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Evidence of Nuclear Structures from K^--Meson Absorption*

G. T. CONDO AND R. D. HILL
Department of Physics, University of Illinois, Urbana, Illinois
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The characteristics of the multinucleon capture of K^- mesons in nuclei have been investigated in both normal and water-soaked $G5$ nuclear emulsion. It has been found that the emission of fast ($\gtrsim 60$ MeV) hyperons is more often associated with K^- captures in light (C,N,O) than in heavy (Ag,Br) nuclei. Further, considering the relative absorptions of Σ hyperons in the parent nucleus in which they are produced, we inferred that the rate of multinucleon K^- absorptions is approximately the same for all nuclei of nuclear emulsion and corresponds to $\sim 17\%$ of all K^- absorptions at rest. From those events which can be definitely assigned to interactions in light nuclei, by virtue of energy and momentum conservation, it was found that the reaction $K^- + (n,n) \rightarrow \Sigma^- + n$ is of comparable intensity with the reaction $K^- + (n,p) \rightarrow \Sigma^- + p$, and that in light nuclei, the major mode of multinucleon K^- absorption in C,N,O appears to be on a pair of nucleons in an α-particle cluster. Comparison of the characteristics of the K^- multinucleon absorptions in light and heavy nuclei shows that α-particle clusters are less likely to be involved in (Ag,Br) than in (C,N,O). An attempt to estimate the nuclear pair correlation function was also made.

I. INTRODUCTION

BOSON absorptions by nuclei have given indications of developing into useful tools for investigating nuclear structures, especially of nucleon correlations in nuclei. It has been shown[1,2] for instance in high-energy ($\sim$300 MeV) photodisintegration, that nearly all those disintegrations giving rise to high-energy protons proceed via interactions with neutron-proton (n,p) pairs. A number of theories, starting from Levinger's[3] pseudodeuteron theory and including intermediate-meson effects,[4] have been invoked to describe the observations of these high-energy photodisintegration experiments. The latest work[5,6] indicates that the primary photon absorption occurs almost entirely on (n,p) pairs and, if meson effects are to be included they must be involved with the primary nucleon pairs.

In the absorption of π mesons by nuclei it was very early appreciated[7,8] that low-energy pions would be principally absorbed by pairs of nucleons. A number of experimental investigations[9,10] showed that this was indeed so, and in a recent experiment[11] a measurement has been made of the ratio of the absorptions according to the two following processes:

$$\text{(a)}\ \pi^- + (p,n) \rightarrow n + n,$$
$$\text{(b)}\ \pi^- + (p,p) \rightarrow n + p.$$

It was found that the ratio of (a) to (b) is approximately four in carbon and aluminum, and this is again consistent with more (n,p) than (p,p) pairs being responsible for absorbing low-energy pions.

The absorption of K^- mesons by nuclei has certain characteristics which are different from both pion and photon absorptions. One of these is that single nucleon absorption of K^- mesons is more probable than dinucleon absorption. This is possible because the single nucleon absorption reaction, $K^- + n$ or $p \rightarrow Y + \pi$, where Y is a hyperon, is the result of a strong interaction in which both energy and momentum are conserved. The two-nucleon reactions

$$K^- + (n,n) \rightarrow Y^- + n,$$
$$K^- + (n,p) \rightarrow Y^0 + n \text{ or } Y^- + p,$$
$$K^- + (p,p) \rightarrow Y^0 + p \text{ or } Y^+ + n,$$

also result from strong interactions, and their yields are less than the single-nucleon reaction probably only to the extent that nucleon pairs of high relative momenta are less frequently present in nuclei than are the "free" nucleons.

Attention was first drawn to multi-nucleon absorption of K^- mesons in nuclear emulsions by the European K^- collaboration group[12] who investigated the relatively high energy hyperons emitted in this type of capture. Depending on the mode of analysis, multinucleon capture has been found to amount to approximately 9–37% of all K^- capture events in nuclei of photographic emulsions[13,14].

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Another important difference between the capture of π^- and K^- mesons is that K^- absorption at rest is significantly stronger than absorption of π^- mesons at rest. This has been pointed out especially by Jones[15] who proposed that K^- meson capture would occur mainly in the nuclear surface. This proposal has been taken up by Wilkinson[16] as a means of exploring the nuclear surface, and he has interpreted the high multinucleon absorption rate as indicative of a considerable amount of alpha-particle substructure occurring on the nuclear surface.

The Wilkinson model, however, has not received general acceptance. McCarthy and Prowse[17] believed that a K^- meson could be also strongly scattered by nucleons in a nuclear surface and might easily reach the nuclear interior before capture. A rebuttal of this argument, on the basis of calculations by Rook, has been given by Wilkinson.[18] The alpha-particle surface model has also been opposed by Eisenberg *et al.*[19] who made measurements of the relative multinucleon K^- capture rates in light and heavy nuclei of photographic emulsions. According to these measurements, which are somewhat at variance with the ones of the Bristol-London group, the amount of multinucleon capture increases significantly with the atomic mass of the capturing nucleus. Eisenberg *et al.* believed that their results were more consistent with whole nuclear volume absorption, and they attributed this characteristic to the production of an intermediate metastable hyperon which could migrate from the surface where it was produced. They have since attempted to identify the intermediate metastable hyperon with the Y^{0*} of mass 1405 MeV.[20]

The intent of the present investigation was to look further into the nature of the differences in the results of the two existing experiments of K-meson multinucleon capture and then attempt to analyze, especially for light nuclear captures, the nature of the substructures involved in the capture process. In the first part of the present paper we describe the experiments and results. In the second part we attempt to interpret the results in terms of existing nuclear models.

II. EXPERIMENTAL METHOD

As we have just seen in the discussion of existing data on the multinucleon absorption of K mesons in nuclear emulsions, there is uncertainty in the degree of relative absorption in light and heavy nuclei. Fortunately, there were available for our experiments two emulsion stacks possessing significantly different compositions of light and heavy nuclei. One stack consisted of normal $G5$ Ilford emulsion; the other of an almost completely water saturated $G5$ Ilford emulsion. The technique of preparing the wet stack and some of the results obtained from this experiment have already been described.[21] The atomic concentrations in the dry and wet stacks, given in units of 10^{22} atoms/cm^3, were as follows:

	Ag	Br	H	C	N	O
Dry $G5$:	1.013	1.007	3.200	1.390	0.318	0.938
Wet $G5$:	0.32	0.32	5.55	0.45	0.10	2.57

In these emulsions the wet stack contained 93% light elements (H,C,N,O) and the dry stack contained 74% (H,C,N,O). Excluding hydrogen the ratio of light (C,N,O) to heavy (Ag,Br) atoms was 4.9 and 1.3 in the wet and dry stacks, respectively. We have endeavored to correlate the light and heavy nuclear captures with the atomic content of the two emulsions.

A total of 2300 proven K^--meson absorption stars in the dry $G5$ stack and 1460 similarly proven K^- stars in the wet $G5$ stack were selected for investigation. In order to be sure that no fast hyperons arising from the K^- stars were missed, all prongs from the K^- stars with a grain density greater than twice plateau value were followed until they reached the end of their range, decayed, interacted in flight, left the emulsion stack, or could be identified with certainty. With this criterion fast Σ hyperons with energies as high as 250 MeV could have been observed. The maximum hyperon kinetic energy to be expected from a K^- meson, captured at rest on a nucleon of 25-MeV Fermi energy, is of the order of only 200 MeV. In fact, Jones *et al.*[14] reported no hyperon of energy greater than 200 MeV in a sample of 140 Σ's, and Eisenberg *et al.*[19] reported only two cases of the order of 200 MeV in a sample of 65 Σ's. The Σ hyperons in the present experiments were identified by their decays, either in flight or at rest, or by their exoergic interactions in flight or at rest.

All K^--meson capture stars were examined closely for a number of points, whether a fast Σ hyperon was emitted or not. Firstly, as evidenced from the grain density-range variation of the incident K^- meson, the capture star was required to have been produced by a K^- meson at rest. All prongs of the K^- star were examined and tabulated, and a thorough inspection was made for recoils and, in the dry stack, for the presence of Auger electrons. Our identification of K^- captures in light and heavy nuclei was based largely both on the low-energy evaporation prong spectrum and on the

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TABLE I. Details of K^- capture events which yield fast hyperons (dry stack).

Event No.	Type	T_Σ (MeV)	Accompanying prong length (μ)	Recoil, blob, or Auger electron
E–34–82	$F\Sigma^{\pm}\pi$ [a]	65	11, 137, 296	
E–45–442	$F\Sigma^{\pm}\pi$	82	2.6, 60, 76, 84, 311	
E–59–56	$F\Sigma^{\pm}\pi$	76	48, 55, 163, 13000	
E–47–28–4	$F\Sigma^{+}\pi$	86	29, 37, 88, 173	blob
E–34–120	$F\Sigma^{\pm}\pi$	69	34, 497, 827, 1590	
E–31–66	$F\Sigma^{+}p$	84	16	
E–38–97	$F\Sigma^{\pm}\pi$	118	4.6, 29	blob
E–60–7–1	$F\Sigma^{\pm}\pi$	77	2.2, 32, 147	
E–28–170	$F\Sigma^{\pm}\pi$	70	15, 164	
E–53–2–6	$R\Sigma^{-}\sigma$	70	34, 980, 14300	
E–50–2–6	$F\Sigma^{\pm}\pi$	67	18, 1310	
E–38–15	$F\Sigma^{+}p$	94	2.4	
E–39–107	$F\Sigma^{\pm}\pi$ [a]	135	22, 27, 41, 149	
E–52–8–5	$F\Sigma^{\pm}\pi$ [a]	82	9.3, 40, 108, 31900	
E–37–AA03	$F\Sigma^{\pm}\pi$ [a]	89	17, 35, 350, 5900	
E–37–142	$R\Sigma^{-}\sigma$ [a]	99	2.5, 33, 57, 129, 15100	
E–60–5–3	$F\Sigma^{\pm}\pi$ [a]	94	42, 61, 277, 282, 658, 1093	
E–55–23–3	$F\Sigma^{-}\pi$ [a]	74	3, 31, 40500	
E–38–95	$F\Sigma^{\pm}\pi$ [a]	67	5.1, 70, 75, 672, 20200	
E–45–11	$F\Sigma^{\pm}\pi$	81	2.8, 140, 206, 976	
E–51–174	$F\Sigma^{\pm}\pi$	89	7, 144, 16200	
E–36–48	$R\Sigma^{+}\pi$	68	60, 488, 1413	1.8 μ recoil or A.e.
E–37–116	$R\Sigma^{+}\pi$	60	102, 149, 310 ($R\Sigma=10420\ \mu$)	blob+6.7 μ A.e. +fast A.e.
E–60–35	$F\Sigma^{+}p$	114	179	1.9 μ recoil +4.3 μ A.e.
E–59–53	$F\Sigma^{+}p$	89	111, 310, 408	blob
E–40–85	$F\Sigma^{\pm}\pi$	66	90, 945	9 μ A.e.+22 μ A.e.
E–47–2–10	$F\Sigma^{\pm}\pi$	71	149, 47500	3.8 μ A.e.
E–54–20–2	$F\Sigma^{\pm}\pi$	72	280, 351, 355	blob
E–55–39	$F\Sigma^{\pm}\pi$	114	5330	blob
E–70–250	$F\Sigma^{\pm}\pi$	90	1290, 19100	12 μ A.e.
E–34–164	$F\Sigma^{\pm}\pi$	109	11590	
E–53–105	$F\Sigma^{\pm}\pi$	124	154	blob+30 μ A.e.
E–68–100	$F\Sigma^{\pm}\pi$	144	303	5 μ A.e.
E–46–14–5	$F\Sigma^{+}p$	108	3.8	

[a] These events have had the sign of the Σ inferred as negative by energy, momentum, and charge conservation, assuming capture by a light nucleus.

Auger electron spectrum. These procedures are discussed in an Appendix.

III. EXPERIMENTAL RESULTS

Two lists of events emitting Σ hyperons of kinetic energies ≥ 60 MeV are given for the dry $G5$ stack in Table I and for the wet $G5$ stack in Table II. In the second columns of both tables, the hyperon type is described by the standard abbreviations: $F\Sigma^{\pm}\pi$, meaning a Σ hyperon which decayed in flight into a neutron and a π meson, for which the charge remained undetermined; $R\Sigma^{-}\sigma$, meaning a Σ^{-} which came to rest and gave rise to a star, for which either two prongs were observed, or a single prong greater than 200 μ range; $F\Sigma^{+}p$, meaning a Σ^{+} hyperon which decayed in flight into a proton and π^0. In the third column of the table, the Σ energies were obtained by the most accurate method available, namely, by range, ionization, or by analysis of the decay kinematics. Whenever possible, more than one method was used to check for internal consistency. The errors of energy determinations are probably no greater than 5–10%. For those events where the energy was determined by range or by decay kinematics, errors of as little as 1–2% probably exist.

Details of the prongs accompanying the K^- capture star are given in column 4, and the presence of a blob or Auger electron is noted in column 5 of Tables I and II. It will be noted that the number of blobs or Auger electrons associated with K^- stars in the wet stack is very much less frequent than in the dry stack. This reflects the fact that the plateau grain density was 50% less in the wet stack than in the dry stack as well as the fact that Auger electrons are much less frequently associated with capture stars caused by absorptions in light nuclei.

It was first pointed out by Evans *et al.*,[22] and subsequently strongly supported by the Bristol-London group,[23] that a considerable fraction of multinucleon captures of K^- mesons can be completely analyzed in terms of K^- capture in an O, N, or C nucleus. From the 56 events listed in Tables I and II, it has been found

TABLE II. Details of K^- capture events which yield fast hyperons (wet stack).

Event No.	Type	Energy of Σ at emission (MeV)	Prong length of accompanying tracks (μ)	Recoil, Auger electron, or blob
D–19–32	$F\Sigma^{\pm}\pi$	80	65, 1860, 19030	
D–20–38	$F\Sigma^{\pm}\pi$	77	1060	blob
D–16–45	$F\Sigma^{\pm}\pi$	92	···	blob +4 grain electron
D–11–3	$F\Sigma^{\pm}\pi$	155	···	blob +3 grain electron
DA–19–30	$F\Sigma^{\pm}\pi$	180	···	
D–8–32	$F\Sigma^{\pm}\pi$	90	122, 218, 1200	
D–16–30	$F\Sigma^{\pm}\pi$	115	27000	
DA–13–57	$F\Sigma^{\pm}\pi$	89	9, 154	
DA–12–36	$F\Sigma^{\pm}\pi$	97	13, 134, 1470	
D–15–34	$F\Sigma^{+}p$	130	7, 22, 275	
D–18–18	$F\Sigma^{\pm}\pi$	108	3.6, 4.2, 368, 32300	
D–10–49	$F\Sigma^{+}\pi$	67	6.9	
D–11–68	$F\Sigma^{\pm}\pi$	104	3.9	
DA–17–30	$F\Sigma^{\pm}\pi$ [a]	92	3.9, 13, 32, 6900	
D–13–31	$F\Sigma^{\pm}\pi$ [a]	99	7.2, 546, 32500	
DA–7–36	$F\Sigma^{\pm}\pi$ [a]	60	4.2, 66, 93, 1370, 1930, 5830	
D–20–71	$F\Sigma^{\pm}\pi$ [a]	65	4.6, 25, 27, 41, 50	
D–7–18	$F\Sigma^{\pm}\pi$ [a]	72	83, 222, 668, 14200	
D–7–28	$F\Sigma^{\pm}\pi$ [a]	63	72, 76, 139, 170, 9320	blob
DA–14–79	$F\Sigma^{\pm}\pi$ [a]	93	43, 56, 82, 140, 12700	
DA–19–40	$F\Sigma^{\pm}\pi$ [a]	85	7, 10, 83, 612, 17200	
DA–13–14	$R\Sigma^{-}$ [a, b]	61	53, 74, 141, 217	

[a] These events, although listed as $\Sigma^{\pm}$, have had the sign of the Σ inferred as negative by energy, momentum, and charge conservation, assuming capture by a light nucleus.

[b] Event DA–13–14 is identified as a Σ^{-}, which comes to rest in the emulsion, by virtue of a blob or Auger electron and 4 μ recoil at 150° with respect to the line of flight of the Σ. This identification is further supported by applying the laws of conservation of energy and momentum to the parent star. The value of the K^- mass, so computed, assuming the emission of a single neutron is 508 MeV.

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TABLE III. Table of analyzable events.

Event No.	Interaction	Momentum imbalance of visible prongs (MeV/c)	Neutron energy (MeV)	Mass of K^- (MeV)
1. *DA*-17-30	$K^-+C^{12}\rightarrow\alpha+\alpha+p+p+n+\Sigma^-$	384	77	497
2. *D*-13-31	$K^-+O^{16}\rightarrow C^{12}+p+p+n+\Sigma^-$	200	21	504
3. *DA*-7-36	$K^-+O^{16}\rightarrow\alpha+\alpha+p+p+p+n+t+\Sigma^-$	256	34	488
4. *D*-20-71	$K^-+O^{16}\rightarrow\alpha+\alpha+\alpha+p+p+n+\Sigma^-$	491	121	503
5. *D*-7-18	$K^-+C^{12}\rightarrow\alpha+\alpha+p+p+n+\Sigma^-$	250	33	498
6. *D*-7-28	$K^-+O^{16}\rightarrow\alpha+\alpha+\alpha+p+p+n+\Sigma^-$	311	50	496
7. *DA*-14-79	$K^-+O^{16}\rightarrow\alpha+\alpha+\alpha+p+p+n+\Sigma^-$	228	27	495
8. *D*-19-40	$K^-+O^{16}\rightarrow\alpha+\alpha+\alpha+p+p+n+\Sigma^-$	253	34	495
9. *E*-55-23-3	$K^-+O^{16}\rightarrow C^{12}+p+p+n+\Sigma^-$	207	22	501
10. *E*-38-95	$K^-+O^{16}\rightarrow\alpha+\alpha+\alpha+p+p+n+\Sigma^-$	153	12	494
11. *E*-39-107	$K^-+C^{12}\rightarrow\alpha+\alpha+p+p+n+\Sigma^-$	332	56	499
12. *E*-52-8-5	$K^-+C^{12}\rightarrow\alpha+\alpha+p+p+n+\Sigma^-$	81	4	501
13. *E*-37-*AAO*3	$K^-+C^{12}\rightarrow\alpha+\alpha+p+p+n+\Sigma^-$	320	53	492
14. *E*-60-5-3	$K^-+O^{16}\rightarrow\alpha+\alpha+p+p+p+t+n+\Sigma^-$	201	21	497
15. *E*-37-142	$K^-+O^{16}\rightarrow\alpha+\alpha+\alpha+p+p+n+\Sigma^-$	146	11	502
16. *E*-34-82	$K^-+O^{16}\rightarrow\alpha+He^3+Be^7+n+\Sigma^-$	330	56	503
17. *DA*-13-14	$K^-+C^{12}\rightarrow\alpha+\alpha+p+p+n+\Sigma^-$	508	129	508

possible to account for no less than seventeen events which are consistent with K^- captures on either C^{12} or O^{16} nuclei. These events are given in Table III. The procedure was to assign to each visible track of an event an identity which could be consistent with the appearance and range of the track. The resultant momentum of all the tracks from the event was then calculated. In no case was this resultant momentum consistent with a zero value, but in the seventeen cases cited, a zero value could be obtained by specifying the emission of a single neutron, which also consistently conserved the energy available from the absorption of the K^- meson. The momentum imbalance in the K^- star, the neutron energy required to obtain momentum conservation in the event, and the mass of the K^- meson evaluated from the total kinetic energies of the particles in the event, are given in columns 3, 4, and 5 of Table III. It is to be observed that the mass of the K^- meson was obtained correctly to approximately 2% or less in these seventeen events. Of the remaining 38 events, none was consistent with any reasonable assignment of identity and energy-momentum balance. Some typical values of the K^- mass obtained in these disallowed events, for stars with three or four stable prongs, are 430, 446, 460, 461, 469, 518, 525, 530, 531, 547, 563 MeV. We note also that all events for which energy and momentum balance were achieved involved the production of a negative hyperon. The production of a fast Σ^+, in general, will result in the emission of more than a single neutron and this type of event is thereby restricted from identification by this method.

IV. ANALYSIS OF RESULTS

A. Relative Emission Probabilities of Fast Σ Hyperons from Light and Heavy Nuclei

Based on the identification of K^- captures in light and heavy nuclei by the short-prong method described in an Appendix, and from the events listed in Table II, the numbers in Table IV were obtained.

The ratio Ω is defined as the number of observed Σ events $\geqslant 60$ MeV in L captures per L capture divided by the number of observed Σ events $\geqslant 60$ MeV in H captures per H capture event. The observed values of Ω for the wet and dry stacks are in close agreement with one another. The fact that they agree so closely, even though the concentrations of light and heavy nuclei in the two emulsions are so different, is a strong indication that the identifications of light and heavy captures are reliable. The mean value of Ω, which should be independent of the relative light and heavy nuclear concentrations in the way that Ω is defined, for our experiment is 1.81 ± 0.33. This value is in good agreement with that computed from the events of Evans *et al.*[23] From their data we find that there are 38 fast hyperons in an estimated 1935 light nuclear events and 25 fast hyperon events in an estimated 3295 heavy nuclear events.[24] Their value of Ω is then 2.59 ± 0.47.

Eisenberg *et al.*[19] have concluded that 22% of the K^- captures in the light nuclei and 50% in the heavy nuclei of emulsion proceed by multinucleon processes. Their observations give the value of Ω equal to 0.44. This is clearly in disagreement with both our observations and those of Evans *et al.*[23] Further difficulties in accepting the results of Eisenberg *et al.* have been discussed elsewhere.[25]

B. Relative Multinucleon Capture in Light and Heavy Nuclei

The mean value of Ω equal to 2.2, obtained in Sec. A, does not represent the relative multinucleon capture probabilities in light and heavy nuclei, a quantity we

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[24] In order to break the K^- capture events into light and heavy nuclear captures, we have used the figure of 37% captures in light and 63% captures in heavy nuclei. These values were obtained from an analysis of the capture probabilities of stopping negative mesons [R. D. Hill, Suppl. Nuovo Cimento **19**, 83 (1961)]. Results of this analysis are supported by the observations of capture probabilities of negative μ mesons.

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shall represent by Z. In order to indicate the relationship between Z and Ω we define a number of quantities by the following symbols:

$$X=\frac{\text{number of multinucleon } K^- \text{ captures in light emulsion nuclei}}{\text{total number of } K^- \text{ captures in light emulsion nuclei}};$$

$$Y=\frac{\text{number of multinucleon } K^- \text{ captures in heavy emulsion nuclei}}{\text{total number of } K^- \text{ captures in heavy emulsion nuclei}};$$

$$Z=X/Y;$$

T_L = probability of a hyperon, created in a light nucleus, escaping that parent nucleus;

T_H = probability of a hyperon, created in a heavy nucleus, escaping that parent nucleus;

$$\alpha=\frac{\text{number of } \geqslant 60\text{-MeV } \Sigma \text{ hyperons observed}}{\text{number of } \geqslant 60\text{-MeV } \Sigma \text{ hyperons escaping parent nuclei}}.$$

If α is the same for heavy and light nuclei, and if T_L/T_H is assumed to be energy independent; also if such quantities as the momentum pair correlation function and the relationship between the production amplitudes for charged and neutral hyperons are assumed equal in light and heavy nuclei, then

$$\Omega=(X/Y)T_L/T_H=Z(T_L/T_H).$$

An estimate of T_L/T_H may be obtained by the following analysis of events associated with the emission of Auger electrons. This analysis has been based on Auger electron emission because it would be misleading to divide the stars emitting Σ hyperons into captures in light and heavy nuclei on the basis of classification by short prongs. This arises because approximately 50% of the Σ-emitting stars are not accompanied by stable particle prongs. Although the complete description of the Auger electron study will be given elsewhere, it can be stated that we observed $(38.1\pm1.6)\%$ of K^- captures in heavy nuclei to have associated Auger electrons and only $(6.3\pm1.0)\%$ in the light nuclei to have Auger electrons. It was further observed that only 64 cases out of 300 K^- captures emitting $\Sigma^\pm$ hyperons in the dry stack were accompanied by Auger electrons. Thus, if Auger electrons are a signature of heavy and light K^- captures in the amounts of 38.1 and 6.3%, respectively, it is easy to show that our sample of charged hyperons represented 158 cases where a light nucleus was the parent and 142 cases where a heavy nucleus was the hyperon emitter. This gives 1.1/1.0 for the ratio of charged Σ emission in light to heavy nuclei.

In our dry emulsion, using the entries in Table IV, we find that capture by light nuclei occurs 37% of the time, with heavy nuclear captures occurring in the remaining 63% of the events. Thus, the ratio of $\Sigma^\pm$ production by the light nuclei to that by the heavy should have been 0.6/1.0. The factor of 1.9 which is, therefore, the ratio of Σ production to Σ emission is probably attributable to the relative transmissibilities, T_L/T_H, of charged hyperons in light and heavy nuclei.

Thus, if it is assumed that the ratio of transmissions of charged Σ's is independent of energy, and if a value of $\sim$2.2 is taken for Ω, we obtain a value of $Z\sim1$. We conclude, therefore, that the probabilities of multinucleon K^- capture in light (C,N,O) and heavy (Ag,Br) nuclei of photographic emulsion are approximately equal.

TABLE IV. Relative K^--meson captures in light and heavy nuclei.

	L captures	H captures	Total	Ratio, Ω
Wet stack				
All events	835	630	1465	1.8 ± 0.5
$\Sigma^\pm$ events $\geqslant$ 60 MeV	15.5$^{(a)}$	6.5$^{(a)}$	22	
Dry stack				
All events	846	1440	2286	2.0 ± 0.4
$\Sigma^\pm$ events $\geqslant$ 60 MeV	22	19$^{(b)}$	41	

[a] One event D-19-32, with one short prong of range 65 μ which is in the zone dividing light and heavy captures, was placed half in the L category and half in the H category.

[b] This number of H captures is a corrected value to allow for the scanning bias resulting from the use of area scanning in this stack. Jones *et al.* (reference 14) found that approximately one-sixth of all K^- stars emitting fast ($\geqslant$60 MeV) Σ hyperons were unaccompanied by other prongs. This type of event was the only significant loss in our area scanning of these emulsions. Since most of these events are believed to have been initiated in heavy nuclei, our observed number of 12 heavy captures emitting fast hyperons has been increased by one sixth of the total expected number of fast Σ stars. The method used to estimate the division of the total number of captures between light and heavy nuclei is described in the Appendix.

C. Relative Multinucleon Capture and Single-Nucleon Capture Probabilities in Light and Heavy Nuclei

From Table IV we have seen that the numbers of multinucleon absorptions in light and heavy nuclei in normal $G5$ are 22 and 19 events, respectively. The corresponding numbers of $\Sigma^\pm$'s arising from both single and multinucleon absorptions in the light and heavy nuclei of the normal $G5$ stack were, as we have seen in Sec. B, 158 and 142 cases, respectively. Again, assuming that the $\Sigma^\pm$ absorption probability, in its parent nucleus, is independent of energy, we can compute the ratio of multinucleon K^- captures to all K^- captures in both the light and heavy emulsion nuclei. If, on account of the Fermi momentum of the capturing nucleons, only 80%[14] of the Σ's created in multinucleon processes emerge with energies $\geqslant$60 MeV, then for light nuclei, we find that $(17\pm5)\%$ of the K^- captures proceed via a multinucleon channel, while for heavy nuclei the corresponding figure is $(16\pm5)\%$. These values are in excellent agreement with one another and also are identical with that of (17±4)% reported for the corresponding quantity by the Helium Bubble Chamber Collaboration Group.[26] It also lies well within the range of 9–30% reported by Jones *et al.*[14] in the most comprehensive emulsion study on the subject to date.

D. Completely Analyzable Light Nuclear Captures

Strong support for the conclusion that light nuclei are the more probable emitters of fast hyperons than are heavy nuclei is given by the identification of light nuclear captures using complete analysis of the K^--capture stars. All of the K^--capture stars emitting Σ hyperons $\geqslant 60$ MeV were investigated for conservation of charge, energy, and momentum. The procedure adopted was similar to the studies of K^- stars made by Evans *et al.*[23], and of π^- stars by Menon *et al.*[27] The results of our analysis have already been indicated in Table III of the identified K^--capture stars in light nuclei. Seventeen events out of a total of 56 events from both light and heavy nuclei emitting fast hyperons were identified in this manner. These events represented approximately one-half of all light nuclear events and were approximately equal to the number of heavy nuclear events.

None of the 17 events was consistent with all the energy being shared by the visible prongs only. However, this feature of the K^- stars is not entirely to be unexpected since the interaction of a negative K meson with any of the nucleon pairs: (n,n), (n,p), (p,p) will produce a neutron in two out of three cases of charged Σ emission. If the nucleon pair is to be considered as likely residing in an alpha-particle substructure of a light nucleus, then the interaction of a negative K meson will always produce either a free neutron or a deuteron in a charged Σ production process. In the 17 cases listed in Table III, it was possible by assuming the emission of a single neutron to balance energy and momentum in the K^- capture star and to reproduce the mass of the K^- meson to ~2%. It may be noted that a negatively charged Σ hyperon was emitted from all events for which energy and momentum balance were achieved. This feature is consistent with the fact that Σ^+ hyperons must always be produced together with one neutron in a multinucleon K^- absorption process and with three neutrons if the interaction is with an alpha-particle sub-unit.

TABLE V. Analyzable light nuclei multinucleon K^- capture events.

Light nucleus	Products	Number of events
C^{12}	$p+p+n+\alpha+\alpha+\Sigma^-$	9
	$p+d+\alpha+\alpha+\Sigma^-$	2
	$p+t+Be^7+\Sigma^-$	1
N^{14}	$p+\alpha+\alpha+\alpha+\Sigma^-$	2
O^{16}	$p+p+p+n+t+\alpha+\alpha+\Sigma^-$	2
	$p+p+n+\alpha+\alpha+\alpha+\Sigma^-$	10
	$p+d+\alpha+\alpha+\alpha+\Sigma^-$	1
	$p+p+n+C^{12}+\Sigma^-$	3
	$n+\alpha+He^3+Be^7+\Sigma^-$	1

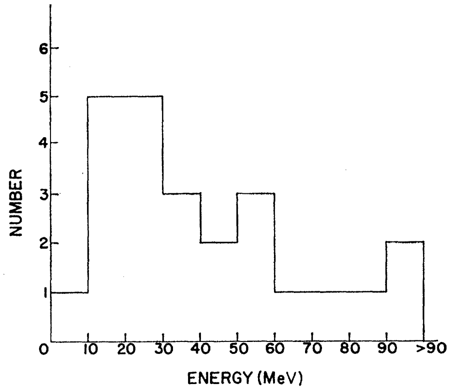

FIG. 1. Energy spectrum of neutrons from those completely analyzable events which appear to correspond to the disintegration of an alpha-particle cluster.

Our results of completely analyzable events are similar to those of Evans *et al.*[23], who were able to completely identify 14 K^- captures in light nuclei which proceeded by the emission of fast Σ^- hyperons. All of the events of both Evans *et al.*[23] and the present experiment are collected together in Table V.

E. Energy Spectra of Protons and Neutrons Accompanying Multinucleon K^- Captures in Light Nuclei

It has been argued by both the Bern[13] and K^- Collaboration[12] groups that the $K^-+(n,n)\rightarrow\Sigma^-+n$ multinucleon reaction may have a much weaker intensity than the $K^-+(n,p)\rightarrow\Sigma^-+p$ and $K^-+(p,p)\rightarrow\Sigma^++n$ reactions. This has derived support from the observations that Σ^- hyperons are generally accompanied by other charged prongs while Σ^+ hyperons are often (~30%) emitted alone.

When one looks at the completely analyzable data on K^- multinucleon captures in light nuclei, however, there appears to be no reason for considering the $K^-+(n,n)$ reaction to be infrequent. (Our completely analyzable data on light nuclei, of course, refer only to Σ^- production.) If one considers a model of the multinucleon capture in which the absorption and Σ^- production processes are confined primarily to the two nucleons involved, one would expect that either a high-energy proton or neutron would accompany the Σ hyperon produced. In general, this will be followed by a secondary process in which the capturing nucleus will undergo reorganization and also the high-energy nucleon and hyperon may make scattering interactions with the

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[26] M. Block (Helium Bubble Chamber Collaboration Group), in *Proceedings of the 1960 Annual International Conference on High-Energy Physics at Rochester*, edited by E. C. G. Sudarshan, J. H. Tinlot, and A. C. Mclissions (Interscience Publishers, Inc., New York, 1960), p. 426.

[27] M. G. K. Menon, H. Muirhead, and O. Rochat, Phil. Mag. 41, 583 (1950)

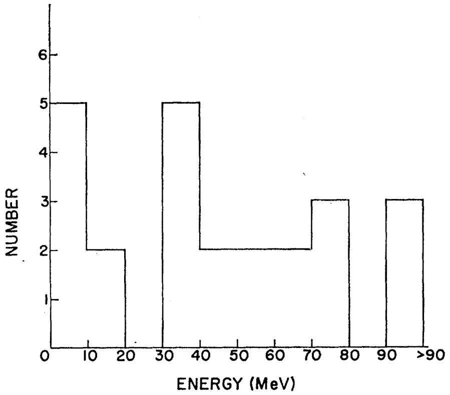

FIG. 2. Energy spectrum of faster protons from those completely analyzable events which appear to correspond to the disintegration of an alpha-particle cluster.

residual nucleus. If both $K^-+(n,n)$ and $K^-+(n,p)$ interactions exist, one would expect both high- and low-energy components of the neutron and proton energy distributions. For 24 analyzable cases where 2 protons and a neutron occur, the single-nucleon spectra are shown in Figs. 1, 2, and 3, which are for (a) neutrons required for energy and momentum conservation, (b) faster proton accompanying the event, and (c) slower proton accompanying the event. It is to be observed that the neutron spectrum is not significantly different from the fast-proton component either in form or in relative numbers. Clearly, there is no low-energy neutron spectrum with an intensity corresponding to that of the low-energy proton spectrum of Fig. 3. We interpret the low-energy protons mainly as "spectator" protons, probably arising from an alpha-particle substructure in the parent nucleus. There would appear to be three reasons for the absence of a very low energy peak in the neutron distribution. First, if an alpha-particle substructure is involved and if matrix elements for the various pairs are equal, there is approximately only one chance in four of a neutron playing a spectator role as compared with a proton. Secondly, by the nature of the analysis, selection of the events has been made on the basis of only one neutron being emitted. Thirdly, there is experimental bias against obtaining complete momentum and energy balance in some events when the neutron energy is low. In so far as light nuclear multinucleon capture of K^- mesons is concerned, we therefore conclude that our results are consistent with comparable numbers of $K^-+(n,n)$ and $K^-+(n,p)$ capture events. Both the K^- collaboration group[14] and Evans *et al.*[23] pointed out that the nonobservance of Σ^- emission unaccompanied by charged prongs could imply the possible K^- interaction with the whole of an alpha-particle subunit in the nucleus.

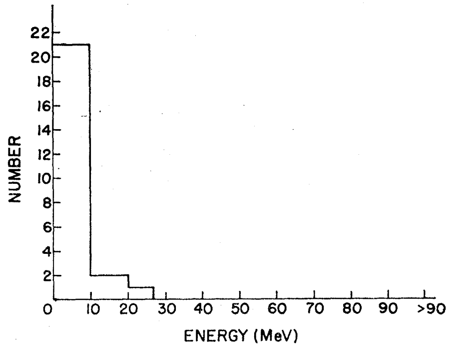

FIG. 3. Energy spectrum of slower protons from those completely analyzable events which appear to correspond to the disintegration of an alpha-particle cluster.

V. DISCUSSION OF MULTINUCLEON ABSORPTION RESULTS IN TERMS OF NUCLEAR MODELS

(i) Absorption in Light Nuclei

Our results, mainly because of the completely analyzable events, give a clearer description of multinucleon absorptions in light than heavy nuclei. Our first remarks will therefore be confined to light nuclear processes.

In the light nuclei (C,N,O) of nuclear emulsion, we believe that the evidence, when taken altogether, favors the existence for a fraction of the time of α-particle subunits in these nuclei. We now attempt to review the various points of evidence. In Sec. D of the results, we have seen that more than one neutron always, in our experience, accompanies multinucleon absorptions of K^- mesons and subsequent emission of a Σ^+ hyperson. (A possible interaction of the type: $K^-+C^{12}\rightarrow {}^+\Sigma+n+\mathrm{Be}^{10}$, would not be consistent with this statement. However, for those events where this reaction was possibly applicable, momentum and energy balancing was attempted without success.) This might not be expected to occur as frequently as we observed it if the primary multinucleon absorption usually occurred on a pseudo di-proton type of substructure. In Sec. E of the results, we have seen that there is a low-energy proton component of the nucleon spectrum of completely analyzable multinucleon absorption events in light nuclei. If K^- absorption had occurred on a pseudo-deuteron type of pair, it is unlikely that the observed Σ^- emission would have been accompanied by such a high intensity of low-energy protons. These low-energy protons are probably to be interpreted as spectator protons in an alpha-particle substructure rather than evaporation protons from the residual nuclear fragment. This last point will be discussed more fully, presently. The neutron spectrum accompanying Σ^- emission from completely analyzable events consists mostly of fast components and does not appear to contain many "spectator" neutrons. This behavior is consistent either with absorption from (n,n) pairs, free in the nucleus, or from alpha-particle substructures in the nucleus.

The fact that there are large numbers of α-particle fragments appearing in the disintegration products of completely analyzable multinucleon events may not in

TABLE VI. Energies of particles emitted from completely analyzable K^- captures in C^{12} and O^{16}.

Event	E_α (MeV)	E_p (MeV)	E_n (MeV)	$E_{\Sigma-}$ (MeV)
*DA*17/30 :C^{12}	0.6, 2.4	1.4, 33	75	92
*DA*13/14 :C^{12}	7.8, 9.4	3.9, 4.6	129	61
D 7/18 :C^{12}	10.2, 36	4.6, 49	33	72
E 39/107 :C^{12}	4.4, 5.3	1.8, 4.6	56	135
E 52/85 :C^{12}	3.0, 14	2.0, 104	4	82
*E*37-*AAO*3 :C^{12}	4.6, 7.4	7.6, 38	54	89
K^-coll :C^{12}	4, 6	2.0, 3.5	80	108
K^-coll :C^{12}	1, 2	7, 68	61	66
D 20/71 :O^{16}	0.8, 5.1, 6.6	1.6, 1.9	122	66
D 7/28 :O^{16}	9.6, 16, 17	2.4, 38	50	63
*DA*14/79 :O^{16}	6.8, 8.1, 10.1	3.9, 46	27	93
D 19/40 :O^{16}	1.2, 2, 10.4	8.4, 54	34	85
E 38/95 :O^{16}	1.9, 11.2, 12.5	11.2, 78	12	67
E 37/142 :O^{16}	1.0, 7, 16	2.5, 66	11	9
K^-coll :O^{16}	7, 18, 24	9.5, 13	48	61
K^-coll :O^{16}	4, 9, 15	5, 57	18	94.5
K^-coll :O^{16}	3, 7, 23	22, 38	25	67
K^-coll :O^{16}	2, 9, 10.5	3, 6.5	43	124

itself be indicative of involvement of alpha-particle substructures in the initial capture process. However, the fact that exceedingly low (but not negligibly low) energy protons are associated with the products seems to indicate that there are low atomic number fragments, such as alpha particles, from which these protons may escape. The energy values of these very low energy protons are given in Table VI where the C^{12} and O^{16} completely analyzable events with only alpha particles and nucleons, from our own experiment and those of the K^- Collaboration work, are listed. We observe, in column 4, that protons of energies as low as 1.4, 1.8, 1.9, 2.0 MeV are not unusual. These energies, which are quite accurately determined, are too low for protons which could surmount the barriers of fragments from C^{12} and O^{16} remaining after the emission of only a Σ^- and a nucleon.

One way in which the emission of low-energy protons might be understood is to envisage the capturing nucleus as distorted at the instant of K-meson absorption. Such a distortion might arise from the strong absorptive potential between the K meson and a pair of nucleons or from the alpha-particle clustering vibration which appears to be present in light nuclei. Whatever the explanation of the process might be, it does appear that some reduction of the barrier height potential is necessary in order to explain the emission of such low energy protons.

It should be pointed out that similar conclusions about nuclear structure were drawn from diffusion cloud chamber studies by Ammiraju and Lederman.[28] From the similarity of the proton spectra from π^- stars in carbon (ethylene) and in helium, and from the large number of alpha particles emitted in the π^--C^{12} absorptions, these authors inferred that the primary absorption process in C^{12} was on a pair of nucleons in an alpha-particle cluster.

Reference to Table VI shows that a fast Σ is usually accompanied by a fast nucleon. There seems to be strong evidence, therefore, that the primary process involves two nucleons and that most of the remaining nucleons and alpha particles are generally involved in a spectator type of role. Sometimes it is observed that there is also another relatively high-energy nucleon emitted. We interpret the emission of two high-energy nucleons as probably arising from some secondary scattering interaction by either the fast Σ or the associated primary fast nucleon. However, it is not implied that every multinucleon interaction, even in light nuclei, is associated with an alpha-particle subunit, for example, event 16 of Table III appears to indicate a direct di-nucleon interaction in O^{16}. It does not appear to be acceptable, though, that the residual nucleus remaining after the ejection of the Σ^- and associated high-energy nucleon should break up from a collective state of the excited residual nucleus. If this were the case, we should expect, on phase-space grounds, the so-called evaporation nucleons to receive greater energies than they do. We have calculated the energy distributions of protons which might be expected to arise from the disintegration of a 50-MeV excited residual nucleus such as C^{10} or B^{10} into the products of $(2\alpha+2p)$ and $(2\alpha+p+n)$, respectively. An excitation of 50 MeV corresponds to the mean energy available to the α's and the two nucleons in the break up of the residual nuclei from K^- captures in C^{12} and O^{16}. According to four-body phase-space calculations,[29] the density of phase space per unit energy interval of one of the nucleons, $d\rho/dT$, is

$$d\rho/dT \sim T^{1/2}[W-(10/9)T]^3,$$

where T is the kinetic energy of one of the observed low-energy nucleons and W is the total kinetic energy available to the two alpha particles and two nucleons in the residual system.

The $d\rho/dT$ histogram as a function of T is shown by the dashed line in Fig. 4 and an experimental histogram of the number of protons versus the energies for the observed C^{12} and O^{16} events of Table V is also given. It is clear that the observed proton spectrum does not agree with the curve calculated on the basis of an intermediate excited state disintegrating according to statistical considerations. On such a statistical decay model, one would expect less than 20% of the disintegra-

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[28] P. Ammiraju, and L. M. Lederman, Nuovo cimento 4, 283 (1956).

[29] For four-body phase space, the variation of the volume of phase space with the energy of one of the particles can be written

$$\frac{d\rho_4}{dp}=4\pi p^2 dp\,\frac{d}{dT}\prod_{i=2}^{4}\left(\int d\mathbf{p}_i\right).$$

Our result above was obtained by evaluating the right-hand side of this equation by the methods used by R. H. Milburn [Revs. Modern Phys. **27**, 1 (1955)] for classical particles. Similar results can be obtained for the disintegration of a fragment into five particles, where now the factor in parenthesis is taken to the 9/2 power and the coefficient of T is changed slightly so as to be consistent with energy and momentum conservation.

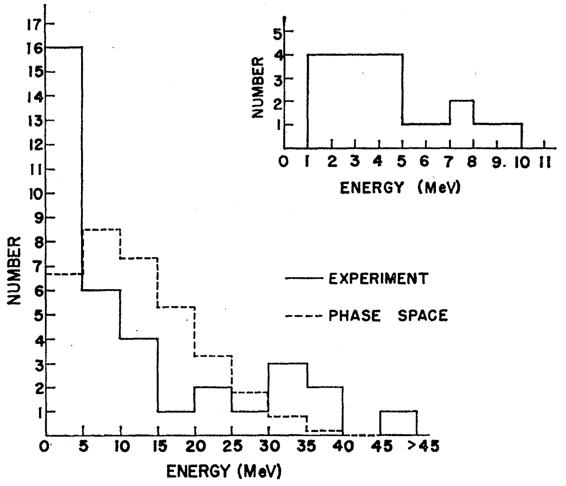

FIG. 4. The solid line represents a histogram of the energy distribution of the two slowest nucleons emitted from those completely analyzable disintegrations in light nuclei. The dashed histogram represents the expected spectrum of nucleons calculated from phase space for the four-particle disintegration of a 50-MeV excited state of B^{10}.

tion protons to be less energetic than 5 MeV. The observed number is 50%.

A possible objection to the above argument is that the excitation of the residual nucleus may not be by any means a constant. The observed energy fluctuations, however, are not large enough to invalidate the tendency which appears to be that there are considerably more low-energy protons than would be expected on the basis of a break up from a compound nucleus. A useful nuclear physics experiment would be to investigate the proton spectrum from nuclei such as C^{10} or O^{14} at excitation energies of the order of 30–80 MeV.

In so far as light nuclei are concerned, there seems to be, at the present time, a considerable amount of support for the alpha particle or clustering of nucleons model. We will not attempt to summarize the present status of this model but will only cite two recent contributions bearing on its relevance. The first is the apparently direct evidence, obtained by Gooding and Igo[30] who observed the elastic scattering of 915-MeV alpha particles by alpha-particle clusters in carbon. The second is the analysis of experimental evidence for cluster structures in light and medium weight nuclei carried out recently by Sheline and Wildermuth.[31] According to these authors, the 0^+ ground state of C^{12} can be represented as a Be^8 ground-state cluster and a He^4 cluster in a relative $3S$, or fourth oscillator number, vibrational state. The 0^+ ground state of O^{16} can also be represented as $C^{12}+He^4$ clusters in a $3S$ vibrational state. These latter authors give for the vibrational frequency parameter ω in C^{12} and O^{16} a value of 2.2×10^{22} sec^{-1}, from which it can be estimated that the energy of the 0^+ vibrational cluster ground state lies approximately 76 MeV above the bottom of the oscillator well. The expectation value of the kinetic energy of the Be^8 cluster in C^{12} can therefore be computed to be 12.7 MeV. Similarly, the expectation value of the kinetic energy of the C^{12} cluster in O^{16} is evaluated to be 9.5 MeV. If a K^- meson is captured by one of the alpha clusters in a light nucleus, it seems reasonable to assume, since the reaction from a K to a Σ occurs so energetically and, as we have seen, apparently largely independently of the rest of the capturing nucleus, that the Be^8 and C^{12} clusters in C^{12} and O^{16}, respectively, will approximately retain their vibrational energies. That this is approximately the case is seen from the observed energy spectra of the Be^8 and C^{12} clusters shown in Fig. 5. These energies have been computed from the momenta of the recoiling alpha particles of the Illinois events listed in Table VI.

(ii) Absorption in Heavy Nuclei

The observation by Evans *et al.*[23] that the probability of multinucleon absorption of K^- mesons in heavy (Ag,Br) nuclei is not significantly different from that in light nuclei appears to be definitely confirmed by the results obtained in the present experiment. This conclusion would seem to make it unnecessary to invoke the influence of a Y^{0*}, in order to explain the unconfirmed results of Eisenberg *et al.*[20] that the multinucleon capture increases significantly with the atomic mass of the absorbing nucleus. According to an estimate by Biswas,[32] if a Y^* were always produced in K^--meson capture and if multinucleon processes were of a Ruderman-Karplus nature involving internal pion conversion, then multinucleon capture rate should increase at least as fast as $A^{1/3}$, where A is the atomic mass of the capturing nucleus. There appears to be no such increase indicated by experiment.

We now attempt to estimate to what extent α-particle subunits are involved in the multinucleon capture of K^- mesons in heavy emulsion nuclei. The combined data of Evans *et al.*[23] and of the present paper yield 76 K^- nonmesonic or multinucleon absorptions in light

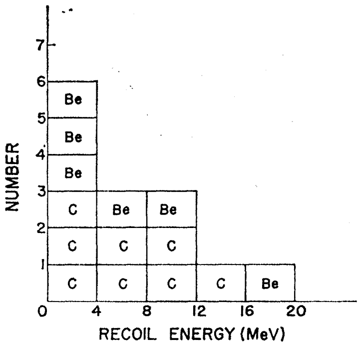

FIG. 5. Energy spectrum of recoiling fragments in unambiguous multinucleon events. C indicates one event where C^{12} is the recoiling fragment. Be indicates one event where Be^8 is considered to be the recoiling fragment. The kinetic energy of the recoiling fragment is computed from the kinematics of its subsequent decay into α particles.

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[30] T. J. Gooding and G. Igo, Phys. Rev. Letters **7**, 28 (1961).

[31] R. K. Sheline and K. Wildermuth, Nucl. Phys. **21**, 196 (1960).

[32] N. N. Biswas, Nuovo Cimento **22**, 654 (1961).

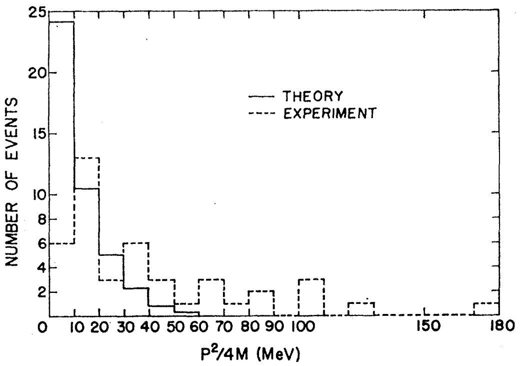

FIG. 6. Comparison of the theoretical nuclear pair correlation function with that obtained from multinucleon K^- absorptions ignoring final-state interactions. The solid line represents Gottfried's calculation for O^{16} while the dashed line represents the experimental data on light nuclei.

nuclei and 43 (+7) in heavy nuclei.[33] Of the 76 light nuclear events, 27 are definitely compatible with the primary multinucleon capture occurring on an alpha-particle cluster. These 27 cases are 16 completely analyzable events of Table III and 11 similar events of Evans *et al.*[23] The direct indication, therefore, is that 27/76 or 36% of the multinucleon captures in light nuclei proceed through the alpha-particle channel. Since multinucleon captures amount to approximately 17% of all captures in light nuclei, alpha-particle clustering is therefore evident in at least 6% of all light nuclear K^- captures.

Among the indications that this is indeed a lower limit, there are 12 other light nuclear events (24% of the 49 remaining cases) which are not completely analyzable but which could conceivably represent[34] the reaction: $K^- + (\alpha)_{\text{bound}} \rightarrow \Sigma^- + 2p + n$. However, we consider these events as "background" to those completely analyzable light nuclear events, and they probably represent cases where more than a single neutral particle was emitted.

Since recoils of very low energy heavy nuclear fragments are not, in general identifiable in emulsions, the heavy nuclear captures were, of course, not compatible with any completely analyzable reaction scheme. However, of the 43 (+7) observed events[33] there were again 12 events (24%) which had the aforementioned characteristic and could conceivably be interpreted as arising from capture by an α-particle cluster (i.e., a fast hyperon accompanied by at least two protons of energy sufficiently great so as to allow them to surmount any Coulomb barrier presented by the heavy nucleus).

If we consider the 12 light nuclear events as a spurious background which is also present in the heavy nuclear events, we find that our results are consistent with no K^- α-particle absorptions in heavy nuclei. Alternatively, in order to set an upper limit, we can assume that all of the possible α cluster absorptions in heavy nuclei represent actual cases. Correspondingly, in order to set an upper limit in heavy nuclei, all of the possible events in light nuclei are considered to be background and to be due to competing processes. This alternative then yields a maximum possible estimate that an α-particle cluster is about 60% as likely to exist in heavy as in light nuclei. Summarizing, we can say that α-particle clusters appear to be consistent with zero and at the most 60% as probable in heavy nuclei as they are in light nuclei.

(iii) An Estimate of the Nuclear Pair Correlation Function in Light Nuclei

Since two nucleons are involved in a primary multinucleon K^- absorption process, it would appear possible to obtain a rather more than qualitative description of the nuclear pair correlation function, at least in light nuclei where the best experimental information has been observed. We follow Gottfried[6] and define the nuclear pair correlation function, $F(P)$ as the probability of two nucleons in a nucleus having zero separation in the Slater determinant and having total momentum P. For the case where the nucleon pairs are in a relative S state and for nuclei having completely closed shells (e.g. O^{16}), Gottfried has evaluated $F(P)$ as a function of $P^2/4M$, where M is the nucleon mass. For the case where the Slater determinant for O^{16} is constructed from the eigenfunction of the harmonic oscillator, the form of $F(P)$ (as a histogram) is shown in Fig. 6.

The experimental histogram in Fig. 6 has been obtained from all the available K^- capture events in light nuclei. The experimental data therefore represent C^{12} nuclei as well as O^{16}. However, there does not appear to be any significant experimental difference, within the limitations of statistics, between the two cases. The values of P in the experimental histogram represent the vector sum of the momenta of the outgoing high-energy ($\geqslant 60$ MeV) Σ hyperon and the fast, presumed associated, nucleon. In the absence of disturbing effects [such as (i) final-state interactions either between Σ and nucleon or between Σ, nucleon, and residual nucleus, and (ii) binding energy losses of the Σ and nucleon in escaping from the capturing nucleus] the total momentum of the Σ and nucleon should also represent the total momentum P of the absorbing nucleon pair.

The data of the experimental histogram refer to 43 cases of light nuclear multinucleon absorption where the hyperon has an energy $\geqslant 60$ MeV and the fast nucleon has an energy of $\geqslant 30$ MeV. The events are from the present experiment and from the K^- collaboration work. Theoretical and experimental histograms are normalized to the same total numbers of events. Two features of the comparison may be significant. The observed number of events with $P^2/4M < 10$ MeV is certainly less

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[33] The (+7) refers to the correction to our data for loss due to area scanning

[34] Any star with a fast hyperon and two protons of ranges greater than 120 μ (or 180 μ in the water-soaked emulsion) is considered eligible for this category. This limit corresponds to the Coulomb barrier height for protons in heavy emulsion nuclei.

than predicted, and the observed momentum spectrum extends to considerably higher values than are predicted theoretically. Although the multinucleon process probably tends to select out those nucleon pairs of relatively high momenta, it seems unlikely that the experimental spectrum should extend so far beyond the theoretical spectrum where $F(P)$ is essentially zero. It would appear more likely that the outgoing Σ and proton momenta are affected by secondary scattering in the residual nucleus. It is observed that the associated Σ's and nucleons in the zero to 10 MeV $P^2/4M$ bin are generally emitted at large angles of approximately 150°, to one another. Very preliminary estimates based on measured $\Sigma^{\pm}$-proton elastic cross sections[35] also indicate that it is highly probable the Σ should be scattered in at least 50% of the events. There may therefore be a tendency for final-state interactions of the Σ and nucleon with the residual nucleus to transfer events from the low $P^2/4M$ part of the spectrum to the high $P^2/4M$ values. We believe that the theoretical and experimental pair correlation functions may not be inconsistent with one another if account is taken of final-state interaction.

APPENDIX. SEPARATION OF K^- CAPTURE STARS INTO LIGHT AND HEAVY NUCLEI

The Coulomb barrier in heavy nuclei (Ag, Br) will inhibit the emission of relatively low kinetic energy particles. For an average heavy emulsion nucleus ($Z=41$, $A=100$), the theoretical barrier height[36] is ~9.6 MeV for α particles and ~4.2 MeV for protons. Many experimenters have measured the height of this barrier by associating it with a minimum in the energy distribution spectrum of short prongs emitted in π^- and K^- capture stars. Values from 6.5 to 10 MeV for α particles have been determined.[7,37] Independent measurements in the present investigation yielded a barrier height of 8.6 MeV, corresponding to α-particle ranges of 46 μ in normal $G5$ emulsion and 60 μ in our particular case of water-soaked emulsion.

Another aspect of the short-prong method of distinguishing captures in light and heavy nuclei is the establishment of a criterion for excluding nuclear recoil tracks from classification as short prongs. In recent experiments on multinucleon K^- capture, Evans *et al.*[23] selected 2 μ as the minimum length of a track to be considered as a prong. Grote *et al.*[38] used 5 μ as the minimum prong lengths. More recently in hyperfragment work, Abedelo *et al.*[39] used 2 μ as a lower limit. In the case of π^- meson absorption, Menon *et al.*[27] showed that the maximum possible heavy nucleus recoil length was about 3 μ. This was for an extreme case in which all possible evaporation particles left the nucleus in the same direction. In the present investigation we have classified an event as a light nucleus capture if one or more prongs were between 2 and 46 μ in normal $G5$ emulsion or between 3 and 60 μ in our water-soaked emulsion. It should be mentioned that according to our experience there was very little chance of confusing a slow Auger electron with a short prong within the limits of these criteria.

In the normal $G5$ stack of the present experiment, 2035 K^- captures, with greater than or equal to 1 prong, were selected for analysis. Events rejected from the analysis were: (i) K^- captures on a free proton, (ii) events too close to the emulsion surface or too close to an emulsion imperfection, (iii) double-star events where the connecting tracks were too short for unambiguous analysis of the capture star. Of the 2035 events, 662 or 32.5% had a prong satisfying the short-prong criterion.

In order to investigate what confidence can be placed on the short-prong method, let it be assumed[24] that the ratio of all types of light nuclear K^- captures to the total nucleon captures in all nuclei in normal $G5$ emulsion is 0.37. Then it can readily be estimated that the fraction of light nucleon captures which from our experiments were found to leave short-prong signatures is 0.325/0.37 or 88%. Thus, the presence of short prongs seems to be a very good indication of capture in a light (C,N,O) nucleus. The 12% of cases where a short prong from a light nuclear capture is not present are probably attributable to events in which a C^{12} or another similar residual fragment is not broken up and does not acquire sufficient energy to be recorded as a recoil of greater length than a 2 μ.

Significantly, there were two events emitting fast Σ's for which both energy and momentum balance in the whole K^- capture star was possible and for which there was no short prong satisfying the selection criterion. It therefore seems that our criterion if anything is over-restrictive. Imposing a rigid cutoff criterion for a large sample of events, as was done when considering all K^- capture stars, will effect some reasonable averaging and will not seriously change the true picture. However, for a small sample of events, such as those emitting the fast Σ hyperons, it is felt that those events with short prongs lying close to the cutoff length should be subject to closer inspection for other indications of their true nature. For the fast hyperon events, therefore, a rather more flexible upper limit of the short-prong criterion was set down. This was: normal $G5$, upper limit from 35 to 55 μ; water soaked $G5$, upper limit 50 to 70 μ.

The present classification of K^- captures into light and heavy nuclei on the basis of the short-prong method was strongly supported by evidence obtained from the Auger effect in the K^- mesonic atom preceding nuclear

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capture of the K meson. Theory and experiment both indicate that the emission probability of Auger electrons should be small in C,N,O as compared with the nuclei of Ag and Br. In the present experiment it was found that Auger electrons accompanied the K^- capture event in approximately 5% of light nuclear captures (as indicated by the short-prong method) and 38% of the heavy nuclear capture (as indicated by the absence of short prongs). The observed total Auger electron emission intensity was 26.1%, thus confirming the value of 25.5% observed by Grote *et al.*[38] In the wet stack 895 K_σ events were selected for analysis by the short-prong method. Of these, 448 or 50% were observed to have at least one prong in the range $3\,\mu$ to $60\,\mu$. This larger percentage of captures in light nuclei as compared with the 32.5% in normal $G5$ is of course mainly associated with the increased oxygen content of the water-soaked emulsions. If the fraction 88% is used to correct from the number of indicated short-prong events to the total number of light nuclear captures, we then estimate that the fraction of light nuclear captures to all K^- captures in the water-soaked emulsion was $50/18.8 \sim 57\%$.

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Radiative Corrections to $K \rightarrow e\nu$ and $K \rightarrow \mu\nu$ Decays*

N. P. Chang
Columbia University, New York, New York

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The radiative corrections to the ratio of the $K \rightarrow e\nu$ rates to the $K \rightarrow \mu\nu$ rates are calculated for an experiment where photon counters are used to help discriminate against the K_{e3} background. This is in contrast to the previously calculated case where all photon energies are included in the rate. The theoretical advantage of including only the low-energy photons is emphasized in this note.

INTRODUCTION

THE $\mu - e$ universality hypothesis will soon be tested in strangeness-nonconserving weak interactions, by means of a comparison of the rate $K \rightarrow e\nu$ decay with that of $K \rightarrow \mu\nu$ decay. Such a test involves quite critically a knowledge of the radiative effects involved in the experiment, as was already the case with $\pi \rightarrow (e,\mu)+\nu$ experiments. The present note is an attempt to calculate the appropriate radiative effects with respect to a particular kind of experiment.

In the $\pi \rightarrow e\nu/\mu\nu$ case, calculations[1,2] on the radiative effects have been carried out for an experiment in which all events with electron energy not less than $E_{\max} - \Delta E$ are accepted, regardless of the energy of the accompanying bremsstrahlung photons. This includes, then, photons of maximum available energy. Such a situation is not desirable in the $K \rightarrow e\nu/\mu\nu$ case. Here we have a sizeable three-body leptonic decay background, with the neutral pions giving rise to an abundant supply of high-energy photons. This makes it hard to distinguish between the K_{e2} electrons from some of the K_{e3} electrons of comparable energy.

An alternate experiment that we envisage would be as follows. All electron events are to be accepted, provided (1) the accompanying photon bremsstrahlung be of energy $\le q_1$, and (2) the electron energy is in the range characterized by

$$E_e \equiv \frac{m_K^2 + m_e^2}{2m_K}(1-y) \qquad 0 \le y \le \frac{2q_1}{m_K}\,\frac{1-(m_e/m_K)^2}{1+(m_e/m_K)^2}, \tag{1}$$

which is the full range of K_{e2} electron energies consistent with the photon discrimination energy.

The main difference from the previous procedure lies in the fact that even if q_1, the photon discrimination threshold energy, be not too small, the experiment itself, as well as its theoretical interpretation, will still not be affected appreciably—for the high-energy photons from the neutral pions can readily be discriminated against. And, theoretically, the radiative effect is rather insensitive to q_1, so long as it stays small with respect to the K-meson mass—in the K-meson rest frame. Moreover, from a theoretical point of view, this procedure contains less ambiguities insofar as neglecting certain unknown decay amplitudes in the inner bremsstrahlung matrix element, as will be seen below.

In Sec. I, we discuss in some detail the bremsstrahlung process $K \rightarrow e\nu\gamma$, with some attention to the general case, where there can be three amplitudes. The inner bremsstrahlung contribution to the rate of K_{e2} is shown in this section. In Sec. II, the virtual photon effects are analyzed. Only those effects which remain in the ratio of $e\nu/\mu\nu$ rates are considered. It is shown that, in fact, even for virtual photons, only q_μ (photon 4-momentum) $\rightarrow 0$ region contributes to the $e\nu/\mu\nu$ ratio. The contribution of the three Feynman diagrams which

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