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Pion Production by Electrons*

W. K. H. PANOFSKY, C. M. NEWTON, AND G. B. YODH
High-Energy Physics Laboratory and Department of Physics, Stanford University, Stanford, California
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The production of π^+-mesons directly by 500-Mev electrons has been studied in lithium. The measurements consist of a precise measurement of the ratio of electron-produced to bremsstrahlung-produced pion yields. Results expressed as "equivalent radiation length" X_e for electron production are $X_e = 0.0233 \pm 0.0012$ for pions of 55 Mev, and 0.0185 ± 0.0014 for pions of 150 Mev at 75° to the incident electron beam. The results are fully compatible with purely electromagnetic interaction of the electrons. Within the limitations of the experimental data obtained to date, and of the available theoretical studies, the results are compatible with magnetic-dipole absorption as the predominant process in photopion production under the conditions indicated.

INTRODUCTION

THE production of pions by nuclear particles on the one hand, and by electromagnetic radiation on the other has been extensively studied. Production by electrons has escaped observation since the experimental conditions for the study of such a process are more severe. Since the cross sections for the process are presumably smaller than those of corresponding photopion processes, the experiment needs thin targets and an electron beam free of x-rays.

Interest in electron-pion production arises from two principal sources: (1) Although it is likely that electron-pion production is directly associated with photopion production via the "virtual-photon" field of relativistic electrons, the possibility of other interactions should at least be examined. (2) If one assumes electron-pion production to be purely electromagnetic in nature, then the ratio of electron-pion to photopion yields is sensitive to the nature of the photon-absorption process. Electron-pion production thus serves as a "tracer" on photoproduction.

The data presented here represent the first definite results on this subject. Although future measurements under varied conditions of energy and angles and using hydrogen will be made, it is felt that the present results are of interest as they have some bearing on the first point, and permit a preliminary observation on the second.

EXPERIMENTAL ARRANGEMENT

This experiment was made possible by the availability of a high-energy collimated electron beam from the Stanford Mark III linear accelerator.[1] The electron beam, on emerging from the end of the accelerator, is accompanied by secondary neutron and gamma flux. The beam was purified and energy-analyzed by a double-deflecting magnetic-analyzing system described elsewhere.[2] The primary electron energy was defined by the magnetic field of the first deflecting magnet and a collimator-slit system. The electron energy was calibrated by the "floating-wire" technique, and is believed to be accurate to better than 4 percent.

The doubly-deflected analyzed beam was fed through a pipe expanding from 4 in. to 8 in. in diameter into the target chamber (Fig. 1). The target chamber contains two airlocks through which the meson target and the radiator can be inserted. A small magnet is provided to deflect the beam downward; the deflection causes the electron beam to miss the targets while any residual gamma-ray or neutron beam impurity would continue to bombard the target. This magnet thus serves to check whether gamma-ray or neutron impurities contribute to the pion yields. The pions from the target were analyzed in angle and energy by a magnet system designed and constructed by K. Crowe, R. Friedman, and D. Hagerman (Fig. 2). During these runs the pion laboratory angle was set at 75° to the incident beam. The current in this analyzing magnet defined the pion energy. The magnet current was calibrated in terms of pion energy using the floating-wire technique.

The pions passed through the channel into a large plastic scintillator (a cylinder 7 in. in diameter and 10 in. in length). For the runs at 55-Mev pion energy the length of the scintillator was sufficient to stop the pions in the middle of the counter. For the 150-Mev runs, a copper absorber was inserted ahead of the

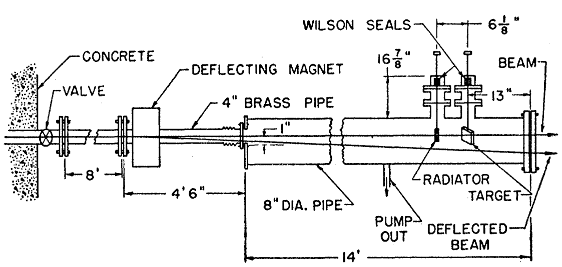

FIG. 1. Vertical cross section through bombardment geometry. Note the magnet used for investigating the effect of neutral impurities in the beam.

* The research reported here was supported by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.

[1] R. B. Neal, Stanford University Microwave Laboratory Report No. 185 (unpublished); Chodorow, Hansen, Ginzton, Kyhl, Neal and Panofsky, Rev. Sci. Instr. 26, 134 (1955).

[2] W. K. H. Panofsky and J. A. McIntyre, Rev. Sci. Instr. 25, 287 (1954).

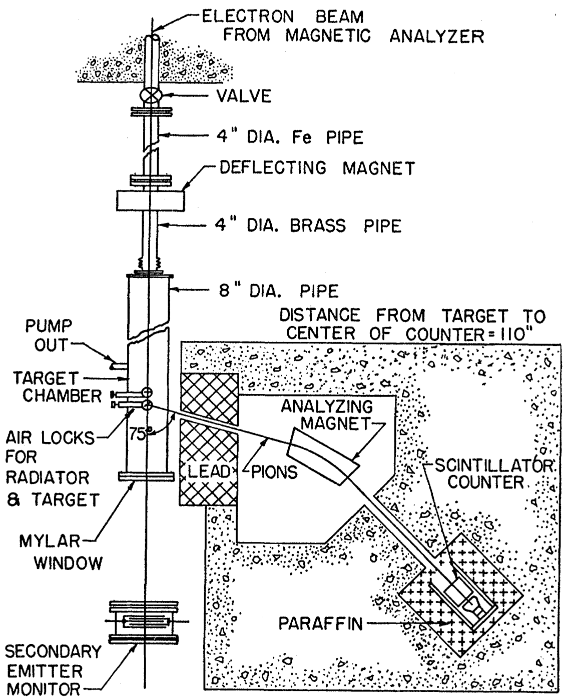

FIG. 2. Horizontal cross section through the bombardment geometry. Note the position of the radiator and target.

counter to reduce the pion energy to 60 Mev before the pions entered the scintillator.

The pions were counted through the decay positrons from the muons. The beam pulse of the linear accelerator is short (<0.5 μsec) and hence background at a time of the order of 2 μsec after the pulse is mainly due to neutrons, radioactivity, scintillator afterpulses, etc., but not to any prompt secondary processes. The scintillation pulses from the plastic as seen by a 5-in. DuMont photomultiplier were clipped and amplified with a gain of roughly 10^3 and rise time of 2×10^{-8} sec. The pulses were then fed into three fast discriminators set at varying levels. The three discriminated outputs were fed into a 3×3 coincidence matrix; each discriminator output was counted in coincidence with three gates delayed after the beam pulse by 2.2 μsec, 4.4 μsec, and 13.2 μsec, and applied to the matrix as shown in Fig. 3.

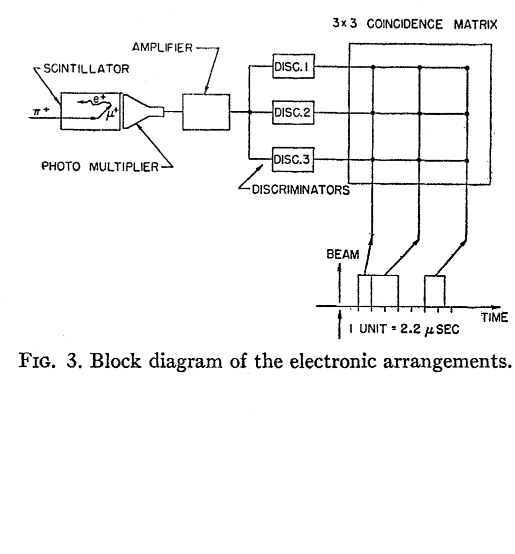

FIG. 3. Block diagram of the electronic arrangements.

The gate widths were 2.2 μsec, 4.4 μsec, and 3.3 μsec, respectively.

The radiator in one run was 0.0960 radiation length of carbon, and in other runs multiples of 0.0362 radiation length of copper. The target was 0.00712 radiation length of lithium in the direction of the beam. The target was oriented with the normal to its plane bisecting the angle between the incident beam and pion beam (Fig. 4). Spectrographic analysis of the lithium indicated a 0.2-percent Na impurity and other imdurities totalling 0.1 percent.

The primary beam leaves the vacuum target chamber through a 0.006-in. mylar window and enters a "secondary electron multiplier," as described by Tautfest and Fechter,[3] pumped by a separate vacuum system. This instrument consists of a set of 0.003-in. aluminum foils arranged inside a high vacuum so that alternate foils can be connected to a high-voltage source and to an electrometer, respectively. Secondary electrons emitted from the foils by the primary beam are collected and the total secondary charge measured. This instrument is essentially nonsaturating, but has a current multiplication generally of less than one; in the instrument used here, the multiplication is 0.1. The collected current is integrated with an electronic integrator.

PROCEDURE

The experiment as described here measured precisely only the ratios of the electron-pion to photopion yields and not their absolute magnitude. The counter system does not operate on a plateau since the discriminator settings reject an arbitrary fraction of the μ-decay positrons. Also the absolute solid angle of the detection system is not accurately known. The measurement consisted of comparing counts of "radiator-in—target-in" runs to those of "radiator-out—target-in" runs. To obtain best accuracy, counts were alternated between "radiator-in—target-in" and "radiator-out—target-in" runs. In addition to this cycle of runs, the following backgrounds were determined: (1) counts with the pion-analyzing magnet de-energized; (2) counts with radiator in, target out; (3) counts with radiator out, target in, and the electron beam deflected down to miss the target; and (4) counts with radiator out and target out.

For the runs with the copper radiator, all these backgrounds were substantially equal within statistics, while in the runs with the carbon radiator, backgrounds (1) and (2) were somewhat higher. Background (2) was applied as a correction to the runs with radiator in and target in, while background (3) was applied as a correction to runs with radiator out and target in. All backgrounds were small, as indicated below. In particular, it can be concluded that the effects of gamma-ray and neutron beam impurities were negligible.

Possible systematic effects on the accuracy of moni-

[3] G. Tautfest and H. Fechter, Phys. Rev. **96**, 35 (1954); Rev. Sci. Instr. **26**, 229 (1955).

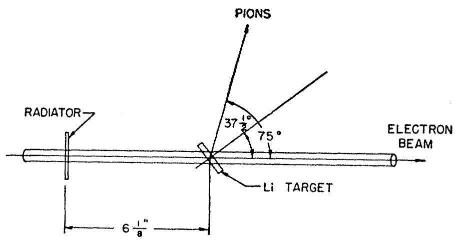

FIG. 4. Detail of the radiator and target geometry.

toring due to the increase in beam size produced by multiple scattering in the radiator were investigated and were found to be absent.

RESULTS

We reduced our results in terms of a quantity X_e, the "equivalent radiation length" for electron production. Let X_T be the thickness in radiation lengths of the target (assumed $\ll 1$) and X_R be the thickness in radiation lengths of the radiator. We then define X_e such that

$$\frac{\text{Counts with radiator in, target in}}{\text{Counts with radiator out, target in}} = \frac{X_R+(X_T/2)+X_e}{(X_T/2)+X_e} = R. \quad (1)$$

The radiation length is here taken as

$$X_0^{-1} = 4\alpha N_v r_0^2 Z(Z+\zeta)\ln(183Z^{-\frac{1}{3}}),$$

where the symbols have their customary meaning, and where ζ is the relative radiation efficiency in the field of an electron. The interpretation of X_e will be discussed in our next section.

Our results are given in Table I. Counts in one of the discriminator channels only are given.

In the reduction of data we have assumed that cascade corrections are negligible. In order to check this assumption, a run was made checking on the linearity between R and X_R as implied by Eq. (1). If R is measured as a function of X_R, then a straight line with an intercept at $-[X_e+(X_T/2)]$ along the X_R axis would result. The ratio R as a function of X_R was measured and is shown in Fig. 5. It is seen that the intercept is in good agreement with the directly calculated values of X_e as shown in Table I and with the assumption of linearity.

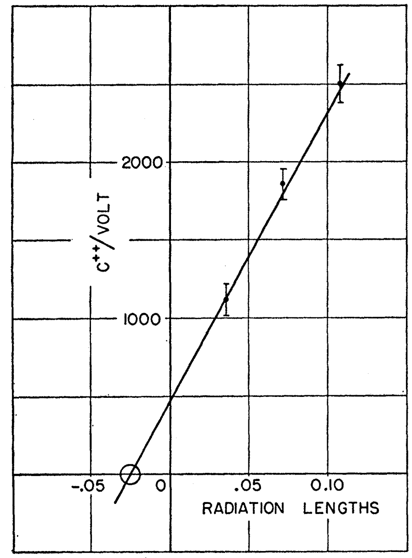

FIG. 5. Plot of meson yield as a function of radiator thickness. The intercept on the abscissa of the straight line through the points corresponds to $-[X_e+(X_T/2)]$.

DISCUSSION

To a first approximation the relation between the cross section $\sigma_\nu(k)$ for a photon of energy k and the cross section $\sigma_e(E_0,E)$ for a highly-relativistic electron of initial energy E_0 and final energy E is given by the Weizsäcker-Williams formula[4,5]:

$$\frac{\sigma_e}{\sigma_\nu} = \frac{2\alpha}{\pi}\ln\left(\frac{\gamma}{kb_{\min}}\right)\frac{\Delta k}{k}, \quad (2)$$

TABLE I. Counts per 10 microcoulombs of beam.

	Target in, radiator in		Target in, radiator out			
	Uncorrected	Corrected	Uncorrected	Corrected	R	X_e
$T_\pi=55$ Mev Carbon radiator ($X_R=0.0960$)	524.0±16.0	512.0±16.0	116.0± 4.5	109.0±5.0	4.71±0.26	0.0224±0.0015
$T_\pi=55$ Mev Copper radiator ($X_R=0.0362$)	135.3± 3.1	131.7± 3.1	61.5±15.0	57.9±1.5	2.28±0.08	0.0243±0.0016
$T_\pi=150$ Mev Copper radiator ($X_R=0.0724$)	86.3± 1.95	81.0± 2.5	23.0± 0.68	19.1±0.85	4.24±0.23	0.0185±0.0014

[4] F. von Weizsäcker and E. J. Williams, Z. Physik **88**, 612 (1934); E. J. Williams, Phys. Rev. **45**, 729 (1934).
[5] Nordheim, Nordheim, Oppenheimer, and Serber, Phys. Rev. **51**, 1057 (1937).

where $k=E_0-E$; $\Delta E=\Delta k$ is the energy band of photon energies accepted by the experiment; $\gamma=E_0/m$ where m is the electron rest mass; and $\hbar=c=1$. If $N_k dk$ is the number of photons between energy k and $(k+dk)$ produced per radiation length of radiator, Eq. (2) can be written

$$X_e=(2\alpha/\pi)\ln(\gamma/kb_{\min})(1/kN_k). \tag{3}$$

To a first approximation we have of course $kN_k\approx 1$. The quantity $b_{\min}$ is the minimum impact parameter to which the collision can be defined; $\gamma=E_0/m$; m is the electron rest energy; $b_{\min}$ depends on the process considered. If the transverse momentum transfer is $P_\perp$, then $b_{\min}\sim P_\perp^{-1}$. For a process such as pair production by electrons involving relativistic light particles only, the electron deflection angles are of order m/E_0 and hence $P_\perp\sim(m/E_0)E_0$ and the logarithm in Eq. (3) becomes $\sim\ln(E_0/k)$. The resultant value of X_e is in good agreement with the experimental facts; e.g., the experiments of Camac[6] on pair production of electrons. For electron processes on heavy particles the cross sections remain large at reasonably large deflection angles; hence $P_\perp\sim E_0$ and the logarithm becomes roughly $\ln(E_0^2/mk)$. The observed yields as shown in Table I are thus fully compatible with purely electromagnetic production.

Of course, it is of interest to inquire whether more quantitative theoretical agreement can be obtained. In this experiment the pion energy and angle are defined. If for the moment we assume free-nucleon kinematics (as would be correct for the planned hydrogen experiments), then the angle between the initial and final electron defines the final electron energy and the direction and magnitude of the final recoil momentum (Fig. 6). Even if the pion energy and angle are defined, the energy loss of the electron and hence the energy of the equivalent photon are not defined exactly.

In general, the angle between the initial and final electron direction is fairly small[7]; the momentum transfer $\mathbf{k}$ to the nucleon-meson system is therefore nearly parallel to the initial electron momentum $\mathbf{P}_i$. It can be shown[8] that the direction of the effective electric field vector is perpendicular to the bisector between $\mathbf{P}_i$ and $\mathbf{P}_f$ and hence is nearly transverse to $\mathbf{P}_i$. The interaction of this field corresponding to the transition of the electron in plane-wave approximation from $\mathbf{P}_i$ to $\mathbf{P}_f$ has been evaluated by Blair[9] and Thie, Mullin, and Guth[10] for the special case that only a single multipole moment represents the absorption by the nuclear system. If these moments are energy-independent the integration over final electron angles can be carried out and yields the formula

$$X_e=\frac{\alpha}{\pi}\left\{\left[1+\left(\frac{E}{E_0}\right)^2\right]\ln\left[\frac{2EE_0}{\mu(E_0-E)}\right]-\lambda\right\}\Big/kN_k, \tag{4}$$

where $\lambda=0$ for the magnetic-dipole absorption; $\lambda=(2E/E_0)$ for electric-dipole absorption; $\lambda=-(8/3)\times[E/(E_0-E)]^2$ for electric-quadrupole absorption; kN_k is clearly only a correction factor equal to the ratio of the actual bremsstrahlung cross section at the given value of E_0 and k to the extreme relativistic limit. It is given by:

$$kN_k=\left\{\left[1+\left(\frac{E}{E_0}\right)^2-\frac{2}{3}\left(\frac{E}{E_0}\right)\right]\times\ln(183Z^{-\frac{1}{3}})+\frac{1}{9}\frac{E}{E_0}\right\}\Big/\ln(183Z^{-\frac{1}{3}}) \tag{5}$$

if screening is complete and by the corresponding relations[11] in the case of intermediate screening. Equation (4) is plotted in Fig. 7 as a function of E.

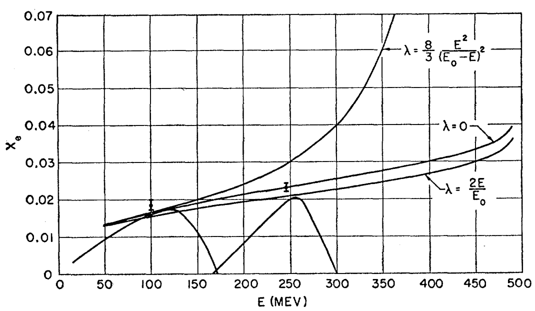

FIG. 7. Plot of the "equivalent radiation length" X_e for bombarding energy of $E_0=500$ Mev as a function of the recoil energy E of the electron. Curves are plotted under the assumption of electric-dipole, magnetic-dipole, or electric-quadrupole absorption with energy-independent moments. In the actual experiment, the final electron energy was not held constant, but the meson angle and momentum were given. For meson production on nucleons, the error made under this assumption is small and has been calculated (see text). For production on nuclei, the effect has been calculated under the assumption of a Fermi gas in a potential well of 28 Mev having an upper limit of kinetic energy of 20 Mev. As a result of these calculations, the final electron energy is broadened as shown by the two curves indicated. Our measurement has been entered on these curves at an abscissa corresponding to the mean value of the final electron energy contributing. Uncertainty in primary energy and pion energy makes the value of E uncertain to about ± 20 Mev.

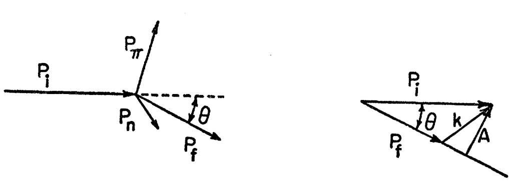

FIG. 6. Vector diagram representing the kinematics of pion production in electron-nucleon collisions, where $\mathbf{A}$ is the vector potential due to transition, $\mathbf{P}_i$, $\mathbf{P}_f$ are the initial and final electron momenta, and $\mathbf{k}=\mathbf{P}_n+\mathbf{P}_\pi$ = momentum of equivalent photon absorbed.

[6] M. Camac, Phys. Rev. 88, 745 (1952).
[7] It will be shown further that 60 percent of the cross section corresponds to electron deflection angles of less than 5°.
[8] D. R. Yennie (private communication).
[9] J. S. Blair, Phys. Rev. 75, 907 (1948); mimeographed notes; and private communications to Richard Wilson and K. L. Brown.
[10] Thie, Mullin and Guth, Phys. Rev. 87, 962 (1952).
[11] See, e.g., H. A. Bethe and J. Ashkin, *Experimental Nuclear Physics*, edited by E. Segrè (John Wiley and Sons, Inc., New York, 1953), Vol. 1, pp. 259–263.

The assumption of absorption by an energy-independent single multipole moment is of course an approximation since the wavelength corresponding to the momentum transfer is not necessarily large compared to the nuclear dimensions. However for a given photon energy the selection rules for the photopion production process $\gamma+p\rightarrow n+\pi^+$ require magnetic-dipole absorption or electric-quadrupole absorption if the final pion-nucleon state shall be a P-state. It is known from the analysis of the photopion production process that, excepting very near threshold,[12] the P-wave cross section predominates although the S-wave contribution continues to cause asymmetry in π^+ production even at higher energies. In π^0 production the S-wave term is essentially absent; if magnetic-dipole absorption were the only initial mechanism, then the center-of-mass angular distribution must be of the form $(d\sigma/d\Omega)\propto(A-\cos^2\theta)$ where $A=5/3$. Experimentally,[13] $A=1.22\pm0.10$, which indicates that at high energies other moments, presumably the electric-quadrupole moment, also contribute. Experimental evidence from other sources leaves the value of A fairly uncertain. It is therefore a matter of great interest to investigate whether this method—i.e., the degree of agreement of the data with Eq. (4)—when extended to hydrogen would have bearing on this point. The fact that the nucleon size is not necessarily small compared to k^{-1} would reflect in terms of k dependence of the effective magnetic moment.

In obtaining the final cross sections, as calculated by Blair[9] and Thie *et al.*,[10] the elementary cross sections are integrated assuming that the final electron energy is constant as a function of electron angle. Figure 8 shows the actual final electron momentum as a function of electron angle for a fixed meson angle and energy. The Blair formula has been re-integrated for the magnetic dipole case using this modified kinematics and yields a result for X_e only 2.5-percent lower than the answer calculated if the momentum had a constant value for all θ. This is, of course, symptomatic of the fact that most of the cross section originates from small electron deflection angles (e.g., 60 percent of the cross section originates from electron deflection angles less than 5° and 75 percent within 15° for the case $T_\pi=55$ Mev). Hence the momentum transfer by the electron is essentially along the incident direction. For this reason it is unlikely that the k dependence of the moments will affect the result greatly.

In addition to these kinematic effects there will be corrections due to the use of plane-wave functions in the calculations of Blair and Thie, Mullin, and Guth

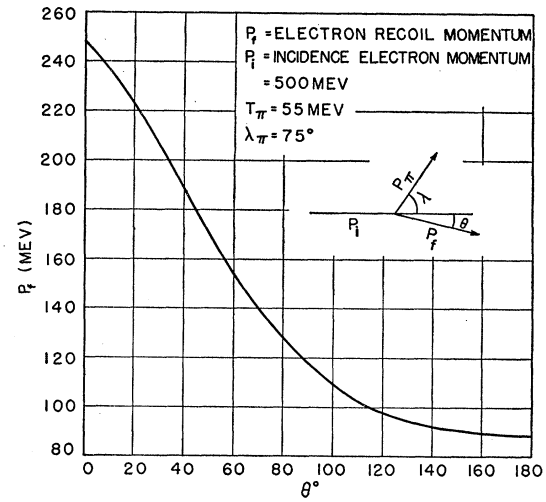

FIG. 8. Plot of final electron momentum *vs* final electron angle, assuming kinematics of meson production on a nucleon. Meson momentum held constant corresponding to a laboratory production angle of 75° and laboratory kinetic energy of 55 Mev.

(these corrections are presumably small for lithium and hydrogen), and higher-order corrections in α.

The above remarks apply to hydrogen only. For lithium, presumably the same considerations apply except that it is necessary to average over initial momenta. This will effectively broaden the values of final electron energy contributing to the results. This spread in E has been calculated in an admittedly crude manner for a Fermi gas of maximum kinetic energy 20 Mev in a well 28-Mev deep and is represented by a set of curves in Fig. 7 where our present results are plotted at a point corresponding to the mean final electron energy. Note that all results are in agreement with magnetic- and possibly also electric-dipole absorption. The electric-quadrupole contribution seems to be small at 55-Mev meson kinematic energy. Clearly the limiting factor in the attainable reliability of the conclusions is the "smearing" effect of the initial momenta. This defect will be removed in hydrogen experiments.

ACKNOWLEDGMENT

This experiment has benefited greatly from the active collaboration of many members of the staff of this laboratory. Dr. K. M. Crowe is primarily responsible for the present arrangement of the magnetic meson analyzer. Mr. G. Masek has contributed considerably to the experimental arrangement. Mr. J. Narud has provided the basic electronic designs of the circuits, used. The linear accelerator operating group, under the direction of Dr. R. F. Mozley, has been of indispensable assistance to this experiment.

Our theoretical understanding of the problem has been aided by discussions with Dr. L. I. Schiff and Dr. R. H. Dalitz; and in particular, the aid of Dr. D. R. Yennie is gratefully acknowledged.

[12] G. Bernardini and E. L. Goldwasser, Phys. Rev. **95**, 857 (1954).

[13] Walker, Oakley, and Tollestrup, Phys. Rev. **97**, 1279 (1955); **89**, 1301 (1953).