Production of Hyperfragments from the Interactions of 800-MeV/c K^- Mesons with Emulsion Nuclei*

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A study has been made of the production of hyperfragments by the interactions of 800-MeV/c K^- mesons in nuclear emulsion. The frequency of production, estimated to be 5.3±0.3%, is about the same as for K^- mesons at rest. The hyperfragments are emitted predominantly in the forward direction and the ratio of nonmesonic to mesonic decays has been found to be 11.5±0.6, much greater than for K^- mesons at rest. The proportion of hyperfragments of short range (range in emulsion $<5\,\mu$) is also much greater. These and other observations indicate that the hyperfragments are heavier than those produced by K^- mesons at rest. In at least 65±4% of cases they come from heavy emulsion nuclei, in contrast to the situation for K mesons at rest where most hyperfragments appear to originate in light emulsion nuclei. A model is proposed which can account for many of the features of the hyperfragment production process.

EXPERIMENTAL PROCEDURE

A STACK of 100 Ilford K5 stripped emulsions was exposed at Berkeley to the Murray beam of 800-Mev/c K^- mesons.[1] The beam composition was 8 K^-:1 π^-:1 μ^-.[2] Area scanning for nuclear disintegrations produced by beam particles was performed and about 8000 stars were found. Every star was scrutinized using a high-power objective to detect the presence of two centers. The smallest separation of such centers which could be detected in this work is estimated as $1\pm\frac{1}{2}\,\mu$, i.e., about 2 grains in the processed emulsion. Every prong from each star was followed within the emulsion sheet containing the event and any secondary interaction or decay recorded. Of the double stars found in this search 388 have been classified as due to the production and subsequent decay of hyperfragments. The lengths of all the prongs from the hyperfragment decay stars and the direction of emission of each hyperfragment with respect to the incident K^- meson direction were measured. In addition, from a sample of 1000 stars, gray prongs in the forward direction of dip angles less than 30° (in unprocessed emulsion) and all black prongs were followed for 1 cm wherever possible and all interactions or decays thus found were noted. No further decay of a hyperfragment was found.

EXPERIMENTAL RESULTS

Of the 388 hyperfragments, 31 decayed mesonically. In the sample of nonmesonic hyperfragments there is probably some contamination due to: (i) chance coincidences, estimated to be negligible in this stack; (ii) the captures of slow negative particles (π^-, K^-, and Σ^-) emitted from the primary disintegrations; and (iii) the interactions in flight of secondary particles. The range distributions of the hyperfragments are given in Figs. 1(a) and (b) and these have been compared with the range distributions of particles, observed in the above sample of 1000 stars, which were captured at rest or interacted in flight. From this comparison it is estimated that the contamination from these sources is not more than 2%. A study of the characteristics of the secondary stars also suggests that this contamination is less than 10%. Thus in the following discussion it has been neglected.

The frequency of hyperfragment production observed in this experiment is 4.9±0.3% of area scanned stars. To obtain the true frequency for K^--meson interactions of this momentum, allowance has to be made for the contamination of π^- mesons in the incident beam. Assuming that the mean free path for interaction of K^- and π^- mesons are[3] 28 and[4] 44 cm, respectively, at 800 Mev/c and that the number of hyperfragments produced in π^--meson interactions at this momentum may be neglected, the frequency of observation of

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[1] P. Bastien, O. Dahl, J. Murray, M. Watson, R. G. Ammar, and P. Schlein, *Proceedings of the International Conference on Instrumentation for High-Energy Physics, Berkeley, 1960* (Interscience Publishers, Inc., New York, 1961).
[2] E. J. Lofgren (private communication, 1961).
[3] J. P. Lagnaux (private communication, 1961).
[4] J. E. Allen, A. J. Apostolakis, Y. J. Lee, J. V. Major, and E. Perez Ferreira, Phil. Mag. 6, 833 (1961).

hyperfragments in K^--meson interactions is found to be $5.3\pm0.3\%$. Some bias is to be expected against the detection of stars with few prongs since the area scanning was performed using a low power objective, but from a comparison with the preliminary results obtained from a sample of line scanned stars this bias is estimated to be small. The frequency is comparable with that for K^- mesons at rest, viz. $5.0\pm0.4\%$.[5]

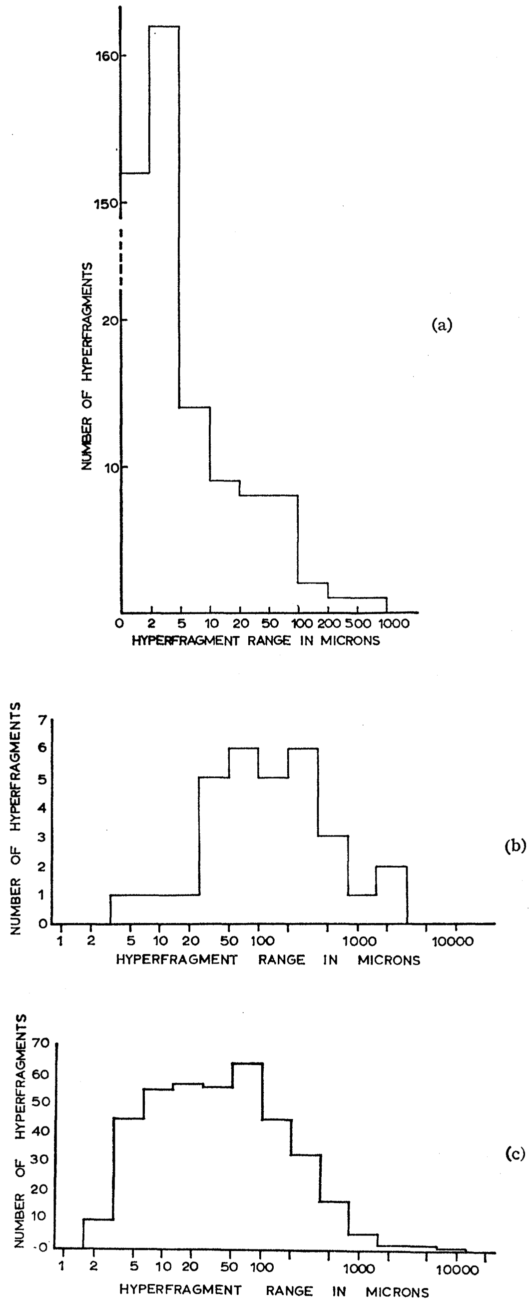

FIG. 1(a). Range distribution of the nonmesonic hyperfragments from the interaction of K^- mesons of 800-Mev/c momentum. (b) Range distribution of the mesonic hyperfragments from the interactions of K^- mesons of 800-Mev/c momentum. (c) Range distribution of the mesonic hyperfragments from the interaction of K^- mesons at rest.

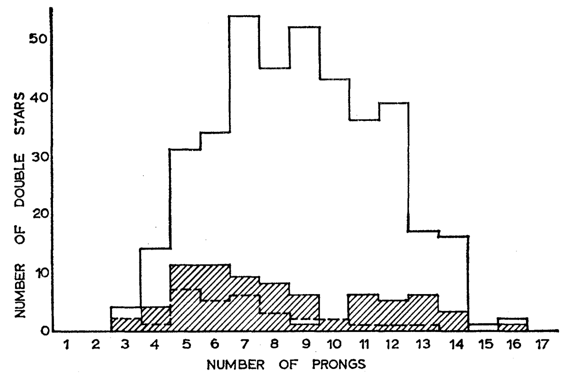

FIG. 2. Total prong distribution of double stars. Broken lines indicate distribution for mesonic hyperfragments. Hatching indicates hyperfragments of range greater than or equal to 5 μ.

The double-centered stars have a larger total number of prongs than those produced by the captures of K^- mesons at rest. The distribution of the sum of the prong numbers of the stars of both the primary interaction and the hyperfragment decay is shown in Fig. 2 (in this distribution tracks of mesons and of hyperfragments themselves have not been included). It is seen that the total prong number exceeds seven in $65\pm4\%$ of all cases whereas for hyperfragments produced by K^- mesons at rest this fraction is only $12.5\pm3.1\%$. (The observation of a total number of prongs greater than seven implies production in a heavy nucleus of the emulsion[6]).

The range distributions of the hyperfragments [Figs. 1(a) and (b)] differ from those for hyperfragments produced by K^- mesons at rest in two respects. The mesonic hyperfragments are, in general, of longer ranges; the range distribution of mesonic hyperfragments emitted from the interactions of K^- mesons at rest[7] is given in Fig. 1(c) for comparison. The range distribution of nonmesonic hyperfragments, however, shows a large proportion of hyperfragments of very short ranges, for example, 88% have ranges less than 5 μ, compared with 63% for hyperfragments produced by stopped K^- mesons.[5]

These nonmesonic hyperfragments of very short ranges ($R<5\ \mu$) are characterized by the comparative rarity of short prongs in the secondary stars. (The presence of short prongs implies the disintegration of a light nucleus.) The fraction of such stars containing at

[5] See e.g. European Collaboration, Nuovo cimento **13**, 705 (1959).

[6] The emission of a π^- meson from the primary star could mean that the charge of the parent nucleus was less by one than the total number of observed prongs. This effect is more than compensated for, however, by the emission of alpha particles and fragments of higher charge.

[7] R. G. Ammar, R. Levi Setti, W. E. Slater, S. Limentani, P. E. Schlein, and P. H. Steinberg, Nuovo cimento **19**, 20 (1961).

least one prong of length between 2 and 30 μ is $13\pm3\%$,[8] compared with a fraction of $31\pm8\%$ for the secondary stars from the hyperfragments of longer range. For hyperfragments emitted from K^--meson interactions at rest the corresponding figures are $44\pm11\%$ and $38\pm9\%$, respectively.[9]

The nonmesonic to mesonic decay ratio of 11.5 ± 0.6 is much higher than that for hyperfragments produced by K^- mesons at rest, viz. 3.1 ± 0.8.[10,11]

The hyperfragments are found to be emitted predominantly in the forward direction. The measured forward to backward ratio is 3.3 ± 0.3. It is more instructive however to divide the sample into two parts according to range. For those hyperfragments with ranges less than 5 μ this ratio is 4.1 ± 0.3 whereas for those of longer ranges it is 1.9 ± 0.3.

INTERPRETATION AND PROPOSED MODEL FOR HYPERFRAGMENT PRODUCTION

The above experimental results lead to the conclusions that the hyperfragments are heavier than those emitted from the interactions of K^- mesons at rest and also that the great majority are produced by interactions with the heavy emulsion nuclei (silver, bromine). The larger proportion of heavier hyperfragments is demonstrated by the higher nonmesonic to mesonic ratio and by the smaller fraction of hyperfragments with prongs of short range, particularly among the hyperfragments of range less than 5 μ. As pointed out, above, the high rate of production in heavy nuclei is evident from the total prong distribution of Fig. 2. It is concluded, therefore, that a lower limit of the proportion of hyperfragments which arise from K^--meson interactions in heavy nuclei is $65\pm4\%$. For stopped K^- mesons, however, it can be estimated from a study of mesonic hyperfragments[12] that the proportion of hyperfragments emitted from the heavy emulsion nuclei may be as low as 20%.

In a large proportion ($\sim80\%$) of those double stars where the total prong number is greater than seven, the hyperfragment has a range of less than 5 μ and would seem, therefore, to have insufficient energy to surmount the Coulomb barrier of a heavy nucleus (see Fig. 2).

These features may be interpreted by supposing that the interactions of 800-Mev/c K^- mesons with heavy nuclei are similar to other high-energy nuclear interactions.[13] A high-energy K^- meson on entering a nucleus initiates a nuclear cascade as a result of which fast mesons and baryons are ejected. A fast hyperfragment may occasionally be among the particles ejected at this stage, but this work indicates that such emission is infrequent. Often a Λ^0 hyperon remains in the highly excited nucleus. In the ensuing evaporation phase nucleons, or clusters of nucleons, are emitted. Sometimes these clusters may contain the Λ hyperon, forming a light hyperfragment. Clearly, however, the large number of heavy hyperfragments cannot be explained on the basis of an evaporation process.[14] It appears that in the majority of cases of hyperfragment formation, therefore, the Λ^0 hyperon is not evaporated but remains within the residual nucleus. In collisions of this kind the average recoil momentum of the residual nucleus is of the order of the incident momentum,[15] which in this case should allow it to produce an observable track in the emulsion.[16] Since it contains a trapped Λ^0 hyperon, it subsequently decays leading to the formation of a double-centered star with a very short interconnecting track.

The observed number of charged particles from the primary stars implies that in many cases the residual nuclei will have mass numbers 20 or 30 nuclear masses less than those of the parent nuclei. Studies by radiochemical methods of spallation produced by protons with momenta of the order of 1 GeV/c have also shown that the cross section is appreciable for the production of fragments of mass number differing by as much as 20 from those of the parent nuclei.[13]

In order to obtain the expected range of the short hyperfragments according to the above model it is necessary to extrapolate some way from existing data. The results of Heckman *et al.*,[17] however, suggest that the range of nucleus of mass number 50 and momentum 1000 MeV/c would be about 3 μ in emulsion.[16] The range of mass numbers and momenta of the original nuclei, as well as straggling, would lead to a broad distribution of ranges below 5 μ, as observed.

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[8] The lower limit of 2 μ is used to avoid confusion with the tracks of electrons or heavy nuclear recoils. The upper limit of 30 μ is adopted as a result of a study of the yield of Auger electrons from the interactions of K^- mesons at rest in nuclear emulsion where it was found that prongs of length 30–50 μ may arise from disintegrations of heavy nuclei (J. Sacton, private communication).

[9] Unpublished data of the European Collaboration.

[10] V. Gorgé, W. Koch, W. Lindt, M. Nikolič, S. Subotic-Nikolič, and H. Winzeler, Nuclear Phys. **21**, 599 (1960).

[11] J. Sacton, Nuovo cimento **18**, 266 (1961).

[12] D. Abeledo, L. Choy, R. G. Ammar, N. Crayton, R. Levi Setti, M. Raymund, and O. Skjeggested, Nuovo cimento **22**, 1171 (1961).

[13] See, e.g., J. M. Miller and J. Hudis, Ann. Rev. Nuclear Sci. **9**, 159 (1959), for general discussions and references. J. B. Harding, Phil. Mag. **40**, 530 (1949) and **42**, 63 (1951).

[14] An estimate of the fraction of the hyperfragments expected to be produced by evaporation can be obtained from a study of hammer tracks. In this work the frequency of emission of $Li^{8,9}$ (and B^8) nuclei has been found to be $0.2\pm0.05\%$. This frequency, as well as the energy distribution of these fragments, can be interpreted in terms of evaporation theory. The hyperfragments found in this experiment have been shown to be heavier than those emitted from K^- mesons at rest where the mean charge number has been estimated to be 4.0 ± 0.3.[11] Evaporation theory would predict a frequency of emission even less than for $Li^{8,9}$ and B^8 nuclei, therefore indicating that evaporation cannot be a dominant process in hyperfragment production in this case.

[15] B. G. Harvey, Ann. Rev. Nuclear Sci. **10**, 235 (1960).

[16] A preliminary study of the characteristics of stars seen to contain hyperfragments and produced by the interaction of 800-MeV/c K^- mesons also suggests that the short hyperfragments have momenta of the order of 1000 MeV/c (J. Sacton, private communication).

[17] H. H. Heckman, B. L. Perkins, W. G. Simon, F. M. Smith, and W. H. Barkas, Phys. Rev. **117**, 544 (1960).

The ratio of the numbers of hyperfragments projected in the forward and backward directions in this experiment can also be understood in terms of the above model. The hyperfragments of short ranges arising from Λ^0 trapping in the residual nuclei would be expected to be markedly influenced by the direction of flight of the K^- mesons. The hyperfragments of longer range would be expected to have a smaller forward to backward ratio if they were mainly evaporated from a slowly moving nucleus.

A similar model may be applied to the interpretation of hyperfragment production by K^- mesons at rest. In this case the momenta of the residual hypernuclei would be expected to be smaller so that fewer of them would have sufficient momentum to form an observable track in the emulsion. This is consistent with the estimate of D. H. Davis *et al.* of the formation of cryptofragments (i.e., hyperfragments which do not produce recognizable tracks) in as many as 30% of the interactions of stopping K^- mesons with emulsion nuclei.[18]

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[18] D. H. Davis, M. Csejthey-Barth, J. Sacton, B. D. Jones, B. Sanjeevaiah, and J. Zakrzewski, Nuovo cimento **22**, 275 (1961); see, however, B. Cester, G. Ciochetti, A. Debenedetti, A Marzari Chiesa, R. Rinaudo, C. Deney, K. Gottstein, and W. Püschel Nuovo cimento **22**, 1069 (1961); and A. Filipkowski, E. Marquit, E. Skrzypszak, and A. Wroblewski (to be published).

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Reaction $p+p\rightarrow\pi^++p+n$ at 405 MeV*

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The azimuthal asymmetry of pion production in the reaction $p+p\rightarrow\pi^++p+n$ was measured using the 53% polarized 405-MeV proton beam from the Carnegie Institute of Technology's synchrocyclotron. Pions produced in a liquid hydrogen target were successively detected on the left and on the right by means of their stopping and subsequent $\pi\mu e$ decay in a 6-in. propane bubble chamber. Elastically scattered protons were used to monitor the incident beam intensity. The pions which stopped in the chamber had an average c.m. momentum of 0.52 μc and c.m. production angles between 80 and 105°. The observed pion asymmetry is $|\epsilon|=(20\pm6.5)\%$, in the same direction as the previously observed asymmetry for the (pp,π^+d) reaction. The similarity between the observed pion asymmetry and that for the (pp,π^+d) reaction suggests that their reaction amplitudes are similar, and thus that ^3S rather than P states are predominant for the final-state nucleons in the (pp,π^+pn) reaction at this energy. The estimated total cross section (0.63±0.06 mb) is in good agreement with the calculation of Mandelstam.

INTRODUCTION

THE production of single positive pions in proton-proton collisions can proceed through either of the following reactions:

$$p+p\rightarrow\pi^++d, \tag{1}$$

$$p+p\rightarrow\pi^++p+n. \tag{2}$$

Numerous measurements of the total cross section and angular distribution for these reactions (using unpolarized proton beams) have been made. Also, the azimuthal asymmetry of reaction (1) with a polarized incident beam has been measured at several energies. For the threshold region ($E_p\lesssim450$ Mev), the experimental results have been interpreted in terms of a phenomenological theory, allowing the identification of the principal angular momentum channels (pion with $l=0$ or 1, and final-state nucleons in a relative $^3S_1$ state) and forming a picture which seems consistent with the experimental results in that energy region.[1] The threshold theory neglects the final-state pion-

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[1] M. Gell-Mann and K. M. Watson, Ann. Rev. Nuclear Sci. 4, 219 (1954).