Some Correlations Between Light Nuclear Phenomena and an Extended Nuclear Cluster Model[1]

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Abstract

The problem of modelling nuclear structure is analysed by extending the alpha cluster model to include the three-body mirror nuclei and the deuteron. It is possible to arrange all the nucleons of any nuclide into a set of from one to three of the four cluster types according to two principles, which are: (1) bound nucleons tend to form the alpha cluster and (2) nucleon excess is conserved by the three-body mirror clusters. In this analysis, each excess neutron forms a triton and each proton-rich, odd-neutron nuclide forms one ^{3}He. Within the series of isotopes for each element nuclear structure is discrete and reactive; the addition or removal of a single neutron changes its set of constituent clusters. The mass range of the isotopes of any element is defined by the model to be $Z+1 \leq A \leq 3Z$. The model correlates structure with a number of light nuclear phenomena, including the β-decay potential and the neutron emission decay mode. The recently observed islands of particle stability beyond the neutron drip-line of fluorine, neon and sodium are analysed as the highest mass isotope of each of those elements coupled to four neutrons, which is interpreted as the bound analogue of the recently observed free tetraneutron.

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Abstrait

Le problème de modeler la structure nucléaire est analysé en prolongeant le modèle de faisceau d'alpha pour inclure les noyaux trois corps de miroir et le deutéron. Il est possible d'arranger tous les nucléons de n'importe quel nuclide dans un ensemble de d'un à trois des quatre types de faisceau selon deux principes, qui sont : (1) les nucléons attachés tendent à former le faisceau d'alpha et (2) l'excès de nucléon est conservé par les faisceaux trois corps de miroir. Dans cette analyse, chaque neutron d'excès forme un triton et chaque proton-riche, nuclide d'impair-neutron forme un 3He. Dans la série d'isotopes pour chaque élément la structure nucléaire est discrète et réactive; l'addition ou le déplacement d'un neutron simple change son ensemble de faisceaux constitutifs. La gamme de masse des isotopes de n'importe quel élément est définie par le modèle pour être $Z+1 \leq A \leq 3Z$. Le modèle corrèle la structure avec un certain nombre de phénomènes nucléaires légers, y compris le potentiel d'β-affaiblissement et le mode d'affaiblissement d'émission de neutron. Les îles récemment observées de la stabilité de particules au delà de la égouttement-ligne de neutron du fluor, du néon et du sodium sont analysées pendant que l'isotope de la masse la plus élevée de chacun de ces éléments couplés à quatre neutrons, qui est interprété pendant que l'analogue attaché du tétraneutron libre récemment observé.

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1. INTRODUCTION

This is the first of a set of papers dealing with the nuclear many-body problem in a fully discrete framework. The essence of the present paper is to deal directly with nuclear structure rather than with the interaction itself. Conventional cluster models treat the alpha particle as an inert constituent of the nucleus because of its well known high binding energy as an isolated particle. Nucleons not accommodated as part of alpha clusters are usually simply separate from the inert core. Instead, we show that by the inclusion of additional clusters, modelled on the three-body mirror nuclei and the deuteron, the nuclei of all the natural elements are embraced by one model in which every nucleon belongs to a potentially reactive cluster. The proposed model is radical and simple but it is well supported by its unification of a number of diverse phenomena.

The study of unstable neutron-rich nuclei has expanded rapidly in recent times due to technical advances in new radioactive ion beam facilities and associated instrumentation.[1] Neutron separation and nuclear binding energy studies have employed various models including the core plus neutron cluster picture.[2] Nuclear structure, as it is currently understood, derives from several models and the guidance they provide in the interpretation of a large body of, mostly, high energy data. The interacting boson model, nuclear shell model and the liquid drop model form the basis of the description of all nuclear phenomena and yet none is more than partially satisfactory. For example, the theoretical description of the deuteron, the simplest bound nucleus, is ambiguous and incomplete and its experimentally determined properties are well beyond the accuracy of nuclear models.[3]

The interacting shell model is currently regarded as the most relevant description of low-energy nuclear structure and the most likely means of solving the fundamental many-body problem. Concepts of nuclear shells and orbits have their origin in the theory of electron shells.[4] However, “for all we know electron shells may not even exist” E. R. Scerri.[5] There is scope for new approaches to model development derivative of the basic facts of nuclear behaviour which are relevant to the nuclei of all the natural elements.

Nuclear phenomena reveal intranuclear grouped behaviour, which has prompted the adoption in nuclear reaction models of clustering in bound nuclei.[6] For example, in the Glauber model of nuclear collision each cluster within the nucleus is treated as a separate projectile. The alpha is unique among bound nucleons in its survival of high energy interactions and the decay of proton-rich and heavy nuclei. Alpha clusters have attracted the attention of theorists from before the discovery of the neutron and they have proved useful in modelling various light even-even nuclei where the individual alpha represents an inert unit of nuclear substructure.[7,8,9,10] There is considerable evidence for clustering in light nuclei and the alpha has been the most thoroughly studied substructural candidate. See Ref. 3 for a detailed review. Triton clusters in light neutron-rich nuclei have also been predicted to be associated with neutron halos.[11]

The present approach to the problem of modelling nuclear structure is a radical departure from the various shell model-based concepts which have been developed over the last seventy years. The chief points of departure are:

1). Concepts of shells and orbits have no physical relevance to structure.

2). Clusters are not inherently inert. All four cluster types are potentially reactive to the addition or removal of one or more nucleons.

3). The structure of every nucleus consists of a set of complete clusters. Substructures (clusters) are not completed or perfected by the addition or removal of nucleons.

The extended cluster model (ECM) is based on two imperatives: (1) nucleon clustering tends towards the alpha configuration and (2) neutron or proton excess is structurally conserved by three-body mirror clusters. That double imperative gives the model a dynamic in which low energy structure evolves discretely from nucleus to nucleus as a function of N and Z in which every A>4 with N$\geq$Z nuclide has its own unique structure. Within the isotope series of every element the addition or removal of a neutron changes the cluster composition of the structure. Clusters react to the N–Z composition of their own environment in a definite and predictable manner; nothing is put in by hand.

The present paper is divided into seven sections. In Sect. 2 we describe the model and the procedure for distributing the protons and neutrons of a nuclide among its constituent clusters.

In Sect. 3 we describe the discrete reactivity of modelled nuclear structure to single nucleon addition and removal. It is found that no part of nuclear structure is inherently inert. The effect of β-decay on structure is then described.

In Sect. 4 we show that the model defines the limits to the series of isotopes for each element. The structure of each isotope reacts to neutron addition or removal by changing its cluster composition until N=2Z, beyond which structure is refractory to additional neutrons. Therefore, N=2Z is the heaviest nuclide of every isotope series.

In Sect. 5 we show that the model is largely congruent with the generally accepted neutron halo nuclides. The model gives a structural basis for the non-participation of halo neutrons in underlying nuclear structure. We show that the model contains a nuclear β-decay potential which is structurally indistinguishable from the recently observed double triton cluster of ^{6}He. A pair of triton clusters is found to be a necessary but not a sufficient condition for nuclear β-decay.

In Sect. 6 we apply the model to the recently observed particle stability beyond the neutron drip-line of F, Ne and Na. The model prompts the interpretation that the three particle-stable nuclei are a tetraneutron bound to the heaviest isotope of each of the three elements.

In Sect. 7 we present a discussion and summary of the model and its correlations. Based upon the model's accommodation of some recently observed nuclear phenomena, it is predicted that particle-stable bound neutrons should be found coupled to the heaviest isotopes of elements in addition to F, Ne and Na.

2. THE EXTENDED CLUSTER MODEL

The choice of clusters is based on the concept that the serial addition of three neutrons to one proton, the neutron capture process, produces the alpha by way of the deuteron, the β-unstable triton and the ^{3}He; the latter two being the fundamental units of nucleon excess. The three-body mirror clusters and the deuteron are incorporated with the alpha as the component clusters of the model. The conservation of nucleon excess in the triton and ^{3}He is the source of structural reactivity and discreteness, which is the basis of the richness of the model.

The present paper deals only with structure and its correlations with nuclear phenomena and omits considerations of energy, dynamics and kinematics. An extension of the theory from the structure model to cluster–cluster interactions and dynamics is to be the subject of a subsequent paper. Consequently, as a foundation, in this paper the description of the model is developed in a classical physical framework, without reference to symmetries or quantum states or statistics and without any consideration of energy states.

The simplest nuclear cluster is the deuteron. It is conceptually achieved by the capture of one neutron by a proton or light hydrogen nucleus and occurs essentially without counteraction by the Coulomb barrier. The further capture of a neutron forms the triton which if isolated transforms by β-decay to its mirror, ^{3}He; which upon the capture of a further single neutron forms ^{4}He, the most stable of all the known nucleon clusters. Importantly, the consequence of the two imperatives, viz. (1) alpha formation and (2) conserved nucleon excess, is that each neutron addition causes the replacement of the existing cluster by a new cluster. The potential for these discrete cluster transformations, whose origin is among the hydrogen and helium isotopes, is the basis for the model which extends to all the $A>4$ structures of the isotopes of the other natural elements. This serial potential among the four nucleons, is postulated to evolve into structure which is effective throughout the nuclear landscape.

The ECM is simple, employing just four clusters which combine to give each even-even and neutron-rich $A>4$ nuclide its own unique structure. There is no assumption that the relevance of shell models extends physically to real atoms. The present approach departs from the concept that open shells can be closed by nucleon addition. Here, the structure of each nuclide, interpreted in terms of the four clusters, is complete and cannot be enhanced and none of its constituent clusters are incomplete. The model is structurally global, embracing all nucleons equally; none are omitted or compartmentalised into proton- or neutron-only domains; each participates in the serial potential within the isotope series of any element.

The three-nucleon configuration is uniquely representative of nucleon excess; the triton for the neutron and the ^{3}He for the proton, and that is its function in the model. In that respect, they actually mirror nuclear facts as they relate to numbers of protons and neutrons, with respect to configurations either side of N=Z. The deuteron is a repository of unactualised potential in odd-$N \geq Z$ nuclides. Being the first step in the discrete evolution from nucleons to the alpha configuration, its retention in the nucleus is analogous to half the potential for alpha formation.

2.1. The Nucleon Assignment Procedure

The two imperatives of the model distribute nucleons of every $A>4$ nuclide among from one to three of the four cluster types according to the following rules:

1. First, each excess neutron forms a triton if there are sufficient protons for the cluster. (Excess means additional to N=Z.)
2. Second, remaining pairs of neutrons form alphas.
3. Third, if there is a residual neutron following alpha formation it forms a deuteron if one proton remains or a ^{3}He if two or more remain.

Any nucleons which this procedure has not included in a cluster are passengers and they do not contribute to the structure of the nucleus.

3. DISCRETE STRUCTURAL REACTIVITY

A consequence of the discreteness of the model is that for the series of isotopes of an element increasing neutron number is accompanied by increasing triton number and decreasing alpha number. Table I shows the structure of the isotopes of carbon, as an example. The alpha forming tendency is complete at ^{12}C. The effects of the serial increase in neutrons are seen to range from increasing alpha numbers among proton-rich isotopes then increasing triton numbers until T=Z, beyond which structure is unchanged by further neutron addition.

The chief feature of the model is its discrete, dynamic collectivity. The addition or removal of a neutron has definite and significant effects on the structure of nuclides which belong within an isotope series. For example, the single neutron difference between ^{4}He and ^{5}He switches their global structure from a single alpha to a triton plus a deuteron, see Table II. The structure reacts to a single neutron addition and the transition is fully discrete; it changes from one set of complete clusters to another. The further addition of one neutron results in the double triton structure. Therefore, the serial double neutron addition to ^{4}He induces two tritons by abolishing first the alpha and then the acquired deuteron.

A second example of the structural novelty of the model is seen in beryllium. Unique among light n-alpha nuclei, ^{8}Be is unbound; all the other n-alphas up to 10-alpha are stably bound. The usual interpretation is that the stable bound isotope ^{9}Be, formed by the single neutron addition to ^{8}Be, consists of two alphas plus one neutron. For nuclear structure, as it is currently understood, the additional neutron, though providing an effective bond for the two alphas, is simply additional to the preexisting unbound substructures which survive the transition from one isotope to the next. That is, the transition from ^{8}Be to ^{9}Be takes place against a background of structural continuity. Such a structure is suggestive of a one-neutron halo, which ^{9}Be is not. However, in the ECM, the structure of the unbound nucleus is radically changed by the addition of one neutron. The alphas react with the additional neutron to produce three bound clusters—a triton, an alpha and a deuteron, which is consistent with its not being a halo nuclide. All light nuclei modelled as one deuteron plus one triton coupled to from one (^{9}Be) to seven alphas (^{31}P) are stable. A key feature of these two near n-alpha transitions is discreteness; additional neutrons are not simple appendices to preexisting structure. Transitions between isotopes do not occur against a background of continuous structure.

Proton-rich isotopes vary structurally with neutron number. By contrast, the model gives proton-rich isotones an invariant underlying structure. Table III. shows the effects on structure of proton addition to $N \geq Z$ and $N < Z$ nuclides. Because individual nucleons are not nuclear structural components, if protons are excess to ^{3}He or ^{4}He clusters of proton-rich nuclides, they are modelled as non structural components of a composite object; the object being a nucleus plus passenger protons. Passenger protons (and neutrons) are those whose addition or removal has no effect upon underlying structure.

It can be seen in Table I that repeated single neutron additions to carbon isotopes eventually converts all the available protons into triton clusters. The further addition of neutrons is ineffective in transforming underlying structure. The removal of neutrons from proton-rich isotopes eliminates structure via the discrete abolition of alphas. It follows from the principle of structural discreteness that the termination of background discontinuity occurs at the mass-limit of any isotope series. Accordingly, structural discreteness has its limits which coincide with the upper and lower mass-limit for each element. Structure is refractory to neutron addition and removal beyond the isotope limits ($Z+1 \leq A \leq 3Z$). The limits for carbon are $Z+1=7$, and $3Z=18$, which define the number of isotopes of that element, i.e. 12.

Nuclear β-decay has a marked effect on structure. As shown in Table IV, the concomitant loss of one neutron and the gain of a proton transforms two triton clusters to an alpha plus deuteron. The requirement of the model for two tritons for β-decay is the result of the simultaneous change of both proton and neutron numbers. These two structural changes illustrate the reactivity of the clusters. Unlike current cluster models in which the alpha is inert, all the clusters of the present model are potentially reactive to changes in nucleon number.

These features of the model for individual elements all follow from the double principle: (1) the preferred cluster is the alpha, and (2) neutron or proton excess is globally conserved in the structure, in the form of the simplest nucleon-excess cluster, provided the minor nucleon is available to complete the mirror cluster.

4. THE ISOTOPIC LIMIT OF THE NATURAL ELEMENTS

The model defines the limits to the series of isotopes for any element according to the principle of structural reactivity to a change in neutron number. Proton-rich nuclei show the same discrete structural change with neutron addition or removal, even though a common underlying structure is a feature of proton-rich isotones. The structure of each isotope is unique in its series and $N \geq Z$ nuclide structures are unique generally, but $N<Z$ structures of any element are common to the proton-rich isotopes of heavier (higher Z) elements. The low mass-limit for any element is marked by the isotope which possesses a single neutron. From Z=N the loss of single neutrons changes the structure and creates passenger protons discretely until the loss of the last neutron and with it the last remnant of structure, which for each element is a single ^{3}He cluster.

Beyond the high mass-limit of serial discrete structural reactivity, the object is described as an atomic nucleus plus some number of passenger neutrons. This definition places a definite limit on the number of isotopes for each element because each isotope has to have a structure which differs from the next in the series. Beyond the limit, neutron addition does not change the underlying structure and therefore does not create new isotopes; the highest mass isotope of the series survives the addition of further neutrons. Therefore, according to the model, there are 2Z isotopes of each of the naturally occurring elements. The hydrogen series obeys the same rule, but ^{1}H is excluded because, being a single proton, it is neither a structure nor a cluster. The model produces a total number of 8,556 isotope structures for the natural elements; being the sum of 2Z for each of the elements up to uranium. These are cluster combinations, most of which may never be physically realised as real isotopes. The number of unique structures is 4,370 and common structures is 4,186. The difference follows from the common structures of $N<Z$ nuclides and unique cluster combinations for $N \geq Z$.

The model gives a structural explanation of the onset of the neutron emission decay mode among the light elements, which is shown in Table V. The addition of one neutron to the heaviest isotope, defined by the model, does not affect its structure. One neutron remains an appendix to the structure of the heaviest isotope and neutron emission is the dominant decay mode for ten of the twelve, shown in Table V; nitrogen and magnesium are the exceptions. Their β-decay branching ratios exceeding branching ratios for neutron emission.[12]

Observation alone, in the absence of a principle, cannot define the upper mass-limit to any series of isotopes or even determine if there is such a limit. The new model provides a pair of principles from which arise the limit for the series of isotopes for all the natural elements, which is independent of neutron number. It follows from the principle that each isotope in a series is characterised by unique and reactive underlying structure and that additional neutrons are not nuclear components but are ingredients, with the nucleus, of a composite object. If the structure survives the addition of a neutron then its reactivity is exhausted and the isotope survives that addition and is the high mass-limit of the element.

By contrast with passenger neutrons, which only attach to the heaviest isotope of an element, passenger protons attach to all proton-rich isotopes except odd-*A* N=Z-1 nuclides. For the isotopes $^{7-11}$C, shown in Table I, structural components are the alpha and the ^{3}He. The additional protons are passengers (shown as +p, +2p, etc.) and are not part of the nuclear structure.

5. LIGHT HALO NUCLEI

The two main features of light halo nuclei are: the comparative ease with which one or two neutrons are removed from the nucleus and their extended size as determined experimentally. Associated with their size is an assumed outer neutron skin or halo. Perhaps the most important feature of these nuclei is their very small neutron separation energies, usually <1 MeV. Such nuclei have a one- or two-neutron halo. The so far generally accepted two-neutron halo nuclei are ^{6}He, ^{11}Li, ^{14}Be and ^{17}B,[13, 14, 15, 16] and the one-neutron halo nuclei are ^{11}Be and ^{19}C.[17, 18, 19, 20] It can be seen from Table VI that the model unites the structures of the above listed two-neutron halo nuclei, except ^{6}He, with a common structural feature which is also attributed to other light element isotopes. The model exactly matches the core–halo picture of current light nuclear theory, but it does so according to a principle, i.e. that of discrete structural reactivity. The addition and removal of passenger (halo) neutrons has no effect on the cluster structures of all but two of the generally accepted halo nuclei. As discussed below, recent observational evidence does not support a core–halo structure for the 18 MeV resonance of ^{6}He.[21] The modelled structure for ^{19}C, an accepted one-neutron halo, is that of ^{18}C plus one passenger neutron, which is exactly congruent with the core–halo picture. The same feature is not seen in ^{11}Be, whose modelled structure is three tritons plus one deuteron. A neutron drip-line nucleus is defined as one to which the addition of one neutron makes the one-neutron separation energy negative. According to the model, four of the six generally accepted light neutron-halo nuclei have a triton-only structure plus passenger neutrons which constitute the halos. The underlying structure is unaffected by the presence of halo neutrons.

The triton-only structure plus passenger neutrons of ^{11}Li, ^{14}Be and ^{17}B is seen in ^{8}He but not in ^{6}He in which all its neutrons are part of its structure; none are passengers. The lack of a principle which explains halo nuclear phenomena and guides classification has meant that their identification has relied upon separation energy data and root mean square (rms) radius estimates and theoretically on shell model calculations. The relevance of rms radii data to the classification of halo nuclei assumes there is a common dense core which retains its structure with the addition of neutrons. In the case of ^{6}He, it has been assumed that two neutrons do not alter the underlying alpha core.[22] The new model predicts that the rms radius of ^{6}He exceeds that of ^{4}He because of the radically different underlying structure of the two nuclei, not the presence and absence, respectively, of halo neutrons—one consists of a single cluster and the other of two (Table II).

This analysis is supported by recent progress on the long-standing question of trinucleon clustering in the *A*=6 triad, ^{6}He, ^{6}Li, and ^{6}Be. There is now good experimental evidence for the di-triton structure of the 18 MeV resonance of ^{6}He.[21] The 18 MeV excited state decays to two tritons with a branching ratio of 90±10%. If ^{6}He has an energy-dependent mixed structure of a halo-core and a di-triton, intuition would suggest that the particle-stable ground state would be the di-triton and the resonance the halo-core. Therefore, the present theory combined with the observed di-triton structure at the resonance energy is consistent with ^{6}He having one structure at both energy levels.

The absence of double three-body signatures for the other members of the *A*=6 triad are consistent with the present model which gives ^{6}Li the alpha plus deuteron configuration and ^{6}Be the alpha plus two passenger protons. The latter is therefore a two-proton halo nuclide, which accords exactly with its single decay mode of double-proton emission.

5.1. The Triton Cluster and β-decay

The di-triton structure of ^{6}He is important to the model because it is the lightest of nuclide structures with the potential for β-decay. It is also the repository of the potential in larger nuclei which undergo β-decay. Therefore, according to the model, nuclear structures with less than two tritons lack the potential to undergo β-decay. This is born out by the correlation between nuclides that are observed to undergo β-decay and the minimum of two tritons which the model gives them.

By contrast, it is known that all the one-triton nuclei (N=Z+1) up to ^{35}Cl and ^{39}K are stable. Although the ^{37}Ar nucleus and all the higher mass one-triton nuclides are unstable, their known decay modes are all electron capture with or without proton emission; none undergoes β-decay. Therefore the cluster model of the β-decay potential is fully congruent with observed nuclear phenomena. Thus, providing further support for the theory.

The distinction between a cluster and a structure is seen in their different β-decay products, which is consistent with the imperative to conserve nucleon excess in the three-body mirror clusters. When a triton is isolated and therefore not part of a structure it is a cluster and decays to ^{3}He, thereby preserving the switched nucleon excess from a neutron to a proton. When a structure decays, in contrast to a cluster, the product is an alpha and a deuteron, which models the consequent reduced neutron excess. This follows from the observed fact that single β-decay of an A>4 nuclide cannot result in proton excess. Like the stable single neutron of the deuteron, one triton in a nuclear structure is also β-stable. On the other hand, two neutrons in a cluster and two tritons in a nucleus may be stable or unstable. The cluster component of structure which is required for β-decay is two tritons, just as β-instability of a cluster requires two neutrons. It does not follow that the presence of the di-triton or neutron pair confer β-instability; they are a necessary but not sufficient condition for the instability.

6. THE ISLAND OF INVERSION IN THE O TO Mg REGION

The model defines the lowest mass isotope for each element as that possessing just one neutron (Table I). At the upper-limit, the picture is complicated by the zone of particle stability beyond the neutron drip-line.[23] However, the highest mass isotope for any element remains the one whose structure survives the addition of one or more neutrons. The predicted “islands of inversion” in the O to Mg region have been observed in high intensity beam experiments.[24, 25] The model reveals, as shown in Table VII, the same pattern of structure for each of the three particle-stable nuclides beyond the neutron drip-line, viz. ^{31}F, ^{34}Ne and ^{37}Na.

The structural feature which characterises those three nuclides is four neutrons bound to nine (F), ten (Ne) and eleven (Na) tritons. The upper limits to the mass of the isotope series for the three elements are ^{27}F, ^{30}Ne and ^{33}Na, as shown in Table VII. Therefore, the model defines those isotopes as composite objects: ^{27}F + ^{4}n, ^{30}Ne + ^{4}n and ^{33}Na + ^{4}n. The appearance of the island of particle-stability, which occurs well beyond the neutron drip line of those three elements, indicates the unusual nature of those objects. They stand out as different from those preceding them in the series.

It is of interest that a free tetraneutron signature has been observed in break-up experiments with ^{14}Be on a carbon target.[26] The reported lifetime of the order of 100 ns or greater suggests that the isolated ^{4}n is particle-stable. Theoretical, few-body NN forces simply cannot accommodate the existence of a 4n cluster.[27] According to the ECM, ^{31}F, ^{34}Ne and ^{37}Na are each a tetraneutron bound to the heaviest isotopic nucleus of those three elements; which means that the tetraneutron is not only stable in isolation, but also when part of a composite object of which a nucleus at the isotopic high mass-limit is the other component.

7. DISCUSSION

If the model did not correlate with observations it would be possible to believe that it is merely an exercise in the algebra of numbers. But the unification of several diverse light nuclear phenomena is indicative of its intrinsic value. Its dynamic collectivity prompts the theory that A=3Z is the upper mass limit of any isotope series; the observed onset of the light element neutron emission decay mode and the islands of particle stability beyond the drip-line connect the theory with physical reality. The model is not based on an arbitrary numerical arrangement of nucleons among the four cluster types. The distribution rules derive from two principles which the model consistently reflects. The coupling of the conservation of nucleon excess, by the three-body mirror clusters, with the established alpha substructural scheme extends naturally throughout the nuclear landscape and the principle of discrete, reactive collectivity falls out of the model.

The observation that the 18 MeV resonance in ^{6}He decays to two tritons with a branching ratio of 90±10% [21] is a strong indicator of an underlying di-triton structure and it is argued that the same structure obtains at the particle-stable ground state. This has several consequences which cannot be currently explained. They include the question: why does the conservation of neutron excess in three-body mirror clusters take structural precedence over the potential to form the more strongly bound alpha? Intuitively, ^{6}He should be a two-neutron halo nucleus with a single alpha core, which is how it is generally considered. The mere presence of the requisite nucleons is seemingly insufficient for alpha cluster formation. According to the model, this order of precedence pervades the whole nuclear landscape, which means that the ^{6}He di-triton data is strong support for the model. If it is the case that nuclear structure is a consequence of the nucleon binding interaction(s) then a deeper understanding of *NN* forces is needed to explain recent light nuclear data.

The precedence of neutron excess-driven triton cluster formation over alpha formation leads naturally to the concept of a mass-limit for the isotope series of each element. This concept is supported by light nuclear neutron emission and halo data. Further additional neutrons are simply passengers because they do not contribute to the creation of new structure. Their observed weak bond and distance from the core is consistent with their non-participation in the structure of the nucleus. This concept has a close parallel with the theory of halo nuclei, with which the model is generally congruent.

A consequence of the passenger neutron concept is that the observed islands of particle stability of F, Ne and Na, beyond the neutron drip-line, are manifestations of an object composed of a tetraneutron coupled to a nucleus. This interpretation, which supports and extends the observation of the free tetraneutron,[26] is completely outside the scope of few-body *NN* forces as they are currently understood.

The model accommodates not only observations which cannot currently be explained but also well accepted light-nuclear phenomena. The current approach deserves attention if only because of its accommodation of uncontroversial light nuclear data. By contrast, perhaps its most surprising correlation is that with the potential for β-decay. The model gives a completely unexpected structure to the potential for nuclear β-decay and ties it directly to the postulated ^{6}He substructure, by way of its observed di-triton clusters. The observed β-stability of all the $N=Z+1$ nuclei confirms that the single triton cluster in an $A>4$ nucleus lacks the potential for β-decay; thus making it a structural analogue of the stability of the single neutron in the deuteron.

It is particularly interesting that the departure of the present study from mainstream structure concepts is matched by the incongruity with established theory of some of the data it models so well. Both the model and some of the explanations of observations it provides are seemingly outside the domain of lattice QCD and nuclear forces as they are currently understood. This leads to the conclusion that the model may assist in an improved understanding of light nuclear phenomena and the interactions which are their genesis.

By extension of the proposed nuclide-coupled tetraneutrons, and in the absence of a theoretical framework to account for free tetraneutrons, it is predicted that particle-stable neutron clusters should be found coupled to other high mass-limit isotopes. The prediction, which is clearly testable, is not limited to four neutrons and neither need they be β-unstable. Such observations, if they are made, will lend further support to the model.

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9. REFERENCES

1. A. Ozawa, T. Kobayashi, H. Sato, D. Hirata, I. Tanihata, O. Yamakawa, K. Omata, K. Sugimoto, D. Olson, W. Christie, and H. Wieman, Phys. Lett. B **334,** 18 (1994).

2. R.K. Gupta, S. Kumar, and W. Scheid, J. Phys. G: Nucl. Part. Phys. **21**, L27 (1995).

3. M. Garçon, and J.W. Van Orden, nucl-th/0102049.

4. M.G. Mayer, and J.H.D. Jensen, Elementary Theory of Nuclear Shell Structure (Wiley, New York, 1955).

5. E.R. Scerri, Foundations of Chemistry **3**, 97 (2001).

6. J. Al-Khalili, and F. Nunes, nucl-th/0306071.

7. H. Fujiwara, H. Horiuchi, K. Ikeda, M. Kamimura, K. Kato, Y.Suzuki, and E. Uegaki, Prog. Theor. Phys. Suppl. No.68, 29 (1980).

8. B.R. Fulton, Clustering Aspects in Nuclear Structure and Dynamics: Proceedings of the 7th International Conference, 42 (Edited by M. Korolija, Z. Basrak, and R. Caplar) (World Scientific, Singapore 1999).

9.A. Tohsaki, H. Horiuchi, P. Schuck, and G. Röpke, Phys. Rev. Letters **87**, 192501 (2001).

10. M. Freer, and A.C. Merchant, Phys. G: Nucl. Part. Phys. **23,** 261 (1997).

11. S.A. Abbas, Mod. Phys. Lett. A **16**, 755 (2001).

12. Kinsey, R.R. et al., The NUDAT/PCNUDAT Program for Nuclear Data: 9th International Symposium of Capture, Gamma ray Spectroscopy and Related Topics, Budapest, Hungary, October 1996. Data extracted from NUDAT database (Jan. 14/1999).

13. I. Tanihata, H. Hamagaki, O. Hashimoto, S. Nagamiya, Y. Shida, N. Yoshikawa, O. Yamakawa, K. Sugimoto, T. Kobayashi, D.E. Greiner, N. Takahashi, and Y. Nojiri, Phys. Lett. B **160,** 380 (1985).

14. I. Tanihata, H. Hamagaki, O. Hashimoto, Y. Shida, N. Yoshikawa, K. Sugimoto, O. Yamakawa, T. Kobayashi, and N. Takahashi, Phys. Rev. Lett. **55,** 2676 (1985).

15. M.G. Saint-Laurent, R. Anne, D. Bazin, D. Guillemaud-Mueller, U. Jahnke, Jin Gen Ming, A.C. Mueller, J.F. Bruandet, F. Glasser, S. Kox, E. Liatard, Tsan Ung Chan, G.J. Costa, C. Heitz, Y. El-Masri, F. Hanappe, R. Bimbot, E. Arnold and R. Neugart, Z. Phys. A **332,** 457 (1989).

16. N.A. Orr, Phys. Rev. C **51,** 3116 (1995).

17. R. Anne, S.E. Arnell, R. Bimbot, S. Dogny, H. Emling, H. Esbensen, D. Guillemaud-Mueller, P.G. Hansen, P. Hornshoj, F. Humbert, B. Jonson, M. Keim, M. Lewitowicz, P. Moller, A.C. Mueller, R. Neugart, T. Nilsson, G. Nyman, F. Pougheon, K. Riisager, M.G. Saint-Laurent, G. Schrieder, O. Sorlin, O. Tengblad, K. Wilhelmsen Rolander and D. Wolski, Phys. Lett. B **304,** 55 (1993).

18. J.H. Kelley, Sam M. Austin, R.A. Kryger, D.J. Morrissesy, N.A. Orr, B.M. Sherrill, M. Thoennessen, J.S. Winfield, J.A. Winger, and B.M. Young, Phys. Rev. Lett. **74,** 30 (1995).

19. F.M. Marqués, E. Liegard, N.A. Orr, J.C. Angélique, L. Axelsson, G. Bizard, W.N. Catford, N.M. Clarke, G. Costa, M. Freer, S. Grévy, D. Guillemand-Mueller, G.J. Gyapong, F. Hanappe, P.G. Hansen, B. Heusch, B. Jonson, C. Le Brun, F.R. Lecolley, F. Lefebvres, M. Lewitowicz, G. Martinez, A.C. Mueller, T. Nilsson, A. Ninane, G. Nyman, B. Petersen, F. Pougheon, K. Riisager, M.G. Saint-Laurent, Y. Schultz, M. Smedberg, O. Sorlin, L. Stuttgé, D.D. Warner, Phys. Lett. B **381,** 407 (1996).

20. D. Bazin, W. Benenson, B.A. Brown, J. Brown, B. Davids, M. Fauerbach, P.G. Hansen, P. Mantica, D.J. Morrissey, C.F. Powell, B.M. Sherrill, and M. Steiner, Phys. Rev. C **57,** 2156 (1998).

21. H. Akimune, T. Yamagata, S. Nakayama, Y. Arimoto, M. Fujiwara, K. Fushimi, K. Hara, M.

Ohta, A. Shiokawa, M. Tanaka, H. Utsunomiya, K.Y. Hara, H.P. Yoshida, and M. Yosoi, Phys. Rev. C **67,** 051302(R) (2003).

22. E. Garrido, and E. Moya de Guerra, nucl-th/9902075.

23. C. Thibault, R. Klapisch, C. Rigaud, A.M. Poskanzer, R. Prieels, L. Lessard, and W. Reisdorf, Phys. Rev. C **12,** 644 (1975).

24. Y.S. Lutostansky, M.V. Zverev, and I.V. Panov, Nuclei Far from Stability: Proceedings of the 5th International Conference, 288 (Am. Inst. of Phys., NewYork, 1988).

25. H. Sakurai, S.M. Lukyanov, M. Notani, N. Aoi, D. Beaumel, N. Fukuda, M. Hirai, E. Ideguchi, N. Imai, M. Ishihara, H. Iwasaki, T. Kubo, K. Kusaka, H. Kumagai, T. Nakamura, H. Ogawa, Yu. E. Penionzhkevich, T. Teranishi, Y.X. Watanabe, K. Yoneda and A. Yoshida, Phys. Lett. B **448,** 180 (1999). Yu. S. Lutostansky, S.M. Lukyanov, Yu. E. Penionzhkevich, and M.V. Zverev, Part. Nucl. Letters **115**, 86 (2002).

26. F.M. Marqués, M. Labiche, N.A. Orr, J.C. Angélique, L. Axelsson, B. Benoit, U.C. Bergmann, M.J.G. Borge, W.N. Catford, S.P.G. Chappell, N.M. Clarke, G. Costa, N. Curtis, A. D'Arrigo, E. de Góes Brennand, F. de Oliveira Santos, O. Dorvaux, G. Fazio, M. Freer, B.R. Fulton, G. Giardina, S. Grévy, D. Guillemaud-Mueller, F. Hanappe, B. Heusch, B. Jonson, C. Le Brun, S. Leenhardt, M. Lewitowicz, M.J. López, K. Markenroth, A.C. Mueller, T. Nilsson, A. Ninane, G. Nyman, I. Piqueras, K. Riisager, M.G. Saint Laurent, F. Sarazin, S.M. Singer, O. Sorlin, and L. Stuttgé, Phys. Rev. C **65**, 044006 (2002).

27. C.A. Bertulani, and V. Zelevinsky, nucl-th/0212060.

Table I. The isotopes of carbon are shown as an example of the discrete, dynamic collectivity and reactivity of nuclear structure and its mass-limits for a single element. Neutron addition beyond ^{18}C (*A*=3Z) fails to alter the underlying structure.

Nucleons			Structure		
A	Z	N	α	T	d
7	6	1		h+4p	
8	6	2	1+4p		
9	6	3	1	h+2p	
10	6	4	2+2p		
11	6	5	2	h	
12	6	6	3		
13	6	7	2	1	1
14	6	8	2	2	
15	6	9	1	3	1
16	6	10	1	4	
17	6	11		5	1
18	6	12		6	
19	6	13		6+n	
20	6	14		6+2n	
21	6	15		6+3n	
22	6	16		6+4n	

Here *A* means atomic number, Z - proton charge, N - neutron number, α - alpha cluster, T - three-body cluster (numeral - triton; h - ^{3}He), d - deuteron cluster; p (proton) and n (neutron) are passenger nucleons which do not contribute to nuclear structure.

Table II. Examples of the effect on nuclear structure of the addition of single neutrons. Each excess neutron forms a triton. All other neutrons tend to form alphas. Odd-neutron nuclides form a deuteron.

	Nucleons		Structure		
Nuclide	Z	N	α	T	d
^{4}He	2	2	1	0	0
^{5}He	2	3	0	1	1
^{6}He	2	4	0	2	0
^{8}Be	4	4	2	0	0
^{9}Be	4	5	1	1	1

Key: see Table I

Table III. Examples of effects on nuclear structure of the serial addition of single protons. Each excess neutron forms a triton. All other neutrons tend to form alphas. A residual neutron forms a ^{3}He if more than one proton is available; remaining protons do not contribute to nuclear structure.

	Nucleons		Structure	
	Z	N	α	T
N $\geq$ Z				
Isotone				
^{37}Cl	17	20	7	3
^{38}Ar	18	20	8	2
^{39}K	19	20	9	1
^{40}Ca	20	20	10	
N < Z				
Isotone				
^{14}F	9	5	2	h+3p
^{13}O	8	5	2	h+2p
^{12}N	7	5	2	h+p
^{11}C	6	5	2	h

Key: see Table I

Table IV. The effect on nuclear structure of serial β-decay beginning with ^{32}Na and terminating with ^{32}S.

	Nucleons		Structure		
Nuclide	Z	N	α	T	d
^{32}Na	11	21		10	1
^{32}Mg	12	20	2	8	
^{32}Al	13	19	3	6	1
^{32}Si	14	18	5	4	
^{32}P	15	17	6	2	1
^{32}S	16	16	8		

Key: see Table I

Table V. The heaviest isotope and the *A*=3Z+1 isotope for each of the twelve lightest elements. For the lighter elements, neutron emission is the dominant decay mode of the *A*=3Z+1. Multiple decay modes, where shown, are in descending order of branching ratios. Half-lives and decay modes are taken from Ref. 12.

	Nucleons			Structure*		Decay Mode
Nuclide	*A*	Z	N	T	~*T*1/2	
^{3}H	3	1	2	1	12.3 y	b
^{4}H	4	1	3	1+n	?	n
^{6}He	6	2	4	2	8 ms	b
^{7}He	7	2	5	2+n	2.9 e-06 fs	n
^{9}Li	9	3	6	3	178 ms	b, b+n, b+n+2α
^{10}Li	10	3	7	3+n	3.8 e-07 fs	n
^{12}Be	12	4	8	4	24 ms	b, b+n
^{13}Be	13	4	9	4+n	2.7 E-21 s	n
^{15}B	15	5	10	5	10 ms	b
^{16}B	16	5	11	5+n	<190 ps	n
^{18}C	18	6	12	6	95 ms	b, b+n
^{19}C	19	6	13	6+n	49 ms	b+n, b
^{21}N	21	7	14	7	87 ms	b, b+n
^{22}N	22	7	15	7+n	18 ms	b, b+n
^{24}O	24	8	16	8	61 ms	b+n, b
^{25}O	25	8	17	8+n	<40 ns	n
^{27}F	27	9	18	9	>200 ns	?
^{28}F	28	9	19	9+n	<40 ns	n
^{30}Ne	30	10	20	10	>200 ns	b
^{31}Ne	31	10	21	10+n	?	?
^{33}Na	33	11	22	11	8 ms	b, b+n, b+2n
^{34}Na	34	11	23	11+n	5 ms	b+2n, b, b+n
^{36}Mg	36	12	24	12	>200 ns	b
^{37}Mg	37	12	25	12+n	>260 ns	b, b+n

* Structure is completely reduced to triton clusters.

Key: see Table I

Table VI. The structure of the generally accepted one- and two-neutron light-element halo nuclei. The heaviest isotope for each element, according to the model, is shown in bold type.

	Nucleons				Structure		
Nuclide	*A*	Z	N		α	T	d
^{6}He	6	2	4	2n halo		2	
^{7}He	7	2	5			2+n	
^{8}He	8	2	6			2+2n	
^{9}Li	9	3	6			3	
^{10}Li	10	3	7			3+n	
^{11}Li	11	3	8	2n halo		3+2n	
^{11}Be	11	4	7	1n halo		3	1
^{12}Be	12	4	8			4	
^{13}Be	13	4	9			4+n	
^{14}Be	14	4	10	2n halo		4+2n	
^{15}B	15	5	10			5	
^{16}B	16	5	11			5+n	
^{17}B	17	5	12	2n halo		5+2n	
^{18}C	18	6	12			6	
^{19}C	19	6	13	1n halo		6+n	

Key: see Table I

Table VII The neutron-rich isotopes of F, Ne and Na and the common structural pattern of the particle-stable nuclei, ^{31}F, ^{34}Ne and ^{37}Na, beyond the neutron drip-line. Half-lives and decay modes are taken from Ref. 12.

	Nucleons			Structure				Decay
	A	Z	N	α	T	d	~*T*1/2	Mode
Fluorine								
	19	9	10	4	1		stable	
	20	9	11	3	2	1	11 s	b
	21	9	12	3	3		4 s	b
	22	9	13	2	4	1	4 s	b
	23	9	14	2	5		2 s	b
	24	9	15	1	6	1	300 ms	b
	25	9	16	1	7		87 ms	b, b+n*
	26	9	17		8	1	190 ms	b, b+n
	27	9	18		9		>200 ns	
	28	9	19		9 +n		<40 ns	n
	29	9	20		9 +2n		>200 ns	b
	30	9	21		9 +3n		?	particle unstable
	31	9	22		9 +4n		?	particle stable
Neon								
	20	10	10	5			stable	
	21	10	11	4	1	1	stable	
	22	10	12	4	2		stable	
	23	10	13	3	3	1	37 s	b
	24	10	14	3	4		3 ms	b
	25	10	15	2	5	1	600 ms	b
	26	10	16	2	6		200 ms	b
	27	10	17	1	7	1	32 ms	b, b+n*
	28	10	18	1	8		14 ms	b, b+n
	29	10	19		9	1	200 ms	b+n
	30	10	20		10		>200 ns	b
	31	10	21		10 +n		?	?

Table VII continued

32	10	22		10 +2n		>200 ns	?
33	10	23		10 +3n		?	particle unstable
34	10	24		10 +4n		?	particle stable

Sodium

23	11	12	5	1		stable	
24	11	13	4	2	1	15 h	b
25	11	14	4	3		59 s	b
26	11	15	3	4	1	1 s	b
27	11	16	3	5		300 ms	b, b+n*
28	11	17	2	6	1	30 ms	b, b+n
29	11	18	2	7		45 ms	b, b+n
30	11	19	1	8	1	48 ms	b, b+n(2n), b+α
31	11	20	1	9		17 ms	b, b+n, b+2n
32	11	21		10	1	13 ms	b, b+n, b+2n
33	11	22		11		8 ms	b, b+n, b+2n
34	11	23		11 +n		5 ms	b, b+2n, b+n
35	11	24		11 +2n		1 ms	b, b+n
36	11	25		11 +3n		?	particle unstable
37	11	26		11 +4n		?	particle stable

Key: see Table I

* marks the onset of the particle-unstable region for each element which gives way to the inverted region of particle stability.