Hypernuclei: Stability and prospects to study the compound nuclear formation and its fragmentation

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OVERVIEW

- Introduction
- Motivation

Part 1

- BE of orbitally excited Hypernuclei
- Various potential to study Y-N interaction
- Result

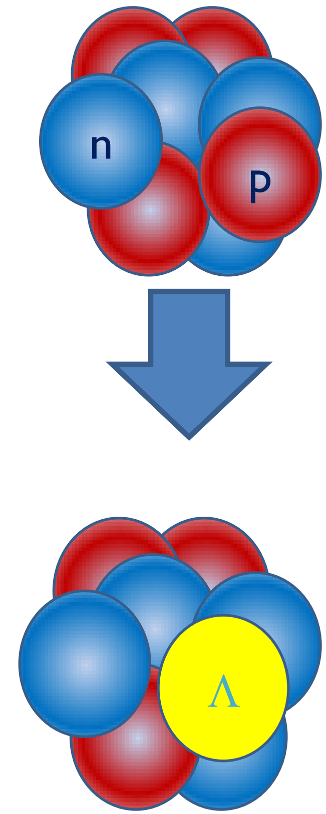
Part 2

- Alpha Decay of heavy Hypernuclei
- Half life time of heavy Hypernuclei
- Summary

INTRODUCTION

Nucleus

many-body system of protons and neutrons



Hypernucleus

Hyperon in a nucleus

a new degree-of-freedom, “strangeness”.

MOTIVATION

- Properties of hypernucleus are of considerable interest among the intermediate energy regime as it stands at the intersection of nuclear and particle physics.
- The enhanced experimental efforts have thus created renewed interest in the theoretical computations of the various properties of hypernuclei. [1, 2].

[1] E. Hiyama and T. Yamada, Progress in Part. and Nuc. Phy. **63**, 339-395 (2009).

[2] O. Hashimoto and H. Tamura, Progress in Part. and Nuc. Phy. **57**, 564-653 (2006).

BE OF HYPERNUCLEI

- To calculate the binding energy of hypernuclei, we have solved Schrodinger equation numerically.

$$\left[-\frac{\hbar^2}{2\,\mu}\,\nabla^2 + V(r)\right]\psi(r) = \epsilon\,\psi(r)$$

$$\mu = \frac{m_{core}\ m_{\Lambda}}{m_{core} + m_{\Lambda}}$$

VARIOUS POTENTIAL FOR Λ-N INTERACTION

1. The Maeda–Schmid *s*-wave potential (MS) (sum of two Woods–Saxon functions)

$$V_{N\,\Lambda}(r) = \frac{V_{rep}}{1+exp\left((r-R_{rep})/a_{rep}\right)} - \frac{V_{att}}{1+exp\left((r-R_{att})/a_{att}\right)}$$

2. The Isle potential (sum of two Gaussians)

$$V_{N\,\Lambda}(r) = V_R \exp[-\left(\frac{r}{b_R}\right)^2] - V_A \exp[-\left(\frac{r}{b_A}\right)^2]$$

3. $U(r) = -D\left[Cosh^2\left(\frac{r}{R}\right)\right]^{-1}$

4. Woods-saxon Potential $\mathrm{V}(r) = -\frac{V_0}{1+exp\left((r-R_{cen})/a_{cen}\right)}$

[1] S. Maeda *et al*. Few-Body Problems in Physics, vol. II, Elsevier, Amsterdam,1984, 379.

[2] Y. Kurihara, Y. Akaishi, H. Tanaka, Phys. Rev. C 31 (1985) 971.

[3] C G Koutroulos , J. Phys. G. Nucl. Part. Phys. 17 (1991) 1069-1076

[4] C. H. Cai et al. Europhys. Lett., 64 (4), pp. 448–453 (2003)

THE PHENOMENOLOGICAL POTENTIAL

$$V_{cen}\,(\mathrm{r}-R_{cen}) = \frac{-\,V_0}{1+e^{\frac{r-R_{cen}}{a_{cen}}}}$$

$$V_0 = U_0 + U_1\,\frac{A-2Z}{A}$$

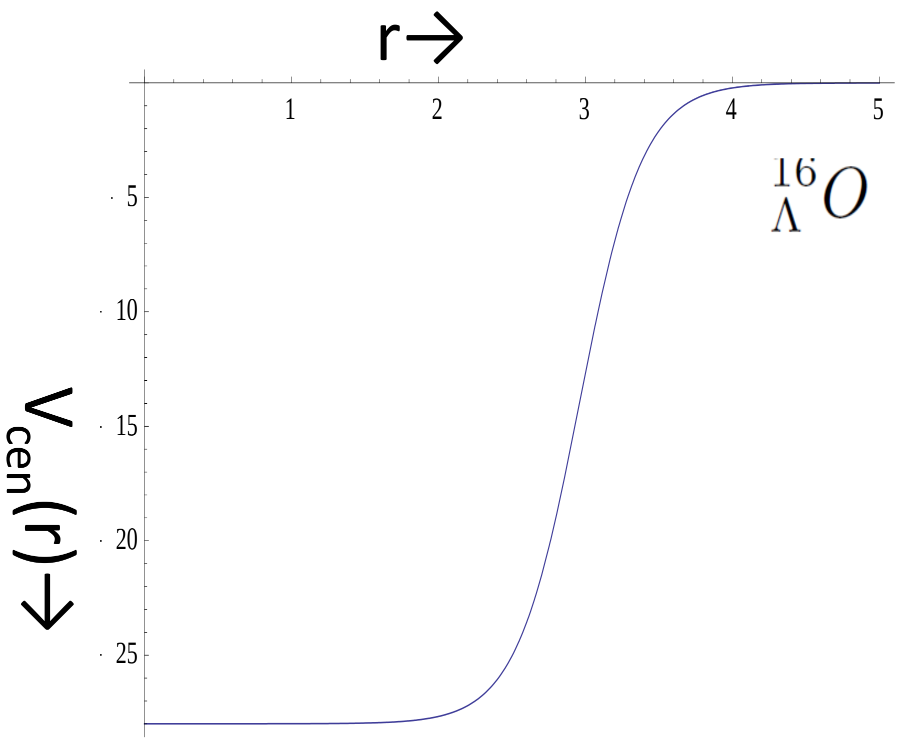
$$R_{cen/so} = r_0\,A^{\frac{1}{3}}$$

r_0 =1.2 fm; a_{so} = a_{cen}= 0.215 fm

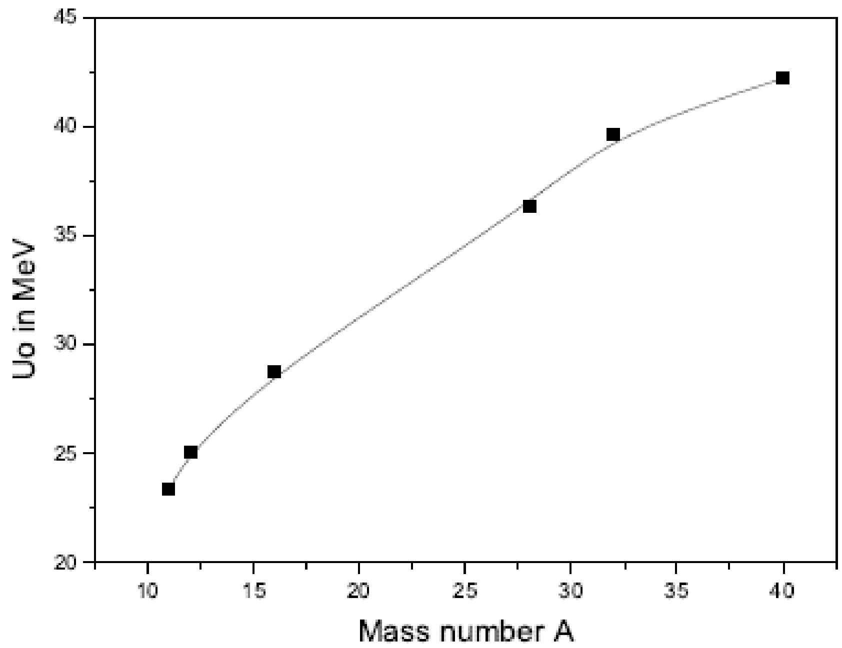
U_1 = - 0.075 MeV; U_{so} = 3.75 MeV

$$V_{so}(r) = -\frac{2\,U_{so}}{r\,a_{so}}[j(j+1)-l(l+1)-s(s+1)] * \frac{Exp[\frac{r-R_{so}}{a_{so}}]}{\left[1+Exp\left[\frac{r-R_{so}}{a_{so}}\right]\right]^2}$$

C. H. Cai et al. Europhys. Lett., 64 (4), pp. 448–453 (2003)



Nature of Woods-Saxon Potential



Variation of Potential depth Vs. A

RESULT

TABLE I: Binding Energy ($-B_\Lambda$) of S and P-states Λ Hypernuclei in MeV.

Nuclei	BE for S-State in MeV			BE for P-State in MeV		
	Present	Other	Expt. [5]	Present	Other	Expt. [5]
${}^{11}_{\Lambda}B$	10.029	10.163 [6] 10.28 [7]	10.20			
${}^{12}_{\Lambda}C$	10.8076	10.928 [6] 10.97 [7]	10.80			
${}^{16}_{\Lambda}O$	12.5031	13.243 [6] 13.15 [7]	12.50	5.812	2.544 [6] 1.92 [7]	2.50
${}^{28}_{\Lambda}Si$	16.0025	16.930 [6] 16.95 [7]	16.00	7.490	8.099 [6] 6.039 [7] 5.83 [8]	7.00
${}^{32}_{\Lambda}S$	17.5251	17.665 [6] 17.77 [7]	17.50	8.220	9.324 [6] 7.047 [7] 7.28 [8]	8.10
${}^{40}_{\Lambda}Ca$	18.7022	18.785 [6] 19.09 [7]	18.70	8.780	11.248 [6] 8.718 [7] 9.56 [8]	11.00

6) C. H. Cai, L. Li, Y. H. Tan and P. Z. Ning, Europhys. Lett., **64** (4): 448-453 (2003).
7) C G Koutroulos, J. Phys. G. Nucl. Part. Phys. **17**: 1069-1076, (1991).

ALPHA DECAY OF HYPERNUCLEI

we extend our understanding of the decay theory of the normal α -emitter nuclei to study the decay properties of heavy hypernuclei such as

1. Q-value for the decay,
2. Tunnelling probabilities,
3. Half life time and
4. Decay constant of heavy Λ-hypernuclei

ALPHA DECAY OF HYPERNUCLEI

Alpha (hyper-alpha) decay of a hypernucleus can be expressed as

$$(A_Y, Z_Y) \rightarrow {}_{2}^{4}He + (A_Y - 4, Z_Y - 2)$$

$$(A_Y, Z_Y) \rightarrow {}_{Y}^{4}He + (A_Y - 4, Z_Y - 2)$$

From the Q value it is found that spontaneous decay of hyper- α from the hypernuclei are not energetically possible.

Q-VALUE FOR THE α DECAY

To calculate the Q-value for α decay of heavy hypernuclei we should know the value of BE and SE of hypernuclei.

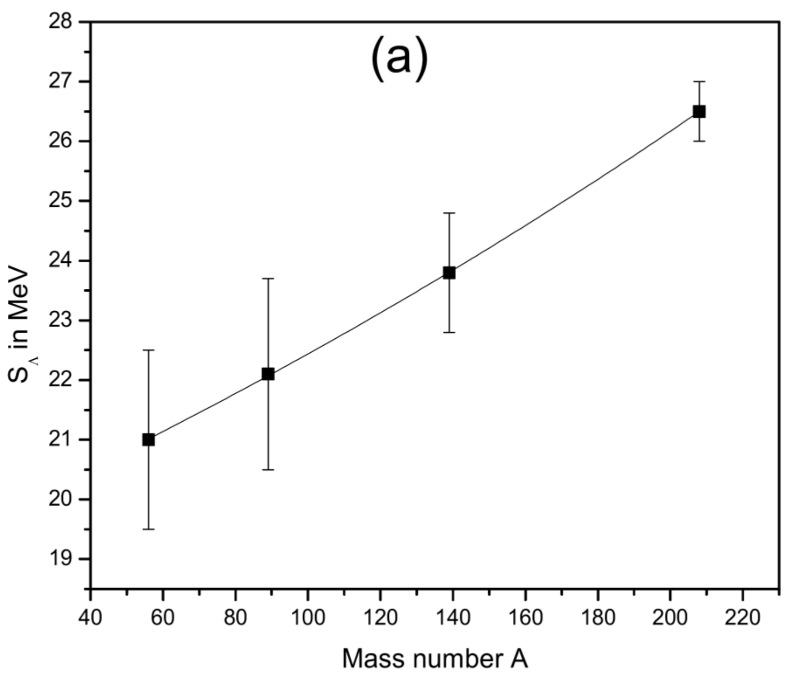
$$\mathrm{BE}\left({}^{A_Y}_{Z_Y}X\right) = \mathrm{BE}\left({}^{A}_{Z}X\right) + S_Y\left({}^{A_Y}_{Z_Y}X\right)$$

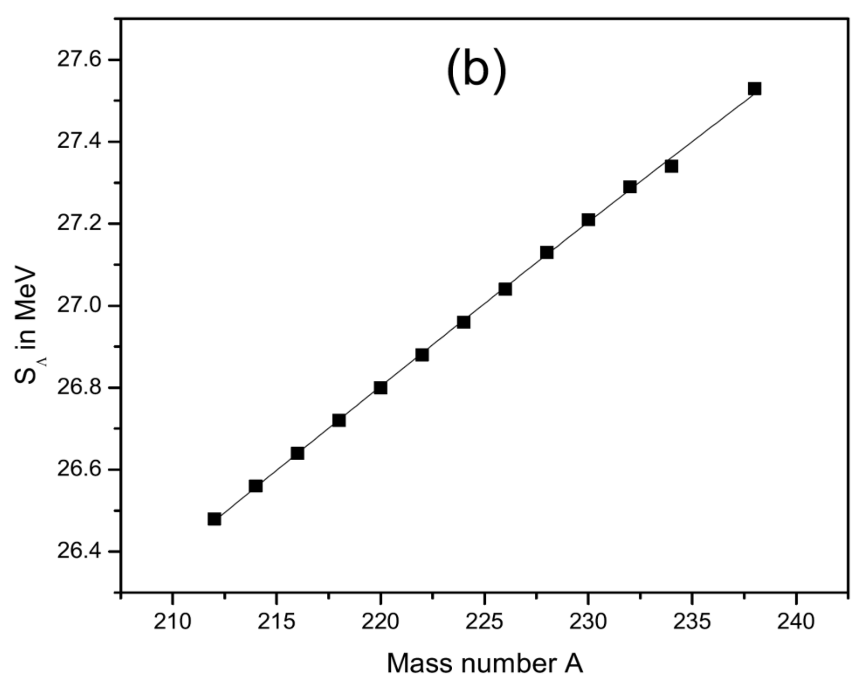
The first term corresponding to the binding energy of core nucleus (excluding hyperon) and the second term indicates separation energy of hyperon in the hypernucleus.

SE OF HPERNUCLEI

- using the experimentally known Λ-separation energies of various hypernuclei we have obtained an empirically fitted formula for the lambda separation energy for A ≥ 56.

$$S_\Lambda = 19.27\, e^{0.0015\, A}$$





TUNNELLING PROBABILITY

$$T = Exp\left[-\frac{2}{h}\int_b^R [2\, m_\alpha\, V(r) - E_\alpha]^{0.5}\right]\mathrm{dr}$$

$$V(r) = \frac{2\, Z_d\, e^2}{4\, \pi\, \epsilon\, r}$$

$$E_\alpha = \frac{m_d\, Q}{m_\alpha + m_d}$$

- Z_d - atomic number of (hyper) nucleus.
- m_d - mass of the daughter (hyper) nucleus.
- m_α - mass of the α particle.
- E_α - KE of the α particle.

HALF LIFE TIME

$$T_{1/2} = \frac{\ln 2}{\nu\, T\, P_0}$$

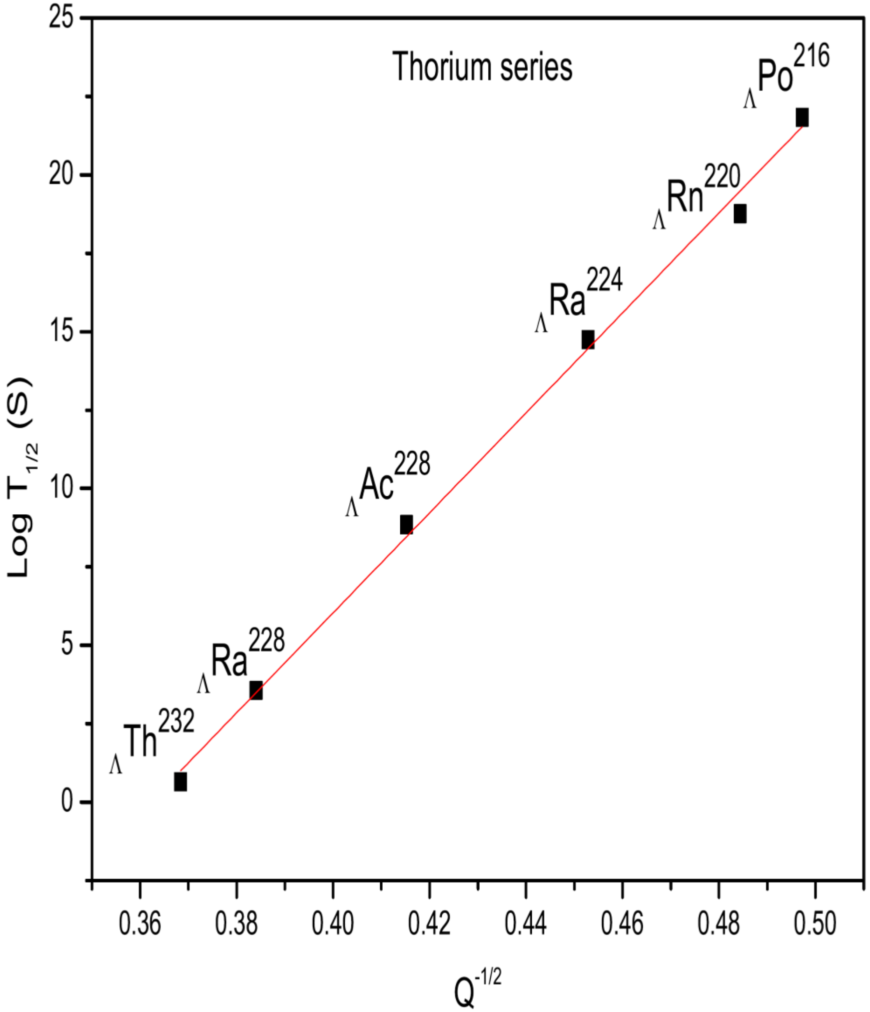
- ν - Frequency of α-collision at the hypernuclear surface.
- T - tunnelling probability.
- P_0 - is the α cluster preformation probability.

RESULT

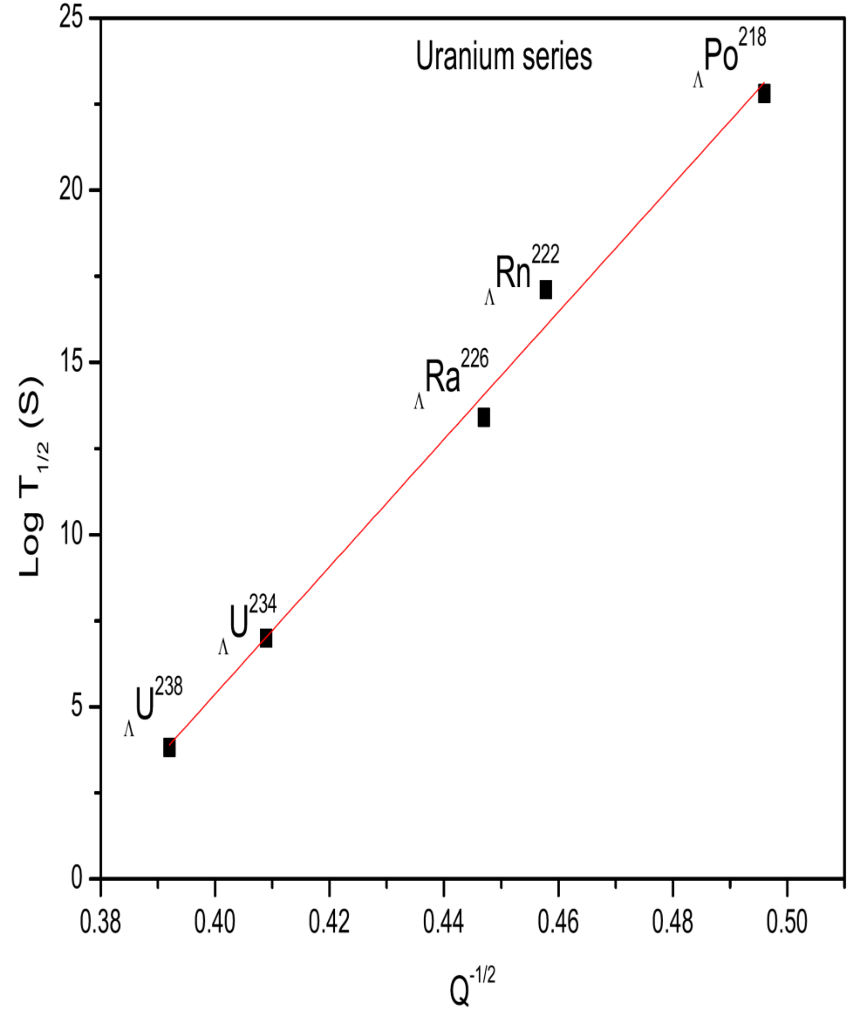
Reaction	Q	TP	$T_{\frac{1}{2}}$ Sec	$\lambda\ Sec^{-1}$	$\frac{T_{1/2}(\Lambda)}{T_{1/2}(\Lambda=0)}$
${}^{232}_{\Lambda}Th \rightarrow {}^{4}_{2}He + {}^{228}_{\Lambda}Ra$	4.045	3.04025×10^{-42}	6.87124×10^{21}	1.00855×10^{-22}	2.17
${}^{228}_{\Lambda}Ra \rightarrow {}^{4}_{2}He + {}^{224}_{\Lambda}Rn$	4.262	3.55441×10^{-39}	5.69377×10^{18}	1.21712×10^{-19}	0.042
${}^{228}_{\Lambda}Ac \rightarrow {}^{4}_{2}He + {}^{224}_{\Lambda}Fr$	4.877	3.34728×10^{-35}	5.65206×10^{14}	1.2261×10^{-15}	0.406
${}^{224}_{\Lambda}Ra \rightarrow {}^{4}_{2}He + {}^{220}_{\Lambda}Rn$	5.800	2.44318×10^{-29}	7.06046×10^{8}	9.81523×10^{-10}	0.867
${}^{220}_{\Lambda}Rn \rightarrow {}^{4}_{2}He + {}^{216}_{\Lambda}Po$	6.782	4.29783×10^{-24}	3.69×10^{3}	1.87792×10^{-4}	0.028
${}^{216}_{\Lambda}Po \rightarrow {}^{4}_{2}He + {}^{212}_{\Lambda}Pb$	7.368	3.37336×10^{-21}	4.48419	0.154543	0.0233

Reaction	Q	TP	$T_{\frac{1}{2}}$ Sec	$\lambda\ Sec^{-1}$	$\frac{T_{1/2}(\Lambda)}{T_{1/2}(\Lambda=0)}$
${}^{238}_{\Lambda}U \rightarrow {}^{4}_{2}He + {}^{234}_{\Lambda}Th$	4.060	3.28743×10^{-43}	6.38966×10^{22}	1.08456×10^{-23}	59.523
${}^{234}_{\Lambda}U \rightarrow {}^{4}_{2}He + {}^{230}_{\Lambda}Th$	4.770	1.47727×10^{-37}	1.30582×10^{17}	5.30701×10^{-18}	4.28
${}^{226}_{\Lambda}Ra \rightarrow {}^{4}_{2}He + {}^{222}_{\Lambda}Rn$	5.000	7.23074×10^{-34}	2.57677×10^{13}	2.68941×10^{-14}	0.13875
${}^{222}_{\Lambda}Rn \rightarrow {}^{4}_{2}He + {}^{218}_{\Lambda}Po$	5.980	1.71563×10^{-27}	9.87359×10^{6}	7.01872×10^{-8}	0.0108
${}^{218}_{\Lambda}Po \rightarrow {}^{4}_{2}He + {}^{214}_{\Lambda}Pb$	6.500	2.43351×10^{-24}	6.637×10^{3}	1.044×10^{-4}	2.71×10^{-3}

RESULT



Thorium series
ΛPo216
ΛRn220
ΛRa224
ΛAc228
ΛRa228
ΛTh232
Log T1/2 (S)
Q-1/2
25
20
15
10
5
0
0.36
0.38
0.40
0.42
0.44
0.46
0.48
0.50



Uranium series
ΛPo218
ΛRn222
ΛRa226
ΛU234
ΛU238
Log T1/2 (S)
Q-1/2
25
20
15
10
5
0
0.38
0.40
0.42
0.44
0.46
0.48
0.50

SUMMARY

We find that the hypernuclei are stable against the hyper-alpha decay because the Λ-binding energy of hyper-alpha is much smaller than those with heavy hypernuclei, that reduces the formation of hyper-alpha cluster within the heavy hypernuclei.

It is found that the presence of a hyperon, Λ inside the normal α -emitter could change their life times considerably.

For instance, the half life times of ${}^{232}_{\Lambda}Th$, ${}^{234}_{\Lambda}U$ and ${}^{238}_{\Lambda}U$are found to be 2, 4 and 60 times larger than their normal counterpart of ${}^{232}Th$, ${}^{234}U$and ${}^{238}U$ respectively.

WORK PLAN

We found that the heavy hypernucleus are stable against the α cluster decay. In future we will plan to study the decay of heavy cluster like ${}^{12}_{Y}C$, ${}^{16}_{Y}O$, ${}^{28}_{Y}Si\ etc$,. from heavy hypernucleus.

We will try to study the fusion of light hypernuclei and will study the change in Coulomb energy.

Thank You