The Very Rich Structure of the Rather Light Nuclei

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ABSTRACT

The structure of the light nuclei, which fill the region from the nuclei described now by *ab initio* calculations to those described in large basis 1s0d-shell and 0f1p-shell calculations, shows a wide variety of interesting features. These include clustering of nucleons, neutron haloes, unbound resonances in the continuum and nuclear molecules bound by valence neutrons in molecular orbitals. Using the beryllium isotopes as a guide, and taking diversions at each mass from ^{4}Be to ^{14}Be, aspects of this interesting structure are explored.

1. INTRODUCTION

The light nuclei up to carbon are represented in figure 1, where the diagonal line represents the start of the neutron rich side of the chart, containing the greater fraction of the nuclei. The alpha-particle, with 2 protons and 2 neutrons, is doubly magic and completely fills the first shell orbital, 0s. This gives this state a special status amongst the light nuclei, because of the exceptionally high binding energy, and the selfconjugate A=4n nuclei containing integral numbers of alpha-particles are interesting because many of their states involve a condensation into alpha-like clusters. Other cluster units such as ^{6}He also appear to be found, and we also find clusters being bound together by valence neutrons or else surrounded by loosely bound and diffuse halo neutrons. The cluster structure, which is in some sense born of the 0s- and 0p-shell structure, also helps to break the shell structure, with the deformation that it brings being a contributor to the breaking of the N=8 magic number in ^{12}Be. We also see exotic structures such as Borromean nuclei, exemplified by ^{6}He or ^{14}Be, and "super-Borromean" or Brunnian nuclei exemplified (uniquely) by ^{10}C. The structures of the various beryllium isotopes are so richly diverse that they offer excellent illustrations of many of these features, and so we take a tour from ^{4}Be to ^{14}Be with diversions to explore other interesting phenomena at each mass along the way.

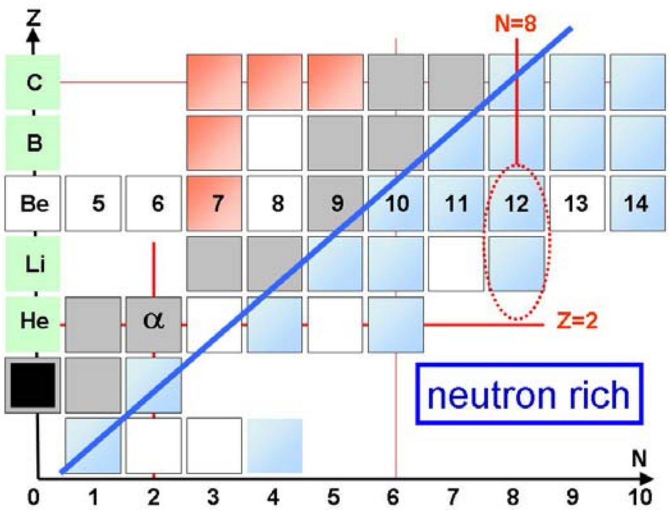


Figure 1: The Segre chart for the light nuclei. White implies "unbound".

2. MASS A=4

The lightest possible isotope of beryllium is of course ^{4}Be. Relative to the tightly bound alpha-particle, two particles are pushed to the next higher shell by the Pauli principle, and this immediately implies a less bound object and indeed ^{4}Be does not exist. However, compared to a system of three identical particles there is a pairing force of attraction and compared to a two-body system there are possible three-body forces. So, perhaps, if we remove the Coulomb repulsion and examine a four-body system of neutrons, then perhaps we can find evidence of a *tetraneutron* system, ^{4}n. Figure 2 shows results from an experiment studying the breakup of ^{14}Be projectiles at GANIL [1]. Tantalisingly, some neutrons appear to transfer more energy to the detector than would be expected according to their energy as measured by time-of-flight (i.e. $E_p/E_n > 1$), and these events are only observed in coincidence with ^{10}Be particles. The simplest interpretation would be that tetraneutrons were produced, but the authors are careful not to make such a claim [1]. Theoretically, a bound tetraneutron is difficult or impossible to accommodate. A more likely interpretation, advanced by the same group [2], is that a low-lying resonance in ^{4}n might be leading to a spatial correlation of neutrons that are then recorded simultaneously at a rate higher than given by chance. It is immensely intriguing that a preliminary analysis of data with the same unique experimental setup, but a beam of ^{8}He, appears to show the same effect only for events coincident with ^{4}He particles [3] and a full analysis of the ^{8}He data will be very interesting to see.

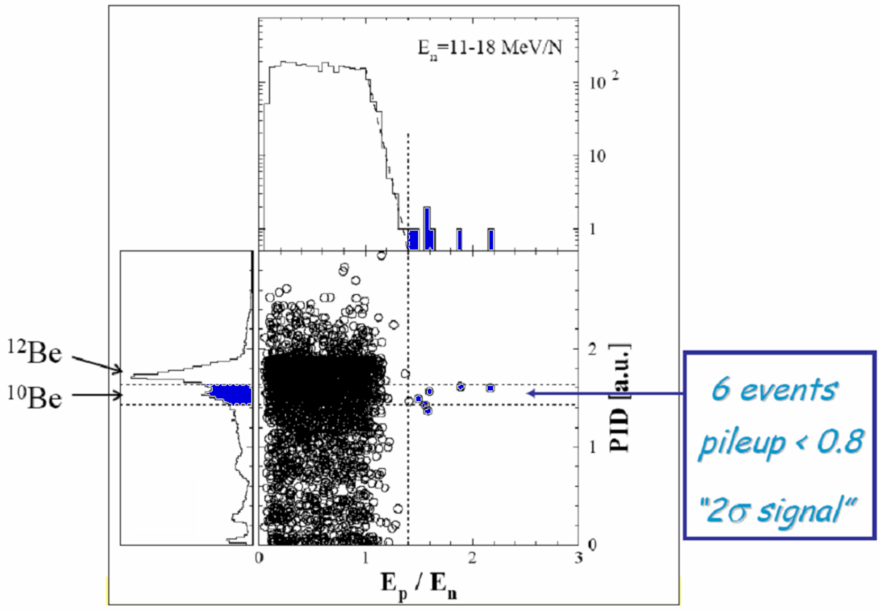


Figure 2: Data from ^{14}Be breakup [1] showing a particle identification parameter for heavy ions vs energy transfer to a neutron detector for coincident "neutrons". Normally the energy E_p/E_n should be less than one.

3. MASS A=5

There is no bound A=5 nucleus. Low-lying resonances are known, for example the $p_{3/2}$ ground states of the mirror systems ^{5}He and ^{5}Li. Because of their proximity to the decay threshold, at an energy comparable with their widths, these states do not show the familiar symmetric Breit-Wigner shape but are markedly asymmetric with a high energy tail and a shape characteristic of their angular momentum. Furthermore, due to interference effects, the observed shape for these broad lineshapes will depend on the *method of production* of the nucleus. This interesting result is discussed in a study of ^{5}He and ^{5}Li produced by different pickup and stripping reactions using heavy ions [4]. Figure 3 shows example results for the ^{5}Li ground state, produced by transfer reactions adding a proton to ^{4}He or removing a neutron from ^{6}Li, and the different behaviour of the tail of the resonance (shaded) is reproduced by R-matrix calculations by Fred Barker [4].

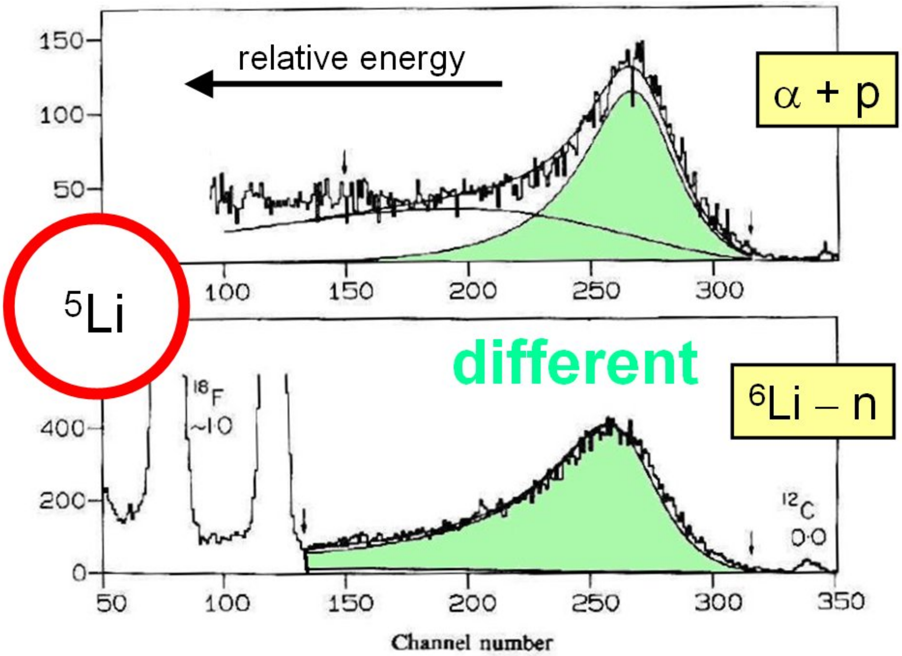


Figure 3: Excitation energy spectra, deduced with the missing mass method, for ^{5}Li particles from heavy ion transfer reactions in which the heavy ion was detected in a magnetic spectrometer [4].

4. MASS A=6

Finally, at mass 6, there is a beryllium isotope that does exist, although only as a resonance. The ground state of ^{6}Be is unbound by 1.372 MeV to the α+p+p decay channel and has a width of 92 keV (lifetime of order 10^{-20}s). It is the isobaric analogue of the 0^{+} ground state of ^{6}He, which is bound to neutron emission by only 1.867 MeV and hence has a neutron halo. Recent work [5] has employed theory to analyse the angular and energy correlations in the multi-body decay into α+p+p in order to test the accuracy of various different few-body models of ^{6}Be. There does appear to be some sensitivity that is testable, experimentally.

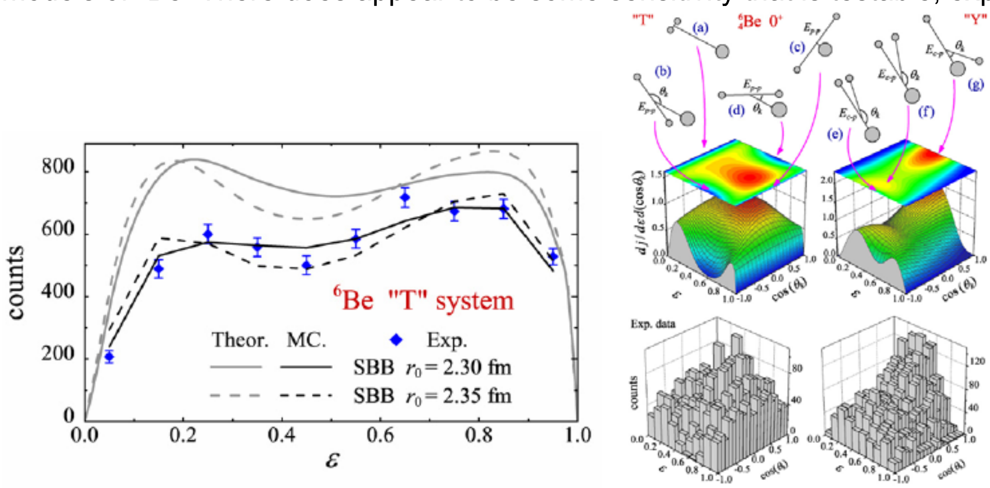


Figure 4: where the fractional energy partition $\varepsilon = E_x/E_T$ (E_x is the relative energy between the pair of particles indicated at top right; E_T is the three-body breakup energy) and θ_k represents the jacobian angle shown at top right [5]. The double peaking in the lower left plot for ε arises from the $(0p)^2$ structure of the p-p wavefunction.

The nucleus ^{6}He, as mentioned above, has a neutron halo structure. It also has a structure known as Borromean, meaning that it can be considered as a bound three-body system α+n+n where no two-body subsystem is bound [6]. As shown in figure 5, the structure of this halo has two components: one called "dineutron" in which the neutrons tend to be found close to each other, outside of the alpha core, and the other "cigar" configuration in which the neutrons tend to be found on opposite sides of the alpha-particle core. This result is reproduced in different theoretical approaches.

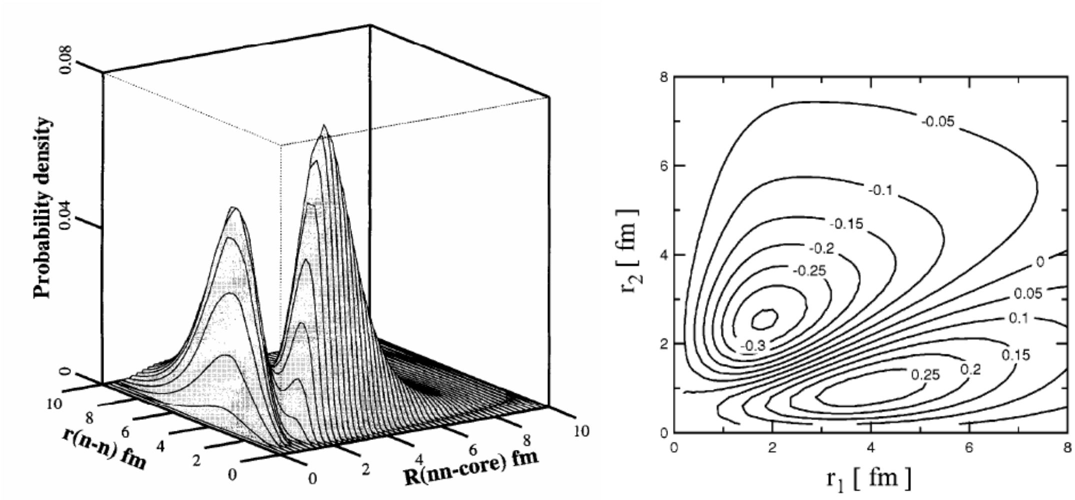


Figure 5: on the left, results from a 3-body model for ^{6}He show coexisting components of "cigar" and "dineutron" configurations [6]. A fully antisymmetrized microscopic cluster calculation for ^{6}He gives a similar result [7].

5. MASS A=7

The nucleus ^{7}Be, like ^{6}Be and ^{6}He, has an alpha sub-unit in its structure, making it a ^{3}He-α cluster system. The mirror nucleus ^{7}Li has a t-α structure and is thus often used as a projectile in alpha-transfer experiments via the (^{7}Li,t) reaction. An interesting point about these A=7 nuclei is that they can be described extremely accurately in a model that supposes that a real alpha particle and a real triton (for ^{7}Li) retain their free space properties and orbit in a simple potential. The parameters of the potential are determined by the measured properties of ^{7}Li. Despite its amazing simplicity, the predictions of this model devised by Buck and coworkers are remarkably good for a whole range of spectroscopic properties [8]. In fact, Buck's model works surprisingly well for a wide range of alpha-core systems and for other clusters orbiting magic cores and can explain alpha-decay systematics with a preformation factor (for the alpha-particle in the parent nucleus) of unity [9]. Most cluster models of nuclei, such as the microscopic cluster model [7] or RGM [10] or AMD [11], do however include full antisymmetrization of the A-body wavefunction.

6. MASS A=8

The ^{8}Be system is, in some ways, the most enigmatic of all the beryllium isotopes. It can be considered as two alpha-particles in orbit with zero angular momentum. Although the alpha-particle subsytems bring with them a high binding energy, the ^{8}Be system is not bound overall. It lies 92 keV above the α+α threshold and has a width of 5.57 eV and hence a lifetime of 0.1 fs. The binding energy is 7.06 MeV/nucleon. The lifetime of the resonant ^{8}Be ground state is of course an important factor in the astrophysical triple-α process, making more likely the chance encounter with a third α-particle in the stellar environment. The reaction ^{8}Be+α to produce ^{12}C then proceeds through a resonance (the so-called "Hoyle state") in ^{12}C that lies at a binding energy of 7.04 MeV/nucleon, very similar to that of ^{8}Be. In fact, the α-particle binding energy is 7.07 MeV/nucleon, and the point is that the ^{8}Be and ^{12}C resonances each lie very close to the breakup threshold into individual α-particles (where the Gamow window for stellar reactions can reach them). The ground state of ^{12}C, for comparison, has a binding energy of 7.68 MeV/nucleon, which it acquires by condensing to a configuration with less surface area which enables a greater number of attractive pair-wise nucleon-nucleon interactions. The tendency for cluster structure to appear close to the energy at which such condensation is energetically allowed (using free space binding energies) is often represented on the Ikeda diagram [12,13]. Using the harmonic oscillator potential for nucleons as a simple illustrative approximation, as discussed in the review of ref. [13] it can be seen in either the two-centre HO or the deformed HO energy levels that the energy for the second set of four particles (second alpha-particle) is reduced as the prolate deformation increases, away from sphericity (cf. figure 6). These approaches somehow presuppose a cluster structure, but there are models in which it can be seen to emerge naturally. An example is the AMD approach [11] that has been developed largely in Japan, in which nucleons are free to move with an effective nucleon-nucleon force, but are found to prefer energetically to congregate into clusters. The AMD calculations predict the persistence of clustering through all of the beryllium isotopes from 6Be to 14Be and have provided plots of the expected matter densities for ground states [11] and specific excited states (e.g. [14]). The existence of a loosely bound system of identical boson particles (α-particles) could lead one to suppose [15] that a link might exist with Bose-Einstein condensates. Indeed, the Hoyle state in 12C can be well described using such an approach [16] and amazingly the wavefunction is essentially equivalent to the microscopic resonating group wavefunction developed 25 years previously by Kamimura's group [17].

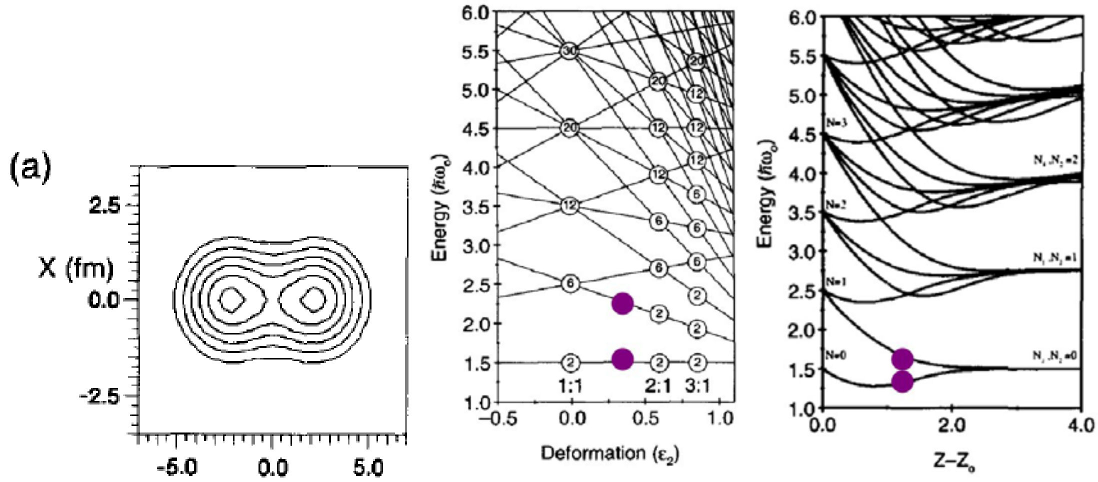
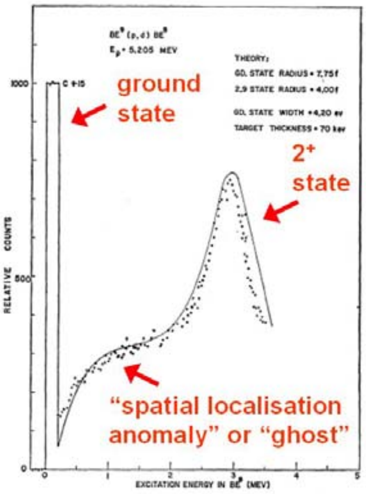


Figure 5: (a) the projected density of particles in ^{8}Be shows a separation into two alpha-like concentrations. The deformed harmonic oscillator (centre) and two-centre harmonic oscillator potentials favour deformation for ^{8}Be.

Another interesting feature of nuclear structure is illustrated by the unbound ground state of ^{8}Be, and is sometimes referred to as the phenomenon of "*ghosts*" [18]. In an experiment performed 50 years ago, the reaction ^{9}Be(p,d)^{8}Be(α)α was studied [19] and the authors reported a "spatial localisation anomaly" to describe the observation of an additional manifestation of excitation strength at energies significantly above the ground state in ^{8}Be, but being in fact a part of the ground state. This is shown in figure 6. The calculations of ref. [18] using the formulae shown in figure 6 show that Γ is a function of energy and depends upon the penetrability P_ℓ. Now, the penetrability of the escaping alpha-particle is an increasing function of energy and is balanced against the falling functional dependence due to the increasing distance in energy, away from the resonance energy. It can happen that the rising penetrability can dominate in some particular range, before the falling part takes over again, and this can produce a second, broad, peak at an energy significantly above the actual resonance. This is the "ghost" phenomenon as illustrated in the data of figure 6.



$$\rho_l^{(1)}(E) = \text{const.}\ \frac{\frac{1}{2}\Gamma_l}{(E_l+\Delta_l-E)^2+(\frac{1}{2}\Gamma_l)^2},$$

$$\Gamma_l = 2P_l\gamma_l^2, \qquad P_l = \rho A_l^{-2},$$

$$\Delta_l = -S_l^0\gamma_l^2, \qquad S_l^0 = \rho A_l^{-1}(\partial A_l/\partial\rho) - \mathbf{B}_l,$$

$$A_l^2 = F_l^2 + G_l^2.$$

Figure 6: the spectrum of ^{8}Be excitation energy measured in ^{9}Be(p,d)^{8}Be [19] showing the “ghost” of the ground state that appears at excitations extending up to and beyond the 2^+ state. Formulae: see text [18].

Predictions are also made by Barker and Tracey in ref. [18] for ghosts of the Hoyle state in ^{12}C, as shown in figure 7. A key point is that the observed distribution of strength (dark shading) and the density of states function (lighter shading) depend on the method of observation – in this case either β-decay or resonant proton scattering. In a recent study of the 3α decay of ^{12}C following β-decay, the observation of this ghost has been reported [20].

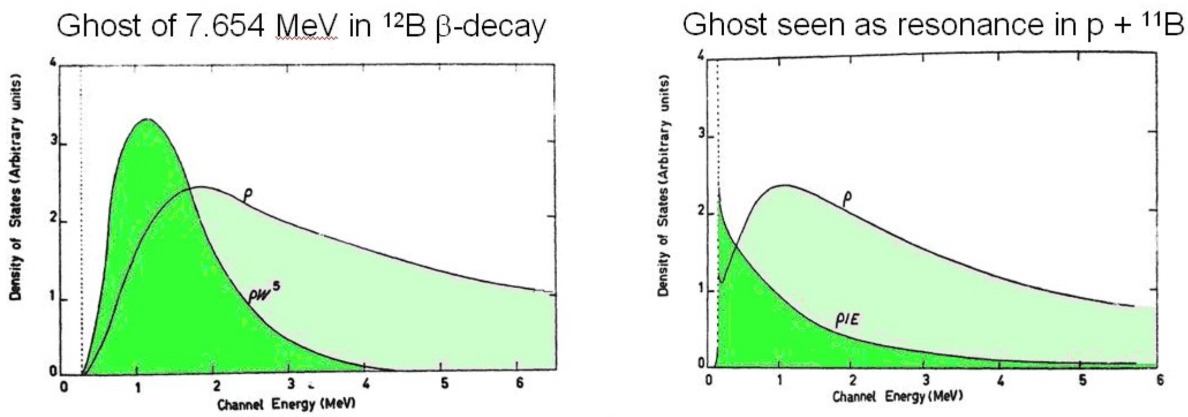


Figure 7: predictions [18] of the appearance of the ghost of the Hoyle state in ^{12}C, observed in different channels.

7. MASS A=9

The dinuclear cluster structure seen in ^{8}Be was not quite bound. In the case of ^{9}Be, the two-centre structure persists but the additional neutron is able to provide the extra force of attraction to make the system bound, at least for the ground state, making it the only particle-bound and non-radioactive state in all of the beryllium isotopes. Natural beryllium is therefore isotopically pure ^{9}Be.

The molecular description of 9Be, in terms of two alpha-particles bound together by a neutron in a molecular orbital, was developed by Seya and collaborators in 1981 [21]. The orbital energies as a function of the separation of the alpha-particles is shown on the left hand side of figure 8. The energies of ^{9}Be states can then be calculated, also as a function of separation, and a minimum is observed for the ground state at a separation of 3 fm. At this separation, if it is fixed, a good reproduction of the excited state energies is also found.

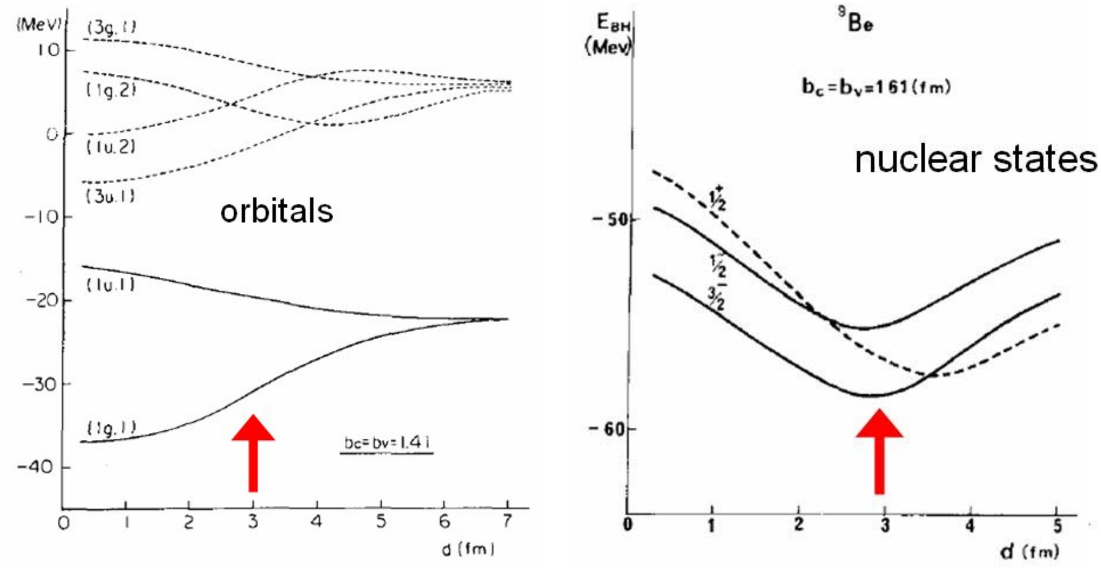


Figure 8: energies of (left) molecular orbitals and (right) the states in ^{9}Be in a molecular orbital model [21].

Interestingly, independent verification of the cluster structure and molecular nature of various beryllium isotopes appears to exist and to have been passed down since 1960 in the form of an LP album cover [22] as shown in figure 9.

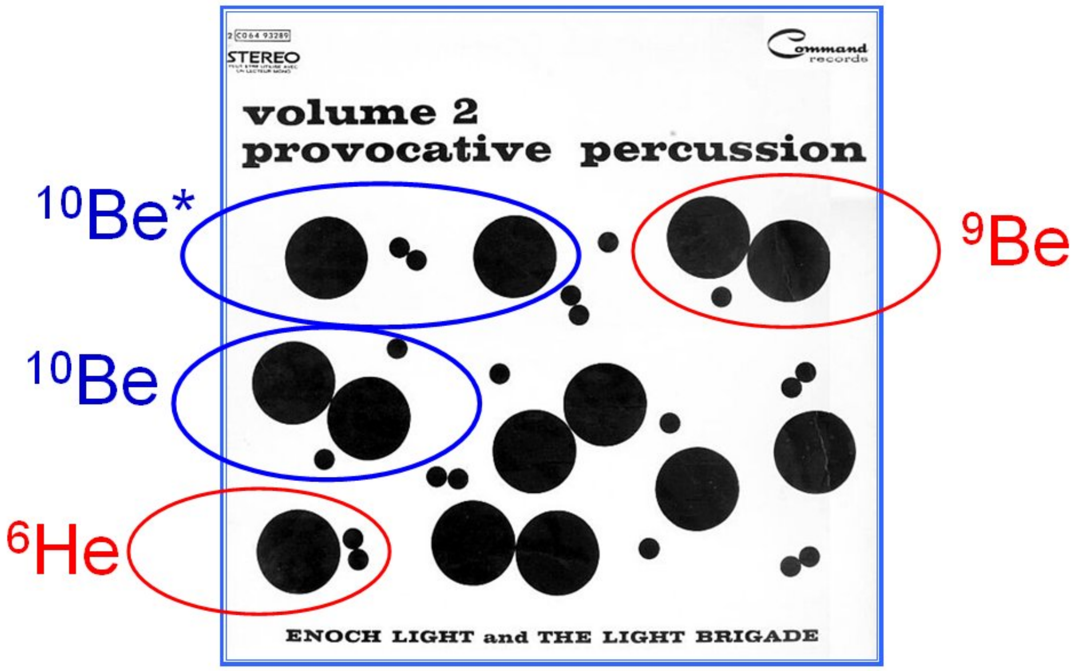


Figure 9: snapshots showing the cluster structure of beryllium isotopes ^{9}Be and ^{10}Be (and also ^{6}He) from a 1960 album by Enoch Light and the Light Brigade [22], a known favourite of shell model theorist B.A. Brown.

The mirror of ^{9}Be is ^{9}B, which has the structure of a proton plus two alpha-particles. Unlike ^{9}Be, the nucleus ^{9}B is unbound by 185 keV to decay to ^{8}Be+p and unbound by 277 keV to three-body α+α+p breakup. The ground state has a width of 0.54 keV and lives for 10^{-18}s. The 1/2+ first excited state in ^{9}B has never been observed in a truly convincing fashion, even though the compilations include a list of its properties [23]. In contrast, the first excited 1/2+ mirror state in ^{9}Be, which is also unbound, is well established. There is great interest in whether the Thomas-Ehrman shift in this case, which is an energy shift between the s-wave neutron and proton states [24], is the same or different to other examples in which one of the two states is bound. Recent data has come from an experiment seeking to improve on the promising data acquired in ref. [23] by repeating the measurement of the ^{6}Li(^{6}Li,t)^{9}B reacation that was believed to populate the 1/2+ state appreciably. This experiment [25] was performed at the Australian National University with a beam of 60 MeV ^{6}Li ions. Unlike the previous experiment [23], the triton was detected in coincidence with the three particles (α+α+p) from the ^{9}B breakup. It was shown conclusively [25] that the (^{6}Li, t) reaction does not directly populate the 1/2+ state in ^{9}B, in contrast with the assumption made in [23]. Further, it was shown that the 1/2+ state does appear to be populated in the sequential neutron decay of ^{10}B states that are produced by the alpha transfer reaction (^{6}Li,d). Using the energies and angles of the four detected particles (α+α+p+d), the missing energy and momentum were calculated and found to be consistent with an unobserved neutron. This evidence for the 1/2+ state, shown in figure 10, is arguably the only reliable data for this state. However, because of the feeding via neutron decay, the strength function across the resonance may be slightly modulated by the varying neutron penetrability. This rules out any detailed fitting of the measured spectrum to deduce the peak properties precisely, but the data do indicate a broad resonance peaked at 0.8-1.0 MeV with a width of order 1.5 MeV.

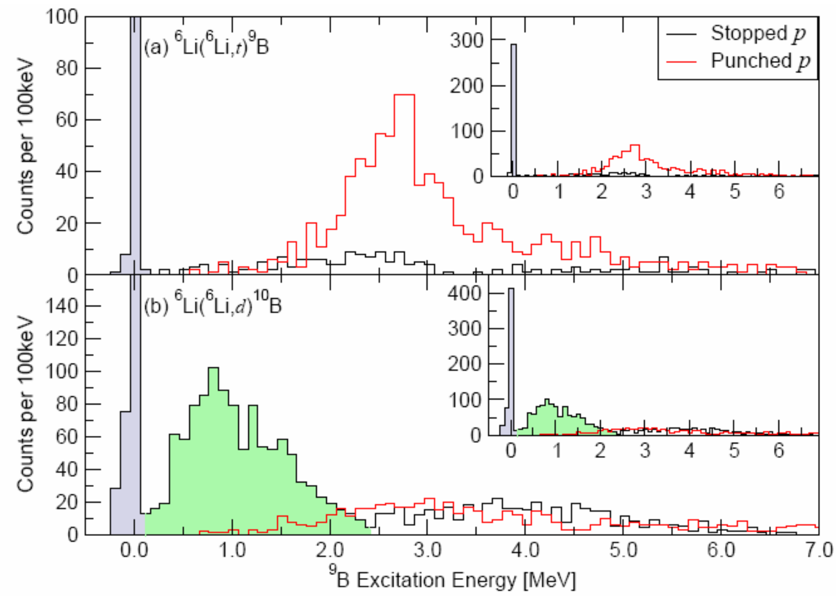


Figure 10: excitation energy spectra measured [25] for ^{9}B in ^{6}Li + ^{6}Li – (a) ^{3}He transfer directly to ^{9}B, and (b) alpha transfer to ^{10}B followed by neutron decay to ^{9}B. The ground state and candidate 1/2+ peaks are shaded.

8. MASS A=10

If ^{9}Be shows molecular cluster structure, then ^{10}Be might be expected to show such structure also, with the covalent bonding orbital being occupied by two neutrons rather than one. It turns that this is true, except that the molecular structure becomes most evident in the excited states of ^{10}Be, with the ground state finding more binding energy in a more compact geometry.

Calculations for the matter densities of protons and neutrons in ^{10}Be within the framework of the AMD model [11] reveal the different structure for the different excited states. Figure 11 shows the densities for just the two valence neutrons. The sigma bond in the excited 0+ state is seen to push the two α-particle centres further apart and accentuate the clustering.

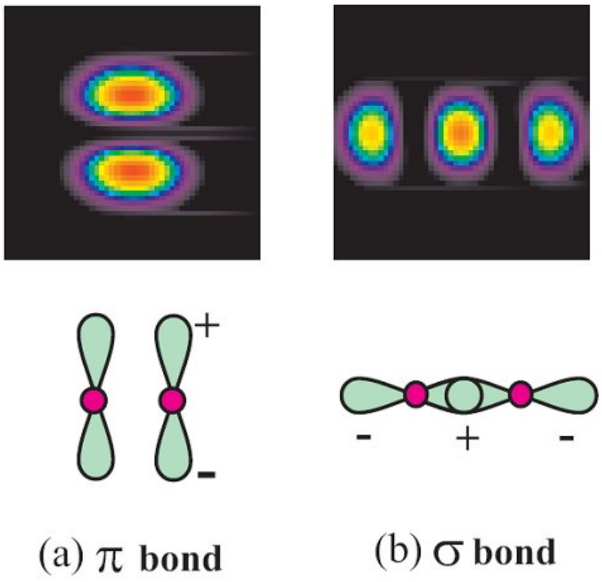


Figure 11: densities of valence (bonding) neutrons in ^{10}Be according to AMD calculations [11], for (a) ground state, and (b) excited 0^+ state near 6 MeV. The interpretation in terms of molecular orbitals is also shown.

Microscopic cluster models can also be applied to understand the structure of ^{10}Be. First, we can note how the same model works at describing the 3-body system of ^{9}Be [26]. Figure 12 shows schematically how the wavefunction can be related to a particular geometry between the alpha-particle centres and the extra neutron. Unlike the relatively simple 3/2– ground state and 1/2– excited state, the 1/2+ intruder state (in shell model parlance) can only achieve its high binding (and low excitation energy) via an admixture of two configurations. These can be characterised as molecular neutron bonding in one case, and as an alpha-^{5}He cluster structure in the other case, as shown schematically for the 1/2+ state in figure 12. The mixing of two configurations in this three-body system is reminiscent of the cigar and dineutron configurations that mix to create the binding the three-body ground state of ^{6}He.

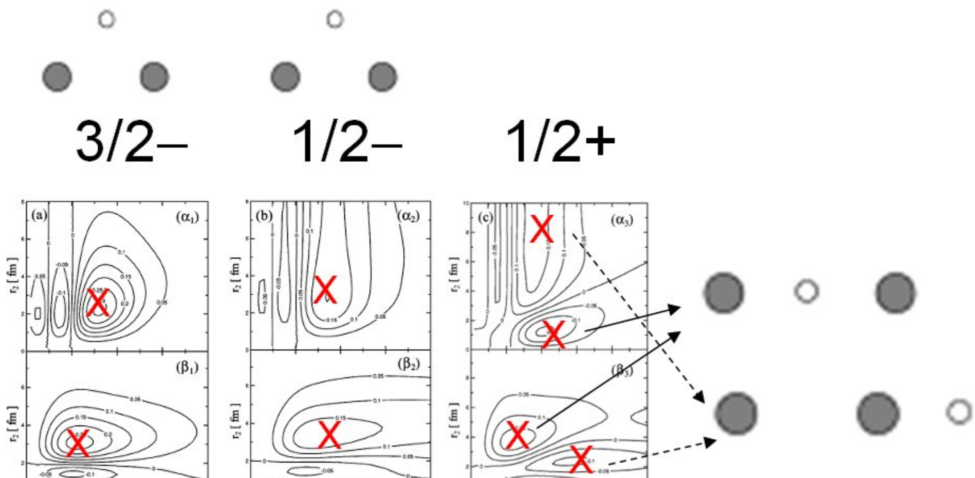


Figure 12: according to microscopic cluster calculations [26] the high binding of the 1/2+ state in ^{9}Be is achieved by the admixture between two different configurations in the wavefunction.

Turning back now to ^{10}Be, the ground state is an admixture of two configurations that are broadly similar in their geometrical interpretation [27]. The relative positions of the alpha-particles and the neutrons is also understandable in terms of figure 11(a) from the AMD theory. The excited 0^+ state has a more complicated structure, with three configurations contributing. In the AMD, this is the sigma bond of figure 11(b). In the cluster model, one configuration indeed has the two neutrons localized between the alpha-particles. The other two configurations can be characterised as ^{5}He-^{5}He and α-^{6}He respectively.

It is interesting that the three-body systems seem to show the existence of one or two configurations in the wavefunction whereas, in the four-body system, this increases to be either two or three configurations that coexist.

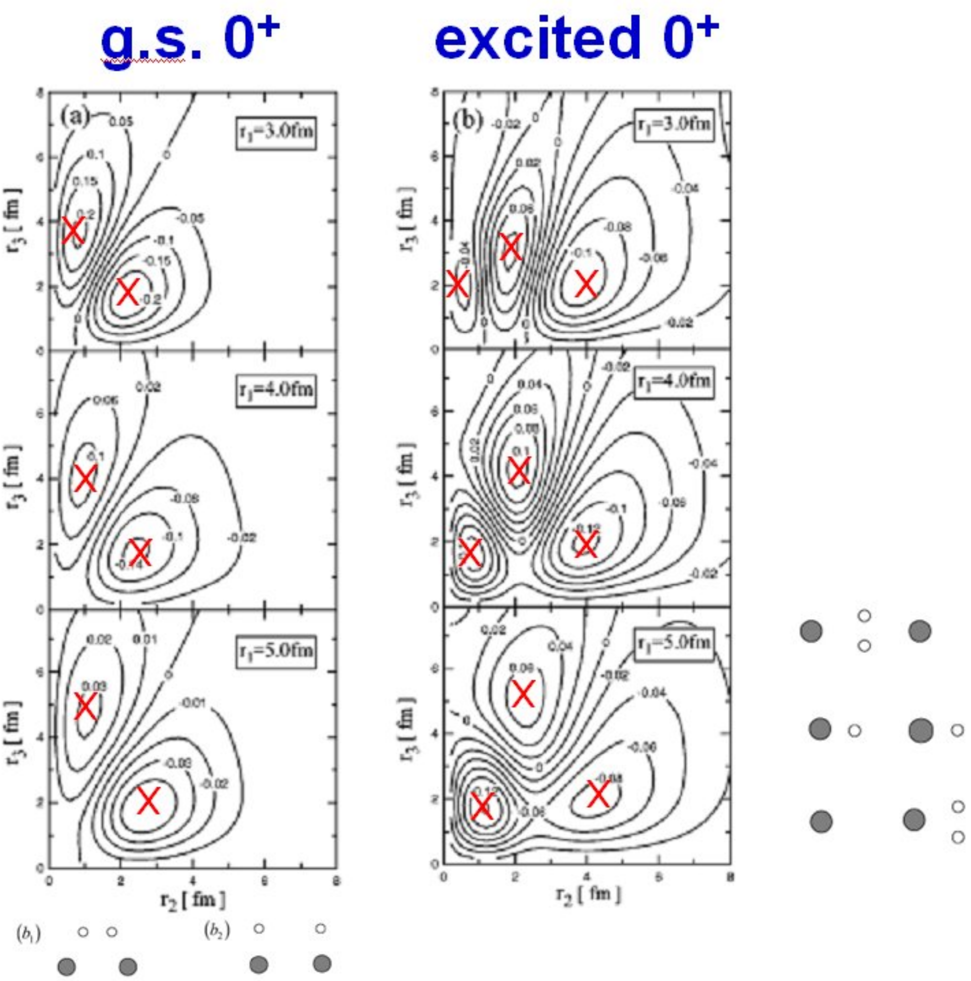


Figure 13: according to microscopic cluster calculations [27] the more compact ground state in ^{10}Be has two components whereas the more clearly molecular excited 0^+ state has three different components mixed.

The isobaric analogue of ^{10}Be is ^{10}C, which is an extremely interesting nucleus. It is bound with a lifetime of 19.3 s and has a single bound excited state (the 2^+). Viewed as a cluster state of α+α+p+p it is a unique example of a “super-Borromean” system, that has also been named “Brunnian” [28] after the concept in topology.

As illustrated in figure 14, four loops can be inter-entwined in such a way that the removal of any one loop causes the whole assembly to fall apart. This is an extension of the three-loop Borromean system. In ^{10}C viewed as α+α+p+p the same is true, i.e. that no three-body subsystem is bound and yet ^{10}C itself is bound. Figure 14 shows how the decay of excited

^{10}C states via either alpha-particle emission or proton emission takes it through a series of unbound subsystems. The decays of excited states in ^{10}C have recently been studied in two different experiments. One aim has been to identify the analogue states of the molecular structures in ^{10}Be, wherein the covalently binding neutrons are replaced by protons. So far, these connections are not clearly established.

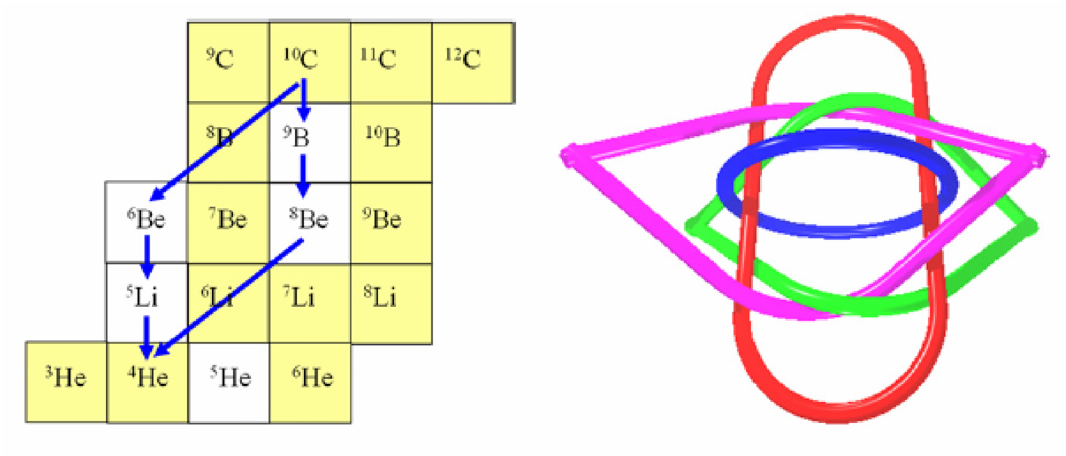


Figure 14: the nucleus ^{10}C can be considered as a bound system of $\alpha+\alpha+p+p$ within which no three-body subsystem is bound. This has led to the name "super-Borromean" or "Brunnian" to describe this nucleus [27]. Left: higher lying, unbound states in ^{10}C will decay to $\alpha+\alpha+p+p$ via two intermediate resonance states.

Figure 15 shows the results for states in ^{10}C from the measurement performed by the Washington University group at Texas A&M [29] and indicates the observed decay pathways. These decays and the production of intermediate resonant states were deduced by kinematical reconstruction of data in which the energies and angles of all emitted particles were accurately measured (as was done also in the ^{9}B measurement described above[25]). A lower lying state near the particle decay threshold, initially reported by the Charissa group from their GANIL data [28] is now found by that group to be an artefact [28].

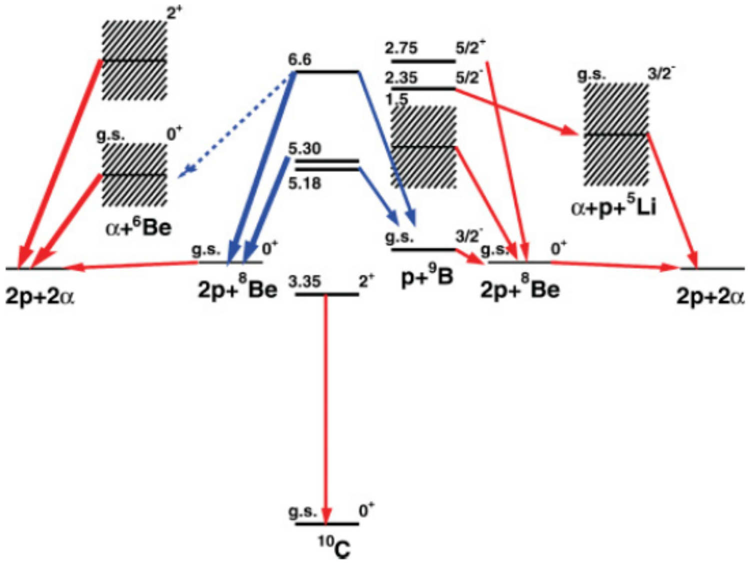


Figure 15: unbound excited states observed in ^{10}C [29] and their decay channels to the $\alpha+\alpha+p+p$ final state. The nucleus ^{10}C has one bound excited state.

9. MASS A=11

The isotope ^{11}Be is famous as the archetypal one-neutron halo nucleus. Bound by only 0.503 MeV to neutron emission, it's 1/2+ ground state is an intruder from the 1s0d-shell. It has a single bound excited state, the 1/2– state at 0.320 MeV that is bound by just 0.183 MeV. The low binding energy of the 1/2+ state automatically implies that the s-wave valence neutron's wavefunction extends to large distances as a result of the matching at the nuclear surface. The wavefunction of the 1/2– state is impeded in this regard by the p-wave's centrifugal barrier, but with the binding energy being less than half that of the ground state it turns out that the radial extent of the excited state wavefunction is about the same as the ground state. This is illustrated in figure 16, where it is compared with the more typical nearby nucleus ^{15}O. The remarkable similarity in these two extremely extended wavefunctions – two overlapping haloes – means that the radial weighting for any matrix element connecting the two states is strongly enhanced. For this reason, the measured B(E1) strength for the 1/2– to 1/2+ transition is extraordinarily large. In fact, it was this large measured strength that led Millener to first deduce that ^{11}Be must genuinely have a very extended halo structure. This is also discussed in the excellent review of the structure of light nuclei given by Millener in ref. [30]. The B(E1) strength of the transition has recently been remeasured at GANIL in an intermediate energy coulomb excitation experiment that confirms earlier measurements and resolves an anomaly in the literature [31]. Recently, as shown schematically in figure 16, laser trap measurements at ISOLDE at CERN have measured that the halo neutron in ^{11}Be is on average 7 fm away from the ^{10}Be core, which itself measures about 2.5 fm in radius [32].

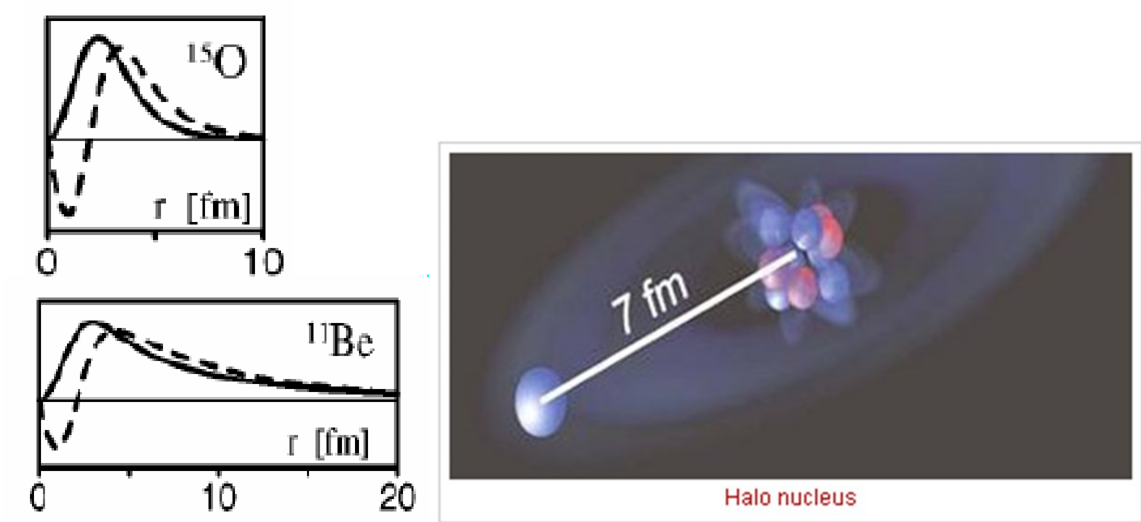


Figure 16: the s-wave ground state and the p-wave excited state in ^{11}Be exhibit haloes that extend far beyond normal nuclear radii. Experiment shows that, on average, the halo neutron is at three times the core radius [32].

The structure of ^{11}Be is however not quite that simple. Whilst it is usually held as the best example of a single neutron halo (and probably is), it is a frustratingly complex object because the ^{10}Be core is of course deformed and even displays a degree of cluster structure. In particular, the collective excitation of the 2+ state of the core cannot be ignored. Thus, the ground state is not simply an s-wave neutron coupled to a spin zero core. There is also a component that can be described as an excited 2+ core coupled to a d-wave $d_{5/2}$ neutron, all coupled to spin and parity 1/2+. The mixing between these two components has been measured using the transfer reaction (p,d) to study the neutron pickup from ^{11}Be [33]. This experiment, performed at GANIL, was one of the very first transfer reaction studies to perform a proper spectroscopic measurement, using an on-line produced radioactive beam.

The ^{10}Be reaction products were detected in the SPEG magnetic spectrometer at zero degrees and their scattering angles were measured relative to the incident projectiles, using beam tracking. The target was polyethylene $(CH_2)_n$ and reactions on the carbon were eliminated by coincident detection of the deuterons from (p,d) using elements of the Charissa array in the target chamber. This experiment [33] is an excellent example of a transfer reaction performed in inverse kinematics and relying principally on measurements of the beam-like particle. The focal plane spectrum, showing the ^{10}Be separated into ground state, 2^+ and other components, is shown in figure 17. The result was that about 3/4 of the wavefunction has the ^{10}Be in the ground state and this is compatible with other measurements using high energy neutron removal or Coulomb dissociation, as discussed for example in ref. [33].

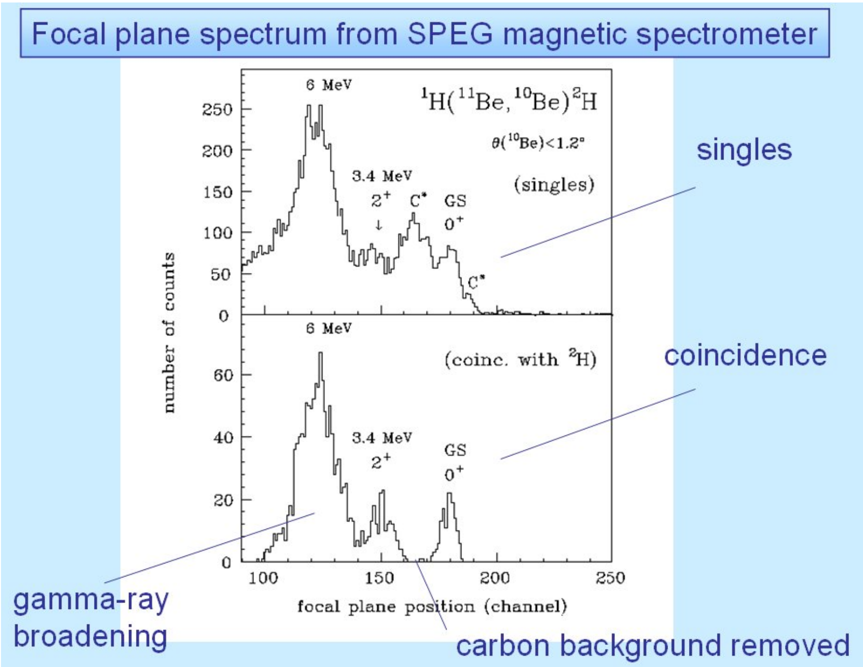


Figure 17: focal plane position spectra (i.e. excitation energy spectra) for ^{10}Be ions from the reaction $^{11}Be(p,d)^{10}Be$ studied in inverse kinematics at GANIL [33]. Differential cross sections were also measured.

10. MASS A=12

The nucleus ^{12}Be sees a complete breakdown of the N=8 magic number, in total contrast to its isotone ^{14}C which is an excellent closed shell doubly magic nucleus. The separation energies for ^{14}C are all in excess of 8 MeV and the first excited state is at an excitation energy of more than 6 MeV, just as in ^{16}O. In ^{12}Be, on the other hand, we see ground state deformation and a very mixed ground state configuration that includes both 0p-shell and 1s0d-shell components for the neutrons [34]. At higher energies, ^6He-^6He di-nuclear cluster structure has been observed [35].

The structure of the ^{12}Be ground state was studied in an experiment at GANIL in which a neutron was removed by an intermediate energy reaction with a ^{12}C target, in which the core survived and was detected [34]. This automatically selects very peripheral reactions which can be modelled theoretically using Glauber and eikonal methods. The final state of ^{11}Be, with an odd neutron, reveals which neutron was removed from the fully paired ^{12}Be. If ^{11}Be was in its 1/2– bound state (identified by observation of the gamma-decay, cf. figure 18) then a neutron from $0p_{1/2}$ was removed. The new feature of the experiment was the ability to detect, also, ^{11}Be when it was produced in the unbound excited 5/2+ state at 1.78 MeV or, indeed, other excited states. This was achieved by kinematical reconstruction of neutrons together with ^{10}Be particles from the sequential decay. The 5/2+ state is seen as a prominent peak at 1.78 MeV in the reconstructed excitation energy spectrum (see figure 18). The result [34] was that the pair of valence neutrons in ^{12}Be spend approximately equal times in each of the three orbitals 0p1/2, 0d5/2 and 1s1/2 and clearly pay no heed to the N=8 magic number.

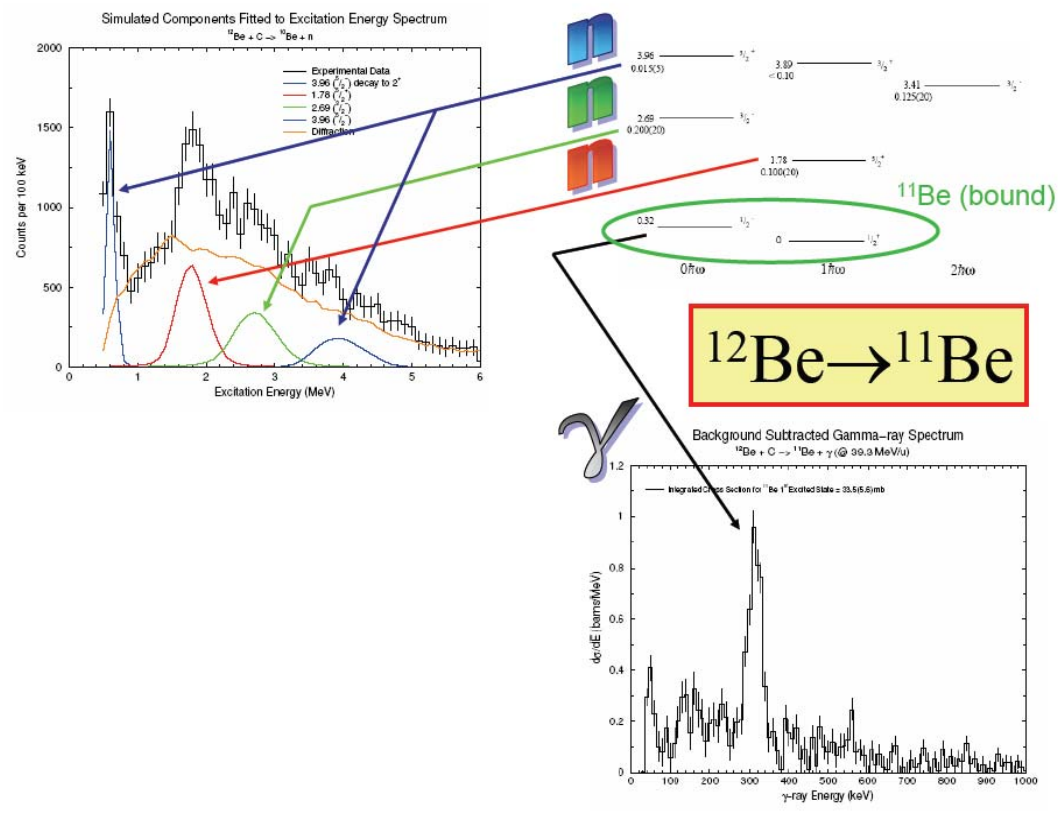


Figure 18: At upper right the energy levels of ^{11}Be are shown, separated into columns according to their particle-hole structure. In the experiment of ref. [34], neutron removal from ^{12}Be leading to the bound excited state of ^{11}Be was tagged by observation of the decay gamma-rays (lower right). Production of unbound states in ^{11}Be was measured by identifying the associated peaks in the reconstructed excitation energy using the measured energies and angles of the neutrons and ^{10}Be particles from the sequential decay (upper left).

The ^{6}He-^{6}He cluster structure of excited states in ^{12}Be was first inferred from an inelastic scattering experiment using a beam of ^{12}Be produced at GANIL [35]. The structure that was deduced is shown in figure 19. The experiment recorded ^{6}He-^{6}He coincidences and ^{8}He-^{4}He coincidences following breakup reactions induced by a polythene $(CH_2)_n$ target. Most of the interesting ^{6}He-^{6}He coincidences appeared to arise from scattering from the protons in the target, rather than the ^{12}C. Angular correlations between the ^{6}He-^{6}He coincidences allowed spin information to be deduced for the assumed parent ^{12}Be states.

A more recent experiment [36] at MSU has attempted to verify and extend the results regarding this molecular structure but, for reasons still to be determined, the new results do not show the same clear structure. This is illustrated by the data from the two experiments, which are compared in figure 20. The GANIL experiment was performed at a beam energy of 31.5 (±0.08) MeV/A and an intensity of 2×10^4 pps, whereas the MSU experiment was at an energy of 50.0 (±0.05) MeV/A and had five times the beam intensity. It is hard to imagine that the different energy and/or any of the other experimental parameters could lead to the observed differences and additional measurements are clearly required, to resolve the apparent discrepancy.

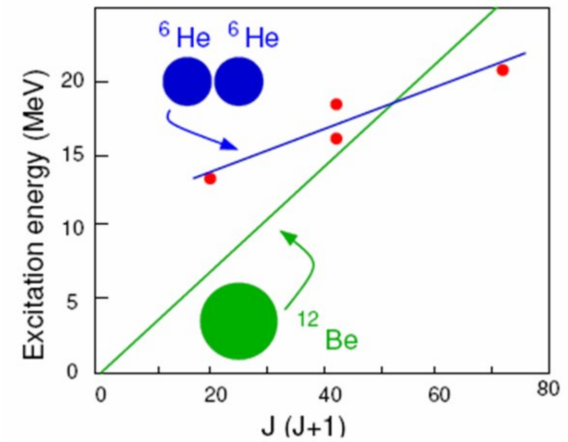


Figure 19: in an experiment at GANIL, excited states in ^{12}Be were inferred to have energy-spin systematics that implied a large moment of inertia, much greater than the ground state band, consistent with a ^{6}He + ^{6}He molecular structure [35].

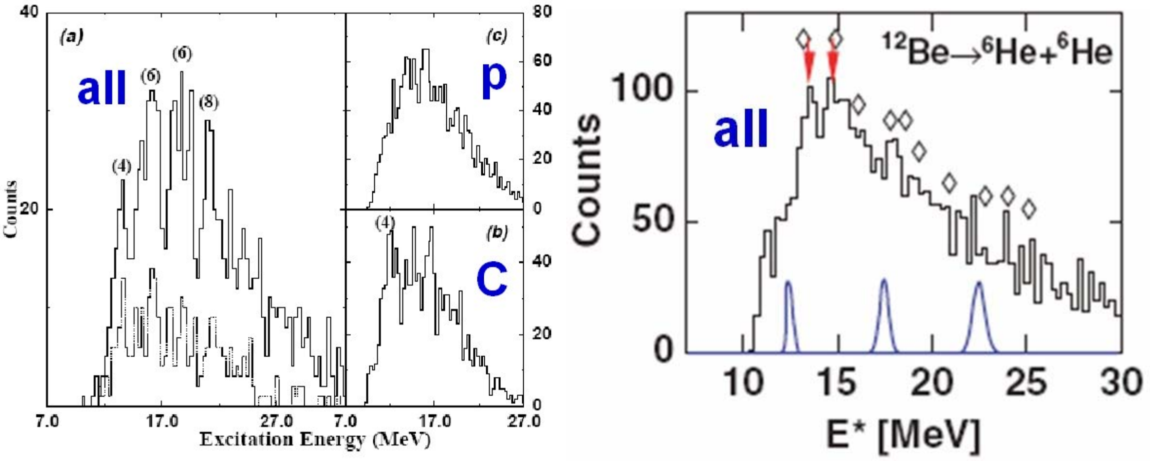


Figure 20: Excitation energy spectra for ^{12}Be states, kinematically reconstructed from ^{6}He + ^{6}He coincidences. Left: from the GANIL experiment [35], showing all counts from the CH_2 target, the separate contributions from proton and carbon target nuclei, and peaks are labelled with the assigned spin. Right: from the MSU experiment [36] where diamonds indicate energies at which states were identified in [35].

11. MASS A=13

The isotope ^{13}Be is the first unbound isotope of beryllium that we encounter on the neutron rich side of the Segre chart (figure 1). It is in the same family as ^{5,7}He, ^{10}Li and ^{16}B in that it has a neighbour with one more neutron that forms a bound Borromean system. It is an interesting question as to how well the remnant unbound system of, say, ^{13}Be can be studied by sudden neutron removal from ^{14}Be. One could then measure the properties of resonances in the unbound sub-systems of Borromean nuclei via such reactions and hence inform the models that attempt to describe the Borromean states. One encouraging result in this regard was in the theoretical study of ref. [37], in which the distribution of strength resulting in unbound neutron resonances, resulting from a neutron removal reaction, was compared with the resonance lineshapes that were built into the structure model. The predicted experimental strength was found to closely match the actual resonance shapes, as shown in figure 21.

In one experimental study of the breakup of ^{14}Be [38], evidence for core-neutron correlations in energy could be found in the exclusive ^{12}Be+n+n data (see figure 21). References to complementary earlier work revealing ^{13}Be resonances can be found in ref. [38].

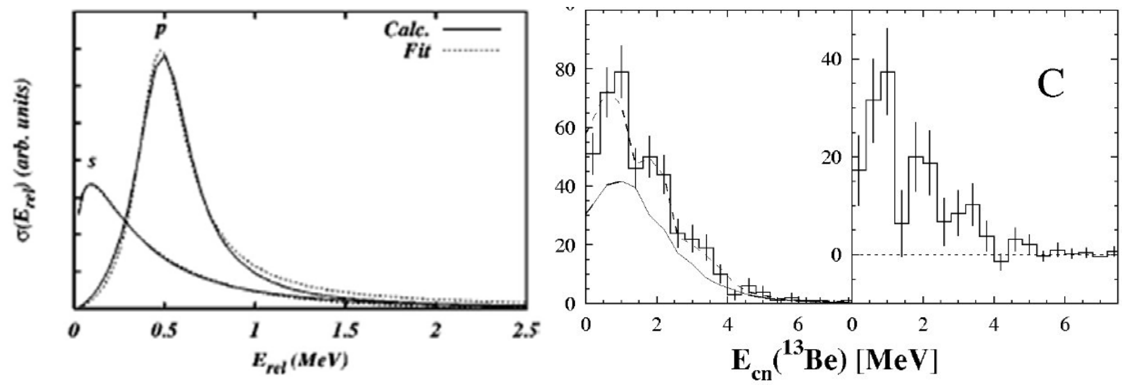


Figure 21: one the left, results from a theoretical investigation [37] suggests that neutron removal from Borromean halo nuclei will reveal the resonance structure of the core+n sub-system. Right: excitation spectrum with and without subtraction of the uncorrelated background, revealing resonance structure in ^{13}Be [38].

12. MASS A=14

The two-neutron separation energy of ^{14}Be is only 1.12 MeV, compared to 3.17 MeV to remove a single neutron from ^{12}Be. Therefore, ^{14}Be is well described as a Borromean system of ^{12}Be+n+n. The large extent of the halo for ^{14}Be is revealed by the total interaction cross section [39] which is shown in figure 21 and compared with simple $A^{1/3}$ radius systematics. The similarities with ^{11}Li are evident; in that nucleus the separation energies again result in a cluster structure of core+n+n, and an example showing the rms separations of these three consituents according to a few-body model [40] is shown in figure 21. Finally, in the figure, the results are shown for interferometry measurements of the sizes of two-neutron haloes in ^{6}He, ^{11}Li and ^{14}Be [41]. These results, obtained by the LPC Caen group in experiments at GANIL, show measured two-neutron halo sizes that are consistent with the measured size of the single neutron halo in ^{11}Be discussed above and in figure 16 [32].

Mention of ^{14}Be, by the way, takes us back also to our starting point in this review, with the tetraneutron ^{4}n possibly being a sub-system of ^{14}Be, and we have in any case exhausted the supply of beryllium isotopes, so it is certainly now time to stop.

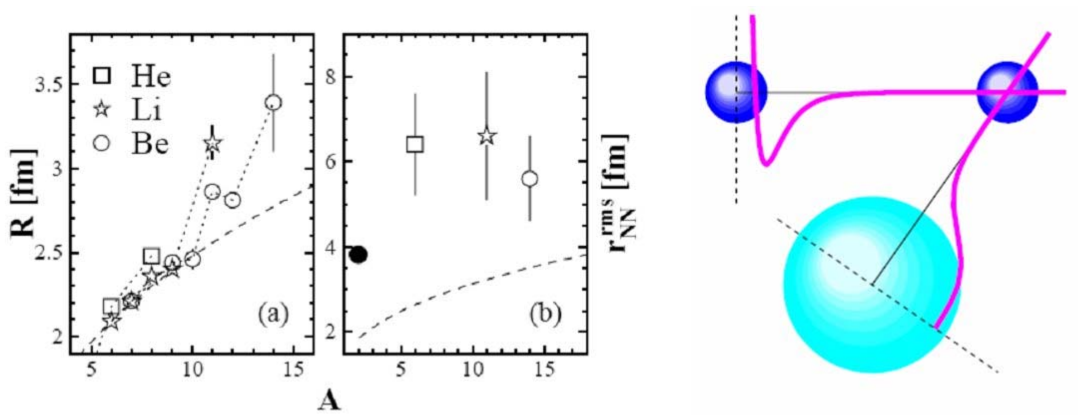


Figure 21: on the right, actual rms distances between core+n+n predicted by a model for 11Li [39]. Left: measured total interaction radii for halo nuclei [40]. Centre: rms halo sizes measured by interferometry [41].

13. CONCLUSIONS

This has been a highly personal choice of topics, as we have reviewed some of the interesting physics revealed in the very rich structure of the rather light nuclei. However, it does serve to illustrate the wide scope and variety of topics that are opened up for study in this region of the nuclear chart. We have not so far seen anything quite as exotic as the complete ring of alpha-particles, held together covalently in a "necklace" state, as discussed speculatively by Wilkinson [42]. Clearly, though, this is very fertile territory for study and there are many interesting things still to be learnt from the rather light nuclei.

Warm thanks to all my colleagues who have contributed to the joint work included here.

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