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Borromean Halo Nuclei

J. S. Vaagen,[1] D. K. Gridnev,[1] H. Heiberg-Andersen,[1] B. V. Danilin,[2,*] S. N. Ershov,[3,*] V. I. Zagrebaev,[3,*] I. J. Thompson,[4,*] M. V. Zhukov[5,*] and J. M. Bang[6,*]

[1] SENTEF, Department of Physics, University of Bergen, N-5007 Bergen, Norway
[2] RRC The Kurchatov Institute, Moscow, Russia
[3] JINR, Dubna, Russia
[4] Department of Physics, University of Surrey, Guildford, United Kingdom
[5] Chalmers University of Technology and Göteborg University, S-41296 Göteborg, Sweden
[6] The Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

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Abstract

Recent studies of lighter dripline nuclei have revealed dramatic deviations from the matter distribution of ordinary stable nuclei and shell model ordering. New stability patterns such as halo nuclei with co-existence of normal and low-density nucleonic matter have been discovered, the Borromean nuclei being the most outstanding. Lessons of the last decade which have led to enrichment of the nuclear paradigm are discussed.

1. Neutron-rich light nuclei: A stability lesson

With access to secondary exotic nuclear beams, the edges of the nuclear landscape itself can be explored, *i.e.* the very limits of nuclear existence. At these limits, the so-called neutron (proton) *driplines,* additional neutrons (protons) can no longer be kept in the nucleus – they literally drip out. The exact locations of the boundaries are far from clear and their complete delineation awaits a better quantitative understanding of the nuclear system. Nuclei far from stability allow us to amplify and isolate particular aspects of the nuclear interaction and dynamics. Using what we learn from these nuclei we can then return to the nuclei of the world around us and understand them far better than ever before.

Light nuclei constitute so far the part of the nuclear landscape where the neutron dripline has been reached. Triggered by Tanihata's discovery (1985) [1] of vastly spatially extended nuclei (^{6,8}He; ^{11}Li; ^{11}Be) at the neutron dripline, the initial idea of (binary) halos was suggested by B. Jonson and P. G. Hansen. Subsequent developments have deepened, and enriched the picture of halos as outstanding structural dripline phenomena with extreme clusterization into an ordinary core nucleus and veil of halo nucleons – forming exceptionally dilute neutron matter. The origin of the stratification is of pure quantum mechanics nature and only partly understood, but a prerequisite is low angular momentum motion for the halo particles and few-body dynamics such as in Borromean nuclei† characterized by pairwise constituents with no bound states. In the limit of vanishing binding extremely large halos may occur.

The Borromean property is clearly exhibited by the hadronic stability of various isotope chains, see Fig. 1. Thus,

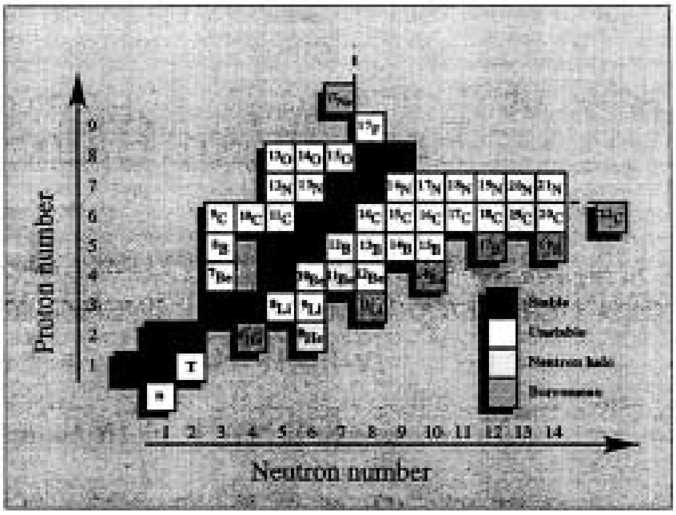

Fig. 1. The nuclear chart exhibits the stability of Borromean nuclei among different isotope chains.

while ^{5}He is unbound ^{6}He is bound,^{7}He is unbound but ^{8}He is again bound.

2. Halo nuclei; Clusters and a veil of extremely dilute and extended neutron matter

The granularity of a halo nucleus, say that of the cardinal case of ^{11}Li, is not trivial, see Fig. 2. The spatial extention is huge, the rms matter radius of ^{11}Li is as large as that of ^{48}Ca, and the radius of the halo neutrons as large as for the outermost neutrons in ^{208}Pb. It is a true challenge for theory to account for both extension and granularity.

The nucleus is a self-organized system, in contrast to atoms where the electronic motion to a large extent is dictated by the central interaction with the nucleus. The complexity of the nuclear many-body problem, where even the interaction between the nucleonic constituents still is a question which is not fully settled, has made nuclear physics a phenomena driven field. Progress in nuclear structure is made at various levels at which one attempts to understand nuclear phenomena;

(*i*) Experimental data and phenomenology,
(*ii*) "Local models" (effective models with few emergent degrees of freedom),

* with RNBT collaboration.
† The three Borromean rings, the heraldic symbol of the Italian Borromeo family, are interlocked in such a way that if any of them were removed, the other two would also fall apart. The three interwined Borromean rings are now widely used as the logo of the halo field.

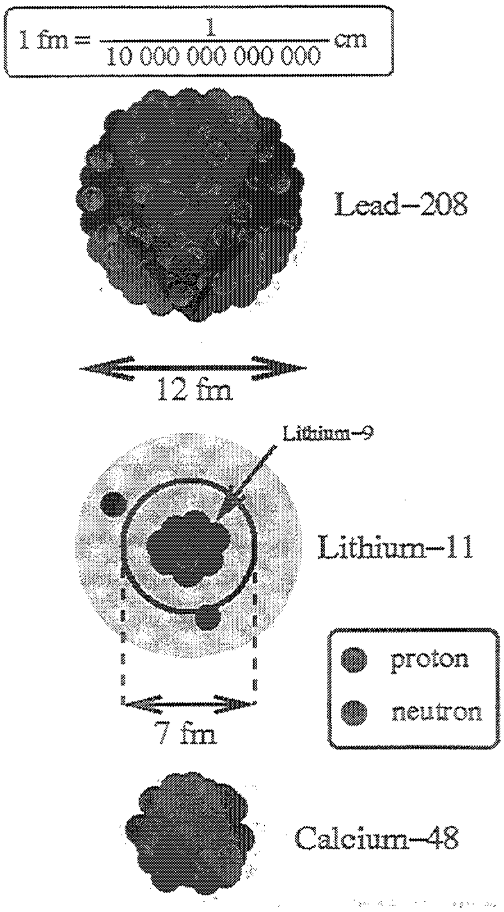

Fig. 2. The matter size of ^{11}Li is compared to that of ^{48}Ca and ^{208}Pb.

(*iii*) "Global nuclear models,"
(*iv*) *Ab initio* NN-interaction based procedures,
(*v*) QCD.

There is an overall effort to explain higher levels in terms of lower ones, but a complete reductionistic "deductive approach" is unlikely to be the efficient way of understanding nuclei (neither can this yet be done technically); the more constructive/physical approach is to isolate and understand the characteristic degrees of freedom of nuclei.

Pioneering activities usually employ some kind of scaffolding and the discoveries are highlighted in terms of heuristic interpretations. These emphasize the new findings. Halo physics is no exception. The binary core-(point) dineutron picture of Hansen and Jonson for two-neutron halos (1987), originally just meant to illustrate how large extension and weak binding may be related, turned out to be an oversimplification. Since 1990 halo models have been developed where the N-N degree of freedom is no longer frozen, but chosen in accordance with the free NN interaction inspired by the dilute character of the halo. Thus focus has been shifted to features genuinely related to the intrinsic character of the halo and the interplay a halo degrees of freedom.

The present picture of a "normal" nucleus veiled in a neutron halo, i.e. co-existence of normal and low density nuclear material, has emerged from a concerted effort between subsequent dedicated measurements and theory. How this stratification takes place still needs to be better understood, but nature seems to have provided a laboratory where "eigenproperties" of the low-density halo can be studied, subjected only to a mild influence from the presence of the core object. Few-body dynamics plays the crucial role in any adequate description of halo properties, since for halo bound states most of the wave function is concentrated in the classically forbidden region. The chain of He isotopes with an alpha core has become particularly useful as benchmark systems.

In three-body models of halo nuclei. such as ^6He, Pauli blocking is needed to remove components of the halo wave function that would disappear under full antisymmetrization. This, and also other aspects of the composite nature of the clusters make the challenge somewhat different from that of three-nucleon systems.

3. Nature's most loosely bound nuclei

With the help of the variational principle it is possible to derive general necessary conditions for existence of a bound state in few-body systems. Conditions of this kind can be formulated for the most loosely bound quantum systems, the Borromean systems, where each pair channel is unbound but has some fraction v of binding (v is the inverse of the coupling constant which is sufficient for the first level to appear).

The most simple of these conditions [2] involves just fractions of binding in each pair channel v_{12}, v_{13}, v_{23} and the mass ratios in the system $m_1 : m_2 : m_3$:

$$v_{12}\left(1-\frac{m_1m_2}{S}\right)+v_{13}\left(1-\frac{m_1m_3}{S}\right)+v_{23}\left(1-\frac{m_2m_3}{S}\right)>1, \quad (1)$$

where S is the sum of all pair products of masses: $S = m_1m_2 + m_1m_3 + m_2m_3$.

Let us illustrate this condition using the physically important example of the nucleus ^6He. Here the two-neutron halo is formed by two external neutrons each with mass ratio to the core equal to $1/4$. In this bound nucleus none of the pair channels are bound so this system is Borromean. If we denote the fractions of binding in the neutron–neutron channel as V_{nn} and in the neutron–core channel as V_{Cn} then all systems lying in the square $0 \leq V_{nn} \leq 1$ and $0 \leq V_{Cn} \leq 1$ are either Borromean or unbound. In this square, we will have a smooth curve, separating the points where a bound state of the three-particle system may exist, from where the whole system is unbound. We will call this plot a phase diagram, since the curve separates the bound and the unbound phase of the system. Inserting the mass ratios we rewrite the necessary condition for a level for ^6He as follows:

$$(8/9)V_{nn} + (10/9)V_{Cn} > 1. \quad (2)$$

The area of possibly bound systems is indicated at Fig. 3. For different potentials there will be different curves, but all of them will lie above the straight line which is predicted theoretically. With the help of this technique it is also possible to estimate the binding energy in the system.

4. Simplicity in complexity

For Borromean nuclei a most important tool has been the Hyper Harmonic method, which has allowed us to understand the leading physics in terms of only a few wave func-

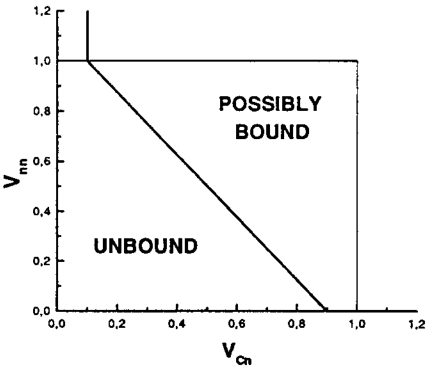

Fig. 3. Phase diagram for systems of ^{6}He-type. The solid line approximately separates the bound phase, the systems under the curve being strictly unbound. ^{6}He is located near the right top corner of the Borromean square since every pair-channel has a low-lying resonance.

tion components [3,4]. For a Borromean 3-body like two-neutron halo system (f.ex. ^{6}He) the asymptotic behavior is simple in the hyperradius, but complicated in shell model coordinates. In the hyperradius ρ, where $\rho^2 = \frac{1}{A}\Sigma A_i A_j r_{ij}^2$, the decay is exponential and governed by the square root of the two-neutron separation energy.

It is customary in fields with a rich history to try to fit the new findings within the ruling formalisms, in nuclear physics a many-particle shell model type picture. The shell model has however, not turned out very suited for halo systems, at least very impractical for neutrons so close to the continuum threshold. The concept of orbits in the sense of relative motions with respect to the core, is on the other hand still fruitful. Thus the recognition of the instrumental role of low angular momentum "intruder" orbits (s and p) has become essential to our understanding of exotic structure formation and the melting of shell structures at the neutron dripline. The lesson learned in few-body treatments may be expressed in translation invariant "shell-model like" coordinates drawn from the core to the halo neutrons. Although this involves large expansions, advances have been made recently with solution procedures in such coordinates. This prepares the ground for future comparison further up the dripline with procedures rooted in a mean field approach (when a spatially realistic surface pairing has been pinned down), where CM motion is less critical. There is currently a need to find lighter nuclei where the two approaches can be meaningfully compared.

A dream dating back to the early years of nuclear physics is that of starting from the free binary interactions, for reactions as well as structure. The influence of the nuclear medium has complicated this approach. For loosely bound dripline nuclei this question has renewed interest, for learning about three-body forces and reaction mechanisms.

The nature of the halo seems sufficiently dilute to justify approaches where the starting point is the free nucleon–nucleon t-matrix, Thus work has been initiated on charge–exchange at higher energies within multiple scattering formalisms (Watson, KMT). Also, few-body reaction theories are being developed which are particularly appropriate to heavier halo candidates. Studies of ^{6}Li(n,p)^{6}He at 200 MeV comparing aysmptotically correct and incorrect oscillator type COSMA [3] form factors show that correct tails matter! This in spite that the COSMA wave functions are tuned to reproduce the correct rms matter radii. Similar conclusions have been derived from recent complete Glauber calculations for elastic scattering of ^{6}He+p at high energies.

5. A Borromean dream – in another field

In a remarkable paper in atomic physics in 1988 [5], "Loosely bound states of three particles", Zhen and Macek write; "Although there is no corresponding experimental data to confirm these results at present, the theory is nevertheless of great interest because it predicts some new physical properties of three-body systems, among which the most remarkable one is the existence of loosely bound states in such systems, even though the interaction potential between the particles has no wells strong enough to bind any two of the three particles separately. Because of this, and since the threebody system is the simplest model in many-body problems, it seems desirable to use the three-body system (instead of two-body) as the basic block of the many-body system".

The dream had already come true, three years earlier – but in another field, at the neutron dripline when Isao Tanihata and his team made their discoveries in 1985. In the following decade ^{6}He and ^{11}Li became understood as realizations of exactly the mechanisms Zhen and Macek were speaking about, and (1993) baptized Borromean halo nuclei [3]. At that time we were, however, not aware of the Zhen/Macek paper.

6. The Borromean gateway to our universe

The Hoyle resonance in ^{12}C plays a crucial role in the synthesis of the elements; "It wouldn't be missed if it didn't exist" to paraphrase (MB) a statement by the Danish writer Piet Hein. It is the doorway to our Universe. The processes leading to this doorway all proceed from ^{4}He via Borromean systems;

(*i*) in Red Giants via the triple α-process,
(*ii*) in Supernovae via $^9_4$Be$_5$ also Borromean and,
(*iii*) lesser probable a side-route to ^{9}Be via ^{6}He. Recall that neither ($\alpha\alpha$), (αn) nor (nn) can form bound binary systems, only resonances.

7. Dissecting Borromean structures

Low-energy two-neutron transfer reactions with Borromean nuclei (like ^{6}He) have recently been shown to be an effective instrument for studying both the structure of such nuclei and the dynamics of nuclear reactions where they take part. A four-body model has been developed to describe such two-nucleon transfer processes within DWBA. A realistic 3-body bound state wave function of ^{6}He is used in the calculations and the role of its separate components [6] has been thoroughly studied. In particular, it is found that the "di-neutron," configuration of the ^{6}He nucleus gives the dominant contribution to the two-neutron transfer cross sections, measured at FLNR, Dubna, see Fig. 4. The possibilities of using multi-neutron transfer reactions for studying the structure of other radioactive nuclei, such as ^{8}He, have

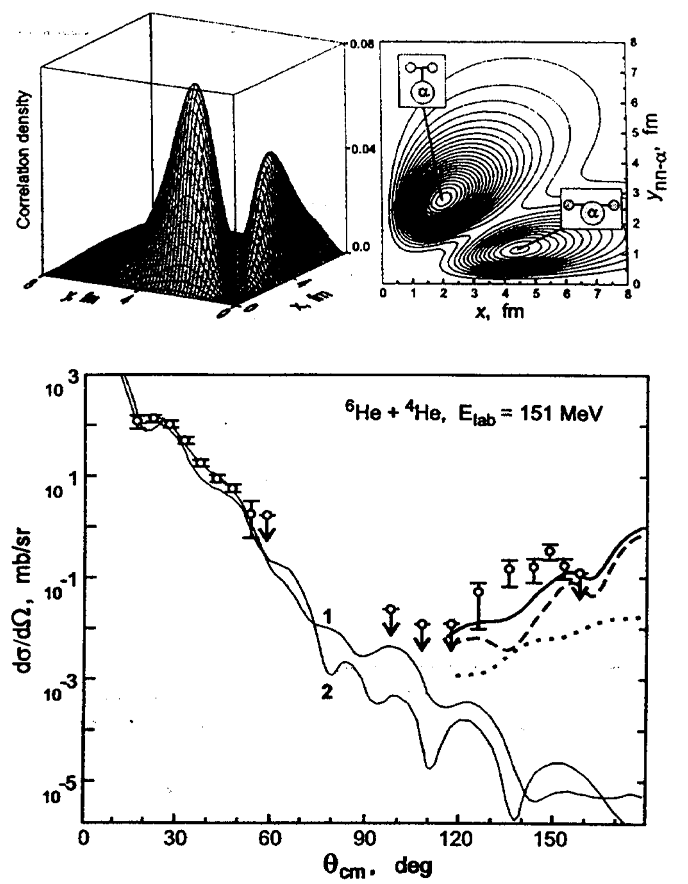

Fig. 4. Top Spatial correlation density plot for the 0^+ ground state of ^{6}He with di-neutron and cigar-like components shown schematically. Bottom – The ^{6}He + ^{4}He elastic scattering at $E_{\rm lab} = 151$ MeV. The thin curves 1 and 2 show the potential scattering. The thick solid line corresponds to the 2n exchange process, whereas the dashed and dotted lines show the contributions of the di-neutron and cigar-like configurations of ^{6}He to the 2n-transfer process.

now become part of the schedule at leading international laboratories.

8. Exciting a Borromean halo

Dripline physics, involving nuclei with only one or a few weakly bound states, is physics of threshold phenomena and structure and reaction theory merge. Recently European theorists have addressed this issue and successfully extended the theoretical few-body approach to also encompass three-body continuum structure, response functions and reactions involving Borromean systems. For the first time it has been demonstrated how even inclusive observables such as diffractive break-up are intimately related to the structure of the three-body continuum. The measurement and analysis of the continuum response of halo systems near threshold directly explores this asymptotic behaviour. This development is also enabling us to understand the physical nature of the famous "soft modes," present in the low-lying continuum of neutron-rich lighter nuclei.

Enormously extended spatial correlations in the three-body Borromean continuum are found within a full three-body dynamical model. Correlated spatial densities for antisymmetrised plane waves, for narrow 3-body resonances as well as densities for wide resonances and for 3-body-virtual excitations are currently being analyzed.

Borromean continuum wave functions are solutions of the three-body scattering problem. Again the Borromean property simplifies the problem solution, which in hyperspherical coordinates resembles binary scattering in a deformed field. The most extensive and reliable analysis has been carried out for ^{6}He [4] where as a cheek point the known 2^+ resonance is reproduced. The calculations give 1^- strength concentrations at lower energies (soft modes) in the proximity of the three-body threshold and predict new 2^+, 1^+ (and possibly 0^+) resonances at slightly higher energies in ^{6}He.

This correlated microscopic continuum structure has been used to gain new insight in halo fragmentation in diffractive breakup. Thus the crucial role of the low-lying three-body resonances and soft modes in determining distribution characteristics (width and shape) has been demonstrated. A surprising memory of the low-lying continuum structure prevails even in inclusive observables.

9. *Ab initio* calculations of halos

The most ambitious of these reductionistic attempts are the variational Monte Carlo (VMC) and improved Green's Function Monte Carlo (GFMC) calculations [7]. According to the authors "These are the first microscopic calculations that directly produce nuclear shell structure from realistic interactions that fit NN scattering data." Another line of approach is the large-basis no-core shell-model (LBSM) calculations of Barrett's group [8], where "It is demonstrated that the shell model combined with microscopic effective interactions derived from modern nucleon–nucleon potentials is capable of providing good agreement with the experimental properties of the ground state as well as those of the low-lying excited states." Comparing the results obtained so far we find that neither GFMC nor LBSM are able to bind loosely bound halo systems like ^{6}He and ^{8}He, missing by several MeV. The newly discovered state in ^{7}He. (unbound, i.e. beyond the dripline) at excitation energy of about 3.2 MeV and to be discussed in Korsheninnikov's talk [9], where he argues for an assignment $5/2^-$, comes out roughly correct in LBSM, and also in GFMC with recently modified three-body force. Both approaches do, however, produce a low-lying $1/2^-$ state which so far has not been seen experimentally.

The size of the GFMC and LBSM calculations regrettably grows beyond what is manageable even before ^{11}Li is reached. The practitioners have, however, already learned some useful lessons from their pioneering attempts. Thus the GFMC calculations for $A = 6$ do produce an alpha-like core object, a promising feature. In the context of $A = 10$ nuclei, the authors of [8] write, "We should note that, as discussed above for the ^{8}He calculation, the shell-model single-particle wave-functions have incorrect asymptotics. The shell model approach is, therefore, not quite suitable for the description of weakly bound states or resonances." This is however very much what the dripline is about!

To check the information content in GFMC type wave functions, beyond binding energies, a joint venture with few-body modeling is needed to explore critical observables and to improve the asymptotic behavior of GFMC. Planning to this end is being initiated and the work will require the best available computer support.

Although progress is being made with models starting at the nucleon level, also the variational stochastic method pioneered by Debrechen, these approaches become increasingly difficult to carry out with growing nucleon number. Thus an amalgamation with cluster-based procedures appears to be the theoretical framework for foreseable future even for light dripline nuclei; A composite approach instead of a unified theory such as that of a mean field.

10. Enriching the nuclear paradigm

Thomas Kuhn, in his famous book "The Structure of Scientific Revolutions" [10] claims that we are hypnotized by our paradigms. Kuhn's conclusions are questioned by Steven Weinberg in a recent article "The Revolution That Didn't Happen," in the New York Review [11]. In particular Weinberg argues that "He (Kulm) was quite wrong in saying that it is no part of the work of normal science to find new sorts of phenomena." Here we side with Weinberg. New discoveries, also fundamental, do not as a rule require overthrowing paradigms, they rather extend and modify a ruling paradigm. What we are doing these days is to enrich and widen the nuclear paradigm. The lessons we have learned during the last decade or so by directing, and with increasing success our nuclear toward extreme conditions are truely remarkable.

The recent theory advances have influenced dripline physics conceptually by adding a new perspective, that of threshold phenomena, and terminology from fewbody physics which captures essential aspects of the new phenomena. The methodology has correspondingly been changed. Two-body recipes have been replaced by appropriate 3-body (few-body) estimates. And more importantly; A theory framework with growing predictive power is emerging. For lighter nuclei a diversity of few-body inspired methods with different virtues have been developed and tested against each other for the ^{6}He and ^{6}Li benchmark systems. For heavier systems our understanding of pairing is making progress, and improved many-body approaches are being developed that are tested on the accumulating data for neutron (proton) rich systems. Theory has contributed to the logistics of the field; A consensus that, parallel to the search for new candidates for outstanding phenomena, high priority be given to systematic investigations around exotic nuclei such as ^{6}He for which fundamental calculations can be performed.

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