Search for Charged Particles with Rest Mass Between that of the Electron and Muon*†

D. H. COWARD, B. GITTELMAN,‡ H. L. LYNCH, AND D. M. RITSON
High-Energy Physics Laboratory, Stanford University, Stanford, California
(Received 25 March 1963)

Singly charged particles with rest mass between that of the electron and muon, produced by electromagnetic pair production, were searched for at the 1-BeV Stanford Electron Accelerator. The experiment had high sensitivity and when combined with theoretical electrodynamics results, rules out the existence of any but very short-lived particles in the range from 1 to 175 m_e.

INTRODUCTION

THE field of high-energy physics has seen the discovery of a large number of new particles and resonances, all with mass larger than the mass of the π meson. However, the mass region between the muon and the electron has not been extensively studied. The experiment reported here was designed to search systematically for singly charged particles (hereafter called submuons) with rest masses between that of the electron and muon.

Before describing the experiment, it seems proper to examine other work that might have detected such particles.[1–3] Table I lists three types of experiments that have been performed. Since the cross section for electromagnetic pair production scales as the inverse square of the rest mass of the pair produced particles, each experiment was sensitive to particles below some maximum mass value. By this we mean that if a charged submuon of rest mass greater than the maximum mass existed, it would not have been detected in the experiment. There is no conclusive experiment to show that charged particles of mass greater than 30 m_e are not produced by electromagnetic interactions.

The nonexistence of submuons with rest mass below 10 m_e may be concluded from theoretical arguments. The measurement of the Lamb shift in hydrogen (the energy splitting of the $2S_{1/2}$ and $2P_{1/2}$ levels in hydrogen) checks the electrodynamic vacuum polarization contribution of electron-positron pairs to about 1%. If the contribution to the Lamb shift for an additional pair of singly-charged fermions is calculated, a limit of about 10 m_e is put on the mass of these particles.[4] By this we mean that, if a submuon existed with mass less than 10 m_e, the effect of vacuum polarization would cause the theoretical and experimental values of the Lamb shift to disagree by more than the theoretical and experimental uncertainties.

The $(g-2)$ result for the magnetic moment of the muon, combined with the total precession frequency of muons in a magnetic field gives an accurate determination of the muon mass. The energy of the $(3D-2P)$ transition of μ-mesonic phosphorus is sensitive to the theoretical predictions of vacuum polarization, and combined with the $(g-2)$ determination of the muon mass checks the theoretical electron-positron vacuum polarization contribution to about 4%. If the effects of an additional singly charged fermion pair are theoretically calculated, a limit on the sub-muon mass of about 10 m_e is again obtained.[4]

The experiment described below used a bremsstrahlung beam incident on a carbon target. The cross sections for pair production of spin-$\frac{1}{2}$ and spin-0 charged particles through their electromagnetic interactions with a Coulomb field are predicted exactly by the Bethe-Heitler[5] and Pauli-Weisskopf[6,7] cross sections, respectively, under the assumption that the produced particles have unit form factor. These formulas must be modified for the structure of the nuclei in the target. Experimentally, it is only necessary to observe one member of the pair and this can be allowed for theoretically by integrating over the coordinates of the unobserved particle.

TABLE I. Experimental mass searches. The numbers in column 2 represent our interpretation of the limits set by the experiments of Refs. 1–3.

Experiments	Maximum detectable mass (m_e)
Cosmic-ray experiments[a]	30
Machine searches[b]	25
Absorption of gamma rays in hydrogen[c]	3

[a] Ref. 1.
[b] Ref. 2.
[c] Ref. 3.

* This work was supported in part by the U. S. Office of Naval Research and the Air Force Office of Scientific Research.
† Based on a thesis submitted by D. H. Coward to the Department of Physics and the Committee on Graduate Study of Stanford University in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.
‡ On leave from Princeton University, Princeton, New Jersey.
[1] G. G. Fazio and M. Widgoff, Phys. Rev. **116**, 1263 (1959).
[2] A. S. Belousov, S. V. Rusakov, E. I. Tamm, and P. A. Čerenkov, Zh. Eksperim. i Teor. Fiz. **37**, 1613 (1959) [translation: Soviet Phys.—JETP **10**, 1143 (1960)].
[3] J. Moffatt, J. J. Thresher, G. C. Weeks, and R. Wilson, Proc. Roy. Soc. (London) **A244**, 245 (1958).
[4] G. Charpak, F. J. M. Farley, R. L. Garwin, T. Muller, J. C. Sens, and A. Zichichi, in *The Proceedings of the 1962 International Conference on High-Energy Physics at CERN* (CERN, Geneva, Switzerland, 1962), p. 476.
[5] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, New York, 1954), 3rd ed., p. 257.
[6] W. Pauli and V. Weisskopf, Helv. Phys. Acta **7**, 709 (1934).
[7] Yongduk Kim, Phys. Rev. **126**, 345 (1962).

The particles produced at an angle of 30° to the target were observed with a mass-sensitive detector and examined for the occurrence or nonoccurrence of submuon masses. The nonoccurrence at the predicted intensities for submuon production was interpreted as showing that sub-muons do not occur in nature. The mass-sensitive detector used the following principle. If a beam of particles of given momentum traverses a block of material and ionization is the dominant energy loss mechanism, the range increases monotonicly as the rest mass of the particle decreases. Electrons simultaneously produced will not proceed through several radiation lengths of material because they lose energy more rapidly by radiation than by ionization and thus have small penetrating power. Any particle that penetrates to a range greater than the muon range will have a mass less than that of the muon. Our experiment apparatus consisted of an accurate momentum defining magnetic spectrometer followed by a range telescope. No particles corresponding in range penetration to masses 175 m_e or less were observed.

PROCEDURE

The incident photon beam was obtained by bombarding a $\frac{31}{32}$-in.-thick (0.093 radiation length) block of carbon with an 800-MeV electron beam from the Stanford Mark III Linear Electron Accelerator. This same block served as the target for the photoproduction process. The electron beam was collimated to $\frac{1}{4}$-in. diam and momentum selected for 1% full width at half-maximum. The beam current was measured by a secondary emission monitor.

The momentum of the secondary particles was determined by using the double-focusing, zero-dispersion magnetic spectrometer described in detail elsewhere.[8] This spectrometer analyses the momentum twice and has a high rejection for off-momentum particles. The momentum chosen was 300 MeV/c, the maximum momentum for the spectrometer. The maximum value was chosen to obtain the best discrimination against electron showers. The spectrometer was positioned at 30 deg to the bremsstrahlung beam so that the predicted submuon counting rate would be high and the electron and photon beams would not hit the spectrometer.

The solid angle of the spectrometer was determined by a 2-in.-thick lead mask placed between the target and the front of the spectrometer. The momentum acceptance of the spectrometer was determined by a set of slits located between the two halves of the spectrometer. The solid angle was 2.46 msr with the slits set to allow a momentum acceptance (dp/p) of 4%.

The particles traversing the spectrometer were detected by a six counter telescope in which the counters were separated by various thicknesses of lead. A six counter telescope was chosen to give positive identification to any particle traversing the telescope and to cut down accidental coincidences. Lead was chosen as the absorber material to provide a large number of radiation lengths and thus to absorb the showers produced by the incident electrons or positrons. The telescope is shown in Fig. 1. Counters 1, 2, and 3 were 3 in.×3 in. in area, counters 4 was 4 in.×4 in., and counters 5 and 6 were 5 in.×5 in. The counters were all made of $\frac{1}{4}$-in.-thick plastic scintillator connected by lucite light pipes to RCA 6810A photomultiplier tubes.

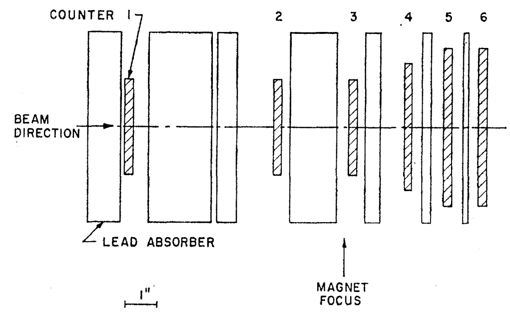

FIG. 1. Section view of the counter telescope containing 6 in. of lead.

The signals from the photomultiplier tubes passed through variable attenuators and delay boxes before entering two three-channel coincidence circuits. These were of the Wenzel type[9] and had resolving times of 5 nsec. Counters 1, 3, and 6, and counters 2, 4, and 5 were each put in triple coincidence. The two coincidence outputs were put through a slow coincidence circuit with resolving time of 30 nsec giving a sixfold coincidence. The two threefold outputs as well as the sixfold output were counted. The circuitry was such that any coincidence from onefold to sixfold could be measured by switching in or out the appropriate channels.

The experiment proceeded in three stages. First the telescope containing all six counters but no lead was calibrated with minimum-ionizing particles, 300 MeV/c electrons scattered from air into the spectrometer. The attenuators were set 6 dB lower than the settings at which they just began to cut into the counting rate.

Second, the carbon target was put in the beam and the electron shower background was studied as a function of absorber thickness. With 6 in. of lead in the telescope and a sixfold counter coincidence, a rejection ratio of better than 2×10^7 for electron showers traversing the telescope was obtained. Thus the background due to electron showers with 6 in. of lead in the telescope was negligible.

Finally, the primary electron energy was raised to 800 MeV and the spectrometer set for positive particles at 300 MeV/c. Positive momentum was chosen because positrons were not expected to be as abundant as electrons. A small amount of lead in front of the first

[8] R. Alvarez, K. L. Brown, W. K. H. Panofsky, and C. T. Rockhold, Rev. Sci. Instr. **31**, 556 (1960).

[9] University of California Lawrence Radiation Laboratory Counting Handbook Report No. UCRL-3307 Rev., 1959, File No. CC3-9A (unpublished).

counter of the telescope stopped the protons that traversed the spectrometer. The final telescope arrangement is shown containing 6 in. (174.0 g cm^{-2}) of lead in Fig. 1. With 6 in. of lead, the muons stopped just short of counter 4.

An absorber curve was run by adding or subtracting various amounts of lead from the telescope. The pion and then the muon counts disappeared as more lead was inserted in the telescope. Because of range straggling, 6 in. of lead were required to insure that no muons could traverse the telescope. We looked for submuons penetrating beyond this range for many hours. Every hour the singles rates in the counters and the coincidence circuits were checked. Every 4 or 5 h the attenuator settings were checked by removing all lead except the first 1-in. block from the telescope and by using the pions for calibration. The counter delays were checked at this time. No variations were found.

Some data were taken with the spectrometer set for negative particles of 300 MeV/c. Despite a rise in the singles rates in the first two counters indicating as many electrons as pions traversing the spectrometer, the absorber curve was similar to that obtained with positive particles. With 6 in. of lead in the telescope we looked for penetrating negative particles for about 2 h and observed one count. This was consistent with the data taken with positive particles. Most of the data were taken with positive particles to avoid the higher singles rates associated with negative particles. A total of four sixfold coincidences were observed with 6 in. of lead in the telescope in a period of 12 h. This counting rate is consistent with the rate caused by fast neutron background and that caused by muons decaying into electrons in the forward direction within the resolving times of the coincidence circuits.

RESULTS AND DISCUSSIONS

The experimental data are listed in Table II. The additional absorber due to the first five counters in the telescope has been added to the amount of lead in the telescope under the assumption that the stopping power of plastic scintillator relative to lead is 1.5.

TABLE II. Experimental data. The data have been reduced to counts/10^{17} incident electrons.

Counts/10^{17} incident electrons	Lead (g cm^{-2})	Lead+counters (g cm^{-2})
$(2.356\pm0.036)\times10^6$	29.5	34.5
$(1.980\pm0.057)\times10^6$	43.6	48.6
$(1.815\pm0.055)\times10^6$	58.6	63.6
$(1.375\pm0.048)\times10^6$	72.7	77.7
$(1.206\pm0.044)\times10^6$	87.0	92.0
$(1.133\pm0.043)\times10^6$	101.8	106.8
$(7.63\ \pm0.25)\ \times10^5$	115.9	120.9
$(3.181\pm0.073)\times10^5$	123.4	128.4
$(8.45\ \pm0.37)\ \times10^4$	130.2	135.2
$(4.78\ \pm0.28)\ \times10^4$	137.7	142.7
$(3.30\ \pm0.23)\ \times10^4$	145.4	150.4
$(1.21\ \pm0.07)\ \times10^4$	152.9	157.9
3135 ± 715	155.8	160.8
631 ± 95.3	159.9	164.9
18.4 ± 18.4	167.3	172.3
4.10 ± 2.05	174.0	179.0

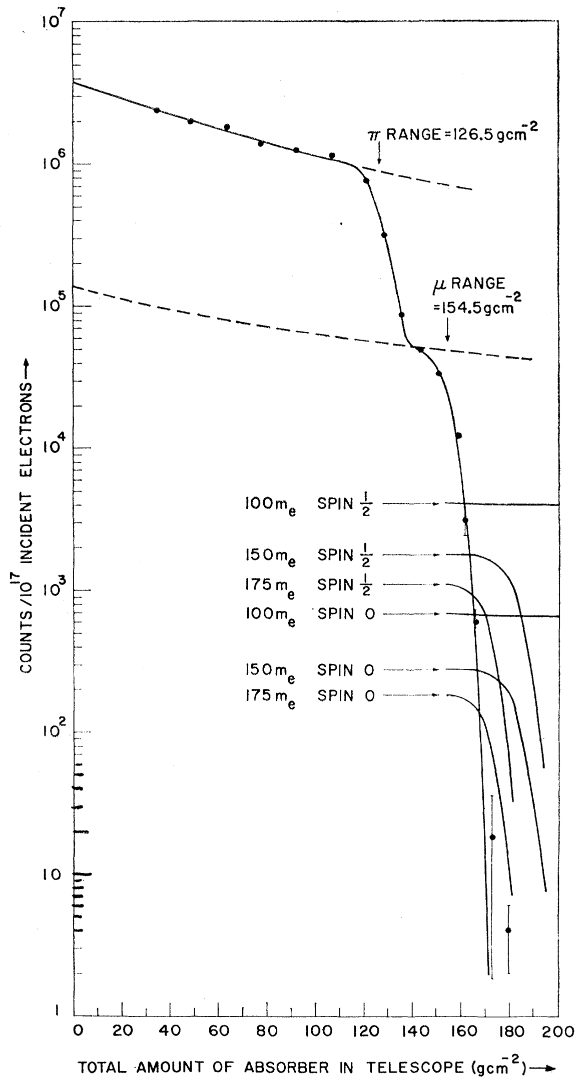

FIG. 2. Plot of experimental data. The curve is a visual fit to the data for absorber thicknesses less than 154.5 g cm^{-2} (experimental muon range). For thicknesses greater than 154.5 g cm^{-2} the curve is a plot of the muon integral range distribution using the straggling parameter given in the text. The counting rate for muons versus absorber thickness and corrected for multiple scattering is given by the lower dashed curve. The predicted range curves for spin-$\frac{1}{2}$ and spin-0 submuons with rest masses of 175, 150, and 100 m_e are also shown.

The experimental results for counting rates versus range are plotted in Fig. 2. The data exhibit the form of a typical integral range curve, the first inflection occurring at the pion range and the second inflection at the muon range. The pions were photoproduced from the carbon target, and the muons mainly came from pions that decayed in flight.

After correcting for the nuclear absorption of π

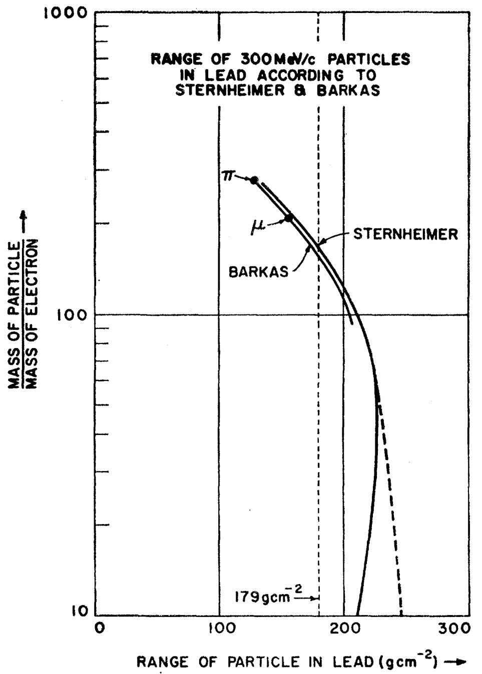

FIG. 3. Range of 300-MeV/c particles in lead. The solid lines show the predictions of Barkas and Sternheimer. The dashed line represents an extrapolation to the asymptotic range of a zero-mass ($\beta=1$) particle and is probably a better approximation for the range of low-mass particles than the predictions of Sternheimer.

mesons by using a geometrical absorption mean free path of 218 g cm^{-2} of lead, and allowing for multiple-scattering losses from the telescope, Gaussian range straggling distributions were fitted to the data giving the following parameters.

Pion range: 126.5 g cm^{-2}

Muon range: 154.5 g cm^{-2}

Pion range straggling parameter: 4.9 g cm^{-2}

Muon range straggling parameter: 4.8 g cm^{-2}.

These ranges are in excellent agreement with the Barkas range-energy tables.[10] Corrections for range foreshortening due to multiple scattering were calculated and were about 2%.

The range of 300-MeV/c particles is plotted as a function of the rest mass of the particles in Fig. 3. The dashed portion of the curve represents an extrapolation to the asymptotic range of a zero-mass (i.e., $\beta=1$) particle. This range is calculated by assuming that the particle has the plateau ionization derived by Fermi,[11] until the end of its range. This is a better approximation to the range for low-mass particles than the results of Sternheimer.[12]

Predicted integral-range curves are plotted for 175 and 150 m_e particles with spin 0 and spin $\frac{1}{2}$ in Fig. 2. Multiple-scattering losses in the telescope were taken into account. A Gaussian distribution in range straggling has been assumed and the range-straggling results of Sternheimer[13] have been used to calculate the theoretical range-straggling parameters.

175 m_e range-straggling parameter: 5.4 g cm^{-2}

150 m_e range-straggling parameter: 6.25 g cm^{-2}.

The predicted intensities were calculated from the appropriate theoretical formulas.[5–7] The effect of the nucleus was treated by a simple sum rule approximation.[14] In this approximation the pair production cross section as far as the nucleus is concerned scales as $Z^2F^2(q^2)+Z(1-F^2(q^2))$, where Z is the nuclear charge of the target material and $F(q^2)$ is the elastic-scattering form factor associated with the nucleus as a function of the square of the four-momentum transferred, q^2. The first term is the elastic coherent contribution and the second term represents the inelastic contribution. The carbon elastic scattering form factor used was that determined by Hofstadter.[15] The integration over the coordinates of the unobserved particles and the fold over the bremsstrahlung distribution were performed on a Borroughs-220 computer.

The experimental results are compared with the predicted intensities in Fig. 2 and definitely rule out spin-0 and spin-$\frac{1}{2}$ particles with masses in the range 5 to 175 m_e.

The lower limit of 5 m_e arises in the following way. As the mass decreases, the radiation probability increases, and at some point a low-mass particle will not traverse the 179 g cm^{-2} of absorber due to radiation losses. Neglecting the small rest mass, low-mass particles of 300 MeV/c momentum will have a kinetic energy of 300 MeV. Such particles will lose 220 MeV of energy by ionization in traversing the absorber. Hence, by calculating the probability that a given mass will radiate less than 80 MeV while traversing the 179 g/cm^2 of lead we obtain a lower mass limit. The formulas in Heitler[16] predict that a particle of mass 5 m_e has a 10% chance of traversing the telescope and a particle of mass 12 m_e has an 80% chance.

If a submuon existed with a short life it could escape observation by decaying in flight. Table III, column 2 lists the expected number of counts that should have been observed with 179.0 g cm^{-2} of absorber in the telescope, if the submuons had a long lifetime. The half life of the submuons necessary to reduce the expected number of counts to the observed four is listed in Table III.

[10] W. H. Barkas, University of California Lawrence Radiation Laboratory Report No. UCRL-10292, 1962.

[11] E. Fermi, Phys. Rev. **57**, 485 (1940).

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[14] S. D. Drell and C. L. Schwartz, Phys. Rev. **112**, 568 (1958).

[15] R. Hofstadter, Ann. Rev. Nucl. Sci. **7**, 231 (1957).

[16] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, London, England, 1954), 3rd ed., p. 379.

TABLE III. The second column lists the predicted counting rates for production of submuons for a time in which four counts were actually observed. Column 3 lists the half-lives necessary to reduce the predicted rates to the observed rate of 4 counts. The total amount of absorber in the telescope was 179.0 g cm^{-2} of lead. The ranges listed for 175, 150, and 100 m_e particles were calculated from Barkas.[11] The other ranges were taken from the dashed curve of Fig. 3.

Submuon mass (m_e)	Predicted number of counts/10^{17} incident electrons	Half-life of submuons to give 4 counts (10^{-10} sec)	Predicted range in lead (g cm^{-2})
	(a) Spin-$\frac{1}{2}$ submuons:		
175	70	22	170.7
150	1200	9.4	182.2
100	3980	5.2	204.0
50	8410	2.3	227
25	12 500	1.1	236
	(b) Spin-0 submuons:		
175	10	68	170.7
150	190	14	182.2
100	660	7.0	204.0
50	1690	3.0	227
25	2870	1.4	236

CONCLUSIONS

The results of this experiment rule out any but very short-lived singly charged particles in the mass range 5−175 m_e. This result, plus the theoretical results on the vacuum polarization described in the introduction make it unlikely that charged particles with rest mass between that of the electron and muon exist.

ACKNOWLEDGMENTS

We appreciate the help given us by all of the staff members of the High-Energy Physics Laboratory, especially John Grant, Lynn Boyer, Eddie Wright and members of the machine shop, and Dr. Perry Wilson and members of the accelerator crew. We are indebted to Dr. W. K. H. Panofsky for helpful suggestions. Our theoretical understanding of the experiment was helped by discussions with Dr. Sam Berman, Dr. S. D. Drell, and Dr. Y. S. Tsai.

PHYSICAL REVIEW VOLUME 131, NUMBER 4 15 AUGUST 1963

Range of Very High-Energy Nucleon-Nucleon Collisions*

FREDA SALZMAN
University of Colorado, Boulder, Colorado
(Received 29 March 1963)

The range of the chain-of-pions interaction is calculated for very high-energy nucleon-nucleon collisions in an approximation which does not require a complete dynamical description of the process. It is assumed that the chain-of-pions interaction is a primary process whose amplitude is not derived from that for "low-energy" processes. The interaction is described by two parameters, the average minimum-momentum transfer Δ_0 and the average fireball mass m_0. Certain results can be expressed in terms of Δ_0 and m_0 alone and are generally valid for all "linked-peripheral" models. In particular, if Δ_0 and m_0 are constant, then the inelasticity is constant, the number of fireballs is proportional to $\ln(s/M^2)$, where $s^{1/2}$ is the total barycentric energy, and the multiplicity is also proportional to $\ln(s/M^2)$. The chain-of-pions interaction in which the nucleons remain unexcited, N-N final states, is expected to be the most important process for small Δ_0 because of the considerably larger phase space available for it compared to that for isobar production. Thus, N-N final states give rise to the longest range part of the interaction and are estimated to make a larger contribution to the cross section than states in which even the $\frac{3}{2}$-$\frac{3}{2}$ pion-nucleon isobar is produced. An additional result is that the iterated dominant "low-energy" pion-exchange model gives a nucleon-nucleon cross section of at most several mb if only low values of the momentum transfer of one of the nucleons or isobars are allowed. With the approximations used, it is then possible to calculate the long-range part of the elastic diffraction scattering amplitude in the almost transparent, purely absorbing, optical approximation. We obtain the Regge behavior in the limit of a large number of fireballs. At incident nucleon laboratory energy $E_L=10^3M$, the amplitude has not yet reached the asymptotic limit. For $\Delta_0^2=5m_\pi^2$ and $m_0=2M$, one finds that the inelasticity is $\frac{1}{3}$, the number of "fireballs" is two, and the range is in close agreement with that given by the one-pole elastic Regge amplitude with $\alpha'=1/M^2$. Finally, it is found that the nucleons which emerge unexcited in the final state lie within a cone whose angular width decreases with energy at a rate such that the transverse momentum P_T also decreases and $P_T\propto(\ln s)^{-1/2}$. This behavior is correlated to the shrinking of the elastic diffraction peak but is apparently in disagreement with high-energy events.

I. INTRODUCTION

IN many high-energy nucleon-nucleon collisions it is observed that the final-state particles have very small transverse momenta and that the secondary particles, mainly pions, appear to be produced in one or more groups called "fireballs."[1,2] It seems reasonable

* Supported in part by a grant from the National Science Foundation.

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[2] A recent review of the data is given by D. H. Perkins, in *Proceedings of the International Conference on Theoretical Aspects of Very High-Energy Phenomena* (CERN, Geneva, 1961), p. 99.