Superheavy Nuclei to Hypernuclei: A Tribute to Walter Greiner

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My first meeting with Professor Walter Greiner was at the International Conference on Atomic and Nuclear clusters held at Santorini, Greece, in 1993.

His vision, enthusiasm, and encouragement touched many lives, and I was one of those privileged ones.

My interests in **Superheavy nuclei, Hypernuclei and Dark matter** were encouraged by Walter.

I will present a brief summary of some exciting developments in these fields, including some of our own work.

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SUPERHEAVY NUCLEI AND BEYOND: HYPERMATTER AND ANTIMATTER

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Abstract. The extension of the periodic system into various new areas is investigated. Experiments for the synthesis of superheavy elements and the predictions of magic numbers are reviewed. Further on, investigations on hypernuclei and the possible production of antimatter-clusters in heavy-ion collisions are reported. Various versions of the meson field theory serve as effective field theories at the basis of modern nuclear structure and suggest structure in the vacuum which might be important for the production of hyper- and antimatter.

1. Introduction

There are fundamental questions in science, like e. g. "how did life emerge" or "how does our brain work" and others. However, the most fundamental of those questions is "how did the world originate?". The material world has to exist be- fore life and thinking can develop. Of particular importance are the substances themselves, i. e. the particles the elements are made of (baryons, mesons, quarks, gluons), i. e. elementary matter. The vacuum and its structure is closely related to that. I want to report on these questions, beginning with the discussion of modern issues in nuclear physics.

Superheavy

In the late sixties, the dream of the Superheavy elements (SHE) arose. Theoretical nuclear physicists around S. G. Nilsson (Lund) and from the Frankfurt school of Germany [1, 2] predicted that the so called **closed proton and neutron shells should counteract the repelling Coulomb forces in some Superheavy nuclei**.

Hence, atomic nuclei with these special "magic" proton and neutron numbers and their neighbours could again be rather stable.

[1] Mosel U and Greiner W 1968, Z. Phys. 217 256; Mosel U and Greiner W 1968, Z. Phys. 222 (1969) 261;

see also Memorandum zur Errichtung eines gemeinsamen Ausbildungszentrums f¨ur Kernphysik Hessischer Hochschulen, this was the initiative for building GSI (1966)

[2] Nilsson S G , Nix J R, Sobiczewski A, Szymaimageski Z, Wycech S, Gustafson C and M¨oller P 1968, Nucl. Phys. A 115 545; Nilsson S G, Thompson S G and Tsang C F 1969, Phys. Lett. B 28 458

Calculations

Samanta, C.; Chowdhury, R. P.; Basu, D.N.,Nucl. Phys. A. 789 (2007) 142–154.

Chowdhury, R. P.; Samanta, C.; Basu, D.N. Atomic Data and Nuclear Data Tables. 94 (2008) 781–806.

In a quantum tunnelling model, we made theoretical estimation for the half lives of about 1700 isotopes of heavy elements with $100 \leq Z \leq 130$ are tabulated using theoretical *Q*-values.

The theoretical *Q*-values were extracted from three different mass estimates:

1. Myers-Swiatecki (MS),
2. Muntian-Hofmann-Patyk-Sobiczewski (M)
3. Koura-Tachibana-Uno-Yamada [KUTY].

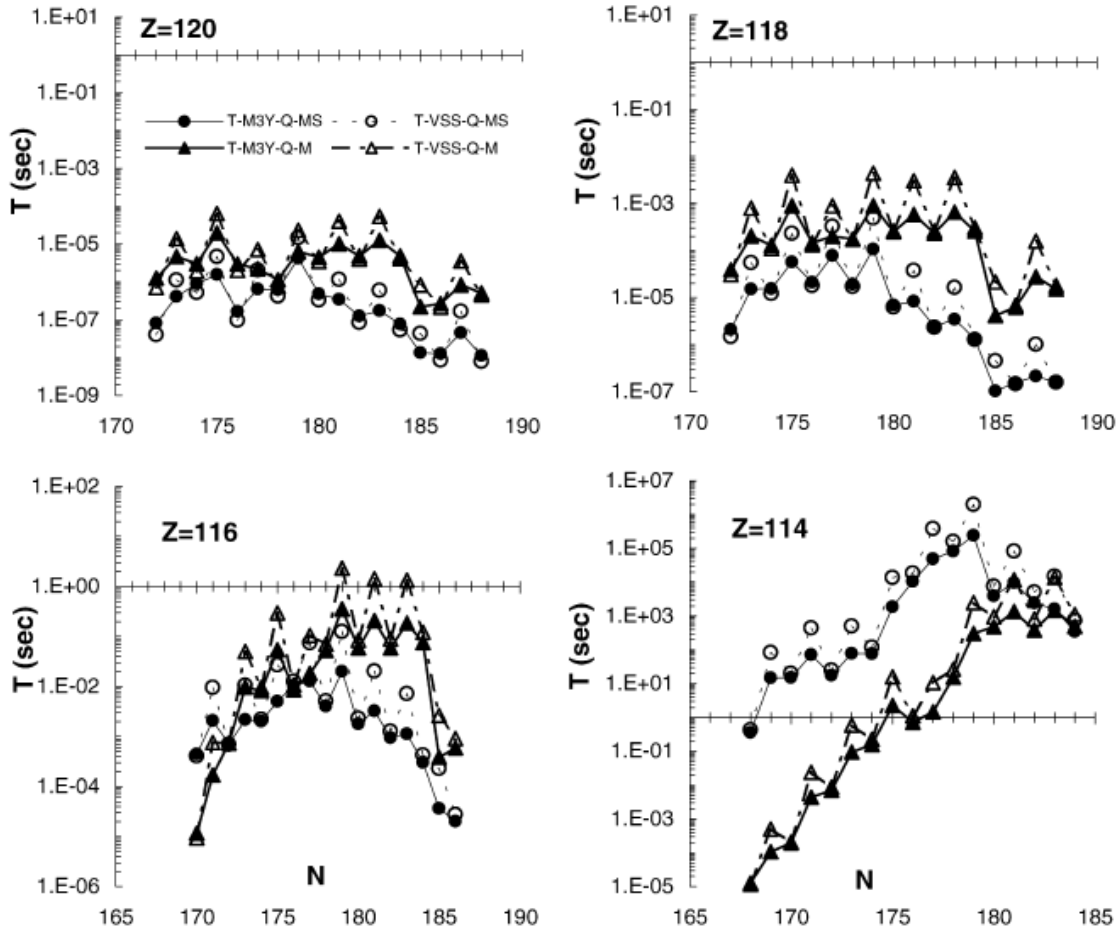
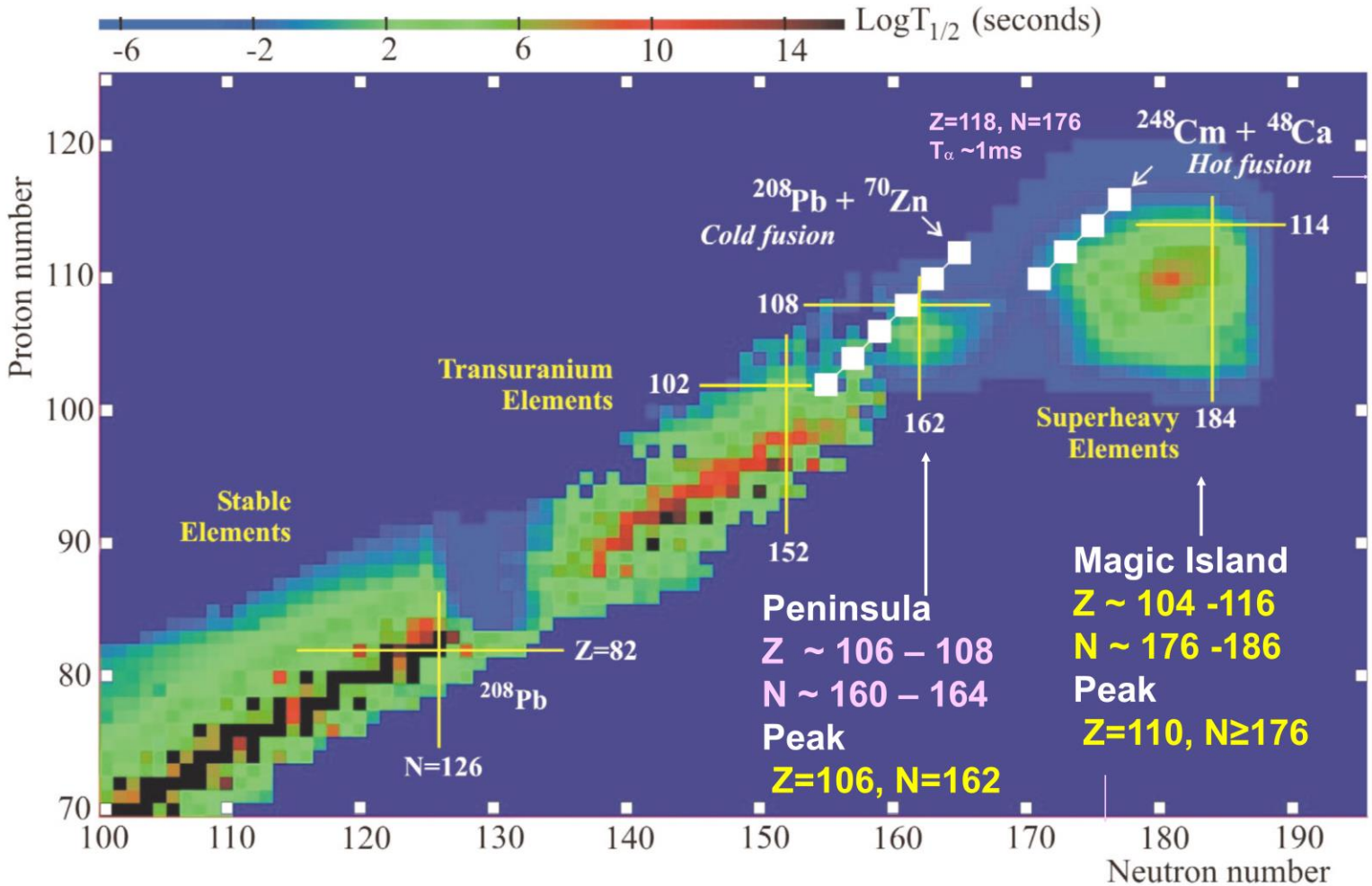


Fig. 1. Plots of alpha decay half life [T (s)] versus neutron number (N) for isotopes of $Z = 120, 118, 116, 114$ calculated using theoretical Q-values from the mass formulae of MS [12] and M [16–18]. (a) DDM3Y with MS is represented by solid circle (T-M3Y-Q-MS), (b) VSS with MS is represented by hollow circle (T-VSS-Q-MS), (c) DDM3Y with M is represented by solid triangle (T-M3Y-Q-M), (d) VSS with M is represented by hollow triangle (T-VSS-Q-M). The lines are guidelines to the eyes.

Half-life goes down with increasing proton number (Z)

As of now, elements upto Z=118 (Oganesson) have been confirmed.



In quantum tunnelling model, we predicted the alpha decay half-life of ^{294}Og to be $0.66^{+0.23}_{-0.18}$ ms.

Chowdhury, Roy P.; Samanta, C.; Basu, D. N., Phys. Rev. C. 73 (2006) 014612

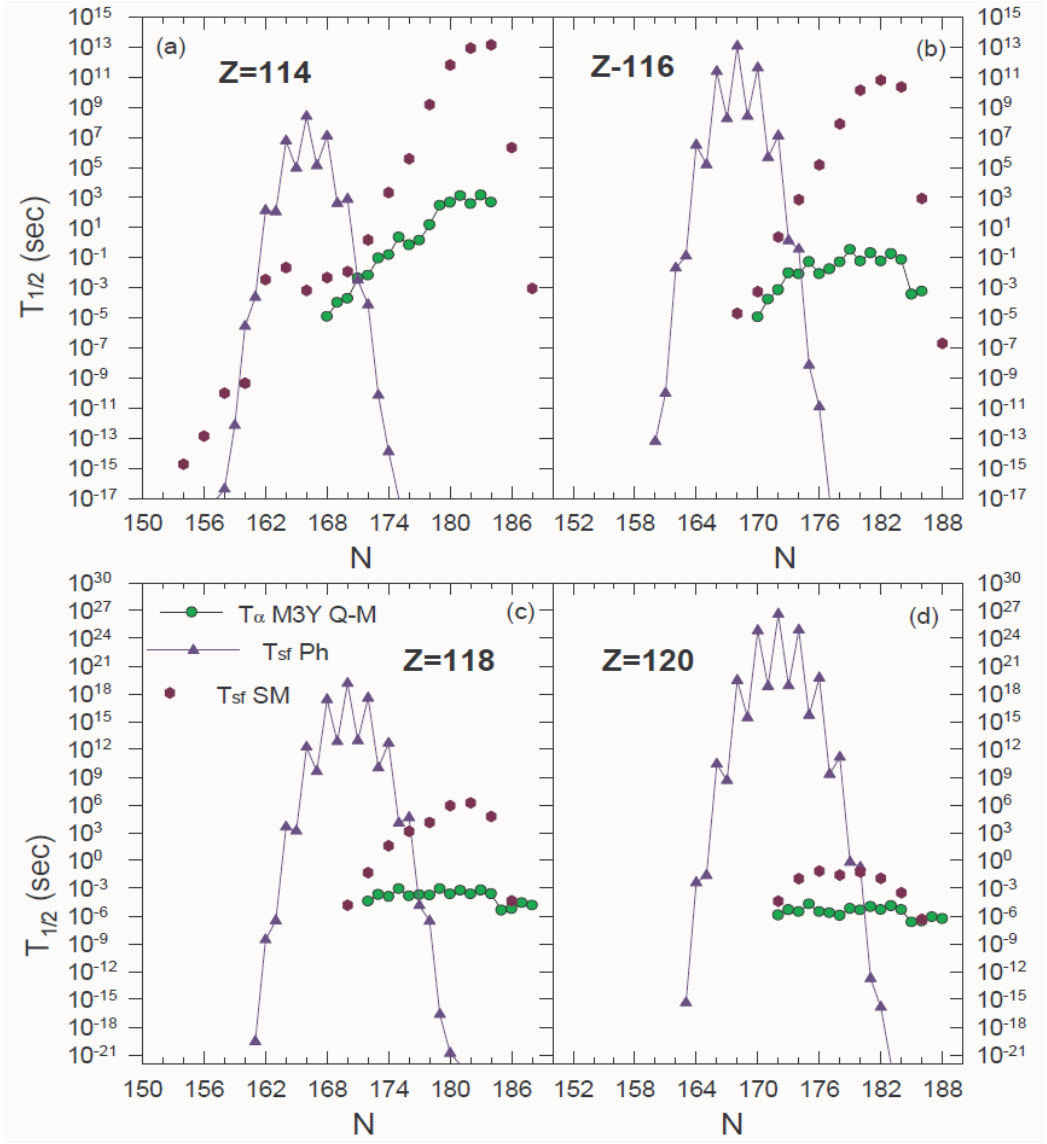
In the experiments, the alpha-decay of three atoms of oganesson was observed. A half-life of ^{294}Og derived from observed lifetimes is: $0.89^{+1.07}_{-0.31}$ ms.

Oganessian, Yu. Ts.; Utyonkov, V. K.; Lobanov, Yu. V.; Abdullin,.et al Physical Review C. 74 (2006) 044602

PHYSICAL REVIEW C 77, 044603 (2008)

Search for long lived heaviest nuclei beyond the valley of stability

P. Roy Chowdhury,[1,*] C. Samanta,[1,2,3,†] and D. N. Basu[4,‡]



Elements beyond Z=118 not only have smaller half-lives, the production cross section is also very low.

Continuous line with green circle (Ta M3Y Q-M) represents alpha-decay half-lives.

Tsf Ph represents spontaneous fission half-lives predicted by phenomenological calculations.

Solid circle (Tsf SM) represents fission half-lives predicted by microscopic calculation.

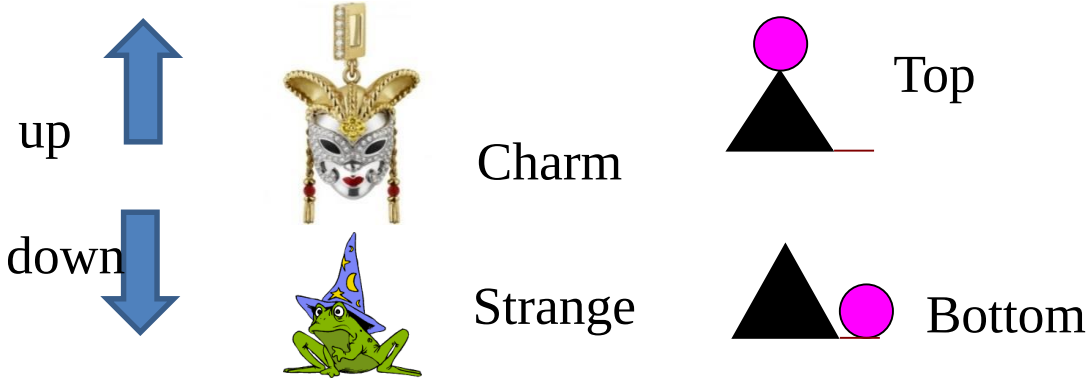
One possible magic number of neutrons for spherical nuclei is 184, and some possible matching proton numbers are 114, 120 and 126 – which would mean that the most stable spherical isotopes would be Flerovium-298, unbinilium-304 and unbihexium-310.

Of particular note is Ubh-310, which would be "doubly magic" (both its proton number of 126 and neutron number of 184 are thought to be magic) and thus the most likely to have a very long half-life.

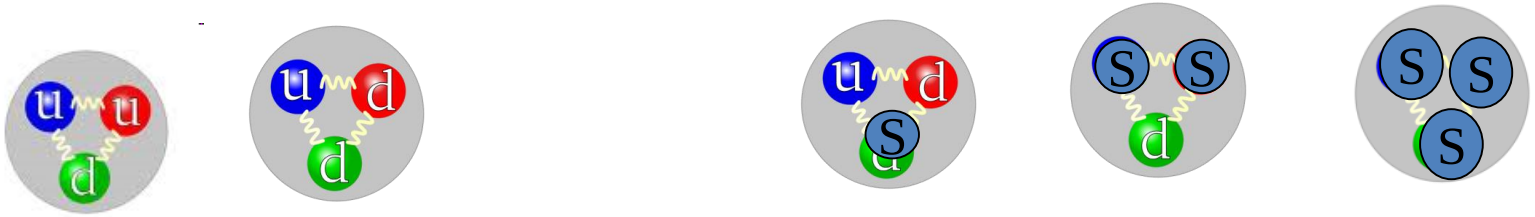
Walter suggested explosion of two nuclear bombs underground to produce those SHE that can not be made in the laboratory due to very low production cross section!

Hypernuclei with Hyperons

There are six flavors of quarks**.** The two lightest are called **Up** and **Down**.



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



p=(**uud**) n=(**udd**)

Nucleons

Λ^0=(**uds**) Ξ^-=(**dss**) Ω^-=(**sss**)

Hyperons

Hypernucleus / 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

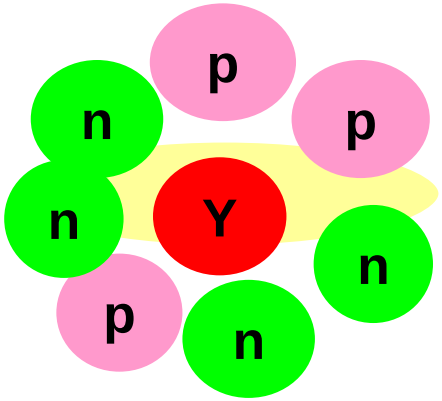
^{A}Z

$Z = Z_p$

=Total Charge of protons

$A = N_n + N_p$

$= N + Z$



$^{A}Z_Y$

Y = Hyperon

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

$A = N_n + N_p + N_Y$

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

1p+4n+1Y = ^{6}**H**$_Y$ **Expected to be Bound!**

Hyperon acts like glue!

Generalized Mass Formula: Non-Strange & Strange nuclei

C. Samanta et al., J.P. G 32 (2006) 363; J.P.G35(2008)065101 ;J. P. G 37(2010) 075104;

A systematic search using experimental separation energy (S_Y) for Λ^o, $\Lambda\Lambda$, Σ^+ 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)

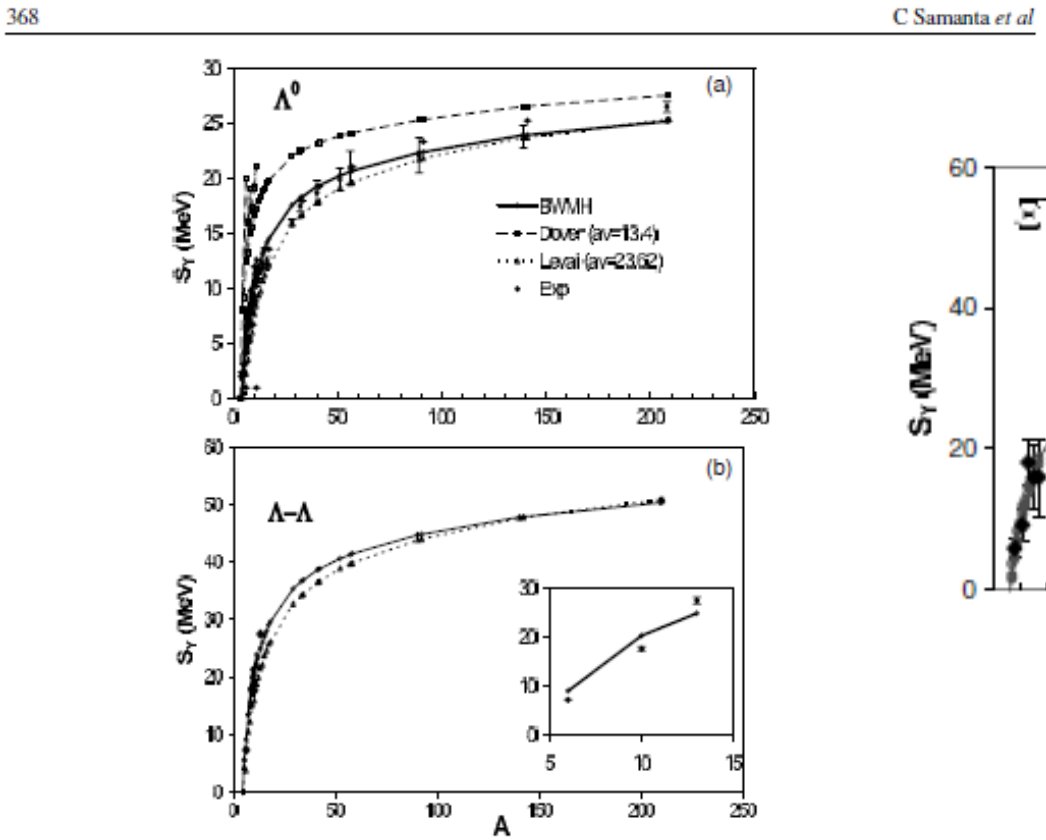
Explicitly depends on Strangeness (S), hyperon mass (m_Y), number of hyperons (n_Y)

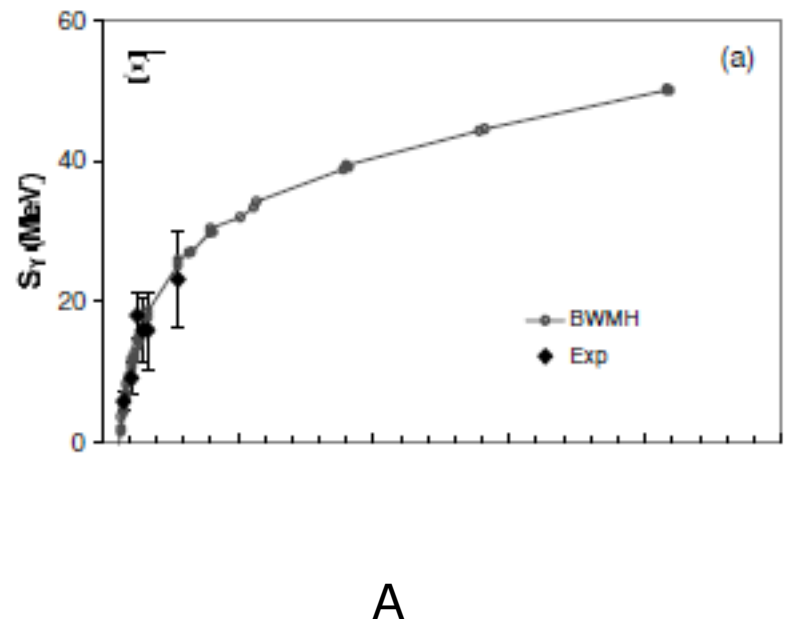
Hyperon	S	m_Y	n_Y
Λ^0	-1	1115.683	1
$\Lambda\Lambda$	-2	1115.683	2
Σ^0	-1	1192.642	1
Ξ^-	-2	1321.71	1
Ξ^0	-2	1314.86	1
Normal	0	-	0

The hyperon separation energy SY , defined as,
$S_Y = B(A, Z)_{hyper} - B(A - nY, Zc)_{core}$,
is the difference between the binding energy of a hypernucleus and the binding energy of its non-strange core nucleus.

Hyperon-Separation Energies of Hypernuclei

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





The Generalised mass formula, without any change of parameter, reproduces experimental Λ, ΛΛ and Ξ^- –separation energies from hypernuclei with different mass number (A).

Production of hypernuclei in multifragmentation Calculated by A.S . Botvina and J. Pochodzalla

PHYSICAL REVIEW C **76**, 024909 (2007)

Production of hypernuclei in multifragmentation of nuclear spectator matter

A. S. Botvina[1] and J. Pochodzalla[2]
[1]*Institute for Nuclear Research, Russian Academy of Sciences, RU-117312 Moscow, Russia*
[2]*Institut für Kernphysik, Johannes Gutenberg-University, Mainz, D-55099 Germany*
(Received 20 March 2007; published 23 August 2007)

We have found that there is a sensitivity of the fragment yields in multifragmentation to the mass formulas used for description of binding energy of hypernuclei. In Fig. 3 we compare SMM calculations performed with the liquid-drop hyperterm (3) in free energy of individual fragments, and with the Samanta term (2). There is a clear difference in the chemical potential ξ, and, as a result, the yields of hyperfragments are also different. As one can see from the bottom panels the liquid-drop formula predicts more strangeness in IMF's than the Samanta formula. The difference in the yields is particularly large for small double hyperfragments. In future, this observable may allow to test experimentally different mass formulas for hypernuclei in multifragmentation.

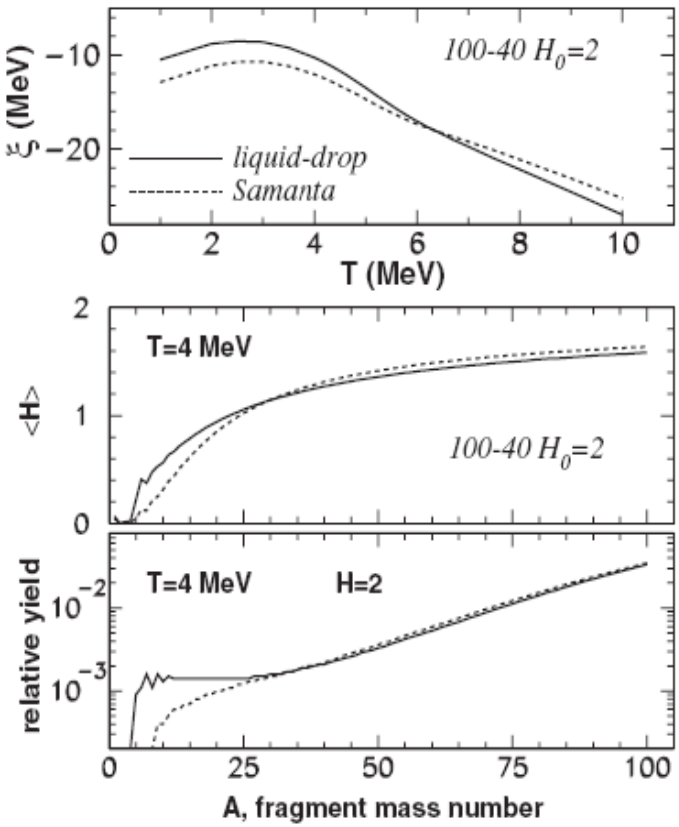


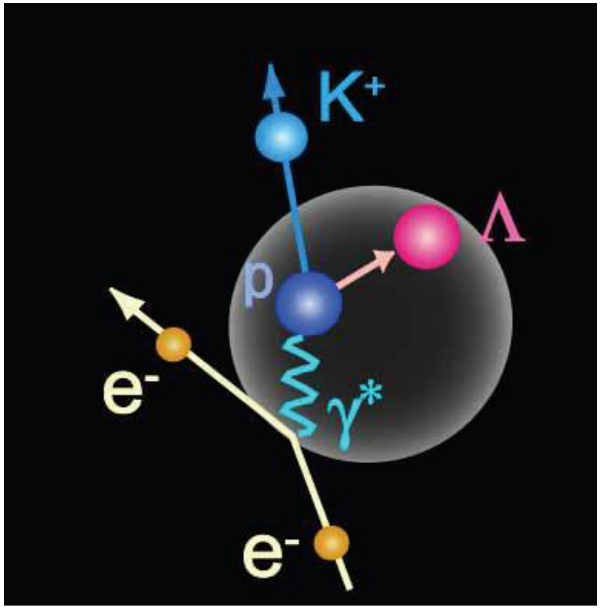
FIG. 3. Comparison of SMM calculations with the liquid-drop and Samanta descriptions of hyper terms in the mass formula, for the same sources as in Fig. 2. Top panel – the strangeness chemical potential ξ versus temperature T. Middle panel – average number of Λ hyperons in fragments, and bottom panel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

Statistical Multifragmentation Model (SMM)

Production of Λ hypernuclei

Jefferson Lab, USA

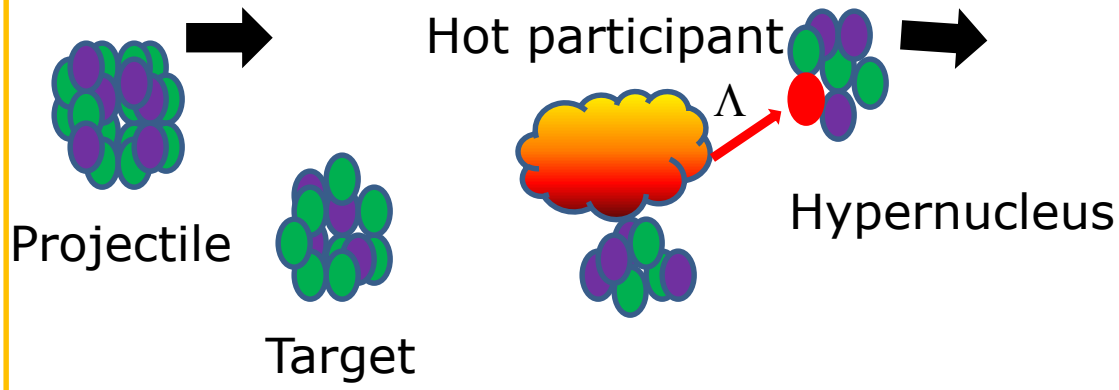
$e^- + p \rightarrow e^- + \Lambda + K^+$



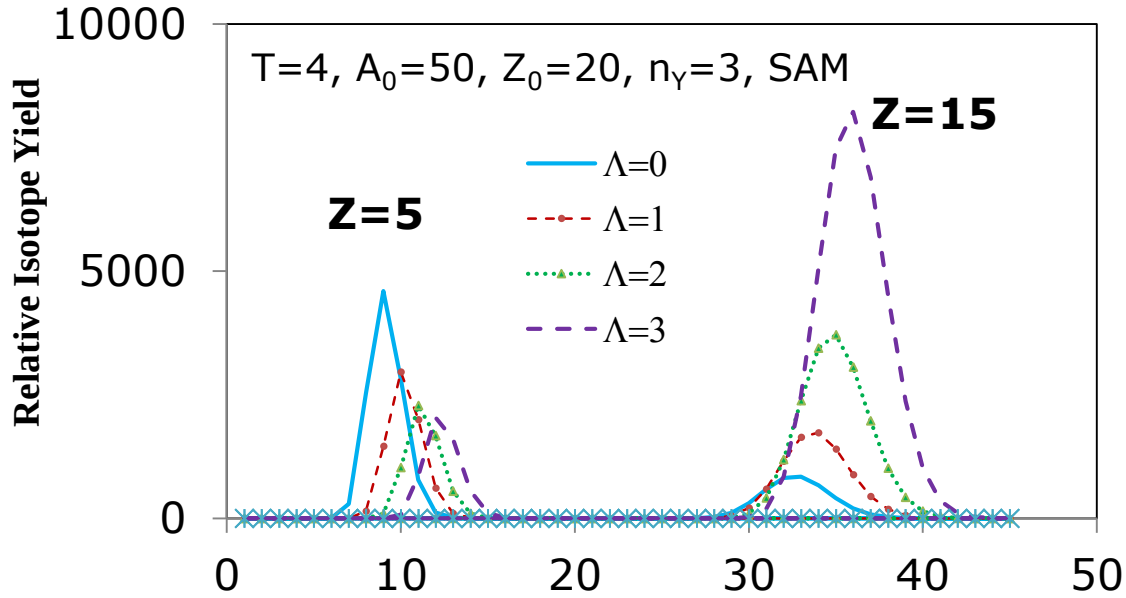
Proton to Λ => Neutron-rich Λ hypernuclei.

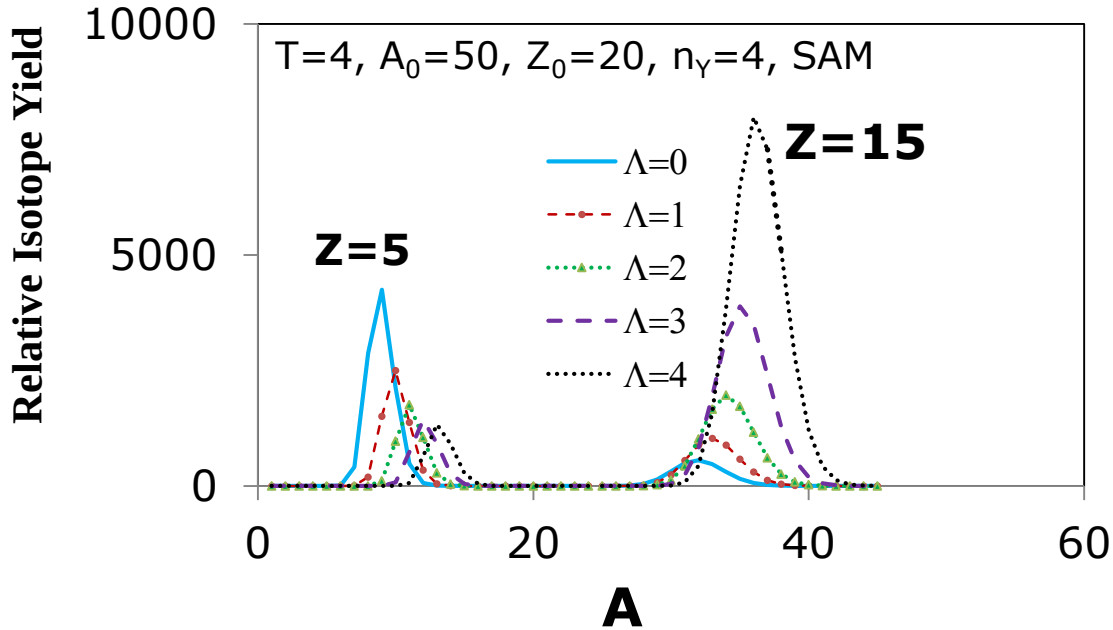
Tang et al., PRC90 (2014) 034320
Sugimura et al., PLB729 (2014) 39
Gogami et al, PRC94 (2016) 021302(R)
Gogami et al, PRC93 (2016) 034314

- Relativistic heavy-ion collisions offer the possibility of creating excited nuclear systems with hyperons.
- Some 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 Probability of Multi-Lambda Hypernuclei is more for higher Z nuclei.





C. Samanta,
A.S. Botvina,
I. Mishustin

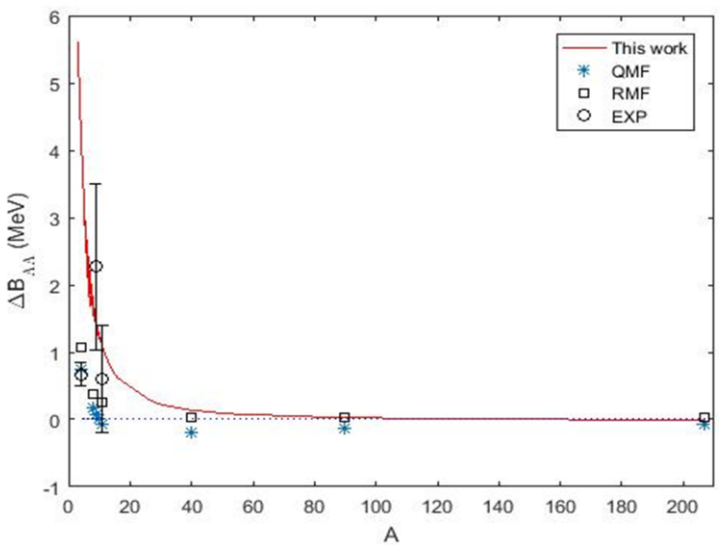
(prepared for communication)

ΛΛ -bond energies

The ΛΛ bond energies ($\Delta B_{\Lambda\Lambda}$) of double-Λ hypernuclei provide a measure of the nature of the in-medium strength of the ΛΛ interaction.

$$\Delta B_{\Lambda\Lambda} = B_{\Lambda\Lambda}\,({}^{A}{}_{\Lambda\Lambda}Z) - 2B_{\Lambda}\,({}^{A-1}{}_{\Lambda}Z),$$

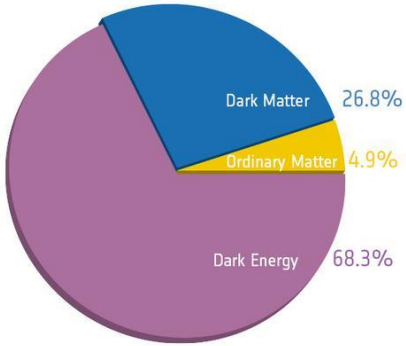
The ΛΛ-separation energy ($B_{\Lambda\Lambda}$) from a double-Λ nucleus is found to exceed twice the value of the Λ-separation energy (B_{Λ}) of a single-Λ nucleus.



Plot of ΛΛ-Bond Energy vs A.

The generalized mass formula is used to calculate the ΛΛ -bond energies and compared with experimental results. The mass formula can predict the bond energies for hypernuclei not studied so far.

[See the poster by Samanta and Schmitt, August 21, 2017].



Dark Matter

The standard model of cosmology indicates that the total mass–energy of the universe contains 4.9% ordinary matter, 26.8% dark matter and 68.3% dark energy.

A dark star composed mostly of normal matter and dark matter may have existed early in the universe before conventional stars were able to form.

The neutron stars could capture weakly interacting dark matter particles (WIMPs) because of their strong gravitational field, high density and finite, but very small, WIMP-to-nucleon cross section. Such kind of dark-matter-admixed neutron stars could explain the measurement of the Shapiro delay in the radio pulsar PSR J1614-2230, which yielded a neutron star mass of $1.97 \pm 0.04 M_{\odot}$. [Ang Li et al., Astro. Phys. 37, (2012)70].

Eur. Phys. J. C (2017) 77:440
DOI 10.1140/epjc/s10052-017-5006-3

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Compact bifluid hybrid stars: hadronic matter mixed with self-interacting fermionic asymmetric dark matter

Somnath Mukhopadhyay[1,a], Debasis Atta[1,2,b], Kouser Imam[1,3,c], D. N. Basu[1,d], C. Samanta[4,e]

We consider the dark matter particle mass of 1 GeV, explore the conditions of equal and different rotational frequencies of nuclear matter and dark matter, and find that the maximum mass of differentially rotating stars, admixed with self-interacting dark matter, to be ~1.94 M_O with radius ~10.4 km.

Thank you!