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INVESTIGATION OF HYPERNUCLEI PRODUCED BY 8.8-Bev PROTONS

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Hyperfragment production in nuclear emulsion by ~ 9-Bev protons was investigated. Fifty-four hyperfragment decays were detected. The hypernuclei B_Λ^{10}, C_Λ^{11}, C_Λ^{14}, C_Λ^{15}, and N_Λ^{14} were observed for the first time. ~ 30% of the observed events can be explained by the single-nucleon mechanism of Λ^0-hyperon interaction. Two decays with anomalously large energy release were observed.

1. EXPERIMENTAL PROCEDURE

THE production of hyperfragments was investigated in a 10×20 cm nuclear emulsion stack 400 μ thick bombarded in the 8.8-Bev internal proton beam of the proton synchrotron at the Joint Institute for Nuclear Research. The beam density was 2.7×10^5 protons/cm^2.

In scanning under 150x total magnification all "connected" stars within a single pellicle were registered. All definite instances of nuclear interaction, σ stars, and elastic scattering were subsequently eliminated. The remaining events satisfied the following criteria: 1) length of connecting track $\geq 20\,\mu$; 2) the existence of scattering at the end of the connecting track; 3) for $Z \geq 4$, thindown at the end of the connecting track.

In 72 cm^3 of emulsion 81 presumable decays of hyperfragments were found satisfying the given criteria. Six mesonic decays and 46 nonmesonic decays were distinguished by means of appropriate treatment and kinematic analysis.

Particle identification depended on previous calibration of the emulsion. The charge of particles having ranges under 1000 μ was determined with calibration curves relating track width d and dip (the d method). Measurements were performed on the tracks of 63 protons, 48 α particles from Be^8 decay and 29 α particles from Li^8 decay. For $Z \geq 4$ the charge was determined mainly on the basis of charge conservation, but also from the thin-down length l.

The mass of singly-charged particles was determined by Perkins' method,[1] for which integral calibration curves were plotted relating the gap count N to the residual range R [the N(R) method] for the tracks of π^+ mesons selected from $\pi^+ \to \mu^+$ decays. In some cases the mass was also determined from measurements of multiple scattering and range.

The Λ^0-hyperon binding energy in the hypernucleus was calculated from

$$B_\Lambda = M + M_{\Lambda^0} - \sum M_i - Q,$$

where M is the rest mass of the nucleus to which the Λ^0 was bound, M_{Λ^0} is the Λ^0 rest mass, 1115.06 ± 0.21 Mev,[2] M_i is the rest mass of emitted particles, and Q is the kinetic energy of all emitted particles. Nuclear masses were taken from [3].

The maximum error in B_Λ was determined from

$$\delta B_\Lambda = \delta_{exp+str} + \delta_{sp} + \delta Q_0 + \delta R_i,$$

$$\delta_{exp+str} = \sum (\delta_{i\,exp}^2 + \delta_{i\,str}^2)^{1/2}, \quad \delta Q_0 = \delta M + \delta M_{\Lambda^0} + \sum \delta M_i,$$

where $\delta_{i\,str}$ includes errors in range determination resulting from the Born approximation, and from microscopic distortion and inhomogeneity of the emulsion; $\delta_{i\,exp}$ represents errors of the MBI-9 microscope; $\delta_{sp} = 3 \times 10^{-4} Q$ is an error associated with the introduction of a correction for the stopping power of the NIKFI-R emulsion; $\delta R_i = 42 \times 10^{-4} Q'$ represents errors arising from the use of range-energy tables,[4] and Q' is the total energy of emitted charged particles.

In all cases except when mesons decayed without emitting a neutral particle, the maximum error in determining B_Λ was of the same order as B_Λ. It can be assumed that normal errors will be smaller than the maximum errors; this is indicated by an estimate based on the distribution of binding energies for hyperfragments with close mass numbers.

Table I

No. of event	Length of connecting track, μ	Decay scheme	B_Λ, Mev
1	84	$\mathrm{He}^4_\Lambda \to \pi^- + p + p + p + n$	0.02 ± 1.59
2*	785	$\mathrm{He}^4_\Lambda \to \pi^- + p + \mathrm{He}^3$	$1,79 \pm 0,94$ $0,32 \pm 0,91$
3**	114	$\mathrm{He}^5_\Lambda \to \pi^- + p + \mathrm{He}^4$	$2.19 \pm 0,62$
		$\mathrm{He}^7_\Lambda \to \pi^- + p + \mathrm{He}^6$	$2,42 \pm 0.61$
4	102	$\mathrm{Li}^7_\Lambda \to p + d + t + n$	$9,09$
5	145	$\mathrm{Li}^7_\Lambda \to p + d + t + n$	$5,83 \pm 7.65$
6	115	$\mathrm{Be}^7_\Lambda \to p + \mathrm{Li}^5 + n$	$3.40 \pm 4,56$
7	50	$\mathrm{Li}^8_\Lambda \to p + \mathrm{He}^6 + n$	$10,08 \pm 9.72$
8	84	$\mathrm{Li}^8_\Lambda \to t + \mathrm{He}^4 + n$	$4,42 \pm 2.95$
9	145	$\mathrm{Be}^8_\Lambda \to d + d + \mathrm{He}^3 + n$	$6,36 \pm 4,83$
10	176	$\mathrm{Li}^8_\Lambda \to p + \mathrm{He}^6 + n$	$7,93 \pm 4,67$
		$\mathrm{Be}^8_\Lambda \to \mathrm{He}^3 + \mathrm{He}^4 + n$	9.50 ± 4.57
		$\mathrm{Be}^8_\Lambda \to \mathrm{He}^4 + \mathrm{He}^3 + n$	$10,79 \pm 6,49$
11	59	$\mathrm{Li}^9_\Lambda \to d + \mathrm{He}^6 + n$	$11,29 \pm 6.13$
12	61	$\mathrm{Be}^9_\Lambda \to \mathrm{He}^4 + \mathrm{He}^4 + n$	$5.49 \pm 5,06$
13	166	$\mathrm{Be}^{10}_\Lambda \to p + \mathrm{Li}^8 + n$	3.06
14	23	$\mathrm{B}^{10}_\Lambda \to p + d + t + \mathrm{He}^3 + n$	$10,78^{+19,25}_{-4,67}$
		$\mathrm{B}^{11}_\Lambda \to p + p + d + \mathrm{He}^6 + n$	$8,38 \pm 13.44$
15	105	$\mathrm{C}^{11}_\Lambda \to \mathrm{He}^3 + \mathrm{He}^4 + \mathrm{He}^3 + n$	$5,13 \pm 15.51$
		$\mathrm{C}^{11}_\Lambda \to \mathrm{He}^4 + \mathrm{He}^3 + \mathrm{He}^3 + n$	$12,49 \pm 14,94$
		$\mathrm{C}^{12}_\Lambda \to \mathrm{He}^4 + \mathrm{He}^4 + \mathrm{He}^3 + n$	12.68 ± 16.67
16	131	$\mathrm{C}^{14}_\Lambda \to \mathrm{Li}^6 + \mathrm{Li}^7 + n$	$12,24 \pm 10,80$
17	215	$\mathrm{N}^{14}_\Lambda \to p + \mathrm{C}^{12} + n$	13.28 ± 18.57
		$\mathrm{C}^{15}_\Lambda \to d + \mathrm{B}^{12} + n$	14.50 ± 17.64

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*The geometry did not permit an unambiguous determination of the pion range.

**The ground state of He^6 is always assumed.

We selected only values of B_Λ agreeing with the average of values given in the literature or with the expected values within the error limits for individual cases.

We note that nonmesonic decays were not regarded as possible π^0 decays of hyperfragments; the estimated number of the latter was ~ 3.

2. RESULTS

Our analysis classified all observed events as either clear or doubtful. Forty-two hyperfragment decays were clear; of these 6 were mesonic (including one instance of decay in flight), while the remainder were nonmesonic.

The binding energy B_Λ was determined in three mesonic decays, although the result was unambiguous in only one instance. B_Λ was determined in 14 nonmesonic decays, including 10 unambiguous values. Table I gives the values of B_Λ and the error limits.

We were apparently the first to observe the decay of certain heavy hyperfragments. Thindown and scattering at the end of each connecting track indicate definitely that these are hyperfragment decays. Confirmation is furnished by the reasonable values of B_Λ obtained from the kinematic analysis. Table II gives details for the decays of the newly discovered hypernuclei, which include B^{10}_Λ, C^{10}_Λ, C^{14}_Λ, C^{15}_Λ, and N^{14}_Λ. It must be noted that the existence of these hypernuclei, with the exception of C^{14}_Λ, is not absolutely certain. Events Nos. 14 and 15 could also be assigned to the previously discovered nuclei B^{11}_Λ and C^{12}_Λ, respectively.[5-7] Event No. 17 could involve either of the previously undiscovered hypernuclei N^{14}_Λ or C^{15}_Λ.

Table II

No. of event	Hyperfragment and its charged decay products*			Ranges, μ	Indentification method	Azimuth	Dip angle	B_{Λ}
	a	b	c					
14	B^{10}_{Λ}	B^{11}_{Λ}		23	*d*	0	+25°50′	$10{,}78^{+19{,}25}_{-4.67}$
	He^3	He^6		39	*d*	31°3′	—32°20′	8,38±13,44
	t	*p*		6,7	From charge conservation	30°	—32°20′	
	d	*d*		7523	*N* (*R*)	220°30′	+ 5°20′	
	p	*p*		10711	*N* (*R*)	56°30′	20°25′	
15	C^{11}_{Λ}	C^{11}_{Λ}	C^{12}_{Λ}	105	*l*, *d*	0	—47°5′	5,13±15,51
	He^3	He^4	He^4	51	*d*	267°24′	+46°	12.49±14,94
	He^4	He^3	He^4	149	*d*	32°54′	—25°30′	12,68±16,67
	He^3	He^3	He^3	521	*d*	27°24′	76°50′	
16	C^{14}_{Λ}			131	*l*, *d*	0	+29°30′	
	Li^7			42	*d*	97°	— 7°52′	12,24±10,80
	Li^6			6.4	From charge conservation	202°30′	—21°12′	
17	N^{14}_{Λ}	C^{15}_{Λ}		215	*l*, *d*	0	+24°10′	13,28±18.57
	p	*d*		558	*d*	30°12′	—16°20′	14,5±17,64
	C^{12}	B^{12}		5,5	From charge conservation	196°30′	—13°	
18**	C_{Λ}	N_{Λ}		234	*l*, *d*	0	+18°20′	—113±24
	p	*p*		1235	*N* (*R*)			
				2044	*n* (Δ*R*)	131°4′	— 4°10′	
	d	*d*		40968	*N* (*R*)	310°15′	+17°20′	
	Be	B		2.4	From charge conservation	335°39′	—63°47′	
19**	Li_{Λ}	Be		70	*l*, *d*	0	—15°20′	—63±9
	p	*d*		31664	*N* (*R*)	226°36′	—50°50′	
	He	Li		3049	*d*	32°39′	+66°50′	

*a, b, c – different interpretations of the same event.

**In events Nos. 18 and 19 the mass numbers of the hyperfragments could not be determined unambiguously.

We also observed decays of other rarely observed hyperfragments. For example, a second instance of Be^{10}_{Λ} decay was observed, which was reported for the first time by Silverstein.[8] The decay of Be^7_{Λ} was observed, although the presence of a previously undetected Li^5 nucleus among the decay products makes this case doubtful. The decay of He^7_{Λ} also deserves mention.

The absence of hyperfragments with $Z = 1$ is accounted for by the scanning procedure, whereby connected tracks within a single pellicle were registered.

Two nonmesonic decays with unusually high energy release were observed; in both instances the connecting track exhibited clear thindown and scattering. The best values of B_{Λ} obtained for these two events were -113 ± 24 and -63 ± 9 Mev, respectively. Table II gives the principal parameters of these events. The tracks were traced and measured by four observers for the purpose of eliminating errors.

In event No. 18 the range of the first particle was not determined unambiguously. At a distance of $1235\,\mu$ from the decay point, this particle probably experienced a nuclear interaction with small energy release, producing a star with a small number of prongs. Two possible residual ranges were therefore considered for this particle. In the first case it was assumed that the end of the track coincided accidentally with the center of the star and that the range was $R = 1235\,\mu$; in the second case it was assumed that the particle interacted in flight.

In order to determine the mass of this particle the measured gap density on the track was compared with the corresponding densities on the differential calibration curves for protons and pions [the $n(\Delta R)$ method]. The results were 1520 ± 243 and $1778 \pm 290\,m_e$, so that this particle may be considered a proton. On the basis of this assumption the residual range for the second case was found to be $2044\,\mu$. The nuclear interaction energy computed from these data was ~ 12 Mev.

It is important to emphasize that the anomalous character of this decay is maintained in both cases.

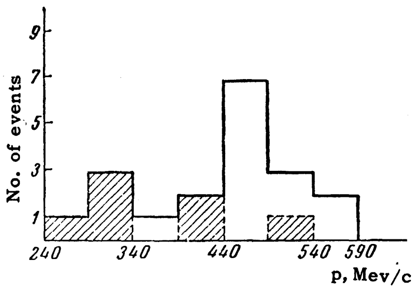

FIG. 1. Momentum spectrum of fast nucleons from nonmesonic decays of hyperfragments. Shaded rectangles – fast protons; unshaded rectangles – fast neutrons.

3. DISCUSSION

All of the observed events involving new hyperfragments had been predicted on Iwao's shell model.[9] Since all hypernuclei known at present agree with Iwao's scheme, the shell-model theory of hypernuclei can be considered to agree satisfactorily with experiment. In the present work members of isotopic multiplets were observed, some for the first time. However, the appreciable errors incurred in determining B_Λ and the small number of events prevent any quantitative check of the consequences of charge independence.

In nonmesonic decays of hyperfragments the ratio of the numbers of decays induced by Λ^0 interactions with neutrons and protons respectively, $R = W_1(\Lambda^0 n \rightarrow nn)/W_2(\Lambda^0 p \rightarrow np)$, can furnish information[10] regarding the character of Λ^0-nucleon interactions. For direct hyperon-nucleon interactions $R \leq 1$, while for interactions through a virtual Σ state $R \geq 0.06$.

In Λ^0 decay induced by a Λ^0-proton interaction the proton acquires energy. Estimates taking into account the energy release in decay and the momentum distribution of nucleons and Λ^0 hyperons in the nucleus indicate that the lower limit of this acquired energy is ~ 30 Mev. The ratio R was computed for definite hyperfragment decays. Accordingly, we take the probability W_2 to equal the number of decays in which protons were emitted with energy above 30 Mev, while W_1 is the number of decays without a fast proton. Our result was $R = 2.43$. According to the results obtained by Ferrari and Fonda[10] this value of R corresponds to a Λ^0-nucleon interaction through a virtual Σ state with nonconservation of parity in the decay.

Figure 1 shows the momentum spectrum of fast nucleons emitted in nonmesonic decays. The momenta are given for all fast protons from definite decay events and for neutrons from events for which definite values of B_Λ were obtained. The higher range of neutron momenta compared with proton momenta agrees with Silverstein's results.[8] This difference in the energy ranges cannot be accounted for by the interaction of a Λ^0 with a single nucleon.

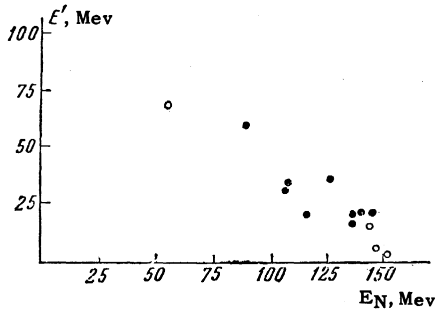

FIG. 2. Relationship between the total energy E_N of fast nucleons and the energy E' of all other particles in decays for which B_Λ was determined definitely. ● – neutron energy in the absence of a fast proton; ○ – combined proton and neutron energy.

Approximately equal mean proton and neutron momenta are observed in decays where a fast proton is produced. Therefore the mechanism of interaction between a Λ^0 and a single nucleon can account for only about 30% of the observed events. When a Λ^0 interacts with a single nucleon the decay products should always include two fast nucleons, whereas in a considerable number of events in which B_Λ was determined definitely only a fast neutron was observed (Fig. 2). We must therefore assume either that in most cases chance values of B_Λ were obtained or that the single-nucleon process is an unsatisfactory hypothesis. An explanation can be sought in the possibility that a Λ^0 interacts with two or more nucleons or individual nuclei. It is evident from Fig. 2 that some events can be explained in this manner, although the energy distribution among the different decay products then remains unaccounted for.

The ratio of nonmesonic to mesonic decays of hyperfragments confirms spin $\frac{1}{2}$ for the Λ^0 hyperon.

Events involving anomalously high energy release cannot be accounted for easily in the conventional manner. An estimated ratio of ~ 0.2 is obtained for accidental passage of a connecting track through a secondary-star center. Some possibility therefore exists that the end fragment track will coincide accidentally with a star center.

If the possibility of chance coincidences is ignored the effect cannot be accounted for satisfactorily by assuming the existence of a Λ^0 hyperon in the nucleus. The existence of hypernuclei with other known hyperons is excluded because of the possibility of strong interactions. The anomaly can then be accounted for by the existence of other strange particles allowed by the scheme of Gell-Mann and Nishijima. The existence of a hyperon with mass ~ $3000\,m_e$ and strangeness +1 would then account for the large energy release in the aforementioned events.

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175