

square of the missing mass of the π^0 in those events which were identified as satisfying the hypothesis (2) at 1090 MeV. Since it shows no peaking in the vicinity of zero, it appears that only about two or three events in this class of identifications could be $\pi^+ + p \rightarrow \pi^+ + \pi^+ + \pi^- + \gamma$. An appreciable number of (π^+, π^-, γ) decays could presumably hide in the large reservoir of identifications of Reaction (1). To set an upper limit on this number we have computed the missing mass $(\pi^+, \pi^-, ?^0)$ carried away by all the secondaries other than the proton and one π^+ . Figure 3(a) shows this missing mass spectrum for 1090 MeV, with the spectrum of effective mass (π^+, π^-) inserted as a control. The computation was performed upon the measured track momenta and angles, not upon the adjusted values obtained by the kinematic fitting process. If these events are indeed correctly identified as Reaction (1), the missing-mass and effective-mass histograms should agree closely. On the other hand, contamination of the sample by $\pi^+ + p \rightarrow p + \pi^+ + \eta^0$ with the eta subsequently decaying to (π^+, π^-, γ) would produce a sharp peak at 550 MeV in the spectrum of missing mass $(\pi^+, \pi^-, ?^0)$ but not in the spectrum of effective mass (π^+, π^-) . Figure 3(a) shows close agreement between the histograms, and it is very unlikely that 20 (π^+, π^-, γ) decays in the region of about 540 to 560 MeV would be masked by background fluctuations. Finally, the class of unidentified four-prong events contains only about four events whose missing mass $(\pi^+, \pi^-, ?^0)$ is consistent with the mass of the eta and they represent part of a continuous background. We conclude that the ratio of the (π^+, π^-, γ)

decay to the charged three-pion decay (π^+, π^-, π^0) is less than 25%. Our estimate is probably too conservative, since we expect a larger fraction of events $\pi^+ + p \rightarrow p + \pi^+ + \pi^+ + \pi^- + \gamma$ to end up in the category of unidentified events. A closer examination of the question of kinematical ambiguities in Reactions (1) and $\pi^+ + p \rightarrow p + \pi^+ + \pi^+ + \pi^- + \gamma$ is likely to reduce our estimate of the relative decay rates of the eta meson.

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¹A. Pevsner, R. Kraemer, M. Nussbaum, C. Richardson, P. Schlein, R. Strand, T. Toohig, M. Block, A. Engler, R. Gessaroli, and C. Meltzer, *Phys. Rev. Letters* **7**, 421 (1962).

²P. Bastien, J. P. Berge, O. I. Dahl, M. Ferro-Luzzi, D. H. Miller, J. J. Murray, A. H. Rosenfeld, and M. B. Watson, *Phys. Rev. Letters* **8**, 114 (1962).

³T. D. Lee and C. N. Yang, *Nuovo cimento* **3**, 749 (1956).

⁴H. Foelsche, E. C. Fowler, H. L. Kraybill, J. R. Sanford, and D. Stonehill, presented by J. Sandweiss to the Annual International Conference on High-Energy Physics at CERN, 1962 (to be published).

⁵E. Pickup, D. K. Robinson, and E. O. Salant, *Phys. Rev. Letters* **8**, 329 (1962).

⁶M. L. Stevenson, L. W. Alvarez, B. C. Maglić, and A. H. Rosenfeld, *Phys. Rev.* **125**, 687 (1962).

PHOTOPRODUCTION OF MUON PAIRS IN CARBON

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Evidence for muon-pair photoproduction in nuclei was given in a pioneering work by Masek and Panofsky,¹ who succeeded in separating one member of the pair from a large background of pions and electrons. We report here on an experiment in which coincidences between the two muons have been detected, at a rate in perfect agreement (within our 5% accuracy) with that deduced from the Bethe-Heitler formula.²

A drawing of the experimental apparatus is

shown in Fig. 1. The 1000-MeV bremsstrahlung beam of the Frascati Electron Synchrotron was collimated into a 2-cm diameter spot to strike a carbon target of 5 cm in length (8.8 g/cm²). Positive muons emitted at 10° in the momentum interval from roughly 300 to 400 MeV/c were deflected by a double-focussing magnetic spectrometer³ to traverse one of the three momentum-defining scintillation counters α , β , and γ , and two wedge-shaped copper absorbers. After

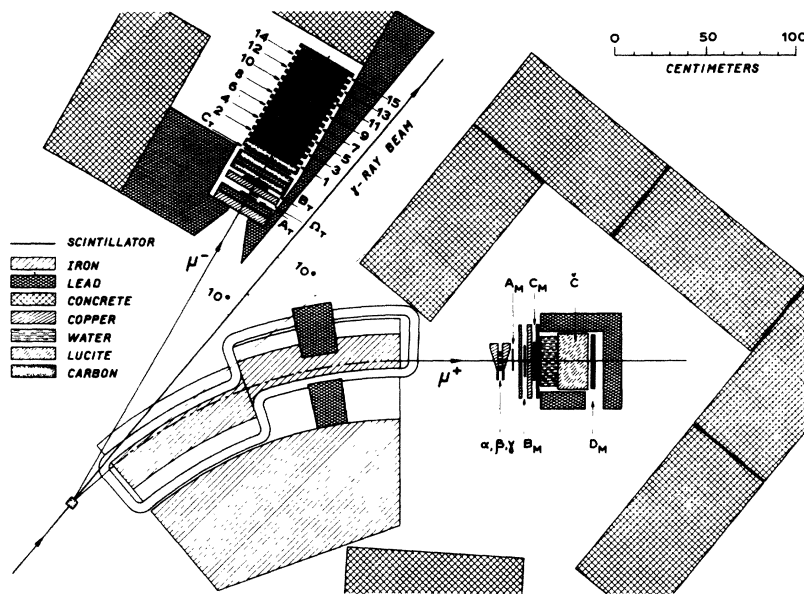


FIG. 1. A drawing of the experimental apparatus.

emerging, approximately monochromatic, from the wedges, the muons produced a fourfold coincidence in scintillators A_M , B_M , C_M , and D_M , and gave Čerenkov light in the water + Lucite counter \check{C} . Pions, on the other hand, were slowed down to about the Čerenkov threshold by copper absorbers. At 10° on the opposite side of the photon beam, negative muons with momentum larger than $446 \text{ MeV}/c$ produced the coincidence $(A_T, B_T, C_T, 1)$ and then came to rest into a range telescope composed of fourteen $30 \times 30 \times 1\text{-cm}^3$ scintillators spaced by carbon layers of 2.3-cm thickness (4.9 g/cm^2). A system of 14 double coincidences (obtained by letting each counter in the telescope make a coincidence with the next) was connected to a hodoscope of 14 indicator lights to give the end point of the muon. This same system of double coincidences, connected through a delayed gate to a second 14-light hodoscope, detected the muon decay electron, and will later enable us to verify the spatial correlation of the two events. The presence or absence of a pulse in counter Ω_T indicated which half of the solid angle the negative muon had traversed, thus improving the angular resolution.

A master coincidence between the outputs of (A_M, B_M, C_M, D_M) and $(A_T, B_T, C_T, 1)$ triggered the sweep of a four-trace oscilloscope. We displayed pulses from counters α , β , and γ on its second trace, pulses from C_T and C_M on the third, and pulses from D_M , \check{C} , and Ω_T on the

fourth. On its first trace, a pulse from the electron gave the time interval between the muon arrival and its decay. Finally, the oscilloscope and hodoscope patterns of each event were both recorded on the same photogram.

The information from the two hodoscopes will eventually permit us to discriminate against pion or electron counts in the telescope, and measurements of the pulse height in \check{C} and D_M enable us to eliminate the surviving background of pion pairs which succeed, through decay, in sending a negative muon into the telescope. On the other hand, owing to loss of muons through scattering out of the telescope, a complete analysis of our data must include a Monte Carlo calculation of our detection efficiency. This is under way, and we present in this note only an alternative analysis in which results from the hodoscopes are not taken into account.

Figure 2 shows the distribution of the time separating the pulses C_T and C_M . Its sharp peak, due to pairs of particles produced in a single elementary act, rises above a background of accidentals showing the expected effect of bunching produced by the synchrotron radio frequency. After subtracting this background, we must correct our data for pairs of pions (plus their decay muons) and for pairs of electrons. To this end, we compared the combined \check{C} and D_M pulse-height distribution for our events with the corresponding distributions for electrons and pions. The distribution for the latter was taken with the

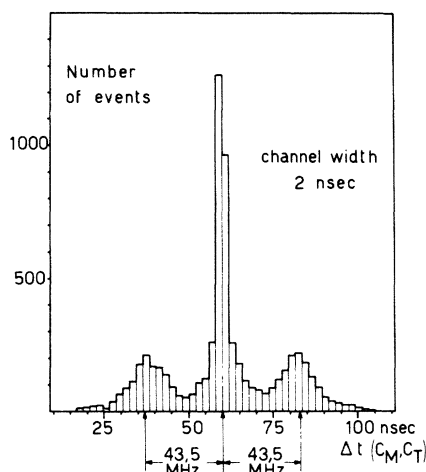


FIG. 2. Timing between pulses from C_T and C_M . The value 43.5 MHz is that of the synchrotron radio frequency.

magnet located at 30° , where counts from electrons or electromagnetic muons are negligible, and the distribution for electrons was taken at 10° with a lead converter increasing the number of electrons in the primary beam. Roughly speaking, pions plus their decay muons give a broad spectrum in \check{C} , while electrons give a broad spectrum in D_M ; on the contrary, the distribution for electromagnetic muons, obtained at 30° by simulating them with pions of appropriate momentum, shows well-defined peaks in both these counters (see Fig. 3). More precisely, we divided our events into three groups: (1) events with D_M pulse height smaller than 4 mm, (2) events with D_M at least 4 mm but \check{C} smaller than 4 mm, and (3) events with both D_M and \check{C} at least 4 mm, and we could show that 98.4% of the electromagnetic muons are in the last group. In it we had 1695 events—collected at a rate of about one every six minutes—and we learned from the other two groups that 42 of these events were electrons and 252 were pions and decay muons.

Table I shows our results, in the form of ratios of the absolute experimental cross sections to the theoretical. To obtain the latter, the Bethe-Heitler proton cross sections were first corrected for the carbon form factor⁴ and for inelastic processes according to the formula⁵ $\sigma_C = \sigma_{BH}[Z^2 F^2 + Z(1 - F^2)]$. They were then integrated over the μ^+ and μ^- solid angles and over the bremsstrahlung spectrum. Folded into the integrals were the resolution curves of the spectrometer, as obtained by extrapolating alpha-

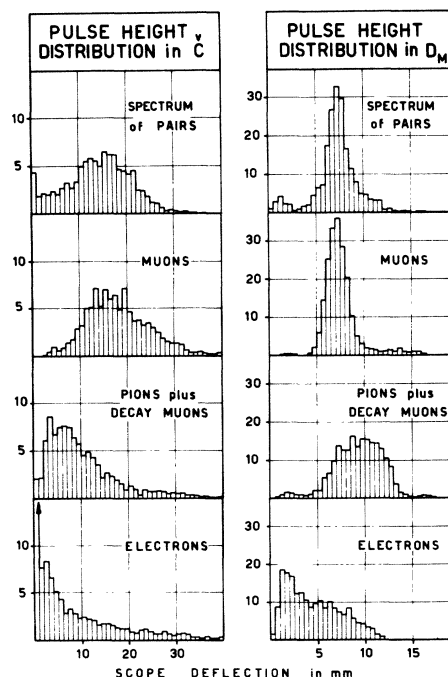


FIG. 3. Pulse-height distributions in D_M and \check{C} obtained under different experimental conditions as explained in the text.

particle calibration measurements³ to our field setting, which was well below saturation. Not included in the calculation were radiative corrections (estimated by Bjorken *et al.*⁶ to be less than 1.5%), Coulomb interaction corrections of the final states, and nuclear recoil effects. The errors quoted in the table are statistical; we estimate other uncertainties in the experimental cross sections (coming mainly from beam calibration and the bremsstrahlung spectrum) to be less than 2%.

Differences from unity in the six ratios shown are hardly significant: The overall average gives 1.00 ± 0.05 . Assuming this error, and taking into account the range of variation of the four-momentum transfer q to the virtual muon (135–185 MeV/c), we conclude that no anomalous behavior

Table I. Ratios of the experimental to the theoretical cross sections for the three momentum channels of the μ^+ and for the two angular channels of the μ^- .

$\frac{\sigma_T}{\bar{F}_M}$	329 MeV/c	360 MeV/c	393 MeV/c
9.3°	0.88 ± 0.13	0.90 ± 0.09	1.04 ± 0.10
10.7°	0.99 ± 0.15	1.15 ± 0.10	1.11 ± 0.10

is observed, within 5% accuracy, down to a distance $\hbar/q = 1.2 \times 10^{-13}$ cm. For those who believe in cutoff theories, we may, of course, push this value further, and set, with 95% confidence, a limit of 2×10^{-14} cm for a cutoff in the virtual muon propagator.⁷ Accordingly, we confirm the well-known result that a group⁸ at CERN has recently obtained by means of a highly accurate measurement of the muon magnetic moment. Finally, the total energy of the two muons in their center of mass ranged from 240 to 290 MeV, and we exclude from this interval muon-muon interaction effects larger than 5%. Effects due to possible leptonic decays of the ω^0 and η^0 particles,⁹ or to the σ^0 meson conjectured by Schwinger,¹⁰ may be observed at higher energies. We are planning an experiment to explore these higher masses, and ranges of higher momentum transfers.

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¹G. Masek and W. Panofsky, Phys. Rev. **101**, 1094 (1956); G. Masek, A. Lazarus, and W. Panofsky, Phys. Rev. **103**, 374 (1956).

²W. Heitler, Quantum Theory of Radiation (Oxford University Press, New York, 1954), 3rd ed., p. 257.

³G. Sacerdoti and L. Tau, Nuclear Instr. and Meth. (to be published).

⁴R. Hofstadter, Ann. Rev. Nuclear Sci. **7**, 231 (1957). Our momentum transfer to the carbon nucleus ranged from 40 to 90 MeV/c, thus F^2 from 0.93 to 0.76.

⁵Inelastic corrections, given by the second term, are of the order of 3%.

⁶J. D. Bjorken, S. D. Drell, and S. C. Frautschi, Phys. Rev. **112**, 1409 (1958).

⁷J. D. Bjorken and S. D. Drell, Phys. Rev. **114**, 1362 (1959); S. Drell, Ann. Phys. **4**, 75 (1958). Criticisms of cutoff theories are found also in R. Feynman, Theory of Fundamental Processes (W. A. Benjamin, New York, 1961), p. 145.

⁸G. Charpak, F. Farley, R. Garwin, J. Sens, V. Tellegdi, and A. Zichichi, Phys. Rev. Letters **6**, 128 (1961).

⁹Y. Nambu and J. Sakurai, Phys. Rev. Letters **8**, 79 (1962).

¹⁰J. Schwinger, Ann. Phys. **2**, 407 (1957).

PROPERTIES OF THE Ξ^- HYPERON*

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The purpose of this note is to report a determination of the properties of the Ξ^- hyperon. In particular, we discuss the mass, lifetime, spin, space, and decay parameters based on a sample of 85 cascades, 74 of which have a visible Λ decay.

The data for this experiment were obtained as part of a continuing study of the K^-p interaction in the 2- to 3-BeV/c range.¹ About 70 000 pictures at 2.3 BeV/c and ~30 000 at 2.5 BeV/c were obtained in a separated K^- beam² at the Brookhaven AGS. Both counter and chamber studies indicate that the beam is composed of

K 's, μ 's, and π 's in the ratio 7.5:2.0:0.5 to an accuracy of ~5%. The sample chosen for analysis consists of all the cascades with a visible Λ decay, and a subsample of cascades without visible Λ decay selected in an unbiased way from a group of completely analyzed events.

The cascade hyperons were produced in the following reactions:

$$K^- + p \rightarrow \Xi^- + K^+, \quad (1)$$

$$K^- + p \rightarrow \Xi^- + K^+ + \pi^0, \quad (2)$$

$$K^- + p \rightarrow \Xi^- + K^0 + \pi^+, \quad (3)$$