as measured by the yearly average of Zurich sunspot numbers for the same period. These relationships are shown in Fig. 1.

The large ratio of 19 to 1 for the percentage change near the north geomagnetic pole to that at the equator is due primarily to the large numbers of low-energy particles in the primary radiation which can get through the earth's magnetic field at Thule and penetrate 15 g cm^{-2} of air and which were present in some numbers during the solar minimum of 1954.

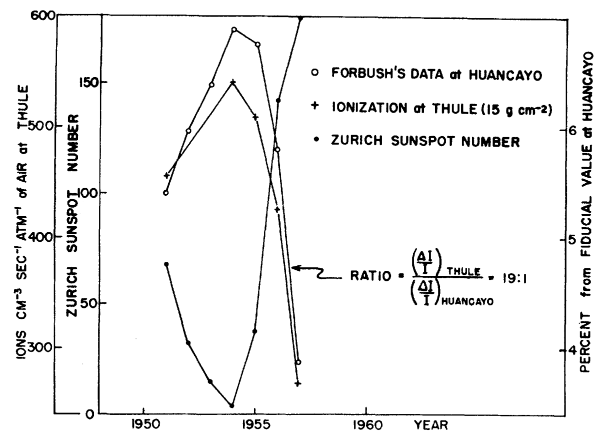

FIG. 1. Long-term correlation between ionization due to cosmic rays at high altitudes (15 g cm^{-2} pressure) near the north geomagnetic pole, the ionization at Huancayo, Peru, and the Zurich sunspot numbers.

The above therefore constitutes further evidence that for these long-time effects, (a) the changes are world wide, (b) the low energy particles are affected more than those of higher energy, (c) the average, yearly Zurich sunspot numbers are a good index of the long-term effect of the sun on the intensity of cosmic rays as measured on the earth.

---

[1]W. Waldmeier, J. Geophys. Research 63, 411 (1958).

[2]S. E. Forbush, J. Geophys. Research 59, 534 (1954).

[3]H. V. Neher and S. E. Forbush, Phys. Rev. 87, 889 (1952).

[4]See Neher, Peterson, and Stern, Phys. Rev. 90, 655 (1953); H. V. Neher, Phys. Rev. 103, 228 (1956); 107, 588 (1957); H. V. Neher and H. Anderson, Phys. Rev. 109, 608 (1958).

PHOTOPION CROSS SECTIONS AND A SECOND RESONANCE*

Ronald F. Peierls
Laboratory of Nuclear Studies,
Cornell University,
Ithaca, New York
(Received August 1, 1958)

In a recent letter[1] Wilson has suggested that the rise in the photopion cross sections above 500 Mev may be interpreted as being due to another resonance in the pion nucleon system. Since the π^+ cross section is the larger, the resonance must presumably be in a $T = 1/2$ state. If we examine the observed angular distributions, it is also possible to determine the probable angular momentum and parity of such a state.

We consider a scheme indicated roughly in Fig. 1. There are three important contributions to the photopion cross section up to about 900 Mev: (A) the $J=3/2$, $T=3/2$, p-wave resonance at about 300 Mev; (B) the proposed $T=1/2$ resonance at about 700 Mev; (C) the "direct photoelectric" production (s-wave, electric dipole), occurring only for π^+. If A, B, C are the three corresponding complex amplitudes, then for the total cross sections we have

$$\sigma(\pi^+) \propto \frac{2}{3}\,|A|^2 + \frac{4}{3}\,|B|^2 + |C|^2,$$

$$\sigma(\pi^0) \propto \frac{4}{3}\,|A|^2 + \frac{2}{3}\,|B|^2. \qquad (1)$$

At the peak, ~ 700 Mev, one has $\sigma(\pi^+) \cong 2\,\sigma(\pi^0)$ whence

$$|C|^2 \cong 2\,|A|^2 \qquad (2)$$

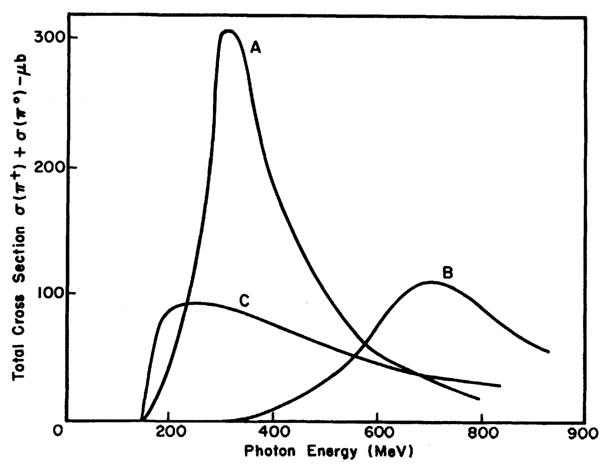

FIG. 1. Major contributions to photoproduction of pions below 900 Mev.

For energies below 350 Mev, the main features of the observed distribution can be explained by A and C alone. For π^0 there is a $2 + 3 \sin^2\theta$ distribution throughout, while the π^+ has one half of this together with an isotropic component and an interference term

$$-2\left(\frac{1}{3}\right)^{\frac{1}{2}} \mathrm{Re}(A^*C)\cos\theta .$$

The phase of C remains small; that of A increases through 90° at resonance, so that this term gives an asymmetric contribution having a backward maximum below resonance and a forward maximum above. For the measurements near 700 Mev the results are somewhat similar[2-4]: the π^0 shows a steady symmetric distribution with a maximum at 90°, while the π^+ distribution has a strong asymmetry which, however, is peaked forward below, as well as above, the resonance. The π^0 distribution rules out $J=5/2$ for the state B (which would require a dip at 90°) and is quite consistent with $J=3/2$. However, the asymmetric term in the π^+ distribution cannot be interpreted as interference between B and C since it does not change sign on going through resonance. We must conclude that the interference between B and C is symmetric about 90° and thus that B and C have the same parity. Hence the most likely assignment for the proposed resonance is $J=3/2$, odd parity ($D_{3/2}$).

This assignment has one difficulty: If A and B are assigned opposite parity, then there must be an interference term (also $\cos\theta$ in this case) between A and B which should also show up in the π^0 distribution. However, the coefficient of this term involves $-\mathrm{Re}(A^*B)$. Since the widths of the resonances A and B are roughly comparable with the separation between them, the phase of B is small at the maximum of A and increases to 90° at 700 Mev, while the phase of A increases from 90° to near 180°. Hence the relative phase of A and B remains near 90° throughout this region and thus any interference term will be suppressed. Above 700 Mev, this relative phase decreases from 90°, and we expect a backward-peaked distribution to occur. This is, in fact, observed at these energies.

It still remains to explain the observed asymmetry in the π^+. As we have seen, the interference between A and C above the maximum of A is peaked forward, and this asymmetry would not be affected by B going through resonance. At the second resonance the π^+ angular distribution may be written

$$|C|^2+ \frac{1}{6} (2+3 \sin^2\theta)(|A|^2+2|B|^2) -2\left(\frac{1}{3}\right)^{\frac{1}{2}} \mathrm{Re}(C^*A).$$

(At resonance, B^*A and B^*C are purely imaginary.) Since A and C are about 180° out of phase at this energy, and because of (2), this becomes

$$\left(2+2\left[\frac{2}{3}\right]^{\frac{1}{2}} \cos\theta\right)|A|^2+ \frac{1}{6} (2+3\sin^2\theta)(|A|^2+2|B|^2).$$

This agrees with the shape of the actual distribution. Since the observed ratio of maximum to minimum is about 3:1, it follows that

$$|B|^2 \cong 4|A|^2 = 2|C|^2.$$

This determination of the relative magnitudes of A, B, C from the data at one energy, assuming a $D_{3/2}$ resonance, agrees extremely well with the extrapolation of lower energy data for A and C — certainly within the possible accuracy of such an oversimplified calculation.

In pion scattering experiments, a $T=1/2$ peak is also observed, but spread over a much wider range of energies. This can be interpreted as two overlapping levels[1] of which the lower corresponds to that seen in photoproduction. We may then ask why the higher one is not also seen, or at least does not overlap so strongly. From the magnitude of the total cross sections this level must have $J \geq 5/2$, and thus may also be a D-state resonance. However, in photoproduction a $D_{3/2}$ level can be excited by electric dipole while a $D_{5/2}$ state requires magnetic quadrupole. Hence, as compared with scattering, the $D_{5/2}$ state should be much less important.

We may conclude that, assuming the existence of a resonance, the angular distributions greatly restrict its possible nature. The fact that we are then led uniquely to reasonable values for the ratios A:B:C, consistent with a resonance picture seems in itself some evidence of the validity of the assumption.

The author is greatly indebted to Professor R. R. Wilson and Professor H. A. Bethe for much stimulating discussion and valuable suggestions.

---

*Work supported by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

[1] R. R. Wilson, Phys. Rev. 110, 1212 (1958).
[2] J. W. DeWire et al., Phys. Rev. 110, 1208 (1958).
[3] P. C. Stein and K. C. Rogers, Phys. Rev. 110, 1209 (1958).
[4] M. Heinberg et al., Phys. Rev. 110, 1211 (1958).