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THE PRODUCTION OF MESONS BY PHOTONS AT 0|

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Nelson Jarmie

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I. ABSTRACT

Hydrogen gas has been bombarded in a high pressure, low temperature target by the 322 Mev bremsstrahlung of the Berkeley synchrotron to produce π^{+} mesons at 0 ± 4 degrees to the beam. The mesons were bent out of the photon beam by a magnetic field. The mesons passed through a lead channel and lead absorbers and were detected in Ilford C-2 emulsions. Data has been obtained for a photon energy of 278 ± 4 Mev. (This is for a meson energy of 134 ± 4 Mev.)

The absolute differential cross section is:

$$\frac{d\sigma}{d\Omega}(k,\theta) = \left(6.2 \begin{array}{l} +2.6 \\ -1.9 \end{array}\right) \times 10^{-30} \text{ cm}^2/\text{ster./proton/quanta}$$

This point has been combined with other data[2] at other angles to give an angular distribution of the form $a + b \cos\theta + c \sin^2\theta$ and this is compared with the phenomenological isobar theory. The cross section has been corrected for nuclear absorption in the gas and meson absorber, scattering, decay in flight and has been transformed to the center of mass system. It must be noted that this cross section was calculated from 10 events.

A study of the calibration of the beam has been made, and a discussion of the theory of errors of a small number of events is included. Mesons from deuterium were also detected and the ratio of the production from deuterium to hydrogen is given but is not statistically significant.

The significance of the experimental results in the light of the phenomenological theory as developed by Watson and Brueckner[7] and Feld[6] is discussed.

THE PRODUCTION OF MESONS BY PHOTONS AT 0°

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II. INTRODUCTION

The field of study of the nature of the meson and subject of nuclear forces that is intimately connected with it has progressed so rapidly in the last few years that it is almost impossible to give a decent summary of the field without writing a book. Many facts have been unearthed, yet the total state of knowledge about the meson is poor indeed. On the one hand, the "static" properties of the meson particle-field are becoming fairly well known: the charge, rest mass, spin, parity, and the lifetime and decay products; but the "dynamics": the laws and theory concerning meson production and interaction with matter and energy, is floundering very badly. It almost seems as if a major revision of some of the concepts of physics on the level of relativity and quantum mechanics will be needed to bring the theory of the meson to the clarity and simplicity that scientists have come to expect about the formulation of the laws of the universe.

The study of the photoproduction of mesons is of very great importance towards this end, primarily because the gamma ray is "used up" in the reaction, reducing the complexity of the reaction and making it more amenable to theoretical investigation. The reactions $\gamma + \rho \longrightarrow \pi^{+} + n$ and $\gamma + \rho \longrightarrow \pi^{0} + \rho$ being only two-body processes, play a leading role in the investigations; and are, at present, being given much attention. Experiments are being done wherever there are high energy gamma ray machines: Cornell, M.I.T., University of Illinois, Cal Tech, and here at the University of California (see references).

From the experimentalist's point of view, one of these two-body processes is completely described by stating the differential cross section $\frac{d\sigma}{d\Omega}(k, \theta)$ at all angles and energies (k is the energy of the photon and θ the angle that the momentum of the meson makes with the momentum of the photon). From this may be derived the angular dependence and excitation function for the production of mesons. A theory must successfully explain both of these, or at least be compatible with them, in order to be worth serious consideration.

It is the purpose of this paper to describe an experiment measuring the differential cross section of the reaction $\gamma + p \longrightarrow \pi^+ + n$ at zero degrees at a gamma ray energy of about 277 Mev, and to discuss how this value is of importance in advancing our knowledge of meson reactions. Information on the reaction $\gamma + d \longrightarrow \pi^+ + n + n$ is also given.

The experiment was originally planned with emphasis on measuring the ratio of the cross sections of the photoproduction of mesons from hydrogen and deuterium at zero degrees. This value, when used in phenomenological calculations[16, 17, 18], gives direct information on the "spin-flip" of the nucleon concerned in the reaction or, in other words, on the mode of coupling between the meson and nucleon. Previous work[2] measured such cross sections at various angles but did not give a "spin-flip" value was statistically significant. However, we found that the cross sections are quite low at zero degrees and that a determination of a significant value for the ratio is very difficult. Therefore, with the recent interest in the absolute value of the cross section of $\gamma + p \longrightarrow \pi^+ + n$ at zero degrees it was decided to turn our efforts to measuring this quantity.

A long time was spent in attempting to measure this quantity with electronic detection equipment, using the pi-mu decay as the characteristic event to detect the pi meson. It became clear that primarily due to the flood of pair electrons and positrons in the forward direction, this method would not be successful.

Essentially the method finally used was to produce the mesons in a high pressure gas target, then to bend them away from the beam with a magnetic field and to detect them in Ilford C-2 nuclear emulsions. There is developed the experimental equation which determines the differential cross section. Then the evaluation of each parameter in that equation is described after which the results are shown. The relationship of the results to other work in the field and their significance with respect to the existing theories are discussed. Long calculations of interest and reference formulas are subjugated to appendices so as not to interfere with the continuity of the paper.

III. GENERAL DESCRIPTION OF THE EXPERIMENT

A diagram of the experimental arrangement is shown in Figure 1. Photons from the 322 Mev bremsstrahlung of the synchrotron pass through a beam monitor (an ionization chamber); are collimated by a tapered 3/4 inch hole in nine inches of lead; pass through a fringing collimator to eliminate the spray from the edges of the primary collimator; and pass through a 24 inch target containing the target gas (hydrogen or deuterium) at a high pressure, about 2100 psi, and cooled to liquid nitrogen temperature. The mesons (and positrons of the same momentum) are bent by a large pair magnet. The entire set-up was carefully aligned with a telescopic optical system. X-ray pictures were taken to check the alignment.

The meson particles are roughly channeled and pass through a thick lead absorber (see Figure 2), and are detected in horizontal Ilford C-2 emulsions. A large number of emulsions were exposed, a few at a time being removed at given periods to give a spectrum of the exposures and to conserve beam time. The synchrotron running time for the collection of the data used was about four 16 hour days.

One of the essential points of the experiment was the use of a very thick absorber; which, although restricting observation to the very high energy mesons, presented many shower lengths (well over the shower maximum) to the positron background and thus served to lower the latter to a usable level. The average energy meson observed was about 134 Mev and used about 12 shower lengths of lead to stop. A series of runs was also tried with 100 Mev mesons, but the plates were too dark to be of use, even in the low exposures, due to the positron contribution to the single grain background in C-2's.

Let us now proceed to relate the cross sections to physical parameters and describe in some detail the determination of these experimental quantities.

IV. EXPERIMENTAL PROCEDURE

A. The Cross Section

The differential cross section, in terms of experimental parameters, may be defined as follows: The number of events for a given phenomena occurring in a given solid angle, at a given angle, due to a certain energy (k) projectile is equal to the differential cross section $\frac{d\sigma}{d\Omega}(k, \theta)$ times the number of target particles per cm^2 times the number of photons of energy k times the solid angle. Symbolically and approximately:

$$\Delta N = \frac{d\sigma}{d\Omega}(k, \theta) \cdot \Delta\Omega \cdot n \cdot dt \cdot d\gamma \qquad (1)$$

where n equals the particle density in the target and dt is the thickness of the target. In our case, $d\gamma$ is the number of photons of energy k in the bremsstrahlung causing the reaction.

Let us define a series of quantities which are to be used in expanding equation (1):

$d\Omega/dA$	is the rate of change of solid angle at the target due to a change of vertical area at the emulsion.
h	is the thickness of the emulsion scanned. (200 microns)
ℓ	is the width of the emulsion scanned.
R	is a parameter of distance along the beam of mesons at the emulsions.
ΔR	is the distance of emulsion scanned along R.
T	is the kinetic energy of the meson.
dR/dT	is the rate of change of the range of mesons due to a change of meson energy at the target.
$f(k)$	is the ordinate of the bremsstrahlung spectrum, in which kN(k) is plotted vs. k. See Figure 5.
Q	is an "equivalent quanta" (e. q.) which is the energy in the photon beam divided by the maximum photon energy (322 Mev).
dQ/dNu	is the calibration of the number of Q in the beam in terms of an arbitrary amount of charge produced in the beam monitor (ion chamber), this amount being called a "nunan" (Nu).

Note that: $\Delta\Omega = \frac{d\Omega}{dA} \cdot \ell \cdot h$

and that the expansion of $d\gamma$ in terms of bremsstrahlung parameters is:

$$d\gamma = \frac{d\gamma}{dk} \cdot \frac{dk}{dT} \cdot \frac{dT}{dR} \cdot \Delta R$$

Now $\frac{d\gamma}{dk}$ is a function of the shape of the bremsstrahlung spectrum and the beam monitoring and, using the definition of f(k), is equal to:

$$\frac{d\gamma}{dk} = \frac{1}{k} \cdot \frac{f(k)}{\text{area}} \cdot 322(\text{Mev}) \cdot \frac{dQ}{dNu} \cdot \Delta Nu$$

where "area" is the area under the curve (bremsstrahlung spectrum) from which f(k) is read.

Putting all this into equation (1) gives:

$$\frac{d\sigma}{d\Omega}(k, \theta) = \frac{N}{\Delta R \cdot \ell \cdot h \cdot n \cdot 322 \cdot \frac{dQ}{dNu} \cdot \Delta Nu \cdot \int_{t=o}^{24\text{ inches}} \frac{d\Omega}{dA} \cdot \frac{dk}{dT} \cdot \frac{dT}{dR} \cdot \frac{1}{k} \left[\frac{f(k)}{\text{area}}\right] \cdot dt} \qquad (2)$$

It is to be emphasized that N must be corrected for nuclear absorption, decay in flight, scattering and efficiency of detection. The cross section will be transformed to the center of mass system for its final form. All units are consistent if centimeters and Mev are used throughout.

B. Determination Of N

1. Magnet The magnet is a large pair spectrometer for general use at the synchrotron, capable of producing around 14, 000 gauss in a 3. 5 inch pole gap, although the experiment was run closer to 13, 000 gauss as a more suitable point. The magnet current was electronically regulated and measured with a Leeds and Northrup Potentiometer. The sign of the field was determined independently by several observers using the deflection of a wire powered by a battery. The magnet was close enough to the synchrotron that the guide field of the accelerator had to be compensated considerably by the crew in order for the

machine to operate at all. Smooth running of the synchrotron indicated the correct performance of the pair magnet during the entire run.

In order to insure that no unsuspected difficulty was encountered with the paths of the mesons in the magnet and channel geometry the meson trajectories were simulated by the magnetic wire technique, using exactly the magnet current and geometry used in the experiment. It was thus clear that the proper energy mesons had roughly the correct curvature and had free access to the emulsion scanned from various parts of the target. The magnetic shield for the target proved to be quite efficient since the trajectories did not bend except for a very little at the junction of the shield and pole piece. The emulsions were protected from the heat of the magnet by the blast of a powerful fan.

2. <u>Emulsions</u>. The Ilford C-2, 200 micron, one by three inch, glass-backed emulsions used were from a batch that had been used by others at the laboratory who had clearly seen pi-mu events with normal grain densities. The emulsions had permanent numbers scratched into them before the experiment to avoid mix-ups, and great care was taken to expose the properly numbered plates at the right time.

A few test plates were developed by a standard technique used at the laboratory. Upon scanning these it was felt that the thickness of emulsion prevented a uniform development felt necessary in the face of a very high single grain background, making track identification more difficult than usual. The author modified a "semi-cold" development (see appendix B) in use locally and developed the plates in groups in order to avoid accidental loss of the entire amount. All of the plates appeared to be in good shape after development. Some difficulty was encountered with peeling during a few very dry winter days.

3. <u>Scanning</u>. The emulsions were scanned with an American Optical Spencer binocular microscope with oil immersion objectives of 45 and 90 power together with oculars of 6 or 10 power. Fairly high speed scanning with low power was possible because of the very low density of tracks. However, when the single grain background became very high, a higher power was used. The mesons, expected to be positive, were detected by the usual indications of track scattering and the high rate of change of grain density towards the end of the track. Any such track with the slightest suspicion of being a meson

was inspected under higher power, and rough grain counts were taken at various points along the track to insure the determination. The majority of these tracks were quickly rejected as being protons. It was assumed that the efficiency for seeing mesons was 100 percent within the accuracy of the experiment. The pi meson was easily detected because of the mu meson emitted, which was clearly seen; but it was also desired to determine the density of the mesons ending with no decay particles visible. Under the present geometry it would be assumed that these were mu meson endings; and, assuming a constant density of pi mesons in the vicinity of the emulsion, one would expect the same number of mu endings as pi endings. This would serve as a check on the data and would also increase the statistics. As it will be seen, this criteria was well satisfied. It is interesting to note that all of the endings with no decay products had track lengths of less than 600 microns (the range of a mu from a pi-mu decay).

There were a large number of knock-on protons in the plates, presumably caused by neutrons produced mainly in the end windows of the target. The background emulsions, exposed to an empty target, showed almost as high a background of single grains and protons as the data plates.

The area scanned for the hydrogen point was 9.03 cm^2 ($=\Delta R \times \ell$), in which 4 pi-mu events were found and 6 mesons without endings were found. The mesons seemed to be scattered randomly over the area scanned and gave no sign of any systematic error. The pi mesons came from the proper direction. The background plates were scanned to 0.75 of the area of the data plates. No meson tracks were found. This agrees with a rough calculation of the fraction of mesons expected from the steel end windows using a variation with A of $A^{2/3}$, giving a value of less than 10 percent.

4. Decay In Flight. A simple relativistic calculation of the number of mesons decaying in flight, using the mean life (in the meson rest frame) of 2.5×10^{-8} sec.[31] gave a correction of only about six percent. It is easily shown that most of the mu's given off are in a tight forward cone and, except for a slightly longer range, also land in the emulsion. The nuclear absorption correction does not apply nearly as heavily to these mesons. With everything taken into account, the decay in flight correction can be neglected.

5. Scattering. The effect of small angle scattering in the absorber is compensated approximately by the "poor geometry" of the emulsion, in which as many mesons should scatter in as scatter out. To insure this, only the central portions of each nuclear plate were scanned. Scattering by the side walls is extremely difficult to calculate and may have added to the number of mesons found in the plate, raising the cross section. However, it is believed that, within the crude statistics of the final result, this effect is not serious.

6. Nuclear Absorption. Nuclear area was used in determining the number of mesons stopped in the absorber by nuclear collision. That is:

$$\sigma_{abs} = \pi r_o^2 A^{2/3} \quad \text{where } r_o \sim \frac{\hbar}{\mu c} = 1.4 \times 10^{-13} \text{cm}$$

this gives a value of $N \simeq N_o \times .59$ (N_o is the original number). The absorption in the gas is included in the calculation. The absorption cross section in hydrogen was taken from an article by Anderson et al[34].

C. The Target

The target was designed by R. Stephen White and is adequately described elsewhere[2]. See also Figures 3 and 4. The gas pressure was checked every few hours and did not vary significantly. The purity of the gases was better than 99 percent. The value of n, the number of target protons per cm^3, was determined as a function of the pressure and temperature from the curves of Johnston et al[24] and was on the order of 2.5×10^{22} protons per cm^3.

D. Solid Angle

The solid angle of a system partly in and partly out of a magnetic field is calculated in appendix A. The result was used to give the solid angle at various points along the target. This was used to help evaluate the integral in equation (2) which was performed stepwise using six sections of the 24 inch target as units. This satisfactorily allowed for the variation of the solid angle and range along the target within the accuracy desired. Using similar considerations it is found that, with the width of emulsion scanned, mesons were accepted with target angles from -5 to +5 degrees.

E. Relativistic Mechanics

The expressions for k as a function of the meson kinetic energy and its derivative dk/dt were straightforwardly derived from the conservation of relativistic total mass and momentum. These formulas agreed with those from many sources and need not be reproduced here. It might be of interest to note that, at the meson energy looked at (134 ± 5 Mev), the photon energy responsible was 277 ± 5 Mev (see Figure 5) and the value of dk/dt is 0.99.

The range energy curves used were those of Aron[32]. From these dT/dR was calculated as well as the energies of the mesons that stopped.

The transformation of solid angle from the lab system to the center of mass system is an interesting one and is done by using the fact that

$$\frac{d\Omega_{lab}}{d\Omega_{cm}} = \frac{d\,(\mathrm{Cos}\ \theta_{lab})}{d\,(\mathrm{Cos}\ \theta_{cm})}$$

using the beam direction as the z axis. The quantity on the right hand side of the equal sign is found by writing the angles in terms of the momentum components and using the relativistic transformation of momentum. When differentiating, it is convenient to have the total momentum written in the center of mass system, since there it does not vary with angle. The rather lengthy resulting expression reduces at zero degrees to:

$$\left(\frac{d\Omega_{lab}}{dZ_{cm}}\right)_{0^o} = \gamma^2 \left[\frac{\beta_o - \beta}{\beta}\right]^2$$

where γ and β refer to the velocity of the center of mass and β_o to the velocity of the particle. Straightforward relativistic principles give the velocity of the center of mass as:

$$\beta = \frac{k}{k + M_p c^2}$$

which, for a 277 Mev photon, is .228. The β_o of a 134 Mev π is .858, giving:

$$\frac{d\Omega_{lab}}{d\Omega_{cm}} \simeq .569$$

F. Bremsstrahlung

The shape of the bremsstrahlung curve was taken from the work of Terwilliger and Jones (see Jones[33]) who have taken the usual Bethe-Heitler curve and corrected it for multiple scattering in the .020 inch Pt target of the synchrotron and for collimator size. An additional correction was made to this for our particular experiment for a slight distribution in the electron energies in the circulating beam of the machine due to the way in which the rf accelerating voltage cuts off. The resulting curve is shown in Figure 5. The ordinate is in arbitrary units which are normalized in equation (2) by the division of the area under the curve which inherently contains the arbitrary factor in it.

G. Calibration Of The Beam

One of the most serious problems that arose was that of the absolute calibration of the beam intensity in terms of the beam monitor. The method of calibration used here at the present time is that used by Blocker, Kenney and Panofsky[29] in 1950, which has to do with our knowledge of pair and compton processes in measuring the charge collected in an ion chamber when various Z converters are placed in front of it. The calibration is expressed Q (equivalent quanta) per nunan (one discharge of an arbitrary condenser charged by the beam monitor).

Recent measurements by Blocker and Kenney, members of the synchrotron crew[30], and the author have disagreed with the earlier values by as much as 50 percent; and also the later values vary a little among themselves. It appears that if the beam level and the general room background level (indicated by separate chambers) are held constant the (recent) calibrations do not vary much at all.

Investigation into past records show that measurements of the intensity of the central part of the beam were made with a Victoreen thimble chamber. These measurements were made relative to the beam monitor. Interestingly enough, values of the measurement, made when the old beam calibration was made, differ from recent values by the same fraction as the difference in the beam calibrations.

This and other considerations have led us to believe that some internal parameters of the nunan meter (the beam monitor) must have changed over the years.

The variation in the later calibrations seems to be a direct function of the ratio of the room background to the beam level. This appears to be reasonable, since the monitor chamber is quite close to the machine. Extra background flooding into the chamber would give the nunan a faster rate for a given beam level and lower the value of the calibration. If one plots the various calibrations versus the ratio of the background to the beam level, there does appear a rough correlation of this sort. This variation of the background to beam ratio is mostly due to the way in which the rf voltage of the synchrotron cuts off, which in turn determines the fraction of electrons that strike the target to become beam and that strike the walls of the "doughnut" to become background. Work is in progress at the synchrotron to improve the monitoring.

To avoid any uncertainty, the author and his co-workers ran a series of calibrations using exactly the same conditions of the experiment: beam level, background level, collimator size, etc. Fluctuations in these values showed our calibration (to be used in our cross section) to be good to better than five percent.

Fortunately, the other experiments done here (which we will want to compare with) were run very close to the early calibration and will be assumed not to be in serious doubt. These experiments have also agreed roughly with work done in other parts of the country[5].

V. RESULTS

Insertion of these experimental values into equation (2) gives a value of:

$$\frac{d\sigma}{d\Omega}(k, \theta) = \left(6.2 \begin{smallmatrix} +2.6 \\ -1.9 \end{smallmatrix}\right) \times 10^{-30} \text{ cm}^2 \text{ ster.}^{-1} \text{ proton}^{-1} \text{ quanta}^{-1}$$

for the cross section of the reaction $\gamma + p \rightarrow \pi^+ + n$ at a photon energy of 277 ± 4 Mev and at 0 ± 4 degrees. This value is shown in Figure 7. The limits of error on this point are predominately determined by the low number of events found. The meaning of the values of the limits are as follows: Assuming a <u>true value</u> for the cross section, if <u>that value</u> were equal to the lower limit, there would have been a 16 percent chance of actually measuring a value equal to or greater than the actual value; and if that true value were equal to the upper limit, there would have been a 16 percent chance of measuring a value equal to or lower than the actual value. This description becomes identical with the familiar "standard deviation" as the number of events becomes large. There is no small amount of confusion concerning the statistics of small numbers, and this point is discussed further in Appendix C.

Also on Figure 7 are shown the data of Steinberger and Bishop[1] and White, Jakobson, and Schulz[2]. The data of Steinberger and Bishop are for 255 Mev photons and are in statistical agreement with White's. We shall use White's 275 Mev Points for comparison with our data.

8.97 cm^2 of deuterium emulsion was scanned, and the following was found: 1 pi-mu decay, 3 mesons without endings, and one undeniable pi-minus star. The ratio of the production of mesons from deuterium to that of hydrogen is about 0.4 and is not very significant. The appearance of the pi-minus was quite disturbing and resulted in a very large amount of double checking possible mistakes in the sign of the magnetic field and in the related geometry. There has been found no reason whatsoever to doubt the correct set-up of the experiment and one is forced to assume that the pi-minus was probably produced in the target and took a fortuitous scatter in the air. Such a scatter is geometrically possible and the meson is coming in about the right direction if this were the case. Production of the π^- by cosmic rays at this altitude (sea level) would have been very improbable.

The 275 Mev points on Figure 7 have been least-squares fitted to a curve of the form $a + b\cos\theta + c\sin^2\theta$ for theoretical reasons that will be explained later. The result is:

$$(1.46 \pm 0.16)\left[(0.72 \pm 0.15) - (0.45 \pm 0.10)\,\mathrm{Cos}\theta + \mathrm{Sin}^2\theta\right] \times 10^{-29}\,\mathrm{cm.}^2\ \mathrm{ster.}^{-1}$$

This curve is shown on Figures 7 and 8. The errors of the coefficients are those for internal consistency; that is, the errors due to the inherent error in each of the experimental points. The external consistency errors, the errors which measure the <u>fit</u> of the least squares curve to the experimental points, were about the same order of magnitude, indicating that the form $a + b\cos\theta + c\sin^2\theta$ is compatible with the experimental data.

The total cross section resulting from this curve is:

$$\sigma\ (275\ \mathrm{Mev}) = (2.5 \pm .5) \times 10^{-28}\ \mathrm{cm}^2$$

VI. DISCUSSION

This section proceeds in the following manner: First there are discussed the results of this experiment in the light of the recent phenomenological isobar theory, and some values of interest that do not depend on the specifics of a meson theory are calculated. The effects of using some aspects of meson theory to predict results and the agreement therewith are discussed. Then, brief mention is made of similar work at other institutions. And finally, possible ways of improving our present knowledge of the subject are developed.

The state of affairs of the theory of meson processes has been very poor in recent years. Attempts to use weak, strong, or intermediate coupling theories[35] have not been very successful and contain serious weaknesses. Such theories have difficulty in presenting even the qualitative description of experimental results. Because of all this trouble, many people have been turning their efforts to extract as much information from the experiments that is as free from specific dependence of any particular meson theory as possible. This approach, termed the "phenomenological" one, has been surprisingly fruitful.

One tentative conclusion seems to be arising that there exists a proton isobar[6, 7, 8] as an intermediate state in meson reactions. Coupled with this is the suspicion that isotopic spin is conserved in reactions, a fact that would add new restrictions to the number of pollible reactions in the same way as spin or parity conservations do. Feld[6], in a rather illuminating article on this subject, mentions that it has been shown that if a process goes through an intermediate state then the angular distribution can be determined by considerations of the conservation laws and the application of the fundamentals of quantum mechanics without specific reference to a particular theory.

Consider the reaction γ + nucleon $\longrightarrow \pi^{\overset{+}{0}}$ + nucleon and assume that it passes through an intermediate state. It is shown in Feld's paper that the angular distribution is a function of only J (the total angular momentum of the intermediate state) and ℓ_γ (the momentum that the photon carries to the reaction). Various combinations of these parameters give distributions, using the conservation laws, of the form $a + b \sin^2\theta + c \sin^4\theta \cdots\cdots\cdots$. For instance, if the photon was absorbed in an electric quadrupole reaction into an intermediate state of $J = 3/2$, then the distribution is of the form $1 + \cos^2\theta$. It is interesting to note that the theory can also roughly predict the dependence of the cross section on the meson momentum near threshold. In our example it turns out to be p^3. It appears from recent experiments[19, 22, 23] that, by applying the above information, the reaction $\gamma + \rho \rightarrow \pi^o + \rho$ goes by absorption of a photon in a magnetic dipole into a state of $J = 3/2$.

The positive meson case does not seem to fall into one of these simple catagories. This can be explained by noting that more than one of these mechanisms may be operating. In this case interference terms appear. In an example that is useful to us, consider magnetic dipole absorption to the $J = 3/2$ state and electric dipole absorption to the $J = 1/2$ state. The resulting angular distribution is:

$$\omega(\theta) = \left|a_{1/2}\right|^2 + 2\,\mathrm{Real}(a_{1/2}\, a_{3/2}^{*})\,\mathrm{Cos}\theta + 1/2\left|a_{3/2}\right|^2(2 + 3\sin^2\theta) \tag{3}$$

where $a_{3/2}$ and $a_{1/2}$ are the amplitudes (a_J) (fractional part of the total matrix element) of the two processes, respectively. In order to completely determine the problem now, we can invoke the conservation of isotopic spin. (It should be remembered that conservation of charge is contained in the system as the conservation of the z-component of the isotopic spin). The isotopic spin is handled almost identically to angular momentum (hence its name) and introduces amplitudes $a_{J,T}$ where T is the isotopic spin state. Feld states that one finds from general considerations that the mixing of the two states gives:

$$a_J(\pi^o) = \sqrt{\frac{2}{3}}\; a_{J,3/2} + \sqrt{\frac{1}{3}}\; a_{J,1/2} \tag{4}$$

$$a_J(\pi^+) = \sqrt{\frac{1}{3}}\; a_{J,3/2} - \sqrt{\frac{2}{3}}\; a_{J,1/2} \tag{5}$$

It seems reasonable that if the π^o and π^+ are to be considered to be the same variety of animal, and with the π^o distribution indicating a simple $a + b \sin^2\theta$ (explainable by $J = 3/2$,) then:

$$a_{1/2}(\pi^o) = 0$$

using this and eq. (4) gives:

$$a_{1/2,\,3/2} = -\frac{1}{\sqrt{2}}\, a_{1/2,\,1/2} \qquad (6)$$

It has also been concluded from meson scattering experiments[14, 34] that:

$$a_{3/2,\,3/2} \gg a_{3/2,\,1/2} \qquad (7)$$

Substituting (5), (6), and (7) into (3) for the positive meson case gives:

$$W(\theta)\Big|_{\pi^+} = \left[\frac{3}{2}\left|a_{1/2,\,1/2}\right|^2 + \frac{1}{3}\left|a_{3/2,\,3/2}\right|^2\right] - \sqrt{2}\,\mathrm{Cos}\theta\ \mathrm{Real}(a_{1/2,\,1/2}\,a^*_{3/2,\,3/2}) + \frac{1}{2}\left|a_{3/2,\,3/2}\right|^2 \mathrm{Sin}^2\theta \qquad (8)$$

We see that this is in a form to compare directly with our experimental results. Doing this should give us a solution for $a_{3/2,\,3/2}$ in terms of $a_{1/2,\,1/2}$ or, in a roundabout way will give the relative fractions of magnetic dipole and electric dipole in positive meson production.

A simple calculation gives:

$$\left|\frac{a_{3/2,\,3/2}}{a_{1/2,\,1/2}}\right| = 7.6 \qquad (9)$$

The phase angle came out to be imaginary, although a real solution was within statistics.

This value would have differed by a factor of i from the value that we would have obtained using Watson and Brueckner's[7] notation. The cause of this disagreement has not been determined and may be just a difference in notation. This makes no difference in the absolute magnitudes and using eq. (5) we get:

$$\frac{\text{magnetic dipole}}{\text{electric dipole}} = \frac{\left|a_{3/2}\,(\pi^+)\right|^2}{\left|a_{1/2}\,(\pi^+)\right|^2} = 11 \qquad (10)$$

It should be emphasized that this result is valid if these are the only two processes operating. This result might be useful in making rough observations and predictions in other π^+ experiments.

Brueckner and Watson[7], who have also covered the work in Feld's paper, have given formulas for the amplitudes, assuming a resonance whose width and energy come from meson scattering experiments, which are derived from some considerations of weak coupling perturbation theory (the resulting distribution is still independent of the meson coupling constant). Putting values of our energy photon and meson into these formulas gives roughly the following distribution (arbitrary absolute magnitude):

$$\frac{d\sigma}{d\Omega} \propto 5.46 - 1.55\,\mathrm{Cos}\,\theta + \mathrm{Sin}^2\theta \qquad (11)$$

This is shown on Figure 8. It can be seen that this curve is not in too good agreement with the experimental results.

Recently[37], more than one valid solution (Yang) has been found to the same set of meson-nucleon scattering data that was used to make the various assumptions in the above calculations. This new solution would change our results and affect the theoretical curve derived from Watson and Brueckner's work. It is possible that with further analysis that the photomeson production angular distribution may choose the correct solution, and work is now in progress on this subject. Preliminary results seem to indicate that Yang's solution would predict a distribution peaked in the forward direction and would be definitely contrary to the experimental results.

If we restrict the meson-nucleon reaction to S and P states, then from parity and spin conservation it is easily seen that the electric quadrupole interaction of the gamma ray is also possible along with the electric and magnetic dipoles. Mixing this in should have the effect of adding more $\sin^2\theta$ to the distribution, which might bring the theoretical curve down at zero and 180 degrees. Preliminary calculations here at the Laboratory[36] have indicated that the addition of the quadrupole may help a little but it still does not resolve the disagreement. The effect of this electric quadrupole on the neutral meson distribution would be merely to shift the ratio of a to b in the relation $a + b \sin^2\theta$. The resulting equation is still in good agreement[19, 22, 23] with experimental results.

Unofficial reports from M.I.T. (Osborne et al) indicate that the angular distribution of $\gamma + p \rightarrow \pi^+ + n$ has been measured at angles above about 22 degrees for a photon energy of 270 Mev. The shape is qualitatively the same but it is flatter and does not seem to fall at 180 degrees. Unofficial reports from Cornell give a distribution of $(13 \pm 2) - (5 \pm 2 \cos\theta + (5 \pm 3) \sin^2\theta$ for a photon energy of 234 Mev. This is not easily compared with our data, but there is evidence from the work of White et al[2] that this data is in rough agreement with our higher energy work.

This discussion should show very clearly the need for a much better determination of the differential cross section as a function of angle for a family of photon energies. To get these values to a better order of magnitude will probably take a definite advance in technology of electronic counting methods for mesons. Even then at small angles, the problem will be difficult. When this is accomplished, then the deuterium-hydrogen ratio for the spin-flip problem should be easily determined. Also of importance are the low meson energy measurements, on which a number of laboratories are working. The difficulties encountered, however, should not be a serious deterrent to the execution of the experiments when their great value is realized.

VII. ACKNOWLEDGMENTS

It would be difficult for the author to adequately thank his co-workers: Steve White and Gordon Repp. It has been a pleasure to work with them in every phase of the experiment. I wish to express my appreciation to Dr. A. C. Helmholz for his patient guidance and advice during my graduate work.

Don Hamlin and Jack Merritt were greatly appreciated for their assistance and sympathy during the electronic phase of the work. My thanks also go to the crew of the synchrotron for their efficient help and congenial personalities. Byron Youtz was responsible for the loan of the magnetic wire equipment and was helpful in setting it up. Rod Byrns was everpresent when the hi-pressure pumping system was in operation and greatly facilitated its operation. I wish to thank Steve Gasiorowicz and Joe Lepore for some interesting theoretical discussions.

It is a pleasure to dedicate this paper to my wife, Joyce, whose comprehension, companionship and encouragement has made this work possible.

VIII. APPENDICES

A. APPENDIX A

Calculation Of The Solid Angle Factor--

In this appendix we shall refer to Figure 6.

All angles except ϕ will be assumed small, and the resulting approximations will be made freely.

$d\Omega = \theta\theta'$ where θ' is the vertical angle (with relationship to the horizontal channel) and is not affected by the magnetic field. We need to find $\theta\theta'$ in terms of du and du' where du is the width of the emulsion and du' is the thickness.

it follows that

$$du' = \theta\,(A + \rho\,\phi) \tag{12}$$

we see that

$$du = Z\ \mathrm{Cos}\ \alpha$$

now $Z^2 = (A\theta)^2 + (\theta\rho)^2 = \theta^2\ \left[A^2 + \rho^2\right]$

also $\alpha = \pi - \phi - \beta$

and $\mathrm{Tan}\ \beta = \dfrac{A}{\rho}$

thus $du = \theta\ \sqrt{A^2 + \rho^2}\ \ \mathrm{Sin}\ (\phi + \beta)$

or

$$du = \theta\ \left[\rho\ \mathrm{Sin}\phi + A\ \mathrm{Cos}\phi\right] \tag{13}$$

from
(12) and (13)

$$d\Omega = \theta\theta' = \frac{dudu'}{(A + \rho\ \phi)\ \left[\rho\ \mathrm{Sin}\phi + A\ \mathrm{Cos}\phi\right]}$$

if we call

$$dudu' = dA$$

then we have

$$\boxed{\frac{d\Omega}{dA} = \frac{1}{(A + \rho\phi)\ \left[\rho\ \mathrm{Sin}\phi + A\ \mathrm{Cos}\phi\right]}} \tag{14}$$

which is the expression desired.

B. APPENDIX B

Development Procedure

Since no measurements were made of track direction, etc, distortion of the emulsion was not a major problem; and elaborate precautions to prevent thermal or pH shock to the emulsion were not taken. The essence of this method is to saturate the emulsion when it is cold and inactive, and then bringing the solution to temperature quickly, insuring even development throughout.

The following procedure was used:

1.	Soak in distilled water.	40 min.	room temp.
2.	Put into icebox (to cool slowly).	40 min.	to 5° C.
3.	Immerse in 6 to 1 D-19 (precooled).	60 min.	5° C.
4.	Immerse in 6 to 1 D-19 (preheated).	20 min.	25° C.
5.	Stop in Acetic Acid 1% (precooled).	40 min.	5° C.
6.	Let stop bath sit at room temp.	20 min.	room temp.
7.	Immerse in cool acid fixer.	10 to 12 hours room temp.	
8.	Fixer should be changed one or two times during this period.		
9.	Wash in running water.	7 to 8 hours room temp.	
10.	Soak in 4% Glycerine soln.	about 5 hours room temp.	
11.	Dry slowly, perhaps in a covered box.		

Notes: Room temp. is about 68° F. The hot development time may vary according to the batch or conditions of the emulsion or exposure. Surface silver should be removed. All solutions were made fresh with distilled water. Temperatures were held to within a degree. Although it is not necessary, all operations were done in complete darkness to prevent accident. Care should be taken to prevent exposure of the emulsion to extremes of humidity, as it will peel off the glass even with the plasticizer in it.

C. APPENDIX C

Statistics

Let us suppose that there exists an inherent "true" value (T) of some sort such that if we measured (M) this value an indefinitely large number of times, our average would be as close as we please to this true value.

The value T is often called the *expected* value or *a priori* value. If we start with this *a priori* value and apply probability theory, we answer the question: Given T, what is the probability of M? In the special case of counting statistics this becomes: If the *a priori* probability of an event is p, then what is the probability P(x) of seeing x events in n trials? Note that np is the expected number and is equal to T.

The laws of probability lead to binomial formula:

$$P(x) = \frac{n!}{x!\,(n-x)!}\; p^{x}\,(1-p)^{n-x}$$

This formula is exact but unwieldy and in those cases when n is very large (say, when n is the product of the number of photons in the beam times the surface density of target protons) and p and np are small (p is the cross section and np the *expected* number of events), then the binomial formula reduces to Poisson's formula, which holds for a small number of events:

$$P_T(x) \simeq \frac{(np)^{x}\,e^{-np}}{x!} = \frac{T^{x}\,e^{-T}}{x!}$$

P_T (x) is the probability that we will see x events (mesons) if the expected number is np (T).

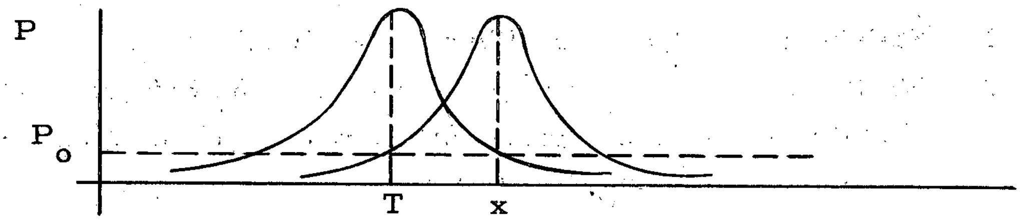
When np is no greater than about 30, Stirling's approximation becomes a useful approximation for the factorial and the familiar gaussian error curve.

$$P_T(x) = C\,e^{\frac{-\delta^{2}}{2np(1-p)}}$$

where $\delta = x - np = x - T$

This gaussian formula still talks about the probability of what happens to a measurement *if we already know the true value*. As it stands, it does not answer the question vital to experimenters: given the measurement, what can we say about the true value? Something more is needed.

Let us make a measurement, x. If this were the true value (let us assume it), we could draw a gaussian distribution curve about it. If we knew where the actual true value was we could draw a gaussian about it, also.



From this we see that because of the symmetry of the gaussian, the probability (P_o) of the measured value occuring a given amount away from the true value is numerically the same as a fictitious "probability" that the true value will lie a given distance from our measured value--this interpretation leads to the usual use of limits of error on measured points. This is actually incorrect as the true value is a fixed a priori value and has no "distribution".

When the number of events is small, the distribution curve is skew (Poisson) and the above mechanism does not hold. Several familiar references[27, 28] say that the Poisson formula also gives the distribution of true values around the measured value ("obviously"):

$$P_x(T) = \frac{T^x e^{-T}}{x!}$$

but the author feels that this is unjustified. A much more sensible view is to remain strictly with the definition of $P_T(x)$ and this is the cause of the rather elaborate way of stating the meaning of the limits in this experiment. (See RESULTS). The numerical values of these limits defined in this fashion have been calculated by Regener[26]. The author is indebted to Mr. John Whittlesey[25] for some illuminating discussions on this problem.

IX. REFERENCES

Experimental--Positive Photomesons From p Or d

1. Steinberger and Bishop, Phys. Rev. 86 171 (1952)
2. White, Jakobson and Schulz, Phys. Rev. 88 836 (1952) This paper contains a rather complete summary of significant experimental photomeson papers prior to 1952.
3. Keck and Littauer, Phys. Rev. 88 139 (1952)
4. Littauer and Walker, Phys. Rev. 86 838 (1952)
5. Recent work has been reported in progress at Cornell, M. I. T., and the University of Illinois.

Theoretical--Photomeson Theory

6. Feld, Phys. Rev. 89 330 (1953) isobar considerations
7. Brueckner and Watson, Phys. Rev. 86 923 (1952) isobar
8. Brueckner and Case, Phys. Rev. 83 1141 (1951) isobar
9. Drell and Henley, Phys. Rev. 88 1053 (1952)
10. Heckrotte, Henrich and Lepore, Phys. Rev. 87 219 (1952) on pi-zero
11. Kaplon, Phys. Rev. 83 712 (1951) pert. calc. on pi-zero
12. Francis and Watson, Phys. Rev. 89 328 (1953)
13. Watson, Phys. Rev. 88 1163 (1952)
14. Brueckner, Phys. Rev. 86 106 (1952) on meson scattering
15. Araki, Prog. Theor. Phys. 5 507 (1950) pert. calculation
16. Lax and Feshbach, Phys. Rev. 88 509 (1952) spin flip calc.
17. Thie, Phys. Rev. 88 420 (1952) spin flip calc.
18. Chew and Lesis, Phys. Rev. 84 779 (1951)

Experimental--Neutral Meson Production

19. Cocconi and Silverman, Phys. Rev. 88 1230 (1952)
20. Panofsky, Steinberger and Steller, Phys. Rev. 86 180 (1952)
21. Silverman and Stearns, Phys. Rev. 83 853 (1951)
22. Goldschmidt-Clermont, Osborne and Scott, Phys. Rev. 89 329 (1953)
23. Recent work has been reported in progress at M. I. T., Cornell and the California Institute of Technology.

Miscellaneous References

24. Johnston et al MDDC-850
25. John Whittlesey, Private communication
26. Regener, Phys. Rev. 84 161
27. Halliday, Introductory Nuclear Physics, Wiley and Sons, 1950, Chap. 5, Section 20, Page 205
28. Rainwater and Wu, Nucleonics 1 60 (Oct., 1947)
29. Blocker, Kenney, and Panofsky, Phys. Rev. 79 419 (1950)
30. Private communication
31. Durbin, Loar, and Littauer, Phys. Rev. 88 139 (1952)
32. Aron, Hoffman, and Williams AECU 663 2nd. revision
33. Jones (UCRL-1916), private communication
34. Anderson, Fermi, Long and Nagle, 85 936, (1952)
35. Marshak "Meson Physics", McGraw Hill, 1952 contains a wealth of references and information, especially on the theoretical side.
36. Gasiorowicz, private communication
37. Rochester High Energy Conference 1952

X. FIGURES

Fig. 1 ---- Schematic diagram of the experiment.

Fig. 2 ---- Detail of the emulsion-absorber arrangement.

Fig. 3 ---- Diagram of the high pressure gas target.

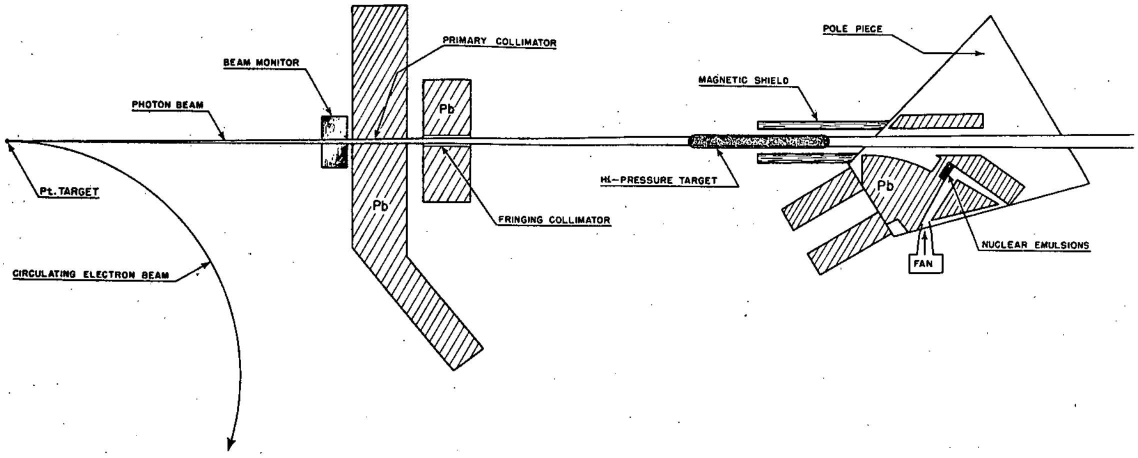
Fig. 4 ---- Schematic of the high pressure pumping system.

Fig. 5 ---- Bremsstrahlung curve, plot of kN(k) vs. k where N(k) is d(number of photons)/dk.

Fig. 6 ---- Geometrical figure used in Appendix A to calculate the solid angle.

Fig. 7 ---- Graph of the experimental results of this and some related experiments.

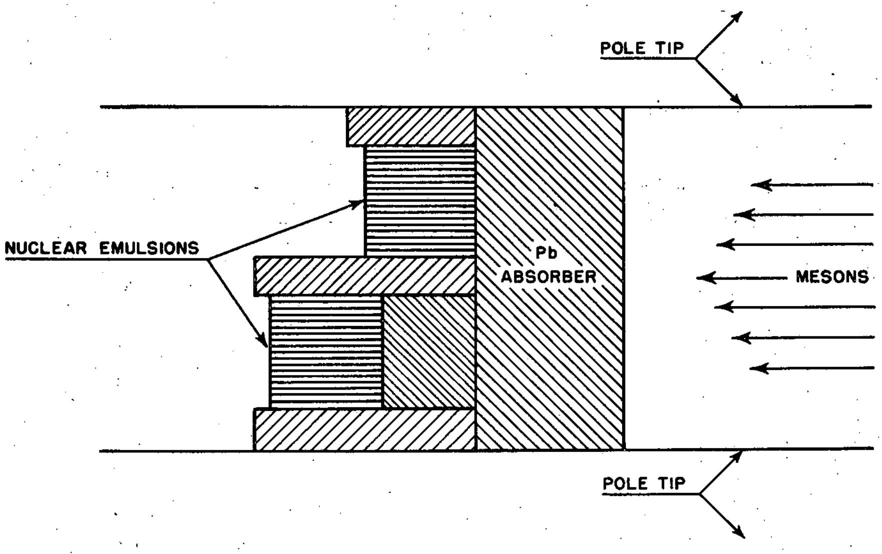
Fig. 8 ---- Graph of the comparison of the experimental results with theory.



SCHEMATIC DIAGRAM OF THE EXPERIMENTAL EQUIPMENT.

MU-4984

Fig. 1



CROSS SECTIONAL SIDE VIEW OF ABSORBER–EMULSION DETAIL.

MU-4982

Fig. 2

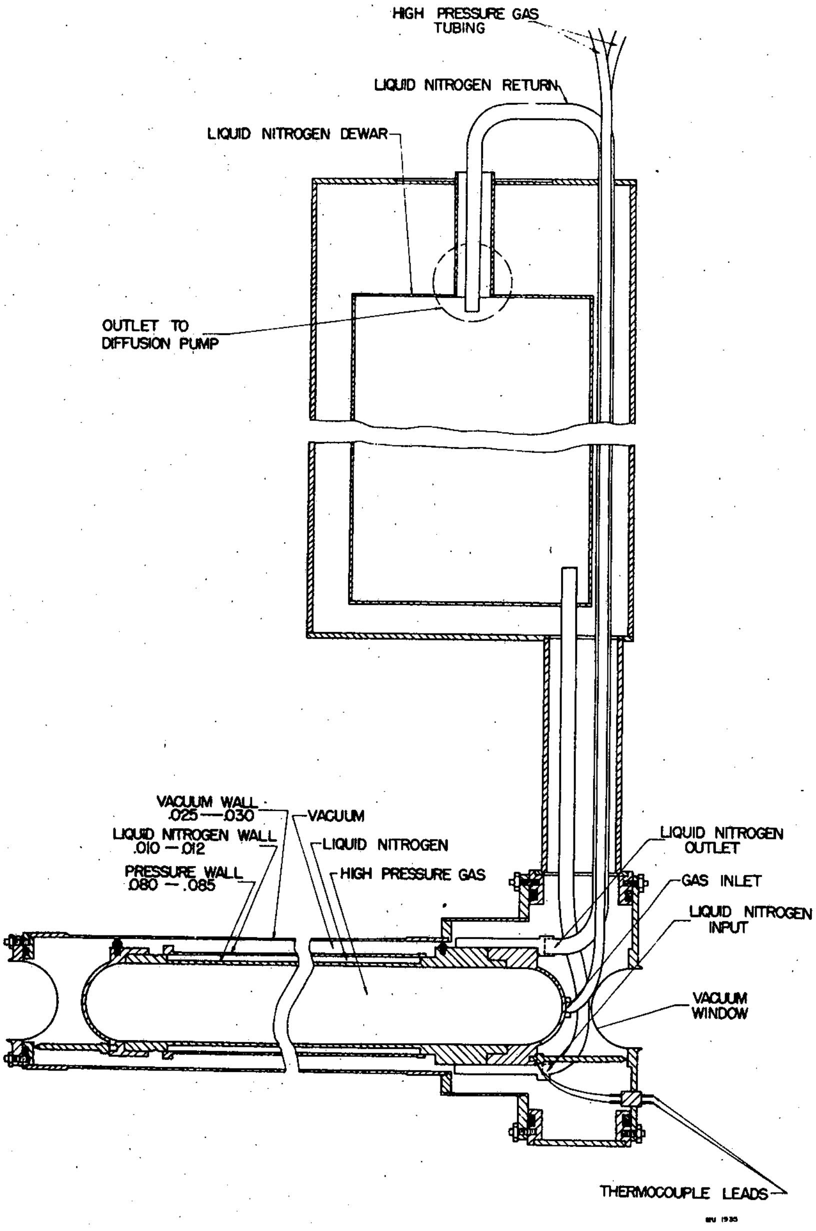

HIGH PRESSURE GAS TUBING
LIQUID NITROGEN RETURN
LIQUID NITROGEN DEWAR
OUTLET TO DIFFUSION PUMP
VACUUM WALL .025 — .030
VACUUM
LIQUID NITROGEN WALL .010 — .012
LIQUID NITROGEN
PRESSURE WALL .080 — .085
HIGH PRESSURE GAS
LIQUID NITROGEN OUTLET
GAS INLET
LIQUID NITROGEN INPUT
VACUUM WINDOW
THERMOCOUPLE LEADS
MU 1935

Fig. 3

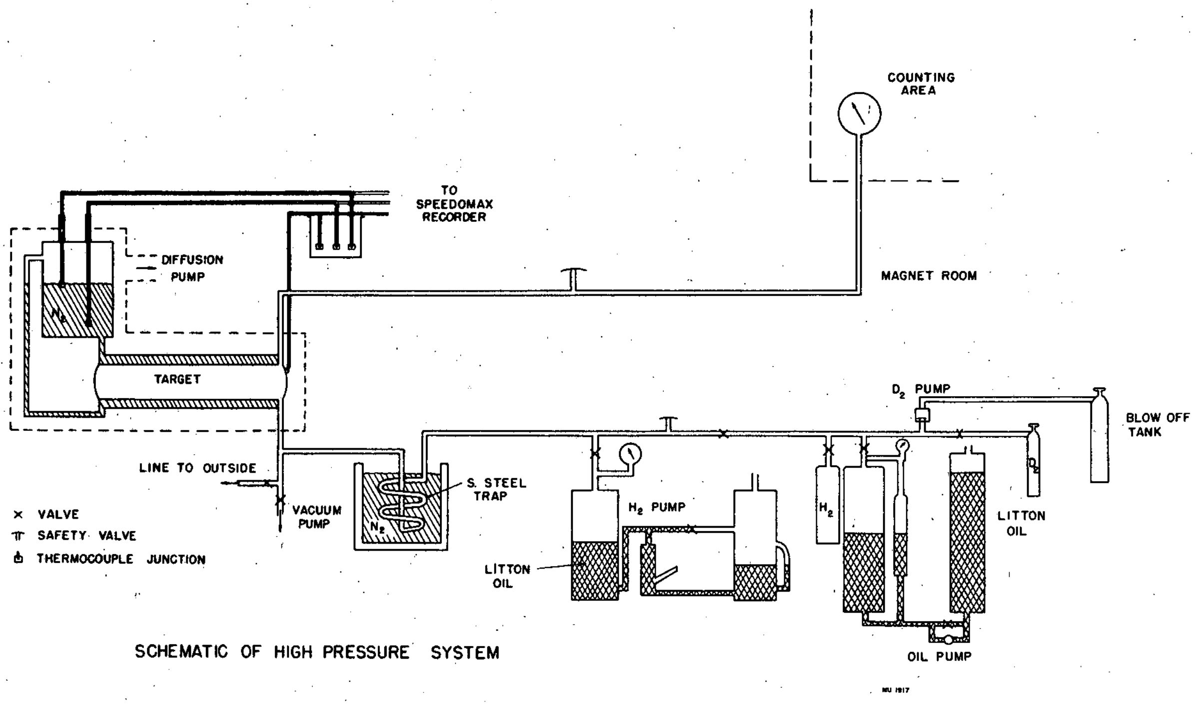
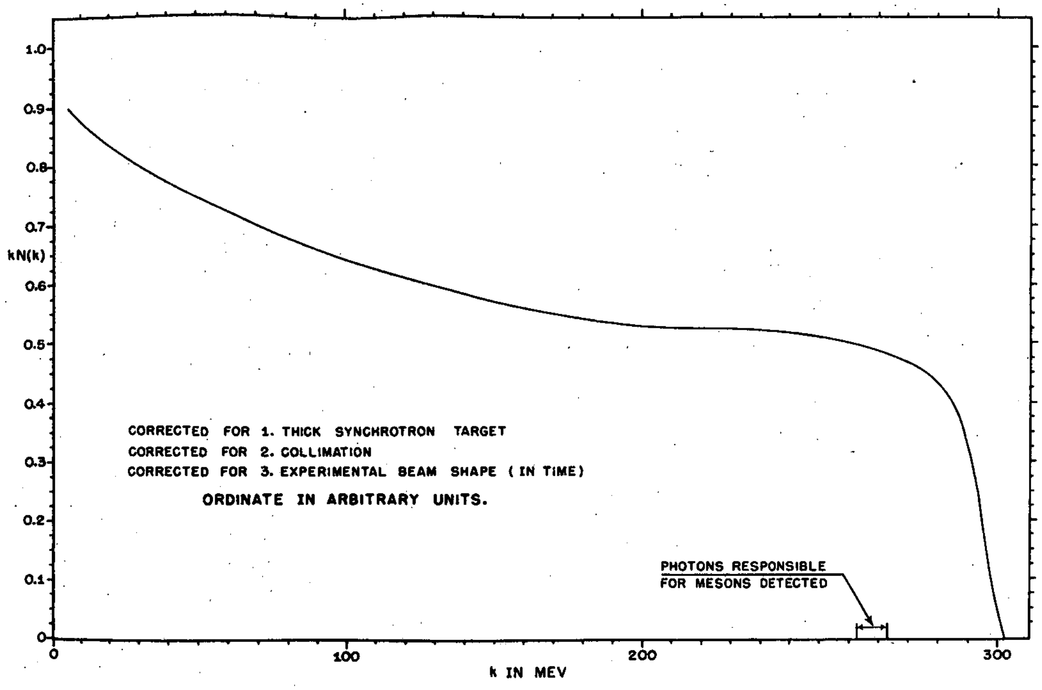

COUNTING AREA
TO SPEEDOMAX RECORDER
DIFFUSION PUMP
MAGNET ROOM
N_2
TARGET
D_2 PUMP
BLOW OFF TANK
LINE TO OUTSIDE
S. STEEL TRAP
VACUUM PUMP
N_2
H_2 PUMP
H_2
D_2
LITTON OIL
LITTON OIL
× VALVE
SAFETY VALVE
THERMOCOUPLE JUNCTION
SCHEMATIC OF HIGH PRESSURE SYSTEM
OIL PUMP
MU 1917

Fig. 4



BREMSSTRAHLUNG ENERGY SPECTRUM.

MU-4983

Fig. 5

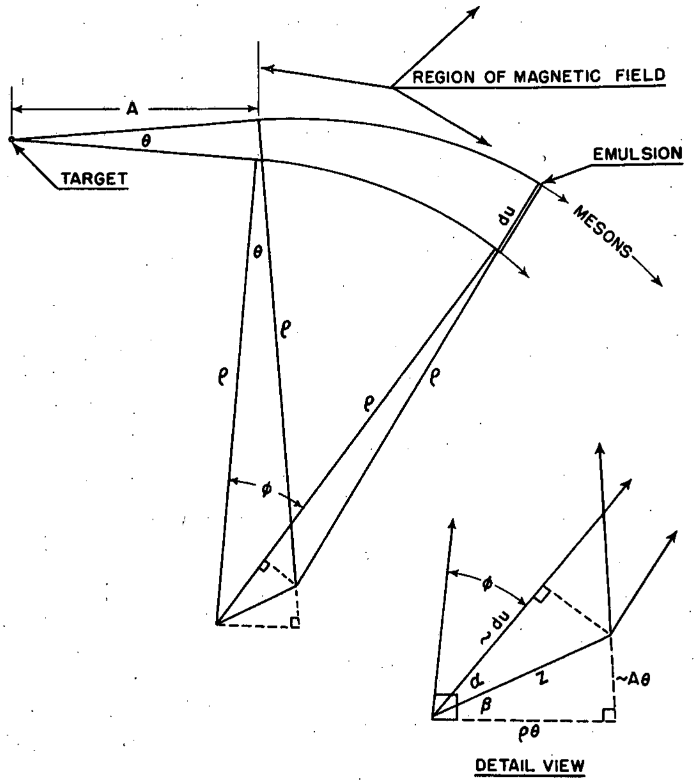


FIGURE FOR APPENDIX "A"

MU-4981

Fig. 6

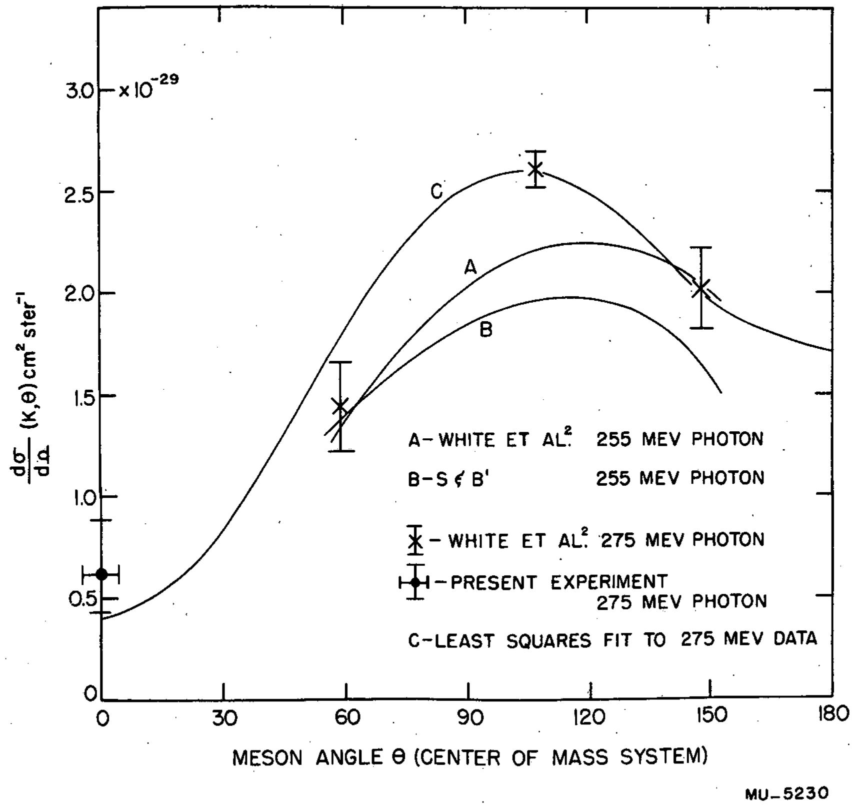
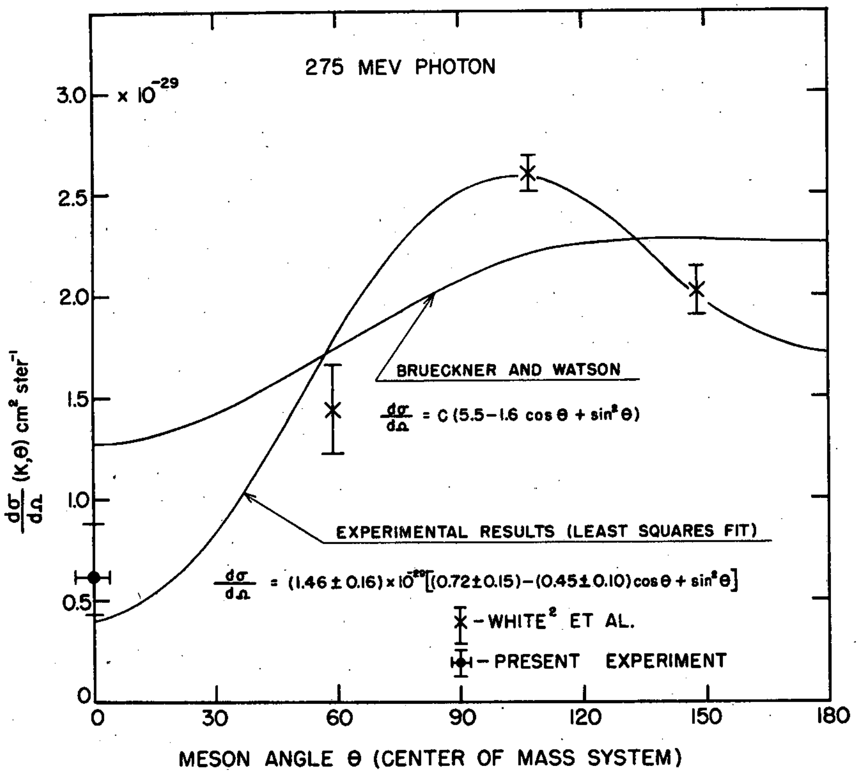

3.0 x 10^{-29}
2.5
2.0
1.5
1.0
0.5
0
$\frac{d\sigma}{d\Omega}$ (K,θ) cm^2 ster^{-1}
C
A
B
A- WHITE ET AL.^{2} 255 MEV PHOTON
B-S & B' 255 MEV PHOTON
- WHITE ET AL.^{2} 275 MEV PHOTON
- PRESENT EXPERIMENT 275 MEV PHOTON
C-LEAST SQUARES FIT TO 275 MEV DATA
0
30
60
90
120
150
180
MESON ANGLE θ (CENTER OF MASS SYSTEM)
MU-5230

Fig. 7


275 MEV PHOTON
3.0
× 10^{-29}
2.5
2.0
1.5
1.0
0.5
0
$\frac{d\sigma}{d\Omega}$ (K,θ) cm^2 ster^{-1}
BRUECKNER AND WATSON
$\frac{d\sigma}{d\Omega} = C(5.5 - 1.6\cos\theta + \sin^2\theta)$
EXPERIMENTAL RESULTS (LEAST SQUARES FIT)
$\frac{d\sigma}{d\Omega} = (1.46 \pm 0.16)\times 10^{-29}[(0.72\pm0.15)-(0.45\pm0.10)\cos\theta + \sin^2\theta]$
- WHITE^2 ET AL.
- PRESENT EXPERIMENT
0
30
60
90
120
150
180
MESON ANGLE θ (CENTER OF MASS SYSTEM)

MU-5229

Fig. 8