E906 and Resonant Mode of Decay

w. D.E.Kahana and D.J.Millener

- In $E906$ at the BNL-AGS, strong evidence for the nuclide ${}_{\Lambda\Lambda}^{4}$H was found.

- The most striking components of this data was the appearance of a narrow low-momentum π^- line at $k_\pi = 104 - 105$ MeV/c, ascribed to the decay into a resonant state in ${}_{\Lambda}^{4}$He.

- The existence of such a state is shown to be plausible and its characteristics delineated.

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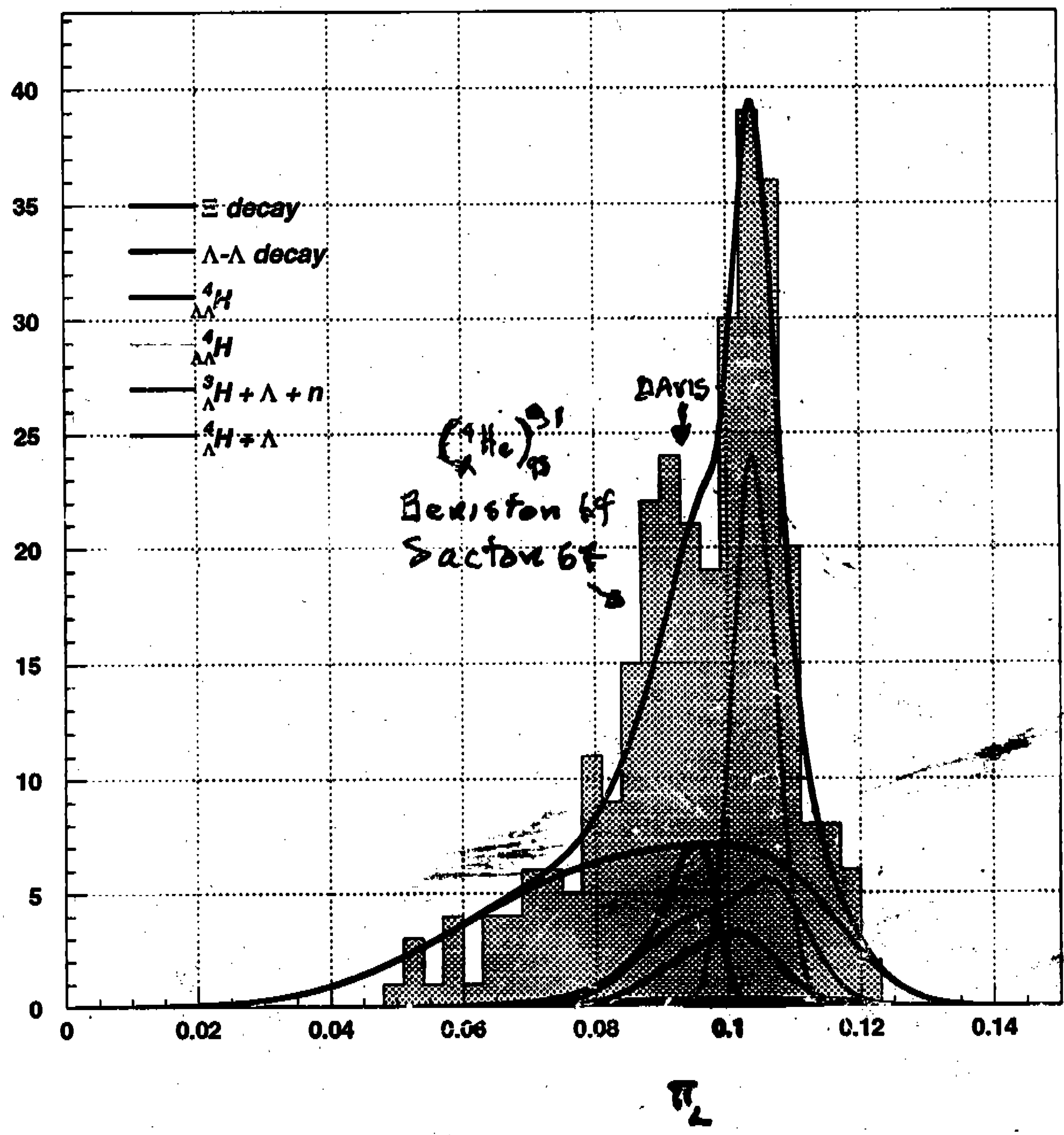
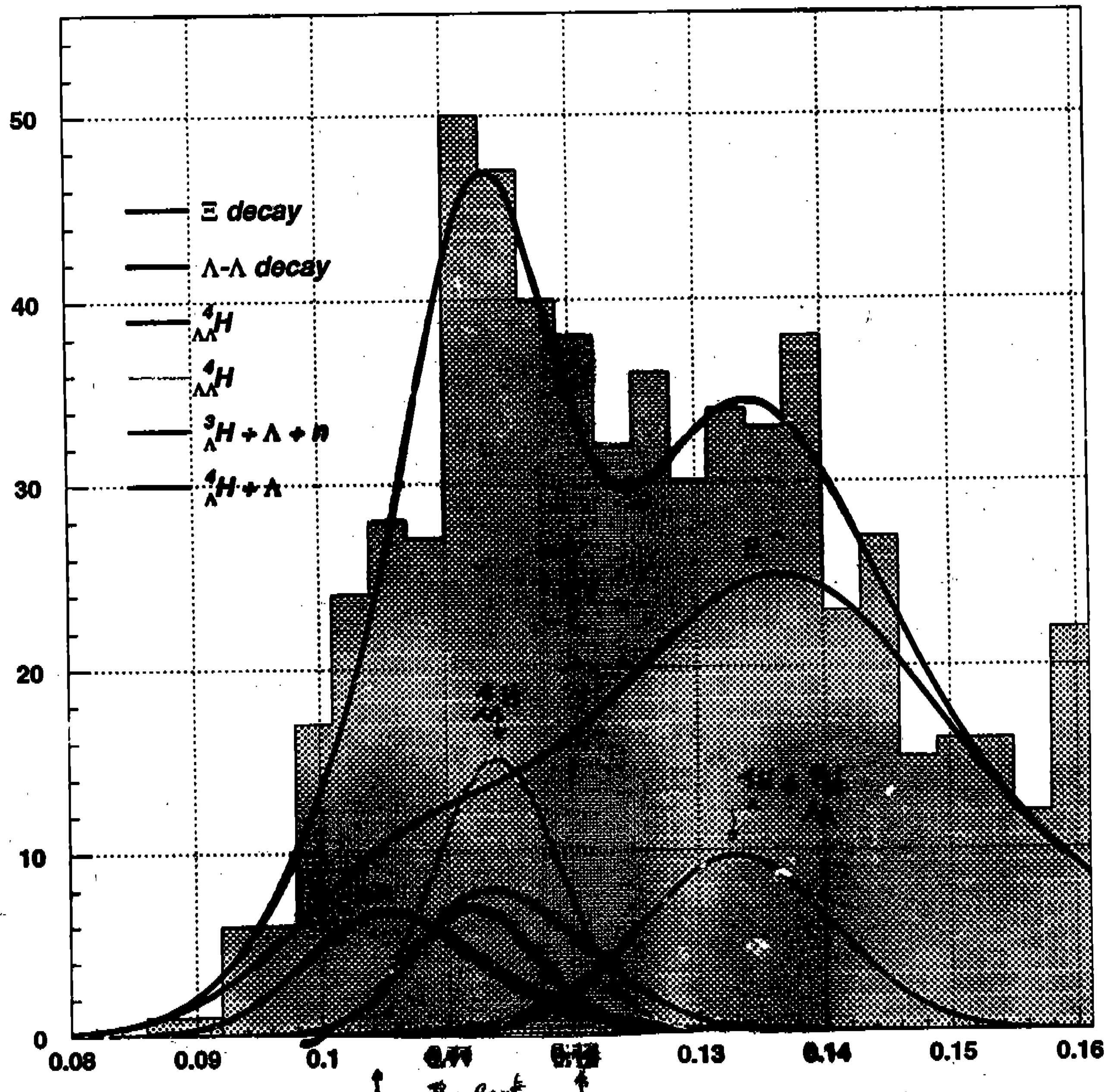


(Correlated pion pair π_H, π_L)

12-



Ξ decay
Λ-Λ decay
$^{4}_{\Lambda\Lambda}H$
$^{4}_{\Lambda\Lambda}H$
$^{3}_{\Lambda}H + \Lambda + n$
$^{4}_{\Lambda}H + \Lambda$
50
40
30
20
10
0
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0.15
0.16

Best Evidence for $4_{\Lambda\Lambda}H$

- Structure at 104-105 MeV/c narrow, unreported.
- Structure at 114-116 broad, **two components**

Correlated

29.

EXPECTED π'S

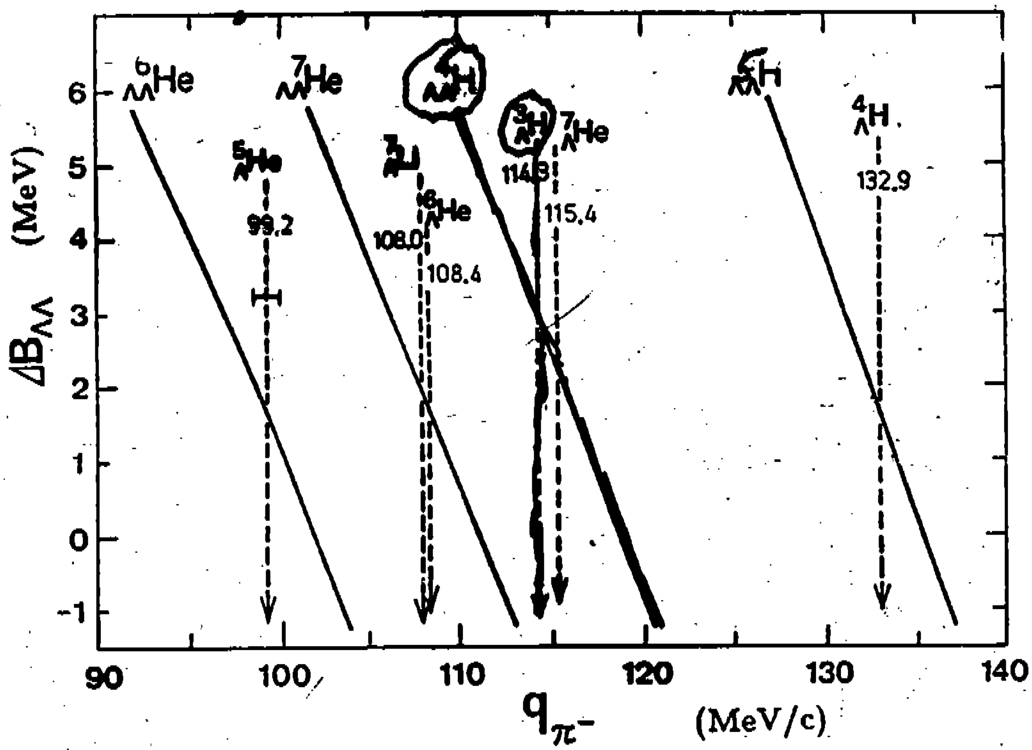


Fig. 8. Λ–Λ binding energy $\Delta B_{\Lambda\Lambda}$ versus discrete pion momenta q_{π^-} (solid lines), which are expected for the two-body π^- decays of the $\Lambda\Lambda$-hypernuclei produced after the compound state formation reaction ^{9}Be(K^-, K^+) → [$^{\ 8}_{\Lambda\Lambda}$He*, $^{\ 8}_{\Lambda\Lambda}$H*]$_{compound}$ +N. The vertical dashed lines indicate the characteristic pion momenta known for the two-body π^- decays of light single-Λ hypernuclei, with the numbers being monochromatic q_{π^-} in MeV/c. In the figure are also included the continuum but very sharp pions from the three-body decays of $^{\ 6}_{\Lambda\Lambda}$He and $^{5}_{\Lambda}$He ($\Delta q_\pi \simeq$ 0.45 MeV/c and 1.7 MeV/c, respectively).

α-Λ potential on the basis of a nonrelativistic quark-cluster model. This would stimulate theoretical investigations about the deeper origin of the central repulsion.

3.1.2 Decay spectrum

The energy spectrum of π^- is shown in Fig. 12 for the Isle case together with the experimental data by Gajewski *et al.* (1969). Again a good agreement is obtained between the theoretical result and the data. In the Green's function calculation a smearing with ΔE=0.5 MeV was done to compare the result with the spectrum data which was obtained by counting emulsion events with 0.5 MeV energy interval.

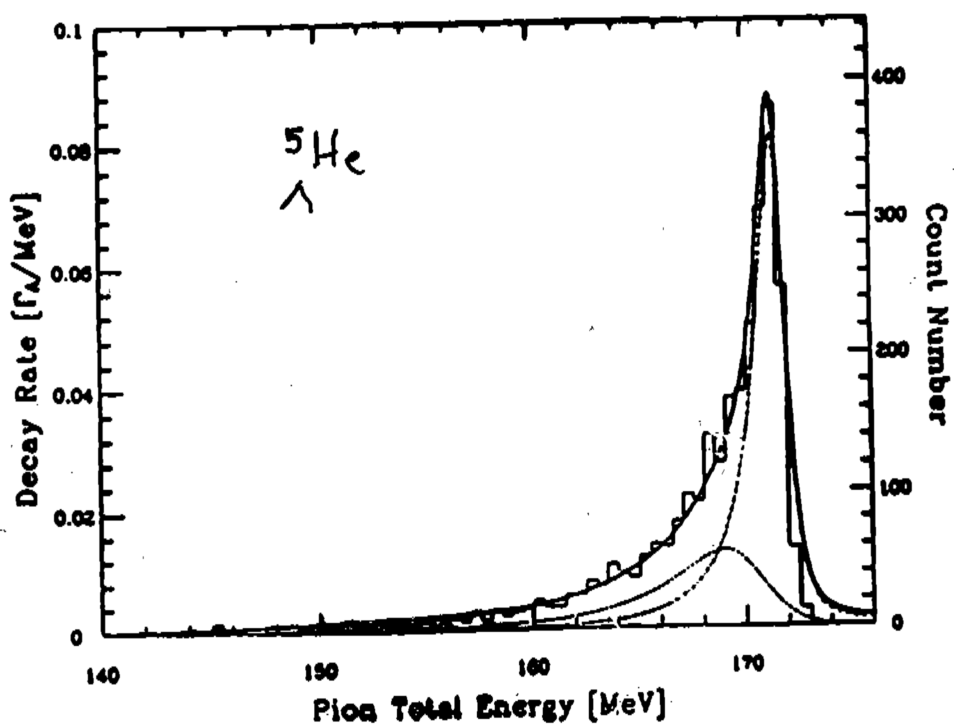
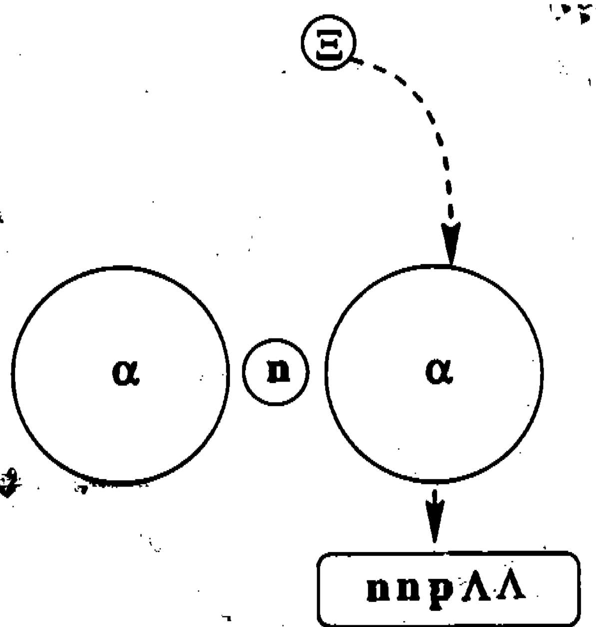


Fig. 12. The π^- energy spectrum of $^5_\Lambda$He. The dash-dotted and dotted curves are the $p_{3/2}$ and $p_{1/2}$ contributions, respectively.

AKAISHI & YAMAZAK
Progress in Particle & Nuclear Phys.
(1997)

REACTION MECHANISM

Likely scenario, consistent with observed species:



$^{5}_{\Lambda\Lambda}H$ $^{4}_{\Lambda\Lambda}H$ $^{4}_{\Lambda}H$ $^{3}_{\Lambda}H$

~~ALSO BORROMEAN~~

Nuclear events initiated with appreciable T_{Ξ} (initially ≲ 10 MeV)

Other possible species: $^{5}_{\Lambda}He$ $^{6}_{\Lambda\Lambda}He$ ... $^{8}_{\Lambda\Lambda}He$, $^{9}_{\Lambda\Lambda}Li$

↓

non-mesonic decays

hurt

$^{4}_{\Lambda\Lambda}$H Decay Modes

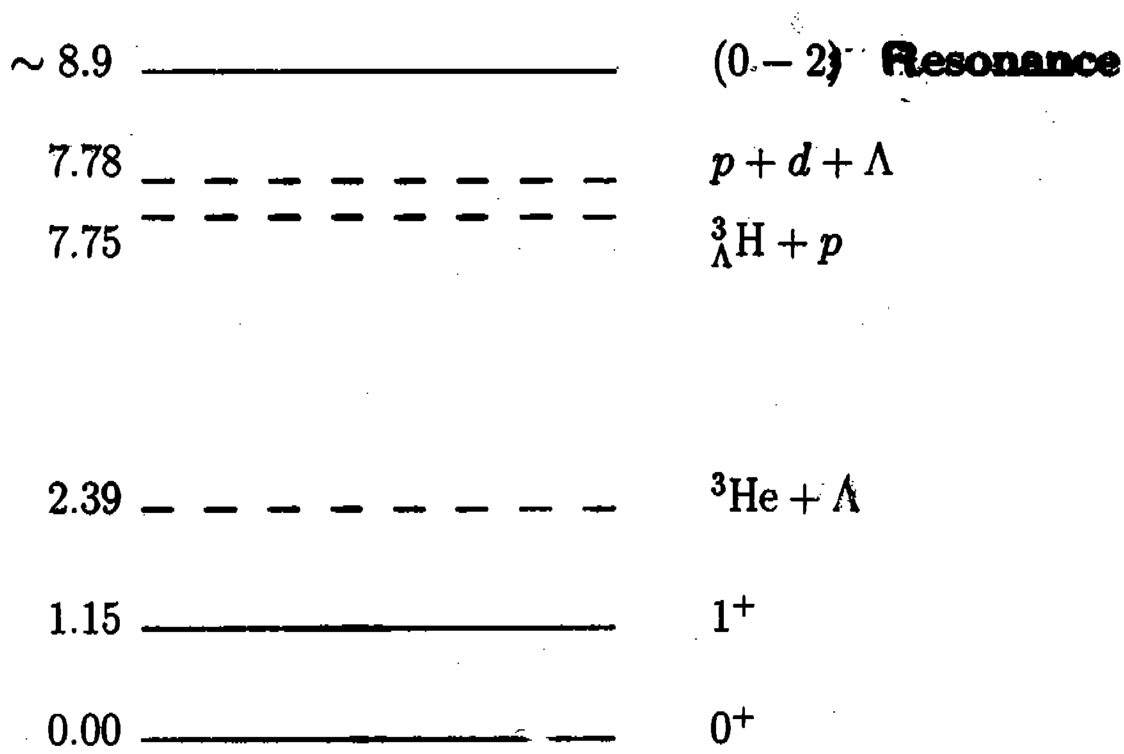
$$\begin{aligned} {}^{4}_{\Lambda\Lambda}H &\rightarrow {}^{4}_{\Lambda}He + \pi^{-}_{H} && (\sim 112 - 118\ MeV/c) && (1) \\ {}^{4}_{\Lambda}He &\rightarrow {}^{3}H + p + \pi^{-}_{L} && (\sim 85 - 95\ MeV/c) && (2) \end{aligned}$$

and also, a decay into a possible excited state of $^{4}_{\Lambda}$He,

$$\begin{aligned} {}^{4}_{\Lambda\Lambda}H &\rightarrow {}^{4}_{\Lambda}He^{*} + \pi^{-}_{L} && (\sim 104 - 105\ MeV/c) && (3) \\ {}^{4}_{\Lambda}He^{*} &\rightarrow {}^{3}_{\Lambda}H + p && && (4) \\ {}^{3}_{\Lambda}H &\rightarrow {}^{3}He + \pi^{-}_{H} && (114.3\ MeV/c), && (5) \end{aligned}$$

CONCENTRATE ←

where π^{-}_{H} and π^{-}_{L} refer to the high and low momentum members of a correlated pair seen in the experiment.



$^4_\Lambda$He Spectrum

Resonance Candidates and Weak Decay

$$\sqrt{\frac{\mu}{3+\mu}}\ (s^2p)[3]1/2 \times s_\Lambda \ - \sqrt{\frac{3}{3+\mu}}\, s^3 \times p_\Lambda \quad (1)$$

$$(s^2p)[21]1/2 \times s_\Lambda \quad (2)$$

$$(s^2p)[21]3/2 \times s_\Lambda \quad (3)$$

$^{4}_{\Lambda\Lambda}$H $\equiv$ $s^3(1)\, s^2_\Lambda(0)$ S = 1

∴ ONLY $^{4}_{\Lambda}$H L = 1 , S = 1 J = 0, 1, 2

Matrix elements for the production of single-Λ hypernuclear configurations in the π^- weak decay of $^{4}_{\Lambda\Lambda}$H are given in the first row in units of $s^2_{\pi^-}\left\langle l_N | j_{l_N}(k_\pi r) | s_\Lambda \right\rangle^2 / 4\pi$ where $\mu/(3+\mu) = 0.284$. The remaining rows specify the breakup of the single-Λ hypernuclear configurations under the assumptions described in the text. Combining production and decay in this simple approach shows that $^{3}_{\Lambda}$H+p is favored over $d + p + \Lambda$ by a factor of 11/3 to 4/3.

Final state	$^{4}_{\Lambda}$He(1^+)	Eq. (1)	Eq. (2)	Eq. (3)
Production	1	$\mu/(3+\mu)$	1	4
$^{4}_{\Lambda}$He(1^+)	1			
^{3}He+Λ		1		
$^{3}_{\Lambda}$H+p		(1/2)	1/9	8/9
$d+p+\Lambda$		(1/2)	8/9	1/9

$\mu = m_\Lambda / m_N$

Average (cluster) ${}^3_\Lambda$H-Proton Potential

$$V^{Surf}(r) = -V_0 \left[\frac{4e^{(r-R)/a}}{(1+e^{(r-R)/a})^2} \right], \qquad (1)$$

with R the radius and a the diffusivity. A Coulomb potential is included, taken as that of a uniform charge distribution with radius parameter $R_C = R$.

Only the strength of $V^{Surf}(r)$ is varied, to reproduce the correct ground state separation energy 7.75 MeV, **yielding a depth**:

$$V_0 = 28.09 MeV, \qquad (2)$$

with radius parameter $R = 2.07$ fm, and diffusivity $a = 0.5$ fm.

In this completely specified well, a p-wave resonance appears at;

$$\epsilon = [1.1\blacksquare - (1/2)1.00] MeV. \qquad (3)$$

N.B. SAME DEPTH FOR ${}^4_\Lambda He^{g.s.}$ & ${}^4_\Lambda H^*$

REPRODUCE (WEAK DECAY) RESULTS OF KUMAGAI-FUSE & OKABE

TO $^{4}_{\Lambda}He$ [1] & TO $^{3}_{\Lambda}H + p$: $0.681\Gamma_\Lambda$ & $0.80\Gamma_\Lambda$

USING ESSENTIALLY $S_{\pi^-}\, j_\Lambda(k_\pi r)\, Y_\Lambda$ Dominant piece, no nucleon spin

SUFFICIENT $^{3}_{\Lambda}H$ produced for scenario to work

STATE IN QS DOESN'T MIX MUCH WITH (2)

(1) OFF DIAGONAL MATRIX ELEMENTS ~ Spin-spin of ΛN

~ Singlet-triplet (both attractive)

(2) $(s^2p)[3]$ purely spurious: no NN overlap with $(s^2p)[21]$ by transl. invariant force

Decay Momentum

With the resonance energy calculated the $\Lambda\Lambda$ pairing energy $\Delta B_{\Lambda\Lambda}$ can be estimated from the position of the narrow π^- peak ascribed to the weak decay from ${}_{\Lambda\Lambda}^{4}$H to ${}_{\Lambda}^{4}He^*$. The π^- momentum k^* is given by

$$\epsilon_\pi + k^{*2}/2M({}_{\Lambda}^{4}He^*) = M({}_{\Lambda\Lambda}^{4}H) - M({}_{\Lambda}^{4}He^*). \tag{1}$$

To a good approximation here,

$$k_\pi^* = (107.466 - 1.6391\Delta)\ MeV/c, \tag{2}$$

where $\Delta = B^* + \epsilon_R$ and

$$B^* = 2\bar{B}_\Lambda({}_{\Lambda}^{3}H) + \Delta B_{\Lambda\Lambda}$$

] → $\epsilon_R + \Delta B_{\Lambda\Lambda}$

is the full binding energy of the Λ pair in ${}_{\Lambda\Lambda}^{4}H$.

$\Delta B_{\Lambda\Lambda}$-Pairing Energy

Taking

$$\epsilon_R = 1.18 MeV, \quad (1)$$

$$\Delta B_{\Lambda\Lambda} = 0.34 MeV, \quad (2)$$

puts the centroid of the decay momentum at

$$k^* = 104.5 MeV/c. \quad (3)$$

Alternatively, ϵ_R = 0.97 MeV and the same decay momentum results in $\Delta B_{\Lambda\Lambda} = 0.55$ MeV.

Assuming 300 KeV uncertainty in k^* produces range:

$$0.17 MeV < \Delta B_{\Lambda\Lambda} < 0.55 MeV. \quad (4)$$

Interestingly, the two body decay of ${}^{4}_{\Lambda\Lambda}H$ for $\Delta B_{\Lambda\Lambda} = 0.34$ now appears at

$$k_\pi = 116.5 MeV/c, \quad (5)$$

Easily distinguishable in a future (better resolution) experiment.

Comments

(1). We see that the existence of states above threshold in $^3_\Lambda H$ + proton system can straightforwardly describe the narrow, low momentum, π^- feature at $104 - 105$ MeV/c observed in the BNL experiment E906.

(2).The inferred energy of the resonance and energy range possible for $\Delta B_{\Lambda\Lambda}$, the latter likely somewhat less than 0.5 MeV, are not unreasonable. Takahashi *et al.* found $\Delta B_{\Lambda\Lambda} = 1.0 \pm 0.38$ MeV for $^{\ 6}_{\Lambda\Lambda}He$. One certainly expects a smaller value for the more extended mass 4 system, but the suggested values and their likely errors allow for consistency.

(3). For the meantime, it is also of importance to perform many-body calculations with $\Sigma - \Lambda$ coupling, and with forces constrained by as much data as is available, including E906. The latter experiment has pointed to the existence of two interesting nuclides, both mass 4 objects, one a very light $S = -2$ hypernucleus, the other an unusual, if not completely unexpected, resonance in an $S = -1$ daughter nucleus.

(4). $B(S = -2) < 4.5$ MeV, $B(H^0) \leq 1.5$ MeV. No bound H^0?