STRANGENESS: A NEW DIMENSION IN NUCLEAR PHYSICS

Chhanda Samanta

Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata, India &
Virginia Commonwealth University, Richmond, VA, USA

Presented at:
Johann Wolfgang Goethe-Universitat,
September 30, 2010
INTRODUCTION

What are the basic Constituents of matter?
What is “Hyperon”?
When was the first discovery of a strange nucleus called, “Hypernucleus”?
What is a Hypernucleus?
How hypernuclei are produced?

HOW TO CALCULATE THE MASS OF HYPERNUCLEI?
Mass formulas for hypernuclei
Comparison with experimental data
Effect of hyperons on normal neutron and proton drip lines
Limits of hyperons in a hypernucleus

FINAL REMARKS
What are the Constituents of Matter?

A quark is an elementary particle and a fundamental constituent of matter. There are six flavors of quarks. "Flavors" simply means different kinds. The two lightest are called Up and Down.

- **Nucleons and hyperons both are called baryons.**
- Each baryon has a corresponding anti-particle (anti-baryon)
- In anti-baryons quarks are replaced by their corresponding anti-quarks.
For this reason, this particular nuclear fragment, and the others obtained afterwards in similar conditions, were called hyperfragments or hypernuclei.

Discovery of a Strange nucleus: Hypernucleus

M. Danysz and J. Pniewski, Philos. Mag. 44 (1953) 348

First-hypernucleus was observed in a stack of photographic emulsions exposed to cosmic rays at about 26 km above the ground.

Incoming high energy proton from cosmic ray

colliding with a nucleus of the emulsion, breaks it in several fragments forming a star.

All nuclear fragments stop in the emulsion after a short path

But, one disintegrates later: revealing the presence inside the fragment of an unstable particle decaying weakly - the Lambda (Λ) hyperon.

For this reason, this particular nuclear fragment, and the others obtained afterwards in similar conditions, were called hyperfragments or hypernuclei.
**Hypernucleus: A Strange Matter**

**Normal nucleus:** consists of nucleon (neutron, proton)

**Hypernucleus:** consists of nucleon (n, p) + hyperon (Y)

Hyperon acts like a glue & makes a nucleus more bound.

- $^{10}\text{Li} (=3p+7n)$ is known to be **unbound**, but
- $^{10}\text{Li}_\Lambda (=3p+6n+1\Lambda)$ is **bound** (*PRL*94,052502’05)

**Notation:** $^A_Y^Z$

- $p + p + n = ^3\text{He}$
- $p + p + \Xi^- = \Xi^- ^3\text{H}$
- $p + p + \Sigma^+ = \Sigma^+ ^3\text{Li}$

Net charge $Z$ denotes the name of the nucleus

- Periodic Table arranges the elements according to their proton number.
- A Hypernucleus can have same proton number, but the different element name.

A = $N_n + N_p + N_Y$

$N_n$ = neutron no.

$N_p$ = proton no.

$N_Y$ = hyperon no.

Net Charge = $Z$

= $Z_p + (N_Y \cdot q_Y)$

$q_Y$ = Charge of the hyperon

$Z \neq$ no. of protons ($Z_p$)!
How many Strange Hypernuclei are discovered so far?

Hypernuclei with following hyperon:

\[ \Lambda^0 \ (S = -1) \sim \text{Fifty} \]
\[ \Lambda\Lambda^- \text{-hypernuclei (Five)} \]
\[ \Sigma^+ \ (S = -1) \ \text{One} \]
\[ \Xi^- \ (S = -2) \ \text{Five} \]
\[ \overline{\Lambda}^0 \ (S = +1) \ \text{One} \]
Production of Hypernuclei

Strangeness exchange: \[ n(K^-, \pi^-)\Lambda \]
\[ p(K^-, \pi^\pm)\Sigma^\mp \]

Associated production: \[ n(\pi^+, K^+)\Lambda \]

Electroproduction: \[ p(e, e'K^+)\Lambda \]

GSI/FAIR
- H.I. Collision
- p-p collision

CERN, BNL, KEK, DAPHNE

BNL, KEK

Jlab, MAMI

International Hyper-nuclear network

 produção de Hypernuclei

Strangeness is conserved in Strong & e.m. interactions.

Hypernuclei live long enough to have sharp energy levels.

Not an overreaching case!
Hypernuclear landscape with HypHI

Phase 1 (2012-2016) at GSI
Proton rich hypernuclei

Phase 2 (2016-) at R3B/FAIR
Neutron rich hypernuclei

Phase 3 (20XX-) at FAIR
Hypernuclear separator

Known hypernuclei
10^4 /week
10^3 /week

With hypernuclear separator
Magnetic moments

Courtesy: Daisuke Nakajima
Can we theoretically suggest the mass or, the binding energy of those Strange-nuclei which have NOT been detected so far?
Relativistic Mean Filed Calculations & Mass Formula

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


Difficult to pursue for all kinds of 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.
Application of Mass Formulae for Multiply Strange Nuclei

Shmuel Balberg,* Avraham Gal*,**, and Jürgen Schaffner

The generalized BW (GBW) mass formula for SHM is constructed\(^9\) in analogy to the ordinary nuclear BW formula, Eq. (8). One assumes that SHM saturates for roughly equal densities of the various species and that the Fermi momentum of the underlying strange baryonic Fermi gas is about the same as for ordinary nuclear matter. Whereas a single Coulomb term and a single surface term are retained in the GBW formula, there are now several volume and symmetry terms, e.g.

\[
E_B(\{\rho, n\}) = -a_v(0)A + a_s(0)A^{2/3} + a_c(0)\frac{Z^2}{A^{1/3}} + a_x(0)\frac{(N-Z)^2}{A}.
\]

\[
a_v(0) \rightarrow a_v - b_v(w)w - b_v(y)y, \tag{10a}
\]

\[
a_x(0)x^2 \rightarrow a_x x^2 + a_u u^2 + a_w w^2 + a_y y^2 + a_{wy} wy, \tag{10b}
\]

where

Does not depend on mass and strangeness of hyperons.

\[
x = (N-Z)/A, \quad u = (E^0 - E^-)/A, \quad w = \left(\frac{N+Z}{2} - \frac{E^0 + E^-}{2}\right)/A,\]

\[
y = ((N+Z+E^0+E^-)/4 - A)/A. \tag{11}
\]

| Table I. Parameter sets for use in the GBW formula.\(^9\) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                | \(a_v\) | \(b_v(w)\) | \(b_v(y)\) | \(a_x\) | \(a_u\) | \(a_w\) | \(a_y\) | \(a_{wy}\) |
| set I          | 10.7    | -35.5      | -16.75        | 43       | 23.7    | 57.1    | 45       | 7.7            |
| set II         | 28.7    | -5.5       | -4.75         | 43       | 23.7    | 57.1    | 45       | 7.7            |
Liquid-drop Mass formula (for Λ-hypernuclei only)


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

\[ A = n + z_c + n_Y : \ n = \text{no. of neutrons}, \ z_c = \text{no. of protons}, \ n_Y = \text{no. of hyperons} \]

Binding Energy: \[ B(A,Z) = m_A - z_c m_p - n m_n - n_Y m_Y = \text{Negative} \]

- Does not depend on mass and strangeness of hyperons.
- Not valid for: \( A = n_Y \)
- No hyperon-asymmetry term
Bethe-Weizsäcker mass formula (no shell effect):

\[ BE(A, Z) = a_v A - a_s A^{2/3} - a_c \frac{Z(Z - 1)}{A^{1/3}} - a_{sym} \frac{(N - Z)^2}{A} + \delta \]

where \( a_v = 15.777 \text{ MeV}, \ a_s = 18.34 \text{ MeV}, \ a_c = 0.71 \text{ MeV}, \ a_{sym} = 23.21 \text{ MeV}, \)

and the pairing term \( \delta = 12 A^{-1/2} \) for even \( N \) and even \( Z \)

\( = -12 A^{-1/2} \) for odd \( N \) and odd \( Z \)

\( = 0 \) for odd \( A \)

It was later extended for light mass nuclei as well as for nuclei away from the valley of stability in which two correction terms were introduced. The parameters were fixed by fitting the available mass data. BE is given by:

\[ BE(A, Z) = a_v A - a_s A^{2/3} - a_c \frac{Z(Z - 1)}{A^{1/3}} - a_{sym} \frac{(N - Z)^2}{A} + \delta_{new} \]

\[ \delta_{new} = \delta \left( 1 - \exp^{-A/30} \right) \]

Binding Energies of Non-Strange Lithium Isotopes


B-W Formula:

\[
BE(A, Z) = a_v A - a_s A^{2/3} - a_c \frac{Z(Z - 1)}{A^{1/3}} - a_{sym} \frac{(N - Z)^2}{A} + \delta
\]

Modified B-W Formula (new):

\[
BE(A, Z) = a_v A - a_s A^{2/3} - a_c \frac{Z(Z - 1)}{A^{1/3}} - a_{sym} \frac{(N - Z)^2}{A\left(1 + \exp^{-A/17}\right)} + \delta_{new}
\]

\[
\delta_{new} = \delta \left(1 - \exp^{-A/30}\right)
\]

Correction terms

Poor agreement of the BW mass formula with the experimental data without the correction terms.
A systematic search using experimental separation energy ($S_Y$) for $\Lambda^0$, $\Lambda\Lambda$, $\Sigma^+$ and $\Xi^-$-hypernuclei leads to a generalized mass formula which is valid for normal nuclei ($n_Y=0$) as well as Hypernuclei ($n_Y\neq0$).

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

$n_Y =$ 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. of Hyperon with proper sign. (viz., q= -1, 0, 1)

The hyperon separation energy $S_Y$ defined as:

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

<table>
<thead>
<tr>
<th>Hyperon</th>
<th>$S$</th>
<th>$n_Y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda^0$</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>$\Lambda\Lambda$</td>
<td>-2</td>
<td>2</td>
</tr>
<tr>
<td>$\Sigma^{+, -, 0}$</td>
<td>-1</td>
<td>1</td>
</tr>
<tr>
<td>$\Xi^-$</td>
<td>-2</td>
<td>1</td>
</tr>
<tr>
<td>$\Theta^+$</td>
<td>+1</td>
<td>1</td>
</tr>
<tr>
<td>Normal</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
Mass formula for Multi-strange Nuclear Systems


We consider: **Hypernucleus = Core** (normal nucleus with nucleons, \( N \)) + **Hyperons(Y)**

A hypernucleus may have one kind of hyperon(s) or a mixture of different kind of hyperons

\[
A = n + z_c + \sum n_Y : n = \text{no. of neutrons}, \ z_c = \text{no. of protons}, \ n_Y = \text{no. of hyperons of each kind}
\]

**The Hyperon-separation energy**

\[
S_Y = BE(A, Z)_{\text{hyper}} - BE(A - n_Y, z_c)_{\text{core}}
\]

**Hyperon-separation energy for multi-strange hypernuclei**

\[
S_Y = B(A, Z) - B(A - \sum_{Y} n_Y, Z)
\]

For a nucleus to be bound:

\[
\text{B.E.} = m_A - z_c m_p - n m_n - n_Y m_Y = \text{Negative}
\]

\[
S_Y = \text{Positive}
\]
Generalized Mass Formula for Non-strange, Strange and Multiply-strange Nuclear Systems

C. Samanta, JGP 37 (2010) 075104

\[ A = n + z_c + n_Y : \quad n= \text{no. of neutrons}, \quad z_c = \text{no. of protons}, \quad n_Y = \text{no. of hyperons} \]

Binding Energy: \[ B(A,Z) = m_A - z_c m_p - n m_n - n_Y m_Y = \text{Negative} \]

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

\[
- a_Y \left\{ (n_\Lambda + n_{\Xi^0} + n_{\Xi^-} - z_c)^2 + (n_\Lambda + n_{\Xi^0} + n_{\Xi^-} - n)^2 \right\} / \left[ (1 + e^{-A/17}) A \right].
\]

\[ m_Y = \text{mass of hyperon in MeV} \]

\[ S = \text{strangeness no. of the hyperon} \]

\[ Z = \text{Net Charge} = \text{Proton charges} + \text{Total hyperon charges} \]

\[ q = -1, 0, 1 \text{ depending on the hyperon type} \]

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!!!
Multi-Strange Nuclei: Model-2 with Y-Y interaction

Effect of the new hyperon-asymmetry term: choice of $a_Y$ value

(a) $E_B/A$ vs. $A$ plots for stable multi-strange systems in relativistic mean field (RMF) calculations based on $^{56}$Ni nuclear cores for model 2 (with YY interaction) of Schaffner et al. (Ref. 1).

(b) Single lambda-hyperon separation energy $S_Y$ vs. $A$ for different elements. With $a_Y=0.0$ and 0.2.

Stable-multiply-strange systems in RMF calculations, based on $^{56}\text{Ni}$, $^{132}\text{Sn}$, $^{208}\text{Pb}$ and $^{310}\text{G}(Z_c=126, n=184)$ core, by:

1. Model-1 of Schaffner et al.,
2. SET-I of Balberg et al.,
3. this work CS1.

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

Model-1=No Y-Y interaction
Model-2=Strong Y-Y interaction

$\text{CS1(BE,Model1)}=\text{CS2(BE,Model2)} - \text{Cr}$

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

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

Stable-multiply-strange systems in RMF calculations, based on $^{56}\text{Ni}$, $^{132}\text{Sn}$, $^{208}\text{Pb}$ and $^{310}\text{G}(Z_c=126, n=184)$ core, by:

1. Model-1 of Schaffner et al.,
2. SET-I of Balberg et al.,
3. this work CS1.
Stable Multiply-strange systems in RMF (Model2, with Y-Y interaction) calculations of Schaffner et al. with $^{56}$Ni and $^{180}$Th core, Set-II of Balberg et al. and this work (CS2).


Λ-Separation Energies: Comparison with the Experimental Data

Set-I (as well as Set-II) of Balberg et al. over predicts the experimental data.

Sy-CS1 and Sy-CS2 agree with experimental data & give comparable results.

For very light elements Sy-CS1 is lower than Sy-CS2.
Double-\(\Lambda\) Hypernuclei via the \(\Xi^+\) Hyperon Capture at Rest Reaction in a Hybrid Emulsion

K. NAKAZAWA for KEK-E176, E373 and J-PARC E07 collaborators

Phys. Dept., Gifu University, Gifu 501-1193, Japan

Table 4: \(B_{\Lambda \Lambda}\) and \(\Delta B_{\Lambda \Lambda}\) for all double-\(\Lambda\) hypernuclei under the assumption that each case resulted from the capture reaction of a \(\Xi^-\) hyperon in a 3D atomic level for each target nucleus.

<table>
<thead>
<tr>
<th>event</th>
<th>(A_{\Lambda \Lambda})</th>
<th>(Z_{\Lambda \Lambda})</th>
<th>Target</th>
<th>(B_{\Lambda \Lambda} [\text{MeV}])</th>
<th>(\Delta B_{\Lambda \Lambda} [\text{MeV}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAGARA</td>
<td>6 (\Lambda)He</td>
<td>(12)C</td>
<td>6.91 ± 0.16</td>
<td>0.67 ± 0.17</td>
<td></td>
</tr>
<tr>
<td>MIKAGE</td>
<td>6 (\Lambda)He</td>
<td>(12)C</td>
<td>10.06 ± 1.72</td>
<td>3.82 ± 1.72</td>
<td></td>
</tr>
<tr>
<td>DEMACHIYANAGI</td>
<td>10 (\Lambda)Be</td>
<td>(12)C</td>
<td>11.90 ± 0.13</td>
<td>−1.52 ± 0.15</td>
<td></td>
</tr>
<tr>
<td>HIDA</td>
<td>11 (\Lambda)Be</td>
<td>(16)O</td>
<td>20.49 ± 1.15</td>
<td>2.27 ± 1.23</td>
<td></td>
</tr>
<tr>
<td>E176</td>
<td>13 (\Lambda)B</td>
<td>(14)N</td>
<td>22.23 ± 1.15</td>
<td>−</td>
<td></td>
</tr>
<tr>
<td>Danysz et al[17]</td>
<td>10 (\Lambda)Be((9)Be*)</td>
<td>(14)N</td>
<td>14.7 ± 0.4</td>
<td>1.3 ± 0.4</td>
<td></td>
</tr>
</tbody>
</table>
Sy-CS2 (Model2) gives a reasonably good fit to the experimental data.
Sy-CS1 (Model1) differs from Sy-CS2 at lower A values.
Sy-Bal1 (Balberg et al, Set-I) predicts much larger values.
Sy-Bal2, not shown here, gives even higher values of $S_{\Lambda\Lambda}$. 

<table>
<thead>
<tr>
<th>$^A_{\Lambda\Lambda}$Z12Be</th>
<th>$S_Y$(exp1)</th>
<th>$S_Y$(exp2)</th>
<th>$S_Y$(exp3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6_{\Lambda\Lambda}$He</td>
<td>6.91 +/- 0.16</td>
<td>10.06 +/- 1.72</td>
<td>7.25 +/- 0.19</td>
</tr>
<tr>
<td>$^{10}_{\Lambda\Lambda}$Be</td>
<td>11.90 +/- 0.13</td>
<td>14.70 +/- 0.40</td>
<td>17.70 +/- 0.40</td>
</tr>
<tr>
<td>$^{11}_{\Lambda\Lambda}$Be</td>
<td>20.49 +/- 1.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{12}_{\Lambda\Lambda}$Be</td>
<td>22.23 +/- 1.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{13}_{\Lambda\Lambda}$B</td>
<td>23.30 +/- 0.70</td>
<td></td>
<td>27.50 +/- 0.70</td>
</tr>
</tbody>
</table>
Experimental data on $\Xi$ hypernuclei are tabulated in:


Old emulsion data
(Ref: Bando et al. IJMPA 5 (1990)4021).

Need more precise experimental data for Cascade hypernuclei.

Experimental data on $\Xi$ hypernuclei are tabulated in:
Comparison between mass formulas of Samanta and Bondorf et al. (Liquid drop model)

Differs at low $A$

$S_\Lambda$ (MeV)

$S_{\Lambda\Lambda}$ (MeV)
Mass Formulas of Samanta & LD differs at both small A and large A

Large A: LD has no hyperon-asymmetry term.

LD: \( ny*(-a_1A+b_1A^{-1/3}) \);
similar to surface term
Samanta: \( ny*(-a_2A+b_2A^{-2/3} -c) \)

Binding energy of \( \Lambda \) single particle states

- Converges to \( B=28 \) MeV
- Experimental data support Linear behavior with \( A^{-2/3} \)

Hyperons do not follow the Pauli Exclusion Principle with Nucleons.
What do we learn from the Separation Energy Versus neutron number plot?

Lambda particle makes a nucleus more bound.

For example, $^{10}\text{Li}$ is known to be unbound, but $^{10}_{\Lambda}\text{Li}$ is bound.

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

Theory: CS1(10.2 MeV), CS2(11.4 MeV).

Does this mean that addition of $\Lambda$ can make very neutron-rich hypernuclei – far beyond the normal drip line? **NOT- if the Hyperon/nucleon Separation Energy is Negative!**

For $^{10}_{\Lambda}\text{Li}$: $S_n \sim 1.06$ MeV.

As neutrons are added one by one, $S_n$ decreases in both hyper and normal nuclei, thus reaching the n-drip line at $N=8$.

Beyond $N=8$, the neutron-separation energy ($S_n$) is negative, although $S_{\Lambda}$ is positive. $^{11}\text{Li}$ and $^{12}_{\Lambda}\text{Li}$ are dripline nuclei.

Nucleus $^{13}_{\Lambda}\text{Li}$ ($Z=3$, $N=9$, $\Lambda=1$), if found, will be truly exotic & beyond the n-dripline.
Charged and Neutral Hyperonic Effects on the Normal Drip lines

Rom_Rep_Phys_62_(2010) 65

- Neutron dripline moves out, proton dripline moves inside!
- This effect however varies from nucleus to nucleus.
upper limit to the $\Lambda$, $\Xi^0$ and $\Xi^-$ Hyperon-numbers

(that could be bound to a normal nucleus)

Maximum no. of hyperons

Hyper-drip points predicted by the mass formula CS2.

$\Xi^0$ is higher due to heavier mass.

$\Xi^-$ is lower due to negative charge adding repulsive force.

Such hyper-rich nuclei can be formed beyond the normal drip lines (in a rapid process) if their lifetimes are greater than particle decay times. Shell effect may also add to the stability.
Lightest Bound Nuclei without any Neutron and Proton!


**Lightest Bound Nuclei without any Neutron and Proton!**

- $6\bar{\Lambda}$
- $9\Xi^0\Xi^0$
- $10\Xi^+\Xi^-$
- $1\Xi^0 + 9\Xi^0$
- $1\Lambda + 8\Xi^-$
- $1\Lambda + 7\Xi^0$
- $1\Xi^0 + 8\Xi^-$
- $2\Lambda + 3\Xi^0 + 3\Xi^-$

**Pure Hyperonic Systems which are Bound (Predicted by CS2)**

No bound pure-hyperonic matter is possible by Model-1
Exotic strongly bound nuclear systems are predicted by CS2 only.

\[ ^8\text{He} = 2p + 2n + 2\Lambda + 2\Xi^0 \]

\[ S_{\Xi^02\Lambda} \text{ (CS1)} = -34.66 \text{ (MeV)} ; \quad S_{\Xi^02\Lambda} \text{ (CS2)} = 19.34 \text{ (MeV)} \]

\[ ^{10}\text{n} = 2p + 2n + 2\Lambda + 2\Xi^0 + 2\Xi^- \]

\[ S_{\Xi^02\Xi^-2\Lambda} \text{ (CS1)} = -77.00 \text{ (MeV)} ; \quad S_{\Xi^02\Xi^-2\Lambda} \text{ (CS2)} = 43.00 \text{ (MeV)} \]

Need experimental data
Is it possible to predict the expected yield of single/multi-strange nuclei before the experiment can be done?

Botvina and Pochodzalla calculated yield for single-strange hypernuclei for heavy-ion collision experiments using two mass formulas.
Production of hypernuclei in multifragmentation of nuclear spectator matter
A.S. Botvina, J. Pochodzalla, PRC 76 (2007) 024909

- Chemical potential
- $\langle H \rangle$ Av. No. of $\Lambda$-hyperons in fragments
- Yield of fragments with two $\Lambda$-hyperons at $T=4$ MeV

SMM = Statistical Multifragmentation model
Hyperons may appear in neutral $\beta$-stable matter through process like:

$$n + e^- \rightarrow \Sigma^- + \nu_e$$

At a density of four to five times that of nuclear matter saturation density $\rho_0$, a neutron star can become a hyperon star.

The presence of strange baryons in neutron stars strongly affect their properties.

The effect strongly depends upon the poorly known interactions of strange baryons.

More data needed to constrain theoretical models.

Recent discovery of anti-Lambda hypernucleus using Heavy Ion Collider (RHIC) at BNL

- March 04, 2010
- Scientists at BNL, USA reported discovery of the first anti-nucleus containing an anti-strange quark.

- It is called: Anti-Hyper-Triton.
- Triton = p + n + n
- Hyper-triton = p + n + \( \Lambda \)
- Anti-Hyper-Triton = \( \bar{p} + \bar{n} + \bar{\Lambda} \)

As it has anti-proton, it is a negatively charged state of Anti-Matter.

Why are we made of matter only? Where did all the anti-matter go?
The new discovery of strange antimatter (anti-hyper-triton) marks the first entry below the 3D (N-Z-S) plane.

S (Strangeness) adds a new dimension to the 2D (N-Z) chart.

S axis is zero for all naturally occurring matter, but could be non-zero in the core of collapsed stars.

The new discovery of strange antimatter (anti-hyper-triton) with an anti-strange quark (an anti-hypernucleus) marks the first entry below the 3D (N-Z-S) plane.
Concluding Remarks

- Strangeness, adding a new dimension into conventional nuclear physics, has opened a door to investigate new phenomena in physics.
- It is an interdisciplinary field which encompasses Astrophysics, Particle Physics and Nuclear Physics.
- Hyperon-hyperon & hyperon-nucleon interactions are still not well understood. But, our limited knowledge predicts that there might be exotic hyper-nuclei beyond the drip lines.
- It is just the beginning of a new field.
- Certainly more experimental data are needed!
Thank you!
Abstract:

Even though our world is not such a strange place, the possible existence of strange objects cannot be ruled out. This strangeness could occur at many levels, from forming heavier than usual isotopes of common elements to an entire class of stars composed largely of strange matter. Strange particles such as hyperons are baryons like neutrons and protons, except that they have built-in strange quarks. This strangeness adds third dimension to the nuclear chart and it has become a topic of great current interest in Physics. Several upcoming and existing accelerators around the world have undertaken projects to study such strange nuclei, called hypernuclei, which are made of neutrons, protons and hyperons. In our world we see lighter cousins of nuclei with neutrons and protons only, not hypernuclei, although their binding energies are larger. One wonders how these strange particles bind with our well known nucleons forming hypernuclei and what their masses are. Is there a limit to this binding? Can we have super-strange nuclei without neutrons and protons? Some of these questions will be addressed in this talk.