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EVIDENCE FOR THE PRODUCTION OF NEUTRAL MESONS BY PHOTONS

J. Steinberger, W. K. H. Panofsky and J. Steller

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Evidence for the Production of Neutral Mesons by Photons

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April, 1950

I. Introduction.

Neutral mesons which are coupled strongly to nuclei must be expected to be unstable against decay into two or more gamma rays. The modes of decay, and expected lifetimes, have been discussed extensively(1). These gamma rays are then supposed responsible for the soft showers which often accompany energetic cosmic ray nuclear events(2). The evidence in favor of the existence of the neutral meson has recently been greatly strengthened by the discovery at Berkeley(3) of gamma rays which behave in all ways as if they were due to the disintegration of a neutral meson. They are produced by proton bombardment of various nuclei and have a production cross section which depends on proton energy much like that of charged mesons. Their energy is approximately 70 Mev on the average, half that of the charged π meson, and the energy spread is in agreement with the Doppler shift due to the velocity of the parent mesons. The lifetime of the mesons is less than 10^{-13} sec., which is in agreement with the theoretical expectations.

The evidence is therefore already much in favor of the existence of a gamma unstable neutral meson. However, until now, coincidences between the two gamma rays have never been observed. We report here the detection of such coincidences, produced by the bombardment of various nuclei in the x-ray beam of the Berkeley synchrotron. This must be regarded as strong additional evidence supporting the existence of the neutral meson.

II. Experimental Arrangement.

The apparatus is sketched in Fig. 1. The synchrotron x-ray beam of 330 Mev maximum energy is collimated in two successive collimators. The second collimator serves only to intercept some of the electrons produced at the edge of the first collimator. The beam then strikes a target, which, for most of the experiment, is a cylinder of beryllium, 1-1/2 inches long and 2 inches in diameter. The particles produced in the target are detected in two telescopes, each consisting of three scintillation counters. A converter, usually 1/4 inch of lead, is inserted between the two crystals nearest the target in each telescope. An event is recorded if simultaneous (resolving time 10^{-7} sec.) pulses are recorded in the outer four crystals, but none in the two near the target. That is, we require that there be two particles, one in each telescope, neutral at first which are converted into charged particles by the lead, and which penetrate one crystal and enter the next. With a beam intensity of about 10^{11} Mev/min the counting rate for such coincidences at favorable orientations of the telescopes is about 10 counts/min.

III. Nature of the Coincidences.

Let us first describe the experiments which identify the particles as gamma rays, indicate their energy and show that their origin is the nuclear rather than the Coulomb field. In Table I we list the relative detection efficiency for various converter materials and thicknesses. Withoutconverters the counting rate is almost zero, then increases as the converter thickness in each arm is increased to 1/4 inch of lead, and only slightly from 1/4 inch to 1/2 inch. This is as expected from shower theory for about 100 Mev photons. 1/4 inch of copper has approximately the same conversion efficiency as 1/16 inch of lead, again in agreement with shower theory, since the number of shower units are the same for these thicknesses.

The coincidences are attenuated by a factor of four when 1/4 inch of lead is inserted between the target and the anti-coincidence crystals. This again is as expected for photons. Furthermore, it can be seen from Table I that both telescopes require converters, so that both particles must be photons.

To measure the energy of the conversion electrons, aluminum absorbers were inserted between the last two crystals of one of the telescopes. Unfortunately at these energies the radiation losses are important, and therefore the straggling large. We have plotted in Fig. 2 the coincidence counting rate as a function of the average energy required to traverse the telescope. Because the photons originate in moving mesons, the average gamma ray energy is expected to be approximately 100 Mev, and the average electron energy 50 Mev, quite in agreement with the observed attenuation.

TABLE I

Relative Detection Efficiency as a Function of Absorber Material and Thickness

Converter in Telescope 1	Converter in Telescope 2	Relative Counting Rate $\alpha = \beta = 90^\circ$
none	none	.01 ± .005
1/32 in. Pb	1/32 in. Pb	.17 ± .013
1/16 in. Pb	1/16 in. Pb	.3 ± .02
1/8 in. Pb	1/8 in. Pb	.67 ± .08
1/4 in. Pb	1/4 in. Pb	1.00 ± .06
1/4 in. Cu	1/4 in. Cu	.39 ± .03
none	1/4 in. Pb	.15 ± .05
1/16 in. Pb	1/4 in. Pb	.62 ± .07
1/2 in. Pb	1/4 in. Pb	1.07 ± .1
1/4 in. Pb	1/4 in. Pb	.28 ± .05

1/4 in. Pb absorbers placed in front of both telescopes.

The nuclear origin of the photons is demonstrated by the fact that the cross section for these coincidences is only six times as big for a lead nucleus as for beryllium, which is less than the ratio of the nuclear areas. On the other hand, ordinary shower cross sections increase by a factor of 400.

Finally, we have looked for coincidences with the beam energy reduced to about 175 Mev with angles α and β of the telescope both 90°. The cross section per Q (the number of Q in a bremsstrahlung beam is equal to the total energy divided by the maximum energy of the spectrum) is at least 50 times smaller here than at 330 Mev. This steep excitation function is also observed for charged meson production.

We believe therefore that it is demonstrated that the observed coincidences are caused by gamma rays of about 100 Mev average energy, of non-Coulombic origin, and with a threshold similar to that for charged mesons.

IV. Angular Correlation and Distribution of the Gamma Rays.

To study further the properties of these coincidences, we have measured their rate as a function of the angle α between the beam direction and the plane of the telescopes and of the correlation angle β (See Fig. 1). Consider first the variation with β at a fixed α, say 90°. 180° coincidences are rare. The counting rate increases with decreasing β to a maximum at 90°, and then drops sharply. This behavior must actually be expected of gamma rays which are the decay products of neutral mesons, because of the motion of the decaying mesons. A meson at rest decaying into two gamma rays, emits them in opposite direction. But when this is seen from a system in which the meson has a total energy E, then the included angle β varies between π and $2 \sin^{-1}\left(\frac{1}{E}\right)$ with a probability which favors the small angles tremendously. The median angle is $2 \sin^{-1}\left[\frac{2}{(3 E^2 + 1)^{1/2}}\right]$. E is the total meson energy in units of its rest energy.

For 70 Mev mesons the minimum angle of β is 84° and the median angle 92°. Since the distribution is so heavily peaked, not much error is introduced if one assumes, as is done in the following, that to an angle β corresponds a unique energy, that of the median angle. Therefore a measurement of the distribution in β is a measure of the distribution in energy of the neutral mesons, although the angular resolution of our telescopes is insufficient to give more than a glimpse of the energy distribution. We have included in Fig. 3 curves in which the observed(4) energy distributions of the π^+ meson made by the same x-rays on hydrogen are transformed into distributions in β and arbitrarily normalized. All corrections due to scattering and angular resolution are omitted. The general shape of the curves is certainly well reproduced by the experiment. It is therefore clear that if the gamma rays are the decay product of intermediate particles, these particles must move with velocities of the order of $\frac{v}{c} \simeq .8$. Excited nucleons of this velocity cannot be produced by x-rays of 330 Mev; the particles must therefore have an intermediate mass. Furthermore, it is possible to see that the decay must be into only 2 photons, since the expected angular distributions for a decay into more than two photons would not show a valley for small angles β.

The distribution in the angle α of the beam with the plane of the telescope shown in Fig. 4, is interesting chiefly because of the difference between this distribution and the angular distribution of π^+ photo mesons(5) from either carbon or hydrogen targets. This is not particularly surprising, since various theories also give quite different results for charged and neutral mesons.

V. Hydrogen Cross Section and Total Cross Section.

At one setting of the telescopic angles, $\alpha = \beta = 90^\circ$, we have compared the cross sections of hydrogen and carbon. This was done by comparing the count from a polyethylene (CH_2) block and a perforated carbon block of the same size and carbon content as the CH_2. The result is: $\sigma_{H_{\pi_0}} / \sigma_{C_{\pi_0}} = .12 \pm .03$. This again differs from the results for positive mesons, where $\sigma_{H_{\pi^+}} / \sigma_{C_{\pi^+}} \simeq .55$. The difference is probably in part due to the fact that both neutrons and protons can contribute to neutral meson production, but only protons to π^+ production. In part, it may also be possible to ascribe this to the same phenomenon which, according to Chew(6) is responsible for the large hydrogen - carbon ratio for the positive mesons. In the case of π^+ production, the reaction is inhibited by the fact that, when the proton is changed into a neutron, there is an oversupply of neutrons in the immediate neighborhood and the number of states available to it is small because of the Pauli principle. This is not significant in the neutral case because the nucleon's charge does not change.

The curves in Fig. 3 can be integrated to yield a total cross section for beryllium. $\sigma_{Be} = 7.5 \times 10^{-28}$ cm^2 per "Q", while for carbon and hydrogen, assuming the same angular distributions, $\sigma_C = 10 \times 10^{-28}$ and $\sigma_H = 1.3 \times 10^{-28}$ cm^2 per "Q". The absolute x-ray intensity is known(8) to about 10 percent, but the efficiency of the detecting system only to within a factor of two, so that there is a corresponding error in the above cross sections. The hydrogen cross section is approximately the same as that for π^+ production(5), those for carbon and beryllium are somewhat higher(7).

One might assume that the charge of the nucleon would play an important role in the production of mesons in the electromagnetic field of the photon. This is contradicted by the observed angular distribution of π^+ mesons produced by photons in H_2. The angular distribution indicates that the principal process responsible for charged meson production is the interaction of the photon with the spin of the nucleon. If the neutral meson has the same transformation properties as the charged it then appears plausible that the production cross sections in hydrogen should be comparable, as seems to be the case. However, actual calculations on the basis of pseudo-scalar theory, both in the classical and in the perturbation theory approximation, which give a reasonable angular distribution for the π^+ production, give smaller values for neutral meson production. Whether or not this is a new difficulty in a theory which already has several, is not clear. From a less restricted point of view it is not a surprising result.

Summary.

In the bombardment of various nuclei by 330 Mev x-rays, photons with the following properties are emitted:

1) At least two are emitted in coincidence.
2) They each have an average energy of about 100 Mev.
3) The Z dependence of the production indicates that they have their origin in a nuclear interaction, and not in the Coulomb field.
4) The threshold for their production is at least 150 Mev.
5) The angular correlation of the photons shows that they are emitted in pairs as the only decay products of particles moving with velocities of the order of $\frac{v}{c} = .8$, and therefore of intermediate mass.
6) The total cross section for production from hydrogen is about the same as that for production of π^+ mesons; other light nuclei cross sections are somewhat higher than those for the positive mesons.

It is clear from these properties that the gamma rays are the decay products of neutral mesons. Since spin 1/2, and spin 1 mesons are forbidden to decay into two photons(1), the spin must be zero, excluding the possibility of very high intrinsic angular momenta. It seems reasonable, and it is in good agreement with all observations, to assume that both charged and neutral mesons are of the same type. It then follows from the angular distribution of the x-ray produced π^+ mesons, and the high cross sections for making neutral mesons by x-rays, that the π meson is a pseudo-scalar. This remark applies, of course, only to the character of the meson, and not to any particular field theory for the interaction of mesons with nucleons.

Acknowledgements.

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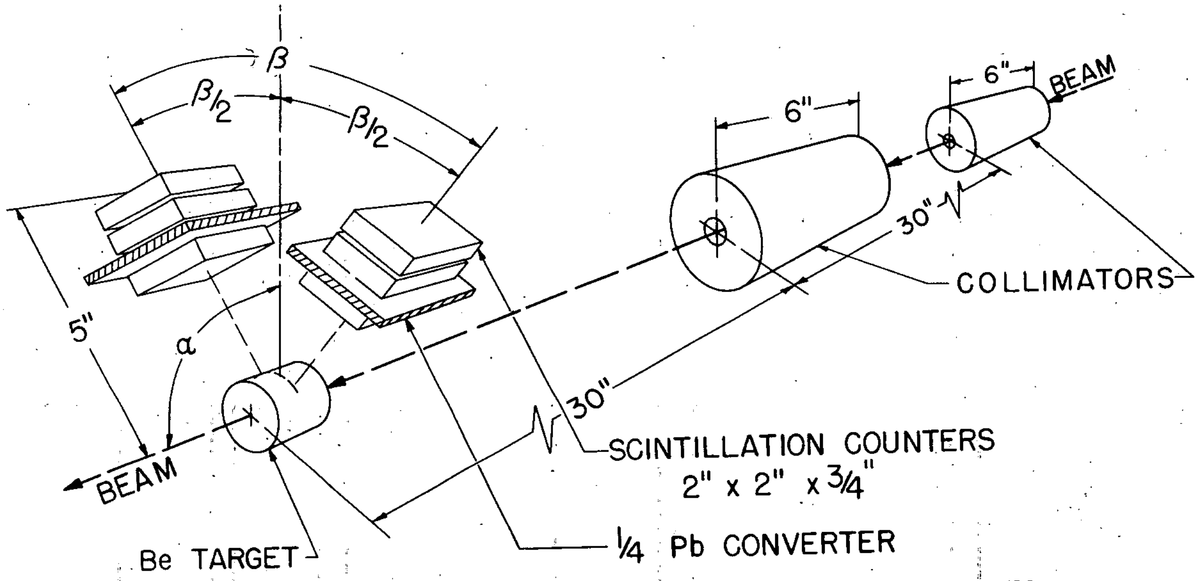
Figure Captions

Fig. 1. Experimental arrangement.

Fig. 2. Absorption of conversion electrons in aluminum. The energy includes the average radiation loss.

Fig. 3. Variation of coincidence rate with the included angle β between the two arms of the telescope. The curves are those expected on the assumption that the gamma rays are the decay products of a neutral meson, emitted with the same energy distribution as are π^+ mesons from hydrogen. The curves are arbitrarily normalized for each angle α.

Fig. 4. Variation with the angle α between the plane of the telescope and the beam. Each point represents an integral over the angle β.


β
β/2
β/2
6"
6"
BEAM
30"
COLLIMATORS
5"
α
30"
BEAM
SCINTILLATION COUNTERS
2" x 2" x 3/4"
Be TARGET
1/4 Pb CONVERTER

Mu 136

FIG. 1

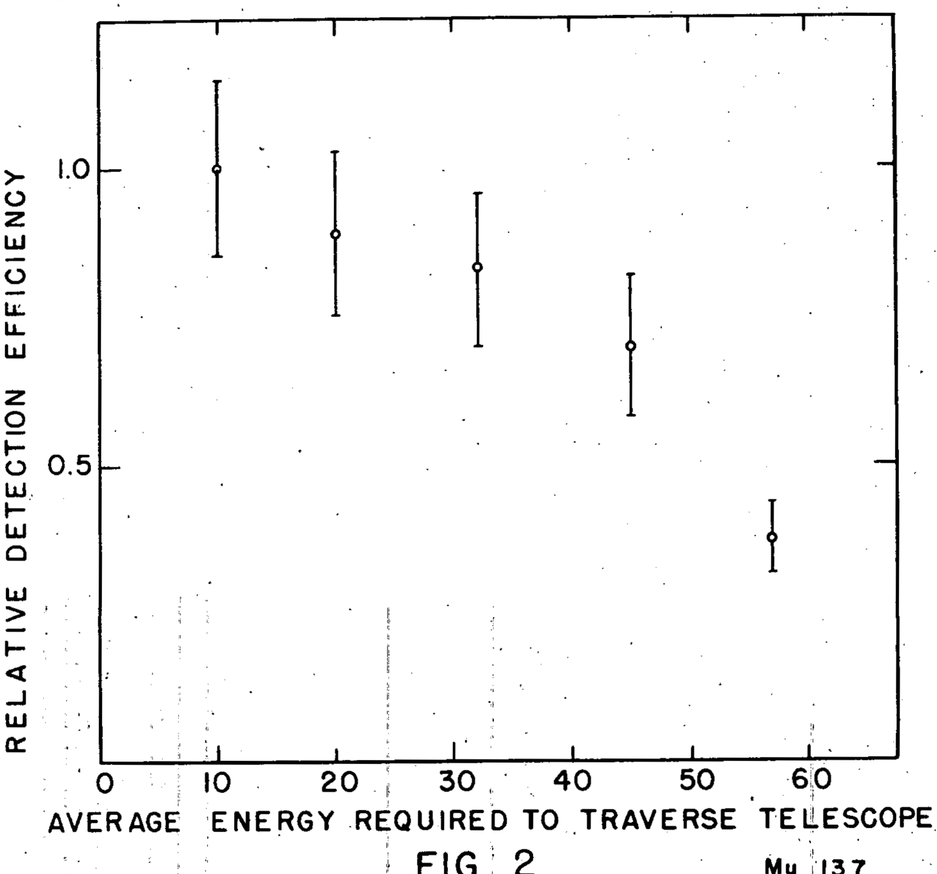

RELATIVE DETECTION EFFICIENCY
1.0
0.5
0
10
20
30
40
50
60
AVERAGE ENERGY REQUIRED TO TRAVERSE TELESCOPE

FIG. 2

Mu 137

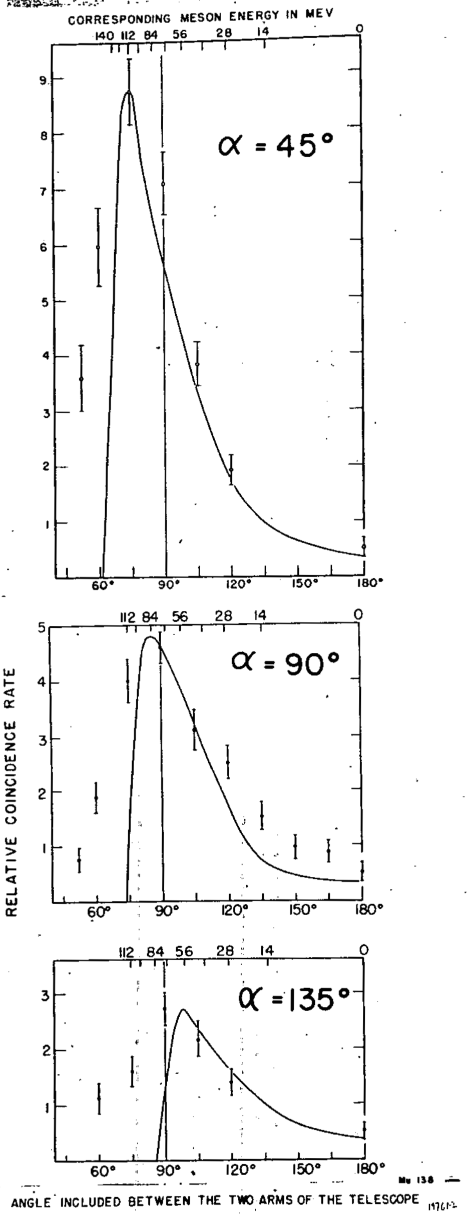

CORRESPONDING MESON ENERGY IN MEV
140 112 84 56 28 14 0
α = 45°
1 2 3 4 5 6 7 8 9
60° 90° 120° 150° 180°
112 84 56 28 14 0
α = 90°
RELATIVE COINCIDENCE RATE
1 2 3 4 5
60° 90° 120° 150° 180°
112 84 56 28 14 0
α = 135°
1 2 3
60° 90° 120° 150° 180°
ANGLE INCLUDED BETWEEN THE TWO ARMS OF THE TELESCOPE
Mu 138
11761-2

FIG. 3

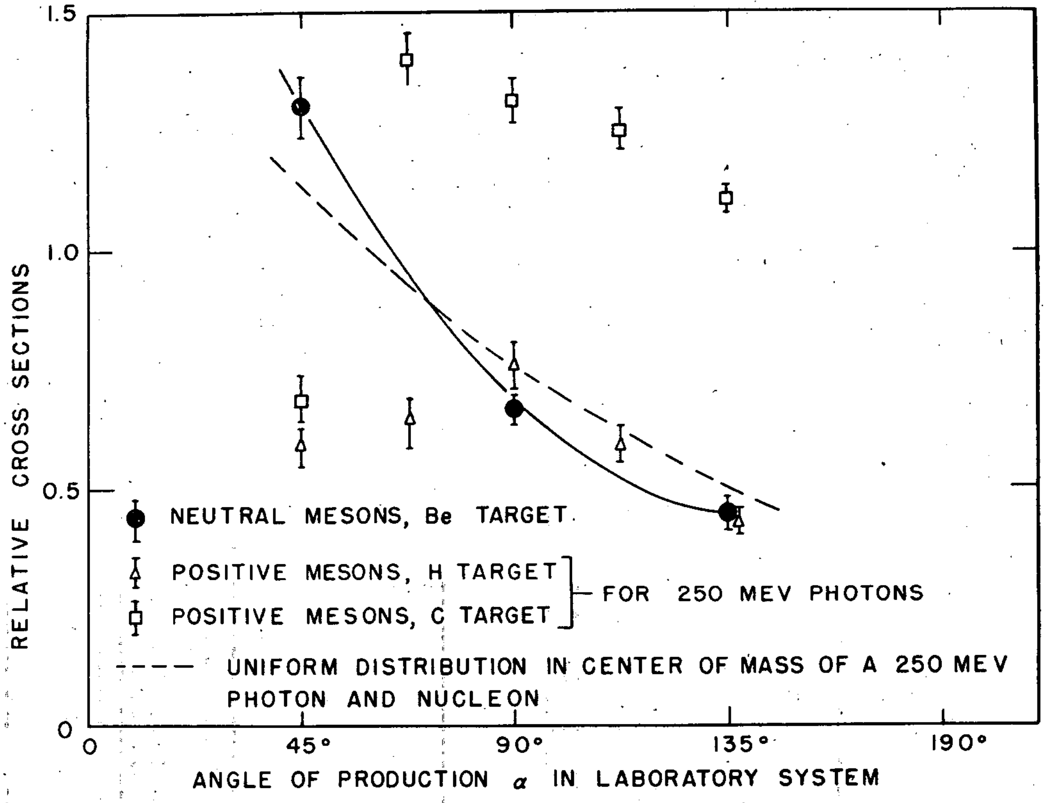

1.5
1.0
0.5
0
RELATIVE CROSS SECTIONS
0
45°
90°
135°
190°
ANGLE OF PRODUCTION α IN LABORATORY SYSTEM
NEUTRAL MESONS, Be TARGET
POSITIVE MESONS, H TARGET
POSITIVE MESONS, C TARGET
FOR 250 MEV PHOTONS
UNIFORM DISTRIBUTION IN CENTER OF MASS OF A 250 MEV PHOTON AND NUCLEON

FIG. 4

Mu 139

0-15