FINAL STATE INTERACTIONS IN THE DECAY OF LIGHT HYPERNUCLEI

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ABSTRACT

The excited states of Li^4, Li^5 and Be^8 have been investigated by studying the final state interactions in the π^--mesic decays of $_{\Lambda}He^4$, $_{\Lambda}He^5$ and $_{\Lambda}Li^8$ respectively. The experimental results indicate the existence of final states like Li^{5*} at $1 \cdot 8$ MeV and Be^{8*} at 0 and $2 \cdot 9$ MeV to be dominant in the decay of $_{\Lambda}He^{5*}$ and $_{\Lambda}Li^8$ respectively; the results on the decay of $_{\Lambda}He^4$ suggest the presence of a Li^{4*} state at about 4 MeV to dominate.

I. INTRODUCTION

IN π^--mesic decays of light hypernuclei, it is possible to investigate whether the decay partly occurs in a two-step process in which an unstable intermediate state is formed which subsequently decays into two or more stable particles. For this purpose, in the present study, the following mesic decays of hypernuclei have been considered:

$$_{\Lambda}He^4 \rightarrow \pi^- + Li^{4*} \rightarrow \pi^- + H^1 + He^3 \qquad (1)$$

$$_{\Lambda}He^5 \rightarrow \pi^- + Li^{5*} \rightarrow \pi^- + H^1 + He^4 \qquad (2)$$

$$_{\Lambda}Li^8 \rightarrow \pi^- + Be^{8*} \rightarrow \pi^- + He^4 + He^4. \qquad (3)$$

Reaction (1) has been investigated by Beniston *et al.*[1] and by Gajewski *et al.*[2]; however the results obtained by the two groups are not in agreement with each other. Reactions (2) and (3) have been investigated by Ammar

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et al.[3] and by Davis *et al.*[4]; these investigators obtained evidence for the formation of Li^{5*} and Be^{8*}.

In the present investigation a further attempt has been made to study the excited states of Li^4, Li^5 and Be^8 by studying the angular correlations and the Q-value distributions between the decay products, in their centre-of-mass system, in the π^--mesic decays of ${}_\Lambda He^4$, ${}_\Lambda He^5$ and ${}_\Lambda Li^8$ respectively. Our results from the study of ${}_\Lambda He^5$ and ${}_\Lambda Li^8$ further support the existence of final states like Li^{5*} at 1·8 MeV and Be^{8*} at 0 and 2·9 MeV levels reported by Ammar *et al.*[3] and Davis *et al.*[4] respectively. On the other hand our results from ${}_\Lambda He^4$ indicate the presence of an excited state of Li^4 at about 4 MeV but not the 10·62 MeV level indicated by Beniston *et al.*[1]

II. Experimental Results and Discussions

We have used an emulsion stack exposed to a stopping K^- beam of the CERN Proton Synchrotron. The details of the stack, the scanning for hypernuclei and the kinematic analysis of mesic decays of hypernuclei have been described by Chaudhari *et al.*[5] Out of a sample of 1312 π^--mesic hypernuclei obtained in this stack, the number of uniquely identified ${}_\Lambda He^4$, ${}_\Lambda He^5$ and ${}_\Lambda Li^8$ are 60, 195 and 47 respectively; further the number of non-unique ${}_\Lambda He$ is 306. These events have been used in the present investigation.

(A) *Helium Hypernuclei*

The helium hypernuclei consist essentially of ${}_\Lambda He^5$ and ${}_\Lambda He^4$. When the range of the recoil in their decay is < 6 μm. in emulsion, it is difficult to distinguish between ${}_\Lambda He^4$ and ${}_\Lambda He^5$. But it is well known that the relative contributions of ${}_\Lambda He^4$ and ${}_\Lambda He^5$ are in the ratio of 1 : 4 as is observed in the uniquely identified events. In our sample we have 60 ${}_\Lambda He^4$, 195 ${}_\Lambda He^5$ and 306 ${}_\Lambda He^{4,5}$ events. Of the last 306 events we expect about 60 to be due to ${}_\Lambda He^4$ and the rest due to ${}_\Lambda He^5$. It should be pointed out that since the unique identification of the hypernucleus is dependent on the range of the recoil, conclusions drawn from a study of uniquely identified events alone suffer from a bias as will be seen later.

(i) ${}_\Lambda$*He*^{5}.—This hypernucleus decays almost exclusively as ${}_\Lambda He^5 \rightarrow \pi^- + H^1 + He^4$. In such a process Byers and Cottingham[8] assumed a pure *s*-wave for the Λ-hyperon decay and chose the final state P-He^4 wave function so as to yield correct phase shifts for proton-alpha scattering experiments. These scattering experiments have indicated resonant states, $p_{3/2}$ at 1·8 MeV and $p_{1/2}$ between 5 and 10 MeV, in the rest system of the proton and alpha particles. The theoretical calculations from such an approach concerning the decay of $_{\Lambda}He^5$ are presented together with those obtained experimentally in this investigation in Figs. 2–4; also we have shown in Fig. 1 the energy spectrum of pions from the decay of doubly charged hypernuclei and in Fig. 5 the Q-value distributions between proton and alpha particles in their rest system in the decay of $_{\Lambda}He^5$. The most striking results exhibited from these figures are as follows:

(*a*) There is a large accumulation of events at the pion energy of around 31 MeV both for $_{\Lambda}He^5$ events (Fig. 1 *b*) and for $_{\Lambda}He^{4,5}$ events (Fig. 1 *c*) and the distributions are similar indicating that most of the $_{\Lambda}He^{4,5}$ are due to $_{\Lambda}He^5$ only; it is to be remarked here that any small differences in the energy spectra of pions are due to the geometrical configuration of the recoil nucleus (He^3 or He^4). For this reason and also because of the bias mentioned earlier it is more meaningful to compare the theoretical results with the combined sample of $_{\Lambda}He^5$ and $_{\Lambda}He^{4,5}$.

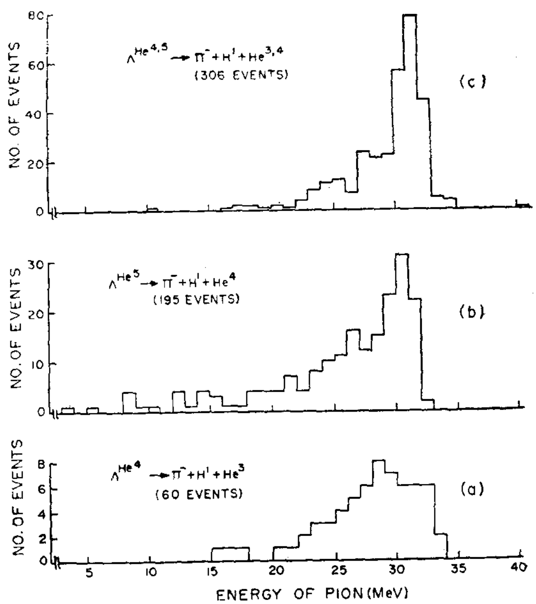

FIG. 1. Kinetic energy distribution of pions from the decay of $_{\Lambda}He^4$, $_{\Lambda}He^5$ and $_{\Lambda}He^{4,5}$ is shown in (*a*), (*b*) and (*c*) respectively.

(*b*) There is a strong forward peak in the cos θ distribution, where θ is the angle between the line of flight of the alpha particle and the direction of emission of the π^--meson in the π^--P rest system (Fig. 2). This distribution is similar for $_{\Lambda}He^5$ and $_{\Lambda}He^{4,5}$ $+_{\Lambda}He^5$ samples. The theoretical calculation of the cos θ distribution by Byers and Cottingham,[8] shown by the solid curve, is in reasonable agreement with the experimental distribution.

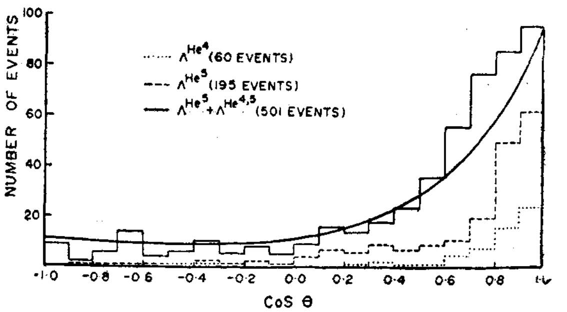

FIG. 2. Distribution of the cosine of the angle θ between the line of flight of α-particle and direction of pion in π^--P rest system. The smooth curve is fitted for the sample of ${}_{\Lambda}He^5$ and ${}_{\Lambda}He^{4,5}$ put together and corresponds to the calculations of Byers and Cottingham.

(*c*) The angular distribution in cos ϕ, where ϕ is the angle between the line of flight of the π^--meson and the direction of the proton in the P-He^4 rest system, shows a strong backward peaking for ${}_{\Lambda}He^5$ events and a forward peaking for ${}_{\Lambda}He^{4,5}+{}_{\Lambda}He^5$ events (Fig. 3). This can be explained as the recoil in ${}_{\Lambda}He^{4,5}$ events is characterised by a range $< 6\ \mu$m. as compared to $\geqslant 6\ \mu$m. for unique ${}_{\Lambda}He^5$ events. The smooth curve fitted to the sample of ${}_{\Lambda}He^5$ and ${}_{\Lambda}He^{4,5}$ is of the form $1 + 3\cos^2\phi$. According to Byers and Cottingham[8] $p_{1/2}$ state for P-He^4 system would yield an isotropic distribution whereas a $p_{3/2}$ would yield a distribution of the form $1 + 3\cos^2\phi$. The experimental one is neither isotropic nor a pure $1 + 3\cos^2\phi$ type; there is a slight asymmetry between the forward and backward directions.

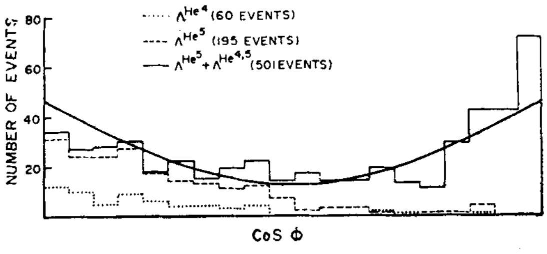

FIG. 3. Distribution of the cosine of the angle ϕ between the line of flight of the pion and the direction of proton in P-α rest system. The smooth curve is fitted for the sample of ${}_{\Lambda}He^5$ and ${}_{\Lambda}He^{4,5}$ put together, and corresponds to the calculations of Byers and Cottingham.

(*d*) A double hump structure for the combined sample of ${}_{\Lambda}He^5$ and ${}_{\Lambda}He^{4,5}$ is seen in the distribution of the resultant momentum of pion and proton ($R_{\pi P}$) in the laboratory system (Fig. 4). This reflects the forward-backward peak observed in cos ϕ distribution. The smooth curve is according to the predictions of Byers and Cottingham.[8] Theoretically one expects a sharp peak at about 120 MeV/c and a broad peak at about 40 MeV/c. Experimentally the lower peak is slightly shifted to higher momentum and the upper peak is broadened.

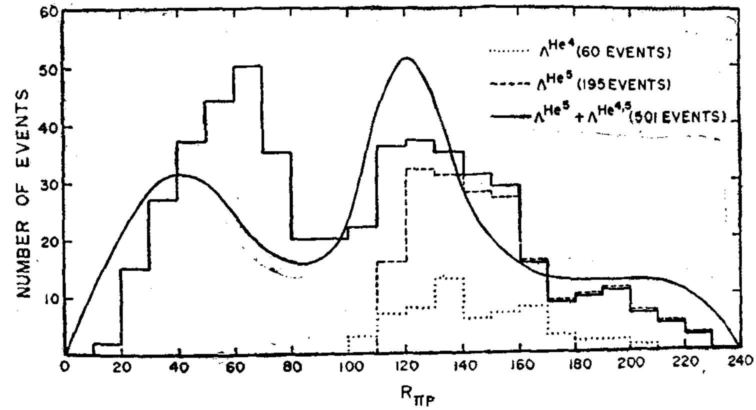

FIG. 4. Distribution of the resultant momentum of pion and proton in the laboratory system. The smooth curve is according to the calculation of Byers and Cottingham and fitted to the sample of $_\Lambda He^5$ and $_\Lambda He^{4,5}$ combined together.

(*e*) The observations in Figs. 2–4 strongly indicate the presence of final state interactions in the decay of $_\Lambda He^5$. In order to find out the exact nature of such interaction we have evaluated the Q-values between the proton and alpha particles in their rest system and plotted in Fig. 5. In the same figure we have also shown the expected Q-values obtained from phase-space consideration (assuming no final state interactions) normalised to the same area shown by the experimental histogram. From this figure it is seen that there is a large concentration of Q-values in the energy region 0–10 MeV with a peak between 2 and 3 MeV; this observation is consistent with the known $P_{3/2}$ level of Li^{5*} at about 1·8 MeV to be predominant in the decay of $_\Lambda He^5$.

Before drawing any meaningful conclusions from the experimental observations one should bear in mind that $_\Lambda He^{4,5}$ contain a small proportion (about 60 in 306 events) of $_\Lambda He^4$ which could not be separated due to experimental difficulty. There is reasonably fair agreement between theory and experiment (Figs. 2–4) and it may be remarked that the use of relativistic kinematics and $|p/s|$ value different from zero would improve the situation. Similar conclusions have been drawn by Ammar *et al.*[3] and Harmsen *et al.*[6]

(ii) $_{\Lambda}He^4$.—The experimental results from the 60 uniquely identified $_{\Lambda}He^4 \rightarrow \pi^- + H^1 + He^3$ are shown in Figs. 1–4 and 6. As discussed earlier the non-unique events $_{\Lambda}He^{4,5}$ (306) contain a comparable number of $_{\Lambda}He^4$ events (≈ 60) which are characterised by having recoil range $< 6\,\mu$m. In order to see whether these events have any peculiarities compared to the unique events we have also shown the experimental features for $_{\Lambda}He^{4,5}$ events in Figs. 1–4. In analogy to the study of $_{\Lambda}He^5$, the angular distributions observed for $_{\Lambda}He^4$ (Figs. 2 and 3) suggest qualitatively the presence of final state interactions between the proton and He^3.

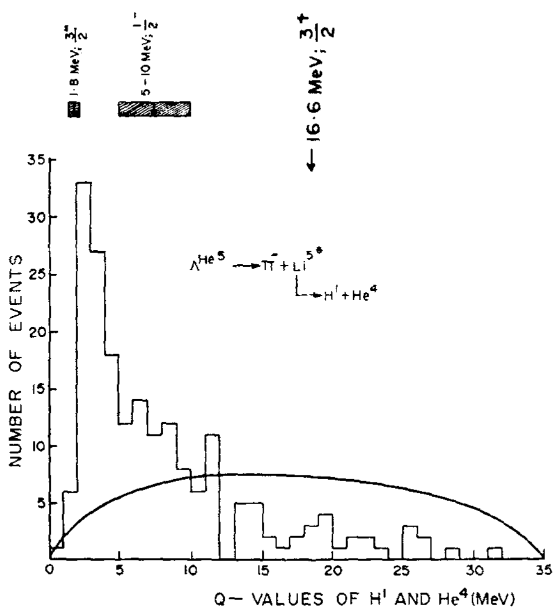

FIG. 5. The histogram represents the Q-value distribution between proton and alpha-particle (He^4) in their rest system in the decay of $_{\Lambda}He^5$. The smooth curve is obtained from phase space calculation.

To understand the nature of such final state interactions we have studied further the energy spectrum of the pions in laboratory system and the Q-value distribution between P-He^3 in their centre of mass system. The pion energy spectrum is shown in Fig. 1 *a*. In a similar study Beniston *et al.*[4] have claimed a sharp peak in pion energy spectrum at $23 \cdot 68 \pm 0 \cdot 08$ MeV corresponding to a Li^{4*} state of isotopic spin $I = 2$ at $10 \cdot 62 \pm 0 \cdot 2$ MeV. Our observations in neither unique $_{\Lambda}He^4$ nor non-unique $_{\Lambda}He$ showed evidence for such a peak and are in agreement with those of Gajewski *et al.*[2]

For a quantitative study of a final state between P and He^3 we have obtained the Q-values between them in their centre of mass system and plotted in Fig. 6. In the same figure we have plotted the Q-value distribution obtained from phase-space calculation. A comparison of these two indicate the existence for a final state of Li^{4*} at about 4 MeV to be predominant in the decay of ${}_{\Lambda}He^4$. It is appropriate to mention here that the scattering data of Tombrello[9] for the reaction He^3 (P, P) He^3 indicated the possible existence of Li^{4*} levels at 4·74, 6·16, 7·94 and 9·8 MeV.

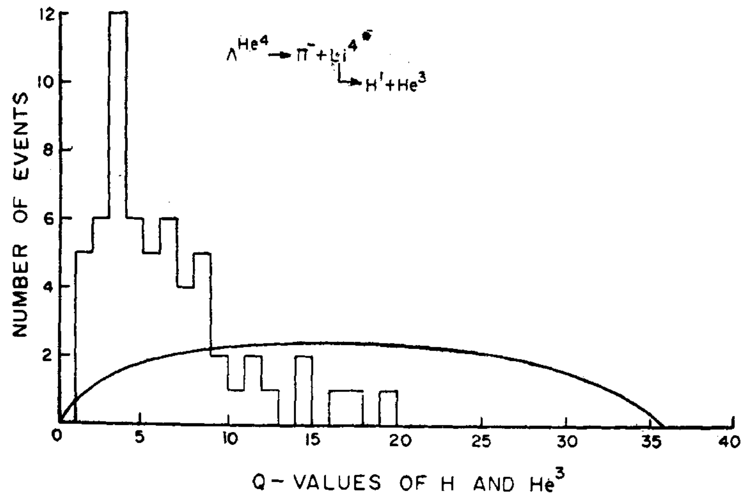

FIG. 6. Histogram of the Q-values between proton and He^3 in their rest system in the decay of ${}_{\Lambda}He^4$. The smooth curve corresponds to the one obtained by phase space calculation.

(B) *Hypernucleus* ${}_{\Lambda}Li^8$

This hypernucleus decays predominantly as ${}_{\Lambda}Li^8 \rightarrow \pi^- + He^4 + He^4$. The Q-value distribution of the two alpha particles in their centre of mass system is computed and shown in Fig. 7 for 47 uniquely identified ${}_{\Lambda}Li^8$ events. In the same figure we have plotted the Q-value distribution obtained from phase-space considerations; also we have indicated in the same figure the energy levels of Be^8 taken from Lauritsen and Ajenberg-selov.[10] A comparison of these energy levels and the Q-distributions indicate that the decay of ${}_{\Lambda}Li^8$ occurs predominantly *via* the intermediate ground (0^+) and 2·9 MeV (2^+) excited states of Be^8.

Figure 8 shows the cos ϕ distribution (ϕ-angle between the line of flight of π^--meson and the direction of alpha particles in their rest system) for 38 events whose Q-values are between 1 and 10 MeV. As this number is statistically poor, we have combined our results with those obtained by EFINS and European groups as given by Sacton[11] and the combined

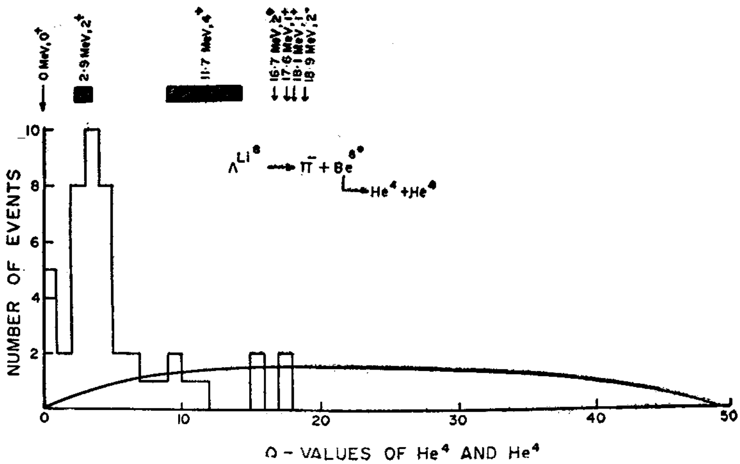

FIG. 7. Histogram of the Q-values of the two alpha-particles, in their rest system, from the decay of $_{\Lambda}Li^8$. The smooth curve refers to the one obtained from phase space calculation.

angular distribution is shown by solid line in Fig. 8. The distribution is of the form $1 + 3\cos^2\phi$; according to the calculations of Dalitz[12] it indicates a spin value 1 for $_{\Lambda}Li^8$.

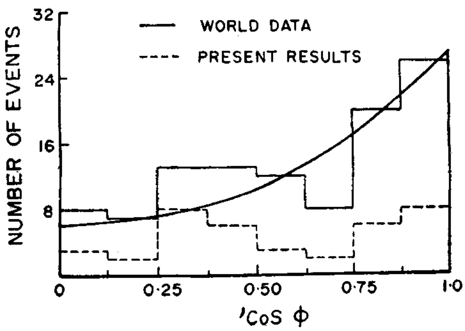

FIG. 8. The cos ϕ distribution, where ϕ is the angle between the line of flight of pion and the direction of alpha-particles in their rest system. The dashed line represents the present data and the solid line refers to the world data (EFINS + European Laboratories + TIFR + Chandigarh). The smooth curve is of the $1 + 3\cos^2\phi$ form.

III. SUMMARY

In the π^--mesic decays of $_{\Lambda}He^4$, $_{\Lambda}He^5$ and $_{\Lambda}Li^8$ there is a good evidence for the existence of final state interactions. In the decay of $_{\Lambda}He^4$ the Li^4

excited state plays an important role with a level between 3 and 4 MeV. In the case of $_{\Lambda}He^5$, the $P_{3/2}$ level of Li^{5*} at 1·8 MeV, and in $_{\Lambda}Li^8$ the ground state and the level at 2·9 MeV of Be^{8*} seem to play a major role.

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