(1) Two-gamma events from multiple π^0 production. The absolute number of these events can be determined from the numbers of 3-, 4-, 5-, and 6-gamma events, together with the detection efficiencies. The shape of the bisector distribution for these events is assumed to be the same as the bisector distribution of two-gamma pairings fabricated from the observed three-gamma sample.

(2) Two-gamma events from neutral Λ^0 decay. The shape of the bisector distribution arising from these events is estimated by Monte Carlo techniques and the absolute normalization is estimated from known cross sections.[4] To minimize these contaminations we restrict ourselves to an opening-angle interval extending from the minimum η^0 opening angle up to an angle which includes approximately 90% of the η^0's.

Table I contains the results of the fits, while Fig. 3 shows the corrected bisector distributions. The highest power of $\cos\theta_{\eta 0}(l_{\max})$ chosen at each energy is that for which the χ^2 probability exceeds 4% and for which the highest term is statistically significant. The distributions are isotropic up to 1003 MeV. The 1003-MeV and 1151-MeV distributions require at least a $\cos\theta_{\eta 0}$ term. This behavior is consistent with $s_{1/2}$ or $p_{1/2}$ production at threshold with some higher states entering at higher energies. It is inconsistent with pure $p_{3/2}$ or $d_{3/2}$ throughout the energy region measured. These results would seem to indicate that the reaction $\pi^- + p \to \eta^0 + n$ does not play a large role in a $d_{3/2}$ pion-nucleon resonance[7] at 600 MeV.

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[1]C. Calvelli et al., to be published.

[2]M. Chretien et al., Phys. Rev. Letters 9, 127 (1962).

[3]C. A. Bordner et al., to be published.

[4]B. T. Feld and W. M. Layson, Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962, edited by J. Prentki (CERN Scientific Information Service, Geneva, Switzerland, 1962), which refers to the following: L. Bertanza et al., Phys. Rev. Letters 8, 332 (1961); F. R. Eisler et al., Rev. Mod. Phys. 33, 436 (1961); and S. E. Wolf et al., Rev. Mod. Phys. 33, 439 (1961).

[5]J. Blatt and V. F. Weisskopf, Theoretical Nuclear Physics (John Wiley & Sons, Inc., New York, 1952).

[6]P. Auvil and C. Lovelace, Nuovo Cimento 33, 473 (1964). These authors predict an inelastic $s_{1/2}$ state in the $\pi^- p$ system just below 600 MeV, which is mainly due to η^0 production. Our data are consistent with this prediction. s-state excitation for the charge-symmetric reaction has been first suggested by E. Pauli et al., Proceedings of the Sienna International Conference on Elementary Particles (Società Italiana di Fisica, Bologna, Italy, 1963), p. 92, from analysis of a deuterium bubble chamber experiment.

[7]P. Carruthers, Phys. Rev. Letters 10, 539 (1963).

SECONDARY DIFFRACTION PEAKS IN πN AND KN SCATTERINGS*

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The secondary diffraction peak in πN [1] and KN [2] scatterings has been discussed on the basis of the optical model by assuming that only a few low partial waves, $l < L$, contribute to the scattering, and that these are purely imaginary.[3,4] The agreement so obtained is, however, very poor.[5] It has been also suggested that the secondary peak in the πN case is related to a maximum at 2.08 GeV/c in the total $\pi^- p$ scattering cross section.[1] No fitting of the data has been given on this basis. The spin effects have been so far completely neglected. It seems to be true that spin effects become small at high energies, if proton-proton polarization experiments[6] are a guide for spin effects in strong interactions at high energies. No direct polarization experi-