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Current photomeson theory is exstremly complex. The most recent formulation of photoproduction amplitudes through the application of dispersion relation techniques gives rise to formulae for crossections which are so complicated that it is almost impossible for a person, not already very familiar with the field, to see the physical significance of the various terms. Each term expresses the intensity of the contribution of a particular physical interaction or pair of interactions, and therefore must be understandable in terms of basic physical concepts.

In planning new experiments it is useful to be able to interpret existing theory in terms of a simple model so that those experiments which test the critical part or parts of a theory can more easily be selected. Certain experiments which can be performed with a machine of the type under construction at Frascati are clearly demanded just by reason of the new energy interval made available by this machine. In the interpretation of these, as well as in the planning of others, an understanding of the situation at lower energies is essential. For these reasons, it is probably worth while to try to make a rational presentation of the experimental facts of low energy photomeson production and to demonstrate their theoretical significance.

Most of the experiments that will be discussed involte the bombardment of H_2 with γ-rays. The target proton is essentially stationary. The bombarding proton is part of a bremstrahlung spectrum. The events of interest will be production of π^+ or π^0 mesons mesons can be detected directly in emulsions or counters. Measurement of the energy (or momentum) and angle of emission of the meson defines completely the dynamics of the two-body process. (It is assumed that meson production accompanied by re-emission of a photon is negligible, being down in amplitude by a factor 1/137 from the simple meson emission). π^0 mesons, because they are neutral particles, cannot be detected directly, but because their lifetime is very short ($\geq 10^{-15}$ secs) the two γ-rays emitted in the decay of the π^0 originate, essentially, at the point of π^0 production. Detection of both γ-rays (angle and energy) would specify completely the kinematics of the π^0 and thus of the photoproduction process. Good resolution of γ- ray energies is difficult, and double coincidence detection is slow;therefore other systems are usually used. Most direct is the detection of the recoil proton angle and energy (or momentum). Just as in the case of the π^+ meson, such an observation completely specifies the photoproduction process, if it truly is the proton recoil of a π^0 production that has been detected. There are, however, other sources of protons and a careful identification of the events being observed is essential. A third method for investigating π^0 photoproduction is to observe the angular distribution of single γ-rays from π^0 decays. This angular distribution is related to the angular distribution of the π^0,s(2).

Combinations of proton and γ-ray detectors may also be used.

The experimental data that will be used at the end of this paper are composites of data obtained at MIT, Cornell, Cal. Tech, Berkeley and Illinois. The arguments will be largely qualitative ones, so experimental uncertainties will not be discussed. In general, the experimental results are good to better than 10%.

The approach will be to select certain experimental facts and, from them, to develop a consistent the-oretical interpretation. Experimental facts have been carefully selected und are presented in an advantageous order. Historically the development was not so simple as it will appear here.

The basic interaction we wish to investigate is $\gamma + p \rightarrow \pi + n$ where n represents a nucleon, proton or neutron, depending on the charge of the pion. In analysing an interaction of this kind, a multipole analysis of the photon absorption or a partial wave analysis of the emitted mesons is often helpful. In order to make use of one of these techniques, we must find some argument which will justify cutting of the multipole expansion at some finite multipole order or cutting of the partial wave analysis at some finite angular momentum limit.

For a multipole expansion, for photon energies above the meson production threshold, λ photon $\leq r$ meson-nucleon system. Therefore r/λ is not $<< l$ for small l's, and there is no strong multipole selection from electro-magnetic considerations alone.

To find if there is a reasonable limit that can be placed on the angular momentum of an emitted meson we shall assume that meson are produced within a region of radius $r = \hbar/\mu c$ around the nucleon (μ=meson rest mass). Then the maximum angular momentum for a meson with linear momentum p, will be:

$$p \times r = p \frac{\hbar}{\mu c} = \hbar \ell_{max}$$

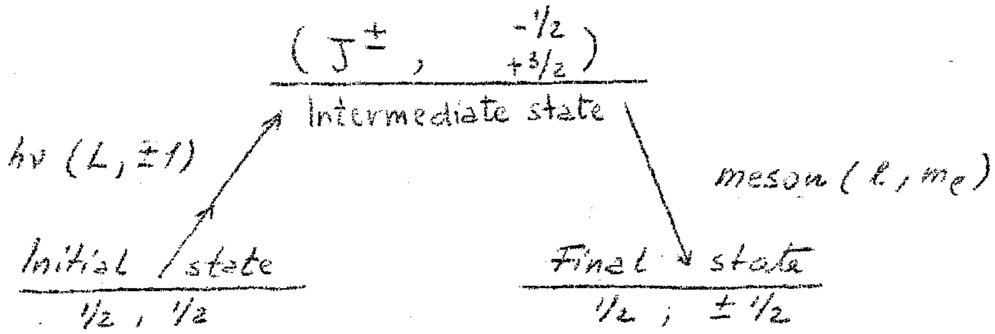
$$\therefore \ \ell_{max} = \frac{p}{\mu c} = \eta$$

Now, $\eta = 1$ for $E_\gamma \simeq 230$ MeV

$\eta = 2$ for $E_\gamma \simeq 400$ MeV

Therefore for experiments in the intermediate energy range, it is reasonable to hope to limit a partial wave analysis to S and P waves. (For a I BEV machine $p/\mu c$ =4,5. Therefore more terms would have to be considered in a partial wave analysis).

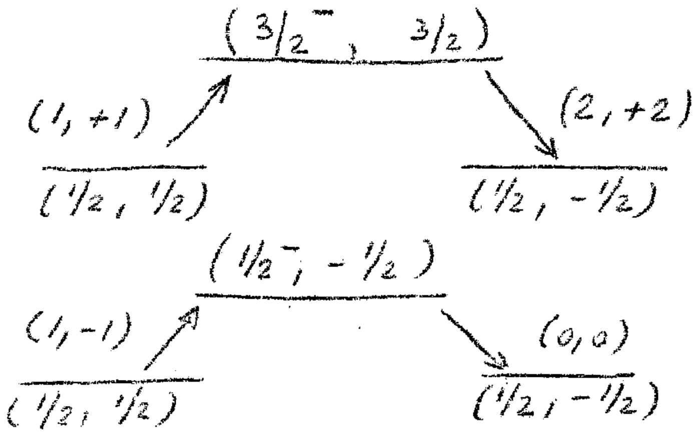
For S and P waves only, the most general angular distribution may be represented by $A_0 + A_1 \cos\theta + A_2 \cos^2\theta$. It is of interest to see what are the possible multipole absorptions which can give rise to S and P wave mesons. This can be determined schematically as indicated below:



In the initial state there is a nucleon, with spin $\frac{1}{2}$, z component $\frac{1}{2}$ with the z axis defined by the direction of the incident photon, $h\nu$. This photon has an angular momentum L consistent with its multipolarity (1 for dipole, 2 for quadrupole, etc.) and a z component of angular momentum, $\pm$ 1, arising from its intrinsic spin (circular polarization) only, since it can have no orbital angular momentum about the z axis, its direction of travel.

This photon absorption by the initial nucleaon state leads to an intermediate state of determined J and

M_J and parity state. Electric dipole, octopole etc. and magnetic quadrupole etc. give odd parity states. Electric quadrupole, etc. and magnetic dipole, octopole, etc. give even parity states. From the intermediate state, the system proceeds, by meson emission to a final state consisting of a nucleon with $S = \frac{1}{2}$, $m_s = \pm\frac{1}{2}$. The emitted meson has orbital angular momentum ℓ with z component m_ℓ. The meson-nucleon system has odd intrinsic parity, and the value of ℓ must be chosen to conserve parity from intermediate to final state, as well as angular momentum. For electric dipole photon absorption the following are the possibilities.



Of these two possibilities, the first gives rise to D wave meson emission and therefore is not of interest in our analysis (S and P waves only). The second leads to S wave meson emission.

By following through this process for all multipoles, it can be found that only the following can give rise to S or P wave meson emission:

Multipole	Intermediate state	ℓ meson	Ang. distrib. A_0	A_2	Moment. Dep	spin flip
E. D.	$1/2^-$	0	A_0	0	q	Yes
M. D.	$1/2^+$	1	A_0	0	q^3	Yes
M. D.	$3/2^+$	1	5	-3	q^3	Yes + No
E. Q.	$3/2^+$	1	1	1	q^3	Yes

With this framework before us, we are prepared to examine more carefully the mechanism of photoproduction. In some way, the incident γ-ray interacts with the pion-nucleon system. We know that a proton, for a linear theory, has two possible meson configurations:

$$p \rightleftarrows \begin{Bmatrix} p + \pi^\circ \\ n + \pi^+ \end{Bmatrix}$$

The electromagnetic interaction should certainly be much greater with the lower state than with the upper. The $n + \pi^+$ system has an electric dipole strength (er) $\sim$6x that for the $p+\pi^\circ$ system. The same can be shown for the anomalous magnetic dipole. Thus we might conclude from these considerations that the π^+ photoproduction crossection would be much bigger than that for the π°.

Experiments show that for an incident photon energy of 300 MeV, the π^+ and π° photoproduction crossections (c.m.) are about equal. At 90° c.m. the differential cross sections are both about 2×10^{-29} cm^2/ steradian. This is the first surprising result of photoproduction experiments. Clearly it cannot be understood in terms of the electromagnetic interactions. Therefore we must look for the effect of some other process. We must turn our attention to the other interaction which is present, that of pion and nucleon.

To understand the effect of this interaction it is necessary first to review briefly the results and analysis of pion nucleon scattering experiments in the same energy region for the pion nucleon system.

Results of the scattering experiments can be summarized roughly as follows

		Relative magnitudes $P_{3/2}$ crossections
$\pi^+ + p \rightarrow \pi^+ + p$	predominant interaction occurs in $P_{3/2}$ State	9
$\pi^- + p \rightarrow \pi^- + p$		2
$\pi^- + p \rightarrow \pi^0 + n$		1

To fit these results into a simple pattern, the concept of isotopic spin is useful. The charge indipendence of nuclear forces suggested a formalism in which n,p were same particle in two different charge states. Following the familiar spin formalism, these states may be called states of different z component of isospin. Therefore for the nucleon, with 2 states,

$$I = \frac{1}{2}\ ,\quad I_z = \pm\frac{1}{2} = \begin{cases} \text{proton,} \\ \text{neutron,} \end{cases}$$

similarly for the pion $\left.\begin{matrix}\pi^+\\ \pi^0\\ \pi^-\end{matrix}\right\} = 3$ states, therefore I=1, $I_z = \begin{matrix}+1\\0\\-1\end{matrix}$ Now, holding to analogy with spin angular momentum systems, we can express various nucleon-meson combinations in terms of probability amplitudes of isospin eigen states, that, is, instead of expressing the state of the system in terms of the particle eigenstates, we express, it in terms of isospin eigen-states. Those are the 'good' states under the pion-nucleon interaction. The amplitudes in the various isospin states are given simply by the Clebsch--Gordon coefficients,

$$\begin{array}{ll}
p\pi^+ & 1\ (I = 3/2\ ,\ I_z = 3/2) \\
p\pi^0 & \sqrt{2/3}\,(3/2, 1/2) + \sqrt{1/2}\,(1/2, 1/2) \\
p\pi^- & \sqrt{1/3}\,(3/2, -1/2) + \sqrt{2/3}\,(1/2, -1/2) \\
n\pi^+ & \sqrt{1/3}\,(3/2, 1/2) - \sqrt{2/3}\,(1/2, 1/2) \\
n\pi^0 & \sqrt{2/3}\,(3/2, -1/2) - \sqrt{1/3}\,(1/2, -1/2) \\
n\pi^- & 1\ (3/2, -3/2)
\end{array}$$

In the above table, the isospin states are defined by the expressions in parenthesis, $(\frac{3}{2}, -\frac{1}{2})$ is the state with $I_{total} = \frac{3}{2}$, $I_z = -\frac{1}{2}$.

Theory suggests the exsistence of a strong pion--nucleon interaction in the $P_{3/2}$, $I=\frac{3}{2}$ state. We can exsamine the expected ratios, of that part of the above scattering experiments, which goes trough this so-called (3,3) state.

In the $I = \frac{3}{2}$ state:

	Product of amplitudes in initial and final studos	Relative magnitudes of σ's $\sim$ $(\mathrm{Ampl})^2$
$(p,\pi^+) \to (p,\pi^+)$	$1 \times 1 = 1$	1
$(p,\pi^-) \to (p,\pi^0)$	$\sqrt{1/3} \times \sqrt{2/3}$	2/9
$(p,\pi^-) \to (p,\pi^-)$	$\sqrt{1/3} \times \sqrt{1/3}$	1/9

Thus we see that the scattering traugh the (3,3) state should have relative intensities 9:2:1. Since this roughly represents the exprrimental observations, may assume in the first approximation that the (3,3) interaction is so strong, in this energy region, that it swamps all others.

In a partial wave analysis, including S and P waves only, there are six phase shifts, $\alpha_1, \alpha_3, \alpha_{11}, \alpha_{13}, \alpha_{31}, \alpha_{33}$, the single subscripts denoting the total I-spin for the S - states, and the double subscripts denoting I-spin and I-angular momentum for P-states. The dominance of the interaction in the (3,3) states indicates that α_{33} the large phase shift. How can we make use of this state of affairs to help explain the photomeson production results?

The strong $\pi - N$ interaction in the (3,3) state gives rise to a system which selectively responds to those multipolarities of photons which can excite this state. The subsequent interaction in the intermediate state gives rise to meson emission in the final state as for the amplitudes discussed above.

Then we can explain the large photoproduction of neutral-mesons as the result of this meson-nucleon interaction, the relative amplitudes pf the (3,3) state in (p, π^0) and (n, π^+) systems are $\sqrt{2/3} : \sqrt{1/3}$. Therefore we expect a 2:1 ratio of σ's favoring π^0's . Then the original difficulty is not removed but symply reversed. The question now is, why is σ^0 equal to σ^+ instead of to $2\sigma^+$. Let's approach this question by comparing σ^0 and σ^+ data with predictions of the model we have so far developed. P - wave only will give an angular distribution $A_0 + A_2 \cos^2\theta$, a momentum dependence proportional to p^3, A_2/A_0 = -0,6 for pure M.D, = +1 for pure E.Q.

Experimental data on π^0 photoproduction (2) (3) (4) shows angular distributions which have $A_1 \simeq 0$. Therefore the p-wave component is predominant as predicted by our model. Also, the ratio $A_2/A_0 \simeq -0.6$ corresponding to M.D, for $E_\gamma \geq 220$ MEV. (Below this energy, the ratio apparently decreases in absolute value, approaching zero at threshold (4), but we shall ignore this point for the time being.). Data on the 90° differential crossection (4) show that there is a momentum dependence $\sim p^3$ at γ energies less than 270 MEV, and then that the crossection peaks at about E_γ = 325 MEV. To see whether this is consistent with the prediction of our model based on scattering experiments, we must compare the results at corresponding energies of the pion-nucleon systems. For E_γ = 325 MEV, pion energy is about 185 MEV, and this is just the energy at which the scattering crossections have their maximum. In a more quantitative analysis (1) (4) it can be shown that the total crossection for photopion production is related to the total crossections for the three scattering processes discribed above, by the following formula.

$$\frac{2\sigma_{photoprod}}{\sigma^{++} + \sigma^{--} - \sigma^{-0}} = \frac{0.0026}{\beta_\pi}$$

where σ^{++} is crossection for scattering $+ \longrightarrow +$

σ^{--} is crossection for scatterin_ $- \longrightarrow -$

σ^{-0} is crossection for scattering $- \longrightarrow 0$

β_{π} is velocity of incident pion in scattering experiment.

This relationship is found to hold well, (4), thus lending strong support to the model we have selected for π^0 photoproduction. We shall call this model the enhanced p-wave model since it depends largely on the strong interaction between pion and nucleon in the P 3/2, I = 3/2 state.

Since π^0 photoproduction experiments seem to be in good agreement with the proposed model, we must look at photoproduction data for an answer to the large observed π^+/π^0 ratio. If we look first at the 90° excitation function (5), we see that here σ does not increase with p^3. Near threshold it evidently has a dependence more close to p^1. If we look at a series of angular distributions (5) from 170 to 300 MEV we find that below 200 MEV, emission is roughly isotropic, whereas from there to 300 MEV there is a strong asymmetry about 90°. The coefficient A_1 evidently has a negative value. Both of these facts suggest the presence of an S-wave. The first, because of the momentum dependence proportional to p; the second, because the asimmetry is of the type that would arise from an S-P interference, What, then, is a possible source of a π^+ photoproduction S-wave which would not be a source also of a π^0 S-wave? It must be a strongly charge-dependent interaction which does not go through an intermedihte state of strongpion-nucleon interactionwhere charge-state mixing could occur. For a pseudoscalar meson, the meson-nucleon coupling is of the form $\hat{\sigma}\cdot\vec{q}$. Now, when an elctromagnetic field is introduced into this system, for a charged meson the Hamiltoniam for the new system can be formed by making the substitutions $V \rightarrow V + e\phi$ and $\vec{q} \rightarrow \vec{q} - \frac{e}{c} A \hat{\varepsilon}$. Thus in the photon-nucleon-charged pion system, there is a photon coupling present which is absent in the case of a neutral pion, namely:

$$\hat{\sigma}\cdot\vec{p} \rightarrow \hat{\sigma}\cdot(\vec{p}-\frac{e}{c}A\hat{\varepsilon}) = \hat{\sigma}\cdot\vec{p} - \underline{\frac{e}{c}\hat{\sigma}\cdot\hat{\varepsilon}A}$$

This $\hat{\sigma}\cdot\hat{\varepsilon}$ term is isotropic for unpolarized photon and protons and is momentum independent. It therefore leads to a term in the photoproduction crossection which is isotropic and which increases with momentum as p^1 from the phase space factor only.

Looking back to our original table we see that this is an electric dipole produced S-wave term.

To, verify that this term does indeed exist and is the one which gives rise to the apparent S-wave effects in the experimentally observed angular distributions, we can make some quantitative measurements and compare the results with evaluations of this term of the theory. When various unitary conditions, etc. are applied, the theory predicts the value of the coefficient of the $\hat{\sigma}\cdot\hat{\varepsilon}$ term. In fact in the 90° σ, it involves a phase space factor, the square of the two co pling constants involved, $e^2 \cdot g^2$, and a function of h, c and themasses. All of these are more or less well known. Bernardini + Goldwasser at Ilinois and Beneventano, Stoppini, Tau Lee here performed an experiment which was intended to separate S+P wave contributions and obtain the value of the square of the S-wave matrix element at threshold (5) (6). The method used was to divide the low energy experimental 90° crossection by the calculated value of the phase space statistical factor. The result of this division should give quantities made up of an S-wave term which is constant, and a p-wave term which increases with energy as p^2. The points thus calculated were then plotted against p^2 and a straight line drawn trough them. The intercept of this straight line at p=0 should be the quantity we were looking for. This type of analysis gave a value of the pion-nucleon coupling constant, $g^2 \simeq 12$ compared to a value of 15 ± 3 from scattering experiments. This seem to be reasonable verification of the hipothesized S-Wave term.

It is worthwhile now to examine further the S-P interference to see what can be learned from it.

Since the S-wave is spin dependent ($\hat{\sigma}$, $\hat{\varepsilon}$) it can interfere only with a spin dependent part of the P-wave, P'.M.D. and E.Q. P-wave amplitudes both have the form

$$\sin\alpha_{33} e^{i\alpha_{33}} \therefore 2 Re\, S \times P' \cos\theta = 2K \cos\alpha_{33} \sin\alpha_{33} \cos\theta = K \sin 2\alpha_{33} \cos\theta$$

and we see that the magnitude of the interference term depends on the value of α_{33}.

In particular, the term should have a maximum at α_{33} = 45° and should go through zero when α_{33} = 90°. The angular distribution obtained at Cal. Tech. at energies up to 450 MEV clearly indicate a change of sign of the interference term between 300 and 350 MEV. Thus α_{33} goes through 90° in this region. Until now we have intentionally referred only to a strong pion-nucleon interaction, not to a resonance. Original analysis of the scattering experiments, indicated that α_{33} did not go through 90°. This behaviour of the π^+ photoproduction interference term is perhaps the strongest experimental evidence that there truly is a resonance.

Is everything now in good shape? To test, we can do the following manipulations with 90° crossections. Start with $\sigma^+(90°)$, subtract S-wave part (now known). Subtract enhanced p-wave (1/2 $\sigma^0(90°)$). This should leave nothing, but there is still something, left, figure 1. What is it?

Evidently we again have run into a charge dependent effect, i.e. it contributes differently to π^+ and π^0 photoproduction.

It is reasonable again to suspect that it is a term which exists for π^+ but not for π^0. It has a maximum at 270 MEV and = 0 at $\sim$ 325 MEV. What kind of term behaves like that?

It has been shown that the real part of the enhan-

$$\left(\frac{d\sigma}{d\Omega^*}\right)^{+}_{90^\circ} - \left(\frac{d\sigma}{d\Omega^*}\right)^{+\,\text{s-wave}}_{90^\circ} - \frac{1}{2}\left(\frac{d\sigma}{d\Omega^*}\right)^{0}_{90^\circ}$$

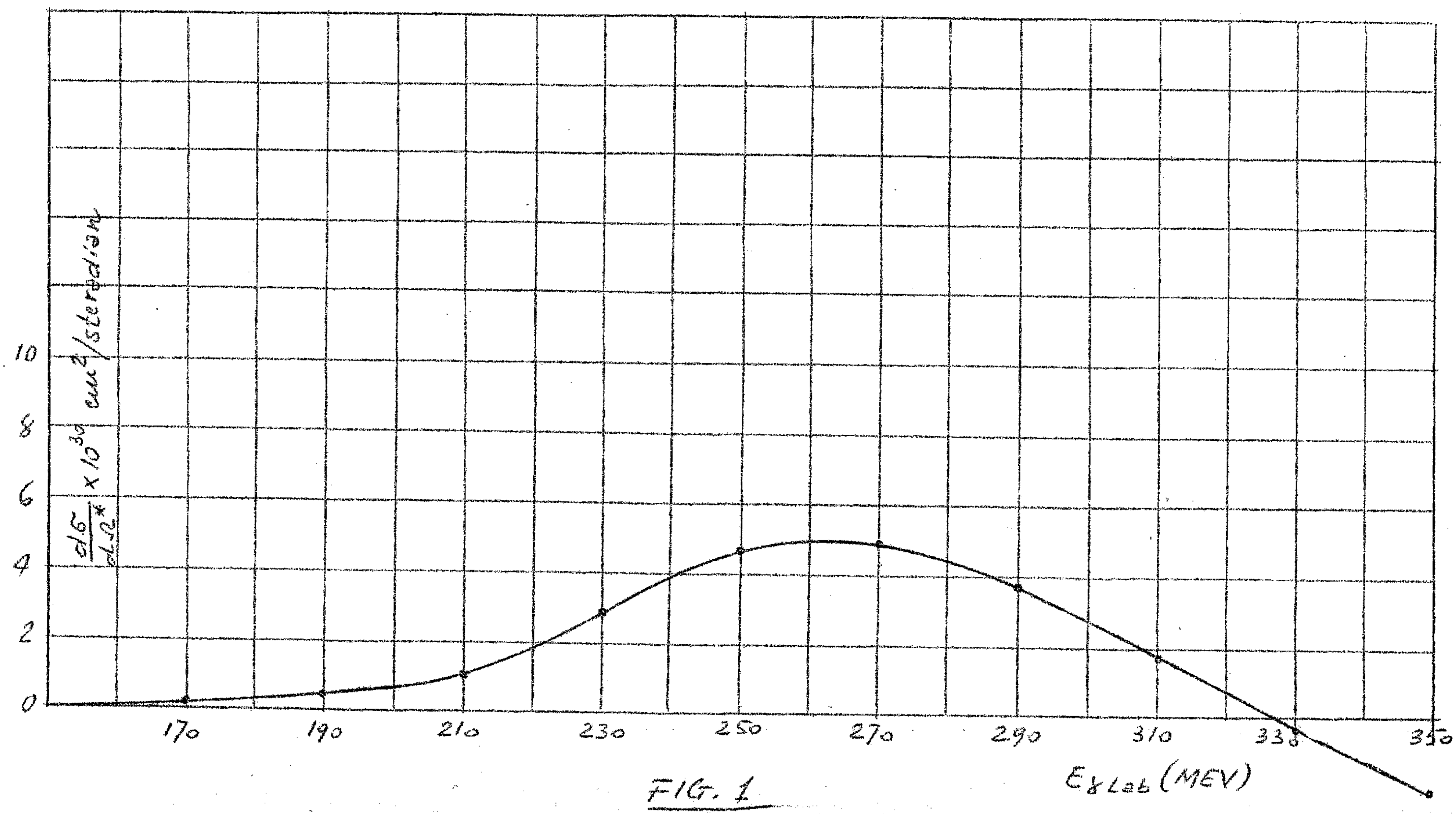
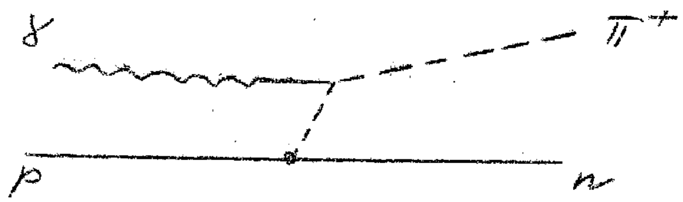


FIG. 1

ced p-wave is proportional to $\sin 2\alpha_{33}$ and ∴ =0 at α_{33} =90° (~ 325 MEV) and = max at α_{33} = 45° (~280 MEV). Thus the residue that we have found in Figure 1 looks like an interference effect, but S-P interference ($\cos\theta$) = 0 at 90°. Thus within our original hypothesis of S and P waves only, we must have a P-P interference. So far we have expressed only the enhanced P-wave. If a non enhanced p-wave term werepresent, it could interfere with the enhanced p-wave giving just such an effect. Another source of photomesons, so far not expressed, is the meson photo-effect



Here there is no strong interaction between meson and nucleon this is often called direct effect, or, because it was first treated in detail by Chew, (7) the Chew term; or, because of the form of the denominator, the retardation term. Its amplitude has the form:

$$\frac{\hat{\sigma}\cdot(\vec{k}-\vec{q})\ \vec{q}\cdot\hat{\varepsilon}}{1+(\vec{k}-\vec{q})^2}$$

where $\vec{k}$ = photon momentum
$\vec{q}$ = meson momentum (in μc units)

Thus the denominator $(\vec{k}-\vec{q})^2+1 = k^2-2qk\cos\theta+q^2+1 =$
$= k^2-2qk\cos\theta+\omega^2 \simeq 2k^2(1-2V\cos\theta+1)=2k^2(1-V\cos\theta)$

Calculations of theoretical σ's including this term show it to have a large effect at very forward angles and at ~ 270 MEV. During the past year Peres-Mendes at Berkley and Malmberg + Robinson at Illinois have made measurements which clearly indicate its presence.

We have now found the effect of an interference between the enhanced p-wave and a non-enhanced P-wave. Since we know quantitatively (from theory or from π^0 photoproduction experiments) the amplitude of the enhanced p-wave, we can calculate from the observed interference the amplitude at 270 MEV of the non-enhanced P-wave,. Knowing this, we can extrapolate its intensity (phase space squared amplitude) to 330 MEV using a p^3 momentum dependence for the p-wave, and we can thus predict a contribution of ~ 7 μbarns from the non-enhanced P-wave at this energy. This should remain as a residual in the experimental crossection after subtracting the s-wave and enhanced p-wave contribution. Actually we have found the residual crossection, following these manipulations, to be about zero at 330 MEV. This can be expained as follows: When we square the sum of the two amplitudes arising from the gauge invariance and the photoeffect interactions,

$$\hat{\sigma}\cdot\hat{\varepsilon} + 2\,\frac{\hat{\sigma}\cdot(\vec{K}-\vec{q})\;\hat{q}\cdot\hat{\varepsilon}}{1+(\vec{K}-\vec{q})^2}$$

we find that there is a remarkable cancellation, first pointed out by Chew (7) between the square of the second and the interference between the first and second. The residual from this cancellation is of the order of 1 μbarn at 330 MEV which is too small to be detectable through the suggested manipulations of the currently available data.

We now have accounted for all of the qualitative effects and incorporated them in a rough model of photo-nucleon interaction It is not worthwhile to pursue further this semi-quantitative discussion. The dispersion relation have been applied (1) to the problem to give numbers for the various amplitudes. They take into account not only the pion-nucleon interaction in a (3,3) state but also include the relatively smaller effects of the other states.

Furthermore, the calculations can be made completely relativistic and all correction of the order $1/M$ can be expressed. One of the most interesting of these is the effect of the nucleon recoil. In the case of an infinite mass nucleon, there is no nucleon recoil and one would expect the

π^+ production from a proton to be identical with the π^- production from a neutron. When we consider a nucleon of finite mass, the interaction between the photon and the neutral recoil (for π^+ production) and the charged recoil (for π^- production) is different. For istance, the electric dipole stronght of the π^- - proton system is greater than for the π^+ - neutron system by a factor of $\frac{1+\omega/M}{1-\omega/M} = 1.35$ at threshold. This factor is of great interest at present. It will be discussed in more detail at a later date.

Appended to the list of references, 1-9, are some additional references not specifically cited here, which give descriptions of other important experimental work and theoretical analysis.

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