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Production of μ-Meson Pairs by Photons*

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Further measurements are reported on the anisotropic component of μ^- mesons from bombardment of an aluminum target by 600-Mev bremsstrahlung. As reported previously, we interpret such a forward peaking as evidence for the direct electromagnetic production of muon pairs. Combining our new data with those previously reported, we obtain a value of 1.42±0.34 (standard deviation) for the ratio of the observed negative-muon cross section to that calculated by assuming the muons to originate as spin-$\frac{1}{2}$ pair fragments from electromagnetic production in the Coulomb field of an aluminum nucleus of finite size. The absolute normalization is believed correct to within a factor of 1.4. However, the theoretical value considers only the contribution from processes leaving the aluminum nucleus in its ground state; inelastic processes could raise the theoretical value by 40%.

Measurements carried out with 450-Mev bremsstrahlung yielded a value of μ^- counts at 12° relative to those at 23° equal to 0.0002±0.0083, while the value observed at 600 Mev is 0.032 ±0.009 in units of the π^+ counts observed at those two energies. This result makes it very unlikely that the forward peaking observed originates from μ mesons derived from π-μ decay. We conclude on the basis of these measurements that the process of direct electromagnetic production of muon pairs exists, and that the yield is compatible with the theory outlined. Measurements carried out on a lead target place only an upper limit on the cross section in lead. This limit (if taken at three standard deviations) gives a value ten times lower than the μ-pair cross section calculated for a point lead nucleus, but compatible with a nucleus of the accepted nuclear radius. This result makes it very unlikely that muon scattering in the range of momentum transfers near 50 Mev/c could give anomalous results.

A. INTRODUCTION

In a previous paper[1] (hereafter referred to as "I"), we have presented a method for investigating the direct electromagnetic production of muons. For reasons discussed in I, we have adopted the forward peaking at small angles of the production cross section of single negative muons as the means of identification of the process.

Measurements have been continued, using the techniques and experimental arrangements as described in I under the heading "Later Runs," except that (1) the primary beam energy was raised to 600 Mev for the high-energy runs, and (2) the combination of DuMont-6292 photomultipliers and associated amplifier chains was replaced by RCA-6810 14-stage photomultipliers.

Table I. Tabulation of results from runs on μ^- yields in aluminum in addition to those previously reported (reference 1). Results are given in ratio to the 70-Mev π^+ counts with lithium final absorber A_3 (Ref-I). The counts establishing the secondary reference (Ref-III) are also given.

Type	A_3 final absorber	Production angle	Counts/1000 monitor units (~10^{15} electrons)	Counts/1000 Ref-I counts (70-Mev, π^+)
μ^- signal (180 Mev, μ^-)	Li	12°	152±3.2	19.8±0.4
	Mg	12°	67.5±2.5	8.8±0.3
	Li	23°	132.2±3.4	17.2±0.4
	Mg	23°	65.6±4.5	8.5±0.6
Ref-III (210 Mev, π^+)	Mg	12°	479±10	···
	Mg	23°	483±12	···
	Li	12°	609±14	79.4±1.8
	Li	23°	590±13	77.0±1.7
Ref-I (70 Mev, π^+)	Li	23°	7660±193	···

The objectives of the further measurements were as follows: (a) to improve the statistical accuracy of the result in order to establish the existence of the process with certainty, (b) to check the behavior of the signals at the energetic threshold of the μ-pair process, (c) to establish the effect of finite nuclear size on the cross section, and (d) to establish some of the auxiliary π^+ cross sections with improved accuracy. All errors quoted are standard deviations.

B. RESULTS WITH AN ALUMINUM TARGET BOMBARDED BY 600-MEV BREMSSTRAHLUNG

The results from these runs are given in Table I. From I, we obtain our reference cross section (referred to as "Ref-I"):

$$\sigma(70\text{-Mev}, \pi^+) = (5.66\pm0.76) \times 10^{-31}\ \text{cm}^2/\text{sterad-Mev-effective photon}. \quad (1)$$

If we assume the contribution to the μ^- count arising from π-μ decay to be entirely isotropic, then the experimental value of $\sigma(\mu^-, 12°)-\sigma(\mu^-, 23°)$ can be deduced by the methods discussed in I. We obtain

$$[\sigma(\mu^-, 12°)-\sigma(\mu^-, 23°)]_{\text{exptl}} = (5.84\pm1.86) \times 10^{-34}\ \text{cm}^2/\text{sterad-Mev-effective photon}. \quad (2)$$

The theoretical cross section based on the integration of the Bethe-Heitler formula carried out by Rawitscher[2] is

$$[\sigma(\mu^-, 12°)-\sigma(\mu^-, 23°)]_{\text{theoret}} = 4.7 \times 10^{-34}\ \text{cm}^2/\text{sterad-Mev-effective photon}, \quad (3)$$

at a maximum photon energy of 600 Mev. The new set of runs thus gives a value of $\sigma_{\text{exptl}}/\sigma_{\text{theoret}} = 1.25\pm0.40$.

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[1] G. E. Masek and W. K. H. Panofsky, Phys. Rev. **101**, 1094 (1956).

[2] G. H. Rawitscher, Phys. Rev. **101**, 423 (1956).

Combined with our results given in I, this gives

$$\sigma_{\text{exptl}}/\sigma_{\text{theoret}} = 1.42 \pm 0.34. \tag{4}$$

The error quoted here reflects the statistical accuracy of the result, taking into account all errors other than those which affect the absolute cross section only. The absolute cross section is uncertain by a factor of 1.4. The sources of this uncertainty are discussed in I.

The theoretical cross section used in comparison with the data includes only those processes which leave the aluminum nucleus in its ground state. The inelastic contribution to the process can be estimated by the application of the sum rule

$$\sigma_{\text{total}} = \sigma_{\text{point}}[|F|^2 Z^2 + Z(1-|F|^2)], \tag{5}$$

where σ_{point} is the cross section as computed for a point Coulomb field corresponding to unit charge, Z is the atomic number, and $|F|^2$ is the square of the nuclear form factor averaged over the momentum transfers contributing to the process under discussion. This sum rule is derived under the closure approximation for the nuclear states. The second (inelastic) term implies the absence of any correlation among the protons in the nucleus. Inclusion of the inelastic contribution amounts to a factor of 1.38; but at this time the uncertainty due to the approximations used is difficult to evaluate. In principle, results derived from inelastic electron scattering could be used to evaluate the factor empirically. Results obtained at this laboratory[3] thus far include only inelastic scattering to specific levels and do not permit a satisfactory estimate of the cross section leading to the continuum.

C. RESULTS WITH 450-MEV BREMSSTRAHLUNG

Observations were made with the primary electron energy lowered to 450 Mev. This energy was chosen as being sufficiently near threshold for the production of 180-Mev muon pair fragments such that a negligible yield should result. Integration of the product of the theoretical yield and the thick-target spectrum produced by 450-Mev electrons predicts a yield 13% of that at 600 Mev.

Since the objective of these "threshold" runs was to check whether muons from π decay somehow simulate the apparent μ-pair effect, it is best to quote the results as counts per pion yield. The result is given in Table II; we tabulate the quantity

$$\frac{\mu}{\pi} = \frac{[(S_{\text{Li}} - S_{\text{Mg}})_{12^\circ} - (S_{\text{Li}} - S_{\text{Mg}})_{23^\circ}]_{180\text{ Mev},\ \mu^-}}{S_{210\text{ Mev},\ \pi^+}}, \tag{6}$$

where S are the signals at the indicated angular settings, for indicated materials for the final absorber A_3, and given particle kinetic energies.

TABLE II. Results of the "threshold" runs.

(a) Total μ^- counts in ratio to π^+ counts at the two angles of observation.

Run	Ref-III Counts/1000 monitor units	$\frac{(S_{\text{Li}}-S_{\text{Mg}})_{12^\circ}}{S(210\text{-Mev}, \pi^+)}$	$\frac{(S_{\text{Li}}-S_{\text{Mg}})_{23^\circ}}{S(210\text{-Mev}, \pi^+)}$
A	313± 7	0.096±0.008	0.087±0.008
B	437±11	0.089±0.011	0.104±0.011
C	366± 9	0.087±0.014	0.089±0.013
Weighted average		0.0924±0.0059	0.0922±0.0058

(b) Comparison of results of the "threshold" runs with the results obtained at 600 Mev. The μ/π ratio is seen to show a significant increase above the μ-pair threshold.

$k_{\max}$	μ/π
450 Mev	0.0002±0.0083
575 and 600 Mev	0.032 ±0.009
Difference	0.032 ±0.012

D. RESULTS WITH A LEAD TARGET

A series of runs was undertaken to place a limit on the muon-pair cross section in lead. As was discussed in I, a large-atomic-number target is undesirable for optimum sensitivity for μ-pair detection if the cross section obeys the theoretical predictions, including the decrease due to finite nuclear size. Instead, the nuclear form factor is expected to cut the yield by a factor of 40 below the yield predicted for a point source of equal charge. Hence, although measurements with lead are not expected to give a significant μ-pair yield, such measurements can give an unequivocal answer concerning the need for introducing the effect of finite nuclear size into the calculation of the μ-pair cross section and also into the calculation of muon Coulomb scattering. The latter point is of interest regarding the interpretation of the experiments in muon scattering discussed in I. Some of these experiments appear to exhibit an excess of large-angle scattering if the data are compared with predictions derived from Coulomb processes in a field from an extended source; a fit can be formally obtained if a point source is used. This explanation is clearly of no physical significance, but it was felt desirable to extend an observation to a lead target in order to place a limit on the finite-size effect.

The experimental runs were executed with a lead target of 1.96 g/cm^2 (0.338 radiation length) as compared to the target of aluminum of 6.85 g/cm^2 (0.286 radiation length) used in the other measurements reported. The yield of muon pairs should essentially vary linearly with the radiation lengths of target times the reduction of the cross section due to the nuclear-finite-size effect.

The procedure adopted for the lead run differed somewhat from the procedure used in the runs carried out with an aluminum target. Since it was intended only to obtain a limit on the cross section, measurements of the total μ^- yield were carried out at 12° only. This means that the μ^- count will include the counts from pion decay. However, as seen below, even the total

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[3] J. H. Fregeau and R. Hofstadter, Phys. Rev. **99**, 1503 (1955) and private communication.

TABLE III. Tabulation of μ^- counts taken with a lead target of 1.96 g/cm² (0.0057×10^{24} atoms/cm²) and of π^+ counts taken with an aluminum target of 6.85 g/cm² (0.157×10^{24} atoms/cm²).

Run	Counts/1000 monitor units μ^- setting, Pb target A_3=Li	 A_3=Mg	 Difference	π^+ setting (Ref-III) Al target	Ratio of μ^- difference to Ref-III count
A	70.6 ± 3.4	54.0 ± 3.3	16.6 ± 4.8	819 ± 42	0.0203 ± 0.0054
B	38.5 ± 2.0	23.6 ± 1.5	14.9 ± 2.5	555 ± 24	0.0267 ± 0.0045
				Weighted mean	0.0244 ± 0.0036

count uncorrected for pion decay is substantially less than the count expected for muon pairs from a point charge of $Z=82$. The pion decay contribution (which here is quite small because of the $A^{\frac{2}{3}}$ dependence of the pion cross section) can be estimated by various methods, and thus a closer limit on the cross section can be obtained.

The experimental results are tabulated in Table III. Using the experimental value of the ratio of Ref-III (210-Mev, π^+) to Ref-I (70-Mev, π^+) counts from aluminum (see Table I); the measured cross section for the production of 70-Mev, π^+ mesons in Al [$(5.66\pm0.76)\times10^{-31}$ cm²/Mev-sterad-effective photon] as discussed in I; and the target parameters; we obtain

$$\sigma(\mu^-,\text{ Pb, }k_{\max}=600\text{ Mev, including }\mu\text{-pair fragments and }\pi\text{-}\mu\text{ decay products})=(1.27\pm0.25)\times10^{-32}\text{ cm}^2/\text{Mev-sterad-effective photon.}\quad(7)$$

The theoretical values computed from the integration of Rawitscher[2] are given in Table IV.

It is immediately evident that even before correcting the experimental result for muons from π-μ decay, a finite radius is required to bring the theory into agreement with observation.

The contribution from π-μ decay can be computed directly from the aluminum results. The counts at $\theta=23°$ are essentially all derivable from π^- decays. In fact, rather than solving for the μ-pair fragment contribution, we can reduce the 600-Mev data for the contribution to the μ^- count from π-μ decay. The result is

$$\frac{\pi\text{-}\mu\text{ decay count}}{[\pi^+\text{ (Ref-III) count}]_{\text{Al}}}=\frac{58.5\pm5.0}{609\pm14}=0.096\pm0.008.\quad(8)$$

Note that this result agrees fully with the total μ^-/π^+ ratios obtained below threshold as given in Table II, thus confirming the conclusion that the 450-Mev μ^- counts are due to π-μ decays only. The aluminum π^- yield can be related to the π^- yield from lead either by theoretical estimates only or by direct measurement. By direct observation on positive pions from the same targets, we obtain

$$\text{yield (210-Mev, }\pi^+\text{, Pb)/yield (210-Mev, }\pi^+\text{, Al)}=0.155\pm0.010.\quad(9)$$

Since the ratio of negative to positive pion yields in lead is certainly greater than this ratio in aluminum, we thus can obtain the inequality

$$\frac{(\pi\text{-}\mu\text{ decay count})_{\text{Pb}}}{[\pi^+\text{ (Ref-III) count}]_{\text{Al}}}>0.0149\pm0.0016,\quad(10)$$

and hence

$$\sigma(\mu^-,\text{ Pb, }k_{\max}=600\text{ Mev, }\mu\text{-pair fragment})<(0.49\pm0.21)\times10^{-32}\text{ cm}^2/\text{sterad-Mev-effective photon.}\quad(11)$$

In order to convert this result into an equality, a direct measurement of the dependence of the π^-/π^+ production ratio on atomic number was carried out. This measurement had to be carried out at an energy where μ pairs would not contribute, but at the same excitation energy for the residual nucleus. Such a measurement was made at a pion energy of 70 Mev and a bremsstrahlung upper limit of 430 Mev, and yielded the ratio

$$(\sigma_{\pi^-}/\sigma_{\pi^+})_{\text{Pb}}/(\sigma_{\pi^-}/\sigma_{\pi^+})_{\text{Al}}=1.96\pm0.29.\quad(12)$$

The measurement involved a rather large background subtraction and hence the precision was fairly poor. Using this value, we obtain

$$\sigma(\mu^-,\text{ Pb, }k_{\max}=600\text{ Mev})=(-0.26\pm0.33)\times10^{-32}\text{ cm}^2/\text{sterad-Mev-effective photon.}\quad(13)$$

We thus conclude that, although we cannot establish the existence of the μ-pair process in lead, the observed yields are compatible with the theoretical cross section using the accepted finite nuclear radius. The result is, however, in disagreement with the result for a point charge by 30 standard deviations and limits any anomalous interactions between muons and nuclei to a very small value. Formally this result covers momentum transfers up to 50 Mev/c, but it throws additional doubt on the interpretation of some of the cosmic-ray muon-scattering experiments in terms of anomalous scattering.

E. CONCLUSIONS

As the result of these experiments, we feel that the existence of the process of electromagnetic production of muon pairs is established with a very high degree of

TABLE IV. Theoretically predicted cross sections for the production of 180-Mev μ^--pair fragments. Data interpolated from the work of Rawitscher.[2]

	Cross section in cm²/sterad-Mev-effective photon $k_{\max}=600$ Mev; $\theta=12°$ $1/k$ spectrum	 Thick-target spectrum 0.020-in. Ta radiator
Point charge, $Z=82$	$11.2\ \times10^{-32}$	$7.5\ \times10^{-32}$
Lead nucleus, radius $r=1.2\times10^{-13}A^{\frac{1}{3}}$ cm	0.33×10^{-32}	0.22×10^{-32}

probability. All results are compatible with the process as described by the theory pertaining to pair creation of Dirac particles in the Coulomb field of a nucleus of finite nuclear size. The theoretical yield for a spin-zero particle[4] is in poorer agreement with the results but is not excluded.

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[4] See footnote 10 of reference 2.

F. ACKNOWLEDGMENTS

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Extraordinary Increase of the Cosmic Radiation on February 23, 1956*

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During the solar flare event of February 23, 1956, the nucleonic intensity increased by an estimated 600% above normal. The ionizing intensities measured with a shielded (20 cm Pb) and an unshielded Geiger counter telescope showed an estimated increase of 38% and 58% above normal at Berkeley. The time of onset occurred in the interval 0345–0400 UT.

An extraordinary increase in the nucleonic and ionizing components of the cosmic radiation was observed at Berkeley (100 m elevation, 44°N geomagnetic latitude, 38°N latitude, 122°W longitude). Between 0345 and 0400, 23 February 1956, UT, the intensity appeared to rise very rapidly reaching a maximum in this interval and then decreasing approximately exponentially with a decay time of about 40 minutes.

The nucleonic component was observed by using four enriched $B^{10}F$ neutron counters. Each counter is enclosed in the center of a 10 cm×10 cm×100 cm paraffin block. This is surrounded on both sides and the top and bottom with 5 cm lead. This unit is located in the basement of a building, under about 160 gm/cm^2 of concrete. The ionizing components are measured with two Geiger counter telescopes, one without any shielding (total) and the other with 20 cm of lead filter (hard). These are located under a thin roof.

Preceding this extraordinary increase, there were decreases of about 5% in the nucleonic intensity and 2% in the ionizing intensities. These decreases start about February 9 and are accompanied by disturbances in the earth's magnetic field. There are also variations in intensity following this event which appear to be associated with magnetic disturbances.

Because the registers recorded only the total counts in each 15-minute interval the time of onset and peak amplitude are somewhat uncertain. The character of the disturbance appears to be a quite sudden increase followed by a decrease that can be well represented by an exponential curve with a time constant of 0.7 hour. Extrapolating back the nearly exponential decrease, so that the extra counts over background are accounted for, gives the time of onset and amplitude of the initial burst as follows:

Radiation	Time	Increase
Neutrons	0349 UT	600%
Total mesons	0352 UT	58%
Hard mesons	0353 UT	38%

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