ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2010. Т. 41. ВЫП. 7

DELAYED CLUSTERS ACCOMPANYING NONMESONIC WEAK DECAY OF THE Λ-HYPERNUCLEI: A CLUE TO NONLEPTONIC PROCESSES

L. Majling[1], *O. Majlingová*[2]

[1]Nuclear Physics Institute, Academy of Sciences, Řež, Czech Republic
[2]Dept. of Mathematics, Czech Technical University, Prague, Czech Republic

The nonmesonic decay of Λ-hypernuclei provides access to the nonleptonic weak decay process $\Lambda N \to NN$, which is achievable only through the observation of hypernuclear ground-state decays. We continue the discussion of some specific cases which make it possible to detect a few exclusive transitions, namely, the stripping of nucleon from the ground state results in a resonance state decaying via emission of two clusters. Delayed clusters accompanying weak decay of light hypernuclei give a unique information on spin dependence of the weak decay matrix elements.

PACS: 21.80+a

1. NONMESONIC DECAY OF Λ-HYPERNUCLEI

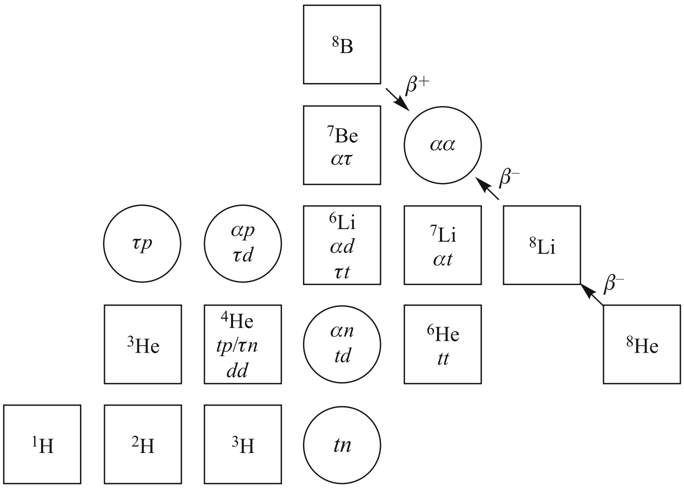
Λ-hypernuclei, bound systems with nucleons and one Λ-hyperon, baryon with a new flavor — strangeness, are not only exotic (the third dimension in the chart of nuclei, new symmetries, etc.) [1]. The realization of the brilliant suggestion by Podgoretskii [2] to study hypernuclear production in the strangeness exchange reaction (K^-, π^-) under proper kinematic conditions, opens a way to study spectra of several dozen hypernuclei [3]. They provide an excellent tool for obtaining information on ΛN interaction and explore the full $SU(3)$ symmetry breaking baryon–baryon interaction. The nonmesonic weak decay (NMWD) is the only way available to study the strangeness-changing interaction between baryons. The strangeness-changing process in which a Λ-hyperon converts into a neutron with the release of up to 176 MeV provides a clear signal for conversion of an s-quark to a u- or d-quark. The weak interaction at the quark level is shortranged, involving W-, Z-exchange [4]. Baryon–baryon interaction is modelled in terms of one-meson-exchange interaction, all pseudoscalar (π, η, K) and vector (ρ, ω, K^*) meson exchanges included. The evaluation of the weak baryon–baryon–meson vertices is quark model based but presented in terms of the symmetry $SU(6)_w$ [5]. Recently, quality of experimental data on NMWD has improved considerably [6].

2. DELAYED CLUSTERS

We explore the well-known fact that in several light p-shell nuclei the stripping of nucleon from the ground state (the one-nucleon induced nonmesonic weak decay mechanism) [7] results in a resonance state decaying via emission of two light nuclei (clusters):

$$\begin{array}{l} {}^{A}_{\Lambda}Z \to (n+N) \quad + \quad {}^{A_f}Z^*_f(E;\ J^\pi T) \\ \qquad\qquad\qquad\quad {}^{A_f}Z^*_f(E;\ J^\pi T) \begin{array}{l} \nearrow\ {}^{A_1}Z_1 \\ \searrow\ {}^{A_2}Z_2 \end{array} \quad E \Rightarrow J^\pi T. \end{array} \tag{1}$$

The energy E between clusters ${}^{A_1}Z_1$ and ${}^{A_2}Z_2$ determines the quantum numbers $(J^\pi T)$ of the resonance state in ${}^{A_f}Z_f$, so in this case it is possible to study the *exclusive channel* of NMWD. The most familiar is the removal of a neutron from ^{9}Be which leads to the formation of ^{8}Be nucleus in several states emitting two α particles [8]. Now, we look for other examples among p-shell hypernuclei [9]. The proper candidates for delayed cluster decay are shown in the Figure.



Light nuclei and their cluster structure. The circle denotes unstable species

We analyze not only the decays with α particles (Λ strips the nucleon from p-shell) but also the decays with three-nucleon clusters (t, τ) — Λ strips the nucleon from s-shell [10].

$$s^4\ p^k\ s_\Lambda \begin{array}{l} \nearrow \\ \searrow \end{array} \begin{array}{llll} s_\Lambda\ p & + & s^4\ p^{k-1} & \nearrow\ \alpha + «(k-1)» \\ s_\Lambda\ s & + & s^3\ p^k & \searrow\ 3N + «k». \end{array} \tag{2}$$

Table 1. **Possible clusters accompanying one-nucleon induced (Γ_{1N}) and two-nucleon induced (Γ_{2N}) decay of hypernuclei**

$^{A}_{\Lambda}Z$	Γ_{1N}		Γ_{2N}		
	Γ_n	Γ_p	Γ_{nn}	Γ_{np}	Γ_{pp}
$^{7}_{\Lambda}$He	$\alpha n + td$		$dd + tp + \tau n$	tn	
$^{7}_{\Lambda}$Li	$\alpha p + \tau d$	$\alpha n + dt$	τp	$dd + tp + \tau n$	tn
$^{7}_{\Lambda}$Be		$\alpha p + \tau d$		τp	$dd + tp + \tau n$
$^{8}_{\Lambda}$He	tt		$\alpha n + td$		
$^{8}_{\Lambda}$Li	$\alpha d + \tau t$	tt	$\alpha p + \tau d$	$\alpha n + td$	
$^{8}_{\Lambda}$Be		$\alpha d + \tau t$		$\alpha p + \tau d$	$\alpha n + td$
$^{8}_{\Lambda}$B					$\alpha p + \tau d$
$^{9}_{\Lambda}$Li	αt		$\alpha d + \tau t$	tt	
$^{9}_{\Lambda}$Be	$\alpha \tau$	αt	$\tau \tau$	$\alpha d + \tau t$	tt
$^{9}_{\Lambda}$B		$\alpha \tau$		$\tau \tau$	$\alpha d + \tau t$
$^{10}_{\Lambda}$Li	^{8}Li	^{8}He	αt		
$^{10}_{\Lambda}$Be	$\alpha \alpha$	^{8}Li	$\alpha \tau$	αt	
$^{10}_{\Lambda}$B	^{8}B	$\alpha \alpha$		$\alpha \tau$	αt
$^{10}_{\Lambda}$C		^{8}B			$\alpha \tau$
$^{11}_{\Lambda}$Be			$\alpha \alpha$	^{8}Li	^{8}He
$^{11}_{\Lambda}$B			^{8}B	$\alpha \alpha$	^{8}Li
$^{11}_{\Lambda}$C				^{8}B	$\alpha \alpha$

The population of final states is governed by spectroscopic factors. They are basic nuclear structure ingredients in transition amplitudes for direct nuclear reactions. When Λ-hyperon interacts with valence nucleon, α clusters appear. Tables of fractional parentage coefficients (FPC) are a standard part of the shell model [11]. The emission of $3N$ clusters in the two-body decay requests more sophisticated methods of computing FPC for separation of the nucleon from the s-shell; we explored Translational Invariant Shell Model [12].

3. PHENOMENOLOGICAL WEAK ΛN INTERACTION

In the first phenomenological analysis, Block and Dalitz (BD) [13] expressed the total NM width as a sum of four rates R_{NS} (ρ_A is the nucleon density in the hypernucleus). The different spin–isospin structure of the ground states of four

s-shell hypernuclei leads to four equations:

$$\begin{aligned}
\Gamma_{nm}({}^{3}_{\Lambda}\mathrm{H}) &= \varrho_3/8(3R_{n0}+1R_{n1}+3R_{p0}+1R_{p1}),\\
\Gamma_{nm}({}^{4}_{\Lambda}\mathrm{H}) &\equiv \Gamma^{n}_{\mathrm{H}}+\Gamma^{p}_{\mathrm{H}} = \varrho_4/6(1R_{n0}+3R_{n1}+2R_{p0}+0R_{p1}),\\
\Gamma_{nm}({}^{4}_{\Lambda}\mathrm{He}) &\equiv \Gamma^{n}_{\mathrm{He}}+\Gamma^{p}_{\mathrm{He}} = \varrho_4/6(2R_{n0}+0R_{n1}+1R_{p0}+3R_{p1}),\\
\Gamma_{nm}({}^{5}_{\Lambda}\mathrm{He}) &= \varrho_5/8(1R_{n0}+3R_{n1}+1R_{p0}+3R_{p1}).
\end{aligned} \tag{3}$$

These relations have an appealing simple form. However, it is still impossible to solve a set of four equations (3), since there are no input data on neutron transitions. Nevertheless, BD analysis has so far been a starting point in discussing weak decay mechanisms [14].

The exclusive $3N$ cluster decay widths for ${}^{7}_{\Lambda}\mathrm{Li}$, (Eq. (4)), are determined by the interaction of Λ with s-shell nucleons, see Eq. (2), so, we could use them in a phenomenological analysis.

$$\begin{aligned}
\Gamma_{\tau d:\,3/2} &= \rho_7\kappa\left(\frac{3}{2}\right)1R_{n1},\\
\Gamma_{\tau d:\,1/2} &= \rho_7\kappa\left(\frac{1}{2}\right)\left(\frac{1}{4}R_{n1}+\frac{3}{4}R_{n0}\right),\\
\Gamma_{td:\,3/2} &= \rho_7\kappa\left(\frac{3}{2}\right)1R_{p1},\\
\Gamma_{td:\,1/2} &= \rho_7\kappa\left(\frac{1}{2}\right)\left(\frac{1}{4}R_{p1}+\frac{3}{4}R_{p0}\right).
\end{aligned} \tag{4}$$

Here, $\kappa(J)$ are square of spin–isospin FPC. In the most simple case (^{6}Li ground-state wave function is $|s^4p^2 : {}^{13}\mathrm{S}_1\rangle$) $\kappa(3/2) = 4/5$ and $\kappa(1/2) = 1/5$. In the NMWD of the ${}^{7}_{\Lambda}\mathrm{Li}$ hypernucleus, a neutron (proton) induced process is linked with the escape of charged cluster — ^{3}He (^{3}H), and there are two spins ($(3/2)^+$, $(1/2)^+$) in residual nuclei. One can determine unambiguously all four matrix elements R_{NS}. The ratios $\mathcal{R}_i$

$$\mathcal{R}_1 \equiv \frac{\Gamma_{\tau d:\,1/2}}{\Gamma_{\tau d:\,3/2}},\quad \mathcal{R}_2 \equiv \frac{\Gamma_{td:\,1/2}}{\Gamma_{td:\,3/2}},\quad \mathcal{R}_3 \equiv \frac{\Gamma_{\tau d:\,3/2}}{\Gamma_{td:\,3/2}} \tag{5}$$

are almost independent of nuclear structure, so, they could discriminate between different models of weak interaction.

The calculations of NMWD for s-shell hypernuclei ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$ with various models of weak interaction: including two pions (TPE) [15], direct quark (DQ) [16], one-meson exchange (OME) [17], were published recently.

Table 2. **Phenomenological interaction**

Ref.	Model	${}^{4}_{\Lambda}\mathrm{H}$	${}^{4}_{\Lambda}\mathrm{He}$	${}^{7}_{\Lambda}\mathrm{Li}$		
		(Γ_n/Γ_p)	(Γ_n/Γ_p)	$\kappa\mathcal{R}_1$	$\kappa\mathcal{R}_2$	$\mathcal{R}_3$
[15]	π	4.1192	0.0475	3.890	1.108	**0.075**
	$+2\pi/\rho$	9.2497	0.0452	2.090	**1.102**	0.188
	$+2\pi/\sigma+\omega$	2.7243	0.1302	6.238	1.302	0.116
	$+\rho$	2.1709	0.3631	**8.719**	1.896	0.233
[16]	ME	2.705	0.417	6.308	2.068	0.397
	DQ+	0.693	0.269	4.600	**5.500**	**0.500**
[17]	PSVE	9.98	0.062	2.007	1.138	0.284
	PKE	27.9	0.031	**1.360**	1.063	0.372
	SPKE	2.70	0.068	1.831	1.127	0.368

Note. Here, $\kappa \equiv \kappa(3/2)/\kappa(1/2)$.

CONCLUSIONS

Delayed cluster widths $\Gamma_{\tau d:J}$ and $\Gamma_{td:J}$ are very sensitive to the model of the weak interaction through the chain

$$\begin{array}{ccccccc}\Gamma_{\tau d:J} & & R_{nS} & & \Gamma^n({}^4\mathrm{H}),\ \Gamma^n({}^4\mathrm{He}) & & \text{model WI :} \\ & \Leftrightarrow & & \Leftrightarrow & & \Leftrightarrow & \\ \Gamma_{td:J} & & R_{pS} & & \Gamma^p({}^4\mathrm{H}),\ \Gamma^p({}^4\mathrm{He}) & & \text{OME or TPE or HQ.}\end{array}$$

Similar relations were found in [8] for α particles accompanying the weak decay of ${}^{10}_{\Lambda}\mathrm{B}$ and ${}^{10}_{\Lambda}\mathrm{Be}$. The results which are expected from Nuclotron [18] will be of great value.

Acknowledgements. The authors thank Yu. Batusov, R. Jolos, V. Kuz'min, J. Lukstins and A. Parfenov for useful discussion and comments. Work of L.M. is supported by grant 2002/08/0984 of the Grant Agency of the Czech Republic. Work of O.M. is supported by Project LA08002 of the Ministry of Education, Youth and Sport of the Czech Republic.

REFERENCES

1. *Greiner W.* // Intern. J. Mod. Phys. E. 1996. V. 5. P. 1.
2. *Podgoretskii M. I.* // Zh. Eksp. Teor. Fiz. 1963. V. 44. P. 695.
3. *Hashimoto O., Tamura H.* // Prog. Part. Nucl. Phys. 2006. V. 57. P. 564.
4. *Okun' B. L.* Leptons and Quarks. M.: Nauka, 1990.

5. *Parreño A.* // Lecture Notes Phys. 2007. V. 724. P. 141.
6. *Bhang H. et al.* // Eur. Phys. J. A. 2007. V. 33. P. 259;
   Agnello M. et al. // Nucl. Phys. A. 2008. V. 804. P. 151.
7. *Tilley D. R. et al.* // Nucl. Phys. A. 2002. V. 708. P. 3.
8. *Majling L., Batusov Yu.* // Nucl. Phys. A. 2001. V. 691. P. 185;
   Batusov Yu. et al. // Part. Nucl. 2005. V. 36. P. 169;
   Majling L., Kuzmin V., Tetereva T. // Phys. At. Nucl. 2006. V. 69. P. 838.
9. *Majlingová O., Majling L.* Relativistic Nuclear Physics and QCD // XIX ISHEP. V. 1. Dubna, 2008. P. 315.
10. *Barbero C. et al.* // Phys. Rev. C. 2008. V. 78. P. 044312.
11. *Neudatchin V., Smirnov Yu.* Nucleon Clusters in Light Nuclei. M.: Nauka, 1969.
12. *Kukulin V., Smirnov Yu., Majling L.* // Nucl. Phys. A. 1967. V. 103. P. 681;
    Zofka J. et al. // Part. Nucl. 1991. V. 22. P. 1292.
13. *Block M. M., Dalitz R. H.* // Phys. Rev. Lett. 1963. V. 11. P. 96.
14. *Schumacher R. A.* // Nucl. Phys. A. 1992. V. 547. P. 143.
15. *Itonaga K. et al.* // Phys. Rev. C. 2002. V. 65. P. 034617.
16. *Sasaki K. et al.* // Phys. Rev. C. 2005. V. 71. P. 035502.
17. *Bauer E. et al.* // Phys. Lett. B. 2009. V. 674. P. 103.
18. *Averyanov A. et al.* // Phys. At. Nucl. 2008. V. 71. P. 2101.