A Brief Introduction to Nuclear Physics

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18 January 2026

Introduction

Stable nuclei are qualitatively described by "simple" models

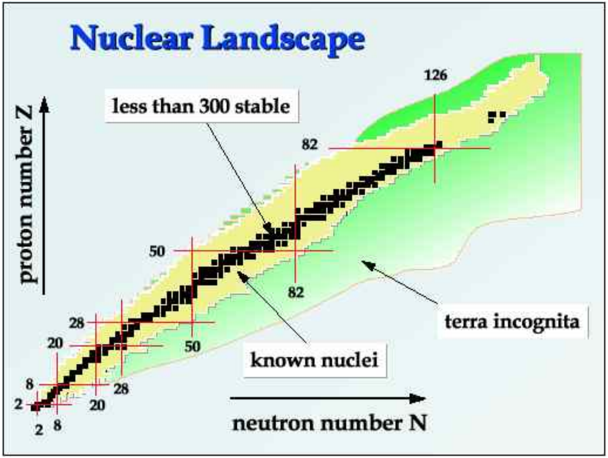
- (semi-empirical) liquid-drop model
- (basic) shell model

New techniques enable *ab initio* methods (A-body models)

What happens far from stability ?
Experimentally, Radioactive-Ion Beams (RIB) available since 80s
⇒ study of structure far from stability
⇒ discovery of exotic structures

- halo nuclei
- shell inversions
- ...

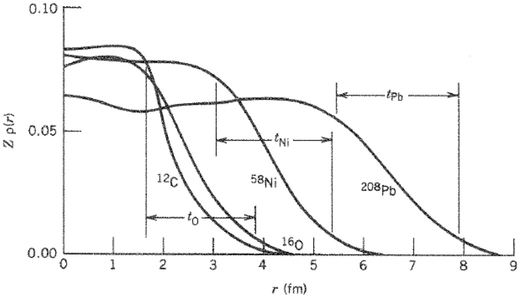
Nuclear Landscape



- 256 stable nuclei
  @ $Z \simeq N$ up to ^{40}Ca
  @ $N > Z$ for $A > 40$
- stable nuclei
  - compact
  - *magic* numbers
- RIB allow to study radioactive nuclei
- Terra incognita between driplines
  n-dripline unknown beyond ^{34}Ne

1. Basic features in nuclear structure
   - Liquid-drop model
   - Shell model
2. Ab initio nuclear models
3. Radioactive-Ion Beams
4. Oddities far from stability
   - Halo nuclei
5. Summary

Charge distributions in (stable) nuclei

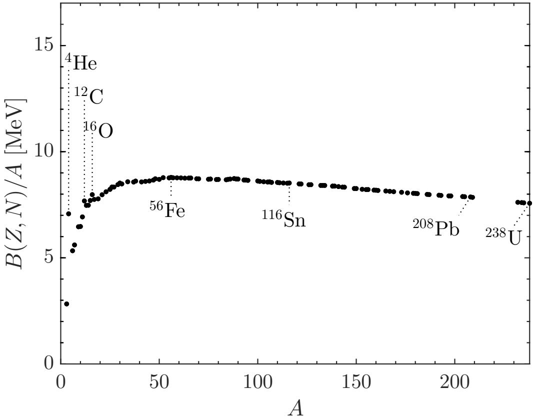


- constant density ρ_0 out to the surface (saturation)
- same skin thickness t

(Stable) nuclei look like liquid drops of radius $R \propto A^{1/3}$

Liquid-drop model

Binding energy per nucleon $B(Z,N)/A$ has smooth behaviour



[F. Colomer]

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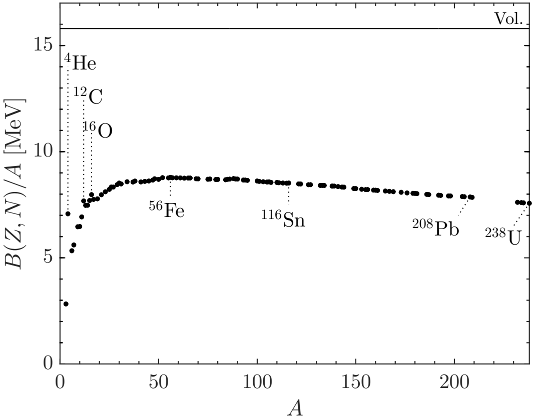
Bethe-Weizsäcker semi-empirical mass formula

$$B(Z,N) = a_v A$$



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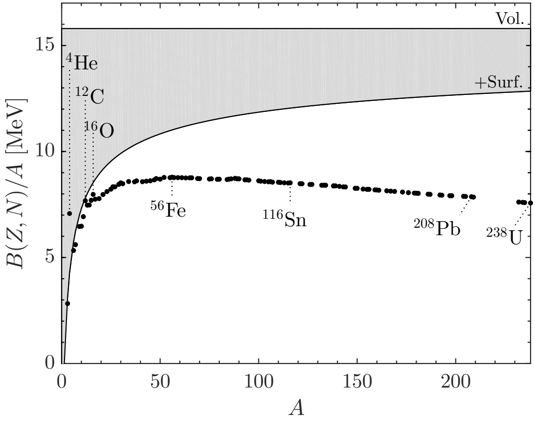

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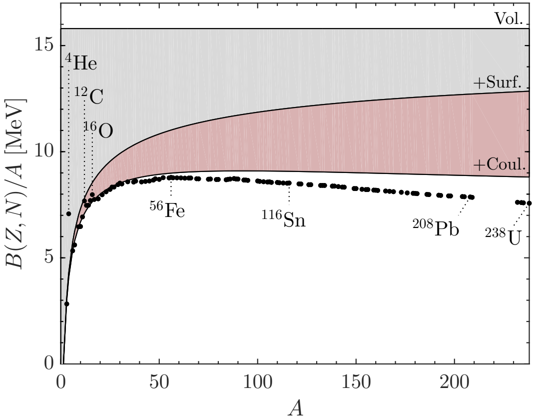

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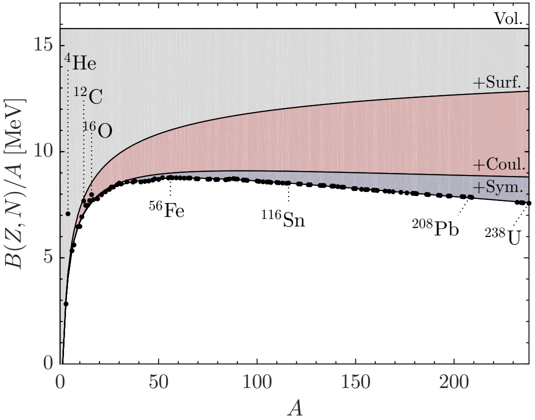
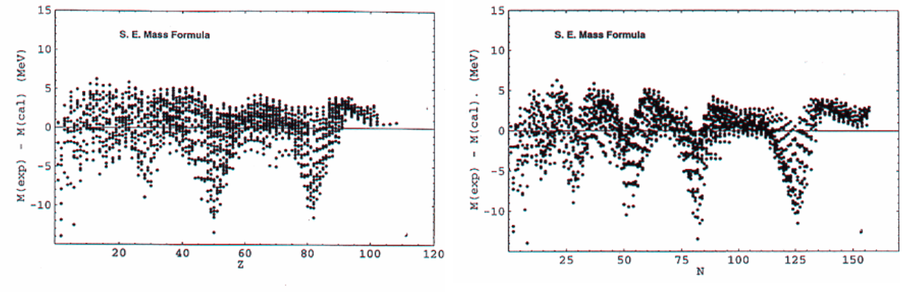
$$B(Z,N) = a_v A - a_s A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_{\mathrm{Sym}} \frac{(A-2Z)^2}{A}$$



[F. Colomer]

Variation from the semi-empirical mass formula



More bound systems at Z or $N = 2, 8, 20, 28, 50, 82, 126$

magic numbers

⇒ shell structure in nuclei as in atoms ?

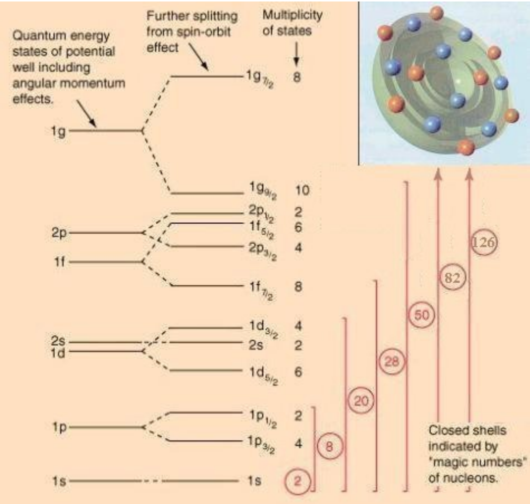
Shell model

Developed in 1949 by M. Goeppert Mayer and H. Jensen

(NP 1963)

As electrons in atoms,
nucleons in nuclei
feel a mean field
and arrange into shells

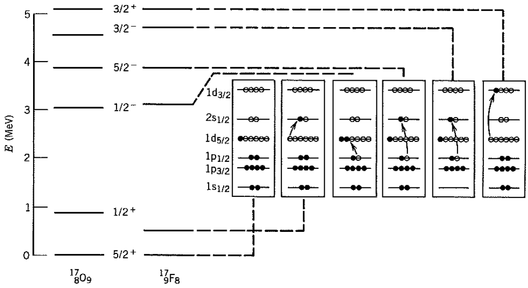
Spin-orbit coupling is crucial
to get right ordering of shells



Example

Shell model explains the higher stability at some Z and N

It predicts the spin and parity of ground state of most nuclei and some of their excited levels, e.g. ^{17}O and ^{17}F



Nowadays

Can we go beyond these models ?

Can we build *ab initio* models ?
i.e. based on first principles

- nucleons as building blocks
- realistic N-N interaction

A-body Hamiltonian

Nuclear-structure calculations : A nucleons (Z protons+N neutrons)

Relative motion described by the A-body Hamiltonian

$$H = \sum_{i=1}^{A} T_i + \sum_{j>i=1}^{A} V_{ij}$$

$\Rightarrow$ solve the A-body Schrödinger equation

$$H\,|\Psi_n\rangle = E_n|\Psi_n\rangle$$

$\{E_n\}$ is the nucleus spectrum

Realistic N-N interactions

V_{ij} not (yet) deduced from QCD
$\Rightarrow$ phenomenological potentials
fitted on N-N observables :
d binding energy,
N-N phaseshifts

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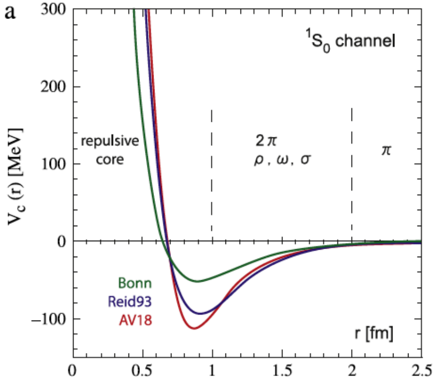
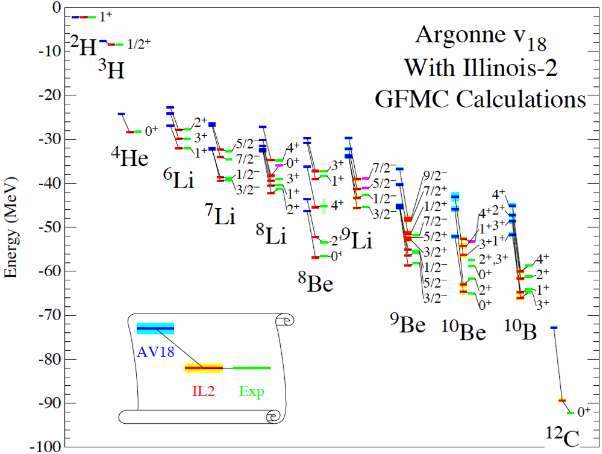
Ex. : Argonne V18, CD-Bonn,...



[see A. Schmidt's talk on Friday]

Light nuclei calculations



[R. Wiringa, Argonne]

Three-body force

Need three-body forces to get it right…

$$H = \sum_{i=1}^{A} T_i + \sum_{j>i=1}^{A} V_{ij} + \sum_{k>j>i=1}^{A} V_{ijk} + \cdots$$

But there is no such thing as three-body force…

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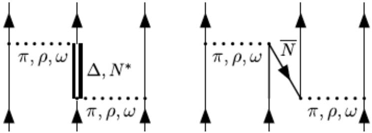
But there is no such thing as three-body force...

They simulate the non-elementary character of nucleons
$\Rightarrow$ include virtual Δ resonances, $\bar{\mathrm{N}}$...



Phenomenological 3-body interaction fitted on $A > 2$ levels : IL2
Alternatively, derived from EFT

Effective Field Theory

EFT is an effective quantum field theory based on QCD symmetries with resolution scale Λ that selects appropriate degrees of freedom : nuclear physics is not built on quarks and gluons,
but on nucleons and mesons

EFT provides the nuclear force with a systematic expansion in Q/Λ

- gives an estimate of theoretical uncertainty

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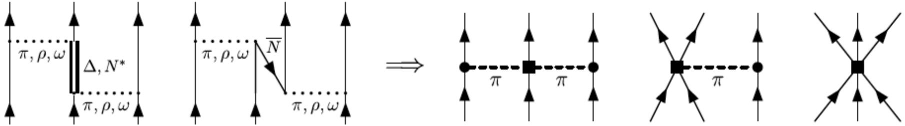
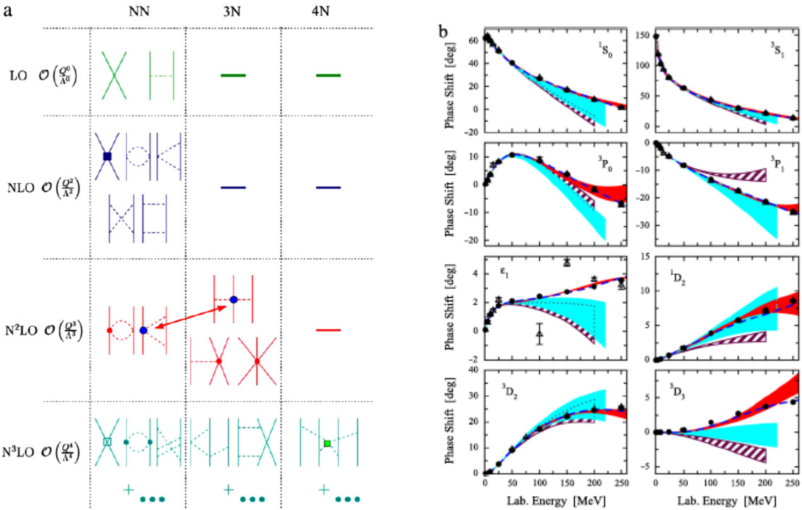
EFT provides the nuclear force with a systematic expansion in Q/Λ

- gives an estimate of theoretical uncertainty
- naturally includes many-body forces



Expansion of the EFT force



Solving the Schrödinger equation

$$H\,|\Psi_n\rangle = E_n|\Psi_n\rangle$$

Ψ usually developed on a basis $\{|\Phi_{[\nu]}\rangle\}$:

$$|\Psi_n\rangle = \sum_{[\nu]}\langle\Phi_{[\nu]}|\Psi_n\rangle\;|\Phi_{[\nu]}\rangle$$

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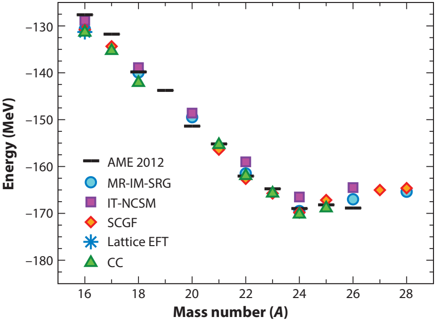
Solving the Schrödinger equation reduces to matrix diagonalisation

$$\begin{aligned}\langle\Phi_{[\mu]}|H|\Psi_n\rangle &= \sum_{[\nu]}\langle\Phi_{[\mu]}|H|\Phi_{[\nu]}\rangle\langle\Phi_{[\nu]}|\Psi_n\rangle \\ &= E_n\,\langle\Phi_{[\mu]}|\Psi_n\rangle\end{aligned}$$

$\Rightarrow$ need to build an efficient set of basis states $\{|\Phi_{[\nu]}\rangle\}$

Clear short review paper : [Bacca EPJ Plus **131**, 107 (2016)]

Example : oxygen isotopes



[Hebeler *et al.* Annu. Rev. Nucl. Part. Sci. **65**, 457 (2015)]

Different *ab initio* models predict similar result
All require $3N$ forces to reproduce the dripline at ^{24}O

What happens far from stability ?

Liquid-drop and shell models are fair models of stable nuclei

What happens away from stability ?

In 80s Radioactive-Ion Beams were developed

[see A. Spyrou on Monday & T. Nilsson on Thursday]

Enable study of nuclear structure

- are radioactive nuclei compact ?
- are shells conserved far from stability ?

Reactions involving radioactive nuclei useful in astrophysics

[see 2nd part
& A. Spyrou on Monday & E. Lopez Saavedra on Wednesday]

How ?

Idea : break a heavy nuclei into pieces to produce exotic isotopes

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- ISOL : Fire a proton at a heavy nucleus

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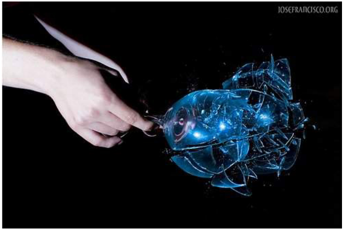
- ISOL : Fire a proton at a heavy nucleus

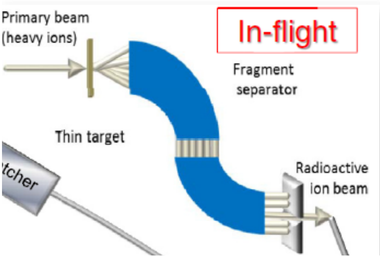
- In-flight : Smash a heavy nucleus on a target



Where ?


ARCTIC OCEAN
Greenland
CANADA
UNITED STATES
NORTH PACIFIC OCEAN
NORTH ATLANTIC OCEAN
RUSSIA
SIBERIA
KAZAKHSTAN
MONGOLIA
CHINA
IRAN
INDIA
ALGERIA
LIBYA
EGYPT
SAHARA
MALI
NIGER
CHAD
SUDAN
BRAZIL
SOUTH PACIFIC OCEAN
SOUTH ATLANTIC OCEAN
INDIAN OCEAN
INDONESIA
AUSTRALIA
SOUTHERN OCEAN
Antarctica
KIRIBATI
Arabian Sea
Philippine Sea

In-flight projectile fragmentation



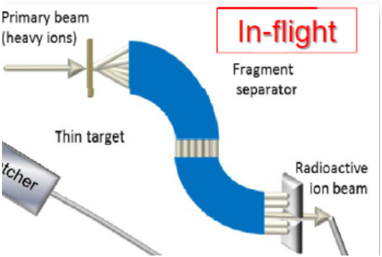
high-energy primary beam
of heavy ions (e.g. ^{18}O, ^{48}Ca, U. . .)

on thin target of light element (Be or C)

$\Rightarrow$ fragmentation/fission produces
many exotic fragments at $\approx v_{\text{beam}}$

Sorted in fragment separator

In-flight projectile fragmentation



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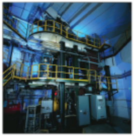
Used for high-energy reactions (KO, breakup. . .)

Examples : FRIB (MSU), RIKEN, GSI/FAIR, GANIL
[see A. Spyrou on Monday & T. Nilsson on Thursday]

FRIB @ MSU

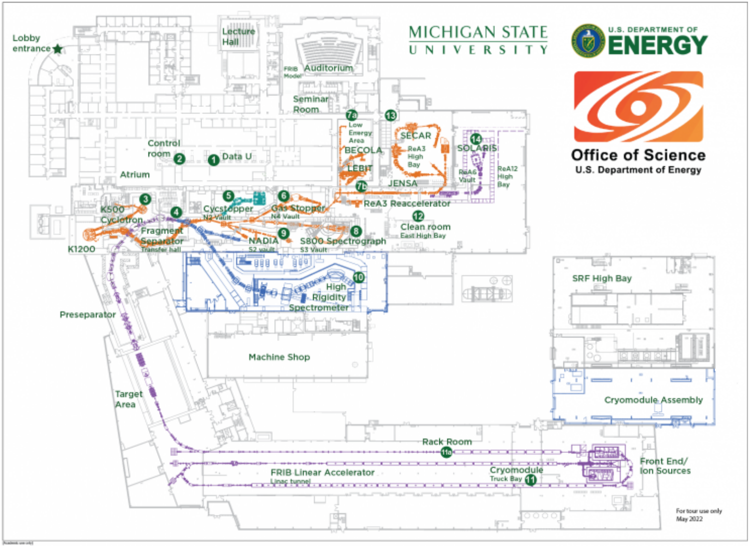
4 Fragment Separator

5 Cycstopper

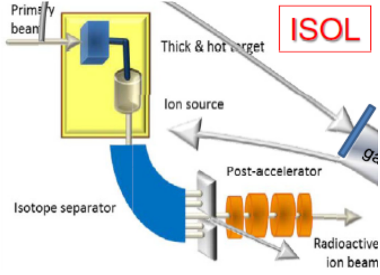


8 S800 Spectrograph & GRETA Gamma-ray detector

FACILITY FOR RARE ISOTOPE BEAMS (FRIB)



ISOL : Isotope Separation On Line



high-energy/intensity primary beam
of light nuclei (e.g. protons)

on thick target of heavy elements (UC_x)

⇒ spallation/fragmentation produces
exotic fragments

Diffuse in the target and
effuse to an ion source

Selected using dipole magnet (A/Q)

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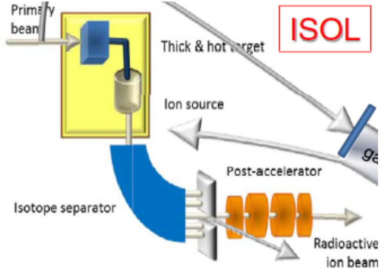

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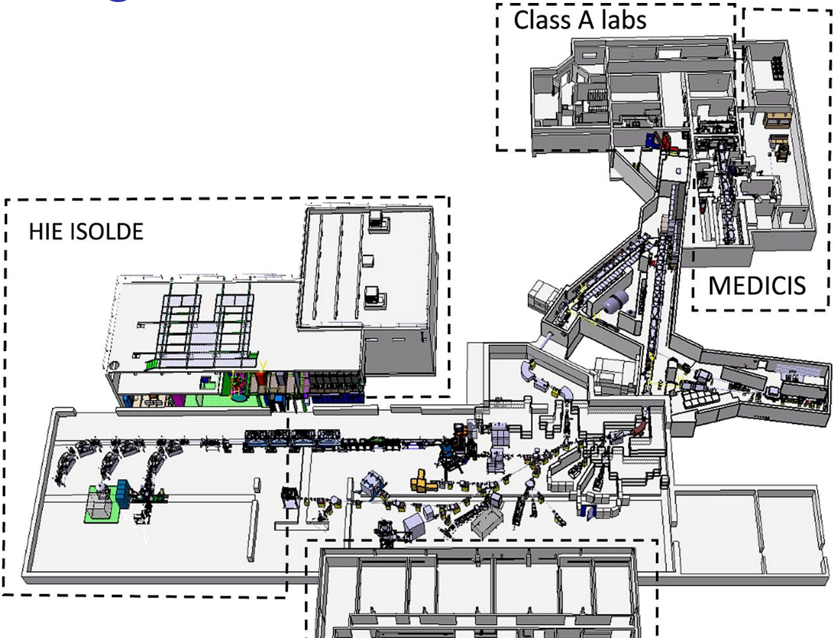
Either used directly (mass measurement, radioactive decay. . .) or post-accelerated for reactions (e.g. astrophysical energy)

Examples : ISOLDE (CERN), TRIUMF, SPIRAL (GANIL)

ISOLDE @ CERN



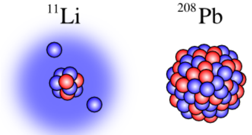
Halo nuclei

Exotic structure discovered by I. Tanihata [PLB 160, 380 (1985)]

Very large matter radius ($R \gg A^{1/3}$)

Seen as core + one or two neutrons at large distance

- Light, neutron-rich nuclei
- small S_n or S_{2n}



One-neutron halo

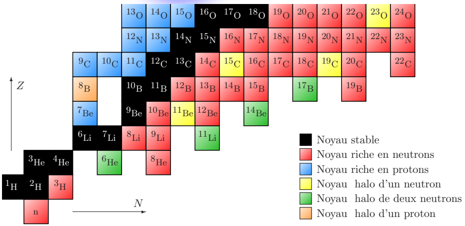
$^{11}Be \equiv {}^{10}Be + n$

$^{15}C \equiv {}^{14}C + n$

Two-neutron halo

$^{6}He \equiv {}^{4}He + n + n$

$^{11}Li \equiv {}^{9}Li + n + n$



[R. Garreau's talk on Tuesday & Q. Bozet's talk on Thursday]

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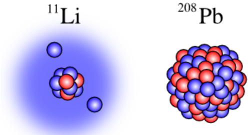

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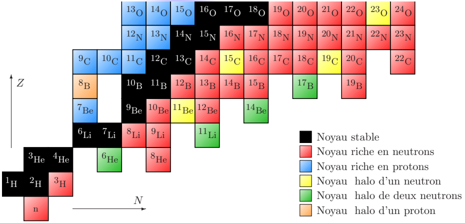


[R. Garreau's talk on Tuesday & Q. Bozet's talk on Thursday]

Two-neutron halo nuclei are Borromean...

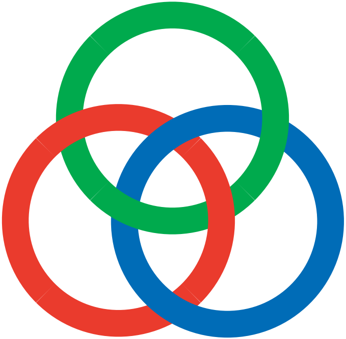
c+n+n is bound but not two-body subsystems

e.g. ^{6}He bound but not ^{5}He nor ^{2}n

Borromean nuclei

Named after the Borromean rings. . .

[M. V. Zhukov *et al.* Phys. Rep. 231, 151 (1993)]



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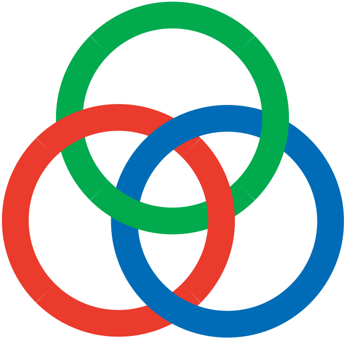

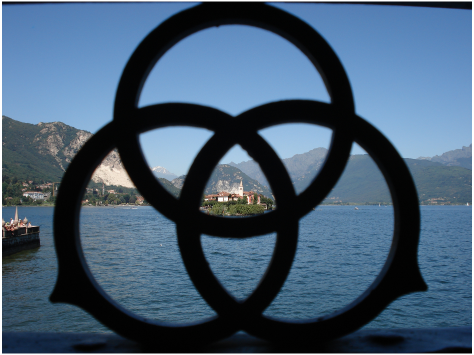

Summary

Liquid-drop and shell model describe qualitatively stable nuclei
Nowadays *ab initio* nuclear-structure models from first principles

RIBs enable us to study nuclear structure far from stability
New exotic structure discovered :

- halo nuclei
  diffuse halo around a compact core
- shell inversions or shell collapse
- nuclei beyond the dripline (resonant ground state)

RIB can be used to study reactions of astrophysical interest...

Properties

ISOL

- Low beam energy
  may require post-acceleration
- Low beam intensity
- Not all elements produced
  - Slow
  - Chemically limited
- Good beam quality :
  can use chemistry and atomic physics to select fragments

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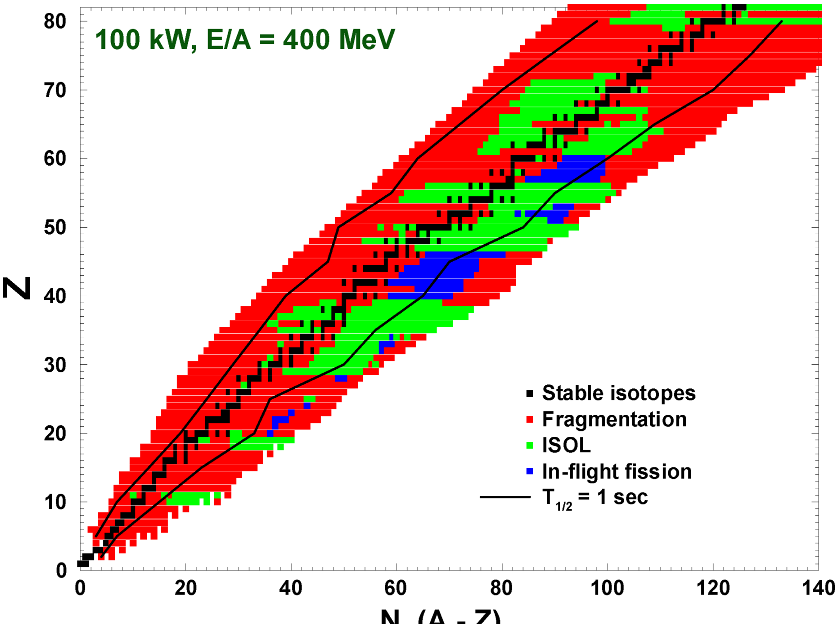
In-flight

- High beam energy
  $v_{\text{fragments}} \approx v_{\text{beam}}$
- High beam intensity
- Efficient production
  - Fast
  - Chemically independent
- Many fragments in beam
  $\Rightarrow$ need ion ID

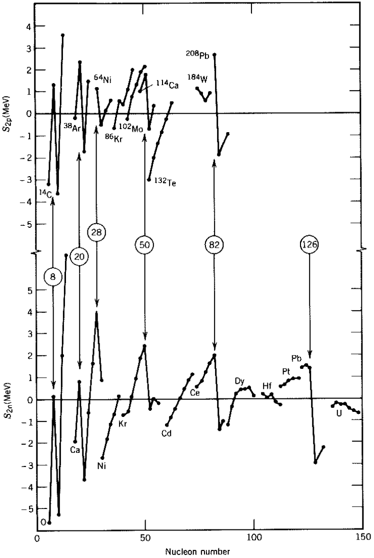
Choose according what you want to measure



Two-nucleon separation energy

Same magic numbers in S_{2p} and S_{2n}

$\Rightarrow$ more bound at shell closure
cf. ionisation energies of atoms



No-Core Shell Model

One should be able to account for the fermion nature of nucleons
⇒ wave function must be antisymmetric
⇒ basis states built as Slater determinants
of 1-body mean-field wave functions ϕ_{ν_i}

$$\begin{aligned}\langle \xi_1 \xi_2 \ldots \xi_A | \Phi_{[\nu]} \rangle &= \mathcal{A}\, \phi_{\nu_1}(\xi_1)\, \phi_{\nu_2}(\xi_2) \ldots \phi_{\nu_A}(\xi_A) \\ &= \frac{1}{\sqrt{A!}} \begin{vmatrix} \phi_{\nu_1}(\xi_1) & \phi_{\nu_1}(\xi_2) & \cdots & \phi_{\nu_1}(\xi_A) \\ \phi_{\nu_2}(\xi_1) & \phi_{\nu_2}(\xi_2) & \cdots & \phi_{\nu_2}(\xi_A) \\ \vdots & \vdots & \ddots & \vdots \\ \phi_{\nu_A}(\xi_1) & \phi_{\nu_A}(\xi_2) & \cdots & \phi_{\nu_A}(\xi_A) \end{vmatrix}\end{aligned}$$

The shell model uses harmonic-oscillator wave functions for ϕ_{ν_i}
The basis size increases with A ⇒ limited to light nuclei