needed is to define a new G matrix

$$G'(\omega)=G(\omega-2c), \tag{21}$$

where c is the amount of the constant translation (negative if downward). This lowering of the spectrum makes G more attractive and results in a lowering of the total energy, the SP levels, and a further decrease in radius. Köhler[32] and Wong[13] have given the rough rule that lowering the particle spectrum by 10 MeV increases the binding per nucleon by 1 MeV. By chance' this is exactly the figure that comes out of our calculations also.

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Nonmesonic Decay of Hydrogen Hyperfragments

R. G. Sorensen, M. W. Holland, H. G. Miller,* and J. P. Roalsvig
Department of Physics and Astronomy, State University of New York, Buffalo, New York 14214

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Approximately 35 000 K$^-$-capture stars in an emulsion stack were examined for hyperfragments. Using a mass selection criterion for all events, a sample of 13 π^--mesonic decays and one nonmesonic decay of hydrogen hyperfragments was identified for the purpose of estimating the relative rates of decay for the π^--mesonic and nonmesonic modes.

I. INTRODUCTION

The study of nonmesonic decays of hyperfragments has been limited by the difficulty in identifying the decaying hyperfragments. This is particularly the case for $_\Lambda$H, where first the charge of the particle must be determined by profile measurements to separate the $Z=1$ events from those with $Z\geq 2$. In order to separate the $_\Lambda$H events from lighter $Z=1$ particles, including a large number of Σ^- capture events, gap or blob measurements must be performed. Although a number of investigations have been carried out on the nonmesonic decays of various hypernuclei, no direct measurement of the nonmesonic decay of $_\Lambda$H has been done previously.

In this work, an attempt has been made to directly identify nonmesonic decays of $_\Lambda$H and estimate the nonmesonic-to-π^--mesonic decay ratio for $_\Lambda H^4$.

II. EXPERIMENTAL PROCEDURE

A. Scanning and Emulsion Stack Calibration

The scanning technique and the calibration of the emulsion stack have been described in a previous paper.[1] In both the previous and the present work, only the 45 interior pellicles from a stack of 100 KTB-5 emulsion pellicles (15 cm×10 cm×0.07 cm) were area-scanned. Approximately 35 000 K^--capture stars (or primary stars) were observed and recorded.

The same range-energy calibration correction has again been used on all measurements made in the present work. Also, the range and angle measurements and the kinematic analysis of the mesonic decays of $_\Lambda$H are the result of the same techniques as described previously.

B. Mesonic Decays of $_\Lambda$H

Of the approximately 300 mesonic hyperfragment decays found in the emulsion plates scanned, 72 mesonic decays of $_\Lambda H^{3,4}$ were identified. From these a sample of 13 hydrogen hyperfragments was selected whose hyperfragment prong had a projected range $R_{HF}\geq 350\,\mu$, and a dip angle $|\alpha|\leq 30°$. Since gap-interval measurements were used in the identification of the nonmesonic

* Present address: Physics Department, University of Saskatchewan, Saskatoon, Saskatchewan, Canada.

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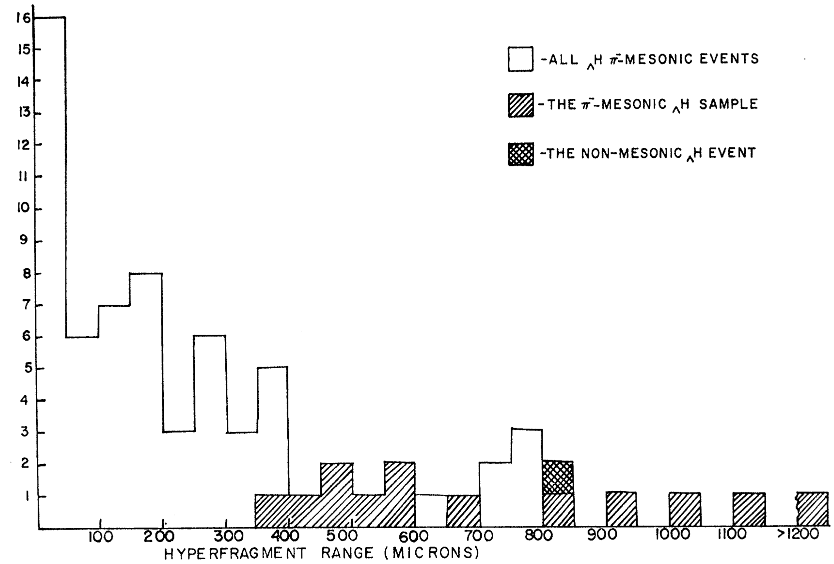

FIG. 1. Hyperfragment ranges of the 72 mesonic $_{\Lambda}$H events, the 13 events in the mesonic $_{\Lambda}$H sample, and the nonmesonic $_{\Lambda}$H event.

$_{\Lambda}$H events, the above criteria on the range and the dip angle of the hyperfragment prong were imposed to improve the reliability of identification. In addition, it was required that the hyperfragment was produced on a K^- capture star which had at least two other dark prongs. This condition was imposed for two reasons: first, it has been shown[4] that production of a hydrogen hyperfragment from K^- capture stars with less than two dark prongs other than the hyperfragment prong is quite infrequent; and, secondly, it minimized the Σ^- contamination in the nonmesonic sample since these particles are produced in a large number of cases with a pion and only one heavy prong in the K^- capture star.

C. Nonmesonic Decays of $_{\Lambda}$H

A group of nonmesonic hydrogen hyperfragment candidates was selected from a group of charge one prongs which had been previously identified using profile (track thickness) measurements.[2] The nonmesonic candidates were further selected using the same criteria as for the mesonic events but with the additional requirements that the secondary range have a range $\geq 20\ \mu$. Those events with a secondary range between 1600 and 1750 μ were omitted since most of these events may be assumed to be Σ^+ particles which decay at rest into a π^0 and a proton of unique momentum. In addition, it was required that at the secondary vertex there be either a scattering angle of at least 75° or a distinct change in the ionization between the primary and the secondary prongs. These latter requirements were imposed in order to minimize the contamination from Coulomb scattering.

An attempt was made to eliminate contamination from Σ^- captures by measuring the size of gaps in the tracks of all unknown events using an image splitting eyepiece. It is to be expected that among charge -1 particles those which are more massive will have a larger volume of track ionized for equal track lengths when measured from the stopping point of the particle. At least 350 and up to 1000 μ of each connecting track was thus measured and the total gap length for gaps $\geq 0.34\ \mu$ was found for each connecting track.

The 13 $_{\Lambda}$H standards were selected from the previously identified mesonic decays of $_{\Lambda}$H, while 20 Σ^+ particles chosen from among those previously omitted from the sample on the basis of their unique proton range were used as Σ standards. Because of a lack of steep Σ^+ standards it was found necessary to find two additional standards from previously identified Σ^- captures (events 31–99 and 35–99). It was also necessary to use three additional steep mesonic $_{\Lambda}$H events for comparative purposes (events 27–4, 61-9, and 64-3) although they were not included as a part of the mesonic $_{\Lambda}$H sample because of their large dip angle.

Thirty-eight standards (22Σ and 16 $_{\Lambda}$H standards) were gap-measured. Since tracks close to the top of the emulsion were found to be developed to a greater extent than deep tracks, the graphs of integrated gap length versus projected range were plotted for two different depth intervals. The particular interval to which a track was assigned was determined by the depth of the midpoint of the track segment. The Σ and $_{\Lambda}$H regions were determined for each of these depth intervals and are separated from each other on the graphs by dashed lines. The $_{\Lambda}$H region is the lower region in all cases. These regions were then used to determine the identities of the unknown connecting tracks.

III. RESULTS

A. Mesonic Decays of $_{\Lambda}$H

Thirteen mesonic decays of $_{\Lambda}$H which fit the previously mentioned criteria were identified. These events are listed in Tables I and II.

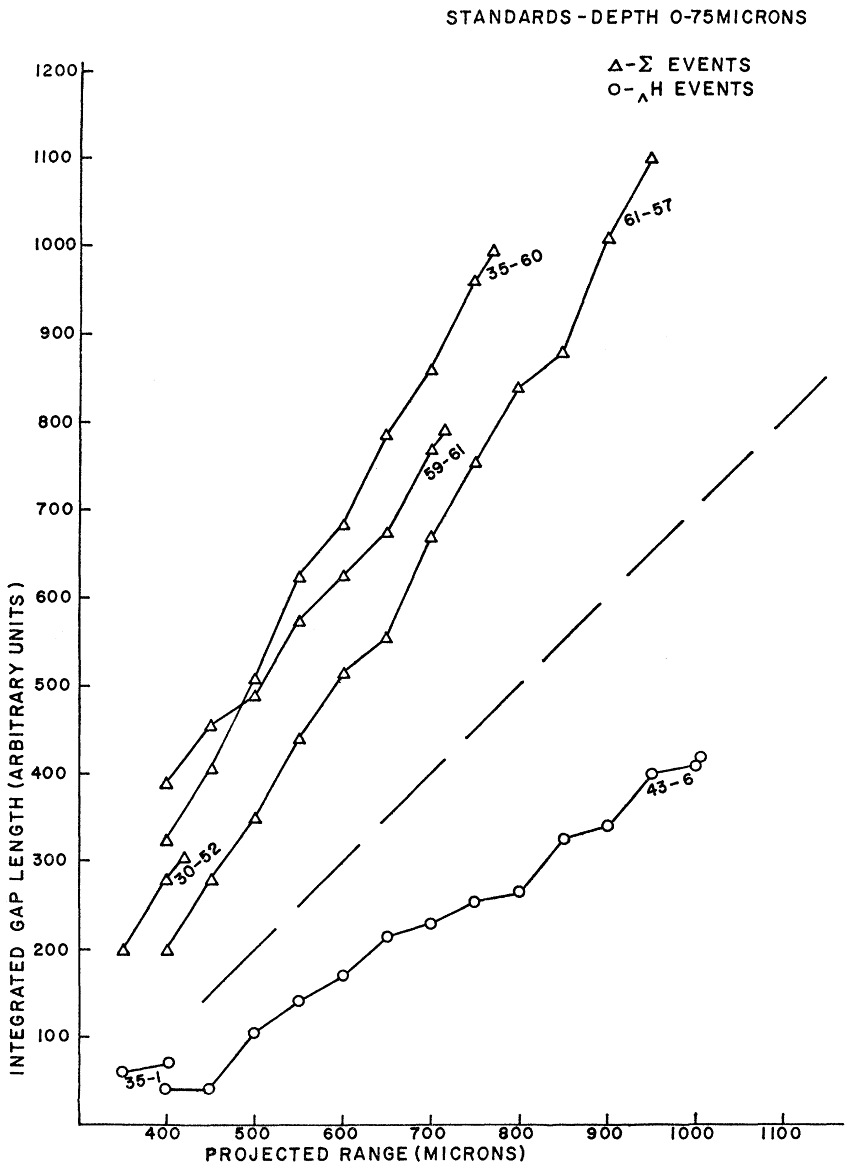

FIG. 2. Gap measurements of Σ^+ and $_\Lambda$H standards at depth 0-75 μ.

TABLE I. List of π^--mesonic decays of $_\Lambda$H.

Event	Identity
28–7	$_\Lambda H^3 \rightarrow \pi^- + He^3$
32–9	$_\Lambda H^4 \rightarrow \pi^- + He^4$
34–4	$_\Lambda H^4 \rightarrow \pi^- + He^4$
35–1	$_\Lambda H^4 \rightarrow \pi^- + He^4$
35–2	$_\Lambda H^4 \rightarrow \pi^- + He^4$
39–4	$_\Lambda H^4 \rightarrow \pi^- + He^4$
42–3	$_\Lambda H^3 \rightarrow \pi^- + He^3$
43–6	$_\Lambda H^4 \rightarrow \pi^- + p + H^3$
44–3	$_\Lambda H^4 \rightarrow \pi^- + He^4$
48–3	$_\Lambda H^4 \rightarrow \pi^- + p + H^3$
48–12	$_\Lambda H^4 \rightarrow \pi^- + He^4$
54–6	$_\Lambda H^3 \rightarrow \pi^- + p + p + n$
61–4	$_\Lambda H^4 \rightarrow \pi^- + He^4$

Since the recoil ranges of the two-body π^--recoil modes are so close as to be indistinguishable, the identities of these modes were determined by tracing the pions to their ends, or in the case of pions which could not be traced or which interacted in flight, grain counts were made in order to accomplish an identification.

Of the thirteen mesonic events which fit our criteria, three were identified as decays of $_\Lambda H^3$, while ten were identified as decays of $_\Lambda H^4$. A histogram of hyperfragment range versus number of events is given in Fig. 1. The crossed area represents the events in the present mesonic sample. The hyperfragment range of the one nonmesonic event is also indicated.

B. Nonmesonic Decays of $_\Lambda$H

Figure 2 contains all standard events which were in the 0–75-μ depth interval as measured from the top of

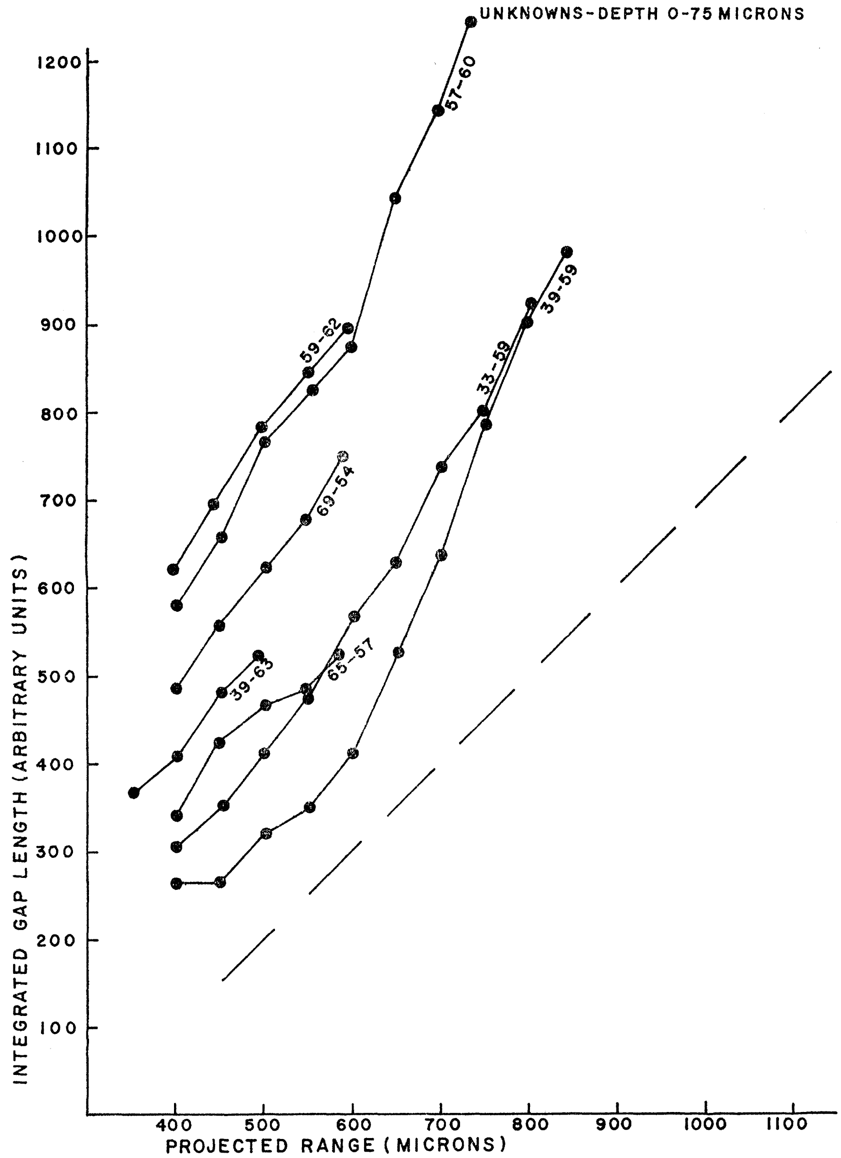

FIG. 3. Gap measurements of unknowns at depth 0-75 μ.

the emulsion. Although the number of events, especially the ${}_{\Lambda}H$ standards, is small, there appears to be a distinct separation between the Σ and ${}_{\Lambda}H$ events.

Figure 3 shows the curves obtained for all unknown events in the same shallow depth region. All of these events are well above the separation between the two regions as obtained from Fig. 2, and are therefore identified as Σ^- capture events.

TABLE II. π^--mesonic decays of ${}_{\Lambda}H$ grouped by decay mode.

Hyper-fragment	Decay mode	No. of events
${}_{\Lambda}H^3$	$\rightarrow\pi^-+He^3$	2
	$\pi^-+p+p+n$	1
${}_{\Lambda}H^4$	$\rightarrow\pi^-+He^4$	8
	π^-+p+H^3	2

Figure 4 contains curves for standard events at depth $>75\ \mu$ and absolute dip angle $<19°$. The five Σ^+ standards and four ${}_{\Lambda}H$ standards shown, form boundaries for their particular regions. Although there is little separation for ranges less than 600 μ, the curves do begin to separate beyond this region.

Figure 5 shows the curves obtained for the unknown events in the deep region. Most of the events are once again clearly above the dividing area and are therefore identified as Σ particles.

Although some of the dependence of gap length on dip angle is eliminated by using the projected range of the track, the dependence appears markedly at large angles. Although they appear to be located in the ${}_{\Lambda}H$ region the two unknown events, 29-52 and 62-60,

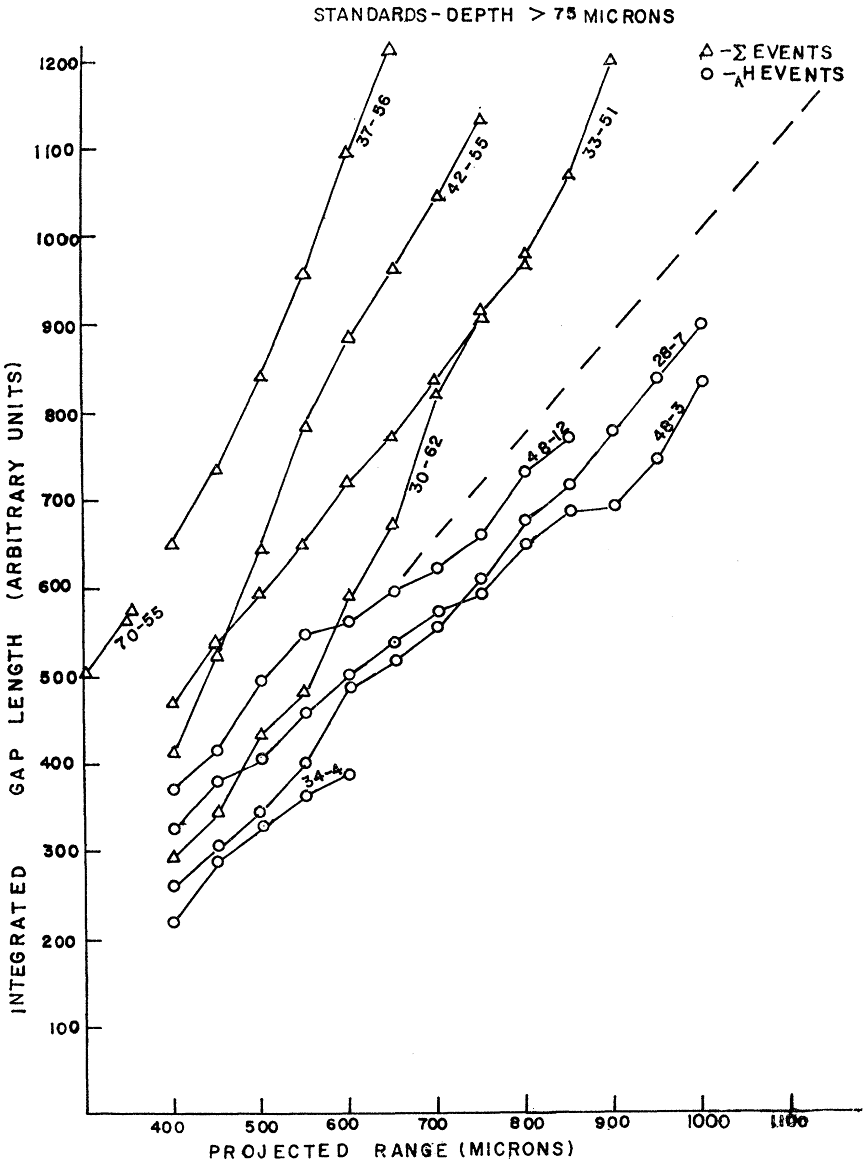

FIG. 4. Gap measurements of Σ^+ and $_\Lambda$H standards at depth greater than 75 μ and a dip angle less than 19°.

cannot be identified as such on the basis of the results shown in Figs. 6 and 7.

Figure 6 contains Σ standards and unknown events which are deep in the emulsion and have absolute dip angles $\geq 19°$, while Fig. 7 contains $_\Lambda$H standards and unknowns with similar characteristics. These two figures indicate the progressive change in integrated gap length with dip angle for these events. The three steep unknown events, 29–52, 50–51, and 62–60, are seen to fit well into this scheme, indicating that 29-52 and 62-60 are Σ particles and that 50-51 is due to nonmesonic decay of $_\Lambda$H. We therefore identify event 50-51 as the only nonmesonic decay of $_\Lambda$H found in our sample.

The five possible nonmesonic decay modes of $_\Lambda$H are given in Table III. The two-body modes can be ruled out as possible modes for event 50–51 on the basis of their unique secondary ranges.

Data pertaining to event 50–51 are given in Table IV.

Since on the basis of theoretical considerations (see Sec. IV B), it can be shown that the nonmesonic decay rate for $_\Lambda H^3$ is very much lower than that for $_\Lambda H^4$, it is likely that event 50–51 is nonmesonic decay of $_\Lambda H^4$.

TABLE III. Possible nonmesonic decay modes $_\Lambda H^{3,4}$.

$_\Lambda H^3 \to H^2 + n$	Energy (deuteron) = 58 MeV
$H^1 + n + n$	Range (deuteron) = 7.1 mm
$_\Lambda H^4 \to H^3 + n$	Energy (triton) = 44 MeV
$H^2 + n + n$	Range (triton) = 3.5 mm
$H^1 + n + n + n$	

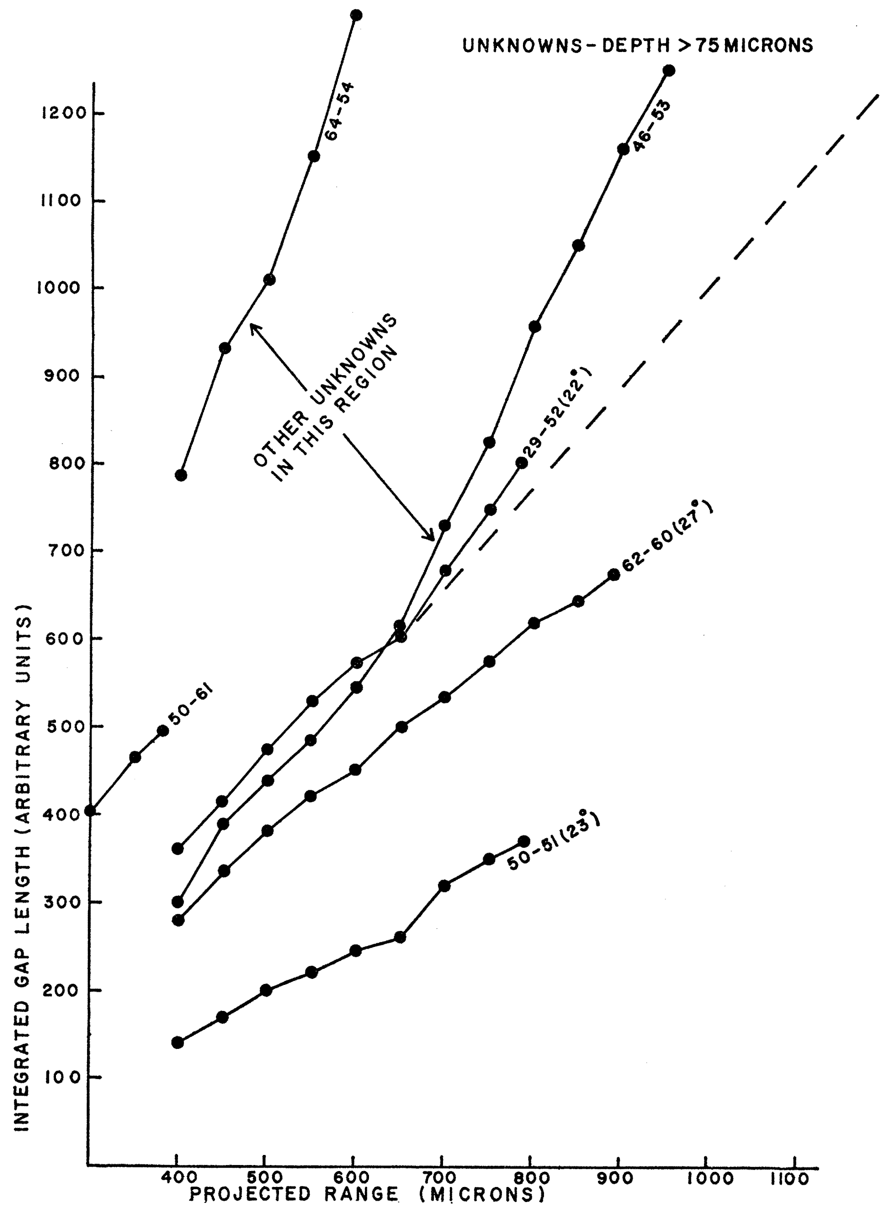

FIG. 5. Gap measurements of unknowns at depth greater than 75 μ.

C. Correction Factors

Because of the light ionization of the pion and the shortness of the recoil, π^--recoil events of $_\Lambda$H are probably the easiest events to miss during area scanning of the plates. Therefore a check of all possible π^--recoil events in five plates was made. The numbers of events found in both scannings were identical, which implies a high efficiency for these plates. It is reasonable therefore to assume that no correction for detection efficiency needs to be made for the entire sample.

Using procedures similar to those reported previously,[2] the contaminations due to decays of hydrogen hyperfragments by the π^0 mode and due to Coulomb scattering of charge-one particles, are each predicted to be considerably smaller than one event for a sample of our size. Also, the loss due to momentum restrictions (range and angle) placed on the visible decay prong, will only be significant if the charged decay prong is emitted rather frequently with momentum less than about 100 MeV/c. From our previous work[2] this seems rather unlikely.

TABLE IV. Summary of nonmesonic decay of $_\Lambda H^4$.

Event No.—50-51
Hyperfragment range—840 μ
Secondary range—5486 μ
Secondary energy for indicated identity proton–37 MeV deuteron–48 MeV

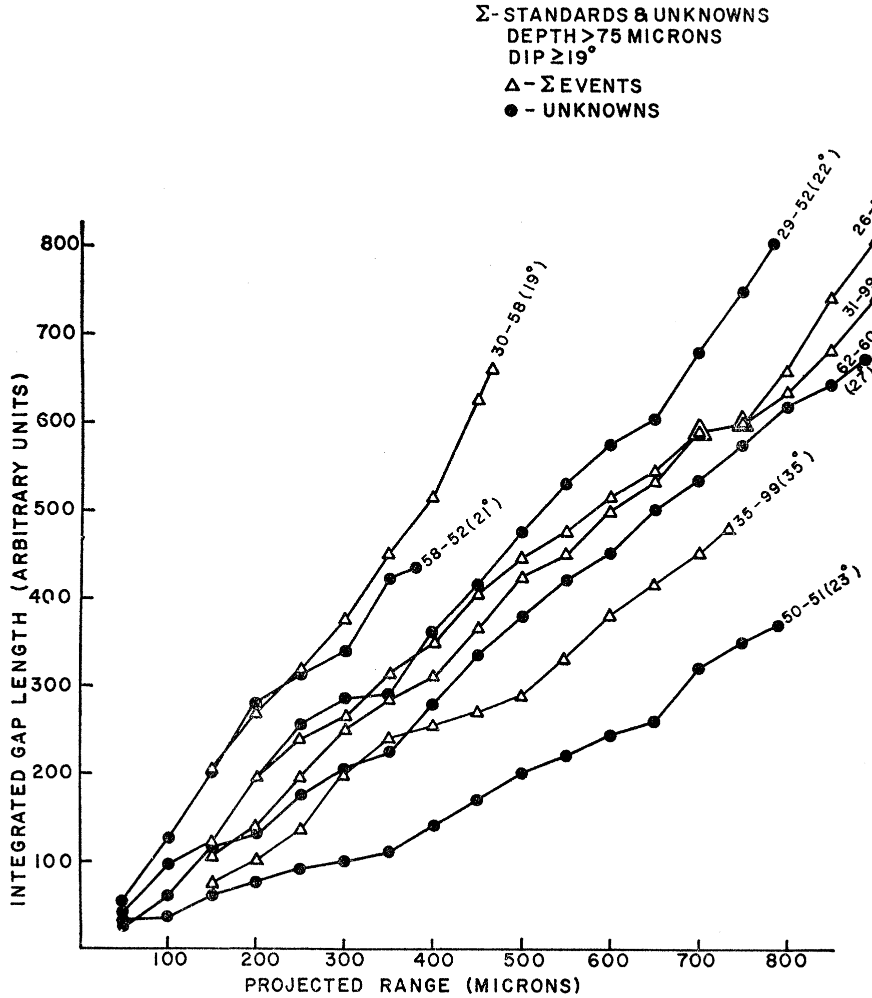

FIG. 6. Gap measurements of Σ standards and unknowns at depth greater than 75 μ and dip angle greater than 19°.

D. Ratio of Nonmesonic to π^--Mesonic Decays of $_\Lambda$H

The nonmesonic to π^--mesonic ratio $[Q(_\Lambda\mathrm{H})]$ for $_\Lambda$H is given by

$$Q(_\Lambda\mathrm{H})=\frac{\text{No. of nonmesonic }_\Lambda\text{H events}}{\text{No. of }\pi^-\text{-mesonic }_\Lambda\text{H events}}$$

The number of mesonic decays of $_\Lambda$H in our sample was 13 while the number of nonmesonic decays was 1, giving a $Q(_\Lambda\mathrm{H})$ of about 0.08.

Similarly, the nonmesonic to π^--mesonic ratio $[Q(_\Lambda\mathrm{H}^4)]$ for $_\Lambda\mathrm{H}^4$ is given by

$$Q(_\Lambda\mathrm{H}^4)=\frac{\text{No. of nonmesonic }_\Lambda\text{H}^4\text{ events}}{\text{No. of }\pi^-\text{-mesonic }_\Lambda\text{H}^4\text{ events}}\,.$$

If our only nonmesonic decay is assumed to be a decay of $_\Lambda\mathrm{H}^4$ and since the number of mesonic decays of $_\Lambda\mathrm{H}^4$ is 10, we obtain $Q(_\Lambda\mathrm{H}^4)$ of about 0.10.

IV. DISCUSSION OF RESULTS

A. Comparison with Previous Results

No other experiment has directly determined Q values for $_\Lambda\mathrm{H}^4$. By an indirect method, however, Block *et al.*[3] obtained the value $Q(_\Lambda\mathrm{H}^4)=0.26\pm0.13$. Our value $Q(_\Lambda\mathrm{H}^4)=0.10$ is in agreement with the value obtained by Block *et al.* within experimental uncertainty.

The π^--decay rate for $_\Lambda\mathrm{H}^4$, $\Gamma_{\pi^-}(_\Lambda\mathrm{H}^4)$, can be obtained by using the following results: $\Gamma_{\pi^0}(_\Lambda\mathrm{H}^4)=(0.10\pm0.02)\,\Gamma_{\pi^-}(_\Lambda\mathrm{H}^4)$ of Block *et al*[4] and

$$\Gamma(_\Lambda\mathrm{H}^4)=[1.86(+0.4,\,-0.8)]\Gamma_\Lambda$$

from Davis and Sacton.[5]

When these values are substituted into the expression $\Gamma(_\Lambda\mathrm{H}^4)=\Gamma_{\pi^-}(_\Lambda\mathrm{H}^4)+\Gamma_{\pi^0}(_\Lambda\mathrm{H}^4)+\Gamma_{nm}(_\Lambda\mathrm{H}^4)$, one obtains $\Gamma_{\pi^-}(_\Lambda\mathrm{H}^4)=1.86\Gamma_\Lambda/[1.1+Q(_\Lambda\mathrm{H}^4)]$. Using the value $Q(_\Lambda\mathrm{H}^4)=0.10$, we obtain $\Gamma_{\pi^-}(_\Lambda\mathrm{H}^4)=1.55\Gamma_\Lambda$. This compares with the value obtained by Block *et al.*[3] using $Q(_\Lambda\mathrm{H}^4)=0.26$, namely, $\Gamma_{\pi^-}(_\Lambda\mathrm{H}^4)=1.36\Gamma_\Lambda$. Both of these values are somewhat larger than the theoretical estimate of $\Gamma_{\pi^-}(_\Lambda\mathrm{H}^4)=1.12\Gamma_\Lambda$ made by Dalitz.[6]

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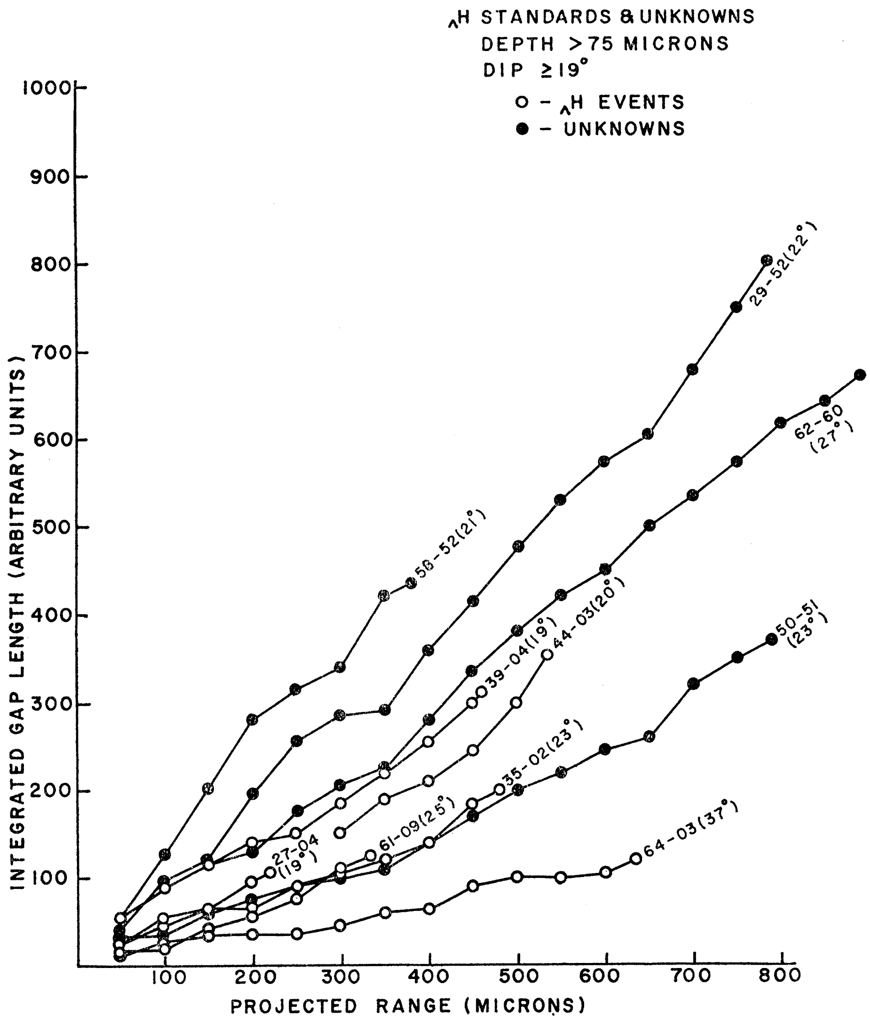

FIG. 7. Gap measurements of $_\Lambda$H standards and unknowns at depth greater than 75 μ and dip angle greater than 19°.

B. Theoretical Considerations

A theoretical method for calculating the nonmesonic decay rates for hypernuclei has been presented by Dalitz.[6–8]

Using the R_{NS} values obtained previously,[2] this method gives $Q(_\Lambda H^3) = 6.1 \times 10^{-3}$. Since we had three π^--mesonic decays of $_\Lambda H^3$ in our sample, no nonmesonic decays of $_\Lambda H^3$ would be expected.

Similarly, a calculation for $_\Lambda H^4$ using the same R_{NS} values gives $\Gamma_{nm}(_\Lambda H^4) = 0.23\ \Gamma_\Lambda$. Taking $\Gamma_{\pi^-}(_\Lambda H^4) = 1.55\ \Gamma_\Lambda$, this will give a $Q(_\Lambda H^4) = 0.15$, which is in good agreement with our experimental value.

The ratio $C(_\Lambda H^4)$ of proton-to-neutron stimulated decays can similarly be calculated to be about 0.2, implying that neutron stimulation should be dominant in nonmesonic decay of $_\Lambda H^4$.

In conclusion it should be noted that while the Q value obtained for $_\Lambda H^4$ is in agreement with that predicted by theory under the $\Delta I = \frac{1}{2}$ rule, our value has a large statistical uncertainty. More important, however, is the indication that the measurement of the π^--mesonic to nonmesonic decay ratio for $_\Lambda H^{3,4}$ can be achieved by direct rather than indirect means. With a much larger sample than ours it may be possible to determine $Q(_\Lambda H^4)$ directly with high enough accuracy that the validity of the $\Delta I = \frac{1}{2}$ rule in Λ-nucleon interactions can be tested.[6–8]

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[8] M. M. Block and R. H. Dalitz, Phys. Rev. Letters 11, 97 (1963).