$$f(\theta) \sim (1+\alpha\bar{P}_\Lambda \cos\theta) d\omega$$

The best-fit asymmetry parameter was found to be

$$\alpha\bar{P}_\Lambda = \frac{3}{N}\sum_{i=1}^{N} \cos\theta_i \pm \sqrt{\frac{3}{N}} = 0.04 \pm 0.08 .$$

Since about 50% of all neutral hyperons are due to conversion, this represents an asymmetry parameter due to Σ conversion events alone, of $\alpha\bar{P}_\Lambda$ (conversion) $\approx 0.07 \pm 0.10$. Thus we find no evidence of parity non-conservation in the Σ-Λ conversion process.

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K⁻ INTERACTIONS AT REST IN HELIUM (*)

The Helium Bubble Chamber Collaboration Group

(presented by M. Block)

INTRODUCTION

A systematic study of K^- interactions at rest in helium has been made with the Duke helium bubble chamber. The chamber, 8″×5″×4″, operated in a 14.0 kg magnetic field, was exposed to a low momentum, separated K^- beam of the Bevatron, and 100,000 pictures were obtained.

TWO-NUCLEON ABSORPTION

Table I shows a preliminary breakdown of 1132 K^-—He^4 interactions in which the K^- was at rest. The various categories correspond to the type of visible emergent hyperon, and whether or not it was accompanied by a charged pion. The category " stars " corresponds to events in which either a) a Λ^0 or $\Sigma^0 \to \Lambda^0$ decayed via the neutral mode $\Lambda^0 \to n+\pi^0$, and thus escaped detection, or b) the Λ^0 decayed outside the chamber. However, a small correction should be made for Σ's decaying near enough to the vertex to escape detection, as well as for unidentified hyperfragments.

If we assume (a) absorption from a single nucleon proceeds via the reaction $K^- + N \to Y + \pi$, and (b) multinucloen capture is via $K^- + 2N \to Y + N$, i.e., no pion is produced, then we are easily able to determine the fraction of multi-nucleon capture from our data. Using charge independence to determine the number of neutral pions $n(\pi^0) = 1/2[n(\pi^+)+n(\pi^-)]$, we see from Fig. 1 that the fraction of multi-nucleon captures is $(17 \pm 4)\%$. The only hypotheses made are (1) charge independence is valid and (2) pion reabsorption in as light a nucleus as He^4 is negligible. This large

(*) This work was supported in part by the Office of Naval Research, U. S. Atomic Energy Commission, Office of Scientific Research, and the National Science Foundation.

Table I. Classification of events

Type	Total		With π^-		With π^+		Without $\pi^\pm$	
	No.	%	No.	%	No.	%	No.	%
Λ^0	360	(31.8)	165	(14.6)	8	(0.7)	187	(16.5)
Stars	447	(39.5)	217	(19.2)	14	(1.2)	216	(19.1)
Σ^+	166	(14.7)	136	(12.0)	0	(0)	30	(2.6)
Σ^-	143	(12.6)	0	(0)	75	(6.6)	68	(6.0)
H.F.	16	(1.4)	14	(1.2)	0	(0)	2	(0.2)
Total	1132	(100.0)	532	(47.0)	97	(8.6)	503	(44.4)

$$\frac{n(\pi^-)}{n(\pi^+)} = \frac{532}{97} = 5.5 \pm 0.6$$
$$n(\pi^+)+n(\pi^-) = 532+97 = 629$$
$$n(\pi^0) = \tfrac{1}{2}[n(\pi^-)+n(\pi^+)] = 315$$
$$n(\pi^+)+n(\pi^-)+n(\pi^0) = 629+315 = 944$$
$$n(2\text{ nucleon}) = 1132-944 = 188$$
$$\text{Fraction of 2 Nucleon} = \frac{188}{1132} = 0.17 \pm 0.04$$

yield of multi-nucleon capture is to be compared on one hand with the deuterium result of about 1%[1] and on the other with the results in nuclear emulsion, estimated by various authors as about 15 to 35%[2]. It is reasonable to expect that in He^4 there is a substantial increase in the probability that two or more nucleons are sufficiently close to absorb the K simultaneously, over the corresponding probability in deuterium, which is a very loosely bound system, and therefore has a substantial spatial separation between the nucleons. The apparent equality with nuclear emulsion is more unexpected. It is known that K^- capture in emulsion is dominantly on the high Z elements, and that it occurs on the surface of these heavy nuclei [3]. Wilkinson [4] has speculated that the nuclear surface of these heavy nuclei behaves as if it

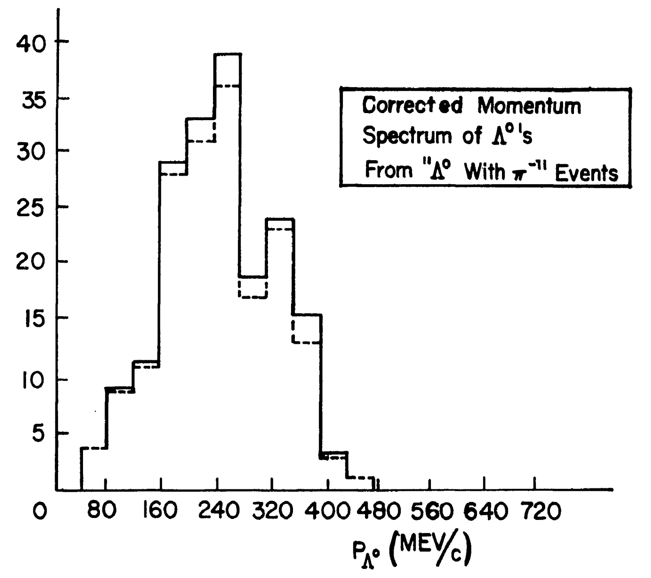

Fig. 1 *(a)* Momentum spectrum of Λ^0's from K^- absorption at rest, when a π^- accompanies the Λ^0.

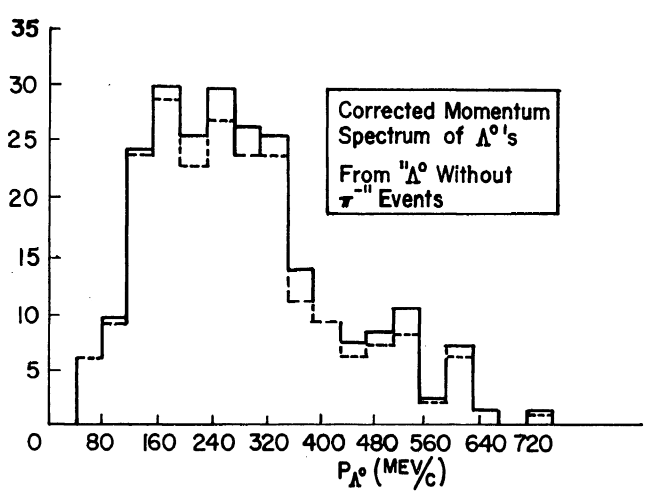

Fig. 1 *(b)* Momentum spectrum of Λ^0's from K^- absorption at rest, when no π^- accompanies the Λ^0.

were a cluster of alpha particles. The striking similarity of the multi-nucleon absorption in He and emulsion thus lends strong support for this model of the heavy nucleus.

We have attempted directly to verify the existence of 2-nucleon absorption by observing that a Λ^0 emitted from the 2-nucleon captures in He should have a momentum of $\sim$580 MeV/c, spread by the motion of the nucleons, whereas a Λ^0 from the reaction $K+N \to \Lambda+\pi$, should have a momentum $\leqslant$500 MeV/c. Figs. 1a and 1b show the momentum spectra of Λ^0's separated into two groups, produced with and without an accompanying π^-. The difference between the two spectra gives good direct evidence for the multi-nucleon capture.

THREE-BODY FINAL STATES :

The reactions

$$K^- + He^4 \to \Sigma^+ + \pi^- + H^3 \quad (a)$$

$$\to \Sigma^- + \pi^+ + H^3 \quad (b)$$

$$\to \Lambda^0 + \pi^- + He^3 \quad (c)$$

are particularly easy to detect and analyze completely since they involve particles all of which are detectable and measurable in the chamber.

The reactions have in common the feature that the 3-nucleons emerge in $S=1/2$, $T=1/2$ states.

We have been able to measure and thus identify, 79 cases of (a), 48 cases of (b), and 33 cases of (c) in the sample of data included in Fig. 1. In another communication to this Conference, we present detailed arguments on the fact that the Λ^0's emerging from the reactions are in large measure due to Σ's that were formed in the basic process $K+N \to \Sigma+\pi$, but the Σ subsequently interacts with a second nucleon on the nucleus and is converted to a Λ^0 via the reaction $\Sigma+N_2 \to \Lambda+N$. Thus, we must compare reaction (c) to only those Λ^0 reactions in which the Λ^0 was directly produced. We can obtain experimentally the fraction of the time that the p, $2n$ emerge as a bound H^3 by obtaining the rate of (a) or (b), compared to the total number of cases in which a Σ^+ and π^- (or $\Sigma^- + \pi^+$) emerge. This rate is found to be 64$\pm$10% for (a) and 63$\pm$10% for (b). We must obtain the corresponding rate for (c) in a somewhat more complicated way, i.e., we must take the rate of (c) over the total number of cases in which a *direct* $\Lambda^0 + {}^-\pi$ emerges; this rate is estimated to be 56$\pm$10%. The mean value for all cases is 61$\pm$6%; thus, about 60% of the time a bound He^3 or H^3 emerges. It must be pointed out that this is the *emergence* rate and not the production rate. The production rate is undoubtedly higher, since final state interactions such as the Σ or Λ scattering off of the 3-nucleons, or the π from reaction (c) (the π energy in (c) is $\sim$150 MeV, an energy where the $\pi - p$ scattering cross section is not far from the (3,3) resonance) off the nucleons would tend to break up the H^3 or He^3. Thus, 61% is a *lower* limit to the production rate of bound 3-nucleon states.

The momentum spectra from *(c)* are shown in Fig. 2 whereas Fig. 3 shows the spectra from $\Sigma^\pm + \pi^\mp + H^3$. We have drawn in theoretical spectra calculated using an impulse model in which a constant matrix element and plane wave states were used. The agreement of Fig. 3 of the pion spectrum with these calculations is remarkably good. Also shown are theoretical curves which were computed from phase space, which neglect completely the internal momentum distribution of the nucleons in the He^4 nucleus. It is clear that they are in violent disagreement with the data. However, when we compare the π^- momentum spectrum of Fig. 2

$$(\Lambda^0 + He^3 + \pi^-)$$

with the impulse model, we see a departure from theory near 170 MeV/c. This probably reflects the results of π-nucleon strong final state interactions

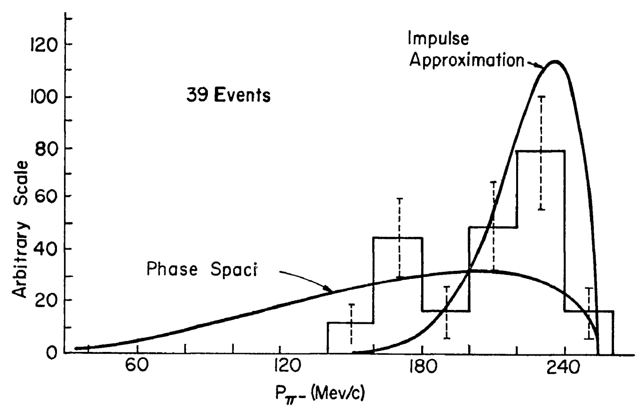

Fig. 2 K^- momentum spectrum from the at-rest reaction $K^- + He^4 \to \Lambda^0 + \pi^- + He^3$.

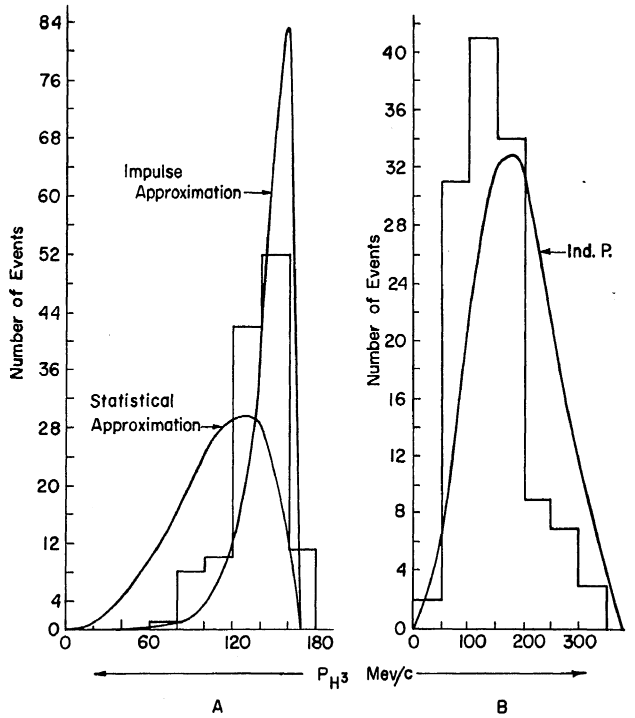

Fig. 3 (A) Pion momentum spectrum from the at-rest reaction $K^- + He^4 \to \Sigma^\pm + \pi^\mp + H^3$.
(B) H^3 momentum spectrum from the same reaction.

that have been neglected in the theory, as well as the strong $\Lambda^0 - N$ forces. Also plotted in Fig. 3 are the triton momentum spectra, compared to the impulse model. The phase space clearly does not fit. The impulse model describes the gross features of the shape, but it is clear that the experimental spectrum is less than the theory for $p_T \sim 210$ MeV/c. This probably reflects the strong final state $\Sigma - N$ interaction. The data are too meager at present to investigate further the very interesting problem of final state $Y - N$ interactions, other than to emphasize their importance.

He^3, H^3 RADIUS

The use of gaussian wave functions for He^3 and He^4 and the impulse model allows us to calculate the fraction of the time a bound H^3 or He^3 will emerge from reactions *(a)*, *(b)* and *(c)*.[5] If $\psi(He^3) = N_3 e^{-\frac{c_3}{2}\Sigma r_{ij}^2}$; $\psi(He^4) = N_4 e^{-\frac{c_4}{2}\Sigma r_{ij}^2}$, where N_3 and N_4 are normalization factors, then the probability that either an H^3 or an He^3 emerge when either a Σ or a Λ is produced is independent of the energy release and is given by $P = \left[\frac{48 c_3 c_4}{(4c_4 + 3c_3)^2}\right]^3$. The relation between c_3 and c_4 and the corresponding r.m.s. radius is given by $R_3 = \frac{1}{\sqrt{3c_3}}$ and $R_4 = \frac{3}{4\sqrt{2c_4}}$ where R_3 and R_4 are the radii of He^3 (H^3) and He^4, respectively. Using $R_4 = 1.66$ (fitted to Hofstadter's measurement[6]) we have plotted this probability versus R_3 in Fig. 4. For $P = 61 \pm 6\%$, we obtain a radius of 2.08 ± 0.08f. It must be emphasized that final state interactions not included in this theoretical treatment, probably lower the experimentally observed value of P. Therefore this radius estimate of He^3 (H^3) is probably somewhat too large.

MODEL OF $K^- + He^4$ INTERACTIONS :

We note that reactions of the type *(a)*, *(b)* and *(c)* where an H^3 or an He^3 emerge, play a rather dominant role. We have found that 61% of the time, the bound 3-nucleon system emerged and have also argued that the true fraction produced was greater. This lends support for our model in which we postulate that in *every* one-nucleon absorption, the remaining three-nucleons emerge in the $S = 1/2$, $T = 1/2$ state, i.e., that the emerging nucleons are *all* the equivalent of the H^3 or He^3 systems. After production, some Σ's convert to Λ^0's on the nucleons in the H^3 or He^3 and cause them to undergo fragmentation. This model severely restricts the production reactions to

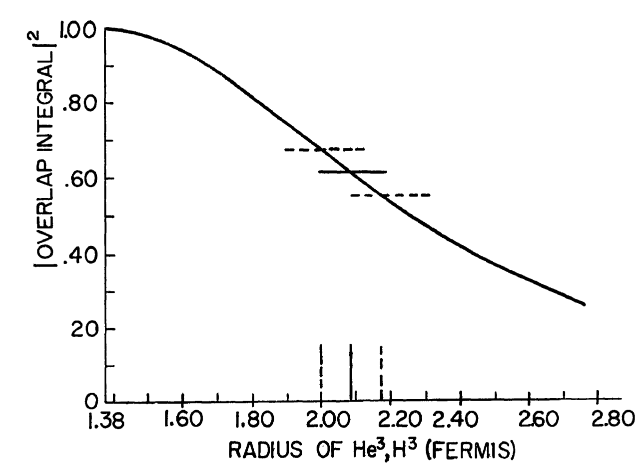

Fig. 4 Radius of He^3, H^3 as a function of the probability of emergence of a bound 3-nucleon system, He^3 or H^3, assuming radius of He^4 to be 1.66 *f*.

the reactions *(a)-(g)* shown in Table II. Also shown is a charge independence analysis of these reactions into singlet and triplet isospin amplitudes M_0 and M_1 for the Σ, π system and a corresponding amplitude N_0 for the Λ, π system.

Table II. Production reaction rates

(a)	$H^3+\Sigma^+ +\pi^- = \frac{1}{3}M_0^2+\frac{1}{6}M_1^2-\frac{\sqrt{2}}{3}\,\mathrm{Re}\, M_0^* M_1$
(b)	$H^3+\Sigma^- +\pi^+ = \frac{1}{3}M_0^2+\frac{1}{6}M_1^2+\frac{\sqrt{2}}{3}\,\mathrm{Re}\, M_0^* M_1$
(c)	$H^3+\Sigma^0+\pi^0 = \frac{1}{3}M_0^2$
(d)	$He^3+\Sigma^-+\pi^0 = \frac{1}{3}M_1^2$
(e)	$He^3+\Sigma^0+\pi^- = \frac{1}{3}M_1^2$
(f)	$H^3+\Lambda^0+\pi^0 = \frac{1}{3}N_0^2$
(g)	$He^3+\Lambda^0+\pi^- = \frac{2}{3}N_0^2$

The corresponding conversion reactions for $\Sigma+N\rightarrow\Lambda+N$ are shown in Table III, along with the isotopic spin weights multiplied by the number of nucleons available for the conversion to give the total weights. It is to be noted that the Σ^- conversion is further forbidden by the Pauli exclusion principle, since the final state is that of 3 neutrons. We then assume a conversion coefficient ε, and regroup the relations of Table III according to the experimentally observable categories.

After subtracting off the " direct " Λ^0 reactions *(f)* and *(g)* as well as 2-nucleon absorptions, we are able to solve these relations and obtain the production rates shown in Table IV.

Table IV. Charge independence solution for production rates

$\frac{\lvert M_0\rvert^2}{\lvert M_1\rvert^2}=6$ Phase angle $\delta\simeq 180$		$4\varepsilon=0.57$ $P=0.75$
For Single Nucleon		
$\Sigma^+:\Sigma^0:\Sigma^-:\Lambda^0$ 317: 224: 130: 252	$\frac{\Sigma^-}{\Sigma^+}\simeq 0.4$	$\frac{\Sigma^{\pm 0}}{\Lambda^0}=2.7$
For Two Nucleon		
$\Sigma^+:\Sigma^0:\Sigma^-:\Lambda^0$ 30: 54: 42: 62	$\frac{\Sigma^{\pm 0}}{\Lambda^0}=2.03$	

We see that the $T=0$ amplitude is greater than the $T=1$ amplitude. Further, the $\Sigma^{\pm,0}/\Lambda^0$ yield is also quite large, and the conversion of Σ's is $\sim 55\%$. Thus, in spite of the fact that emergent

Table III. Conversion reactions

	Isospin Wt.	× No. Conv. Nuc.	= Total Wt.
$\Sigma^+ +\pi^- +H^3\rightarrow\Lambda^0+\pi^- +(ppn)$	2	2	4
$\Sigma^0+\pi^0+H^3\rightarrow\Lambda^0+\pi^0+(pnn)$	1	3	3
$\Sigma^- +\pi^+ +H^3\rightarrow\Lambda^0+\pi^+ +(nnn)$	2	1	$2P$ (*)
$\Sigma^- +\pi^0+He^3\rightarrow\Lambda^0+\pi^0+(pnn)$	2	2	4
$\Sigma^0+\pi^- +He^4\rightarrow\Lambda^0+\pi^- +(ppn)$	1	3	3

Observed no. of events

$(\Sigma^+,\pi^-)=a(1-4\varepsilon)$ $(\Lambda^0,\pi^-)=4\varepsilon a+e+g$ $(\Lambda^0)=c+4\varepsilon d+f$ $(\Sigma^-)=d(1-4\varepsilon)$ $(\Lambda^0,\pi^+)=b\times 2\varepsilon P$	4ε represents conversion rate of Σ+nuc.$\rightarrow\Lambda^0$+nuc.

(*) *P* represents reduction of rate due to Pauli exclusion principle on 3 neutrons.

Λ^0's accounted for about 75% of all interactions, we see that most of these are due to Σ conversions. We note that the Pauli principle has not seriously diminished the Σ^- conversion rate, which reflects the fact that the neutron emergent from the conversion has $T \sim 45$ MeV and thus does not appreciably overlap the remaining slow nucleons.

We gratefully acknowledge the aid of the Lawrence Radiation Laboratory and the Bevatron staffs in making this experiment possible.

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DISCUSSION

FEYNMAN: What were the numbers of Σ^+, Σ^- and Λ^0 before you made all the re-analysis?

BLOCK: There are 79 of the Σ^+, 48 with the Σ^- and 33 Λ^0's and to answer your question a little more fully, the number of the Λ^0's was 360 emerging +447 stars, in other words, about 800 Λ^0's, 166Σ^+ and 143Σ^- and 16 hyperfragments.

MILLER: What is the point of this kind of an analysis...is it to shed light on the K-nucleon interaction or just to perform a phenomenology on the K-helium system? What is your conclusion?

BLOCK: Well, there are two points in doing this analysis. One point was to look and see if we have a Σ^+ to Σ^- ratio in accord with the deuterium results. After all, we have a very substantial amount of conversion. This is a secondary process. We would like to look back at the production amplitudes to see if they were similar. Secondly, we would like to be able to compare with the K-nucleon data to see if there is any basic difference. One finds quite a bit of difference actually if you take the parameter $\Sigma^- : \Sigma^+$ as a scaling factor. You found a number not far from 1 : 1. The hydrogen people find more like 2 : 1. We are finding systematically lower values. These all represent different energy releases in the system because after all the K has about 28 MeV less mass energy inside the helium nucleus because of the helium binding. One would like to see if this ratio is very sensitive to the energy available in the reaction. There seems to be a good bit of evidence that as you go to in-flight data the ratio changes very dramatically. We are going into the negative energy region so to speak, by absorbing in the heavy nucleus.

SNOW: Is not this analysis very sensitive to the re-scattering of sigmas off He^3 and H^3, so that it is very difficult to go back to the original production amplitudes? There is more than just conversion; there is also re-scattering as Rodberg and Karplus have indicated.

BLOCK: Oh yes, this is as I said a very simplified approach. I use the language of Leitner. He had a zeroth order, ours was a first order description. One should take into account many more effects. This was a first look. One could also analyse in a very similar fashion the emergent isotopic spin states. We have also done that. One basically does not get an answer very different from this.