The Very Rich Structure of the Rather Light Nuclei

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Ecole Joliot Curie, September 2009

Photo: Coconuts Beach Resort, Samoa (2005)
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U.S. citizen Heather Penner, who works at Coconut Resort at Maninoa Siumu on the southern coast of Western Samoa walks through the remains of her Tsunami destroyed workplace.
• Experimental overview of some nuclei, after all the theory
• Theorists.... Please interrupt and explain, if you like
• Rather light nuclei....
• Olivier will cover the heavier nuclei, later
• No equations, but some interesting phenomena...
neutron rich
Strongly bound alpha-particle $\nu(s_1/2)^2 \pi(s_1/2)^2$
No stable nuclear system with mass $A=5$.
Multiple alpha-systems – two-alpha is unbound, three-alpha exists but as unbound excited state
Gaps appear towards neutron drip line, and neutrons are only bound if they are paired.
Magic number (shell gap) at N=8 does not exist in the neutron rich region.
4-proton system doesn’t exist…
proton repulsion and Pauli effects

“Maximally symmetric” alpha-particle has a particularly high binding energy

Could a 4-neutron system exist…?
no repulsion but still have Pauli effects
“Tetraneutron”
$S_{4n}(^{14}\text{Be}) = 5.2$ MeV

F. M. MARQUÉS et al.

PHYSICAL REVIEW C. VOLUME 65. 044006

6 events
pileup < 0.8
"2σ signal"
There is no stable mass A=5 system

$^5\text{Li}$ and $^5\text{He}$ exist as low-lying p-wave resonances

The resonances have asymmetric shapes due to the changing barrier penetrability as a function of the relative energy (alpha-nucleon) AND

The lineshape depends on the production method, e.g. stripping from $^6\text{Li}$ or pickup onto $^4\text{He}$
50 MeV $^7$Li beam $^4$He($^7$Li,$^6$He)$^5$Li 6°lab

Enge split pole spectro
$\Delta \Omega = 0.1^\circ H \times 2.5^\circ V$
Fit = 3/2− and 1/2− plus high lying 3/2− and 1/2−

50 MeV $^7$Li beam $^6$Li($^{13}$C,$^{14}$C)$^5$Li 5.2°lab

α + p

$^5$Li

different

$^6$Li − n

$^4$He($^7$Li,$^6$He)$^5$He 6°lab
$^4$He($^7$Li,$^6$He)$^5$Li 6°lab

$^5$Li

α + p

$^5$He
This is unbound, but observable as a low-lying resonance, and is the $T_z = -1$ analog of $T_z = 1$ weakly bound nucleus $^6\text{He}$.

$^6\text{Be}$

Unbound by 1.372 MeV to $\alpha + p + p$,
Width of $0^+$ ground state resonance = 92 keV,
$(\hbar/2\pi)/\text{width} = (6.578 \times 10^{-22} \text{ MeV.s})/0.092 \sim 10^{-20} \text{ s}$

$^6\text{He}$

Weakly bound, $S_n = 1.867 \text{ MeV}$
$(S_p = 26.52 \text{ MeV})$
($\beta$-decays, half-life = 806.7 ms)

Neutron skin, or halo
Structure of unbound system revealed by decay kinematics

Double-hump from (0p)^2 structure, Sensitivity to model parameters.
$^6$He

full three-body model

"cigar" configuration

"dineutron"

"dineutron"

microscopic cluster model

"dineutron"

PHYSICAL REVIEW C 69, 014309 (2004)
These $A=7$ nuclei are well described as orbiting clusters of $\alpha + ^3\text{He}/^3\text{H}$

A “few-body model” (here, two-body) works very well, using free-space properties of the two clusters, after including Pauli approximately with nodal requirements. (Fully antisymmetrized models also exist, of course, e.g. RGM, Brink model) (Most cluster models do include full antisymmetrization.)
Although it consists of two $\alpha$-particles, $^8\text{Be}$ itself is not bound.

- $E_{\text{rel}} = 92$ keV to $\alpha + \alpha$
- $\text{Width} = 5.57$ eV, $(h/2\pi)/\text{width} \sim 0.1$ fs
- $\text{BE}/A = 7.07$ MeV/A

$^3\text{C}$

- Three-$\alpha$ cluster state
- Is not the ground state
- $E_x = 7654$ keV
- $E_{\text{rel}} = 287.55$ keV $\alpha + ^8\text{Be}$
- $\text{Width} = 8.5$ eV (some $\gamma$ !)
- $(h/2\pi)/\text{width} \sim 0.1$ fs
- $\text{BE}/A = 7.04$ MeV

$^8\text{Be}$

In summary, close to threshold we tend to see states with cluster structure...

(see Ikeda diagram...)
Ikeda Diagram

In either the **deformed Harmonic Oscillator** or the **two centre Harmonic Oscillator**, the energy of the second 4 nucleons drops with deformation. This pushes towards deformation until surface tension limits the deformation.

![Diagram](image)

The projection of the matter density in a DHO or TCHO shows “clusters.”

The sum of the 2 $\Psi$ quartet densities (one even, one odd parity) shows a dip indicating clustering.

An alternative linear combination of wave functions $\Phi$ highlights the clustering.

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M. Freer, R.R. Betts, A.H. Wuosmaa
Clustering emerges naturally in Antisymmetrised Molecular Dynamics. In which there are independent nucleons with no assumed clustering. Here we see the predicted matter density for all beryllium isotopes shown from $^6\text{Be}$ to $^{14}\text{Be}$. On the left, total intrinsic matter density, then proton density, then neutron density.
"Spatial localisation anomaly" in $^9\text{Be}(p,d)^8\text{Be}(\alpha)\alpha$


F. C. Barker and P. B. Treacy

_Nuclear Physics_ 38 (1962) 33-49
As was pointed out by Beckner et al. 3) the plateau at an excitation energy of about 1 MeV in the cross section for the reaction \( ^9\text{Be}(p, d)\) \(^8\text{Be}(\alpha)\) \(^4\text{He}\) is due to transitions through the \(^8\text{Be}\) ground state. The ground state contribution, shown in fig. 1, has two peaks, the one corresponding to a \(^8\text{Be}\) excitation \( E \approx E_0 = 0.094 \text{ MeV} \) and the other to \( E \approx 1 \text{ MeV} \). Such a behaviour is expected for

in which \(^8\text{Be}\) occurs as the intermediate nucleus. However, usually the upper peak will be masked by the tail of the contribution from the 2.9 MeV state of \(^8\text{Be}\) (as for example in the \( B^{1/2}(p, \alpha)\) \(^8\text{Be}(\alpha)\) \(^4\text{He}\) reaction 3)).

(1) similar anomalous peaks, or "ghosts", might be expected in the spectra of excitation energies of nuclei B for which a level, well separated from other levels of the same spin and parity, exists close to a threshold, so that in an energy region above threshold.

For the same reason, similar ghosts might appear in the cross section for a normal resonance reaction

\[ A + a \rightarrow B \rightarrow C + c \]

provided B has an isolated level near enough to either the \((A+a)\) or the \((C+c)\) threshold.


F. C. BARKER AND P. B. TREACY

Nuclear Physics 38 (1962) 33—49
$^{12}\text{C}$

Ghosts

$7.654$ MeV $0^+\ 3\alpha$ state

Ghost of $7.654$ MeV in $^{12}\text{B} \ \beta$-decay

Ghost seen as resonance in $p + ^{11}\text{B}$

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Fig. 3. Density-of-states function $\rho_{^{11}\text{B}}^{11}(E)$ associated with the break-up of the $7.66$ MeV state of $^{11}\text{C}$ into $^{10}\text{Be} + \alpha$, as a function of channel energy $E$. The dotted portion of the curve corresponds to the $7.66$ MeV peak with a width of $8$ eV and a height of $4 \times 10^9$. The curve labelled $\rho W^5$ gives the yield of $^{11}\text{C}^*$ from the $\beta$-decay of $^{11}\text{B}$, $W$ being the available $\beta$-energy.

Fig. 4. Density-of-states function $\rho_{^{11}\text{B}}^{11}(E)$ associated with the break-up of the $16.11$ MeV state of $^{11}\text{C}$ into $^{10}\text{Be} + p$, as a function of channel energy $E$. The dotted portion of the curve corresponds to the $16.11$ MeV peak with a width of $5$ keV and a height of $100$. The curve labelled $\rho E$ gives the cross section for the reaction $^{11}\text{B}(p, \alpha)\text{Be}^*$ due to this state.

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F. C. BARKER AND P. B. TREACY

*Nuclear Physics* **38** (1962) **33–49**
$^9$B has no bound states and a key question is the energy of the $1/2^+$ state that is predicted but for which there is a lot of poor quality data.

$^9$B to $^8$Be + p 185 keV
$^9$B to $\alpha + \alpha + p$ 278 keV
Width = 0.54 keV, $\sim 10^{-18}$ s

$^9$Be has a remarkable “nuclear molecule” structure based on two $\alpha$-particles and a valence neutron

$^9$He is unbound and very neutron rich. It can be observed as a resonance in the $^8$He + n system. (is there level inversion like $^{11}$Be?)
($1/2^+$ below $1/2^-$ ?)
M. Seya, M. Kohno and S. Nagata
Progress of Theoretical Physics, Vol. 65, No. 1, January 1981
page 204
A favourite of Alex Brown, but in fact it proves the existence of nuclear cluster states...

\[ ^{10}\text{Be}^* \]

\[ ^{10}\text{Be} \]

\[ ^6\text{He} \]

\[ ^9\text{Be} \]

... this turns out to be a successful prediction for \(^{10}\text{Be}\) (see later)

CHARISSA+DEMON at GANIL

Reconstruct $E_{\text{rel}}(^8\text{He} + n)$ from measured angles and energies

Some evidence for persistence of $1s_{1/2}$ and $0p_{1/2}$ level inversion as seen in $^{11}\text{Be}$ and $^{10}\text{Li}$
Ground state is $3/2^-$

The $1/2^+$ state can be compared to the $^9$Be mirror (Thomas-Ehrman shift) (both are unbound for $A=9$)

Controversial…
- identity
- energy
- seems to be “too low”
$^{10}\text{C}$ shows molecular structure, but mostly in the excited states.

$^{10}\text{Be}$ is the analog of $^{10}\text{Be}$, with two protons replacing two valence neutrons – do the same structures exist?

Lifetime = 19.3 s
One bound excited $2^+$ state

$^{10}\text{Be}$ shows molecular structure, but mostly in the excited states.
<table>
<thead>
<tr>
<th>( \rho / 2 )</th>
<th>( \rho_p )</th>
<th>( \rho_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0(_1^+)</td>
<td></td>
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<tr>
<td>2(_1^+)</td>
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<tr>
<td>2(_2^+)</td>
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<td>0(_2^+)</td>
<td></td>
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<tr>
<td>1(^-)</td>
<td></td>
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</tr>
<tr>
<td>3(^-)</td>
<td>10 fm</td>
<td>10 fm</td>
</tr>
</tbody>
</table>

Fig. 30. The intrinsic structure of the excited states of \(^{10}\text{Be}\) obtained by VAP calculations. The density distribution of matter, protons and neutrons of the intrinsic states are shown at left, middle and right, respectively. The density is integrated along the axis perpendicular to adequate planes. The figures are for the results with the interaction (g).

Y. Kanada-En’yo and H. Horiuchi
Progress of Theoretical Physics Supplement No. 142, 2001

Valence neutrons occupy genuine molecular orbitals.
Microscopic cluster model (as for $^6\text{He}$ earlier)

$^10\text{Be}$

$^9\text{Be}$ results

Coexistence of two configurations

Necessary, to explain high binding of $1/2^+$
Coexistence of THREE configurations

Necessary, to explain covalent molecular 0+
Super- Borromean… “Brunnian”

Martin Freer
Super- Borromean… “Brunnian”

$^{10}\text{C} @ 10.7 \text{ MeV/A on } ^9\text{Be Texas A&M}$

R. J. CHARITY et al.  
PHYSICAL REVIEW C 75, 051304(R) (2007)

$^{10}\text{C} @ 33.3 \text{ MeV/A on } ^{12}\text{C GANIL}$

N. CURTIS et al.  
PHYSICAL REVIEW C 77, 021301(R) (2008)
Weakly bound
$S_n = 0.xx$ MeV

Halo nucleus

This is a classic single-neutron halo nucleus, where the weak binding automatically leads to a halo.

Both the intruder $1/2^+$ ground state and the low $1/2^-$ state have a halo – despite the centrifugal barrier for the $p_{1/2}$ state.

The halo is not pure, however, and there is a component of the ground state in which the deformed core is excited to $2^+$ and a d-wave neutron is coupled to give spin $1/2$. 
Structure of unstable light nuclei

D.J. Millener

Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA

Nuclear Physics A 693 (2001) 394–410

Abstract

The structure of light nuclei out to the drip lines and beyond up to Z ~ 8 is interpreted in terms of the shell model. Special emphasis is given to the underlying supermultiplet symmetry of the p-shell nuclei which form cores for neutrons and protons added in sd-shell orbits. Detailed results are given on the wave functions, widths, and Coulomb energy shifts for a wide range of non-normal parity states in the p-shell. © 2001 Elsevier Science B.V. All rights reserved.
Physicists in Europe and North America have measured the radius of an unusual beryllium isotope containing a single neutron a long way from the rest of the nuclear core. Although the radii of other such “halo” isotopes have been determined before, this is the first time that the measurement has been made on a nucleus with just a single halo neutron. The researchers found that the halo neutron in beryllium–11 is, on average, about 7 fm (7 x 10^{-15} m) from the nuclear core, which itself has a radius of about 2.5 fm.

**Measurements and calculations**

The new study was carried out at the ISOLDE facility at CERN by Wilfried Nörtershäuser at the University of Mainz and colleagues in Germany, Canada and Switzerland (Phys. Rev. Lett. 102 062503).

The experiment involved producing four different isotopes of beryllium (with 7, 9, 10 and 11 nucleons) by firing a 1.4 GeV proton beam into a uranium-carbide target. This created beryllium atoms, which were then ionized using a laser and accelerated to 50 kV. Transitions in electron energy levels were induced by firing two ultraviolet laser beams at the ions. One beam was fired straight at the oncoming ions, while the other was fired in the opposite direction from behind the ions to cancel out the experimental uncertainty in the kinetic energy of the ions.
Measuring $^{11}\text{Be}$ structure as superposition of $^{10}\text{Be}(0^+)+\nu(s_{1/2})$ and $^{10}\text{Be}(2^+)+\nu(d_{5/2})$

Removal of last neutron via ($p,d$) transfer

J.S. Winfield et al. / Nuclear Physics A 683 (2001) 48–78
Focal plane spectrum from SPEG magnetic spectrometer

- singles
- coincidence
- gamma-ray broadening
- carbon background removed
Separation Energy form factor

Vibrational form factor

\[ \alpha^2 \quad \beta^2 \]

- poor form factor
- no core coupling
- no \(^{11}\text{Be}/d\) breakup

- vibrational model
- core-excited model
- realistic form factor

- 0.74 0.19
  - Shell model

- 0.84 0.16
  - 11Be/d breakup

\[ 0^+ \quad 2^+ \]

- 0.49 0.51

\( \text{do/d} \Omega \) \( \text{mb/sr} \)
$^{14}$C is magic – p3/2 protons closed
p1/2 neutrons closed
N=8 closure is good

$S_p = 20.832 \text{ MeV}$
$S_n = 8.177 \text{ MeV}$
$S_{\alpha} = 12.012 \text{ MeV}$

$^{14}$C

$^{12}$Be sees a total collapse of magicity.. just by the…

…removal of two protons but keeping N=8

Excited states in $^{12}$Be seem to show $^6$He+$^6$He clustering behaviour.
$^{14}\text{C}$ is magic – p3/2 protons closed p1/2 neutrons closed N=8 closure is good

$S_p = 20.832$ MeV

$S_n = 8.177$ MeV

$S_\alpha = 12.012$ MeV
12Be

PPAC - DeMoN

10000 pps @ 39 A.MeV
3290 MeV/c
95% pure

12Be
Simulated Components Fitted to Excitation Energy Spectrum

$^9\text{Be} + \text{C} \rightarrow ^8\text{Be} + \gamma$

Counts per 100 keV

Occupancy Percent

- $S_1/2$: 0.44, 30%
- $d_5/2$: 0.48, 32%
- $p_1/2$: 0.56, 38%

$^{12}\text{Be} \rightarrow ^{11}\text{Be}$

Steve Pain et al., PRL 96, 032502 (2006)
Be


Ground state – a more normal deformation,
Excited band – 2:1 $^6$He+$^6$He cluster configuration
Both $^{13}\text{Be}$ and $^{10}\text{Li}$ are unbound sub-systems of bound halo systems ($^{14}\text{Be}$ and $^{11}\text{Li}$).

If we remove a single neutron from the bound halo system:  
And then observe the other neutron and the core nucleus,  
And then reconstruct the relative momentum…

Do we measure the neutron-core interaction in an accurate manner,  
or do we observe some vestige of the structure in the original halo…?
How well do reconstructed resonances in the sub-system resemble the actual sub-system and how much are they a remnant of the initial state? Are standard resonance line-shapes expected? .... (YES)

Calculated reaction products compared with resonances

For several structure models, comparison of relative peak strengths in reaction with relative strengths in the initial wavefunction

G. F. BERTSCH, K. HENCKEN, AND H. ESSENSEN
PRC 37 (1998) 1366
There may be a component of the ground state that has this structure, which may account for the observation of the “tetraneutron” events (possible 4n resonance?)

Borromean halo nucleus
$S_{2n} = 1.12$ MeV

$^{12}$Be $S_n = 3.17$ MeV
Borromean halo nucleus
$S_{2n} = 1.12 \text{ MeV}$

$^{12}\text{Be}$ $S_n = 3.17 \text{ MeV}$

rms separations for core and neutrons in few-body $^{11}\text{Li}$ model, compared to ranges of potentials

Interferometry between the two neutrons at GANIL/DEMON measures their rms separation in the $^{14}\text{Be}$ source

F. M. MARQUES et al. 
PHYSICAL REVIEW C 64 061301(R)

The interaction radius from total cross section measurements is clearly larger for halo nuclei


rms separations for core and neutrons in few-body $^{11}\text{Li}$ model, compared to ranges of potentials

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