previously, the $\pi^- + p$ and $\pi^+ + p$ elastic-scattering curves show little or no Regge-pole-type shrinkage compared to the $p + p$ elastic-scattering curves.

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[1] K. J. Foley, S. J. Lindenbaum, W. A. Love, S. Ozaki, J. J. Russell, and L. C. L. Yuan, Phys. Rev. Letters 10, 376, 543 (1963).

[2] S. J. Lindenbaum, W. A. Love, J. A. Niederer, S. Ozaki, J. J. Russell, and L. C. L. Yuan, Phys. Rev. Letters 7, 185 (1961).

[3] S. J. Lindenbaum, W. A. Love, J. A. Niederer, S. Ozaki, J. J. Russell, and L. C. L. Yuan, Phys. Rev. Letters 7, 362 (1961).

[4] G. von Dardel, D. Dekkers, R. Mermod, M. Vivargent, G. Weber, and K. Winter, Phys. Rev. Letters 8, 173 (1962).

[5] S. Brandt, V. T. Cocconi, D. R. O. Morrison, A. Wroblewski, P. Fleury, G. Kayas, F. Muller, and C. Pelletier, Phys. Rev. Letters 10, 413 (1963).

[6] A. N. Diddens, E. Lillethun, G. Manning, A. E. Taylor, T. G. Walker, and A. M. Wetherell, Phys. Rev. Letters 9, 108 (1962).

[7] Do In Seb, L. F. Kirillova, P. K. Markov, L. G. Popova, I. N. Silin, E. N. Tsyganov, M. G. Shafranova, B. A. Shakhbazyan, and A. A. Yuldashev, Zh. Eksperim. i Teor. Fiz. 41, 1748 (1961) [translation: Soviet Phys.-JETP 14, 1243 (1962)].

[8] B. Cork, W. A. Wenzel, and C. W. Causey, Jr., Phys. Rev. 107, 859 (1957).

[9] G. Czapek, G. Kellner, and H. Pietschmann, Phys. Letters 1, 226 (1962).

[10] Wang Kang-Ch'ang, Wang Ts'U-Chieng, Ting Ta-Ts'ao, V. G. Ivanov, Yu. V. Katyshev, E. N. Kladnitskaya, L. A. Kulyukina, Nguyen Dinh Ty, A. V. Nikitin, S. Z. Otvinovskii, M. I. Solov'ev, R. Sosnovskii, and M. D. Shafranov, Zh. Eksperim. i Teor. Fiz. 38, 426 (1960) [translation: Soviet Phys.-JETP 11, 313 (1960)].

[11] V. A. Bull and D. A. Garbutt, Phys. Rev. 130, 1182 (1963).

[12] V. G. Grishin, Proceedings of the International Conference on Nucleon Structure, Stanford, California, 24-27 June 1963 (unpublished).

[13] Several experiments have measured cross sections in the region where Coulomb interference with a real amplitude should be important. At 3.7 BeV/c, Preston et al. [W. M. Preston, Richard Wilson, and J. C. Street, Phys. Rev. 118, 579 (1960)] limited the real amplitude at <10% of the imaginary. Grishin (reference 6) at 7 and 11 BeV/c finds a real part about half the imaginary.

DOUBLE-HYPERFRAGMENT EVENT PRODUCED BY K^- INTERACTION AT 2.3 BeV/c IN NUCLEAR EMULSION*

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A camera lucida[1] drawing of an event is shown in Fig. 1, which consists of two hyperfragments and a K^+ meson, coming from a single beam interaction star. This event was found in an area scan of 54 201 beam stars in a stack of Ilford K-5 nuclear emulsions exposed to 2.3-BeV/c K^- (80%) and 2.5-BeV/c K^- (20%) at the Brookhaven AGS.[2] Presumably the primary particle is a K^- meson.[3]

The hyperfragments decay at rest at A and B with ranges 319 microns and 2820 microns, respectively, and the angle between them is 166°. The emission angles, taken with respect to the direction of the primary, are 90° for A, and 79° for B. The K^+ meson comes to rest at C after a range of 19.6 millimeters and decays via the $K_{\mu 3}$ mode. The μ^+ stops after 40 millimeters giving rise to a clearly visible positron.

The A hyperfragment decays via the $\pi p r$ mode; the decay π^- is identified by the capture star it produces at F. Owing to the small recoil range and inferred momentum (1 micron, 26 MeV/c), a unique identification of the hyperfragment is impossible. However, the binding energy, $B_\Lambda = 1.8 \pm 0.5$ MeV, favors ${}_\Lambda H^4$ or ${}_\Lambda He^4$.[4] Furthermore, the presence of only one δ ray along the hyperfragment track as compared with the expected number four for helium hyperfragments and zero for hydrogen hyperfragments slightly favors the ${}_\Lambda H^4$ identification.[5] Particle data for the A-hyperfragment decay are given in Table I.

The B hyperfragment decays into a π^+ meson and a single dark prong. The π^+ meson decays at rest at D into a μ^+ of range 591 microns. The positron from the μ^+ ending is clearly visible at E. All one- and two-neutron assumptions in the analysis were found to give negative binding energies except for the following:

$${}_\Lambda He^4 \rightarrow \pi^+ + n + H^3, \quad B_\Lambda = 2.0 \pm 0.4 \text{ MeV}; \qquad (1)$$

$${}_\Lambda He^4 \rightarrow \pi^+ + 2n + H^2, \quad B_\Lambda \leq 7.1 \text{ MeV}. \qquad (2)$$

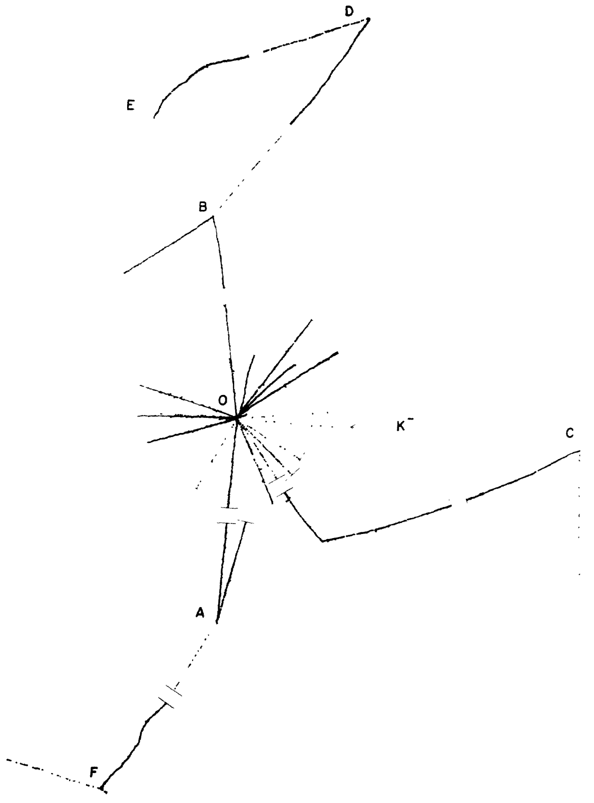

FIG. 1. Camera-ludica drawing of double-hyperfragment event.

The close agreement between the binding energy for scheme (1), and the value (2.40± 0.11 MeV), given by the EFINS-NU binding energy compilation,[4] makes this scheme strongly favored. Several examples of this rare decay mode have been previously reported in emulsion.[6] Particle data for the decay are given in Table II.

The *a priori* probability is small, but not negligible for these hyperfragments to be produced by the normal mechanism in which two Λ particles are produced and are trapped in the target nucleus and later become bound to out-going nuclear fragments. The chance for observing such an event produced by this mechanism in the present experiment is estimated to be about two percent.[7]

Table I. Particle data for hyperfragment *A*.

Prong	Range^a (microns)	Azimuthal angle (degrees)	Dip angle (degrees)
π^-	15 077	0	-24.6
p	248	164.9	+24.6
H^3, He^3	1	297	0

^{a}Normalized to standard emulsion density 3.815 g/cm^3.

Table II. Particle data for hyperfragment *B*.

Prong	Range^a (microns)	Azimuthal angle (degrees)	Dip angle (degrees)
π^+	3790	0	-13
$H^{2,3}$	172	195.7	-10.5

^{a}Normalized to standard emulsion density 3.815 g/cm^3.

A similar event has been reported by Wilkinson *et al.*[8] These authors suggest that their event represents the formation of a short-lived Ξ hypernucleus which subsequently decays into two $_\Lambda H^4$ hyperfragments due to the conversion reaction $\Xi + N \rightarrow 2\Lambda$. Although the conversion reaction is technically fast, they argue that the Ξ hypernucleus lives long enough to decay free of interference from the parent star. Such an explanation could not readily apply to the event reported here.

The kinetic energy in the center of mass of the two-hyperfragment system is 92.3 MeV, if *A* is $_\Lambda H^4$, and 120.9 MeV, if *A* is He^4. On the other hand, the energy release in the corresponding two-body decays of $_\Xi Li^8$ or $_\Xi Be^8$ is about 12 MeV.[9]

The in-flight decay of $_\Xi Li^9$, or $_\Xi Be^9$, into hyperfragments *A* and *B* and a single neutron can also be ruled out. It can be shown that no rest frame exists for the cascade hypernucleus in which the kinetic energy of *A*, *B*, and the neutron does not exceed the 8-MeV decay energy.[9]

Besides the normal mechanism of production discussed above, there remains a possibility that the two hyperfragments come from the decay of a Ξ* hypernucleus.[10,11] Here again the two-body decay and the in-flight three-body decay with a single pion are forbidden in the present event by energy and momentum conservation. However, the in-flight three-body decay with a single neutron is allowed. The corresponding in-flight three-body decay with a single proton is ruled out by the failure to find any proton in the parent star which gives a satisfactory kinematical fit. In attempting to fit these protons, the Ξ* binding energy is required to be positive and no larger than 20 MeV. In every case tried, this binding energy is found to be negative except in one case where the binding energy is 56 MeV.

One cannot, on the bases of the information available in this single event, determine the nature of the production mechanism. Production by the normal mechanism cannot be ruled out, and the only basis for the Ξ^* hypothesis is that it is not forbidden by energy and momentum conservation.

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[1] We are indebted to the Emulsion Group at the U. S. Naval Research Laboratory for making their camera-lucida apparatus available to us.

[2] J. Leitner, G. Moneti, and N. P. Samios, Nucl. Instr. Methods 20, 42 (1963).

[3] The beam composition is $K:\mu:\pi = 7.5:2.0:0.5$ (see reference 9). The chance that the primary particle is a pion is regarded to be small. The total visible energy release in the star, assuming all stable particles to be protons, is 0.95 BeV. On the other hand, the total energy release for a 2.3-BeV/c or 2.5-BeV/c π^- producing two $A = 4$ hyperfragments and two K mesons is approximately 0.9 BeV and 1.1 BeV, respectively.

[4] N. Crayton, R. Levi Setti, M. Raymund, O. Skjeggestad, D. Abeledo, R. G. Ammar, J. H. Roberts, and E. N. Shipley, Rev. Mod. Phys. 34, 186 (1962).

[5] The integrated δ-ray counts up to 319 microns for hydrogen and helium hyperfragments are calibrated with six ${}_{\Lambda}He^4$ and ${}_{\Lambda}He^5$, and three ${}_{\Lambda}H^4$ tracks.

[6] Y. W. Kang et al., Nuovo Cimento 22, 1297 (1961); A. Z. M. Ismail et al., Phys. Letters 1, 199 (1962); P. Allen, Sr., et al., Phys. Letters 3, 274 (1963); S. N. Ganguli et al., Nuovo Cimento 18, 1258 (1963).

[7] The probability per interaction for producing two hyperfragments by the normal mechanism is approximated by the formula

$$P_2 = p_{\Lambda\Lambda}(P_1/p_{\Lambda})^2,$$

where $p_{\Lambda\Lambda}$ is the probability per interaction for producing two Λ particles, and P_1 is the probability per interaction for producing a single hyperfragment. An underestimate for $p_{\Lambda\Lambda}$ of 2×10^{-4} is obtained from observations on K^- interactions in a heavy liquid bubble chamber at 1.5 BeV/c [H. Bingham (private communication)]. The total hyperfragment production rate in our experiment is 2.1%. However, 70% of this rate corresponds to the production of short-range (≤ 5 micron), recoil hyperfragments in which the Λ particle remains trapped inside of the residual target nucleus [see B. D. Jones et al., Phys. Rev. 127, 236 (1962)]. An estimate of P_1, which is more in accord with the nature of this event, is 6×10^{-3}. The mesonic hyperfragment production rate is 1.5×10^{-3}. The single Λ-production probability, p_{Λ}, may be estimated from known elementary cross sections [L. Bertanza et al., Proceedings of the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN Scientific Information Service, Geneva, Switzerland, 1962), p. 284]. The resulting value for P_2 is 4.5×10^{-7}. In arriving at this estimate, no account is taken of the fact that one of the hyperfragments, the B hyperfragment, is emitted with the unusually large momentum of 910 MeV/c, or 227 MeV/c per baryon. Only 5 out of 84 mesonic hyperfragments, in this experiment, are emitted with a momentum per baryon equal to or greater than 225 MeV/c. If this feature of the event is taken into consideration, the value of P_2 is reduced, at least by a factor 0.06.

[8] D. H. Wilkinson, S. J. St. Lorant, D. K. Robinson, and S. Lokanathan, Phys. Rev. Letters 3, 397 (1959). A possible double-hyperfragment event has also been reported by Walter H. Barkas, Nripendra N. Biswas, Donald A. Delise, John N. Dyer, Harry H. Heckman, and Francis M. Smith, Phys. Rev. Letters 2, 466 (1959).

[9] The masses of the Ξ hypernuclei are computed assuming the core nuclei to be in their ground states and the binding energies of Ξ hyperon to be zero. The cascade mass, $M_{\Xi^-} = 1321$ MeV, is taken from L. Bertanza, V. Brisson, P. L. Connolly, E. L. Hart, I. S. Mittra, G. C. Moneti, R. R. Rau, N. P. Samios, I. O. Skillicorn, S. S. Yamamoto, M. Goldberg, L. Gray, J. Leitner, S. Lichtman, and J. Westgard, Phys. Rev. Letters 9, 229 (1962).

[10] G. M. Pjerrou, D. J. Prowse, P. Schlein, W. E. Slater, D. H. Stork, and H. K. Ticho, Phys. Rev. Letters 9, 114 (1962).

[11] L. Bertanza et al., Phys. Rev. Letters 9, 180 (1962).