Charged Photomesons from Various Nuclei*

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The yield of π^- and π^+ photomesons from a wide range of nuclei has been measured. The irradiating photon flux was 310-Mev bremsstrahlung and the mesons were selected magnetically at 135° with an energy of 65±15 Mev. The experimental results include the following features: (1) the π^-/π^+ ratio from deuterium is close to unity; (2) the charged meson cross sections for deuterium are close to that for hydrogen; (3) the total charged meson cross section per nucleus varies as $A^{\frac{2}{3}}$; (4) the π^-/π^+ ratios show a remarkable correlation with the masses of the isobars adjacent in Z to the target nucleus; (5) the π^-/π^+ ratio from beryllium is energy sensitive. The implications of these results are discussed.

I. INTRODUCTION

THE production of charged π-mesons by high energy gamma-rays incident on nuclei was first observed by McMillan, Peterson and White,[1] and has since been studied by a number of workers. The elementary particle interactions which presumably give rise to the production can be written

$$\gamma+p\rightarrow n+\pi^+ \tag{1}$$

and

$$\gamma+n\rightarrow p+\pi^-. \tag{2}$$

A complete experimental investigation of these reactions should be of great interest in view of their bearing on the nature of the coupling of the π-meson, the nucleons, and the electromagnetic field. In particular, it is of interest whether the coupling with the electromagnetic field is via the electric interaction only, or whether the magnetic moment of the nucleons plays an important role.

Reaction (1) can of course be studied directly by irradiating a hydrogenous material, or preferably liquid or compressed hydrogen, with high energy gamma-rays; a fairly detailed study of this case has already been made.[2,3] The complementary reaction (2) is not as easily accessible, since free neutrons are not available in sufficient density. Now one of the chief points of interest lies in the comparison between reactions (1) and (2), since this will give some information about the importance of the coupling with the nucleon magnetic moment. Thus, in the absence of a direct comparison between (1) and (2), one must be content with an investigation of the relative production rates of negative and positive mesons from more complex nuclei. In this case, however, factors other than the elementary interactions will enter into consideration. Most important among them are the following: (a) the nucleons in a complex nucleus are not at rest; (b) the proximity of a nucleon may affect the meson cloud surrounding another nucleon and thus alter its interaction with the gamma-ray; (c) the presence of the other nucleons will limit the number of states available to the recoiling nucleon after the interaction, and will affect the energy balance of the reaction; and (d) mesons produced in the interior of the nucleus may be reabsorbed before they can escape.

These effects should be least important in the case of the deuteron, which is a very loosely bound structure. Thus, the photoproduction of mesons from deuterium is the nearest approach we have for a comparison between reactions (1) and (2). Even here, however, the effects mentioned above may not be negligible.

Experimentally, the most easily accessible quantity is the relative yield of negative and positive mesons from nuclei considerably heavier than the deuteron. (Alone, deuterium must be used in the form of either compressed gas or low temperature targets, while deuterium in a chemical compound necessitates a subtraction method.) Accordingly, most of the early measurements were made with carbon as target material.

The mesons may be detected in a photographic emulsion, or some form of electronic counting technique may be employed. In the former case, uncertainty in the relative detection efficiencies for positive and negative mesons may arise from the fact that different criteria are used for the identification of the π^- and π^+ mesons. This point is well illustrated by the wide discrepancies among the first estimates of the π^-/π^+

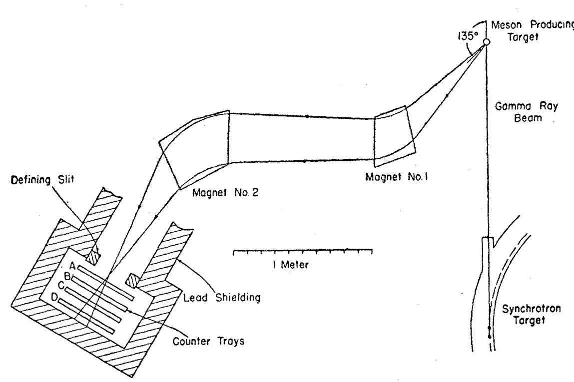

FIG. 1. Diagrammatic view of apparatus.

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[1] McMillan, Peterson, and White, Science **110**, 579 (1949).
[2] J. Steinberger and A. S. Bishop, Phys. Rev. **78**, 494 (1950).
[3] Bishop, Steinberger, and Cook, Phys. Rev. **80**, 291 (1950).

ratio from carbon. The emulsion technique has now been much improved, however.

The electronic counting methods usually require a rather complex arrangement for the identification of a particle as a meson; frequently magnetic fields are employed as an aid for this purpose, the magnetic field at the same time determining the sign of the charge. In the case of the positive meson, which decays at rest before it undergoes nuclear interaction, the $\pi^+ \to \mu^+ \to \beta^+$ decay can be utilized to give an unambiguous identification without the use of a magnetic field. Unfortunately, no such unique process is available in the case of the negative meson.

The present work was undertaken when relatively little was yet known in this field. The estimates of the π^-/π^+ ratio from carbon had converged towards the value of about 1.3; the energy spectrum and angular distribution of π^+ mesons from hydrogen had been measured, and a measurement of the relative yield of π^+ mesons from various elements had been made.[4] The aim of the present investigation was to make a preliminary survey of the relative yields of mesons of both signs from a wide range of nuclei, using essentially the same method of detection for both π^- and π^+ mesons. The apparatus used for the work was to a large extent available from a previous experiment;[5] it consisted of a pair of electromagnets so arranged that mesons from a target bombarded by high energy bremsstrahlung from the Cornell 310-Mev electron synchrotron could be focused into a region relatively free from other radiations. The previous experiments with a cloud chamber had already established the fact that the flux of mesons from the magnets was almost entirely uncontaminated by other particles; it therefore seemed desirable to use the apparatus in its existing form for a preliminary survey, accepting its limitations for the time being and reserving a more detailed inquiry for the time when the general character of the results should become apparent.

During the course of the work a number of surprising features were observed, notably the wide variation of the π^-/π^+ ratio from nucleus to nucleus. The investigation was thus extended to include as large a number of nuclei as possible, in the hope of finding regularities which would permit some conclusions to be drawn. It became clear that, beyond some general features, a detailed interpretation of the results would require far greater knowledge of the effects concerned than is at present available. Thus the work has evolved into a compromise between the generality of a first survey and the particular conditions of experiment as dictated by the existing apparatus.

II. EXPERIMENTAL METHOD

The experimental arrangement is shown diagrammatically in Fig. 1. The gamma-rays used to bombard the targets were produced in the Cornell 310-Mev electron synchrotron. The circulating electron beam of this machine strikes an internal target, consisting of a 0.040-inch diameter tungsten wire, and produces a sharply collimated beam of bremsstrahlung which differs only slightly in energy distribution from the theoretically predicted distributions for infinitely thin targets. The maximum energy is 315±3 Mev.[6] The gamma-flux is delivered in 30 bursts per second, the duration of the bursts being adjustable between a few microseconds and about 2 milliseconds.

TABLE I. Details of photomeson targets.

Element	A	Isotopic abundance %	Target material used	Weight of target (grams)	Notes
H	1	99.98	H_2O	118.7+120.6	
D	2	[a]	D_2O	132.4+132.6	f, g
			C	118.7+120.9	
C	12	98.9	$CH_{1.86}$[b]	105.8+106.0	
O	16	99.8	$CD_{1.72}$[c]	57.54	f, h
Li	7	92.5	Li	67.7	i, j
Be	9	100	Be	111.7	k, l
F	19	100	$(CF_2)_n$[d]	127.8+126.3	f, g
Al	27	100	Al	138.1	
P	31	100	P	137.2	
S	32	95.1	S	156.7	
K	39	93.4	K[e]	100.9	i
Ca	40	97.0	CaF_2	128.9+127.8	f, g
Mn	55	100	MnO_2	228.0	f, k
Co	59	100	Co	216.4	h, k
As	75	100	As_2O_3	284.6	f, k
I	127	100	I	201.9	
Bi	209	100	Bi	236.3	

[a] D_2O purity >99.8 percent; $CD_{1.72}$ deuterated >96 percent.
[b] Commercial white petrolatum, combustion analysis.
[c] >96 percent deuterated oil, chemical analysis by combustion.
[d] Teflon.
[e] Fused under kerosene.
[f] Subtraction method.
[g] Two-bulb target (see text).
[h] Smaller glass bulb.
[i] Stopping power too low.
[j] No glass envelope, thin coating of paraffin wax.
[k] Stopping power too high.
[l] No glass envelope.

The target materials for photomeson production were placed, for the most part, in thin-walled glass containers. These consisted of the envelopes of 60-watt electric light bulbs onto which a thin-walled filling tube, 1 inch in diameter, had been sealed. These bulbs have been found to be very uniform in diameter (6 cm) and wall thickness (0.5 mm).

The density of the fillings was adjusted, as far as possible, so that the mean energy loss (~5 Mev) of the escaping mesons was roughly the same for all the targets. This was arranged by choosing the mode of subdivision and packing of the material; the standard energy loss was that in the water target. In the case of some materials, however, it was found impossible to obtain the correct stopping power. The details for all the targets will be found in Table I.

[4] R. F. Mozley, Phys. Rev. **80**, 493 (1950).

[5] Camac, Corson, Littauer, Shapiro, Silverman, Wilson, and Woodward, Phys. Rev. **82**, 745 (1951).

[6] J. W. DeWire and L. A. Beach, Phys. Rev. **83**, 476 (1951). The figure 315 Mev gives the maximum photon energy if the circulating electron beam strikes the internal target at exactly peak magnetic field, a condition which was not quite realized during the calibrating experiments, nor during the present experiment.

For the investigation we selected mono-isotopic elements, or those in which one isotope predominates overwhelmingly. It was also required that the elemental form, or a simple compound suitable for subtraction measurements, be readily available in a sufficient degree of chemical purity.

The particles emerging from the target were analyzed as to momentum and charge by an arrangement of two magnets which has been described previously.[7] This arrangement provides rather crude refocusing of the selected mesons in both horizontal and vertical planes; the aberration is largely due to the presence of fringe fields in the wide pole gaps which it was found necessary to employ. Owing to these field inhomogeneities, the energy of the mesons leaving the magnets was not very well defined. From absorption measurements and an investigation with a stretched current-carrying wire we estimate the energy to cover the range from 45–75 Mev, which corresponds to an energy of 65 ± 15 Mev for the mesons, at creation.[8]

It is possible, of course, to vary the energy of the mesons accepted by changing the field settings of the two magnets; unfortunately, however, the detection efficiency will vary in an unknown manner at the same time, owing to the fact that the fringing fields and focusing properties will not remain constant. Moreover, the coincidence array used to detect the mesons imposes a lower limit on the energy that can be used without loss of geometrical efficiency, on account of the fact that the cylindrical walls of the counters present a non-uniform absorber to the mesons. For these reasons it is not possible to make a meaningful measurement of the energy spectrum of the mesons in this way. The mean energy of mesons accepted was lowered on one occasion in order to find out how the π^-/π^+ ratios varied (see Sec. IV); no significance can however be attached to the relative counting rates for the two magnet settings.

Fortunately it appears from the above experiment as well as from other measurements, since published, that the π^-/π^+ ratios do not depend critically on the energy, at least in the case of carbon,[9] beryllium,[10] and deuterium.[11] This means that the energy spread in the present work will not prove too great an obstacle to its interpretation. To reduce the energy spread significantly, it would have been necessary to sacrifice geometrical efficiency and thus statistical accuracy in a reasonable time of counting. It seemed preferable to obtain better statistics under less well defined conditions, since it was possible to maintain these conditions accurately constant for relative measurements.

The mesons emerging from the magnets were detected by coincidence in three trays of Geiger counters, each consisting of four 1 in.×18 in. brass counters with 0.030 in. brass walls. The four counters were slightly staggered and so arranged that there were no insensitive gaps between them. The fact that the counters had cylindrical walls meant that the amount of absorber in the path of a particle varied with the exact position of its trajectory. Mesons of energy above about 40 Mev, however, could penetrate over essentially the whole area of the trays, so that the geometrical efficiency above this energy approached unity. The sensitive length of the trays was restricted to 10 in. by lead stops which were kept in a fixed position relative to the magnet system. The counters and magnet gaps were enclosed in a lead shield of about 9 in. wall thickness.

As an over-all check on the method of detecting mesons, the triple coincidence counting rate was measured as a function of (a) target position both along and perpendicular to the gamma-ray beam; (b) magnet currents; (c) Geiger counter overvoltages; (d) absorbers placed between the trays of counters. Statisfactory plateaux in the counting rate could be obtained as a function of each of these variables. This, together with the high degree of internal consistency of the various runs, indicates a high "resetting accuracy" in the experiment. Since subtractions were involved in most of the determinations, this fact is very important.

A previous investigation with a cloud chamber[5] had shown that the contamination of the mexon flux by other particles, especially by electrons, did not exceed 2 percent. The time of flight of the mesons through the system is about one-half mean life, so that some π-mesons decay into μ-mesons before they reach the detector. In most cases, however, the decay will throw the particles out of the region of acceptance of the magnets. For the interpretation of the present experiment, we have assumed that the decay characteristics of positive and negative π-mesons are identical.[12]

Although the magnets and counters were heavily shielded, a certain background single counting rate could not be eliminated. This background is important because of the dead-time losses it produces in the Geiger counters. With the best shielding conveniently possible, each Geiger tray was fired about once in three bursts of the synchrotron. A careful examination disclosed that about 70 percent of the background counts occurred after the time of the gamma-ray burst, with delays ranging up to several hundred microseconds.[13] By working with a short gamma-ray burst, and by suitable electronic gating, it was thus possible to reduce the background counting rate to about one count in ten bursts. Working with a short gamma-burst has the additional advantage that the exact dead-time of the counters becomes unimportant: once a counter is fired,

[7] M. Camac, Rev. Sci. Instr. **22**, 197 (1951).
[8] The mean energy of "about 50 Mev" quoted in the earlier reports was in error owing to an inaccurate analysis of the absorption curves.
[9] Peterson, Gilbert, and White, Phys. Rev. **81**, 1003 (1951).
[10] H. A. Medicus, Phys. Rev. **83**, 662 (1951).
[11] R. S. White, Ph.D. thesis, University of California, 1951.
[12] See the work of C. E. Wiegand, Phys. Rev. **83**, 1085 (1951); and of Lederman, Booth, Byfield, and Kessler, Phys. Rev. **83**, 685 (1951).
[13] Presumably this delayed background is due to capture gamma-rays from neutrons, whose slowing-down time is of the right order of magnitude.

it remains dead for the whole of the burst, but certainly recovers for the next burst. The dead-time losses are still relatively high in this mode of operation, however: about 5 percent for each tray, or 15 percent of the triple coincidence rate (the background counts in the trays were uncorrelated).

An experimental method of measuring over-all losses in one representative tray was devised as follows: behind the three trays A, B, and C used for counting the mesons, a fourth tray D was placed (see Fig. 1). Together with the triple rate ABC, the two rates $ABCD$ and ACD were also measured. Their difference gives the loss in tray B from all causes. Since the losses in A, B, and C are identical (the background rates are the same, the trays are physically similar) it is then possible to deduce the over-all loss in triple coincidences for the particular run and make the necessary correction.

The random triple coincidence rate was negligible. Background coincidences due to mesons from the glass envelope of the target and possibly due to penetrating particles from other sources in the system were determined by running with an unfilled glass bulb, and subtracted out. This background was usually about 10 percent of the total coincidence rate, and was not the same for positive and negative magnet settings. It therefore had to be determined separately for the two polarities. Target and background runs, the two polarities, and various target materials used in the subtraction measurements were alternated throughout the course of the experiment to avoid the danger of any unknown, and possibly progressive, systematic errors. The internal consistency of the various runs was as good as their statistical accuracy.

The gamma-ray flux was standardized by means of a thin ionization chamber placed in front of the meson target, and a current integrator. In the case of the heavy target materials, correction had to be made for the absorption of the gamma-rays in traversing the target: here it was assumed that the daughter products of a gamma ray, once it had initiated a shower, were degraded in energy sufficiently so that they gave no further contribution to the meson production in the energy range accepted.

The nuclear absorption of mesons leaving the target was very small, and nearly equal for all the materials used. No correction has thus been made for this effect.

Owing to a number of uncertain factors, such as the effective solid angle of acceptance of the magnet system and the effective energy interval of the mesons, no attempt has been made here to obtain yields in absolute value. Instead, all yields are given relative to that of π^+ mesons from hydrogen.

III. RESULTS[14]

Table I gives a list of the various targets which were used in the investigation. The measured counting rates from these targets were reduced as follows: each run was corrected for the measured dead-time loss ($\sim$15 percent), and then all runs from a given target and with a given magnet polarity were pooled. The result was then corrected by subtracting the empty bulb background count ($\sim$10 percent) and by allowing for the absorption of the gamma-rays in traversing the targets (usually 1–3 percent, but reaching 30 percent for Bi). In the case of compound targets, the appropriate subtractions were then carried out in order to obtain the yield per nucleus for each of the elements. For deuterium, two independent methods were employed, one involving the direct difference between a deuterated hydrocarbon and a carbon target, the other a chain of subtractions between water, heavy water, a hydrocarbon, and carbon. The former, despite its merit of directness, contributed very little to the statistical information on account of the small quantity of deuterated oil (60 cc) available. The use of heavy water allowed a more accurate determination; for this purpose, two bulbs were filled with each of the target materials and irradiated simultaneously, one behind the other. Since the magnet system accepted particles from a wide region, this procedure almost doubled the counting rates. A separate check was made to determine the exact ratio of the counting efficiencies with one bulb and with two bulbs, and it was also verified that the measured π^-/π^+ ratios remained unaffected by the modification.

A further advantage of the method using heavy water is that the exact composition of the targets is known; in the case of the deuterated oil,[15] the chemical composition was determined by means of a combustion analysis, and the results of this were slightly uncertain owing to the presence of a volatile component. Within the statistical accuracy achieved, the two methods gave the same result, and in what follows a suitably weighted mean has been taken as the best estimate.

In Table II we have collected all the results. The yields have been normalized arbitrarily in such a

TABLE II. Yields Y of π^- and π^+ mesons per nucleus. Meson energy $=65\pm15$ Mev, angle of emission $=135°$. Maximum photon energy $=310\pm10$ Mev.

Element	A	Z	$Y(\pi^+)$	$Y(\pi^-)$	$Y(\pi^+)+Y(\pi^-)$	$Y(\pi^-)/Y(\pi^+)$
H	1	1	1.00 ± 0.05	0.04 ± 0.05	1.04 ± 0.07	—
D	2	1	0.87 ± 0.07	1.04 ± 0.07	1.91 ± 0.10	1.19 ± 0.12
Li	7	3	2.25 ± 0.14	4.65 ± 0.28	6.90 ± 0.31	2.06 ± 0.18
Be	9	4	2.39 ± 0.01	5.39 ± 0.02	7.78 ± 0.03	2.25 ± 0.11
C	12	6	3.54 ± 0.05	3.77 ± 0.06	7.31 ± 0.08	1.06 ± 0.02
O	16	8	4.08 ± 0.13	4.25 ± 0.13	8.33 ± 0.18	1.04 ± 0.05
F	19	9	4.26 ± 0.13	6.04 ± 0.14	10.3 ± 0.18	1.42 ± 0.05
Al	27	13	6.01 ± 0.20	7.18 ± 0.21	13.2 ± 0.29	1.20 ± 0.05
P	31	15	7.25 ± 0.28	7.54 ± 0.28	14.8 ± 0.4	1.04 ± 0.06
S	32	16	7.76 ± 0.18	6.63 ± 0.16	14.4 ± 0.24	0.85 ± 0.03
K	39	19	9.37 ± 0.42	9.58 ± 0.42	19.0 ± 0.6	1.02 ± 0.1
Ca	40	20	9.01 ± 0.46	5.20 ± 0.46	14.2 ± 0.7	0.58 ± 0.06
Mn	55	25	9.08 ± 0.56	10.9 ± 0.7	20.0 ± 0.9	1.20 ± 0.11
Co	59	27	9.79 ± 0.35	13.1 ± 0.35	22.9 ± 0.5	1.34 ± 0.07
As	75	33	9.72 ± 0.49	13.9 ± 0.7	23.6 ± 0.9	1.43 ± 0.1
I	127	53	15.8 ± 0.7	23.2 ± 0.8	39.0 ± 1.1	1.46 ± 0.08
Bi	209	83	19.2 ± 1.4	25.3 ± 1.4	44.5 ± 2.0	1.32 ± 0.12

[14] Some of the results of this work have already been published [R. M. Littauer and D. Walker, Phys. Rev. **83**, 206 (1951); **82**, 746 (1951)] and are here included for completeness.

[15] This oil is a residue in the manufacture of deuterated paraffin, and is thus presumably deuterated to the same extent as the final product, the quoted figure for which was >96 percent.

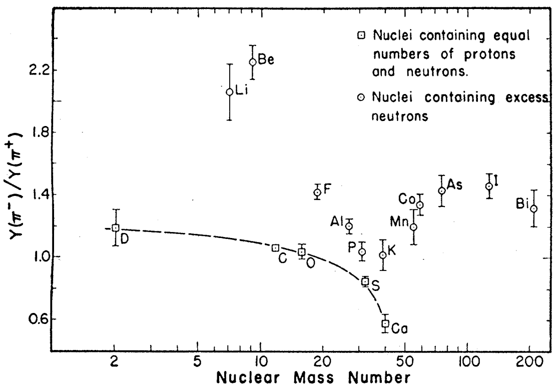

FIG. 2. Measured π^-/π^+ ratios. Errors are statistical standard deviations.

manner that the best estimate for the yield of π^+ mesons from hydrogen is 1.00. The errors associated with each measurement are kept separate, and are not compounded during the normalization. The quoted errors are statistical standard deviations in all cases. From internal consistency and a number of other checks (see Sec. II) it is believed that any systematic errors are smaller than the smallest statistical deviations quoted.

Table II contains, in addition to the relative yields of negative and positive mesons from the various elements, the π^-/π^+ ratios computed from these yields, and the total yields of charged mesons, independent of sign.

The π^-/π^+ ratios are exhibited also in Fig. 2. The dashed curve in this figure connects the points for the nuclei containing equal numbers of protons and neutrons, ranging from deuterium to calcium. The remaining nuclei contain excess neutrons, one each for all those below and including potassium, more for those above. In the case of bismuth, the neutron excess amounts to over 50 percent.

The total yield of charged mesons is plotted logarithmically against nuclear mass number in Fig. 3. It is seen that this yield is very closely represented by a law of the form

$$Y = kA^{\frac{2}{3}}.$$

It is interesting to note from Table II that, within statistical error, no π^- mesons were observed from hydrogen. The accuracy of the determination limits the π^- cross section for hydrogen to about 7 percent of the π^+ cross section.

All the results quoted above apply to a maximum gamma-ray energy of 310±10 Mev,[16] a meson energy of 65±15 Mev (extreme limits), and an angle of emission of 135°. It is interesting to compare some of them with the results of other workers, where possible.

Peterson, Gilbert, and White[9] have used a photographic emulsion method for examining mesons of both signs produced by 322-Mev bremsstrahlung on carbon. They have measured the π^-/π^+ ratio both as a function of meson energy and of angle; unfortunately the statistical errors in the individual determinations do not allow one to see any significant variation of the ratio with these variables. The authors take an average to arrive at a figure of 1.34±0.20 for the π^-/π^+ ratio at 135°, with a median energy around 60 Mev. This ratio is slightly higher than the one reported in the present work; however, if one takes into account only those points which correspond strictly to the conditions of our experiment, there is agreement within statistical error.

Medicus,[10] using the same apparatus as Peterson, Gilbert and White,[9] has investigated the π^-/π^+ ratio for Be at 90°. He finds no significant change over the energy region 30–70 Mev within an accuracy of about 20 percent, and quotes an over-all value of 2.2±0.25, which is in excellent agreement with our value measured at 135°.

White[11] has measured the π^-/π^+ ratio from deuterium at 45° and 90° for mesons of energy 45–85 Mev, using a gas target and photographic detection. His values are 0.96±0.11 and 0.98±0.18, respectively.

Mozley[4] has measured the relative yield of π^+ mesons from a number of elements and finds that the yield per nucleus follows approximately an $A^{\frac{2}{3}}$ dependence. The same result has been demonstrated in the present work, and holds most accurately for the total yield of charged mesons of both signs (see Fig. 3).

IV. ENERGY DEPENDENCE OF THE π^-/π^+ RATIO FROM BERYLLIUM

Since the photons used for these experiments are not monochromatic, any variation in the energy balance of the reactions will alter the amount of the bremsstrahlung spectrum which can be utilized, and thus affect the over-all yield. It is of interest, therefore, to find out whether the observed π^-/π^+ ratios depend on the meson energy and on the maximum energy of the bremsstrahlung. In particular, the dependence should

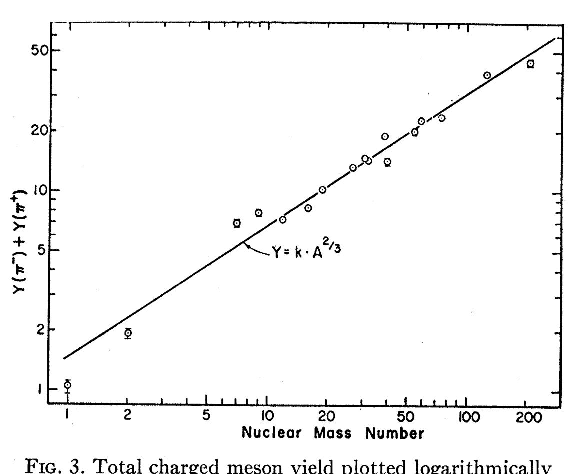

FIG. 3. Total charged meson yield plotted logarithmically against mass number.

[16] The limits of error on the beam energy have been increased slightly to allow for a small error that was made by not extracting the beam at exactly the peak magnetic field of the synchrotron.

be greatest for those nuclei which have π^-/π^+ ratios deviating strongly from unity (see Sec. V).

The dependence of the π^- and π^+ yields from beryllium on energy was investigated by changing both the maximum energy of the bremsstrahlung spectrum and the mean energy of mesons accepted by the magnet system. The meson energy was lowered to approximately 50 Mev by reducing the magnetic fields of the two magnets in the same ratio. The uncertainties connected with our knowledge of the meson energy have already been discussed in Sec. II, and it was also pointed out there that the relative counting rates at the two magnet settings could not be compared. Thus only the variation of the π^-/π^+ ratio is significant as far as dependence on meson energy is concerned.

More detailed information can be gained by varying the maximum energy of the photon spectrum, keeping the magnet settings unchanged. Here even the variation of the single π^- or π^+ counting rates is significant and may give evidence as to the energy of the photon which was responsible for the production.

The maximum photon energy was varied by contracting the circulating electron beam of the synchrotron onto the internal target at different times during the magnetic cycle. The two energies here employed were 310±10 Mev (as during the main body of the work) and 256±10 Mev. At both these photon energies the yields were measured for the two magnet settings corresponding to mean meson energies of about 65 and 50 Mev. The results, normalized to a constant number of effective quanta‡ in the irradiation, are displayed in Tables III and IV. In Table III, for the single π^- and π^+ counting rates at the two meson energies, the yields have been normalized in each case so that at the higher photon energy the π^- yield is 1.00.

It is evident from these results that the π^- and π^+ yields as well as their ratio depends on the energy balance of the reaction. The π^-/π^+ ratio deviates further from unity the stricter the energy requirements of the reaction are made, whether this is done by lowering the photon energy or by increasing the required meson energy. The variation with meson energy over the range here covered, however, is not very steep; since the meson energy ranges overlap in the two cases, no quantitative deductions can be made from this variation in any case.

V. DISCUSSION

(a) The $A^{2/3}$ Dependence

The simplest assumption that can be made to explain the variation of meson yield with nuclear mass is that the elementary cross section per nucleon is roughly constant, and that the mesons are observed only from

‡ The number of effective quanta is defined as

$$Q=(\int EN(E)dE)/E_{\max},$$

where $N(E)dE$ is the well-known bremsstrahlung spectrum of upper energy $E_{\max}$.

TABLE III. Yield of photomesons from beryllium as a function of energy (arbitrary normalization at the two meson energies).

$E_{\max}$ (Mev)	$E_\pi=65\pm15$ Mev $Y(\pi^-)$	$Y(\pi^+)$	$E_\pi=50\pm10$ Mev $Y(\pi^-)$	$Y(\pi^+)$
310±10	1.00±0.02	0.44 ±0.01	1.00±0.02	0.47±0.01
256±10	0.24±0.01	0.064±0.004	0.33±0.01	0.13±0.01

TABLE IV. Variation of the π^-/π^+ ratio from beryllium with energy.

$E_{\max}$ (Mev)	$E_\pi=65\pm15$ Mev	$E_\pi=50\pm10$ Mev
310±10	2.27±0.07	2.12±0.06
256±10	3.7 ±0.3	2.56±0.16

the surface of the nucleus. To explain the suppression of mesons from the interior of the nucleus, one can postulate a strong reabsorption as they traverse nuclear matter;[4] it is known from direct absorption experiments[17] that the mean free path of mesons of about 50 Mev in nuclear matter is of the order of $2-3a_0$ (a_0=standard nuclear radius 1.4×10^{-13} cm). However, for reabsorption to give an $A^{\frac{2}{3}}$ dependence valid down to the lightest nuclei, it would be necessary to assume a mean free path shorter than consistent with the absorption experiments; it appears, therefore, that either some additional mechanism for the suppression of meson production inside a nucleus must contribute, or else the validity of the $A^{\frac{2}{3}}$ law down to the lightest nuclei is a chance combination of other effects. There can be little doubt, however, that in the heavier nuclei reabsorption plays an important role; we shall return to this point below in connection with the variation of the π^-/π^+ ratios. In displaying the $A^{\frac{2}{3}}$ dependence, we have chosen the total charged meson production as our variable, since the relative concentration of protons and neutrons on the surface of a nucleus may be materially affected by the Coulomb repulsion and by the relative binding of the individual particles.

(b) The π^-/π^+ Ratios

An interesting result of the present work, and probably the most fundamentally significant, is the fact that the π^-/π^+ ratio from deuterium does not depart significantly from unity (this result has since been independently confirmed by White[11]). One would expect the effects of nuclear binding on meson production to be very small in deuterium; moreover they would presumably be the same for π^- as for π^+ production, apart from the small effects of the Coulomb interaction. Thus a measurement of the π^-/π^+ ratio from deuterium comes as close as is possible to a direct comparison between the elementary reactions (1) and (2) defined in Sec. I. Brueckner[18] has shown that the ratio of the cross sections for these reactions should vary strongly with energy and angle if the interaction of the electro-

[17] H. A. Bethe and R. R. Wilson, Phys. Rev. 83, 690 (1951).
[18] K. A. Brueckner, Phys. Rev. 79, 641 (1950).

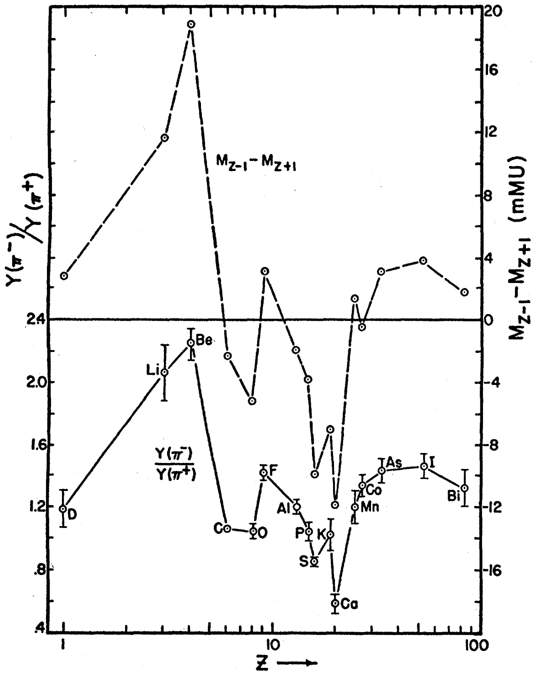

FIG. 4. π^-/π^+ ratios and mass differences (see text) plotted against Z.

magnetic field with only the currents of the particles is considered. If in addition the interaction with the magnetic moments is taken into account, the ratio becomes very close to unity and insensitive to both energy and angle. The predicted value for 135° and 65-Mev mesons is about 1.1, which would have to be corrected for the slight effect of the Coulomb barrier before comparison with the experimental figure of 1.19 ± 0.12. It appears established, then, that the interaction of the electromagnetic field with the nucleon magnetic moments plays an important role.

From Table II it can be seen that the production cross sections for mesons from deuterium are very close to that of π^+ from hydrogen, a result which is to be expected from the loosely bound nature of the deuteron.

The wide variations of the π^-/π^+ ratios from element to element suggest that they are connected with some detailed feature of nuclear structure rather than with a variation of the elementary production process itself. In an effort to find some empirical correlation that would give a clue to the nature of this nuclear factor, we have plotted the mass differences $M_{Z-1}-M_{Z+1}$ side by side with the π^-/π^+ ratios. M_{Z-1} and M_{Z+1} are the masses of the ground states of the final isobars $Z-1$ and $Z+1$ produced by removing or adding one charge to the initial target nucleus Z.[19] The resulting curves are displayed in Fig. 4. It is at once apparent that a strong correlation between the mass differences and the π^-/π^+ ratios exists. The same fact is brought out in Fig. 5, where a direct linear plot of the two variables has been made. The points fall remarkably close to a straight line, extending over a range of more than 3:1 in the π^-/π^+ ratio and from -12 to $+19$ mMU in the mass differences (1 mMU=0.93 Mev). There can thus be no doubt that a functional relationship, direct or indirect, exists between the two variables. It must be remembered, however, that there are many nuclear features which vary sympathetically with the masses of the ground states, and thus the functional dependence displayed above may be quite indirect. The fact that the plot of Fig. 5 is so nearly linear might also be fortuitous.

The factors which may modify the meson production from a complex nucleus have been mentioned in Sec. I; we shall regroup them here in a slightly different way, and attempt a very elementary discussion of their effects. These factors may be listed under the following three heads: (a) specifically mesonic factors, i.e., the effect of the overlap of meson clouds within the nucleus on the elementary production process; (b) effects of nuclear structure, including the initial momentum distribution of the nucleons, the absorption of outgoing mesons, and the limitation of momentum space available to recoil particles; (c) effects concerned with energy balance in the reaction and the fact that the primary photon spectrum is not monochromatic.

The results of the present experiment are of course not cross sections for meson production in the usual sense of the word, but rather meson yields integrated over the relevant part of the bremsstrahlung spectrum. To account for this fact, one might write the yields in the form

$$Y\sim(\text{Number of nucleons of relevent sign})\times\int N(E)\sigma(E)\eta(E)\rho(E)dE.$$

Here $N(E)$ is the number of photons of energy E; $\sigma(E)$ is the elementary production cross section; $\eta(E)$ is the nuclear modification factor mentioned in (a) above, averaged over the nucleus while taking account of reabsorption; and $\rho(E)$ is a weighting factor to account for the number of initial and final states possible in the reaction, always keeping the meson angle and energy fixed as dictated by the conditions of experiment. The above separation of variables is, of course, quite arbitrary and is intended solely as a basis for discussion.

If the production of mesons is from a free nucleon at rest, the factor $\rho(E)$ will be zero everywhere except at $E=E_0$ corresponding to the correct energy and momentum relationships. The effect of nuclear structure on $\rho(E)$ is to smear out the delta-function into a more or less broad curve, whose width will be primarily determined by the initial momenta of the target nucleons within the nucleus. The center of gravity of the curve

[19] Above and including O^{16}, the nuclear masses have been taken from a semi-empirical formula (E. Fermi, *Nuclear Physics*, revised edition (University of Chicago Press, Chicago, 1950). For the mass of He^7 we have used He^6+n; for Li^9, Li^8+n.

may be shifted in energy: the fact that during charged meson production the isotopic spin of a nucleon is changed implies a potential energy "opposition" ΔE from the rest of the nucleus, which will lead to the subtraction of some 20–40 Mev from the energy available in the reaction.

In a complex nucleus there is also the possibility that the elementary reaction takes place involving more than one nucleon. In this case, the energy of the photon required to produce a given meson would be lowered, and incidentally the nucleon recoil energy reduced. During the present discussion, we shall restrict ourselves to the case in which only one nucleon takes part in the primary production process, a condition which is likely to be satisfied in view of the high energies involved in the reaction.

The effect of $\rho(E)$ on the integral for Y can be visualized as a weighting function imposed on the other variables $N(E)\sigma(E)\eta(E)$. Since little is known about $\eta(E)$, we will leave this factor out of consideration for the moment. For $\sigma(E)$ we can assume as a first approximation the cross section for meson production from hydrogen as measured by Bishop, Steinberger and Cook.[3] In Fig. 6 we have plotted the product $N(E)\sigma(E)$ as a function of E, using for $N(E)$ the well-known bremsstrahlung spectrum with an upper limit of 310 Mev. The arrow at 290 Mev marks the value E_0 for which the 65-Mev mesons can be produced at 135° from free nucleons. For production of mesons from single nucleons in a complex nucleus, $\rho(E)$ will presumably be centered about the somewhat higher gamma-ray energy $E_0+\Delta E$.

$\rho(E)$ thus covers a very steep part of the curve, suggesting that slight changes in the energy balance of the reaction would affect the yield considerably. To determine the exact extent of this energy sensitivity, we would need to know the shape of $\rho(E)$ and its placing on the energy scale. Owing to the wide range of internal momenta for the nucleons in a complex nucleus, $\rho(E)$ will be a very broad curve, thus offsetting in part the steepness of the function $N(E)\sigma(E)$.

It is possible that the observed variations of the π^-/π^+ ratios from nucleus to nucleus are produced largely by the energy sensitivity of the individual yield functions. If there is a difference in the energy balance of the reaction according to whether a positive or a negative meson is produced, then the π^-/π^+ ratio will be altered correspondingly. Such an energy difference might be due to the Coulomb potential, or specifically nuclear factors may also contribute.[20]

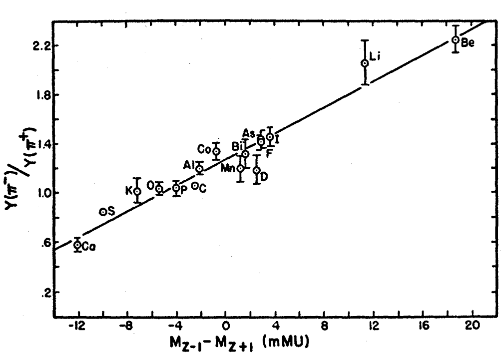

FIG. 5. π^-/π^+ ratios plotted against mass differences.

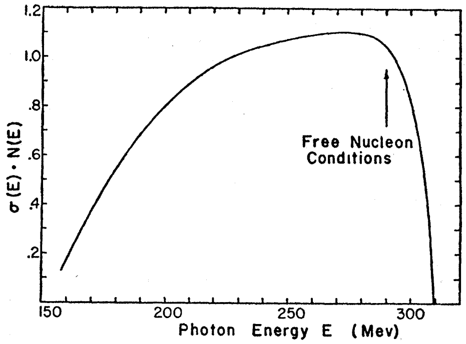

FIG. 6. $\sigma(E)N(E)$ as a function of E (see text).

If the variation of the π^-/π^+ ratios is governed by these energy considerations, one would expect the ratios to be energy sensitive, deviating further from unity the tighter the energy requirements are made. In Sec. IV we have described an experiment to investigate the variation of the π^-/π^+ ratio for beryllium with energy. From the results it is evident that there is a fairly strong energy dependence, so that the above arguments are borne out at least qualitatively. A quantitative interpretation would require, as has been pointed out above, an exact knowledge of the shape of $\rho(E)$ and of the energy balance of the reaction.

Apart from the energy dependence of $\rho(E)$, this factor influences the production rates through the density of initial and final states it contains. The exclusion principle will limit the number of states available for a recoiling nucleon, and in a rough way one would say that all energies below the Fermi surface for the residual nuclear core will be excluded.[21] The number of final

[20] A plausible way of analyzing the production process would be to consider first the creation of a meson by the impact of a photon on a single nucleon, then the fate of the particles as they recoil through the remainder of the nucleus. In the first instance, creation of a meson does not alter the local charge density in the nucleus, and will thus not give rise to an electrostatic potential energy. The change of the isotopic spin of the nucleon, however, causes an opposing potential ΔE of some 20–40 Mev. ΔE need not necessarily be the same when a proton is changed into a neutron as for the inverse process, and this difference $\Delta E_+ - \Delta E_-$ is the first factor which may distinguish positive from negative meson production. Although no Coulomb energy is required at the instant of creation, positive and negative mesons will behave differently upon escaping from the nucleus, the ones experiencing an acceleration on crossing the potential barrier, the others a retardation. When we observe mesons of a given energy in the laboratory, therefore, their energy at creation will not be the same, differing for the two signs by approximately 2.4 times the height of the potential barrier of the nucleus (the average potential inside the nucleus is 1.2 times the potential barrier). This is, in a way, equivalent to a difference between the energy balances of the reaction for the two cases.

[21] If the recoiling nucleons tended to be of relatively low energy, as would be the case if there were more than one nucleon involved

states thus excluded will depend of course on the position of the Fermi surface, which varies with the ground state energy. Bethe and Hayakawa[22] have estimated the magnitude of the variations to be expected from this effect, and find that they account for no more than 10–20 percent.

The factor $\eta(E)$ represents the modification of the production cross section by the presence of other nucleons, averaged over the nucleus while taking into account reabsorption of the mesons produced. The reabsorption makes the surface of the nucleus more effective for producing mesons externally observed than the interior; one will thus expect the relative concentration of neutrons and protons on the surface to have an important effect on the π^-/π^+ ratio. If there are other factors which reduce $\eta(E)$ in the interior of the nucleus, one might, following Butler,[23] consider the extreme case in which mesons are produced from only that part of a nucleon's wave function which exists outside the nuclear radius $a_0A^{\frac{1}{3}}$. This means that the binding of a nucleon becomes an important factor in its availability for meson production, since the more loosely bound nucleons spend more time outside the nuclear potential well than the more tightly bound particles. Thus, on a nuclear shell model, the last-added "odd" particle has the largest meson yield. Although this line of argument depends on somewhat extreme assumptions about the factor $\eta(E)$, there are certain experimental features which bear it out in a qualitative way. Consider first the variation of the π^-/π^+ ratio among the elements containing equal numbers of protons and neutrons. In Fig. 2 the relevant points have been connected by a smooth curve, which decreases steadily with increasing A. This decrease is paralleled by a progressively looser binding of the protons in these nuclei. The elements with one excess neutron in this region all have π^-/π^+ ratios lying above the curve. One can make the formal assumption[14] that the increased π^- yield is due entirely to the odd neutron, which will be more loosely bound than the other particles. On this basis one can work out the meson cross section from the odd neutron in terms of the cross sections from the paired neutrons in the same nucleus, and finds in all cases that the cross section is larger by a factor of about 4. This formal line of approach meets with difficulties, however, since it would attribute to the odd neutron a meson yield greater than that from the free proton (more than twice the free proton yield in the case of Be^9) which is not a very plausible conclusion. Moreover, an indirect measurement of the π^- production from the loose neutron in Be^9 has been made in this laboratory,[24] which indicates the cross section to be of the same order as that from the free proton.

in the interaction, we might have to consider the density of states in the whole excited product nucleus.

[22] H. A. Bethe and S. Hayakawa (private communication).

[23] S. Butler (private communication).

[24] J. C. Keck and R. M. Littauer (to be published).

With less extreme assumptions about the suppression of mesons from the interior of the nucleus, there will remain nevertheless an effect on the π^-/π^+ ratios which varies in the correct sense from nucleus to nucleus, although it will probably not be sufficiently large to account by itself for the observed deviations from unity.

VI. CONCLUSION

The most important features of the experimental results presented in this paper are:

(1) that the π^-/π^+ ratio from deuterium is close to unity, showing that the electromagnetic field interacts with the magnetic moments of the nucleons during charged meson production;

(2) that the charged meson cross sections for deuterium are close to that for π^+ from hydrogen;

(3) that the total charged meson cross section per nucleus varies as $A^{\frac{2}{3}}$, showing that the production is largely a surface effect, as is to be expected in the case of the heavier nuclei from the known absorption of mesons in nuclear matter;

(4) that the π^-/π^+ ratios vary widely from nucleus to nucleus, showing a remarkable correlation with the masses of the isobars adjacent in Z to the target nucleus; and

(5) that the π^-/π^+ ratio from beryllium is energy sensitive, bearing out qualitatively an argument concerning the effect of the bremsstrahlung distribution on the observed meson yields.

A detailed theory of the variations of the π^-/π^+ ratio has not yet been given, but a number of effects are suggested, each of which would contribute in the right sense to modifying the production of mesons according to their sign. The effects mentioned in the discussion are (1) the variation of the amount of bremsstrahlung spectrum utilized in the production because of the energy requirements of the reaction; (2) the relative proportion of neutrons and protons on the surface of the nuclei; and (3) the limitations of recoil momentum imposed on the nucleons by the residual nuclear core through the exclusion principle.

Although none of these effects appears by itself large enough to account for the variations of the π^-/π^+ ratio, it seems probable that together they will produce a sufficient deviation of this ratio from unity. The accurate linear correlation with the mass differences displayed in Figs. 4 and 5 remains, however, a somewhat puzzling feature.

Thanks are due to Mr. M. Camac for the design of the magnet system, and to the members of the first experimental team[5] for their contribution to the construction of the apparatus.

We are indebted to Professor H. A. Bethe for many valuable discussions and to Mr. S. Butler for permission to discuss some of his results before publication.