Hyperfragments from the lightest p-shell hypernuclei Recent progress and the next steps

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AGENDA

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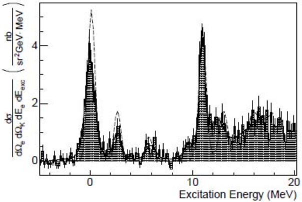
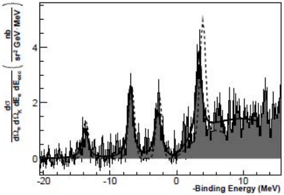
1.	Motivation	Experiment **MAMI**, JLab
2.	Approach	Shell Model
3.	Extension	$\mathrm{N}_{\mathrm{min}}+2$
4.	Suggestions	

Example : closed shell nuclei

${}^{12}_{\Lambda}$B : M. Iodice *et al.*, PRL **99**, 052501 (2007)

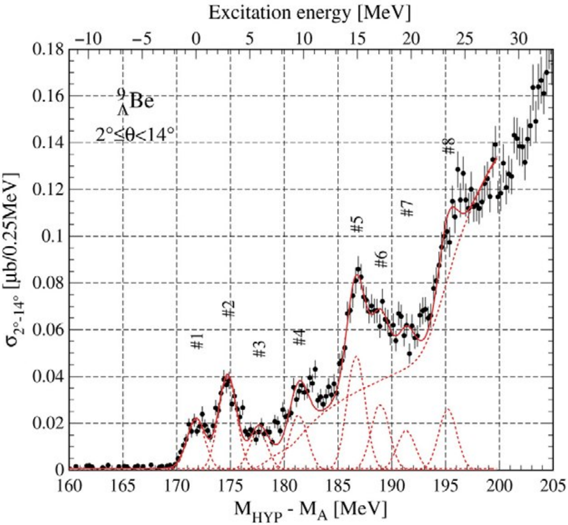


${}^{16}_{\Lambda}$N : F. Cusanno *et al.*, PRL **103**, 202501 (2009)

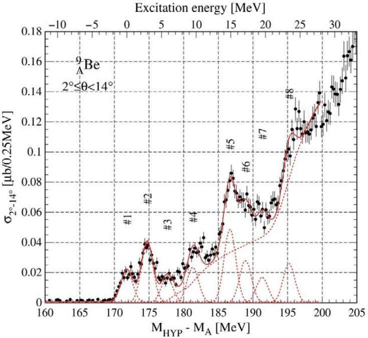


Example : Spectrum of $^{9}_{\Lambda}$Be

Spectrum of $^{9}_{\Lambda}$Be measured using the (π^{+}, K^{+}) reaction.
From O. Hashimoto and H. Tamura



Deciphering spectrum of ${}^{9}_{\Lambda}$Be



. p^{-1} s_Λ p_Λ

. p^{-1} s_Λ p_Λ

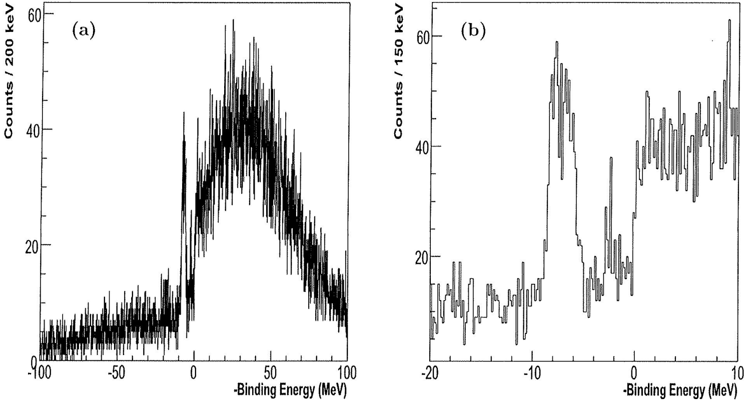
. s^{-1} s_Λ s_Λ

^{8}Be :

J^π; T	E_{ex}	shell model	"hole"
0^+; 0	0.0	s^4p^4 [44] S	p^{-1}
2^+; 0	3.0	s^4p^4 [44] D	p^{-1}
. . .			
2^+; 0+1	16.7	s^4p^4 [431]D	p^{-1}
. . .			
2^-; 0	18.9	s^3 p^5[44] P	s^{-1}
. . .			
$(1,2)^-$; 1	24.0	s^3p^5 [431]P	s^{-1}

No		l_n^{-1} l_Λ
1,2		$p^{-1}s_\Lambda$
3,4		$p^{-1}p_\Lambda$
5	}	$p^{-1}s_\Lambda$
6		$s^{-1}s_\Lambda$
7		$p^{-1}p_\Lambda$
8		$s^{-1}s_\Lambda$

"Our" hypernucleus $^{9}_{\Lambda}$Li



. the whole energy range the region of interest

Excitation spectrum of $^{9}_{\Lambda}$Li measured using the $(e, e'K^{+})$ reaction
Jefferson Lab Hall A Collaboration arXiv:1405.5839

Hyperfragments from ${}^{9}_{\Lambda}$Li

Pochodzalla, Acta Phys.Polon. (2011):

	(${}^{6}_{\Lambda}$Li) $3n$ 19.0	${}^{7}_{\Lambda}$Li $2n$ 12.2	${}^{8}_{\Lambda}$Li n 3.7	${}^{9}_{\Lambda}$Li Λ 8.5
${}^{4}_{\Lambda}$He tnn 31.5	${}^{5}_{\Lambda}$He tn 9.9	${}^{6}_{\Lambda}$He t 9.7	${}^{7}_{\Lambda}$He d 13.0	${}^{8}_{\Lambda}$He p 13.8
${}^{3}_{\Lambda}$H ^{6}He 18.2	${}^{4}_{\Lambda}$H ^{5}He 11.8	(${}^{5}_{\Lambda}$H) ^{4}He	${}^{6}_{\Lambda}$H ^{3}He 38.5	(${}^{7}_{\Lambda}$H) $2p$

Shell Model - 1

Seminal papers

Gal, Soper, Dalitz, AP **63** (1971), **72** (1972) **113** (1978)

$\Psi({}^{A+1}_{\Lambda}Z) = \Psi({}^{A}Z) \cdot \psi^{\Lambda}$ "weak coupling"

for *p*-shell hypernuclei:

$$\underbrace{|s^4 \; p^{A-4} : J_A^{\pi} T_A}_{\textit{Cohen Kurath,}} \quad \otimes \quad s_{\Lambda} : J >$$

Discrete part of spectra ($0\hbar\omega$ excitations) :

Millener, Lecture Notes in Physics, vol. 724, 2007, Springer

Shell Model - 2

EXCITED nuclear states:

LS coupling

$$|0s^{ks}[f_s] \quad 1p^{kp}[f_p] \quad \ell^{k\ell}[f_\ell] : \quad \underset{\substack{TS \\ SU(4)}}{\underline{[f]}} \quad \underset{\substack{L \\ SU(3)}}{\underline{(\lambda\mu)}} \qquad : J >$$

Wigner(1939) *Elliott(1968)*

$$ks + kp + k\ell = A \qquad\qquad \ell = 2d, 2s; \quad 3f, 3p; \ldots$$

Excited states of p-shell nuclei

$0\hbar\omega_N\ (k)\ :$

$$|0s^4[4]\ 1p^k[f_p] \qquad : [f_A]\ (\lambda\mu) > \ = \ \Phi_k^{(A)}[f_A](\lambda\mu)\cdot\Psi_0(R_A)$$

$$[f_A] = [\mathbf{4}f_p]$$

$1\hbar\omega_N\ (k+1)\ :$

$$\left.\begin{array}{lll} |0s^4[4]\ 1p^{k-1}[f_p] & 2d\ [1] & : [f_A]\ (\lambda\mu) > \\ |0s^3[3]\ 1p^{k+1}[f'_p] & & : [f_A]\ (\lambda\mu) > \end{array}\right\} \begin{array}{l} \Phi_k^{(A)}[f_A](\lambda\mu)\cdot\Psi_1(R_A) \\ \Phi_{k+1}^{(A)}[f_A](\lambda\mu)\cdot\Psi_0(R_A) \end{array}$$

$$[f_A] = [4f_p],\ [\mathbf{3}f'_p]$$

$2\hbar\omega_N\ (k+2)\ :$

$$\begin{array}{llll} |0s^4[4]\ 1p^{k-1}[f_p] & 3f\ [1] & : [f_A]\ (\lambda\mu) > & \Phi_k^{(A)}[f_A](\lambda\mu)\cdot\Psi_2(R_A) \\ |0s^4[4]\ 1p^{k-2}[f'_p] & 2d^2[f_d] & : [f_A]\ (\lambda\mu) > & \Phi_k^{(A)}[f_A](\lambda\mu)\cdot\Psi_2(R_A) \\ |0s^3[3]\ 1p^{k}\ \ [f''_p] & 2d\ [1] & : [f_A]\ (\lambda\mu) > & \Phi_{k+1}^{(A)}[f_A](\lambda\mu)\cdot\Psi_1(R_A) \\ |0s^2[2]\ 1p^{k+2}[f'''_p] & & : [f_A]\ (\lambda\mu) > & \Phi_{k+2}^{(A)}[f_A](\lambda\mu)\cdot\Psi_0(R_A) \end{array}$$

$$[f_A] = [4f_p],\ [3f'_p],\ [\mathbf{2}f''_p]$$

^{4}He

Due to NON-CENTRAL forces,
the wave function for the ^{4}He $J^\pi = 0^+$ ground state
is a mixture of $^1\mathrm{S}_0$, $^3\mathrm{P}_0$, and $^5\mathrm{D}_0$ states

Recent calculations:

ref.	interaction	$^{11}\mathrm{S}_0$	$^{13}\mathrm{P}_0$	$^{15}\mathrm{D}_0$
[1]	AV8':	85.7 %	0.4 %	13.9 %
[2]	AV18 + UIX:	83.2 %	0.8 %	16.0 %

[1] PR C 64, 044001 ('01) K. Kamada *et al.*:
Benchmark test calculation of a 4N bound state

[2] PR C 65 054003 ('02) A. Nogga *et al.*:
The α particle based on modern forces

$$^{15}\mathrm{D}_0\text{: } |0s^2\ 1p^2 : [22] >$$

Excited states of p-shell HYPERNUCLEI:

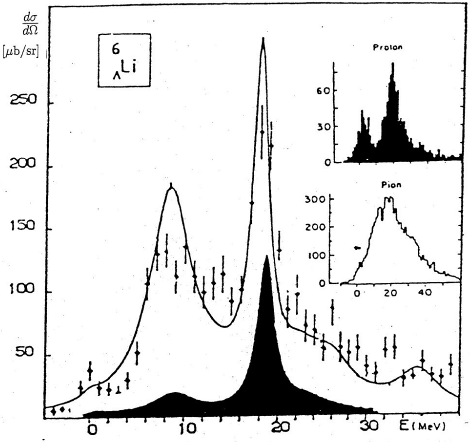
$\hbar\omega$:	$\hbar\omega_k + \hbar\omega_\Lambda$		
0	$0+0$	$\Phi_k^{(A)} \cdot \varphi_0^\Lambda(R_A - r_\Lambda)$	$(\varphi_0^\Lambda \equiv 0s_{\frac{1}{2}}^\Lambda)$
1	$0+1$	$\Phi_k^{(A)} \cdot \varphi_1^\Lambda$	$(\varphi_1^\Lambda \equiv 1p_{\frac{3}{2}}^\Lambda,\ 1p_{\frac{1}{2}}^\Lambda)$
	$1+0$	$\Phi_{k+1}^{(A)} \cdot \varphi_0^\Lambda$	
2	$0+2$	$\Phi_k^{(A)} \cdot \varphi_2^\Lambda$	$(\varphi_2^\Lambda \equiv 2d_{\frac{5}{2}}^\Lambda,\ 2d_{\frac{3}{2}}^\Lambda,\ 2s_{\frac{1}{2}}^\Lambda)$
	$1+1$	$\Phi_{k+1}^{(A)} \cdot \varphi_1^\Lambda$	
	$2+0$	$\Phi_{k+2}^{(A)} \cdot \varphi_0^\Lambda$	

Example : structure $({}^7_\Lambda\text{He})$

N	^{6}He	$\Phi_N^{(6)}$	$[f_6]$				$^7_\Lambda$He	
2	$s^4\ p^2$	$\Phi_2^{(6)}$	$[42], \dots$			s_Λ	p_Λ	d_Λ
3	$s^4\ p\ d$	$\Phi_3^{(6)}$	$[42], \dots$				s_Λ	p_Λ
3	$s^3\ p^3$	$\Phi_3^{(6)}$	$[42], \dots$	$[\ \underline{\mathbf{3}}\ 3], \dots$			s_Λ	p_Λ
4	$s^4\ p\ f$	$\Phi_4^{(6)}$	$[42], \dots$					s_Λ
4	$s^4\ d^2$	$\Phi_4^{(6)}$	$[42], \dots$					s_Λ
4	$s^3\ p^2\ d$	$\Phi_4^{(6)}$	$[42], \dots$	$[33], \dots$				s_Λ
4	$s^2\ p^4$	$\Phi_4^{(6)}$	$[42], \dots$	$[33], \dots$	$[\ \underline{\mathbf{2}}\ 22]$			s_Λ

Spectrum of ${}^{6}_{\Lambda}$Li

deciphering:	$p^{-1}s_\Lambda$	$p^{-1}p_\Lambda$	$s^{-1}s_\Lambda$
.	[41]	[41]	[32]



The (K^-, π^-) spectrum of the ${}^{6}_{\Lambda}$Li production.

Cluster wave function in Shell Model

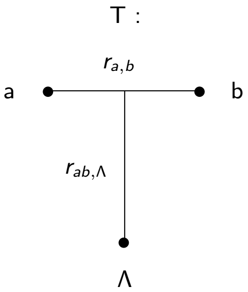
$$\Phi^{(A)}_{NA}[f_A](\lambda\mu)_A = \sum g^a \; g^b \quad \phi^{(a)}_{na}[f_a](\lambda\mu)_a \quad \phi^{(b)}_{nb}[f_b](\lambda\mu)_b \quad \varphi_\nu(r_{a,b})$$

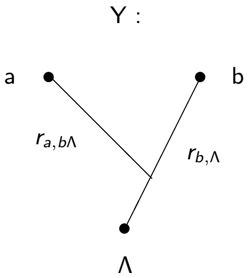
$g^a (g^b)$: coefficient of fractional parentage for a (b) particles

constrains:

$$\begin{aligned} na + nb + \nu &= N_A \\ [f_a] + [f_b] &= [f_A] \\ (\lambda\mu)_a + (\lambda\mu)_b + (\nu 0) &= (\lambda\mu)_A \\ L_a + L_b &= L_A \end{aligned}$$

Hyper FRAGMENTS





Transformation of Jacobi coordinates:

$$< \varphi_\nu(r_{ab})\varphi_0^\Lambda(r_{ab,\Lambda})|\varphi_0(r_{b,\Lambda})\varphi_\nu(r_{a,b\Lambda}) >= \left(\frac{m_A+1}{m_A}\frac{m_b}{m_b+1}\right)^{\frac{\nu}{2}}$$

Hyperfragments from ${}^{7}_{\Lambda}$He

E_{th}			$[f_c]$
2.82	${}^{6}_{\Lambda}\mathrm{He}$	$+\ n$	[41]
3.08	${}^{5}_{\Lambda}\mathrm{He}$	$+\ 2n$	[4]
5.23	${}^{6}\mathrm{He}$	$+\ \Lambda$	[42]
6.95	${}^{5}\mathrm{He}$	$+\ \Lambda n$	[41]
15.49	${}^{4}_{\Lambda}\mathbf{H}$	$+\ t$	**[3]**
21.41	${}^{4}_{\Lambda}\mathrm{He}$	$+\ 3n$	[3]
23.66	${}^{3}_{\Lambda}\mathbf{H}$	$+\ tn$	**[2]**
23.81	${}^{6}_{\Lambda}\mathbf{H}$	$+\ p$	**[32]**

Hyperfragments from ${}^{9}_{\Lambda}\mathrm{Li}$

E_{thr}	decay	$[f_i][f_k]$	$T_1\ T_2$
3.7	$n + {}^{8}_{\Lambda}\mathrm{Li}$	[43][1]	$\frac{1}{2}\,\frac{1}{2}$
8.5	${}^{8}\mathrm{Li} + \Lambda$	[431]	1 0
9.7	$t + {}^{6}_{\Lambda}\mathrm{He}$	[3][41]	$\frac{1}{2}\,\frac{1}{2}$
	$\downarrow$		
9.9	$tn + {}^{5}_{\Lambda}\mathrm{He}$	[3][1][4]	$\frac{1}{2}\,\frac{1}{2}\,0$
11.8	${}^{5}\mathrm{He} + {}^{4}_{\Lambda}\mathbf{H}$	[41][**3**]	$\frac{1}{2}\,\frac{1}{2}$
12.2	$2n + {}^{7}_{\Lambda}\mathrm{Li}$	[2][42]	1 0
13.0	$d + {}^{7}_{\Lambda}\mathrm{He}$	[2][42]	0 1
13.8	$p + {}^{8}_{\Lambda}\mathrm{He}$	[1][421]	$\frac{1}{2}\,\frac{3}{2}$
18.2	${}^{6}\mathrm{He} + {}^{3}_{\Lambda}\mathbf{H}$	[42][**2**]	1 0
31.5	$tnn + {}^{4}_{\Lambda}\mathrm{He}$	[3][1][1][3]	$\frac{1}{2}\,\frac{1}{2}\,\frac{1}{2}\,\frac{1}{2}$
38.5	${}^{3}\mathrm{He} + {}^{6}_{\Lambda}\mathbf{H}$	**[3][32]**	$\frac{1}{2}\,\frac{3}{2}$

SUGGESTIONS

Some SUGGESTIONS for next steps:

- see for ${}^{4}_{\Lambda}$H in other *p*-shell targets;
- see for ${}^{3}_{\Lambda}$H in *p*-shell targets;
- ^{7}Li is a source of ${}^{6}_{\Lambda}$H hyperfragment.