Quantum Chromodynamics based model: a new perspective on halo-structure and new-magicity in exotic nuclei

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Abstract

A quite recent, ingenious experimental paper (Raabe et al., Nature 431 (2004) 823), studied fusion of an incoming beam of halo nucleus ^6He with the target nucleus ^{238}U. They managed to extract information which could make basic discrimination between the structures of the target nucleus (behaving as standard nucleus with density distribution described with canonical RMS radius r = $r_0 A^{\frac{1}{3}}$ with r_0 = 1.2 fm), and the **"core"** of the halo nucleus, which surprisingly, does not follow the standard density distribution with the above RMS radius. This provides unambiguous and strong support for a Quantum Chromodyanamics based model structure, which shows as to how and why the halo structure arises. This model succeeds in identifyng all known halo nuclei and also makes clear-cut and unique predictions for new halo nuclei. It also provides a consistent and unified understanding of what is imlied for the emergence of new magic numbers in the study of exotic nuclei. It is triton clustering, as apparent from experimental data on neutron-rich nuclei, which guides us to this new model. It provides a new perspective, of how QCD leads to a consistent understanding of the nuclear phenomenon, both of the $N \sim Z$ nuclei, and of those which are far away from this limit.

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Within the framework of the studies of neutron rich nuclei, it is of great importance to know whether fusion of nuclei involving weakly bound particles is enhanced or not. We look at the experimental data in this connection, and try to extract some basic structures which these ingenious experiments are trying to point out to us.

Raabe et al. [1] fired both ^4He and 2-neutron halo nucleus ^6He onto the target nucleus ^{238}U. In agreement with an earlier experiment [2], they did obtain a much increased product with the above neutron halo beam. These large yields due to fission, may be attributed to fusion of ^6He on the target-nucleus. However, the same may be due to a transfer of neutrons from ^6He, first onto ^{238}U, and thereafter a fission from this fattened nucleus. The earlier experiment [2] was unable to distinguish between these two. Raabe et al. [1] cleverly, were able to distinguish between the above two physically possible occurrences. If a fission event was detected in coincidence with an ^4He, it was identified with the transfer case, while one without an accompanying ^4He, was attributed to complete fusion. Remarkably, they demonstrated clearly, that the large fission yields do not result from fusion with ^6He, but from neutron transfer. Thus the **"core"** of the projectile nucleus sees a targer nucleus which has "eaten and digested" the halo neutrons [3]. So what is amazing here, is the new phenomenon of fusion only of the projectile "core" with a neutron-fattened target nucleus, which may itself be in an excited state [3].

What is this experiment trying to tell us? Using Ockham's razor, what it is telling us is that though the 2-neutron halo is weakly bound with the **core** ^4He in ^6He, it is strongly attracted to the target nucleus. Hence minimal requirement is that the **"core"** of the halo, and the **"target"** itself, should differ from each other, is some minimal significant manner. Now we know that the density distribution of the standard nuclear medium is given by the RMS radius r = $r_0 A^{\frac{1}{3}}$ with $r_0 = 1.2$ fm). This is definitely true of the target nucleus ^{238}U. And as the two neutrons (from the projectile nucleus) feel strong nuclear attraction with it, we would expect that the neutron fattened target nucleus would be a standard (though perhaps excited) nucleus with density distribution conforming to the above standard nuclear RMS radius. This means that, therefore, the **"core" of the projectile nucleus should be different from the initial target nucleus**, in some fundamental manner. Note how this fusion experiment allows us to talk of the density distribution of the "core" of the whole halo nucleus. The beauty of

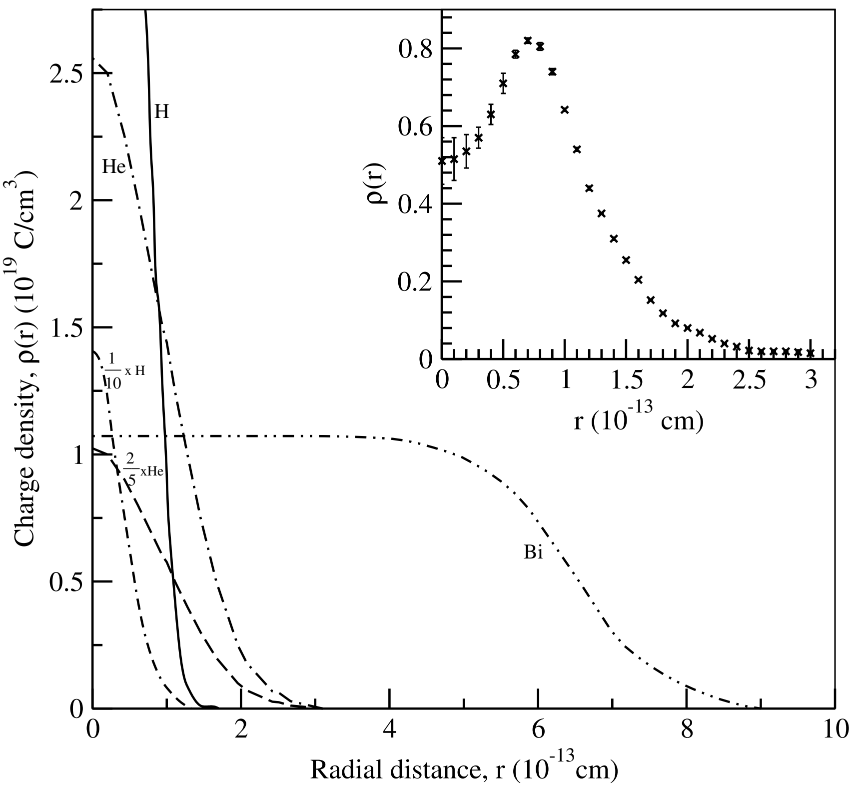

Figure 1: Schematic density distributon of nuclei as determined by electroc scattering. Inset shows the same from a better experiemnt - showing a marked "hole" at the centre.

this experimental analysis by Raabe et al. [1], is that it is allowing us to separate out the structure of the core-nucleus itself, which is sitting within the whole halo nucleus. But what does it mean?

I would like to draw the reader's attention to the density distribytion as was extracted from the classical electron scattering on nuclei. This is plotted in Fig. 1 here. These are well known figures. What is most significant is that the central density of ^4He is about 2.5 times higher than that of heavy nuclei like bismuth, lead etc.. In fact, ^3He has similar density distribution as that of ^4He. Not only that, as determinded from meticulous electron scattering experiemts, both ^4He and ^3He have a "hole" (the central significant depression near $r \rightarrow 0$) at the centre. This is plotted in the inset of Fig. 1 [4,5]. It is known that light nuclei are basically "all surface". Because of the central hole, this is more pronounced for these two nuclei. As to matter distribution of ^3H, it is very much the same as that of ^3He.

Now to understand the fusion process of neutron halo beam, forced us to conclude logically, using the Ockham's Razor based argument, that the core of the projectile nucleus should be different from the target nucleus in some fundamental manner. This can now be extracted from a study of Fig. 1. The much-bigger-in-magnitude "surface-nature" of density distribution of ^4He, should be the reason of this "fundamental-manner-difference", between the target and the core of the projectile nucleus.

But is there a theoretical model which brings out this unique aspect of the above reality? Indeed, there exists a model suggested in 2001, which precisely does that [6].

Arguments originating from Quantum Chromodynamics, have allowed us to provide an understanding of this phenomenon. The author thus arrived at a model which could explain all halo nuclei and provide clearcut preditions for many more halo nuclei - which were later discovered, and thus validating this model [6,7,8,9,10]. It also provided a new symmetry stucture for this stucture and showed how and why the new magic numbers arise. For the sake of completeness and also due to the fact that most nuclear physicists (both theorists and experimentalists) are likely to be unaware of it, we discuss the essential points of this model in the Appendix. The reader is invited to glance through it, so as to be able to appreciate its basic arguments, and how it is successful globally, to explain the halo phenomenon, and the new magic numbers, which arise in the exotic nuclei.

So it is the central depression and high density on the surface of A=4 nucleus ^4He and A=3 nuclei ^3He and ^3H, which singly or collectivey play a major defining role in forming the core of halo nuclei. Any collections of these, shall also be a nucleus with central density depression and surface enhancement (labeled as "tennis-ball" like nucleus - see Appendix). ^9Li be treated as made up of 3 ^3H clusters and which should have hole at the centre. As per our model, therefore, ^{11}Li would be a two-halo-neutrons sitting outside a compact core of ^9Li, which is made up of three tritons. Similarly e.g. $^{17}B, ^{19}C$, *etc* would be neutron halo nuclei and so on. These specific predictions of 2001 have been confirmed in later years [14].

Still more heavy nucleus ^{31}Ne, predicted to be one neutron-halo as per our model, found experimental confirmation in 2009 [15]. Still heavier nucleus ^{37}Mg, was found to be a one neutron halo nucleus in 2014 [16], one more confirmation of our model. All this provides clear and unambiguos support to our model. ^{37}Mg remains the heaviest halo nucleus discovered so far. However our model predicts many more and experimentalists are urged to look for those.

Next, the puzzling issue of discovery of emergence of new magic numbers like N=16, 32, 34 etc., and the destruction of the old ones like N=20, 28 etc.[17]. Our model is singularly successful in explaining these also.

To understand the new magicities within the structure of our above triton cluster model, using the best compiled empirical published data available then, we plotted [8] the one-neutron and two-neutron separation energies both as a function of neutron number N as well as that of proton number Z. Also we did the same for one-proton and two-proton separation energies as well. This was done for light nuclei, where data does appear to span N=2Z region in several cases. The aim was to see what the experiments are telling us through a sytematic analysis of the data. We found that whenever the proton number and neutron number pair (Z,N) was (4,8), (6,12), (8,16), (10,20), (11,22), (12,24); then these nuclei displayed extra stability or magicity. Thus clearly these N = 2Z nuclei do appear to display new magicities.

Such explicit exposition of structural symmetry seems to be demanding an underlying group. This was indeed suggested as a new group $SU_{\mathcal{A}}(2)$ called the "nusospin" group [7,8]. 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) (helion h is ^{3}He, and triton t is ^{3}H) forms the fundamental representation of the new nusospin $SU_{\mathcal{A}}(2)$ group.

Just as the SU(2)-isospin group forms the basis for the shell model of the Independent Particle Model in nuclear physics, let us assume that the $SU_{\mathcal{A}}(2)$ nusospin group also forms a basis of a new shell structure, which may be dispalyed say, for the appropriate neutron rich nuclei.

Hence we are treating all $^{3Z}_{Z}X_{2Z}$ nuclei as being a bound state of Z-number of tritons ($^{3}_{1}H_{2}$). Viewed in this manner, the relevant degree of freedom is tritons, treated as "elementary" entities. Let us pick and knock out a single triton from this unique bound state of tritons. This is clearly a single-triton separation energy defined as

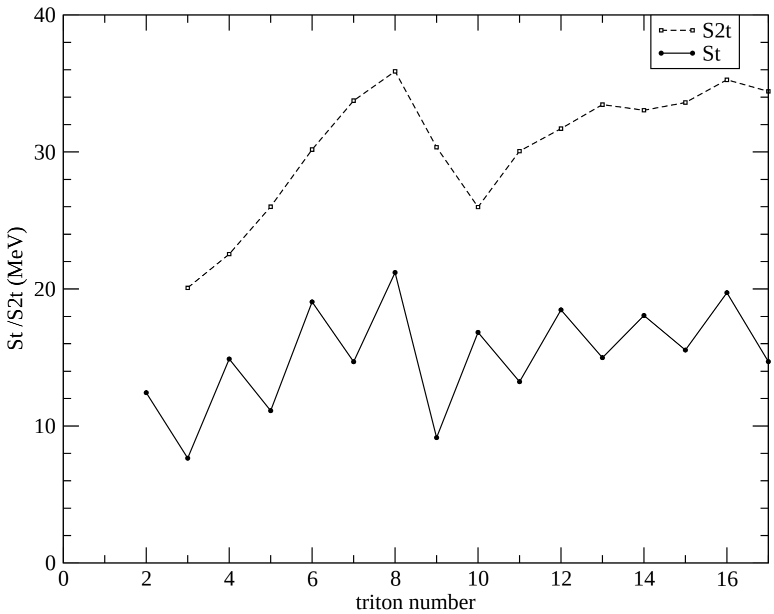

Figure 2: Experimental one- and two-triton separation energies.

$$S_t = \text{BE(Z,N)-BE(Z-1,N-2)-BE(t)}$$

Similarly for two-triton separation energy as well. One plots S_t and S_{2t} as a function of the number of tritons. Note e.g. triton number 8 would correspond to the nucleus ^{24}O. In 2009 we took the best experimental data available then [18], and we plot here the same as Fig. 2. Note, no published data above 17-triton i.e. 51-Cl.

We observe clear-cut [18] even-odd effects in triton numbers. Whenever triton number was even, the triton separation energy was significantly higher than the adjoining odd triton numbers. This feature is similar to the odd-even effects seen in one neutron and one proton separation energies plotted with respect to the neutron and proton numbers respectively. Therein that is conventionally understood as evidence for identical particle n-n and p-p pairing in nuclei.

Howeve, the odd-even effect seen here in Fig, 2 cannot be attributed to identical nucleon n-n or p-p pairing. Here we are forced to attribute it to two triton pairing i.e. a t-t pairing effect, in these triton constituent nuclei.

Note that the pairing n-n and p-p, necessarily arises from a shell structure, wherein n-n and p-p are most strongly paired if they are in the same shell. This analogy can be carried over to the bound states of triton in our example here as well. Two tritons in the same shell seem to be strongly paired, thereby leading to a stronger binding with respect to a single unpaired triton.

The next most prominent feature was the highest peak in the separation energy for N_t=8, i.e. for ^{24}O and an equally sharp dip for N_t=9 , i.e. for ^{27}F.

We know that such drops in one-neutron and one-proton separation energies when going from one Z/N number to the next one, is a signal of magicity character of a particular Z/N number. In the context of our discussion here, magicity means a much stronger binding for a particular number of tritons as compared to the adjoining number of tritons. Hence clearly here N_t=8 is a magic number with respect to different bound states of tritons. So clearly there exists a shell structure of the bound states of tritons and wherein there is a large extra stability for N_t=8, which indicates magicity for this nucleus.

Recently Kanungo et al. [19] have reported strong evidence indicating that 24-O is a doubly-closed magic-number nucleus. It turns out that 24-O is as good a doubly magic nucleus as 16-O is. In fact one may find similarity of strength of ^4He magicity in 24-O as being akin to that of the doubly magic nucleus 4-He. 4-He is so stable that it does not allow other neutrons to add to it easily. So much so that the next stable even-even nucleus is 12-C. In the same manner the strong double magicity of 24-O prevents 28-O (with conventional N=20 being magic) to be even bound [15]. This is a strong vindication of our triton cluster model structure here.

The data did not go upto N_t=20 in 2009 [18]. But clearly as per our model, we predicted that that the next doubly magic nucleus would be ^{60}Ca, as a bound state of twenty tritons. This prediction has now been experimentally confirmed recently in 2018 [20]. This should be treated as a smoking-gun evidence in support of our model.

The above [18] was a systematic analysis of the experiemntal data in support of our nusospin group idea, and that of triton clustering in neutron-rich nuclei. Recently we have employed very successful relativistic mean field (RMF) models with latest interactions like NL3*, NL3 and TM1 to calculate binding energies of nuclei with N=2Z [21]. This is extension of what we did in 2009 [18] with RMF model calculations. We have predicted [19] six prominent magic nuclei: ${}^{24}_{8}\mathrm{O}_{16}$, ${}^{60}_{20}\mathrm{Ca}_{40}$, ${}^{105}_{35}\mathrm{Br}_{70}$, ${}^{123}_{41}\mathrm{Nb}_{82}$, ${}^{189}_{63}\mathrm{Eu}_{126}$ and ${}^{276}_{92}\mathrm{U}_{184}$. The available experimental observations match with the RMF results. We also obtained, in standard conventional manner, one-neutron and two-neutron separation energies for the isotopes of these newly identified magic nuclei in order to understand the role played by neutron and proton magic numbers, and to investigate if these magicities are being translated into triton magic numbers for N=2Z nuclei. The standard binding energy per particle plot for all the N=2Z≤240 nuclei too predicts the same magic nuclei as obtained by extracting one- and two-triton separation energies [21]. This strengthens our confidence in the $\mathrm{SU}_{\mathcal{A}}(2)$ nusopin group.

The successful application of the structures arising from proper interpretation of the empirical lack of enhancement of fusion probability with ${}^{238}U$ by the neutron halo of ${}^{6}He$, leads to unambiguos support to our QCD based model. At the base sits the prediction of a prominent "surface-structure" in the density distribution of the core of all the halo nuclei. In the light of recent exciting work of experimentally determining the density distribution of halo nuclei with electron scattering (as emphasized by Bertulani [22]). We look forward to advaced precisions in these experiments, which will allow them to see the central density depression or a "hole" in these neutron-rich nuclei, as uniquely predicted by our model.

Hence we see that there are two independent SU(2) groups. isospin and nusospin, which provide two independent shell-model structures. These are

$$SU(2)_I \;\; with\; fundamental\; representation \quad N = \begin{pmatrix} \psi_p \\ \psi_n \end{pmatrix} \tag{1}$$

and

$$SU(2)_{\mathcal{A}} \;\; with\; fundamental\; representation \quad T = \begin{pmatrix} \psi_h \\ \psi_t \end{pmatrix} \tag{2}$$

It is reasonable to suggest the following enlarged group structure

$$SU(4)_{I\mathcal{A}} \supset SU(2)_I \bigotimes SU(2)_{\mathcal{A}} \tag{3}$$

with fundamental representation given by

$$\Psi = \begin{pmatrix} \psi_p \otimes \psi_h \\ \psi_p \otimes \psi_t \\ \psi_n \otimes \psi_h \\ \psi_n \otimes \psi_t \end{pmatrix} \tag{4}$$

This helps us in resolving a puzzle in the structure of ${}^4_2He_2$ nucleus. It is now well known [23], that contrary to expectations, the ground state of ${}^4_2He_2$ contains very little of deutron-deutron configuration; and the same is actually built upon h-n and t-p configurations [23]. It is a puzzle as to how come the first excited state of this even-even nucleus is another 0^+ with T=0 state (the same as the ground state) at a high value of 20.2 MeV. However this finds a natural explanation in our model. The wave functions of the ground state and the first excited state of ${}^4_2He_2$ in our model is naturally given as

$$\Psi_{gs} = \frac{[\psi_n \otimes \psi_h - \psi_p \otimes \psi_t]}{\sqrt{2}} \tag{5}$$

$$\Psi_{20.2} = \frac{[\psi_n \otimes \psi_h + \psi_p \otimes \psi_t]}{\sqrt{2}} \tag{6}$$

Note however that in eqn. (4), the states $\psi_p \otimes \psi_h \sim {}^4_3Li_1$ and $\psi_n \otimes \psi_t \sim {}^4_1H_3$, both of which do not exist. Hence the $SU(4)_{I\mathcal{A}}$ is broken; but clearly, still the wave functions for 4-He as given in eqns. (5) and (6) do hold good. Thus for nuclei going beyond 4-He, one would expect that the group would be $SU(2)_I \otimes SU(2)_{\mathcal{A}}$. This will allow for the observed small deuteron-deuteron admixtute [23, see Table 3.1], as per the group $SU(2)_I$ of the product group $SU(2)_I \otimes SU(2)_{\mathcal{A}}$.

One would expect that of the product group $SU(2)_I \otimes SU(2)_{\mathcal{A}}$, the group $SU(2)_I$ would be predominant for nuclei with $N \sim Z$, and the group $SU(2)_{\mathcal{A}}$ for nuclei far from this limit. And for other intermediate cases, the whole product group shall manifest itself.

We know that the isospin symmetry $SU(2)_I$ group holds good for $N \sim Z$ nuclei where the standard magic numbers are N/Z = 2, 8, 20, 28, 50, 82.. . Let us understand how the new magic numbers, in exotic neutron rich nuclei, arise within our model here.

Note that the one triton separation energy S_t, as plotted in Fig. 2 have much higher value than the corresponding one neutron separation energy S_n, of the same nucleus. Thus for all (both even or odd) triton cluster nuclei $S_t >> S_n$. So e.g. the empirical values of ${}^{24}_{8}\mathrm{O}_{16}$ for $S_t = 21.691\ MeV$ while $S_n = 4.211\ MeV$. This is true of all triton cluster dominant nuclei, treated as ${}^{3Z}_{Z}X_{2Z} = Z\ {}^{3}_{1}H_2$, as per the nusospin group $\mathrm{SU}_{\mathcal{A}}(2)$. Hence the pair (Z,N)=(8,16) are magic. This was discussed in detail by the author in Ref. [8]. Hence N=16 is magic in conjunction with Z=8. However N=16 will manifest itself as a new magic number even for nuclei with other proton numbers in the vicinity of Z=8 as well, due to the fact that for 24-O $S_t = 21.691 MeV >> S_n = 4.211 MeV$. This is what holds experimentally too [14,15,17]. Similarly for ${}^{60}_{20}Ca_{40} = 20\ {}^{3}_{1}H_2$, the magicity at N=40 would hold for Z=20, but also for other nuclei with proton numbers in the vicinity of Z=20.

Similarly nuclei ${}^{48}_{16}S_{32} = 16\ {}^{3}_{1}H_2$ and ${}^{51}_{17}Cl_{34} = 17\ {}^{3}_{1}H_2$ provide pair (Z,N) of new magic numbers, (16,32) and (17,34) respectively. However, The new N-number magicity would be so dominant that it will enforce magicity on neighbouring proton numbers other than the ones in the above pairs. Hence experimentally it is found that N=32 magicity holds good also for ${}^{53}_{21}Sc_{32}$ [24], as well as for ${}^{50}_{18}Ar_{32}$ [25]. Also the new magic number N=34, holds good for ${}^{54}_{20}Ca_{34}$ [26], and for ${}^{52}_{18}Ar_{34}$ [27].

This way, we may explain the existence of all the magic numbers discovered so far, and of course, also predict as to how more new ones may arise. This is a clear vindication of our model.

Ingenious experiments are continuing to expand our horizon, and are challenging theorists to match these amazing results with appropriate new perspectives. The success of our QCD based model here, both with respect to new halo nuclei and new magic numbers, demonstrates convincingly, that it indeed does provide that much needed "new perspective". It should be of help to both the experimentalists and the theorists, by providing them with an appropriate new language. This will allow them to analyze the amazing new results, which seem to be demanding such an expanded picture, which appears to be necessary to provide a consistent understanding of the "nuclear phenomenon" in its wholeness.

Appendix

As per Quantum Chromodynamics, the physically observed hadrons correspond to the colour singlet representation. So for a baryon in $3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$, of all the representattons, it is only the singlet which provides observable single baryons. All the other representations appear as spurious and unnecessary. But this may not be true for multiquark systems, where $8 \otimes 8 = 1 + ...$ and hence in 6-quarks this colour singlet representation may be present [10]. But in nuclear physics, we treat the sysytem as made up only of individual colour singlet protons and neutrons, with the commonly held belief that no quarks would show up in low energy nuclear physics; and only at sufficiently high energies, these may manifest themselves in terms of a Quark-Gluon-Plasma. However, this naive view is not correct. Even at low energies, quarks do place their identifiable imprints in a nucleus.

Deterons should have configurations where the two nucleons overlap strongly in regions of size $\leq 1fm$ to form 6-quark bags. Why is deuteron such a big and loose system? The reason has to do with the structure of the 6-q bags formed, had the two nucleons overlapped strongly. As per the colour confinement hypothesis of QCD, the 6-q wave function looks like:

$$|6q>= \frac{1}{\sqrt{5}}|1 \otimes 1> + \frac{2}{\sqrt{5}}|8 \otimes 8> \tag{7}$$

where '1' represents a 3-quark cluster which is singlet in colour space and '8' represents the same as octet in colour space. Hence $|8 \otimes 8>$ is overall colour singlet. This part is called the hidden colour because as per confinement ideas of QCD, these octets cannot be separated out asymptotically, and so manifest themselves only within the 6-q colour-singlet system. Group theoretically this part was found to be 80%, and this would prevent the two nucleons to come together and overlap strongly [10,11]. Therefore the hidden colour would manifest itself as short range repulsion in the region $\leq 1fm$ in deuteron. So the two nucleons though bound, stay considerably away from each other.

For the ground state and low energy description of nucleons, we assume that $SU(2)_F$ with u- and d-quarks is required. Hence we assume that 9- and 12-quarks belong to the totally antisymmetric representation of the group $SU(12) \supset SU(4)_{SF} \otimes SU(3)_C$ where $SU(3)_c$ is the QCD group and $SU(4)_{SF} \supset SU(2)_F \otimes SU(2)_S$ where S denotes spin. Note that up to 12-quarks can sit in the s-state in the group SU(12). The calculation of the hidden colour components for 9- and 12-quark systems requires the determination of the coefficients of fractional parentage for the group $SU(12) \supset SU(4) \otimes SU(3)$ which becomes quite complicated for large number of quarks [12]. Using this group theoretical technique [12], the author determined [10,13] that the hidden colour component of the 9-q system is 97.6% while the 12-q system is 99.8% i.e. is almost completely coloured.

What is the relevance of these 9- and 12-quark configurations in nuclear physics? The A=3,4 nuclei ^3H, ^3He and ^4He have sizes of 1.7 fm, 1.88 fm and 1.674 fm respectively. Given the fact that each nucleon is itself a rather diffuse object, quite clearly in a size $\leq 1fm$ at the centre of these nuclei, the 3 or 4 nucleons would overlap strongly. As the corresponding 9- and 12-q are predominantly hidden colour, there would be an effective repulsion at the centre keeping the 3 or 4 nucleons away from the centre. Hence it was predicted by the author [13] that there should be a hole at the centre of ^3H, ^3He and ^4He. And indeed, this is what is found through electron scattering [4,5]. This is shown as inset in Fig. 1 here. Hence the hole, i.e. significant depression in the central density of ^3H, ^3He and ^4He, is a signature of quarks in this ground state property.

This understanding of hole within QCD based arguments, leads us to provide a consistent understanding of the halo structure pheneommeneon and the emergence of new magic numbers [6,7,8,9,10].

Due to the significantly higher density at the boundary and very small at the centre, ^4He is like a "tennis-ball". The word tennis-ball is used to emphasize the predominance of the "surface-ness" property in the density distribution in the corresponding nuclei. Add two more neutrons to ^4He to make it ^6He, a bound system. As the two neutrons approach the surface, they will bounce off. As the two neutrons are bound, these will ricochet on the compact tennis-ball like nucleus. A neutron halo would be manifested as these neutrons shall be kept significantly away from the core.

How do we understand this effect? Macroscopically, as the density of the ^4He core is high on the boundary, any extra neutrons would not be able to penetrate it, as this would entail much larger density on ^4He surface than the system would allow dynamically. Microscopically, any penetration of extra neutron through the surface of ^4He would necessarily imply the existence of five or six nucleons at the centre. As already indicated, due to the relevant SU(12) group, only 12-quarks can sit in the s-state, which already is predominantly hidden colour. Any extra quarks hence would have to go to the p-orbital; and in the ground state of nucleus, there is not sufficient energy to allow this. Hence, the two neutrons are consigned to stay outside the ^4He boundary. In addition, if at any instant the two neutrons come close to each other while still being close to the surface, locally the system would be like three nucleons overlapping, and which would look like a 9-q system. This too would be prevented by the local hidden colour repulsion. Hence as found experimentally, the two neutrons in the halo would not come close to each other, resulting in the neutron halo in ^6He [6].

Let us treat ^{12}C as 3α cluster with the α's sitting at the vertices of an equilateral triangle. Because of tennis-ball like structure the three α particles cannot come too close to each other. Firstly, the surface of the ball would prevent it and secondly if some part of the 3 α 's still overlap at the centre, it would look like a 6- or 9-quark system. Therein the hidden colour components would repel, ensuring that the 3 α clusters do not approach too closely at the centre. This too would imply a depression in the central density of ^{12}C. Indeed, from the density distribution determination by electron scattering, this is so in ^{12}C. ^{16}O treated as 4α sitting at the vertices of a regular tetrahedron would, for the reasons stated above, too have a central density depression, again as seen in the electron scattering. Due to the central depression, C^{12} and ^{16}O would appear more surface-like (or even tennis-ball-like) as well.

So far we have explained neutron halo nuclei ^6He as arising due to 2n ricochet off the stiff tennis-ball like core of ^4He. In addition, nuclei like ^{12}C are made up of 3 ball like α's and also develops tennis-ball like properties. What happens when 2n are added to it ? Could one have two neutron halos for ^{14}C ? This is not so. The reason is because of the following. Going through the binding energy systematics of neutron rich nuclei, one notices that as the number of α's increases along with the neutrons, each ^4He + 2n pair tends to behave like a cluster of two $^3_1H_2$ nuclei. Remember that though $^3_1H_2$ is somewhat less strongly bound (ie. 8.48 MeV) it is still very compact (ie. 1.7 fm), almost as compact as ^4He (1.674 fm). In addition it too has a hole at the centre. Hence ^3H is also tennis-ball like nucleus. This splitting tendency of neutron rich nuclei becomes more marked as there are fewer and fewer of ^4He nuclei left intact by the addition of 2n. Hence ^7Li which is $^4He +^3 H$ with two more neutrons, becomes ^9Li which can be treated as made up of 3 $^3_1H_2$ clusters and should have hole at the centre. Similarly ^{12}Be consists of 4 $^3_1H_2$ clusters and ^{15}B of 5 $^3_1H_2$ clusters etc. Other evidences like the actual decrease of radius as one goes from ^{11}Be to ^{12}Be [14, see Fig. 4] supports the view that it (i.e. ^{12}Be) must be made up of four compact clusters of ^3H.

The tennis-ball like nature of ^3H and ^3He has a unique structural property which even ^4He does not have. The nuclei ^3H and ^3He along with deuteron, are the only known nuclei which have no excited state. Either they are there or not there as a single rigid entity. Due to quantum mechanics, right upto their binding energy of 8.48 MeV, tritons would be immune to any excitations; and thus their tennis-ball like nature would be more explicitly exchibited.

What we are saying is that the neutron rich nuclei which are made up of n-number of tritons, each of which is tennis-ball like and compact, should be compact as well. These too would develop tennis-ball like property. This is, because the surface is itself made up of tennis-ball like clusters. Hence when more neutrons are added to this ball of triton clusters, these extra neutrons will ricochet on the surface. Hence we expect that one or two neutrons outside these compact clusters would behave like neutron halos. Therefore ^{11}Li with $^9Li + 2n$ should be two neutron halo nuclei - which it is. So should ^{14}Be be. It turns out that internal dynamics of ^{11}Be is such that it is a cluster of $\alpha - t - t$ (which also has to do with ^9Li having a good 3-t cluster) with one extra neutron halo around it.

Thus all light neutron rich nuclei $^{3Z}_{Z}A_{2Z}$ are made up of Z $^3_1H_2$ clusters. Due to hidden colour considerations arising from QCD, all these should have holes at the centre. This would lead to tennis-ball like property of these nuclei. One or two (or more) extra neutrons added to these core nuclei would ricochet on the surface of the core nucleus and form halos around it. All known and well-studied neutron halo nuclei fit into this pattern. This makes unambiguous predictions about which nuclei should be neutron halo nuclei and for what reason. The proton halo nuclei can also be understood in the same manner. Here another nucleus with a hole at the centre $^3_2He_1$ (binding energy 7.7 MeV, size 1.88 fm) would play a significant role.

So it should be clear now that it is quarks, through hidden colour configuration, which lead to a hole at the centre of ^3H, ^3He and ^4He [13]. As the relevant group is SU(12) no more than 12 quarks can sit in the lowest orbital. Hence the hole at the centre of ^4He is special. Clustering of these nuclei is also determined by their bouncing tennis-ball like property. This gives new insight into $\alpha-$ clustering in nuclei and predicts existence of clusters of triton

(and helion) nuclei. All these nuclei are themselves compact and tennis-ball like. One, two or more neutrons outside these nuclei ricochet to give halo like structures.

Our experience from the field of particle physics is, that as more of new structures show up empirically, new symmentry structures are invoked to understand these consistently. So (p,n) of isospin group SU(2) goes over to a new group SU(3) to understand strange hadrons; still a newer group SU(4) to understand charm baryons etc. Hence what new group structure may exist to understand the empirically large number of halos? Indeed, a new group was suggested by the author [7]. Therein triton ("t") ${}^{3}_{1}H_{2}$ helion ("h") ${}^{3}_{2}He_{1}$, are treated as fundamental represenations of a new symmetry group $SU(2)_{\mathcal{A}}$, called the "nusosoin" group. The power and usefulness of this new symmetry is that it can, in addition to explaining the mysterious halo structures, explains and predicts correctly the emergence of new magic numbers.

It was shown [8] that nuclei with pair of proton number Z and neutron number N, (Z,N) : (6,12), (8,16), (10,20), (11,22) and (12,24) exhibited exceptional stability or magicity. As such these new magic numbers appear in pairs. This correlation is shown here to be indicative of predominance of tritons in the ground state of these neutron rich nuclei. Thus ${}^{30}_{10}Ne_{20}$ has the structure of 10 ${}^{3}_{1}H_{2}$ in the ground state. We have looked at several evidences from empirical data, which gave strong support to the presence of clustering of tritons and helions in nuclei [9].

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