The search for exotic nuclear structure far from stability

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Introduction

Stable nuclei are qualitatively described by “simple” models

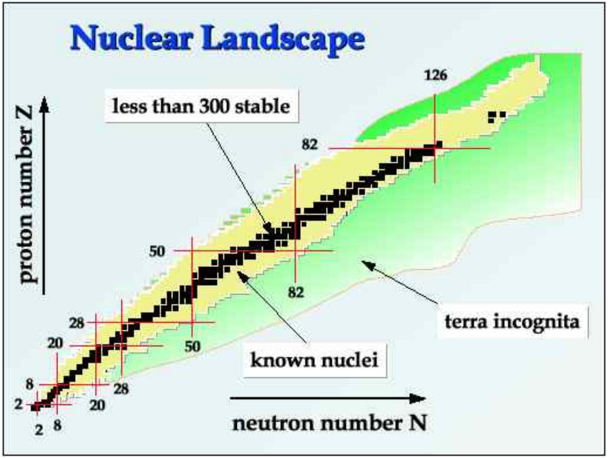
- (semi-empirical) liquid-drop model
- (basic) shell model

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

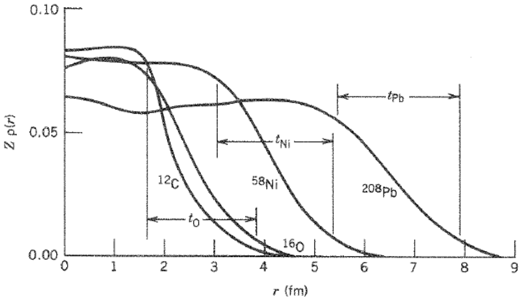
- halo nuclei
- shell inversions
- …

Nuclear Landscape



- ~ 300 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 O

Charge distributions in (stable) nuclei



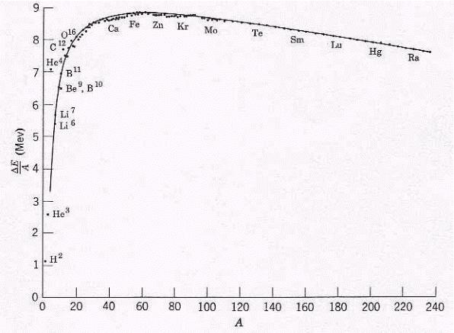
- constant density ρ_0 out to the surface (saturation)
- same skin thickness t

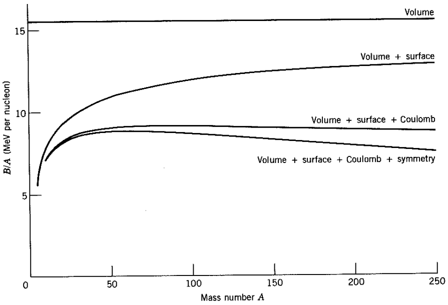
(Stable) nuclei look like liquid drops of radius $R \propto A^{1/3}$

Liquid-drop model

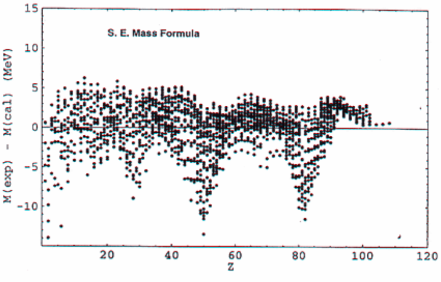
Binding energy per nucleon $B(Z,N)/A$ has smooth behaviour
Bethe-Weizsäcker semi-empirical mass formula

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





Variation from the semi-empirical mass formula



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

magic numbers

$\Rightarrow$ shell structure in nuclei as in atoms ?

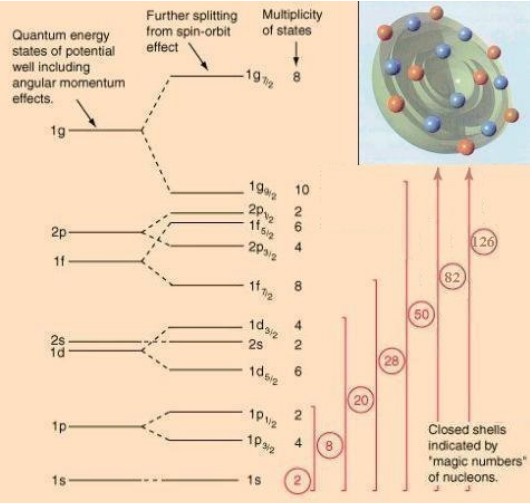
Shell model

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

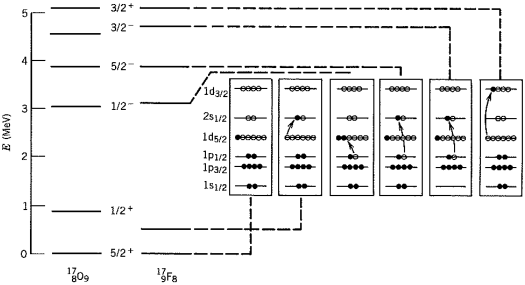
Spin-orbit coupling is crucial
to get right ordering of shells



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

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

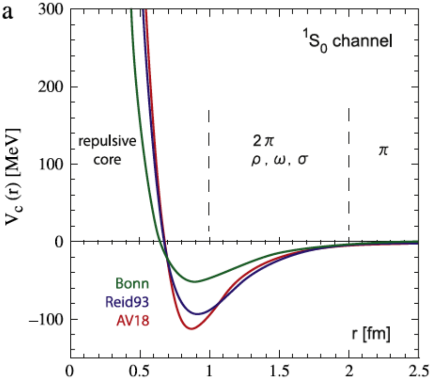
$\Rightarrow$ solve the A-body Schrödinger equation

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

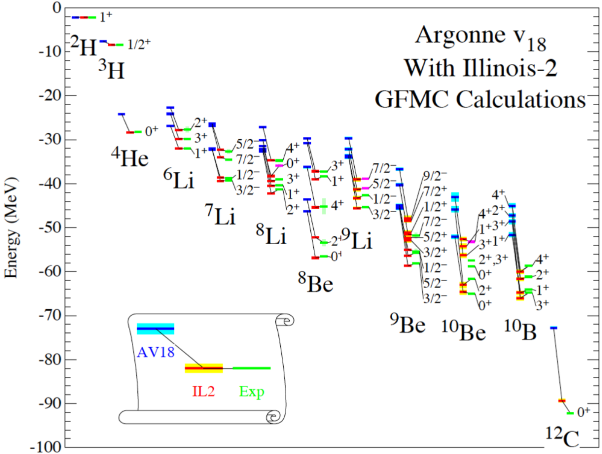
$\{E_n\}$ is the nucleus spectrum

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



Light nuclei calculations



[R. Wiringa, Argonne]

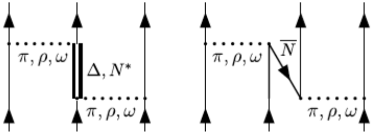
Three-body force

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...

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



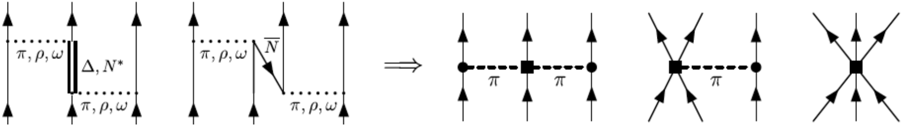
Phenomenological 3-body interaction fitted on $A > 2$ levels : IL2
Alternatively, derived from EFT

Effective Field Theory

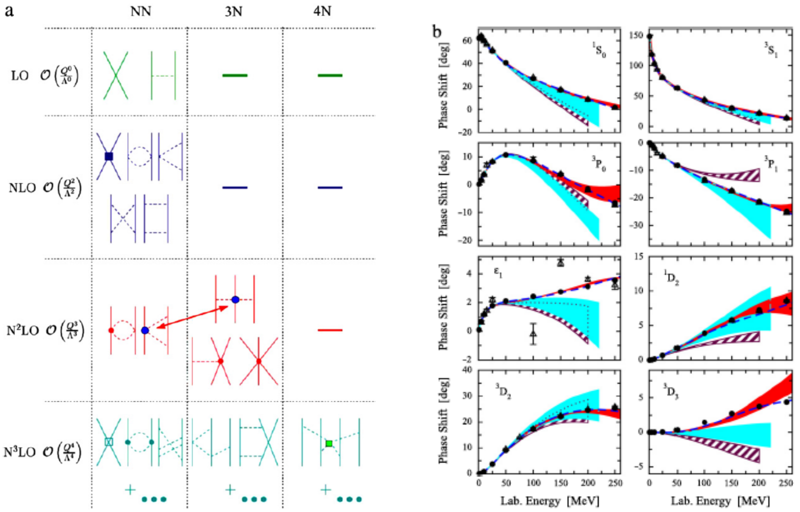
EFT is an effective quantum field theory based on QCD symmetries with resolution scale Λ that selects appropriate degrees of freedom : nuclear physics is not built on quarks and gluons,
but on nucleons and mesons

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

- gives an estimate of theoretical uncertainty
- 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 $\{|\Phi_{[\nu]}\rangle\}$:

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

Solving the Schrödinger equation reduces to matrix diagonalisation

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

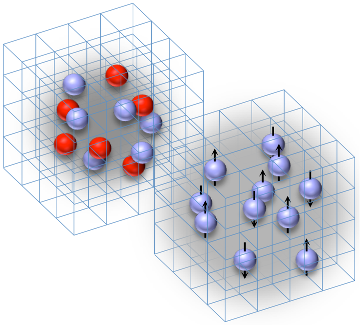
$\Rightarrow$ need to build an efficient set of basis states $\{|\Phi_{[\nu]}\rangle\}$

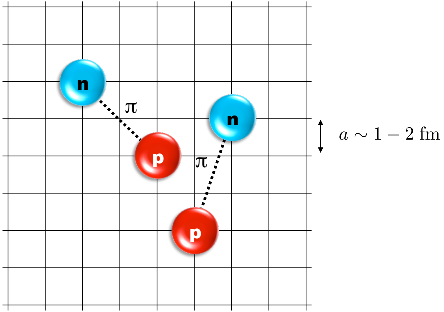
Clear short review paper : [Bacca EPJ Plus **131**, 107 (2016)]

Solving the Schrödinger equation on the lattice

Alternatively, solve Schrödinger equation numerically on the lattice

(like in lattice QCD)

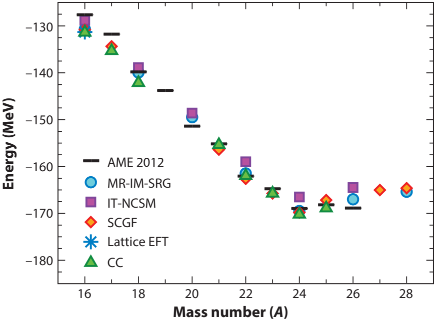




Review paper : [D. Lee Prog. Part. Nucl. Phys. **63** 117 (2009)]
TALENT lecture in 2016

[see D. Lee's talk on Monday]

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
Enable study of nuclear structure

[see T. Nakamura on Thursday and I. Tanihata on Friday]

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

Reactions involving radioactive nuclei useful in astrophysics

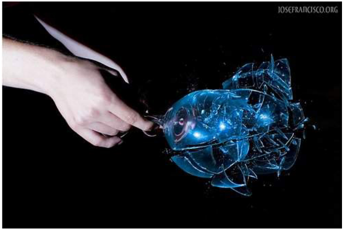
[see 2nd part,
C. Gustavino on Tuesday and A. Tumino on Friday]

How ?

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

- ISOL : Fire a proton at a heavy nucleus

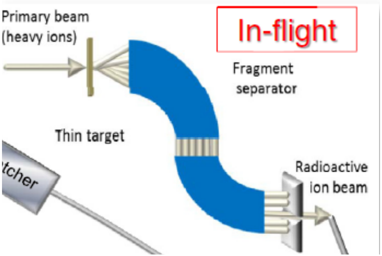
- In-flight : Smash a heavy nucleus on a target



Where ?


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

In-flight projectile fragmentation

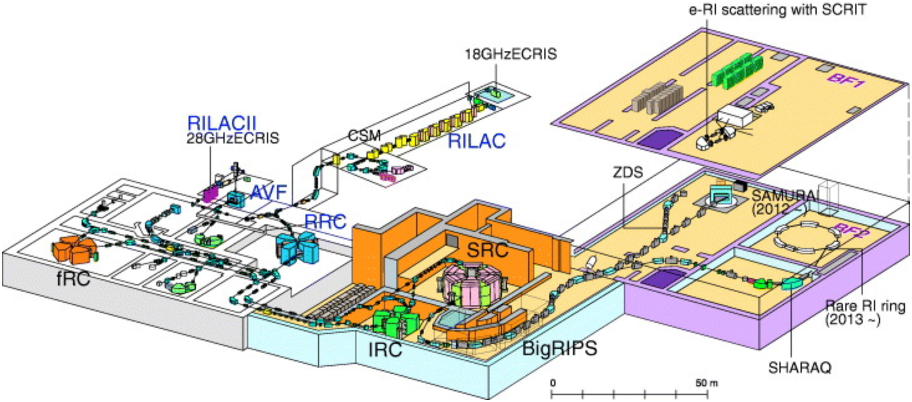


high-energy primary beam
of heavy ions (e.g. ^{18}O, ^{48}Ca, U...)
on thin target of light element (Be or C)
$\Rightarrow$ fragmentation/fission produces
many exotic fragments at $\approx v_{\text{beam}}$
Sorted in fragment separator

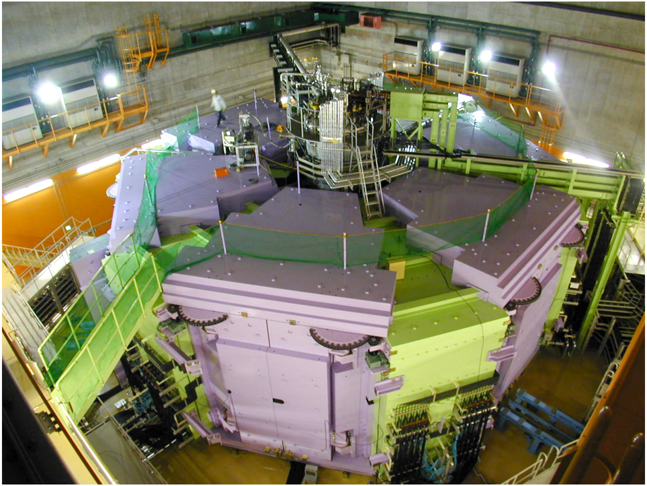
Used for high-energy reactions (KO, breakup...)
[see T. Nakamura talk on Thursday]

Examples : RIKEN, NSCL (MSU), GSI, GANIL

RIBF @ RIKEN


e-RI scattering with SCRIT
18GHzECRIS
BF1
RILACII
28GHzECRIS
CSM
RILAC
ZDS
AVF
SAMURAI
(2012 ~)
RRC
BF2
SRC
fRC
Rare RI ring
(2013 ~)
IRC
BigRIPS
SHARAQ
0
50 m

Superconducting Ring Cyclotron



Largest superconducting cyclotron in the world
Delivers a U beam at $350A$MeV

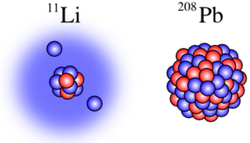
Halo nuclei

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 $S_{2\mathrm{n}}$



One-neutron halo

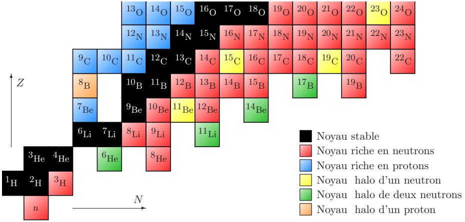
^{11}Be ≡ ^{10}Be + n

^{15}C ≡ ^{14}C + n

Two-neutron halo

^{6}He ≡ ^{4}He + n + n

^{11}Li ≡ ^{9}Li + n + n



[T. Nakamura's talk on Thursday and posters of C. Hebborn, L. Moschini and N. Sokołowska on Monday]

Change in *magic numbers*

Far from stability usual magic numbers disappear :

- ^{10}He $(Z = 2, N = 8)$ is unbound
- ^{28}O $(Z = 8, N = 20)$ is unbound

and new magic numbers appear : $N = 6, 14, 16 \ldots$

One possible explanation is the blocking effect of tensor force

[see I. Tanihata's talk on Friday]

Tensor force is a component of NN interaction

$$\begin{aligned} V^T &= v_T(r)\, S_{12} \\ \text{where } S_{12} &= 4\left[\frac{3}{r^2}(\boldsymbol{s}_1 \cdot \boldsymbol{r})(\boldsymbol{s}_2 \cdot \boldsymbol{r}) - \boldsymbol{s}_1 \cdot \boldsymbol{s}_2\right] \\ &= \frac{6}{r^2}\,(\boldsymbol{S} \cdot \boldsymbol{r})^2 - 2\,\boldsymbol{S}^2 \end{aligned}$$

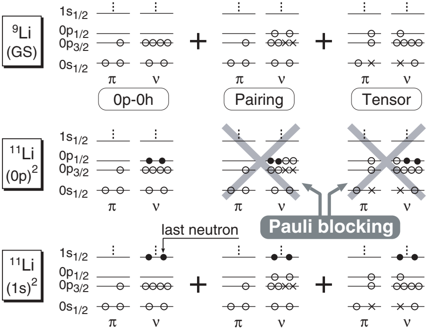
This interaction can lead to $\Delta L = 2$ excitation in np pairs which is responsible for $Q_d \neq 0$ and $\mu_d \neq 0$

Tensor blocking

Tensor force responsible for a significant part of α binding

[Myo *et al.* PTP **117**, 257 (2007)]

In asymmetric nuclei ($N \gg Z$) these couplings are Pauli blocked



[Myo *et al.* PRC **76**, 024305 (2007)]

Explains why *magic* $N = 8 \rightarrow 6$ in He and $N = 20 \rightarrow 14, 16$ in O

[see also T. Nakamura's talk on Thursday]

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. . .