Triton Clustering in Neutron Rich Nuclei

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This talk is based on the following work:

1. A A Usmani, S A Abbas, U Rahaman, M Ikram, F H Bhat, "The role of the elemental nature of A = 3 nuclei in neutron-rich nuclei", Int J Mod Phys, E27 (2018) 1850060
2. S A Abbas and F H Bhat, "Triton Clustering in Neutron Rich Nuclei", arXiv:0902.9299 [nucl-th]
3. S A. Abbas, "Quarks in Neutron Halo Nuclei, Nuclear Clusters, and Nuclear Molecues", Mod. Phys. Lett. A 16 (2001) 755
4. S A Abbas, "Structure of A=6 Nuclei: 6-He, 6-Li, 6-Be", Mod. Phys. Lett. A 19 (2004) 2365
5. S A Abbas, "New Proton and Neutron Magic Numbers in Neutron-Rich Nuclei" Mod. Phys. Lett. A 33 (2005) 2553
6. S. A. Abbas and S. Ahmad, "A=3 Clustering in Nuclei", Int. J. Mod. Phys. E 20 (2011) 2101

Also see:

7. S. A. Abbas, "Group Theory in Particle, Nuclear, and Hadron Physics", (CRC Press, Boca Raton, Florida, 2016).

Plan of presentation-

Introduction

- Experimentalists are producing huge amount of interesting data related to neutron rich nuclei.
- New information : neutron halo structure, nuclear molecules, new magicities, emission of new and novel clusters, etc.
- Big challenge for theorists.
- Are we forced to go beyond the conventional nuclear language? Indeed, it seems to be so!
- In nuclear physics today the experimentalists are leading and theory has been unable to match the kind of innovation and foresight that these experiments are demanding.
- Here we take a global perspective and analyze the experimental data first, to seek new patterns, and then try to find hidden systematic structure within it; and next, analyze the systematics in a mathematically and physically consistent manner.

Evidence of Triton Clustering in Nuclei

•The light N=Z nuclei with A=4n, n=1,2,3,4... may be treated as being composed of n-α clusters. So 12-C is made up of 3-α clusters, and 16-0 of 4-α clusters. The initial motivation for such cluster srtucture came from the binding energy of these alpha-composite nuclei indicated presenec of these clusters inside these nuclei.

• Similarly, is it possible that we may have tritonic clusters sitting inside N=2Z nuclei, i.e. ${}^{3Z}_{Z}X_{2Z}$ nuclei, making it a bound state of Z-number of tritons $({}^{3}_{1}H_{2})$. So e.g. ^{9}Li is 3-trtons ${}^{12}Be$ is 4-tritons, ^{24}O is 8-tritons and ${}^{27}F$ is 9-tritons.
We write the binding energy of these N = 2 Z nuclei as

$$E_B = 8.48n + Ck \tag{1}$$

where 8.48 MeV is the binding energy of ${}^{3}_{1}H_{2}$. We take these n-cluster of tritons as forming k bonds and with C as inter-triton-bond energy. We are assuming here the same geometric structure of clusters in these nuclei as conventionally done for α - clusters in A=4n nuclei. So all numbers arise from similar configurations.

Table : Inter-triton cluster bond energy of neutron-rich nuclei.

Nucleus	n	k	E_B-8.48n(MeV)	C(MeV)
^{9}Li	3	3	19.90	6.63
^{12}Be	4	6	34.73	5.79
^{15}B	5	9	45.79	5.09
^{18}C	6	12	64.78	5.40
^{21}N	7	16	79.43	4.96
^{24}O	8	19	100.64	5.30

Note that inter-triton cluster energy is about the same at a value of about 5.4 MeV.

^{42}Si as made up of 14-triton clusters still has inter-triton cluster energy of about 5.4 MeV.

So this picture (just as it was vealid for the alpha case) is valid for these neutron rich nuclei.

Next, a strong experimental evidence supporting the existence of triton- and helion-clusters in nuclei. Let us look of the possible existence of helion and triton clusters in ^{6}Li nuclei.

Indeed the same has been very convincingly demonstrated through **direct trinucleon knockout - both triton and helion**, from ^{6}Li via exclusive electron reaction [Connelly et. al, Phys Rev C57(1998)1569].

Mirror reactions $^6\mathrm{Li}(\mathrm{e},\mathrm{e}'^3\mathrm{He})^3\mathrm{H}$ and $^6\mathrm{Li}(\mathrm{e},\mathrm{e}'^3\mathrm{H})^3\mathrm{He}$ were measured. The momentum transfer dependence was found to be in complete disagreement with the fundamental spectrum of a direct-single nucleon knockout.

On the other hand the momentum dependence was in good agreement with a direct A=3 knockout mechanism
This clearly demonstrated that h- and t- clusters existed as primary entities in ^{6}Li.

$SU_{\mathcal{A}}(2)$ Nusospin Group

- So there are convincing evidences from studies in nuclear physics, which treat the (h,t) pair as elementary. Within the sphere of low energy nuclear structure studies, a new group $SU_{\mathcal{A}}(2)$ called nusospin has been proposed by me. Just as one takes the pair (p,n) as forming the fundamental representation of the nuclear SU(2) isospin group, in the same manner one hypothesizes that the pair (h,t) forms the fundamental representation of the new nusopin $SU_{\mathcal{A}}(2)$ group.
- This idea appears to hold good [Abbas, 2001, 2004,2005]. For example nusospin group predicts new magic numbers of the (Z,N) pair of (4,8), (6,12), (8,16), (10,20) [Abbas, 2005], and binding energy data bears it out.
- Support for the nusospin group also comes from the EPM model in particle physics (as we see below), for the $SU_{\mathcal{A}}(2)$ nusospin group. All this justifies the treatment of the pair (h,t) as a fundamental entity.

Experimentally there is a hole at the centre of ^3H, ^3He and ^4He [ref. 3] making these as more compact and extra-stable. And thus these may be treated as "tennis -ball" like nuclei. Similarly we expect that compact tritons too would make clusters like 9-Li. 12-Be etc. more stable and tennis ball like. Thus extra neutrons attaching to these "tennis-ball" like nuclkei would appear as "halos". Thus 11-Li is 2-neutron halo outside stable and compact 9-Li.

Thus this model predicts that 11-Li, 14-Be, 17-B, 20-C, 23-N, 26-O etc should be 2-neuron halo nuclei.

Indeed, these are good predictions - being varified by experiments. It also predicts which nuclei should appear as 2-neutron halo nuclei!

This triton cluster model can resolve many puzzles arising from within the conventional model structures!

It has been found that the doubly magic nucleus ^{28}O is unbound and in fact the heaviest isotope of oxygen is ^{24}O. On the other hand adding just one more proton to oxygen leads to a very neutron rich bound state of ^{31}F. Both these results are puzzling. As stated by Sakurai [Eur.Phys.J.A13(2002)49], "It is remarkable that six additional neutrons can be bound by moving from oxygen to fluorine, where Z differs by one. The sudden change in stability from oxygen to fluorine indicates an extra push of stability for the very neutron-rich fluorine isotope". The reason for this "extra push" is not understood [2], a consistent description of all these effects, in the same theoretical framework, is sadly lacking.

However, the above puzzle is consistently resolved in our triton model.

First look at ^4He. It is an exceptionally bound nucleus and its binding energy is already saturated. it does not allow extra nucleons to be bound to it. In fact the next bound even-even nucleus after ^4He is actually ^{12}C. So extra-stability and saturation translates into lack of interest in interacting with other nucleons to form bound structures.

As we shall show below , ^{24}O is such a strongly bound system of eight tritons. In fact we show that it is "magic" nucleus of 8-tritons. Thus as for 4-He, it does not allow any more neutrons to bind to it.

And this is why the "putative doubly magic nucleus ^{28}O" is predicted to be bound by conventional models, is predicted to be unbound by our triton model. And so is it empirically!

Also the fact that $^{27}_{9}F_{18} = 9^3_1H_2 = 3^9_3Li_6$ and so $^{31}_{9}F_{22} = ^{27}_{9}F_{18} + 4n = 3^9_3Li_6 + 4n$. 9-tritons, as such would be willing to add 4-extra neutrons as halo in the bound state ^{31}F.

Hence it appears that this feature of oxygen and fluorine is a result of the reality of triton clustering in the neutron-rich isotopes of these nuclei.

We follow up on this new structure and try to see if it may provide further understanding of the currently acquired rich empirical information on the neutron rich nuclei.

The N $\sim$ Z nuclei are very well explained by the SU(2) isospin group with (p,n) pair providing basis for a description for these nuclei.

Now for the (h,t) pair of the $SU_{\mathcal{A}}(2)$ nusospin group, as these correspond to proton richer (with ^{3}He as base) and neutron richer (with ^{3}H as base) nuclei respectively, so these may be more directly useful for the studies of proton rich and neutron rich nuclei. Due to the Coulomb interaction, as nature prefers to create neutron rich nuclei, we study these in more detail here.

As the nuclear SU(2) isospin generates and validates the shell model structure of N $\sim$ Z nuclei, we extrapolate this logic to find a suitable shell model structure generated by and validated by the $SU_{\mathcal{A}}(2)$ nusospin group. We have already seen how the nusospin group predicts new magic numbers of the (Z,N) pair of (4,8), (6,12), (8,16), (10,20). So it is logical to assume that there may be a different shell structure associated with this new group.

One-proton and one-neutron (as well as two-proton and two-neutron) separation energies play an important role in determining magic numbers and we pursue similar ideas. This is mostly within the framework where SU(2) symmetry based on elementarity of the (p,n) pair is basic.

We extrapolate this idea to the $SU_{\mathcal{A}}(2)$ nusopin with the (h,t) pair forming elemental entities. Thus, we should be able to talk of one-triton, two-triton separation energies in neutron rich nuclei while treating these as made of tritons as elementary entities.

EPM model and Triton clustering

The phenomenological Elementary Particle Model (EPM) of Kim and Primakoff (1965) treats the pair $(^3\mathrm{He}, ^3\mathrm{H}) \simeq (\mathrm{h}, \mathrm{t})$ as elementary. In analogy with the corresponding nucleon weak currents, EPM parametrizes the nuclear charge-changing currents in terms of the trinucleon form factors. Amazingly this is found to give as good a result as those obtained with more complicated composite structures for the ground state in nuclear microscopic models.

For example, EPM has been successful in understanding μ^- weak capture on ^{3}He, $\mu^- + ^3\mathrm{He} \rightarrow ^3\mathrm{H} + \nu_\mu$. It matches the experimental results as well as the more elaborate and extensive microscopic calculations where full nuclear wave function which arise from realistic two- and three-body interaction terms are used.

Using EPM, Mintz (1973) studied the reaction,
$\mu^- +^6$ Li $\rightarrow^3$ H $+^3$ H $+ \nu_\mu$. Taking clue from the GSW model,

$$\begin{aligned} & <^3 \mathrm{H}(1),^3 \mathrm{H}(2), \nu | \mathrm{H}_{\mathrm{W}}^{(0)} |^6\mathrm{Li}, \mu^- > \\ = \quad & \frac{G \cos\theta_c}{\sqrt{2}} \bar{u}_\nu (1-\gamma_5) u_\mu <^3 \mathrm{H}(1),^3 \mathrm{H}(2) | J_\lambda^\dagger(0) |^6\mathrm{Li} >, \end{aligned} \tag{2}$$

$\cos\theta_c = 0.98$, θ_c Cabbibo angle, weak coupling constant G $= 1.02$ $\times 10^{-5} m_p^{-2}$, $J_\lambda(0) = V_\lambda(0) - A_\lambda(0)$. V and A are vector and axial vector part of the hadronic weak current.

Next, draw a parallel between the reactions $\mu^- +^6$ Li $\rightarrow^3$ H $+^3$ H $+ \nu_\mu$ and $\mu^- + d \rightarrow n + n + \nu_\mu$. The current matrix elements $< nn | \mathrm{A}_\lambda^\dagger(0) | d >$ and $< nn | \mathrm{V}_\lambda^\dagger(0) | d >$ thus have the same structure as $<^3 \mathrm{H}^3\mathrm{H} | \mathrm{A}_\lambda^\dagger(0) |^6\mathrm{Li} >$ and $<^3 \mathrm{H}^3\mathrm{H} | \mathrm{V}_\lambda^\dagger(0) |^6\mathrm{Li} >$, respectively. These are needed to evaluate the above matrix element in Eq. 1.

Relevant physically measurable quantities are determined in terms of four form factors which are obtained from data from reactions $\gamma +^6 \mathrm{Li} \rightarrow^3 \mathrm{H} +^3 \mathrm{He}$, $^3\mathrm{H} +^3 \mathrm{H} \rightarrow^6 \mathrm{Li} + \gamma$ and $\pi^- +^6 \mathrm{Li} \rightarrow^3 \mathrm{H} +^3 \mathrm{H}$ by using CVC and PCAC. This model is very successful in fitting the data, thus confirming the validity of the EPM.

Thus what we call nusospin model here in nuclear physics and what is called Elementary Particle Model in particle physics , are essentially talking about the **same physical reality of (h,t) being fundamental and elementary**, though using them in different framework of nuclear studies; the former one in nuclear strong interaction studies while the latter in the electro-weak studies. Their independent empirical successes basically are complementing each other.

Relativistic Mean Field Theory

- Many body system is very difficult to solve exactly, so main goal of mean field is to replace all interactions to any one-body with an average or effective interaction.
- Many body to one-body problem by choosing an one-body appropriate operator.

$$H = \sum_{i} T_i + \sum_{i<j} V_{ij}$$

$$H = \sum_{i} (T_i + O_i) + \sum_{i<j} (V_{ij} - O_i)$$

- If we neglect the effective term, then we get only one-body problem.
- This is the whole idea of mean field.

- RMF theory is a phenomenological model for the description of nuclear many-body problem.
- Its development is followed by relativistic quantum mechanics and relativistic quantum field theory.
- Dirac fields are quantized.
- Meson field operators are replaced by their expectation values, therefore it is called semi-classical theory.
- RMF approach which essentially is an extention of the original $\sigma - \omega$ model of Walecka.
- Degree's of freedom are :
  Dirac spinors, σ-meson scalar, ω-meson vector, ρ-meson iso-vector.

Basic formulation of RMF

This model describes the nucleus as a system of Dirac nucleons which interact via the exchanges of mesons and photon fields.
σ couples to the scalar density of baryons through $g_\sigma \bar{\psi}\sigma\psi$
and ω_μ couples to conserved baryon current through $g_\omega \bar{\psi}\gamma^\mu \psi \omega_\mu$.
The effective Lagrangian density for the present model is given as

$$\begin{aligned}
\mathcal{L} &= \bar{\psi}[i\gamma^\mu \partial_\mu - M]\psi + \frac{1}{2}\partial_\mu \sigma \partial^\mu \sigma - U(\sigma) - U(\omega) \\
&- \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} + \frac{1}{2}m_\omega^2 \omega_\mu \omega^\mu - \frac{1}{4}F^{\mu\nu}F_{\mu\nu} - g_\omega \bar{\psi}\gamma_\mu \omega^\mu \psi - g_\sigma \bar{\psi}\sigma\psi \\
&- g_\rho \bar{\psi}\gamma^\mu \tau \psi \rho_\mu - \frac{1}{4}R^{\mu\nu}R_{\mu\nu} - \frac{1}{2}m_\rho^2 \rho_\mu \rho^\mu - e\bar{\psi}\gamma_\mu \frac{(1-\tau_3)}{2}\psi A_\mu \, .
\end{aligned}$$

The model includes the nonlinear self-coupling for σ and ω-fields

$$U(\sigma) = \frac{1}{2}m_\sigma \sigma^2 + \frac{1}{3}g_2 \sigma^3 + \frac{1}{4}g_3 \sigma^4 \, .$$

$$U(\omega) = \frac{1}{2}c_4 (\omega_\mu \omega^\mu)^2 \, .$$

The quadrupole deformation parameter β_2 is extracted from the calculated quadrupole moments of neutrons and protons through

$$Q = Q_n + Q_p = \sqrt{\frac{16\pi}{5}}\left(\frac{3}{4\pi}AR^2\beta_2\right),$$

where $R = 1.2A^{1/3}$. The formulae of various rms radii are defined as

$$\langle r_p^2 \rangle = \frac{1}{Z}\int r_p^2 d^3r\rho_p \ ,$$

$$\langle r_n^2 \rangle = \frac{1}{N}\int r_n^2 d^3r\rho_n \ ,$$

$$\langle r_m^2 \rangle = \frac{1}{A}\int r_m^2 d^3r\rho \ .$$

The energy of the system is given by the expression

$$E = \int d^3r\mathcal{H}(r) = E_{part} + E_\sigma + E_\omega + E_\rho + E_c + E_{c.m.} \ .$$

Results of present work

One-proton and one-neutron (as well as two-proton and two-neutron) separation energies play an important role in determining magic numbers and we pursue similar ideas. This is mostly within the framework where SU(2) symmetry based on elementarity of the (p,n) pair is basic.

We extrapolate this idea to the $SU_{\mathcal{A}}(2)$ nusopin with the (h,t) pair forming elemental entities. Thus, we should be able to talk of one-triton, two-triton separation energies in neutron rich nuclei while treating these as made of tritons as elementary entities.

- First of all, we extract one- and two-triton separation energies, which may respectively be obtained as,

$$s_{1t} = B({}^{A}_{Z}X_{N}) - B({}^{A-3}_{Z-1}Y_{N-2}) - B({}^{3}_{1}H_{2})$$

$$s_{2t} = B({}^{A}_{Z}X_{N}) - B({}^{A-6}_{Z-2}Y_{N-4}) - 2B({}^{3}_{1}H_{2})$$

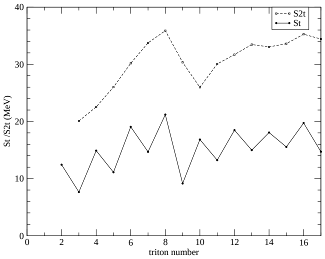

Figure : EXPERIMENTAL one- and two- triton separation energies. Data from: Wang,Audi,Kondev,Huang,Huand,Xu, Chin.Phys C41(2017) - highest here is 17-triton i.e. 51-Cl. NOTE - NO published data above this

Figure taken from: S. A. Abbas and F. H. Bhat, Triton Clustering in Neutron Rich Nuclei, arXiv:0902.9299 [nucl-th]
NOTE odd-even staggering. Clearly it is t-t PAIRING effect here.

So our 2009 paper (above) predicts that all ${}^{3Z}_{Z}X_{2Z} = Z^3_1H_2$ nuclei to be bound/stable states of tritons. More so for the even Z-number. **Hence 60-Ca as stable triton based nucleus was our unambiguos and UNIQUE PREDICTION of 2009. This has been CONFIRMED now in 2018**.

Taraspv et. al. PRL121,022501(2018) "Discovery of 60-Ca.", Discovered 47-P, 49-S, 52-Cl, 54-Ar, 57;59-K, 59;60-Ca, and 62-Sc.

- However as per our model prediction these nuclei have the tritonic strucrure as: 45-P=15-t,48-S=16-t,51-Cl=17-t,54-Ar=18-t,57-K=19-t,60-Ca=20-t,and 63-Sc=21-t. So their discovery CONFORMATION of our predictions: 54-Ar=18-t,57-K=19-t,60-Ca=20-t, so experimenatlist to look for 63-Sc=21-t as a bound state. Our model also says that their 47-P=(45-P)+2n, hence it is 2-neutron halo around a compact/closed 45-P nucleus. Similarly nucleus 49-S is a 1-neutron halo outside a 48-P=16-t; and nucleus 52-Cl is a 1-neutron halo outside 51-Cl.
- **Hence our $SU_{\mathcal{A}}(2)$ Nusospin Group model is vindicated**.
- The EXPERIMENTALISTS are URGED to look for such unique predicstions of our model.

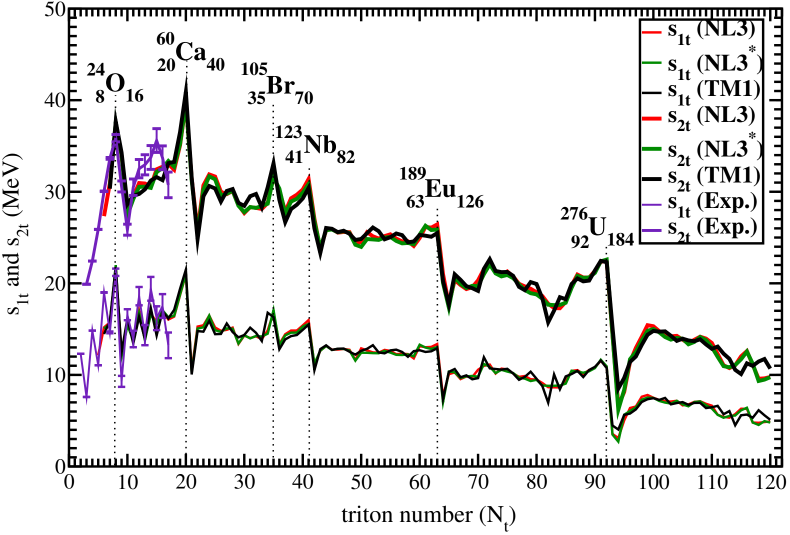

Figure : One- and two- triton separation energies in respect of Z=5 to 120 isotopes.

- The most prominent feature in Fig. 1 is the first peak shown by data and RMF both e.g., for N_t=8 *i.e.* for ${}^{24}_{8}O_{16}$ and an equally sharp dip for N_t=9 i.e., for ${}^{27}_{9}F_{18}$.
- Besides limited experimental data the vast RMF results clearly show N_t=8, 20, 35, 41, 63 and 92 as magic numbers, which correspond to N =16, 40, 70, 82, 126 and 184.
- In Ref.[1], the magicity at $N = 184$ is associated with $Z = 120$; that is ${}^{304}_{120}X_{184}$. The $N = 184$ magicity in our work is however true only for $Z = 92$. This $N = 2Z$ link is basic in our work.

[1] J. J. Li, W. H. Long, J. Margueron, N. V. Giai, Phys. Lett. **B 732**, 169(2014).C

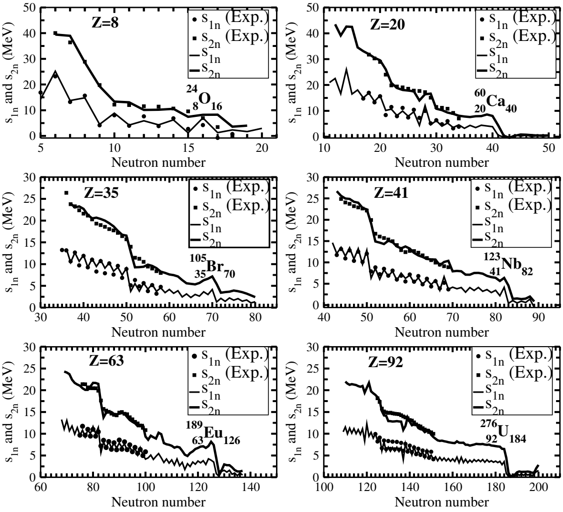

Figure : One- and two-neutron separation energies (s_{1n} and s_{2n}, respectively) for the isotopes of the newly identified magic nuclei in Fig-1.

- The magic nuclei that appear in the triton picture are ${}^{24}_{8}O_{16}$, ${}^{60}_{20}Ca_{40}$, ${}^{105}_{35}Br_{70}$, ${}^{123}_{41}Nb_{82}$, ${}^{189}_{63}Eu_{126}$ and ${}^{276}_{92}U_{184}$.
- Are these magic nuclei an effective manifestation of proton and neutron magic numbers?
- We investigate it in Fig. 2, wherein we plot one- and two-neutron separation energies. This figure shows that for N = 40, 70, 82, 126 and 184 there is a sharp fall indicating magicities at $Z = N/2$ i.e., triton numbers N_t=20, 35, 41, 63 and 92.
- We also note that ${}^{24}_{8}O_{16}$ is a magic nucleus, which is in line with the findings of the study[2].
- We conclude that for the heavier nuclei with large number of neutrons, it is neutrons which decide the effective magicities in terms of tritons, and for lighter nucleus like ${}^{24}_{8}O_{16}$, it is protons which play this role.

[2] A. Ozawa, T. Kobayashi, T. Suzuki, K. Yoshida and I. Tanihata, Phys. Rev. Lett. **84**, 5493(2000).

- In Fig. 3, we plot binding energy per nucleon for all the ${}^{A=3Z}_{Z}X_{N=2Z}$ nuclei studied here.
- It too shows clear magicities of the same set of nuclei: ${}^{24}_{8}O_{16}$, ${}^{60}_{20}Ca_{40}$, ${}^{105}_{35}Br_{70}$, ${}^{123}_{41}Nb_{82}$, ${}^{189}_{63}Eu_{126}$ and ${}^{276}_{92}U_{184}$.
- This consolidates our assertions above on new magicities.

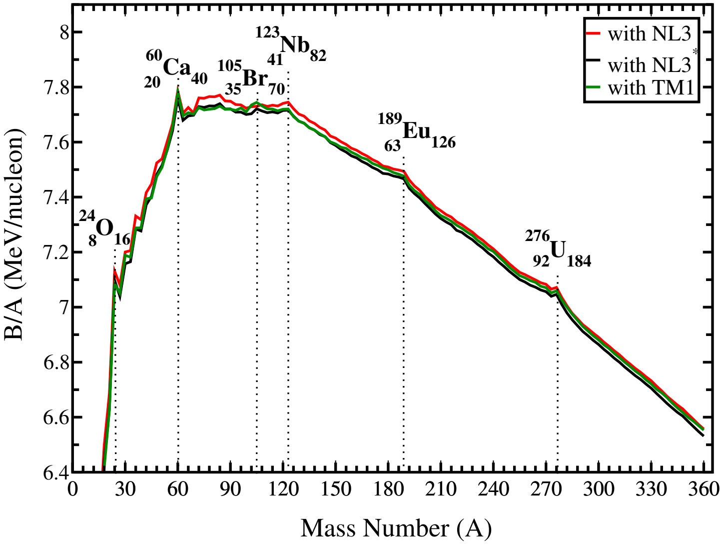

Figure : B/A for $^{A=3Z}_{Z}X_{N=2Z}$ nuclei

Summary

- There are good empirical reasons to believe that ${}^{3Z}_{Z}X_{2Z}$ nuclei masy be tresated as bound state of Z-number of tritons.
- By treating the (h,t) pair as elementary, a new group $\mathrm{SU}_{\mathcal{A}}(2)$ called nusospin, has been proposed by me. Just as one takes the pair (p,n) as forming the fundamental representation of the nuclear SU(2) isospin group, similarly one hypothesizes that the pair (h,t) forms the fundamental representation of the new nusopin $\mathrm{SU}_{\mathcal{A}}(2)$ group.
- The EPM results are found to be as good as those obtained from nuclear microscopic models using two- and three-body forces.
- Thus what we call nusospin model here in nuclear physics and Elementary Particle Model in particle physics , are essentially talking about the **same physical reality of (h,t) being fundamental and elementary**, though using them in different frameworksl; the former one in nuclear strong interaction studies while the latter in the electro-weak studies. Their independent empirical successes basically are complementing each other.

- We extend this concept to investigate the validity of the elemental nature of $A = 3$ nuclei through studies of nuclear structure of neutron-rich nuclei.
- By treating neutron-rich nuclei as primarily made up of tritons as its building blocks, we extract one- and two-triton separation energies of these nuclei.
- Clear evidence arises of a new shell structure with well-defined predictions of new magic nuclei.
- These unique predictions have been consolidated by standard one- and two-neutron separation energy calculations.
- The BE/A plots of these nuclei also confirm these predictions.
- We make unambiguos prediction of six magic nuclei: ${}^{24}_{8}O_{16}$, ${}^{60}_{20}Ca_{40}$, ${}^{105}_{35}Br_{70}$, ${}^{123}_{41}Nb_{82}$, ${}^{189}_{63}Eu_{126}$ and ${}^{276}_{92}U_{184}$.
- The triton picture of $N = 2Z$ nuclei as well as conventional studies of one- and two-neutron seperation energies indicate magicity of some special nuclei, e.g., ${}^{24}_{8}O_{16}$, ${}^{60}_{20}Ca_{40}$, ${}^{105}_{35}Br_{70}$, ${}^{123}_{41}Nb_{82}$, ${}^{189}_{63}Eu_{126}$ and ${}^{276}_{92}U_{184}$.
- The superheavy nucleus ${}^{276}_{92}U_{184}$, may be accessible to experimental confirmation due to its small charge, $Z = 92$.