purity energy level width is small (10 or less). This situation is described as resonant scattering.

[6]Kazumi Maki, Phys. Rev. 153, 428 (1967).

[7]B. T. Matthias, H. Suhl, and E. Corenzwit, Phys. Rev. Letters 1, 92 (1958).

[8]B. Coqblin and A. Blandin, to be published.

[9]A. S. Edelstein, Phys. Rev. (to be published).

[10]D. L. Johnson and D. K. Finnemore, Phys. Rev. 158, 376 (1967).

[11]H. J. Levinstein, V. G. Chirba, and J. E. Kunzler, Phys. Letters 24A, 362 (1967).

[12]Magnetic measurements have been made on bulk fcc samples. Our interpretation of these measurements differs from that of Ref. 4 and will be published subsequently.

[13]Tadashi Sugawara and Hiroko Eguchi, Institute for Solid State Physics, University of Tokyo, Technical Report Ser. A, No. 271, 1967 (unpublished).

EVIDENCE FOR THE EXISTENCE OF THE HYPERNUCLEUS $_\Lambda Li^6$

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An event has been observed in nuclear emulsion which is attributed to the decay of a $_\Lambda Li^6$ hypernucleus, $_\Lambda Li^6 \to \pi^- + p + p + He^4$, with a total binding energy of $B = 3.92 \pm 0.37$ MeV relative to the free-particle system $\Lambda + p + He^4$.

During a systematic investigation of mesonic decays of hypernuclei into four charged particles, an event was observed which is best interpreted as the decay

$$_\Lambda Li^6 \to \pi^- + p + p + He^4, \quad (1)$$

with a binding energy $B = 3.92 \pm 0.37$ MeV relative to the free-particle system $\Lambda + p + He^4$.

A stack of Ilford $K5$ nuclear emulsion was exposed to about 10^6 stopping K^- mesons from a separated K^- beam at the Brookhaven alternating-gradient synchrotron. The density of the emulsion pellicles at the time of exposure was determined by the measurement of the range of 38 proton tracks from the decay of Σ^+ hyperons. The protons have a mean range of $R = 1707 \pm 4\ \mu$, compared with $R = 1677 \pm 2\ \mu$ for standard nuclear emulsion (density $\rho = 3.815$ g/cm^3). The hypernucleus is emitted from a K^--meson capture star together with three other nucleonic charged particles. The hypernucleus track, which has a dip angle of 7° relative to the emulsion plane, exhibits a thinning down of its profile towards the end of its range which is typical of stopping fragments of charge $Z \geq 3$. It has a range of 38.1 μ and decays mesonically into four charged particles. The pion from the decay star comes to rest in the emulsion giving rise to a three-prong star, and its track does not exhibit detectable inelastic collisions. The measurement data for the production and the decay star are given in Table I. A photomicrograph of the event is shown in Fig. 1.

For the analysis of the decay star a χ^2-minimizing computer program[1] has been used. This enables a certain probability to be attributed to each of the solutions fitting the kinematics of the decay. Fits were tried under the assumptions that the hypernucleus decayed at rest and that, in turn, (a) only particles giving visible tracks were emitted from the decay; (b) one neutron could be emitted in the decay; and (c) one charged particle making no visible track could be emitted in addition to the visible ones. Also tried were fits for a hypernucleus decay in flight.

Only one fit under assumption (a) was found, i.e., the decay $_\Lambda Li^6 \to \pi^- + p + p + He^4$, yielding a momentum unbalance before the fit of $\Delta P = 14.7$ MeV/c, and a value of the binding energy, relative to the free-particle system ($\Delta + p + He^4$) after the fit, $B(_\Lambda Li^6) = 3.92 \pm 0.37$ MeV. The χ^2 value for this hypothesis, correspond-

Table I. Measurement data of the event 5K-70-21.

Track identity	Range (μm)	Dip angle λ (deg)	Azimuth φ (deg)
	Production star		
1	1580	−34.99	347.52
2	151.8	−39.39	351.53
3	63.0	0.00	273.59
Hyperfragment	38.1	7.06	238.93
	Decay star		
π^-	3434	−7.37	242.95
p	1551	11.24	0.00
p	25.7	−7.48	192.21
He^4	7.5	−13.94	153.53

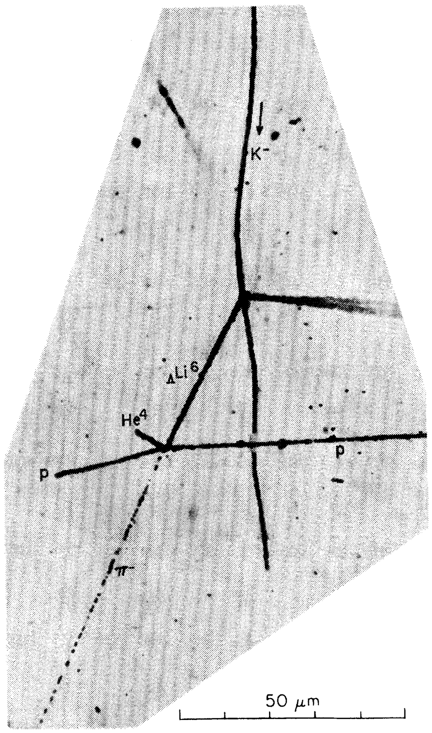

FIG. 1. Photomicrograph of the decay of a $_{\Lambda}Li^6$ hypernucleus.

ing to three degrees of freedom, is $\chi^2=2.05$. No other fit was obtained when the possibility of a decay in flight was considered under assumption (a). No fits were found under assumption (b). Two fits were obtained under assumption (c), both for $_{\Lambda}Be^7 \rightarrow \pi^- + p + p + p + He^4$. The fit in which the invisible track is identified with He^4 [binding energy $B_{\Lambda}(_{\Lambda}Be^7) = 5.65 \pm 0.36$ MeV] would require for such track the following geometrical data: $R=3.6$ μm, $\lambda=-8.5°$, and $\varphi = 145.9°$. This fit can be ruled out because such a track should not be obscured by other tracks and, therefore, should be visible. The other fit, in which the invisible track is taken to be a proton [binding energy $B_{\Lambda}(_{\Lambda}Be^7) = 5.12 \pm 0.51$ MeV], would require for the invisible track the following geometrical data: $R=1.4$ μm, $\lambda=36.7°$, and $\varphi=58.3°$. Careful examination of the decay vertex did not reveal any evidence for such a recoil.[2]

An analysis of the production star has been attempted, using a computer program written by Frodesen, Kolbig, and Nikolic.[3] This program considers the capture of a negative meson on the light emulsion nuclei C^{12}, N^{14}, and O^{16}, leading to the formation of a number of charged secondaries of which one may be a hypernucleus and, at the most, one neutral particle. Under these assumptions no fits were obtained in which a hypernucleus of charge $Z>3$ was produced.

Three fits lead to the production of a $_{\Lambda}Li^6$ hypernucleus and are consistent with the fit obtained for the decay star. On the other hand, since the momentum unbalance at the production star is in the order of 600-700 MeV/c, the emission of more than one neutron cannot be ruled out. Under this assumption several fits are possible in which a $_{\Lambda}Be^7$ could be emitted. Thus, the analysis of the production star is inconclusive as to the identity of the emitted hypernucleus.

The identification of this event as the decay of a $_{\Lambda}Be^7$ hypernucleus is unlikely in view of several arguments.

Only about 2% (1 event out of 54) of all identified $_{\Lambda}Be$ hypernuclei produced by stopping K^- mesons[4] have a range greater than 25 μ, which is to be compared with the range of this hypernucleus being 38.1 μ.

The data of 13 decays $_{\Lambda}Be^7 \rightarrow \pi^- + p + p + p + He^4$ have been reported.[4-6] The range spectrum of the 39 decay protons from these events leads to the estimate that no more than 10% of all π^--mesonic $_{\Lambda}Be^7$ hypernuclei should emit a proton of range shorter than 2.5 μ.[7] Thus, one is led to estimate that the combined probability of a $_{\Lambda}Be^7$ in the observed configuration is most likely less than 0.002. Making the assumption that in this event a recoil proton of 1.4 μ was indeed emitted but remained unseen, and considering an estimate of the world sample of $_{\Lambda}Be^7$ events from stopping K^- mesons, the odds against the $_{\Lambda}Be^7$ interpretation for the present event are at least 30:1. Although this possibility cannot reasonably be excluded, it is felt that the event described here provides, nevertheless, positive evidence for the existence of $_{\Lambda}Li^6$.

The observed stability of the hypernucleus $_{\Lambda}Be^7$ imposes an upper limit of 3.72 ± 0.15 MeV on the total binding energy of $_{\Lambda}Li^6$.[8] This is to be compared with the present experimental value of 3.92 ± 0.37 MeV, which exceeds the upper limit by 0.20 ± 0.40 MeV and is compatible with it within the error.

Experimental evidence for the existence of $_{\Lambda}Li^6$ hypernuclei is very scarce. A possible example of the decay $_{\Lambda}Li^6 \rightarrow \pi^- + p + p + He^4$ has been reported by Mayeur et al.[9] However, the configuration of the event is such that one of the proton tracks could be due to a large-angle scattering of the hypernucleus, in which case the event fits the decay of a ${}_{\Lambda}He^5$ hypernucleus. A search for a resonant state of ${}_{\Lambda}Li^6$ as a p-wave resonance in the system $p+{}_{\Lambda}He^5$ was made by several authors.[10,11] Their experimental data did not reveal such a resonant state.

The binding energy observed for the ${}_{\Lambda}Li^6$ interpretation of the event described here leads to a rather puzzling implication. Charge symmetry of the Λ-nucleon interaction leads to the expectation that the Λ hyperon should have equal binding energy in mirror hypernuclei, e.g., ${}_{\Lambda}H^4$-${}_{\Lambda}He^4$ or ${}_{\Lambda}He^6$-${}_{\Lambda}Li^6$. A careful measurement of the binding energy of the mirror hypernuclei ${}_{\Lambda}He^4$-${}_{\Lambda}H^4$ revealed a difference[12] which amounts, with the much-increased statistics of the European K^- Collaboration,[13] to

$$B_{\Lambda}({}_{\Lambda}He^4)-B_{\Lambda}({}_{\Lambda}H^4)=0.27\pm0.06\text{ MeV}. \qquad (2)$$

This difference has been explained by the assumption of charge-symmetry breaking contributions to the Λ-nucleon interaction.[14-17]

With $B_{\Lambda}({}_{\Lambda}He^6)=4.19\pm0.17$ MeV,[13] and with a binding energy of ${}_{\Lambda}Li^6$ relative to the ground state of Li^5 $B_{\Lambda}({}_{\Lambda}Li^6)=5.89\pm0.37$ MeV, the binding energy difference of the mirror hypernuclei ${}_{\Lambda}Li^6$-${}_{\Lambda}He^6$ would be

$$B_{\Lambda}({}_{\Lambda}Li^6)-B_{\Lambda}({}_{\Lambda}He^6)=1.7\pm0.4\text{ MeV}, \qquad (3)$$

which is much larger than the binding energy difference of the ${}_{\Lambda}He^4$-${}_{\Lambda}H^4$ mirror hypernuclei. Either this might indicate a rather large failure of charge symmetry for the Λ-nucleon interaction or it might be due to the possibility that the masses of the bound core nuclei in ${}_{\Lambda}He^6$ and ${}_{\Lambda}Li^6$ differ from those of the unbound He^5 and Li^5 $p_{3/2}$ resonant states.[18]

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[1]W. Gajewski, Bull. Inst. Phys. Bruxelles No. 29 (1966).

[2]The decay vertex is located at a depth of 125 μ (in the developed emulsion) below the emulsion surface. Thus, the optical conditions were favorable for high-resolution observation, using 100× objective.

[3]A. G. Frodesen, K. S. Kolbig, and M. M. Nikolic, CERN Report No. 65-6, 1965 (unpublished).

[4]European K^- Collaboration, Bull. Inst. Phys. Bruxelles No. 26 and 27 (1966).

[5]S. J. St. Lorant and S. Lokanathan, Phys. Letters 1, 223 (1962); R. G. Ammar, M. Holland, J. H. Roberts, and E. N. Shipley, Nuovo Cimento 27, 769 (1963); K. N. Chaudhari, S. N. Ganguli, N. K. Rao, and M. S. Swami, Proc. Indian Acad. Sci. 64A, 51 (1966).

[6]J. Sacton, private communication.

[7]It should be mentioned that the unidentified mesonic four-prong hypernuclei contain only a negligible fraction of possible ${}_{\Lambda}Be^7\to\pi^-+p+p+p+He^4$. The requirements for a four-prong hypernucleus to be identified with ${}_{\Lambda}Be^7$ are, apart from an acceptable binding energy, that the four visible prongs be consistent with identification in terms of π^-, p, p, and He^4, and that this configuration should yield a momentum unbalance such as to be accounted for by an unseen proton. This, however, represents exactly the configuration of a possible ${}_{\Lambda}Li^6$, and one can assume that such an event would have been very carefully analyzed by earlier investigators.

[8]The binding energy of ${}_{\Lambda}Be^7$ relative to the free-particle system $\Lambda+p+p+He^4$ is defined by ${}_{\Lambda}Be^7=\Lambda+p+p+He^4-B({}_{\Lambda}Be^7)$. Similarly, the binding energy of ${}_{\Lambda}Li^6$ is given by ${}_{\Lambda}Li^6=\Lambda+p+He^4-B({}_{\Lambda}Li^6)$. We, therefore, have ${}_{\Lambda}Be^7=p+{}_{\Lambda}Li^6-B({}_{\Lambda}Be^7)+B({}_{\Lambda}Li^6)$, and the stability of ${}_{\Lambda}Be^7$ requires that $B({}_{\Lambda}Li^6)$ be smaller than $B({}_{\Lambda}Be^7)$.

[9]C. Mayeur, J. Sacton, P. Vilain, G. Wilquet, D. Stanley, P. Allen, D. H. Davis, E. R. Fletcher, D. A. Garbutt, M. A. Shaukat, J. E. Allen, V. A. Bull, A. P. Conway, and P. V. March, Nuovo Cimento 43A, 180 (1966).

[10]M. Raymund, unpublished data (private communication).

[11]D. T. Goodhead and D. A. Evans, Nucl. Phys. B2, 121 (1967).

[12]M. Raymund, Nuovo Cimento 32, 555 (1964).

[13]D. H. Davis and J. Sacton, Bull. Inst. Phys. Bruxelles No. 34 (1967).

[14]R. H. Dalitz and B. W. Downs, Phys. Rev. 111, 967 (1958).

[15]R. H. Dalitz and F. von Hippel, Phys. Letters 10, 153 (1964).

[16]B. W. Downs and R. J. N. Phillips, Nuovo Cimento 41A, 374 (1966).
[17]B. W. Downs, Nuovo Cimento 43A, 454 (1966).
[18]R. H. Dalitz, private communication.

PRODUCTION OF HIGH-MOMENTUM DEUTERONS FROM NUCLEI BOMBARDED BY 1-BeV PROTONS*

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It has been known[1] for many years that large numbers of deuterons are produced whenever nuclei are bombarded by high-energy protons. In general, the previous data[1] were measured at large angles and low deuteron momenta, with the qualitative results that the ratio of the number of deuterons to protons varied between 1 and 10%. About ten years ago, Azhgirei et al.,[2] in analyzing the high-momentum spectra of particles produced by a 675-MeV proton beam incident on light nuclei, observed a small peak on the high-energy tail of the elastically scattered protons. From the momentum of this peak they concluded that these particles were deuterons resulting from the collision of the incident protons with quasifree n-p pairs in the nucleus.

The data of Ref. 2 were obtained using ^{7}Li, ^{9}Be, ^{12}C, and ^{16}O at only one deuteron-scattering angle, 7.6°, to the incident proton beam. Using a magnetic spectrometer[3] and a time-of-flight system to separate deuterons from protons, we have carried out similar measurements on ^{4}He, ^{6}Li, ^{12}C, ^{16}O, and natural Pb nuclei at several forward deuteron angles, $\theta_L = 5°$, 10°, and 15°. The (1.00 ± 0.01)-BeV proton beam came from the Brookhaven Cosmotron. All of the results are consistent with the reaction $p+(A,Z)\rightarrow d+p+(A-2,Z-1)$.

In Fig. 1 we show typical deuteron-momentum spectra for helium and oxygen. The maximum possible deuteron momentum, 2.15 BeV/c, is obtained from the pickup or knockout reaction, $p+{}^{16}\mathrm{O}\rightarrow d+{}^{15}\mathrm{O}$, which leaves the residual nucleus in its ground state. No events were observed at this momentum. The peak in the spectra occurs about 20 MeV below the kinematic point for free p-d scattering. This difference is due to the binding energy of the deu-

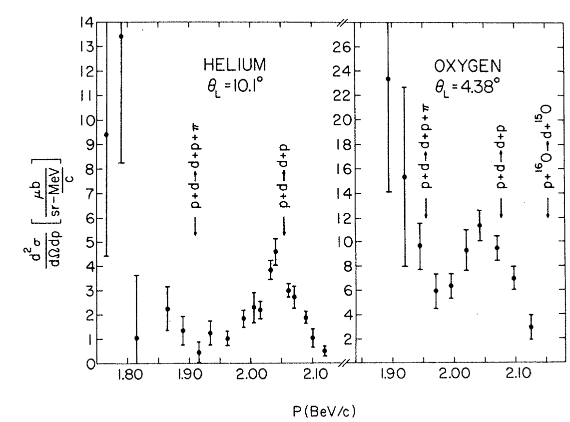

FIG. 1. Typical deuteron-momentum spectra at small angles to the incident proton beam.

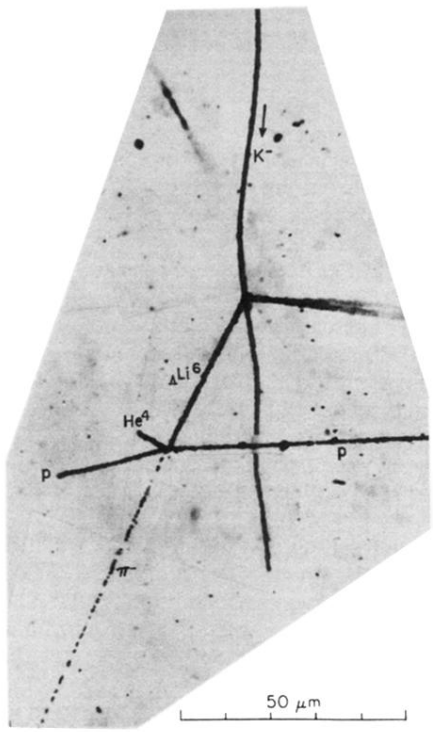

FIG. 1. Photomicrograph of the decay of a $_\Lambda Li^6$ hypernucleus.