Abstract

It is shown that the hole in the centre of $^3H$, $^3He$ and $^4He$, the neutron halos in nuclei, the $\alpha-$ and other clustering effects in nuclei and the nuclear molecules all basically arise due to the same underlying effect. We shall show that all these ground state properties of nuclei are manifestations of quark effects. The role of triton clustering in very neutron rich nuclei is emphasized. All these require the concept of hidden colour states which arise from confinement ideas of QCD for the multi-quark systems. This provides comprehensive understanding of diverse nuclear effects and makes unique predictions.
It is generally believed that quarks would explicitly manifest themselves in nuclei only at higher energies, for example as in the EMC effect or the quark gluon plasma etc. However, this need not always be true. There may be specific ground state or low energy (\( \sim 10 - 20 \) MeV excitations) properties where quarks may be placing their identifiable signatures. Already it has been shown by the author that the ground state property of 'hole' in the centre of the density distribution of \(^3H\), \(^3He\) and \(^4He\) is a unique signature of quark effects in nuclei [1,2]. Here we show that the neutron halo in nuclei [3,4], the clustering effects in nuclei [5,6,7,8] and the nuclear molecules [8,9] arise as a result of quark effects. Note that all these are ground state or low excitation properties of nuclei.

All these effects, the hole at the centre of \(^3H\), \(^3He\) and \(^4He\), the neutron halo nuclei, the clustering effects in nuclei and the nuclear molecules, as we shall see below, would require an understanding of two or more nucleons strongly overlapping over a small region of \( \leq 1 \) fm. This would necessarily imply a study of multi-quark states in regions \( \leq 1 \) fm. This would lead to the concept of hidden colour. There have been some claims [10] that hidden colour may not be a useful concept as these coloured states may be rewritten in terms of asymptotic colour singlet states. Below, we shall show that this is not always true. In special circumstances, as shall be discussed here, hidden colour are unambiguously defined states, basic to physics under consideration.

As we shall be discussing the structure of nuclei in the ground state, we should also have the structure of nucleons in the ground state as well. Hence we view the nucleon as consisting of 3 constituent quarks in the s-state. Another point that should be borne in mind is that though the r.m.s. radius of nucleon is 0.8 fm, it is a very diffuse system with matter distribution given by \( \rho(r) = \rho_0 \exp(-mr) \) and hence matter extends significantly beyond 0.8 fm.

Hence when two such nucleons come together to form a bound system like deuteron, why do they not have configuration where the two nucleons overlap strongly in regions of size \( \leq 1 \) fm 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 the 6-q wave function looks like [10]:
$|6q> = \frac{1}{\sqrt{5}}|SS> + \frac{2}{\sqrt{5}}|CC>$  \hspace{1cm} (1)

where S represents a 3-quark cluster which is singlet in colour space and C represents the same as octet in colour space. Hence $|CC>$ 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. Hence this 80% colour part would prevent the two nucleons to come together and overlap strongly [10]. Therefore the hidden colour would manifest itself as short range repulsion in the region $\leq 1 fm$ in deuteron. So the two nucleons though bound, stay considerably away from each other.

There have been some claims [11] that hidden colour may not be a useful concept as these hidden colour states can be rearranged in terms of asymptotic colour singlet states. But as discussed in ref. [11] the hidden colour concept is not unique only when the two clusters do not overlap strongly and asymptotically can be separated out. However when the clusters of 3-q each overlap strongly so that the relative distance between them goes to zero then the hidden colour concept becomes relevant and unique as shown in ref. [11]. We would like to point out that indeed, this necessarily is the situation for deuteron discussed above. Also note that for the ground state the quark configuration is $s^6$ given by configuration space representation [6] while $s^4p^2$ given by [4] does not come into play as there is not enough energy to put two quarks into the p-orbital [12].

Group theoretically the author had earlier obtained the hidden colour components in 9- and 12-quark systems [1,2]. 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 $SU(12) \supset SU(4)_S \otimes SU(3)_C$ where $SU(3)_c$ is the QCD group and $SU(4)_S \supset SU(2)_F \otimes SU(2)_S$ 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 $SU(12) \supset SU(4) \otimes SU(3)$ [1,2] which becomes quite complicated for large number of quarks. The author found that the hidden colour component [1,2] of the 9-q system is 97.6% while the 12-q system is 99.8% ie. practically all coloured.
Where would these 9- and 12-quark configurations be relevant 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 \([13]\). 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 \([1,2]\) that there should be a hole at the centre of \( {}^3H \), \( {}^3He \) and \( {}^4He \). And indeed, this is what is found through electron scattering \([1,2] \) for references\). 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.

Now about neutron halo nuclei. Neutron halos have been discovered in several neutron rich nuclei like \( {}^6He, {}^{11}Li, {}^{11}Be, {}^{14}Be \) etc. \([3,4]\). For example the rms radius of \( {}^{11}Li \) is 3.2 fm while that of \( {}^9Li \) is 2.3 fm. Hence in this halo nuclei it is believed that 2n are very loosely bound to a compact core of \( {}^9Li \). So also the 2n in \( {}^6He \) etc. The existence of 2n in nuclear forbidden zone is an outstanding puzzle of nuclear structure.

Note that \( {}^4He \) is a very strongly bound system with binding energy of 28.29 MeV. It is a compact object of size 1.674 fm. Due to specific quark hidden colour state, as we discussed above, it has a hole of size \( \sim 1fm \) at the centre. Thus it has a significantly higher density at the boundary and very small at the centre. Hence \( {}^4He \) is like a tennis-ball. Add two more neutrons to \( {}^4He \) to make it \( {}^6He \), a bound system. This is like adding 2 neutrons to a tennis-ball nucleus. 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. Hence they shall be kept significantly away from the core and this effect would be manifested as a neutron halo.

This neutron halo can be viewed in two complementary manners. Macroscopically, as the density of the \( {}^4He \) core is high on the boundary, any extra neutrons would not be able to penetrate 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 nuclei,
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 looking 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 [3,4]. Hence the neutron halo in $^6He$ is due to quark effects. About other neutron (and proton) halo nuclei we shall discuss shortly.

Now about clusters in nuclei. Clusters, especially $^4He$ clusters have a very important role in nuclear structures [5,6,7,8]. Clusters are crucial for studies of light nuclei like $^8Be$, $^9Be$, $^7Li$, $^7Li$, $^{12}C$, $^{16}O$. Even for heavier nuclei like $^{20}Ne$, $^{24}Mg$, $^{28}Si$, $^{44}Ti$ and others they are important [5,6,7,8]. It is commonly stated that $^4He$ clusters are formed in nuclei because it is so strongly bound, ie. 28.29 MeV. Here we would like to point out that $^4He$ forms good clusters because in addition it has a hole at the centre so it is like a tennis-ball. These balls in a bound system of several $^4He$ nuclei would bounce from each other. Note that even fullerenes traveling at $3 \times 10^5km/s$ can bounce off intact from hard steel surfaces.

Again the reason for resistance to inter-penetration of two $\alpha$ clusters would be hidden colour repulsion of the relevant 6-, 9- and 12-quark systems plus the fact that more than 12 quarks are not permitted in the lowest s-state in the group SU(12).

We may treat $^{12}C$ as 3$\alpha$ cluster with the $\alpha$’s sitting at the vertices of an equilateral triangle. Because of tennis-ball like structure the three $\alpha$ 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 $\alpha$’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 $\alpha$ 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 $^{12}C$ [13]. $^{16}O$ treated as 4$\alpha$ 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 [13]. Due to the central depression, $^{12}C$ and $^{16}O$ would appear tennis-ball like as well.

In conventional cluster models (see refs. [5,6,7,8]) $^{20}Ne$, $^{24}Mg$, $^{28}Si$, $^{32}S$ are treated as close packing of 5,6,7 and 8 $\alpha$ clusters. Our model of $\alpha$ clusters
with understanding provided from quark considerations does not support this idea. Here $^{16}O$ of 4 $\alpha$ at the vertices of a regular tetrahedron is special. Just as $^{4}He$ with 12-q structure at centre is special due to the degeneracies of the group SU(12) so also $^{16}O$ with 4 $\alpha$ is special for the same reason. For $^{20}Ne$ the fifth $\alpha$ would not just penetrate $^{16}O$ but would try to form a regular tetrahedron locally with any of the 3 $\alpha$ surface of the 4 $\alpha$ cluster. Similarly we can keep on adding $\alpha$’s until $^{32}S$ where 4 $\alpha$’s are sitting on top of four 3 $\alpha$ clusters surfaces of $^{16}O$. Hence for $\alpha$’s 5 to 8 it is close packing on top of 4 $\alpha$’s of $^{16}O$ which has a hole at the centre. Hence all these nuclei should have hole at the center. Beyond 8 $\alpha$ clusters, the geometry is such that the 9th $\alpha$ - particle cannot be simply close packed on top of $^{32}S$.

We have shown that the $^{12}C$ with 3 $\alpha$ and $^{16}O$ with 4 $\alpha$ has central density depression. Though the effect may be softened compared to $^{3}H$, $^{3}He$ as 3N and and $^{4}He$ as 4N ball structures, nevertheless these nuclei should also act tennis-ball like. No wonder one observes nuclear molecules in C-C, C-O, O-O systems. The stability of nuclear molecules has to do with the bounciness of the C,O nuclei coupled with the fact that their large size is due to the largeness of the constituent clusters. Also obviously molecular structures would exist for nuclei $^{20}Ne$, $^{24}Mg$, $^{28}Si$ and $^{32}S$ [8,9]. Hence nuclear molecules [8,9] too arise basically due to quark effects.

Earlier we had explained neutron halo nuclei $^{6}He$ as arising due to 2n ricochet off the stiff tennis-ball like core of $^{4}He$. In addition, nuclei like $^{12}C$ are made up of 3 ball like $\alpha$’s and also develops 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 $\alpha$’s increases along with the neutrons, each $^{4}He$ + 2n pair tends to behave like a cluster of two $^{3}H_2$ nuclei. Remember that though $^{3}H_2$ is somewhat less strongly bound (ie. 8.48 MeV ) it is still very compact (ie. 1.7 fm ), almost as compact as $^{4}He$ (1.674 fm). In addition it too has a hole at the centre. Hence $^{3}H$ is also tennis-ball like nucleus. This splitting tendency of neutron rich nuclei becomes more marked as there are fewer and fewer of $^{4}He$ nuclei left intact by the addition of 2n. Hence $^{7}Li$ which is $^{4}He + ^{3}H$ with 2n becomes $^{9}Li$ which can be treated as made up of 3 $^{3}H$ clusters and should have hole at the centre. Similarly $^{12}Be$ consists of 4 $^{3}H_2$ clusters and $^{15}B$ of 5 $^{3}H_2$ clusters etc. Other evidences like the actual decrease of radius as one goes from $^{11}Be$ to $^{12}Be$ supports the view that it (
ie $^{12}\text{Be}$ ) must be made up of four compact clusters of $^3\text{H}$.

Just as several light N=Z nuclei with A=4n, n=1,2,3,4 ... can be treated as made up of n $\alpha$ clusters, in Table 1 we show several neutron rich nuclei which can be treated as made up of n $^3\text{H}_2$ clusters. We can write the binding energy of these nuclei as

$$E_b = 8.48n + Cm$$ \hspace{1cm} (2)

where n $^3\text{H}_2$ clusters form m bonds and where C is the inter-triton bond energy. We have assumed the same geometric structure of clusters in these nuclei as for $\alpha$ clusters of A = 4n nuclei as given above. All the bond numbers arise due to these configurations. We notice from Table 1 that this holds good and that the inter-triton cluster bond energy is approximately 5.4 MeV. We notice that this value seems to work for even heavier neutron rich nuclei. For example for $^{42}\text{Si}$ the inter-triton cluster energy is still 5.4 MeV. Notice that the geometry of these cluster structures of $^3\text{H}$ becomes more complex as the number increases but nevertheless, it holds well.

The point is that these neutron rich nuclei, 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 as there are no more $^4\text{He}$ clusters to break 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 $^{11}\text{Li}$ with $^9\text{Li} + 2n$ should be two neutron halo nuclei - which it is [3,4]. So should $^{14}\text{Be}$ be [3,4]. It turns out that internal dynamics of $^{11}\text{Be}$ is such that it is a cluster of $\alpha - t - t$ (which also has to do with $^9\text{Li}$ having a good 3 $\alpha$ cluster) with one extra neutron halo around it. Next $^{17}\text{B},^{19}\text{C},^{20}\text{C}$ would be neutron halo nuclei and so on.

Hence all light neutron rich nuclei $^{3Z}Z_{2Z}$ are made up of Z $^{3H}_2$ clusters. Due to hidden colour considerations arising from quark effects, 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. At the base, it is quarks which
cause neutron halo \([3,4]\). The proton halo nuclei can also be understood in the same manner. Here another nucleus with a hole at the centre \(\frac{3}{2}He_1\) (binding energy 7.7 MeV, size 1.88 fm) would play a significant role.

In summary, it is quarks through hidden colour configuration which lead to a hole at the centre of \(\frac{3}{2}H\), \(\frac{3}{2}He\) and \(\frac{4}{2}He\). 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 \(\frac{4}{2}He\) 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. Large nuclear molecules can also be understood in the same manner. All these diverse effects arise as a signature of quarks in these ground state properties of nuclei. These new insights would be expected to give a better and unified understanding of several structural properties of low, intermediate and heavy nuclei and also help solve outstanding puzzles of nuclear astrophysics.
Table 1
Inter-triton cluster bond energies of neutron rich nuclei

| Nucleus | n  | m  | $E_B - 8.48n$(MeV) | C(MeV) |
|---------|----|----|-------------------|--------|
| $^9\text{Li}$ | 3  | 3  | 19.90             | 6.63   |
| $^{12}\text{Be}$ | 4  | 6  | 34.73             | 5.79   |
| $^{15}\text{B}$ | 5  | 9  | 45.79             | 5.09   |
| $^{18}\text{C}$ | 6  | 12 | 64.78             | 5.40   |
| $^{21}\text{N}$ | 7  | 15 | 79.43             | 5.29   |
| $^{24}\text{O}$ | 8  | 18 | 100.64            | 5.59   |

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