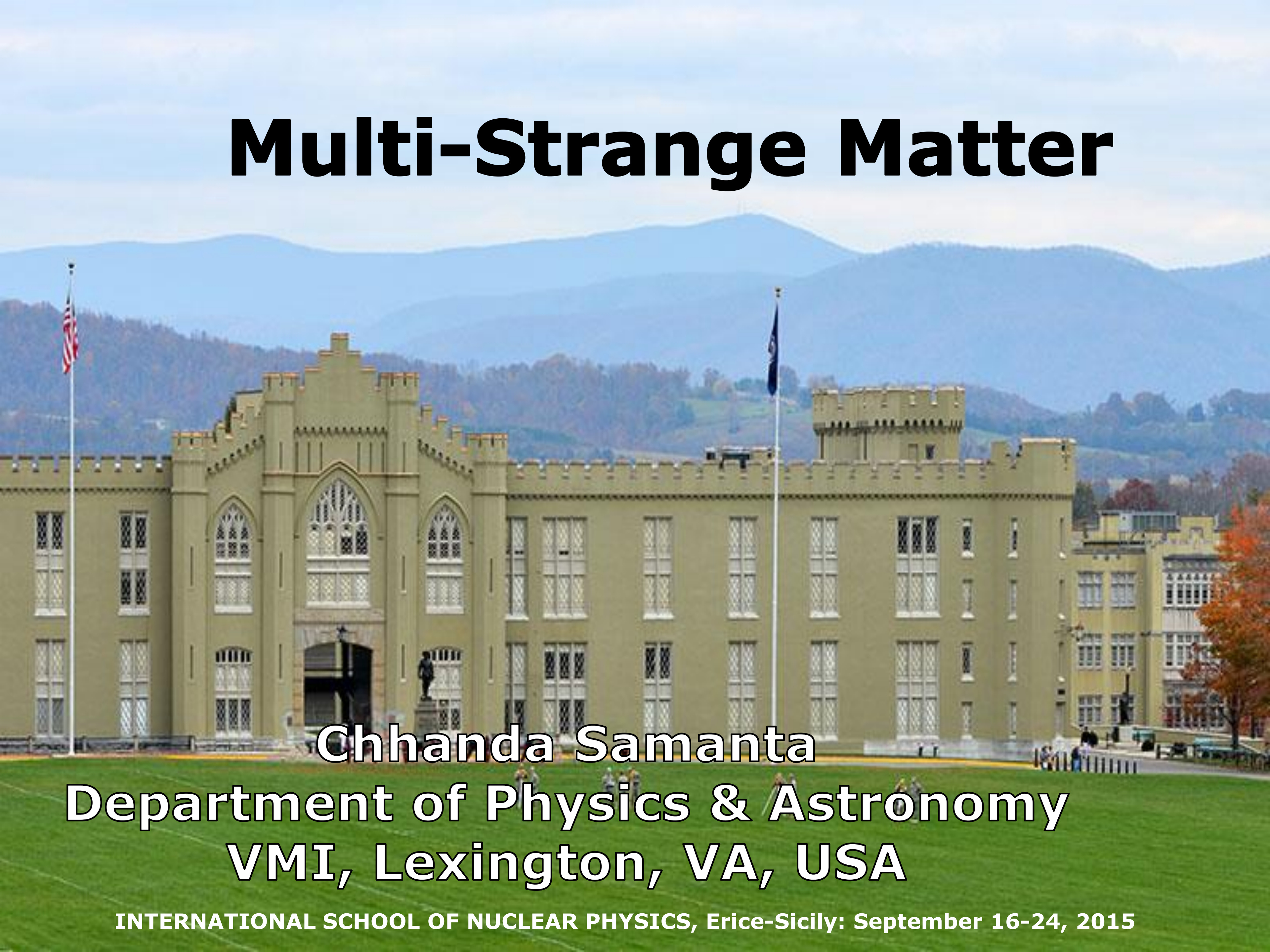
Multi-Strange Matter



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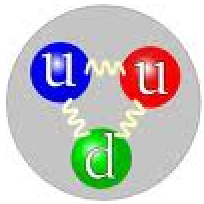
INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS, Erice-Sicily: September 16-24, 2015

Outline

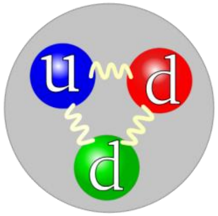
- What is a Hyperon?
- What is a Strange-nucleus?
- What is a multi- strange nucleus?
- How to find the the Binding energy and Relative yield of such Strange-nuclei ?
- What are the nucleon- and hyperon-drip points for a strange nucleus?
- Nuclei without any neutrons and protons.
- Summary

What is a Hyperon?

An atomic nucleus consists of two types of **nucleons**: Protons and neutrons.



p=(uud)

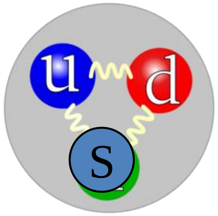


n=(udd)

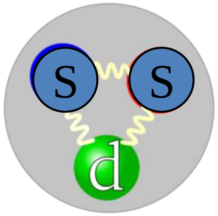
Nucleons

A **baryon** is a composite subatomic particle made up of three quarks.

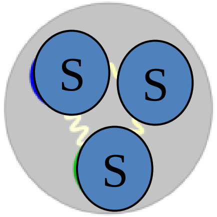
A **Hyperon** is any **baryon** containing one or more strange quarks, but no charm, bottom, or top quark.



Λ^0=(uds)



Ξ^-=(dss)



Ω^-=(sss)

Hyperons

Properties of Baryons

	Nucleons		←		Hyperons			→
Name	**n**	**p**	Λ^0	Σ^-	Σ^0	Σ^+	Ξ^-	Ξ^0
Structure	udd	uud	uds	dds	uds	uus	dss	uss
No. of **S** quark	0	0	1	1	1	1	2	2
Isospin **I**	1/2	1/2	0	1	1	1	1/2	1/2
$\mathbf{I_3}$	-1/2	+1/2	0	-1	0	+1	-1/2	+1/2
Hyper-charge **Y**	1	1	0	0	0	0	-1	-1
Baryon No. **B**	1	1	1	1	1	1	1	1
Strangeness **S=Y-B**	0	0	-1	-1	-1	-1	-2	-2
Mass (MeV)	939.6	938.3	1115.6	1197.3	1192.5	1189.5	1321	1315

What is a Hypernucleus or, a Strange Nucleus?

Nucleus: consists of **nucleons (n, p)**

Hypernucleus: consists of **nucleons (n, p) + hyperons (Y)**

Total Charge of a Nucleus => Name of the element

Symbols:

Nucleus:

^{A}Z

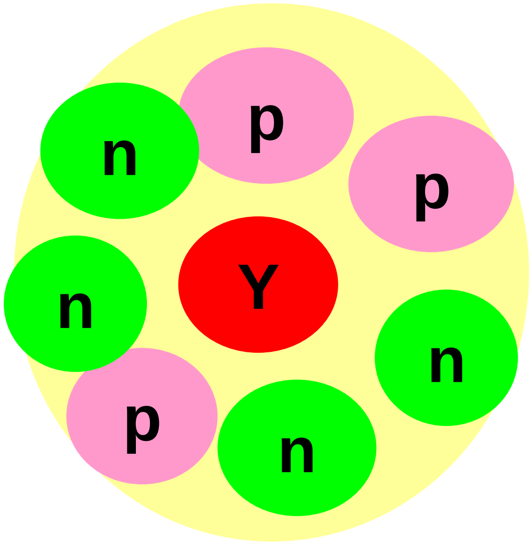
$Z = Z_p$

=Total Charge of protons

N_n = No. of neutrons

N_p = No. of protons

$A = N_n + N_p$



Hypernucleus:

$^{A}_{Y}Z$

Y = Hyperon

N_Y = No. of Hyperons

q_Y = Charge of a hyperon

$Z \neq Z_p$

$Z = Z_p + (N_Y \cdot q_Y)$

$A = N_n + N_p + N_Y$

A **multi-strange nucleus** has more than one hyperon (Y).

How many Strange Hypernuclei are discovered so far?

Hypernuclei with the following hyperon:

Λ^0 (S = -1) ~40 $\Lambda\Lambda$-hypernuclei (Five)

Σ^+ (S = -1) One

Ξ^- (S = -2) Five

$\bar{\Lambda}^0$ (S = +1) One

Can we theoretically suggest

the **Binding energy**

and **Relative yield** of such

Strange-nuclei?

Relativistic Mean Field Calculations & Mass Formula

❖Relativistic-mean-field (RMF) calculations have provided results for a limited number of medium heavy and heavy hypernuclei.

J. Schaffner J, C.B. Dover, A. Gal , C. Greiner, D.J. Millener and H. Stöcker, Ann. Phys. NY 235 (1994) 35

Microscopic calculations are difficult to pursue for all kinds on nuclei.

❖A properly constructed mass formula can

- provide a quick check on the RMF calculations
- extrapolate to a wider mass region from light to heavy - beyond the domain of RMF.

Two Mass Formulas

Here two Hypernuclear Mass Formulas are presented:

1. A liquid drop model by Botvina and Pochodzalla

   -applicable for Λ -hypernuclei only.

1. A generalized mass formula of Samanta et al.

   - applicable for all $(\Lambda, \Xi, \Sigma,..)$ –hypernuclei
   - applicable to multi-strange hypernuclei.

Liquid-drop Mass formula (for Λ-hyernuclei only)

J. P. Bondorf, A. S. Botvina, A. S. Iljinov, I. N. Mishustin, and K. Sneppen, Phys. Rep. **257**, 133 (1995).

$B(A,Z) = -16A + 18A^{2/3} + 0.72z^2/A^{1/3} + 25(N - z)^2/(A - n_Y) - (n_Y/A)$
$[10.68A + 21.27\ A^{2/3}]$

$\mathbf{A} = \mathbf{n} + \mathbf{z_c} + \mathbf{n_Y}$: **n**= no. of neutrons, $\mathbf{z_c}$ = no. of protons, $\mathbf{n_Y}$ = no. of hyperons

Binding Energy: $B(A,Z) = m_A - z_c.m_p - n.m_n - n_Y.m_Y$ = Negative

- Does not depend on mass and strangeness of hyperons.
- Not valid for: $A = n_Y$
- No hyperon-asymmetry term

A Generalized Mass Formula for both Non-Strange normal & Strange hyper-nuclei

C. Samanta et al., J. Phys. G 32 (2006) 363

A systematic search using experimental separation energy (S_Y) for $\Lambda^o, \Lambda\Lambda, \Sigma^+$ and Ξ^- -hypernuclei leads to a single generalized mass formula that is valid for Normal nuclei (n_Y=0) as well as Hypernuclei ($n_Y \neq 0$) of all kind, having different Mass and Strangeness.

$$B(A,Z) = 15.777A - 18.34A^{2/3} - 0.71\frac{Z(Z-1)}{A^{1/3}} - \frac{23.21(N-Z_c)^2}{[(1+e^{-A/17})A]} + (1-e^{-A/30})\delta$$
$$+ n_Y[0.0335(m_Y) - 26.7 - 48.7|S|A^{-2/3}],$$

n_Y = no. of hyperons in a nucleus

m_Y = mass of hyperon in MeV

S = strangeness no. of the hyperon,

A = N + Z_c+ n_Y = total no. of baryons

Z_c = no. of protons,

Z = Z_c + n_Y q = net charge no.

q = charge no. with proper sign. (viz., q= -1, 0, 1)

Hyperon separation energy S_Y defined as:

S_Y = BE(A, Z)$_{hyper}$ – BE(A - n_Y, Z_c)$_{core}$

Explicitly depends on Strangeness (S), hyperon mass (m_Y), number of hyperons (n_Y)

Hyperon	S	m_Y	n_Y
Λ^0	-1	1115.683	1
$\Lambda\Lambda$	-2	1115.683	2
Σ^0	-1	1192.642	1
Ξ^-	-2	1321.71	1
Ξ^0	-2	1314.86	1
Normal	0	-	0

Hyperon-Separation Energies of Hypernuclei & Mass formula

C. Samanta et al., J. Phys. G 32 (2006) 363

368 C Samanta et al

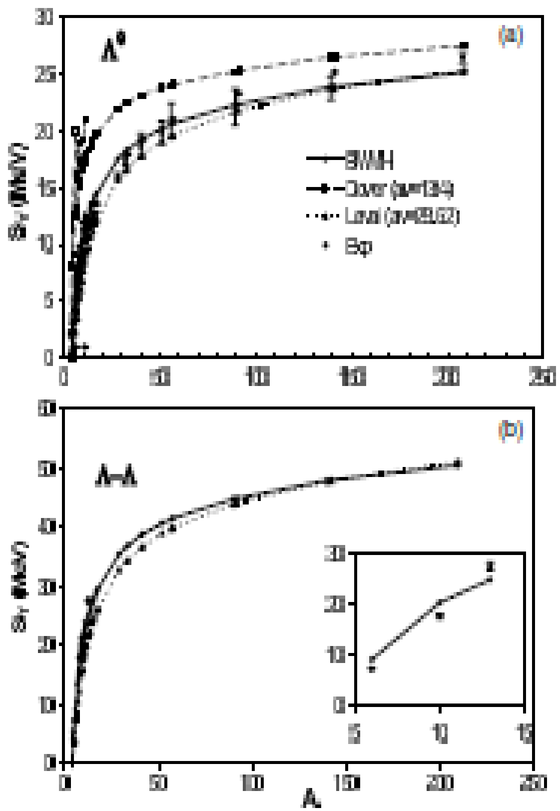


Figure 1. Hyperon separation energy S_Y versus mass number A for (a) single Λ (m_Y = 1115.63 MeV) predicted by BWMH (solid), Dover *et al* [3] (topmost, dashed line) and Levai *et al* [20] (dotted) and experimental values [1, 2] (rhombus with error bars); and (b) double Λ predicted by BWMH (solid), and Levai *et al* [20] (dotted) and experimental values [1, 2] (rhombus with error bars). In the inset the three data points of double Λ are shown with predictions of BWMH. In all the figures, lines are added only as guides to the eyes.

Generalized mass formula for non-strange and hypernuclei with $SU(6)$ symmetry breaking 369

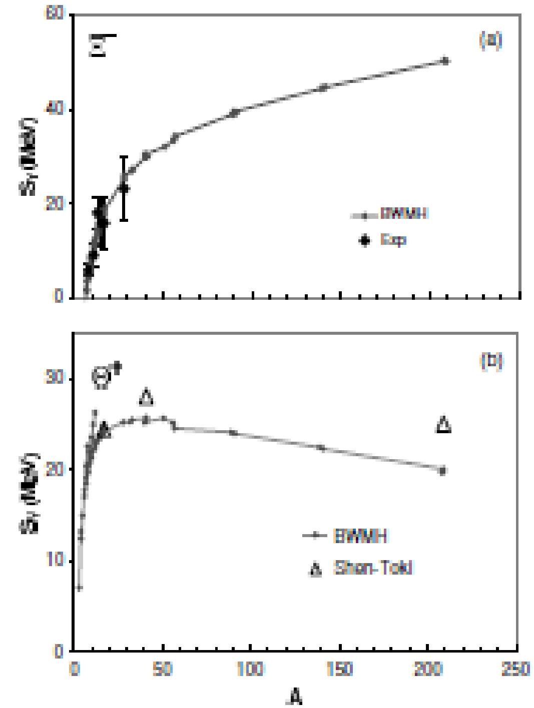
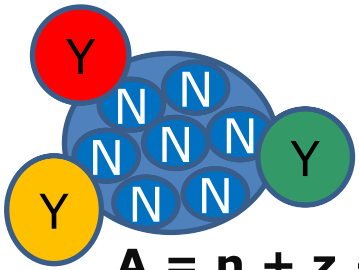


Figure 2. Hyperon separation energy S_Y versus mass number A for (a) single Ξ^- (m_Y = 1321.32 MeV) and experimental values [1], and (b) single Θ^+ (m_Y = 1540 MeV) separation and quark mean-field calculations of Shen and Toki [19].

So far no experimental data exists on the bound theta hypernuclei (uddus). The θ+ separation energies are found to be close to the quark mean-field (QMF) calculations of Shen and Toki, 2005 *Phys. Rev* C **71** 065208

Generalized Mass Formula for Non-strange, Strange and Multiply-strange Nuclear Systems

C. Samanta, JPG 37 (2010) 075104



N= nucleon, Y= hyperon

$\mathbf{A = n + z_c + n_Y}$: **n**= no. of neutrons, $\mathbf{z_c}$ = no. of protons, $\mathbf{n_Y}$ = no. of hyperons

Binding Energy: $B(A,Z) = m_A - z_c.m_p - n.m_n - n_Y.m_Y$ = Negative

$$\begin{aligned} B(A,Z) = \quad & 15.777A - 18.34A^{2/3} - 0.71Z(Z-1)/A^{1/3} - 23.21(n-z_c)^2/[(1+e^{-A/17})A] + (1-e^{-A/30})\delta \\ & + \sum_Y n_Y[0.0335(m_Y) - 26.7 - 48.7\,|\,S\,|\,/A^{2/3} \\ & - a_Y\{(n_\Lambda + n_{\Xi^o} + n_{\Xi^-} - z_c)^2 + (n_\Lambda + n_{\Xi^o} + n_{\Xi^-} - n)^2\}/\{(1+e^{-A/17})A\}]. \end{aligned}$$

$\mathbf{m_Y}$ = mass of hyperon in MeV

S = strangeness no. of the hyperon

$$Z = \left| z_c + \sum_Y n_Y q_Y \right|$$

Z= Net Charge

= Proton charges+Total hyperon charges

q = -1, 0, 1 depending on the hyperon type

Note: the **net charge of a nucleus can be negative** if the hyperon number is larger than the proton number and the hyperon has a negative charge!!!!

Comparison between the generalized multi-strange mass formula and Microscopic calculations

C. Samanta, JPG 37 (2010) 075104

Schaffner J, Dover C B, Gal A, Greiner C, Millener D J and Stöcker H 1994 *Ann. Phys., NY* **235** 35

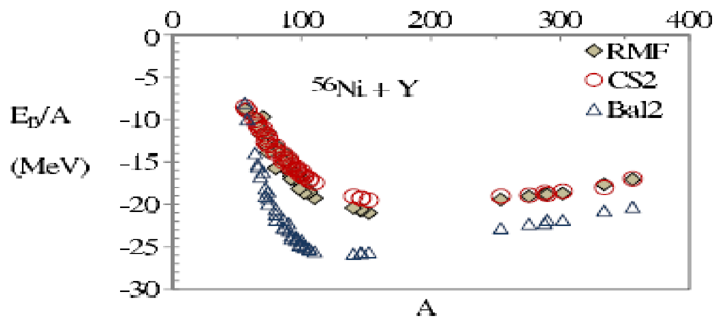
Model-1=No Y-Y interaction

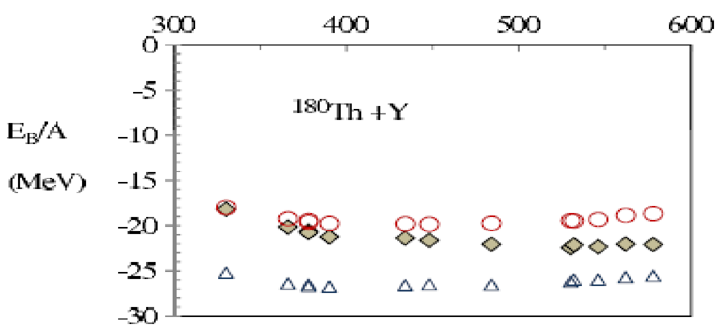
Model-2=Strong Y-Y interaction

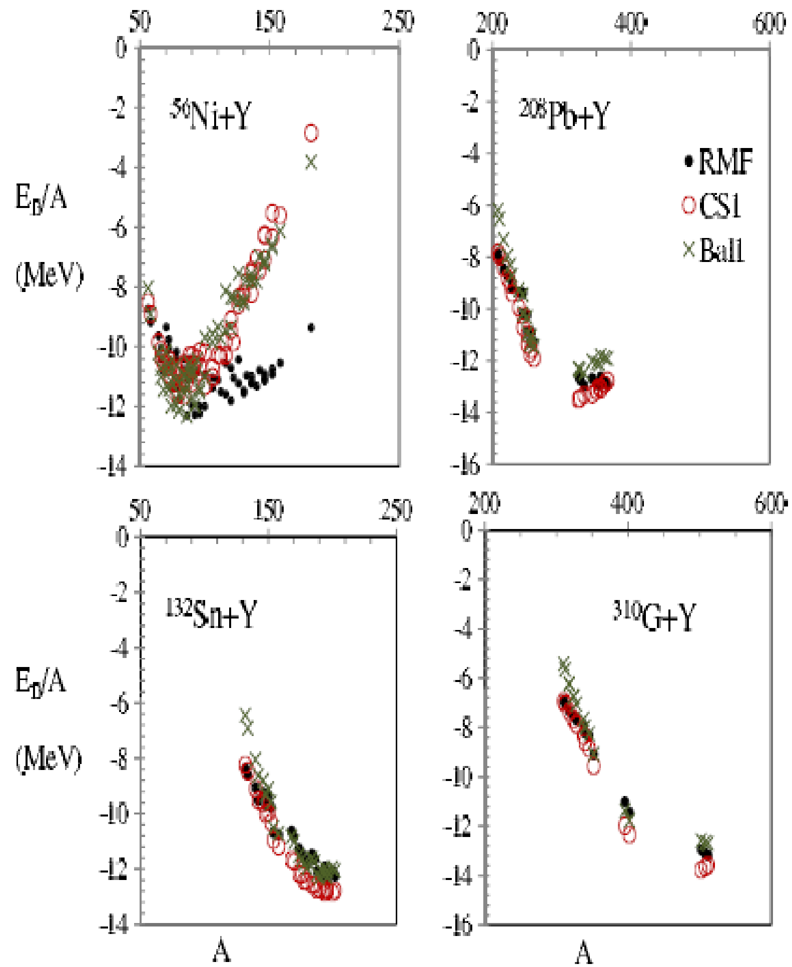
CS1(BE,Model1)=CS2(BE,Model2) -Cr

$$C_r = 12.0 A f_s (f_\Lambda + f_{\Xi^0} + f_{\Xi^-})$$

$$f_s = \sum_Y n_Y |S| / A.$$







(Current wisdom: Y-Y interaction is weak.)

What do we learn from the neutron-separation energy (S_n) versus neutron number (N) plot?

- Zero or, negative neutron-separation energy (S_n) means, unbound nucleus.

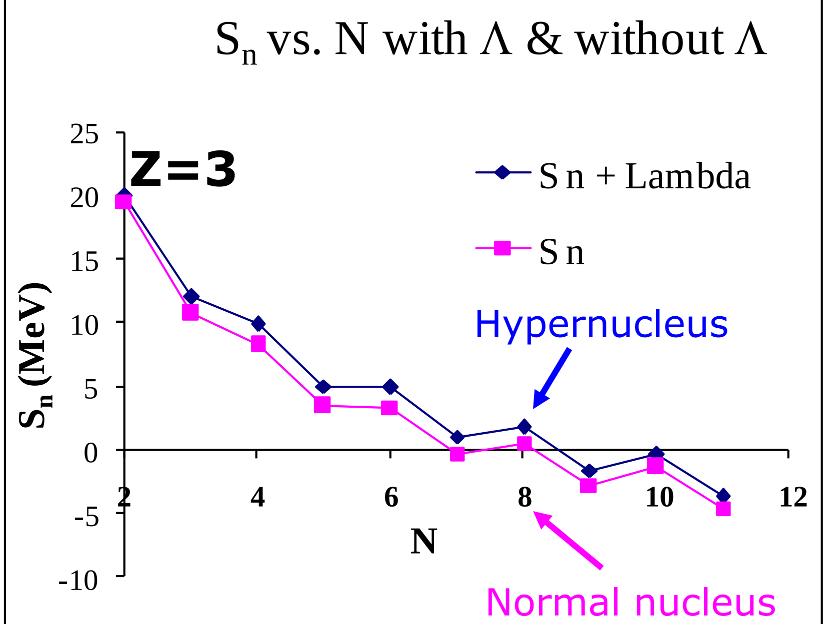
^{10}Li (=3p+7n) is unbound (Sn<0), but **$^{10}{}_{\Lambda}$Li (=3p+6n+1Λ) is bound (Sn >0).**

Experiment: S_{Λ}($^{10}{}_{\Lambda}$**Li**) ~10-12 MeV [Ref: *P.K. Saha,PRL94(2005) 052502*]

Mass Formula: CS1(10.2 MeV), CS2(11.4 MeV)

- ^{11}Li (Z=3, N=8) is the last bound normal nucleus, but, ^{12}Li (Z=3, N=8, Λ=1) appears to be bound.
  - Does this mean that addition of Λ can make very neutron-rich hypernuclei – far beyond the normal drip line?

Possible, provided the baryon (hyperon/nucleon) separation energy is not zero or, negative!



Nucleus $^{14}{}_{\Lambda}$Li (Z=3, N=10, Λ=1), if found, will be truly exotic & beyond the normal n-dripline.

$^{6}_{\Lambda}$H production experiment by FINUDA

M. Agnello et al., FINUDA Collaboration, PRL 108 (2012) 042501

1p+4n = ^{5}H
Unbound

1p+4n+1Λ = $^{6}_{\Lambda}$H
predicted to be Bound.

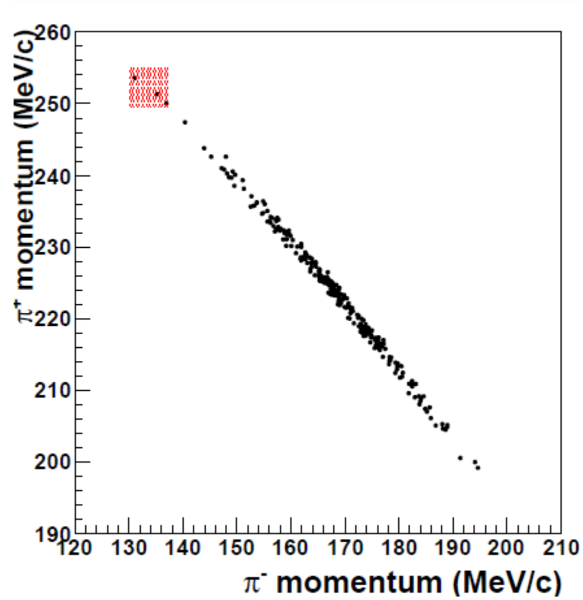
Hyperon acts like glue!

- ^{6}Li(stopped K^-,π^+) reaction
  - Measured formation and weak decay in coincidence

$$K^- + {}^{6}Li \rightarrow \pi^+ + {}^{6}_{\Lambda}H$$

$${}^{6}_{\Lambda}H \rightarrow \pi^- + {}^{6}He$$

  - cut on T(π^+)+T(π^-)
- 3 events of candidates found



$T_{\rm tot}$ (MeV)	p_{π^+} (MeV/c)	p_{π^-} (MeV/c)	$M(^{6}_{\Lambda}\rm H)$ prod. (MeV)	$M(^{6}_{\Lambda}\rm H)$ decay (MeV)	$M(^{6}_{\Lambda}\rm H)$ mean (MeV)	$\Delta M(^{6}_{\Lambda}\rm H)$ (MeV)
202.6±1.3	251.3±1.1	135.1±1.2	5802.33±0.96	5801.41±0.84	5801.87±0.96	0.92±1.28
202.7±1.3	250.1±1.1	136.9±1.2	5803.45±0.96	5802.73±0.84	5803.09±0.96	0.72±1.28
202.1±1.3	253.8±1.1	131.2±1.2	5799.97±0.96	5798.66±0.84	5799.32±0.96	1.31±1.28

However...

Physics Letters B 729 (2014) 39–44

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Search for ${}^{6}_{\Lambda}$H hypernucleus by the ^{6}Li(π^-, K^+) reaction at $p_{\pi^-} = 1.2$ GeV/c

CrossMark

J-PARC E10 Collaboration

H. Sugimura[a,b,*], M. Agnello[c,d], J.K. Ahn[e], S. Ajimura[f], Y. Akazawa[g], N. Amano[a], K. Aoki[h], H.C. Bhang[i], N. Chiga[g], M. Endo[j], P. Evtoukhovitch[k], A. Feliciello[d], H. Fujioka[a], T. Fukuda[l], S. Hasegawa[b], S. Hayakawa[j], R. Honda[g], K. Hosomi[g], S.H. Hwang[b], Y. Ichikawa[a,b], Y. Igarashi[h], K. Imai[b], N. Ishibashi[j], R. Iwasaki[h], C.W. Joo[i], R. Kiuchi[i,b], J.K. Lee[e], J.Y. Lee[i], K. Matsuda[j], Y. Matsumoto[g], K. Matsuoka[j], K. Miwa[g], Y. Mizoi[l], M. Moritsu[f], T. Nagae[a], S. Nagamiya[b], M. Nakagawa[j], M. Naruki[a], H. Noumi[f], R. Ota[j], B.J. Roy[m], P.K. Saha[b], A. Sakaguchi[j], H. Sako[b], C. Samanta[n], V. Samoilov[k], Y. Sasaki[g], S. Sato[b], M. Sekimoto[h], Y. Shimizu[l], T. Shiozaki[g], K. Shirotori[f], T. Soyama[j], T. Takahashi[h], T.N. Takahashi[o], H. Tamura[g], K. Tanabe[g], T. Tanaka[j], K. Tanida[i], A.O. Tokiyasu[f], Z. Tsamalaidze[k], M. Ukai[g], T.O. Yamamoto[g], Y. Yamamoto[g], S.B. Yang[i], K. Yoshida[j]

ABSTRACT

We have carried out an experiment to search for a neutron-rich hypernucleus, ${}^{6}_{\Lambda}$H, by the ^{6}Li(π^-, K^+) reaction at $p_{\pi^-} = 1.2$ GeV/c. The obtained missing-mass spectrum with an estimated energy resolution of 3.2 MeV (FWHM) showed no peak structure corresponding to the ${}^{6}_{\Lambda}$H hypernucleus neither below nor above the ${}^{4}_{\Lambda}$H + 2n particle decay threshold. An upper limit of the production cross section for the bound ${}^{6}_{\Lambda}$H hypernucleus was estimated to be 1.2 nb/sr at 90% confidence level.

Effect of addition of a lambda (Λ) hyperon on neutron and proton drip-lines

J. Phys. G: Nucl. Part. Phys. 35 (2008) 065101 C Samanta *et al*

Table 1. One-nucleon separation energies (in MeV) on drip lines for each element with the lowest and highest numbers of bound neutrons in normal and Λ-hypernuclei.

Symbol Z	Normal p-drip $^{A}Z, S_p$	Normal n-drip $^{A}Z, S_n$	Hyper p-drip $^{A}Z, S_p$	Hyper n-drip $^{A}Z, S_n$
Li	^{5}Li, 3.36	^{11}Li, 0.58	$^{5}_{\Lambda}$Li, 1.22	$^{12}_{\Lambda}$Li, 1.87
Be	^{6}Be, 1.11	^{14}Be, 0.90	$^{7}_{\Lambda}$Be, 3.79	$^{15}_{\Lambda}$Be, 1.84
B	^{8}B, 0.74	^{17}B, 0.99	$^{9}_{\Lambda}$B, 2.39	$^{18}_{\Lambda}$B, 1.73
C	^{9}C, 0.17	^{20}C, 1.01	$^{10}_{\Lambda}$C, 1.80	$^{21}_{\Lambda}$C, 1.63
N	^{12}N, 1.98	^{23}N, 0.97	$^{12}_{\Lambda}$N, 0.24	$^{24}_{\Lambda}$N, 1.50
O	^{13}O, 1.98	^{26}O, 0.94	$^{13}_{\Lambda}$O, 0.44	$^{27}_{\Lambda}$O, 1.40
F	^{15}F, 0.09	^{29}F, 0.89	$^{16}_{\Lambda}$F, 0.81	$^{32}_{\Lambda}$F, 0.01
Ne	^{16}Ne, 0.64	^{32}Ne, 0.87	$^{17}_{\Lambda}$Ne, 1.39	$^{35}_{\Lambda}$Ne, 0.04
Na	^{19}Na, 0.54	^{35}Na, 0.84	$^{20}_{\Lambda}$Na, 1.05	$^{38}_{\Lambda}$Na, 0.08
Mg	^{20}Mg, 1.37	^{38}Mg, 0.84	$^{20}_{\Lambda}$Mg, 0.05	$^{41}_{\Lambda}$Mg, 0.13

In general,

- n-drip line is pushed out
- p-drip line is pulled in

Microscopic calculation is needed.

Neutron Drip-point of Mg and Mg+Λ nuclei

Torsten Schürhof, Stefan Schramm, Chhanda Samanta, arXiv:1405.7211v1 [nucl-th]

Experimentally measured last neutron-rich Mg isotope is **^{40}Mg**. (N=28).

- We investigated Neutron-drip point:

Normal Nuclei: ^{24}Mg, ^{25}Mg, ^{26}Mg, ^{27}Mg, ^{28}Mg, ^{29}Mg, ^{30}Mg, ^{31}Mg, ^{32}Mg, ……**?**

Hyper-Nuclei: $^{25}{}_{\Lambda}$Mg, $^{26}{}_{\Lambda}$Mg,$^{27}{}_{\Lambda}$Mg,$^{28}{}_{\Lambda}$Mg,$^{29}{}_{\Lambda}$Mg,$^{30}{}_{\Lambda}$Mg,$^{31}{}_{\Lambda}$Mg,$^{32}{}_{\Lambda}$Mg,$^{33}{}_{L}$Mg….**?**

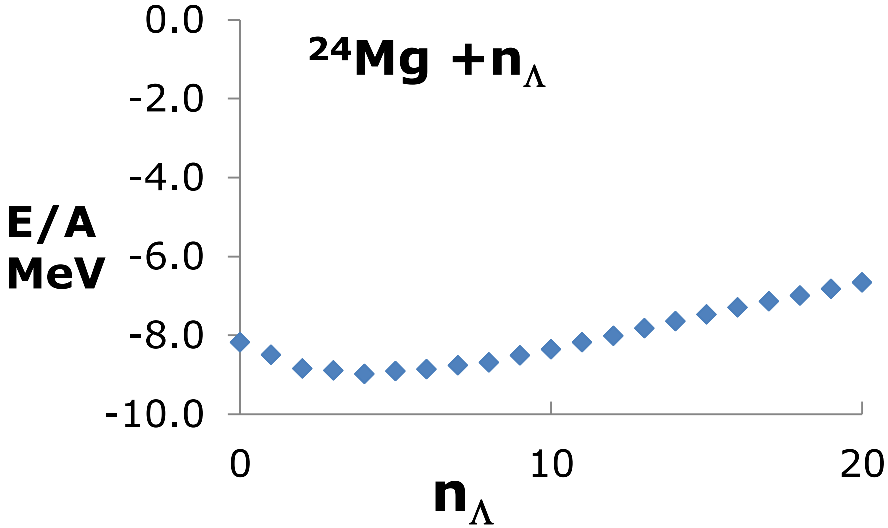
- Used Relativistic Mean Field theory with TS2, NL3 and SPL-40 parameter sets.
- All 3 parameter sets successfully describes the existing experimental data on hypernuclei.
  - But, the results near the drip line is very much models dependent.

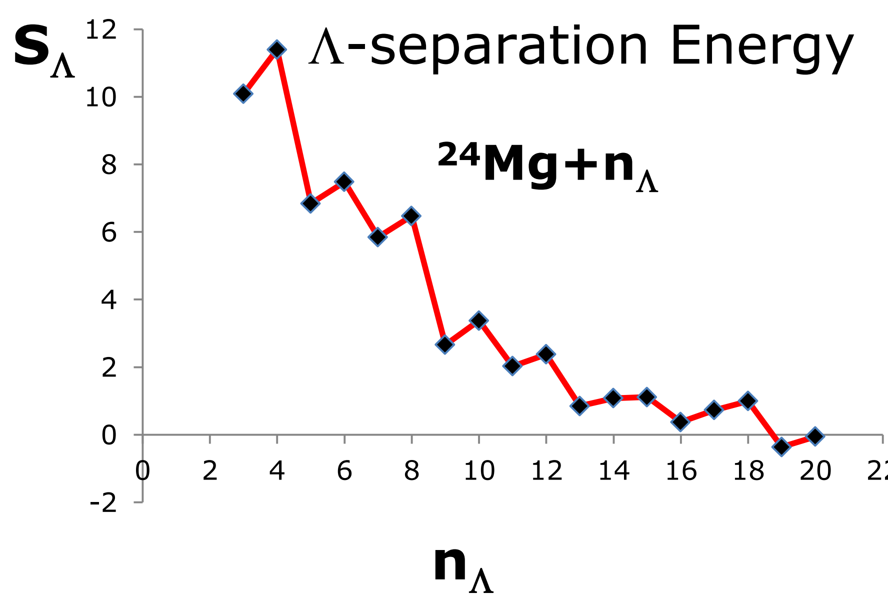
  If one-Lambda hyperon is added to the drip-line normal Magnesium nucleus:
    - NL3 suggests binding of no extra neutron.
    - TS2 suggests binding of 8 extra neutrons.
    - SPL-40 suggests ejection of existing 6 neutrons!

❖ **Experimental data are needed for confirmation.**

Lambda Drip-Point for Multi-Lambda Hypernuclei

C. Samanta, S. Schramm, T. Schuerhoff
(To be communicated)

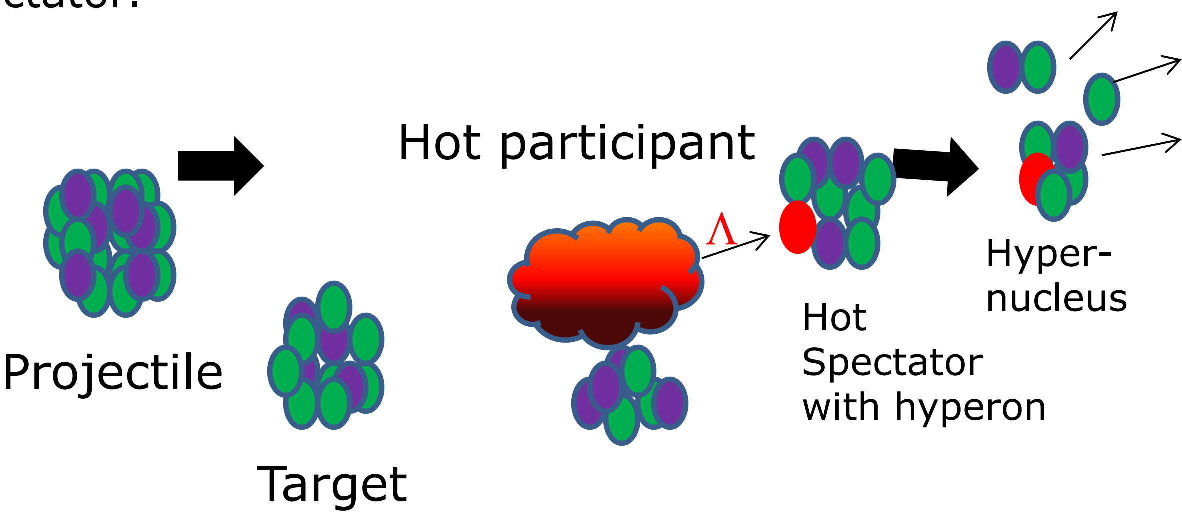




The Λ -drip point ^{24}Mg+n$_\Lambda$ appears to be close to be n$_\Lambda$~20.

Production of multi-Λ hypernuclei in Heavy-Ion Collision

- Relativistic heavy-ion collisions offer the possibility of creating excited nuclear systems with lambda (Λ) -hyperons.
- Some Λ –hyperons can be absorbed in the spectator part of the colliding nuclei.
- Then single- and multi-lambda hypernuclei can be produced after Multifragmentation of this spectator.



Production of hypernuclei in multifragmentation of nuclear spectator matter

A.S. Botvina, J. Pochodzalla, Phys. Rev. C76 (2007) 024909

At low A, the statistical multifragmentation model (SMM) shows a discrepancy between the two mass formulas.

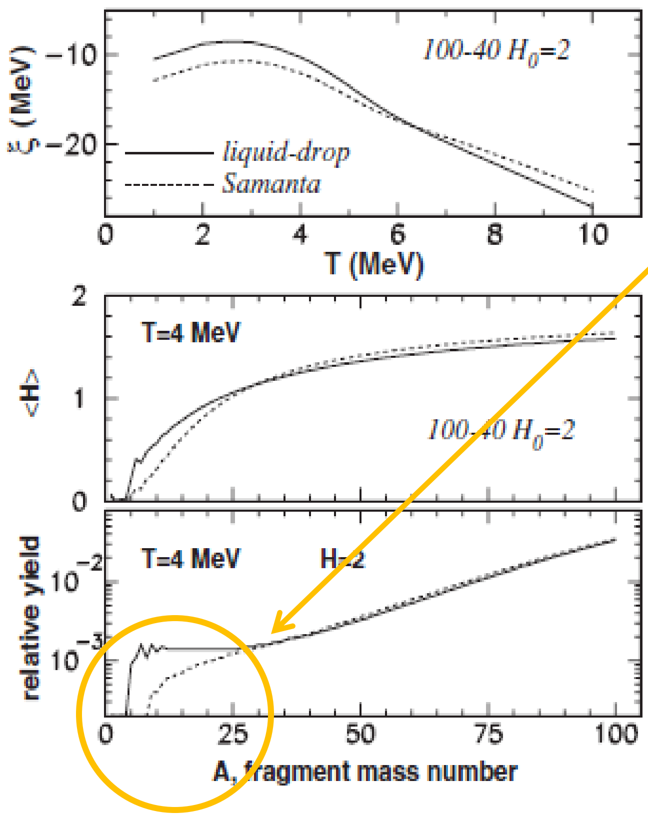
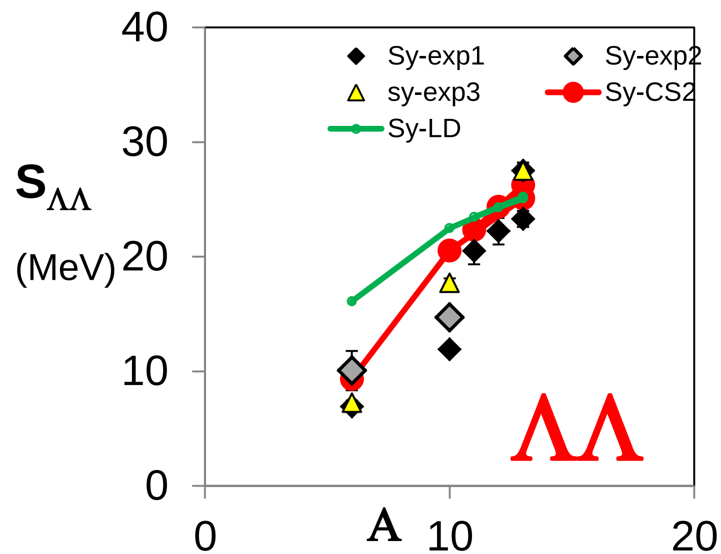
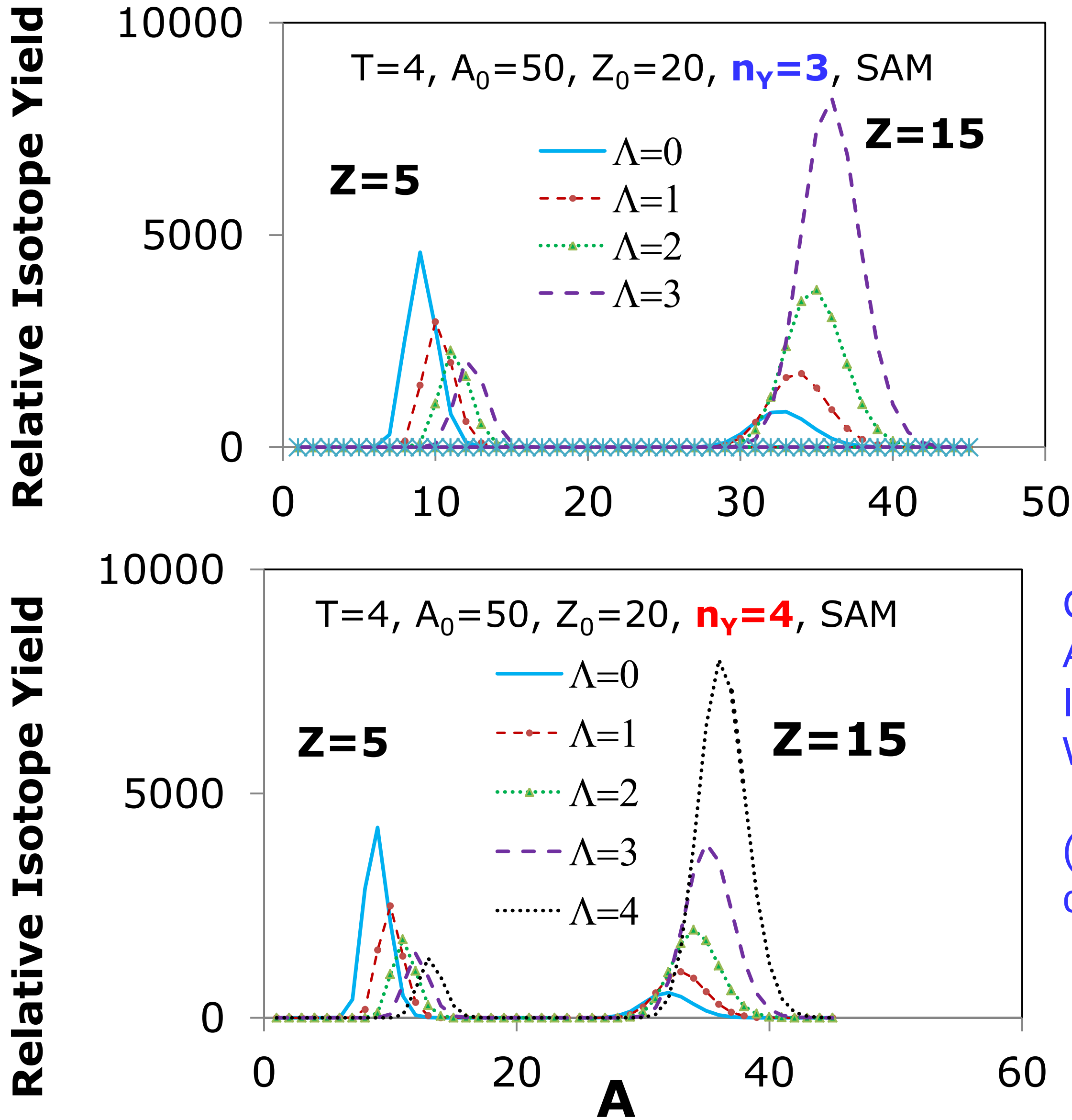


FIG. 3. Comparison of SMM calculations with the liquid-drop and Samanta descriptions of hyper terms in the mass formula, for the same sources as in Fig. 2. Top panel – the strangeness chemical potential ξ versus temperature T. Middle panel – average number of Λ hyperons in fragments, and bottom panel – yields of fragments with two Λ, at $T = 4$ MeV.



The source of discrepancy is the difference between the Samanta formula (Red Line) and Botvina-Pochodzalla mass formula (**Green line**) at low A (the latter over-predicts Expt. $\Lambda\Lambda$-separation energy).

Prediction of the Multi-Lambda Production Yield By the Statistical Multifragmentation Model (SMM)



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(to be communicated)

Lightest Bound Multi-Strange Nuclei without any Neutrons and Protons!

C. Samanta, Jour. Phys. G: Nucl. Part. Phys. 37 (2010)075104

6Λ

$10\Xi^0$

$11\Xi^-$

$1\Xi^- + 8\Xi^0$

$1\Lambda + 8\Xi^-$

$1\Lambda+7\Xi^0$

$1\Xi^0+9\Xi^-$

$2\Lambda+3\Xi^0+3\Xi^-$

Pure Hyperonic Systems which are bound (predicted by CS2)

No bound pure-hyperonic matter is possible by Model-1

Summary

❖Hyperons are Baryons with Strange quark in addition to Up and Down quarks.

❖A single generalized mass formula is prescribed (JPG 37 (2010) 075104) that gives a rough and quick estimation of the hyperon-separation energy for both strange and multi-strange hypernuclei. It reproduces experimental data as well as RMF calculations.

❖Addition of a Λ makes a nucleus more bound, and shifts neutron and proton drip lines. The n-drip point of Mg is n~30 (^{42}Mg) while the Λ–drip point of ^{24}Mg is found to be $\Lambda \sim 20$ ($^{44}{}_{\Lambda}$Mg).

❖Interestingly, RMF calculations show that the non-strange drip-nucleus may spit out 6 neutrons when a Λ–hyperon is added, thus pulling the drip line in, instead of pushing it out!

❖Relative yields of multi-strange nuclei are calculated using Statistical Multifragmentation Model (SMM) and two different mass formulas (Botvina-Pochodzalla and Samanta et al.).

❖SMM calculations indicate production yield of 2Λ, 3Λ and 4Λ-hypernuclei to be higher than normal nuclei at T=4 for fragments with larger mass number.

❖There could be truly multi-strange nuclei without any neutrons and protons.

❖A systematic study of hypernuclei needs to be carried out both theoretically and experimentally.

Thank you!