The Halo at the Center of the Atom

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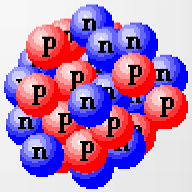
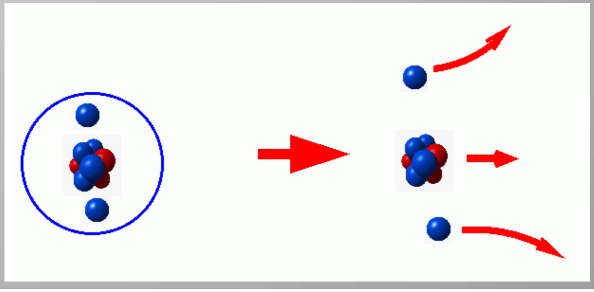
Topics of the Talk

- The Nucleus in the Atom.
- Where nuclei come from?
- The Halo at the Centre of the Atom!
- How the halo holds together?
- Quantum features!
- What next?

Nuclear Physics



- The task of nuclear physics is to see and understand:
  - Which nuclei exist, their size and shape,
  - How protons and neutrons hold together,
  - The energies of the protons and neutrons,
  - Whether they decay into different forms,
  - How they react to collisions from outside,
  - Nuclear energy, etc.

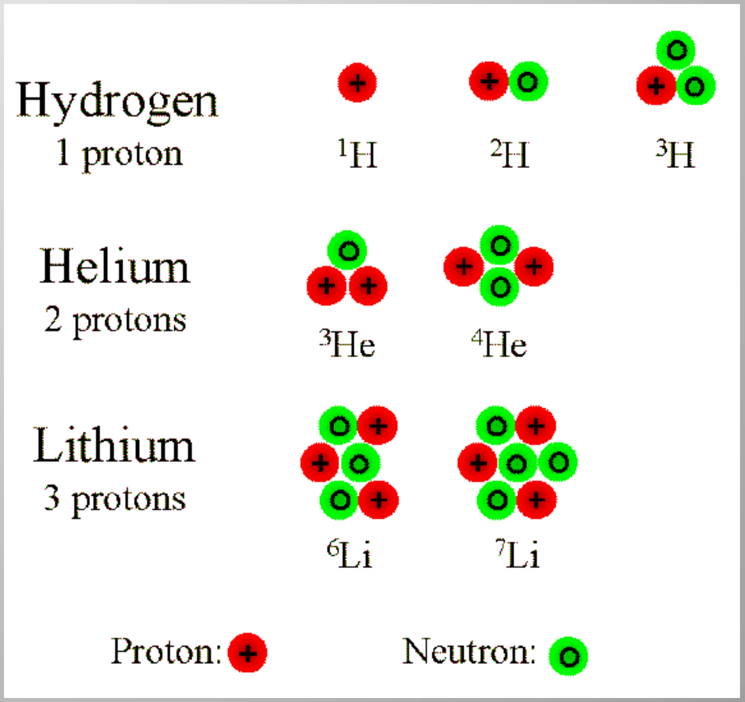


The Quantum Realm

- Nuclei do not obey the classical laws of ordinary matter,
- But the peculiar laws of Quantum Mechanics, which govern atoms and all they contain.
- Nuclei exhibit a unique range of quantum phenomena,
- e.g. the Haloes we look at later.

Holding the nucleus together

- Neutrons attract protons and each other, so they are a kind of glue
- Nucleus has more or less glue
- Different number of neutrons: different isotopes.
- Neutrons by themselves are not stable.



Examples of Isotopes

- Hydrogen (1 proton)

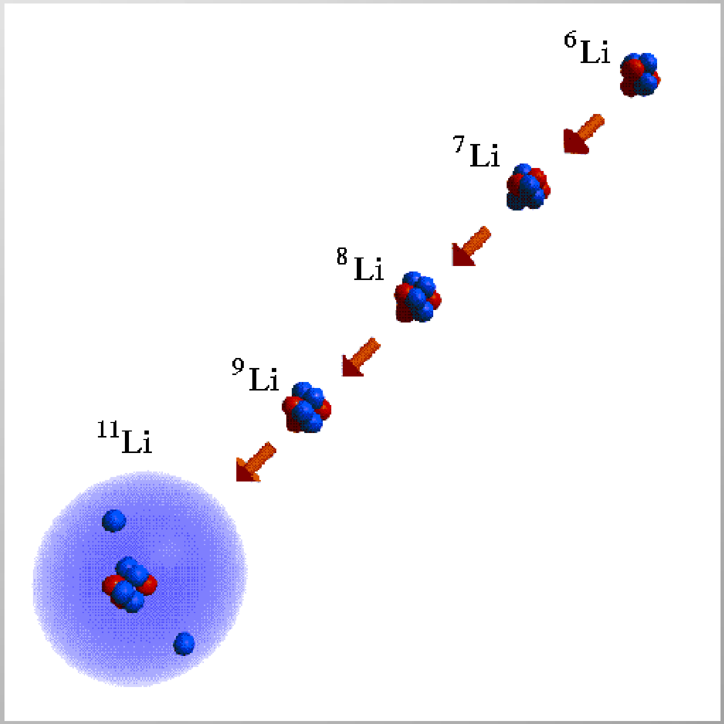
  + neutron ⇒ deuteron ^{2}H

  + 2 neutrons ⇒ triton ^{3}H

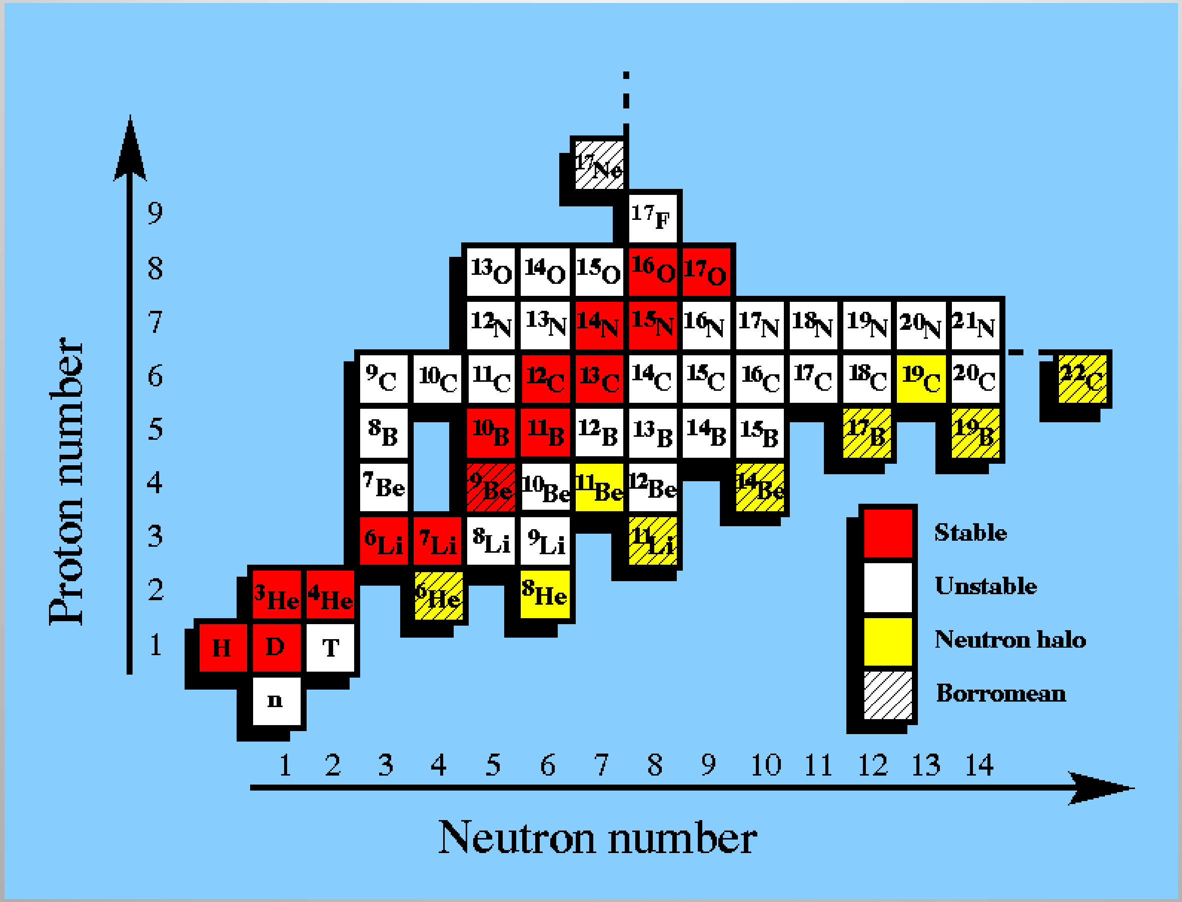
- Lithium (3 protons)
  - usually 3 or 4 neutrons (^{6}Li, ^{7}Li)
  - also exists with 5, 6 and 8 neutrons! (^{8}Li, ^{9}Li, ^{11}Li)
  - Not with 2 or 7. Why?

- Why is ^{11}Li so big?

Total mass = neutrons + protons



Periodic Table of Isotopes

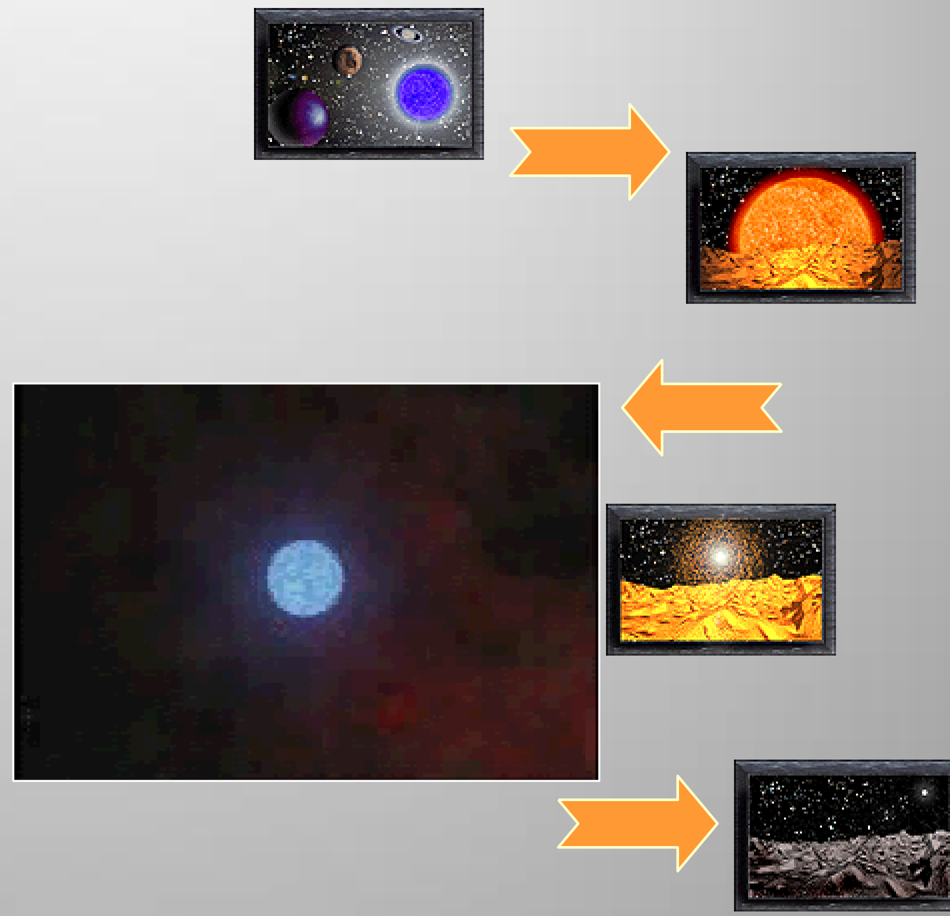


Where do elements and isotopes come from?

- From the BIG BANG
- From stars
  - Our sun produces Helium from Hydrogen, giving light and heat. Generates some heavier elements.
  - Supernovae produce many more kinds of isotopes & elements, very rapidly!

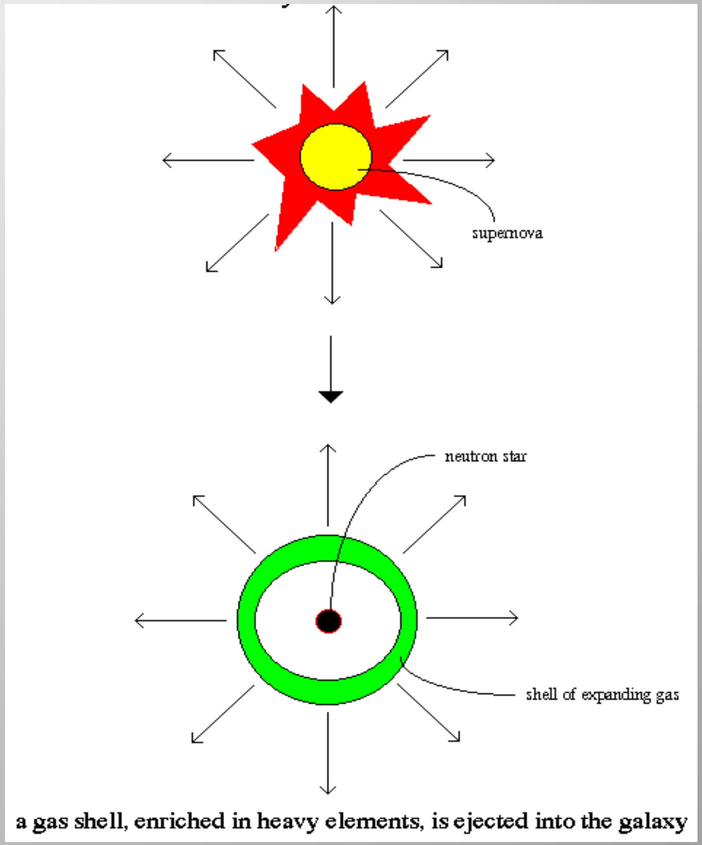
Star cycle ends as a Supernova

- Suns ends by using all its Hydrogen
- Converts to elements up to iron
- Large stars explode as Supernova! (we think)
- Debri in space, leaving a neutron star.



During the Explosion (hypothetically)

- The collapse of the core creates a shock wave that propagates outward and blows the outer layers of the star off.
- Neutrons are created in the blast wave that results.
- These neutrons combine with nuclei of the lighter elements, created, to produce elements heavier than iron.

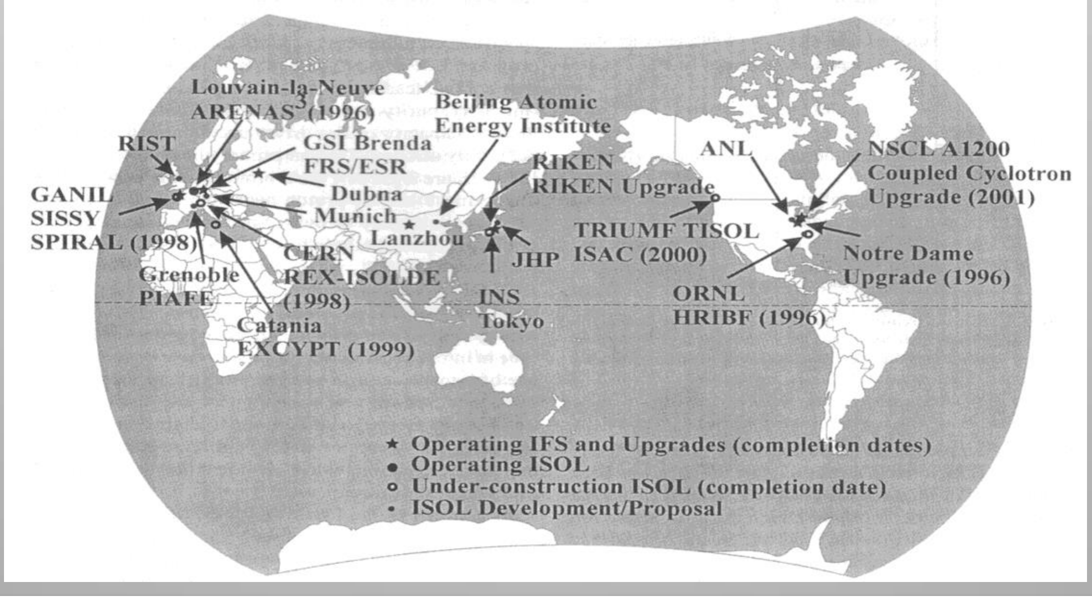


Neutrons to build up nuclei

- During the supernova explosion, there are large numbers of free neutrons
  - These breakup down existing nuclei,
  - and start to build them up again.
- Form many new Elements, and
- new Isotopes with many extra neutrons, so
- Need to understand neutron-rich isotopes!

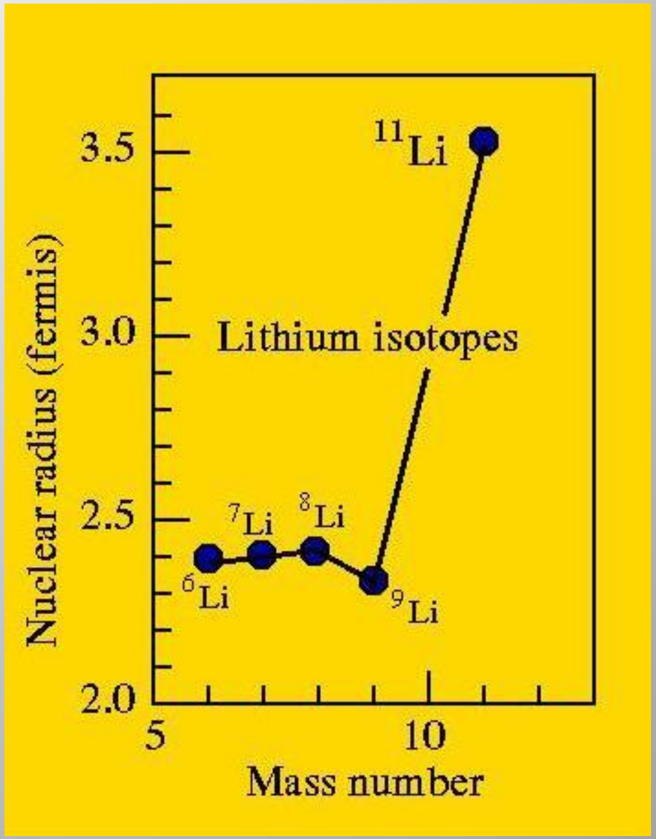
Neutron-rich Nuclei today

- **These nuclei only last a fraction of second before decaying.**
- **Make <u>Radioactive Nuclear Beams</u> in special laboratories,**
- **And do experiments on them immediately!**



Halo at the Centre of the Atom

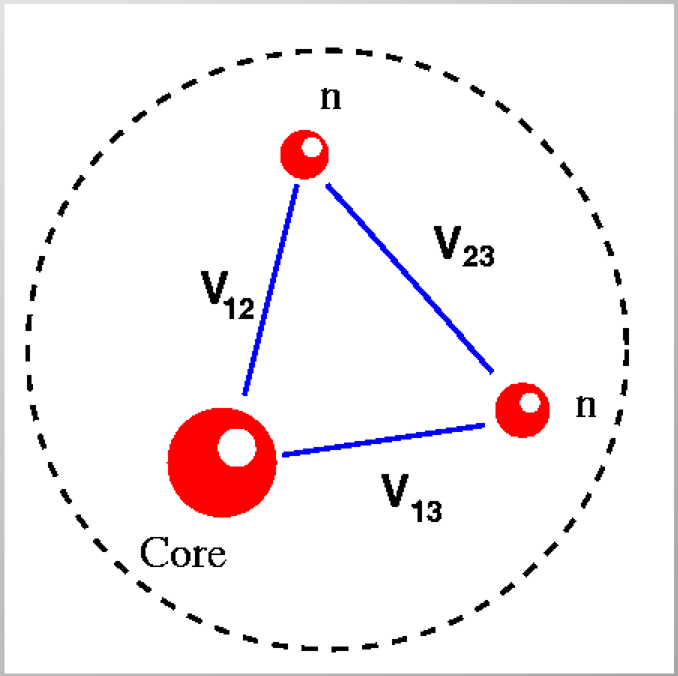
- Some neutron-rich nuclei are very big!
- For example, ^{11}Li is much larger than ^{9}Li
- The last two neutrons form a <u>HALO</u> outside the central core.
- New dilute form of matter



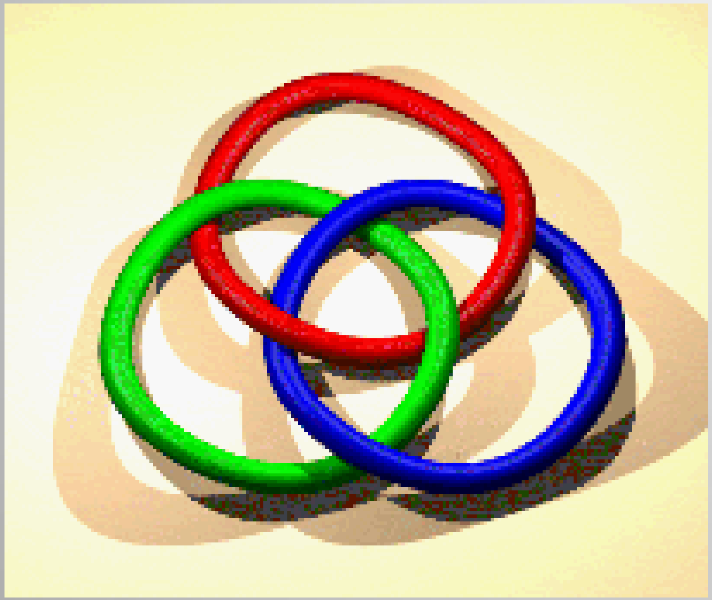
Other Kinds of Haloes

What holds the Halo together?

- The two neutrons and the core attract each other, but
- each pair does not hold together,   yet
- the whole three-body system is bound!
- A Borromean system.

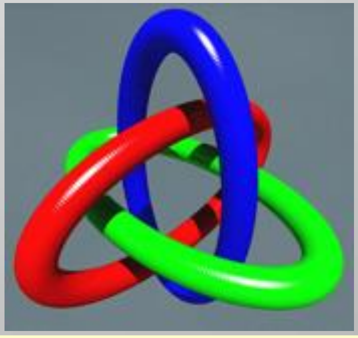


Borromean Rings



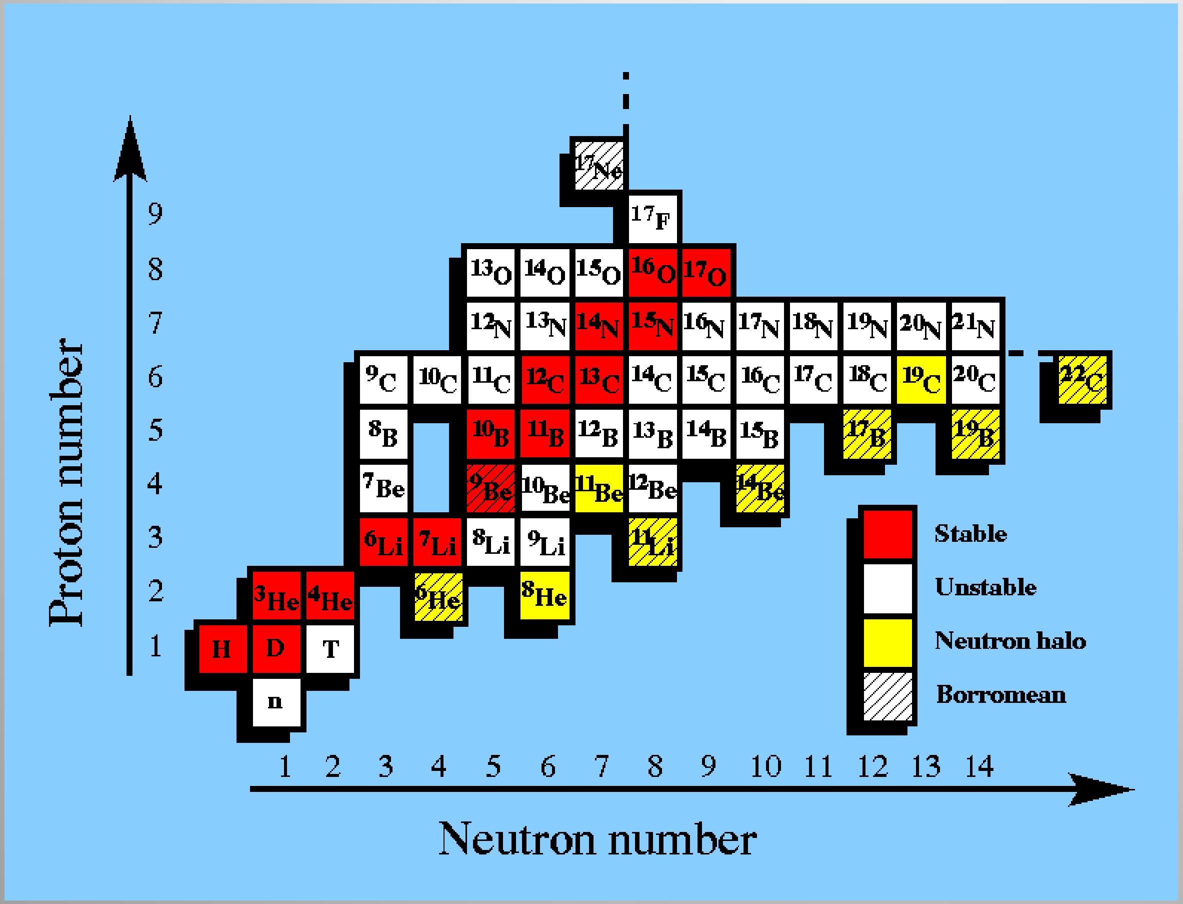
Three rings interlinked in such a way that

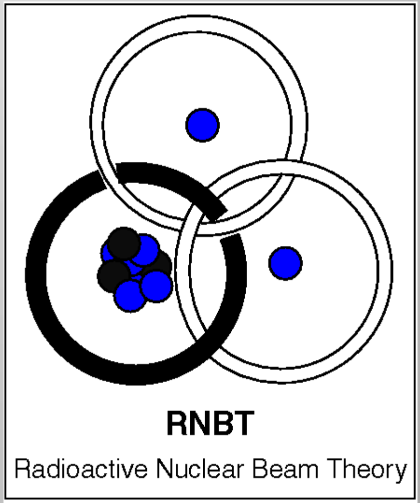
- All three hold together
- Remove any one, and the other two fall apart!



Borromean rings, the heraldic symbol of the Princes of Borromeo, are carved in the stone of their castle in Lake Maggiore in northern Italy.

Borromean Nuclei



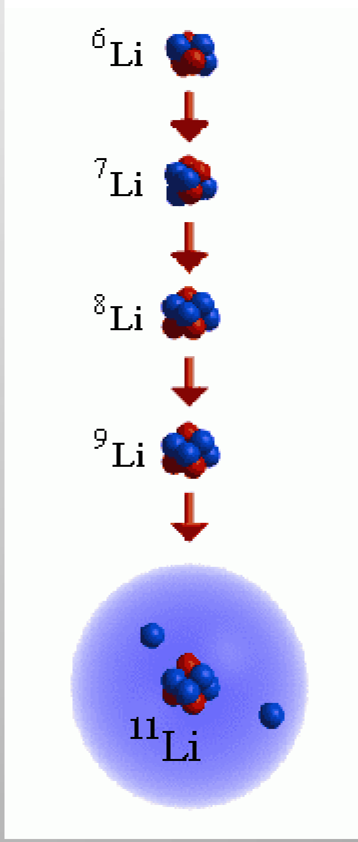


RUSSIAN-NORDIC-BRITISH
THEORY COLLABORATION

What holds the Halo together?

- The three bodies attract each other at short distances,   but
- Much of the halo size is beyond the range of the forces!
- What does hold the halo together???

This is what we find out, by research



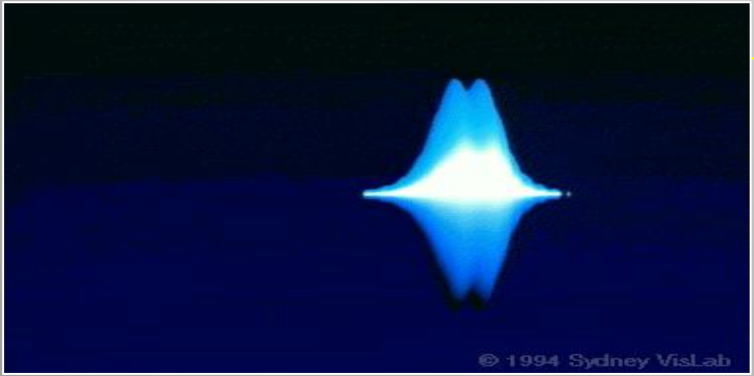
Quantum Physics

- The small particles in nature
  - are NOT solid bodies (as Newton thought);
  - But are clouds of tendencies (as discovered in the 1920's in quantum physics), as a wave function.

- Wavelike patterns for possible actions;
  - (corresponds to us, before we decide what to do!).
  - More like intention than already-completed result.
  - Spread out, but then acts as a whole: non-local.

Energy and Momentum

- <u>Classical Physics::</u>
- for particle of mass *m* and velocity *v*:
  - Energy $E = ½\, m\, v^2$
  - Momentum $p = m\, v$



- <u>Quantum Physics::</u>
  - Tendency field $\Psi(x,t)$
  - Governed by the Schrödinger Equation
- Energy: time variation
  - $E \propto \partial\Psi(x,t)/\partial t$
- Momentum: spatial variation
  - $p \propto \partial\Psi(x,t)/\partial x$

Energy, Tendency and Action

‘Active Energy’ → **Tendency Wave** → **Actual Outcome**

(Hamiltonian)

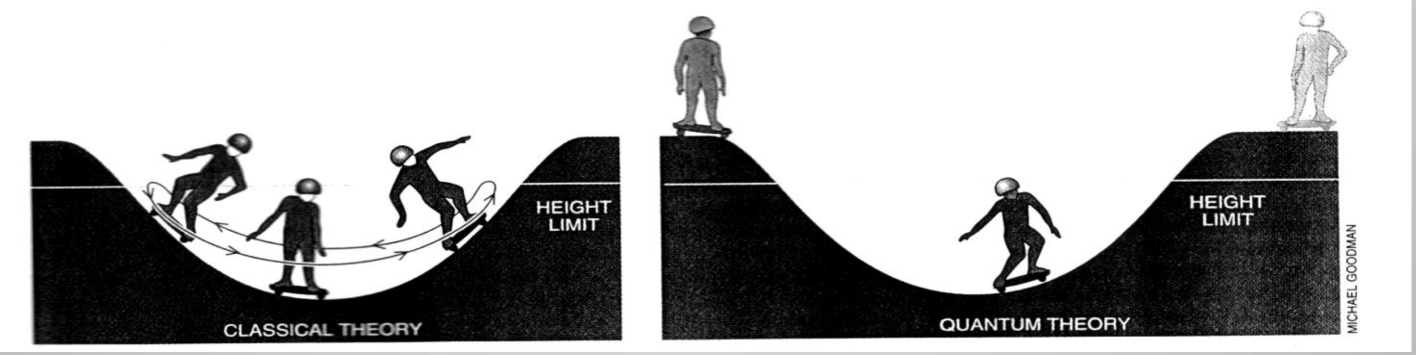
Schrödinger Equation **Probabilities by Born Law**

- Three degrees of production in physics, appear to correspond to
- Three degrees of production in psychology:

Intention → **Possible Plans** → **Action**

(desires) **(thoughts)**

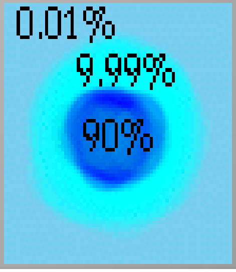
Residing in Forbidden Space



- Classical physics on left: definite limit in space
- Quantum physics on right: some tendency persists past classical limit (fainter figures): tunnelling.
- This makes haloes bigger in the quantum world.

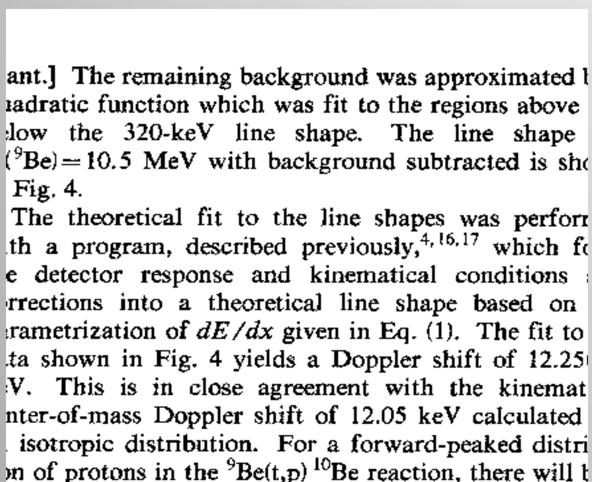
The neutrons and the core in a halo still attract, as long as their tendency fields at least partly overlap!

Distributions of probabilities

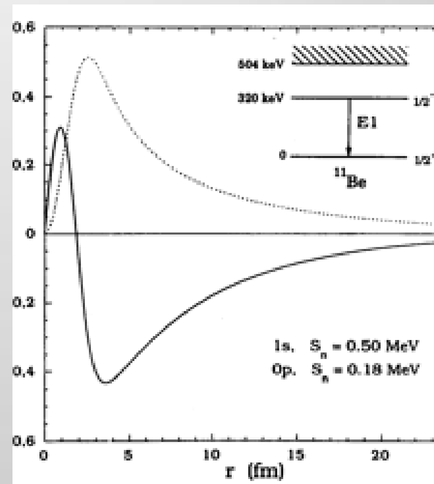


The First Halo: ^{11}Be

- Strong electric dipole decay in ^{11}Be:


ant.] The remaining background was approximated b
uadratic function which was fit to the regions above
elow the 320-keV line shape. The line shape
(^{9}Be)=10.5 MeV with background subtracted is sho
Fig. 4.
The theoretical fit to the line shapes was perform
ith a program, described previously,[4,16,17] which fo
e detector response and kinematical conditions
rrections into a theoretical line shape based on
arametrization of dE/dx given in Eq. (1). The fit to
ata shown in Fig. 4 yields a Doppler shift of 12.25
eV. This is in close agreement with the kinemat
nter-of-mass Doppler shift of 12.05 keV calculated
isotropic distribution. For a forward-peaked distri
on of protons in the ^{9}Be(t,p)^{10}Be reaction, there will b

| = 168(17) fs: B(E1) = 0.36(3) W.u.
Millener et al., PRC 28 (1983) 497

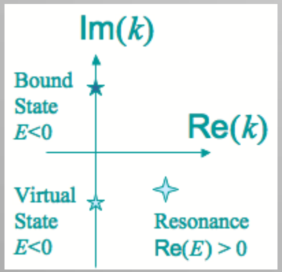


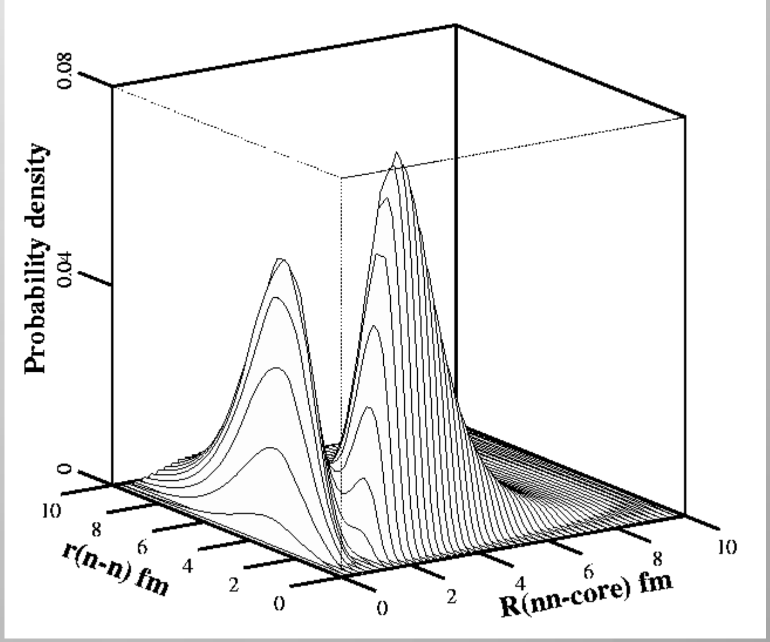
"We note that to obtain the $s_{1/2}$ $p_{1/2}$ matrix element for low binding energies
it is necessary to integrate out to large radii"

Two-neutron halo example: ^{6}He

- The neutrons and the core in a halo still attract, as long as their tendency fields at least partly overlap!

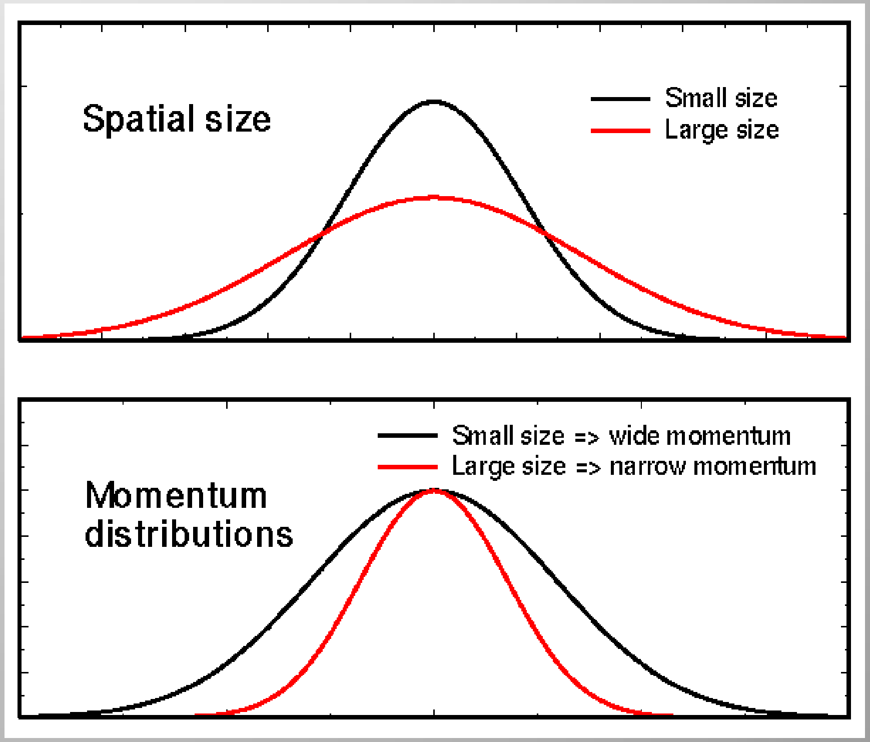
  - Two Neutrons and an α particle bound at S_{2n} = 0.97 MeV
  - n-α unbound, but $p_{3/2}$ resonance at 0.8 MeV
  - n-n unbound, but virtual state a_{nn} = −18.8 ± 0.3 fm



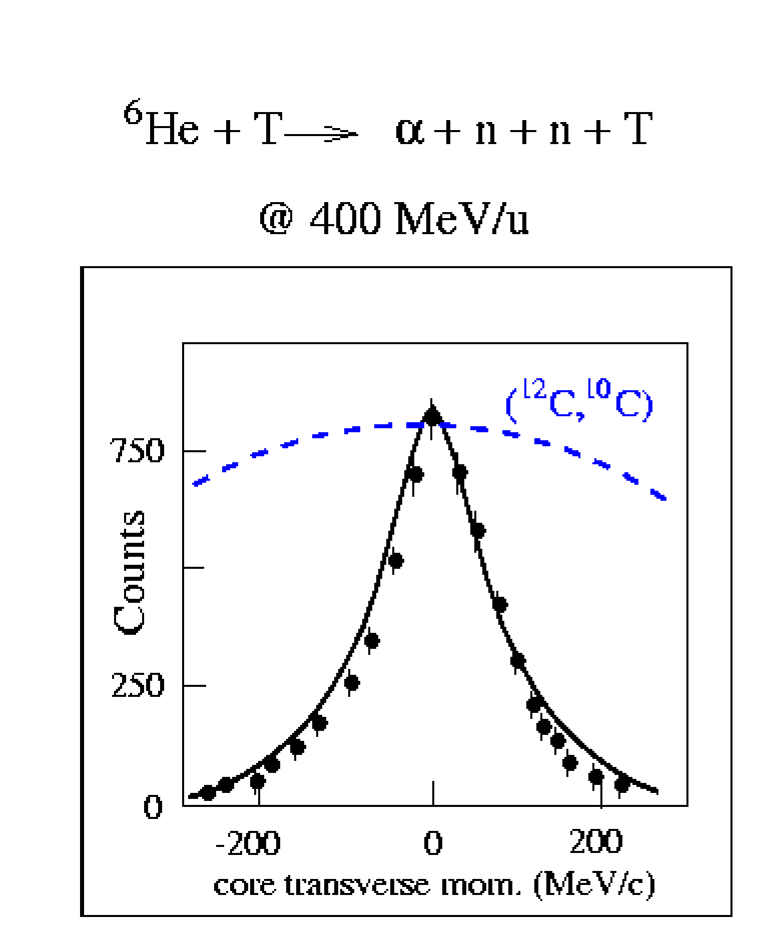


To Measure the Halo Size

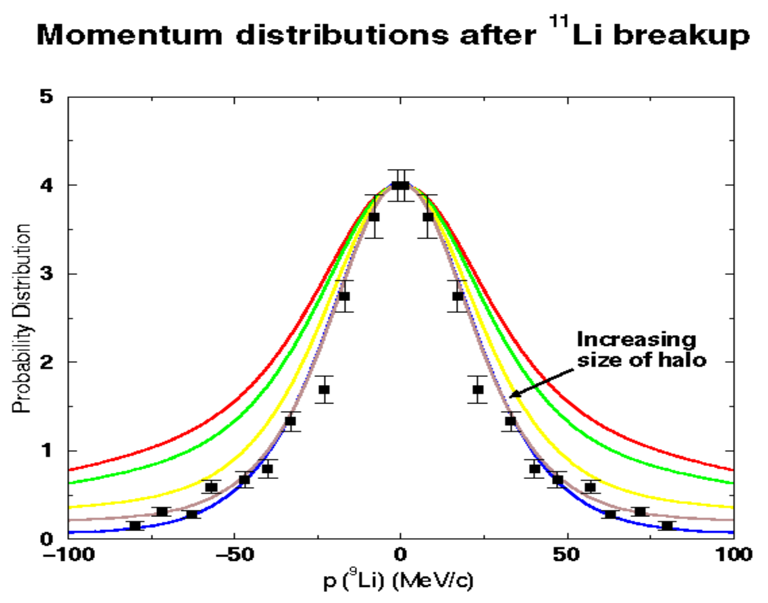
- Heisenberg's Uncertainty Principle:
  - Small size $\Rightarrow$ larger momentum
  - Large size $\Rightarrow$ smaller momentum
  - (From $p \propto \partial\Psi(x,t)/\partial x$)



Halo size from Experiments



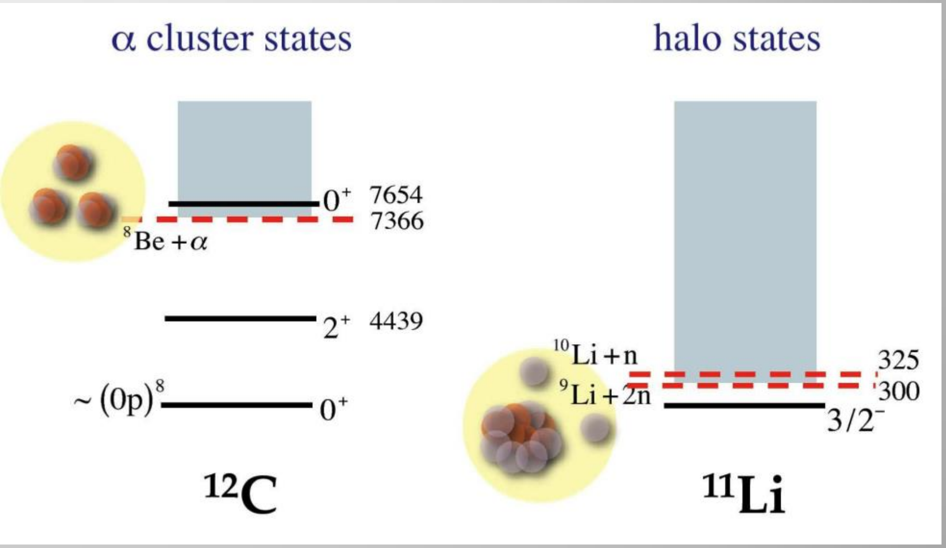
- The momentum distributions are found to be very narrow (on nuclear scales),
- So: large halo size!



Halo depend on nearness of thresholds

- In ^{11}Li, there is three-body clustering ($n+n+{}^{9}Li$) near the ground state.
- In ^{12}C, there is clustering into 3 alpha particles, but at 7.6 MeV excitation.

  This is the Hoyle state at 290 keV that is critical for making ^{12}C from 3 alphas
- The difference is because of the thresholds (dashed red lines): the energies where the fragments can break up.
- All nuclei may have halos at some higher energy.



Examples of Halo Nuclei

One neutron:

- ^{11}Be (S_n = 0.504 MeV)

Two-neutron Borromean:

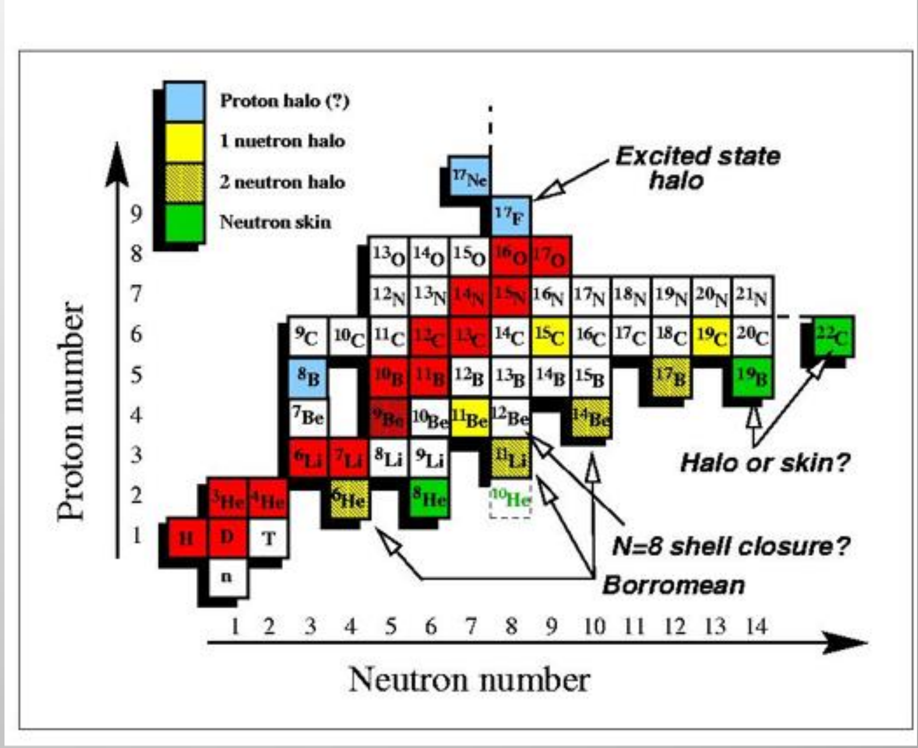
- ^{6}He (S_{2n} = 0.97 MeV),
- ^{11}Li (S_{2n} = 0.30 MeV),

One-proton

- ^{8}B (S_p = 0.137 MeV),

Two-proton Borromean:

- ^{17}Ne (S_{2p} = 0.96 MeV),



What Use are Haloes?

- Help in production of new isotopes for many applications (maybe).
- Test our understanding of few-body and collective phenomena in the quantum world,
  especially at boundary of bound and continuum states.
- Understand the production of elements, both in astronomy & new superheavies.

Conclusions

- Haloes are a new form of matter,
- Haloes display essential quantum features common to all microscopic matter,
- Haloes help us understand element production in stars and supernovae.
- Haloes help in production of new isotopes.

Collaborators and Students

- **Theory Collaborators**
  - Michigan State University: Filomena Nunes, Alex Brown,
  - Surrey: Jeff Tostevin, Ron Johnson, Jim Al-Khalili.
  - RNBT (Russian-Nordic-British Theory Collaboration):
    Jan Vaagen, Boris Danilin, Mikhail Zhukov, Sergei Ershov, Victor Efros, Jens Bang.
  - Portugal: Raquel Crespo, Ana Eiró.
  - Spain: Manuela Gallardo, Antonio Moro.
  - India: Radhey Shyam.
- **Postdoctoral Researchers**
  - Natalia Timofeyuk, Leonid Grigorenko, Alexis Diaz-Torres, Prabir Banerjee, Supagorn Rugmai, Neil Summers,
- **Doctoral Students**
  - Brian Cross, Filomena Nunes, James Stott, Tatiana Taroutina, John Mortimer, Paul Batham, Amy Bartlett, Manuela Gallardo, Ivan Brida, Jesus Casal,

Further Reading

- *Bound State Properties Of Borromean Halo Nuclei: ^{6}He and ^{11}Li*, M.V. Zhukov, B.V. Danilin, D.V. Fedorov, J.M. Bang, I.J. Thompson and J.S. Vaagen, Physics Reports **231** (1993) 151 - 199
- *Halo Nuclei*, Sam Austin and George Bertsch, Scientific American, June 1995.
- *Structure and reactions of quantum halos*, A. S. Jensen, K. Riisager, and D. V. Fedorov and E. Garrido, Reviews of Modern Physics, **76** (2004) 215-261

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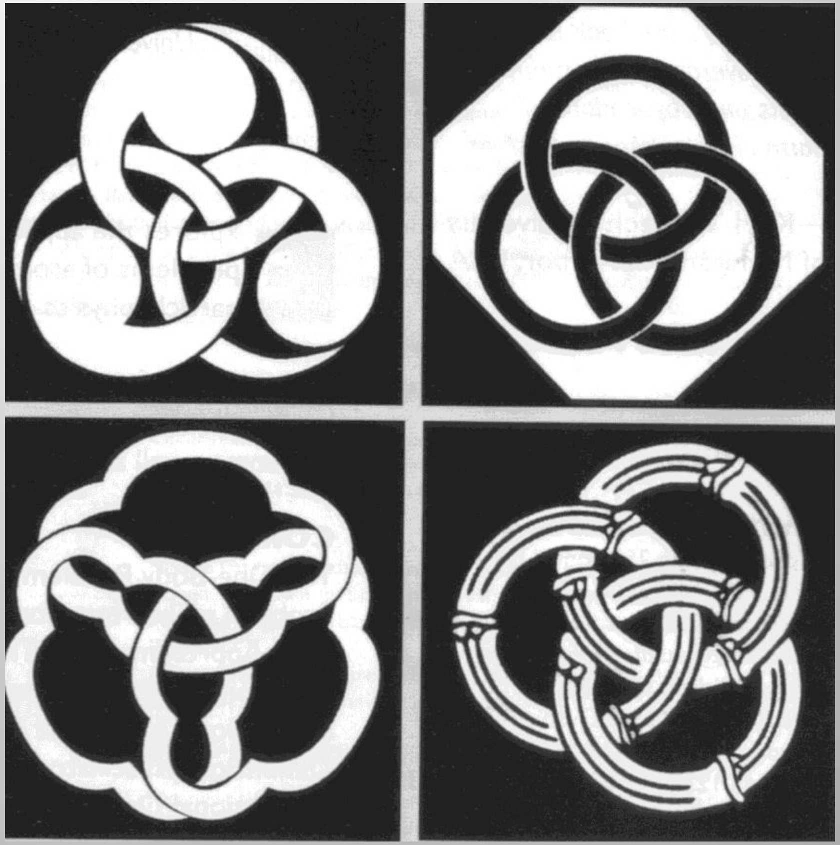
Test

- Which of these knots are NOT Borromean?
- (These are Japanese family emblems)



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