The study of nuclear structure far from stability

Pierre Capel

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Introduction

Stable nuclei are qualitatively described by “simple” models

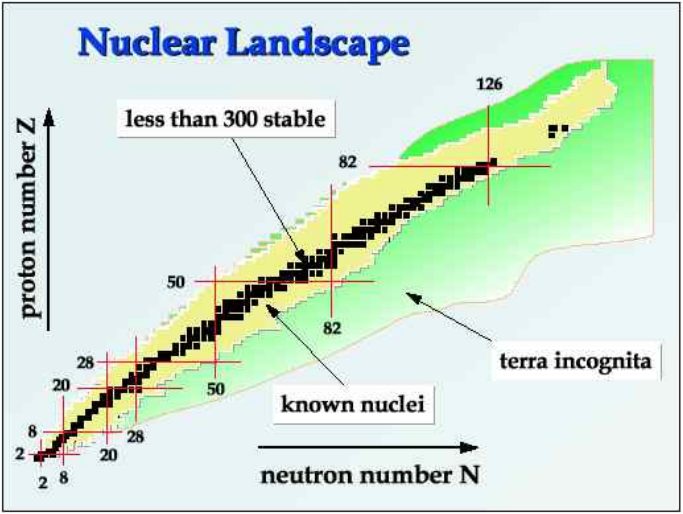
- (semi-empirical) liquid-drop model
- (basic) shell model

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

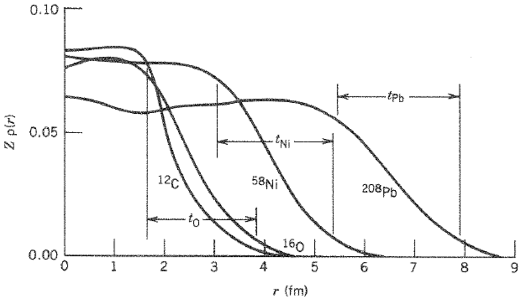
- super-heavy elements
- halo nuclei
- shell inversions

Nuclear Landscape



1. Basic features in nuclear structure
   - Liquid-drop model
   - Shell model
2. Ab-initio nuclear models
3. Superheavy nuclei
4. Radioactive-Ion Beams
5. Oddities far from stability : halo nuclei
6. Experimental techniques
   - Knockout reactions
   - In-beam γ spectroscopy
   - Transfer reactions
7. Summary

Charge distributions in (stable) nuclei



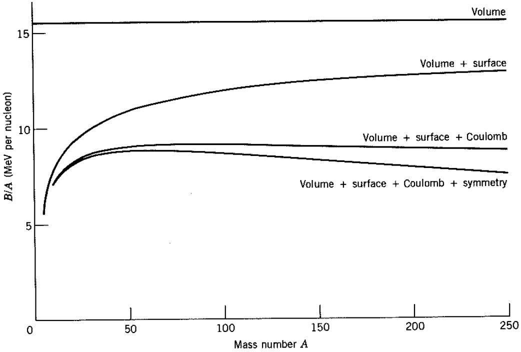
- constant density ρ_0 out to the surface (saturation)
- same skin thickness t

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

Liquid-drop model

Bethe-Weizsäcker semi-empirical mass formula

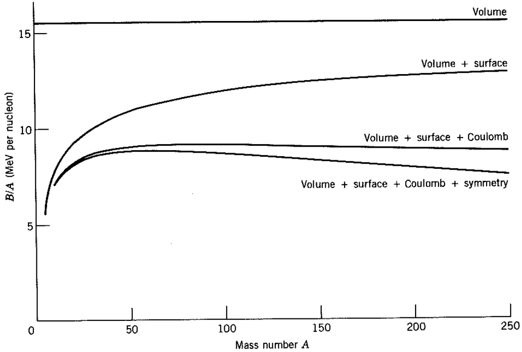
$$B(Z, N) = a_v A$$



Liquid-drop model

Bethe-Weizsäcker semi-empirical mass formula

$$B(Z,N) = a_v A - a_s A^{2/3}$$



Liquid-drop model

Bethe-Weizsäcker semi-empirical mass formula

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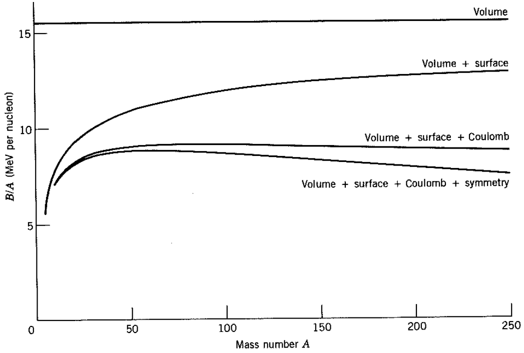

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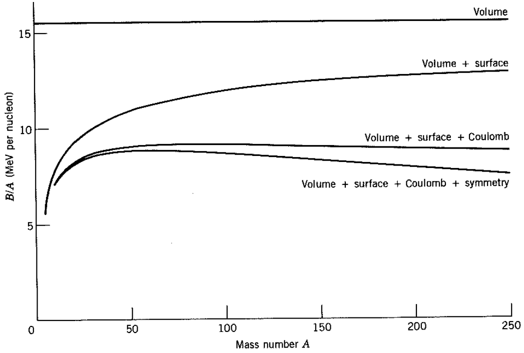
$$B(Z,N) = a_v A - a_s A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_{\mathrm{Sym}} \frac{(A-2Z)^2}{A}$$



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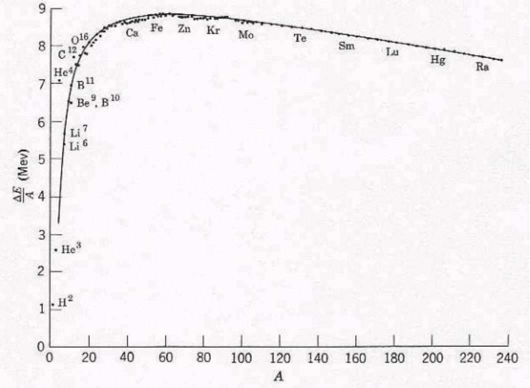

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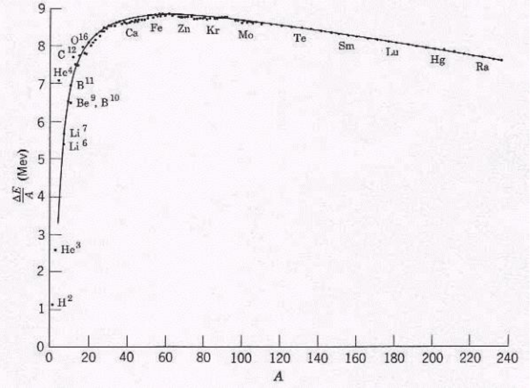
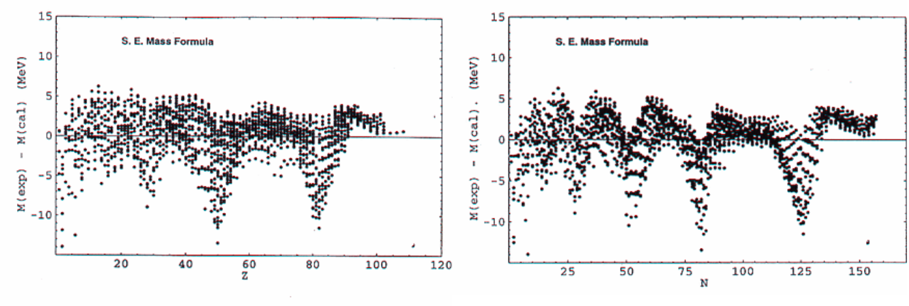
Exoenergetic reactions :

- fission of heavy nuclei (nuclear power plants, atomic bomb)
- fusion of light nuclei (stars, thermonuclear weapons)



Variation from the semi-empirical mass formula



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

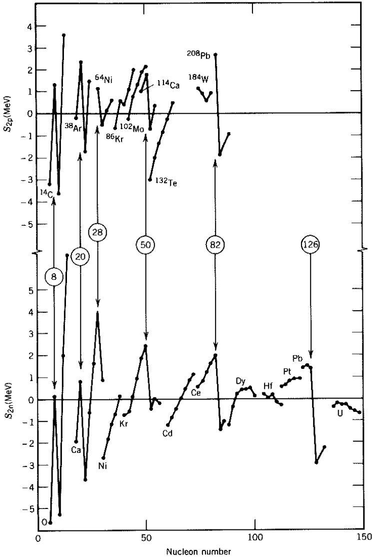
magic numbers

⇒ shell structure in nuclei as in atoms ?

Two-nucleon separation energy

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

⇒ more bound at shell closure
cf. ionisation energies of atoms

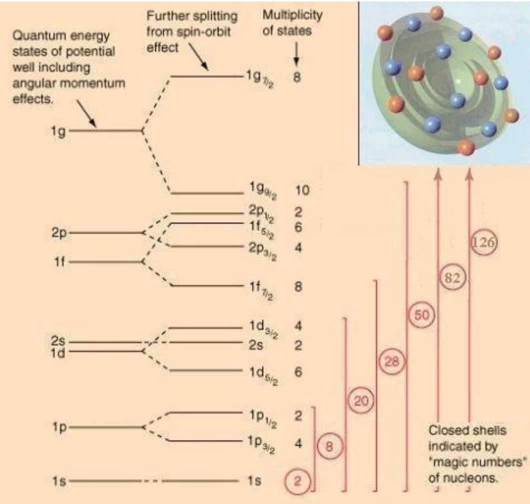


Shell model

Developed in 1949 by M. Goeppert Mayer, H. Jensen and E. Wigner (NP 1963)

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

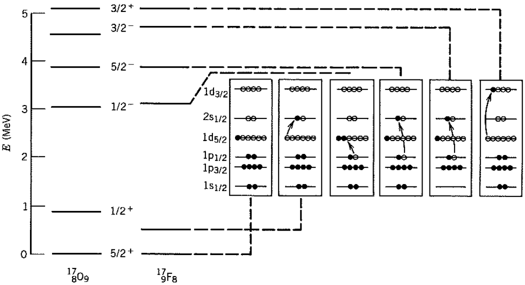
Spin-orbit coupling is crucial to get right ordering of shells



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



Confirmed within coupled-cluster calculation

[G. Hagen *et al.* PRL 104, 182501 (2010)]

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

What happens away from stability ?

- Is there an island of stability for heavy nuclei ?
- Is nuclear density similar for radioactive nuclei ?
- Are magic numbers conserved ?

A-body Hamiltonian

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

Relative motion described by the A-body Hamiltonian

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

⇒ 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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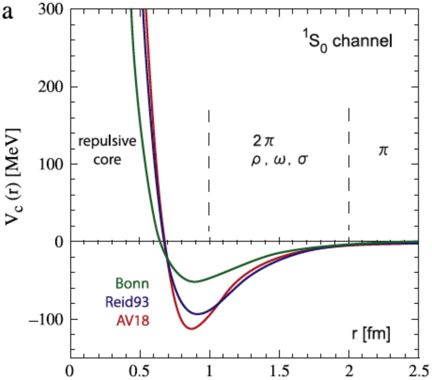
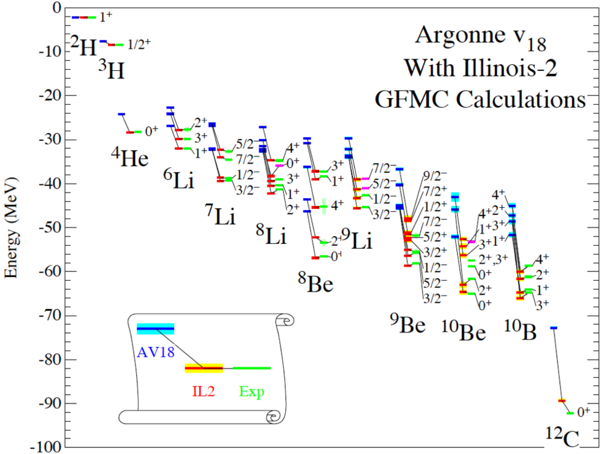
Ex. : Argonne V18, CD-Bonn,…



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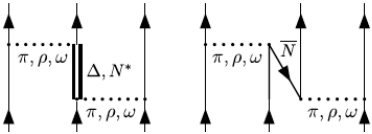
They simulate the non-elementary character of nucleons
$\Rightarrow$ include virtual Δ resonances, $\bar{\mathrm{N}}$...



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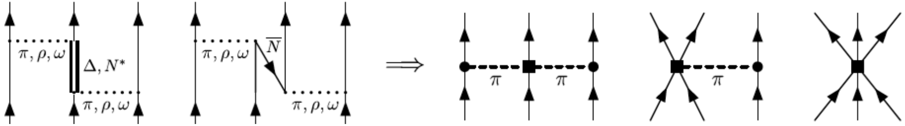
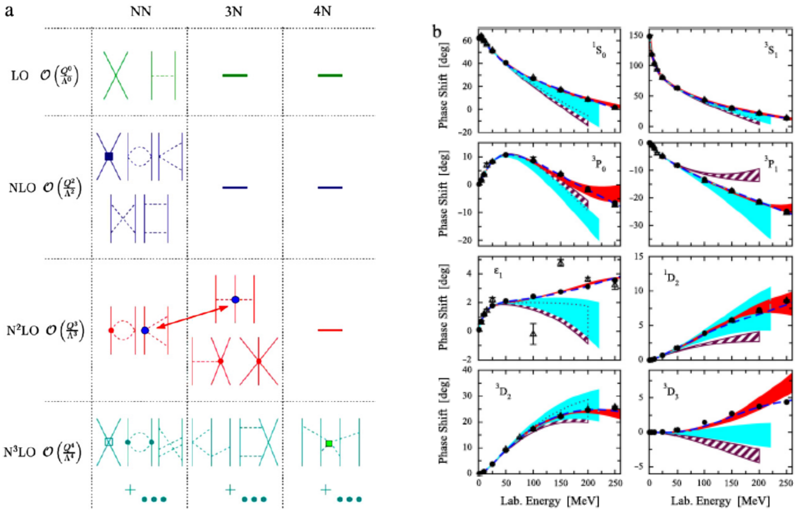
EFT provides the nuclear force with a systematic expansion in Q/Λ

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



[see G. Hagen's talk on Wednesday morning and J. Holt on Tuesday afternoon]

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

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

No-core shell model

Slater determinants of 1-body mean-field wave functions ϕ_{ν_i}

$$\langle \xi_1 \xi_2 \ldots \xi_A | \Phi_{[\nu]} \rangle = \mathcal{A}\, \phi_{\nu_1}(\xi_1)\, \phi_{\nu_2}(\xi_2) \ldots \phi_{\nu_A}(\xi_A)$$

But short-range correlations couple low and high momenta

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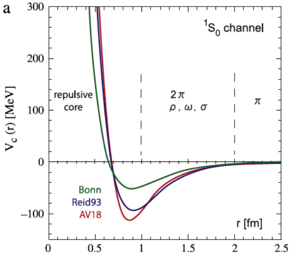
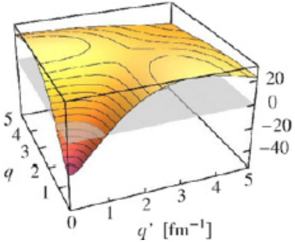


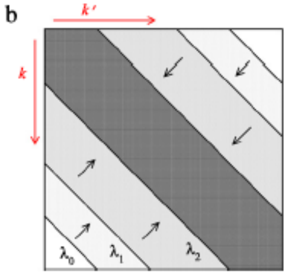


$\Rightarrow$ requires large basis $|\Phi_{[\nu]}\rangle$

Similarity Renormalisation Group

Idea : apply a unitary transformation

$$|\widetilde{\Phi}_{[\nu]}\rangle = U|\Phi_{[\nu]}\rangle$$
$$\Leftrightarrow H_{\text{eff}} = U^{\dagger} H U$$

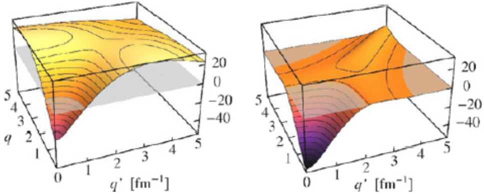


- keeps the same spectrum (unitary)
- keeps the same on-shell properties (phaseshifts)
- removes the short-range correlations

This has a costs : induces “unphysical” three-body forces

SRG : example on ^{4}He

SRG lowers correlations

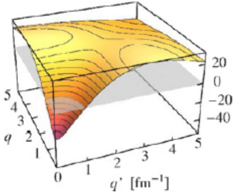


(a) V_{AVIS}. (b) V_{SRG}.

[see G. Hagen's talk on Wednesday morning
and J. Holt on Tuesday afternoon]

SRG : example on ^{4}He

SRG lowers correlations ⇒ fastens convergence



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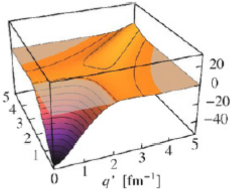

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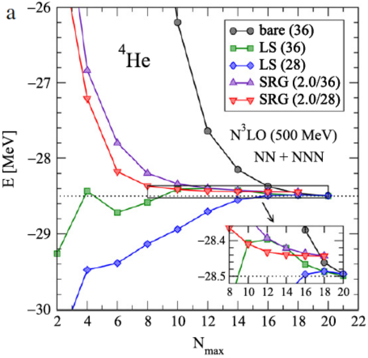


[see G. Hagen's talk on Wednesday morning and J. Holt on Tuesday afternoon]

What happens far from stability ?

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

What happens away from stability ?

Are there superheavy nuclei ? Recent discovery of new elements ($Z = 113, 115, 117$, and 118)

In 80s Radioactive-Ion Beams were developed
Enable study of nuclear structure [see A. Obertelli's talk on Friday]

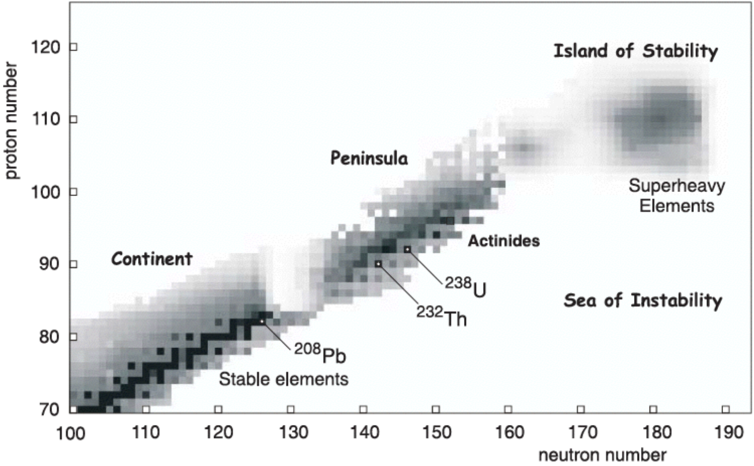
- are radioactive nuclei compact ?
- are shells conserved far from stability ?

Reactions involving radioactive nuclei useful in astrophysics

Superheavy nuclei

Does the stability end with U ? Or is there an island of stability ?

Is $Z \sim 114 - 126$ a new magic number ?



[Oganessian Rad. Act. 99, 429 (2011)]

Synthesis of Super Heavy Elements

Search elements heavier than U has started in the 40's
Pu produced by U+d and U+n (identified by Seaborg in 1941)
High flux of n on U or Pu → $_{100}$Fm

$Z = 101$–106 obtained by bombarding actinides by light elements

Heavier elements ($Z = 107$–113) by cold fusion
^{208}Pb or ^{209}Bi + massive projectile ($A \geq 50$) → high Z + n

Nowadays, hot fusion : ^{48}Ca on actinide target → SHE + 4–5 n

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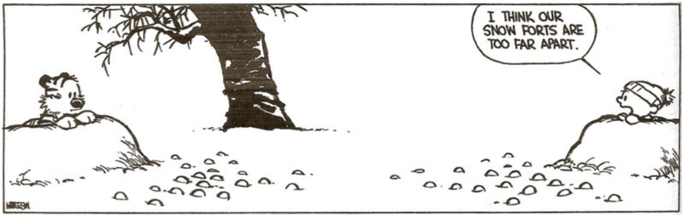

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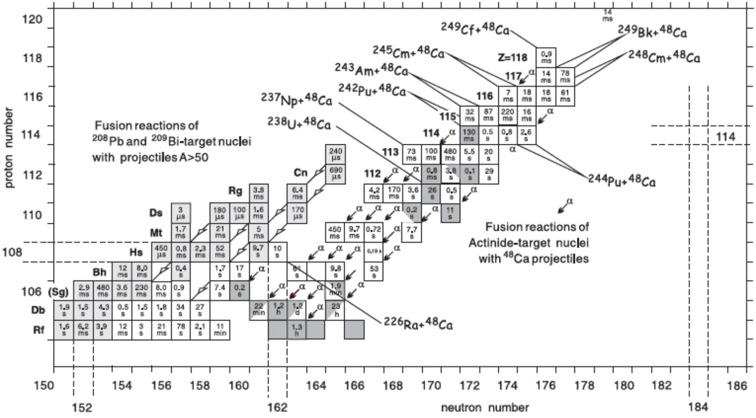
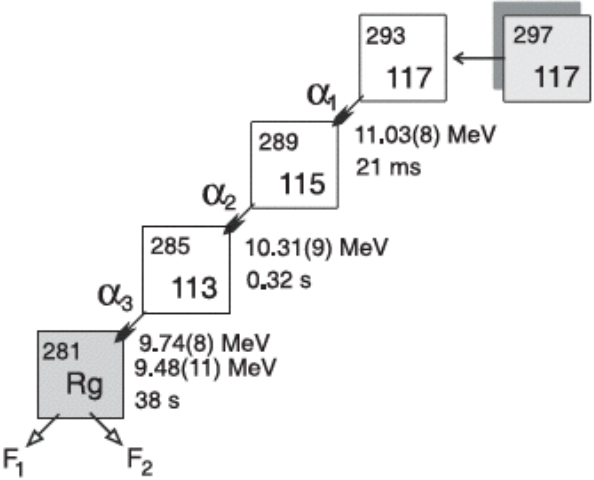
$Z = 113, 115, 117$, and 118 recently recognised by IUPAC



[Oganessian Rad. Act. 99, 429 (2011)]

Identification by α decay chain



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How ?

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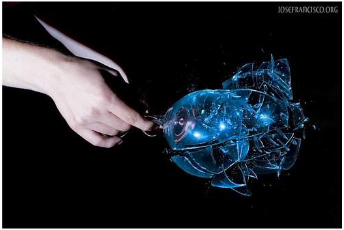
- ISOL : Fire a proton at a heavy nucleus

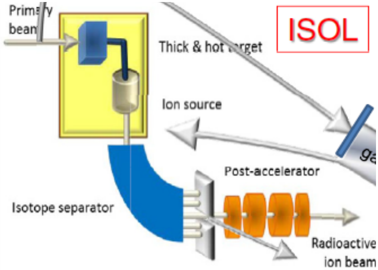
- In-flight : Smash a heavy nucleus on a target



Where ?


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

ISOL : Isotope Separation On Line



high-energy/intensity primary beam of light nuclei (e.g. protons) on thick target of heavy elements (Ta or UC_x)

⇒ spallation/fragmentation produces exotic fragments

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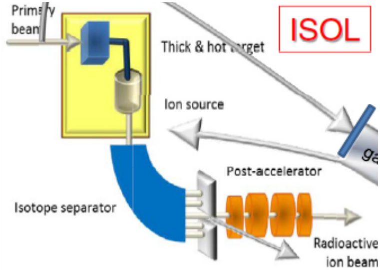

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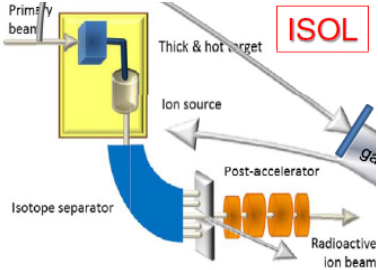

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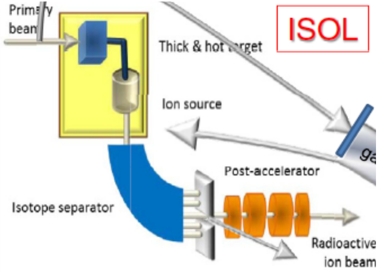

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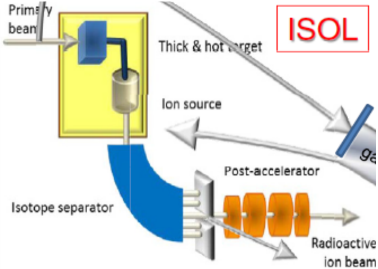

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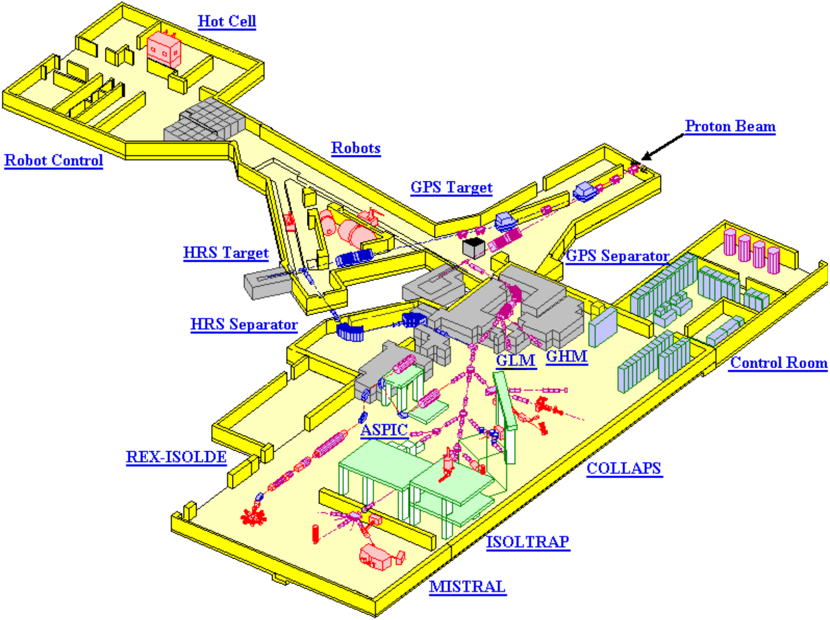
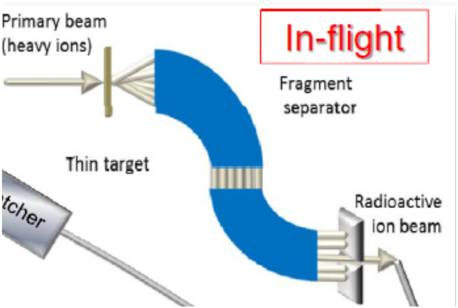
Examples : ISOLDE (CERN), TRIUMF, SPIRAL (GANIL)

ISOLDE @ CERN


Hot Cell
Proton Beam
Robots
Robot Control
GPS Target
HRS Target
GPS Separator
HRS Separator
GLM
GHM
Control Room
ASPIC
REX-ISOLDE
COLLAPS
ISOLTRAP
MISTRAL

In-flight projectile fragmentation



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

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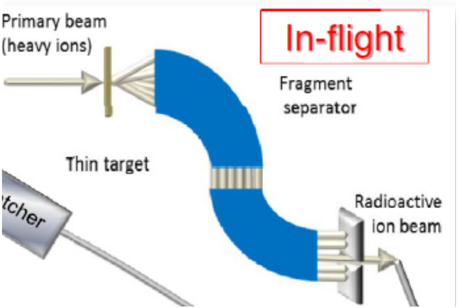

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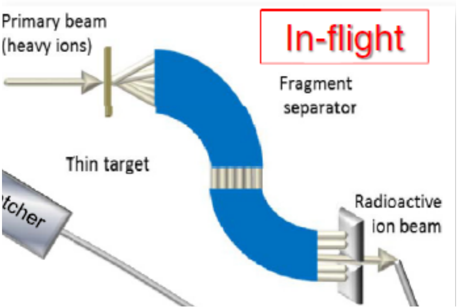

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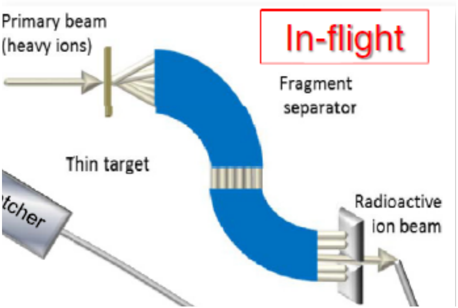
Sorted in fragment separator
Used for high-energy reactions (KO, breakup...)

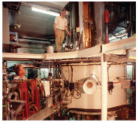
In-flight projectile fragmentation



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

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

Existing NSCL

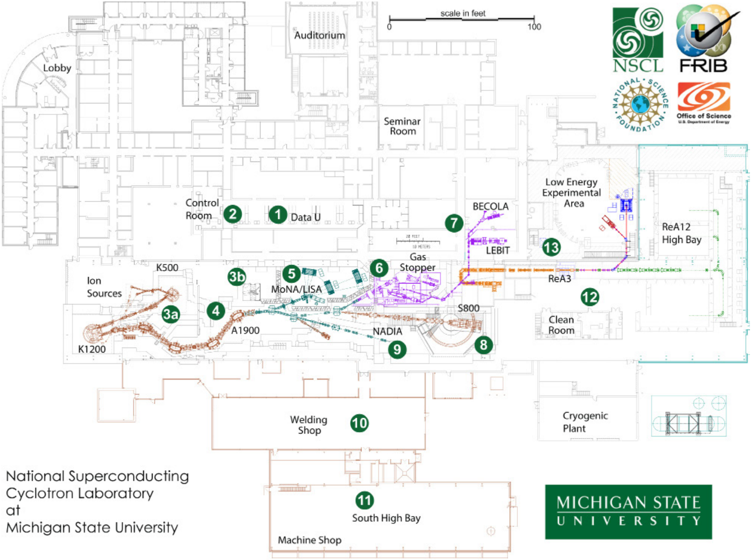


3a K500 Cyclotron

4 A1900 Fragment Separator

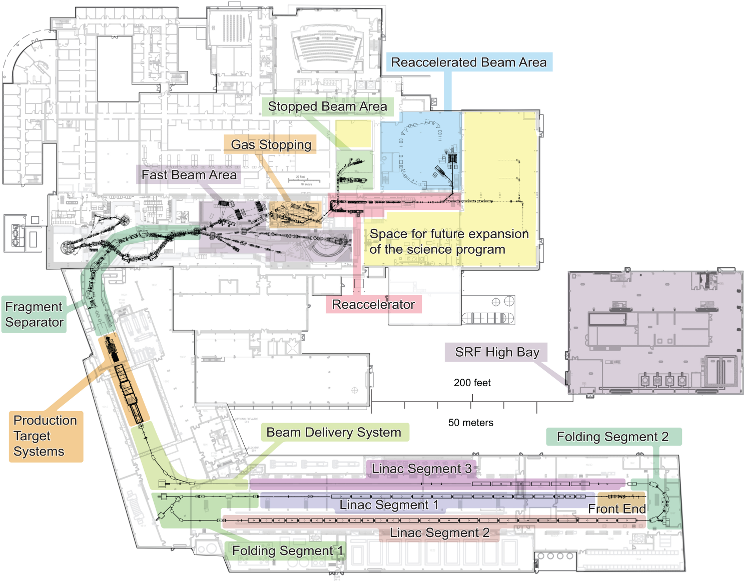
5 Modular Neutron Array

8 S800 Spectrograph



National Superconducting Cyclotron Laboratory at Michigan State University

Future : FRIB


Reaccelerated Beam Area
Stopped Beam Area
Gas Stopping
Fast Beam Area
Space for future expansion of the science program
Fragment Separator
Reaccelerator
SRF High Bay
200 feet
50 meters
Production Target Systems
Beam Delivery System
Folding Segment 2
Linac Segment 3
Linac Segment 1
Front End
Linac Segment 2
Folding Segment 1

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 to select fragments

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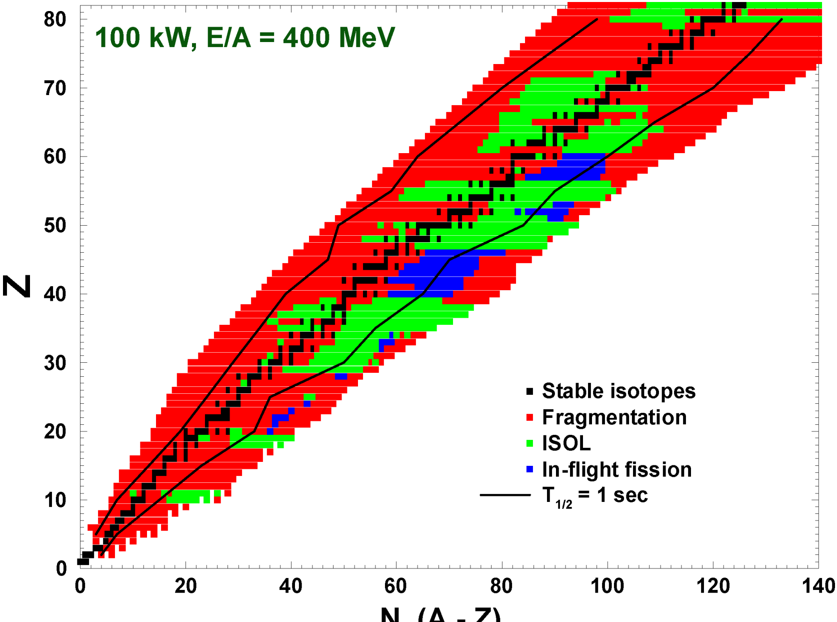
In-flight

- 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



Halo structure

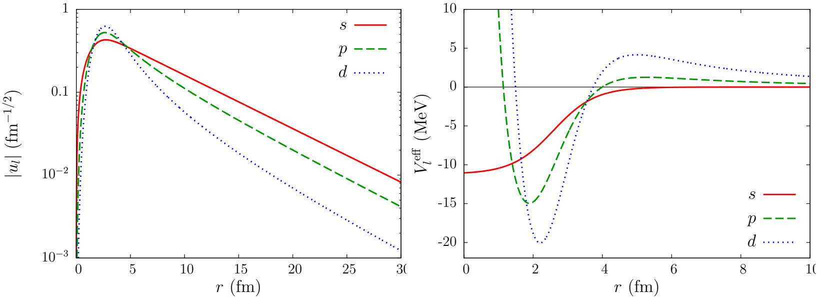
Seen as core + one or two neutrons at large distance

[P. G. Hansen and B. Jonson, Europhys. Lett. 4, 409 (1987)]

Peculiar structure of nuclei due to small S_{n} or $S_{2\mathrm{n}}$

$\Rightarrow$ neutrons tunnel far from the core to form a halo

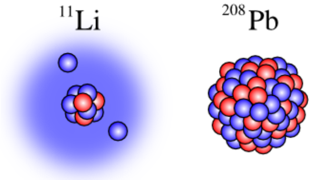
Halo only appears for low centrifugal barrier (low ℓ)



see F. Colomer's poster on Monday

Halo nuclei

- Light, neutron-rich nuclei
- small S_{n} or $S_{2\mathrm{n}}$
- low-ℓ orbital



One-neutron halo

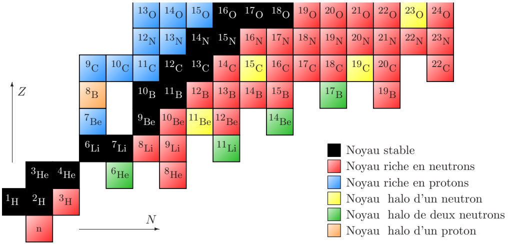
^{11}Be ≡ ^{10}Be + n

^{15}C ≡ ^{14}C + n

Two-neutron halo

^{6}He ≡ ^{4}He + n + n

^{11}Li ≡ ^{9}Li + n + n



Proton halœs are possible but less probable : ^{8}B, ^{17}F

Halo nuclei

- Light, neutron-rich nuclei
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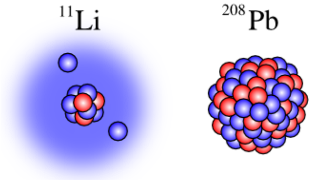
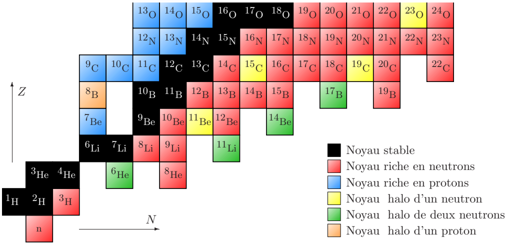


One-neutron halo
$^{11}\mathrm{Be} \equiv {}^{10}\mathrm{Be} + \mathrm{n}$
$^{15}\mathrm{C} \equiv {}^{14}\mathrm{C} + \mathrm{n}$

Two-neutron halo
$^{6}\mathrm{He} \equiv {}^{4}\mathrm{He} + \mathrm{n} + \mathrm{n}$
$^{11}\mathrm{Li} \equiv {}^{9}\mathrm{Li} + \mathrm{n} + \mathrm{n}$



Proton halœs are possible but less probable : ^{8}B, ^{17}F

Two-neutron halo nuclei are Borromean. . .

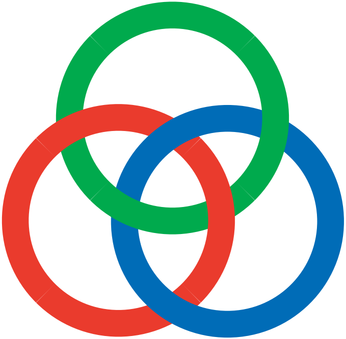
c+n+n is bound but not two-body subsystems

e.g. ^{6}He bound but not ^{5}He or ^{2}n

Borromean nuclei

Named after the Borromean rings. . .

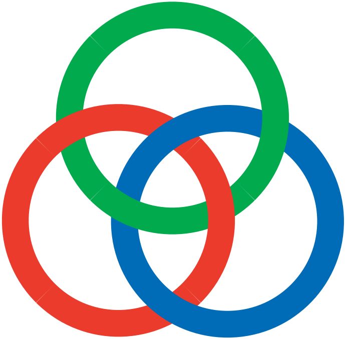
[M. V. Zhukov *et al.* Phys. Rep. 231, 151 (1993)]

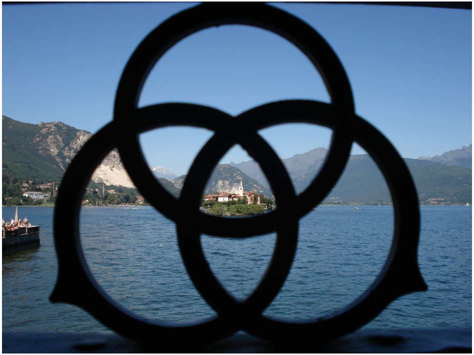


Borromean nuclei

Named after the Borromean rings...

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





Knockout reactions

Knockout reaction : direct removal of one nucleon

For exotic nuclei, measured in inverse kinematics

on light target (C or Be) at intermediate energy ($70A$MeV)

$$^{11}\text{Be} + {}^{9}\text{Be} \rightarrow {}^{10}\text{Be} + \text{X}$$

Inclusive measurement (KO nucleon not measured)

Used to probe the shell-model wave function of nuclei

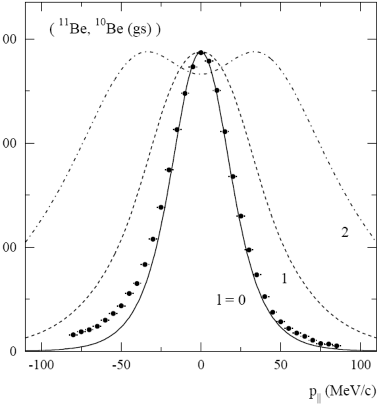
The valence nucleon occupies a shell outside a core :

$$^{A}Y(J^{\pi}) = {}^{A-1}X(J_c^{\pi}) \otimes \psi_{lm} + \ldots$$

Analysis of reaction within eikonal model (sudden approximation)

- Parallel-momentum distribution of the core gives nucleon shell
- Total $\sigma_{-\text{N}}$ provides Spectroscopic Factor (SF)

^{9}Be(^{11}Be,^{10} Be + γ)X @ 60AMeV



[Aumann *et al.* PRL 84, 35 (2000)]

- Shell model predicts

$$^{11}\text{Be} \equiv \ ^{10}\text{Be}(0^+) \otimes \nu_{0p1/2}$$

- Experiment shows shell inversion

$$^{11}\text{Be} \equiv \ ^{10}\text{Be}(0^+) \otimes \nu_{1s1/2}$$

- Narrow momentum distribution
  $\Leftrightarrow$ extended spacial distribution
  $\Rightarrow$ confirms the neutron halo

Study of nuclear spectroscopy

Reaction models rely on single-particle model :

$$[T_r + V_{cf}(r) - \epsilon]\phi_{nlm}(\boldsymbol{r}) = 0 \qquad \text{with } \|\phi_{nlm}\| = 1$$

In reality, there is admixture of configurations :

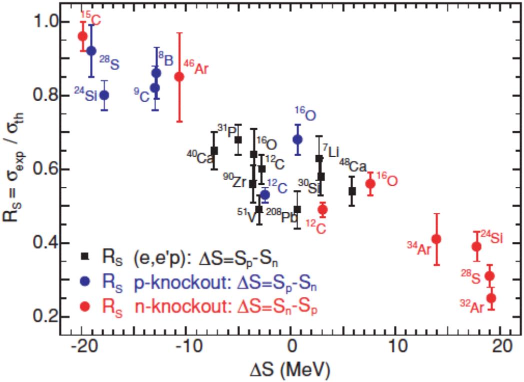
$$^{A}Y(J^{\pi}) = \ ^{A-1}X(J_c^{\pi}) \otimes \psi_{lm} + \ldots$$

where ψ_{lm} is the overlap wave function
Spectroscopic Factor : $\mathcal{S}_l = \|\psi_{lm}\|^2$

Single-particle approximation $\equiv \psi_{lm} = \sqrt{\mathcal{S}_l}\, \phi_{nlm}$
$\Rightarrow$ usual idea : $\mathcal{S}_l = \sigma_{\rm bu}^{exp}/\sigma_{\rm bu}^{th}$

Reduction of the SF

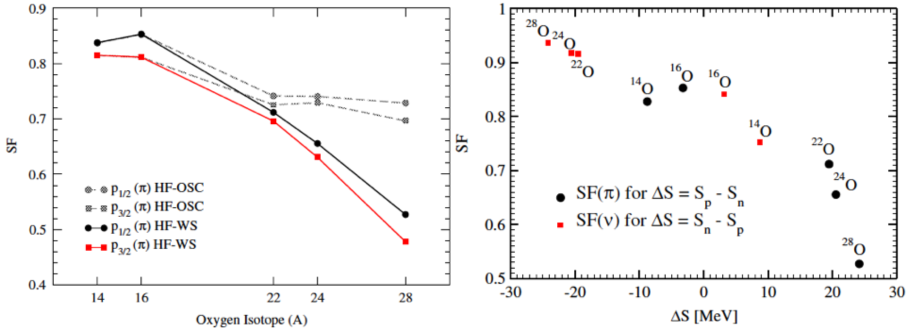
Predicted shell-model SF too high for deeply-bound nucleons



[Gade *et al.* PRC 77, 044306 (2008)]

- Something missing in usual shell-model calculations ?
- Problem in the reaction modelling ?

Quenching of SF



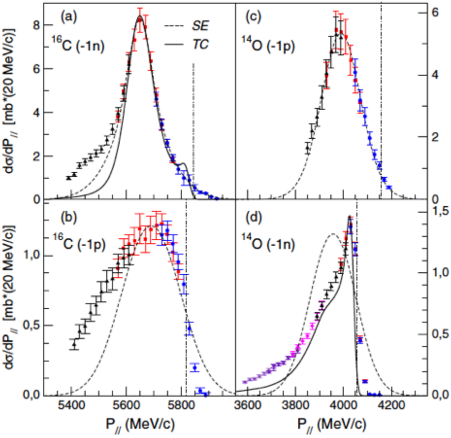
[Jensen *et al.* PRL 107, 032501 (2011)] ; see also G. Hagen's talk on Wednesday

Inclusion of continuum in shell-model basis reduces SF

⇒ solves partly the problem

KO reaction dynamics

- For loosely-bound nucleons
  $S_n(^{16}\text{C}) = 4.25$ MeV
  $S_p(^{14}\text{O}) = 4.63$ MeV
  eikonal model works fine
- For deeply-bound nucleons
  $S_p(^{16}\text{C}) = 22.6$ MeV
  $S_n(^{14}\text{O}) = 23.2$ MeV
  energy conservation must be taken into account



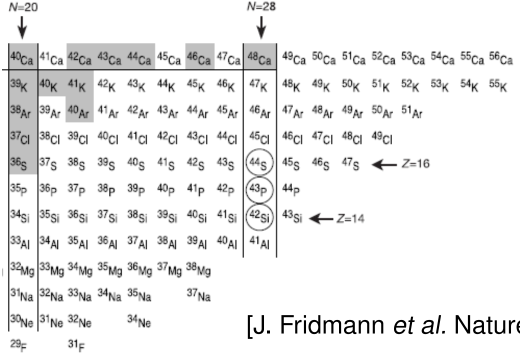
[Flavigny *et al.* PRL 108, 252501 (2012)]
see A. Obertelli's talk on Friday

⇒ solves another part of the problem ?

New magic numbers ?

New magic $Z = 14$ in ^{42}Si ?

$$^{44}\mathrm{S} + {}^{9}\mathrm{Be} \rightarrow {}^{42}\mathrm{Si} + \mathrm{X} \ @ \ 99A\mathrm{MeV}$$



[J. Fridmann *et al.* Nature 435, 922 (2005)]

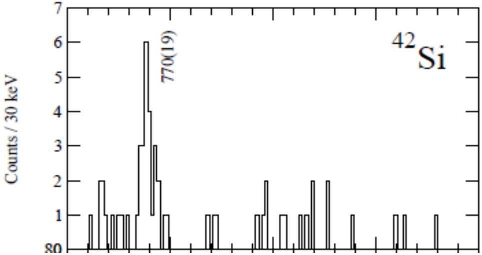
Analysis within shell-model calculation suggests $Z = 14$ to be magic far from stability. . .

However. . .

Measurement of γ in coincidence with proton stripping

see A. Obertelli's and L. Atar's talks on Friday

$$^{44}\text{S} + {}^{12}\text{C} \rightarrow {}^{42}\text{Si} + \gamma + \text{X @ } 60A\text{MeV}$$



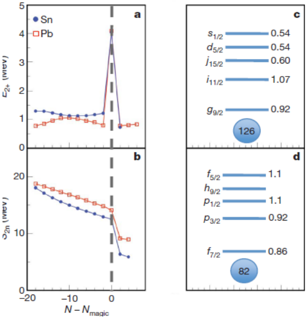
[B. Bastin *et al.* PRL 99, 022503 (2007)]

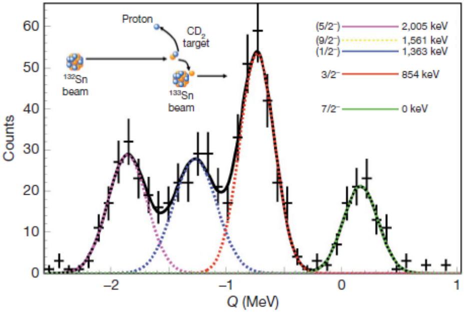
Indicates a low-lying state in ^{42}Si $\Rightarrow Z = 14$ not magic
and collapse of $N = 28$ far from stability

Confirmed magic numbers

Transfer reaction can be used to study shell structure

$$^{132}\mathrm{Sn} + \mathrm{d} \rightarrow \ ^{133}\mathrm{Sn} + \mathrm{p}$$





[K. Jones *et al.* Nature 465, 454 (2010)]

Confirms the single-particle structure of ^{133}Sn
and hence that ^{132}Sn is magic (i.e. $N = 82$ at $Z = 50$)

Summary

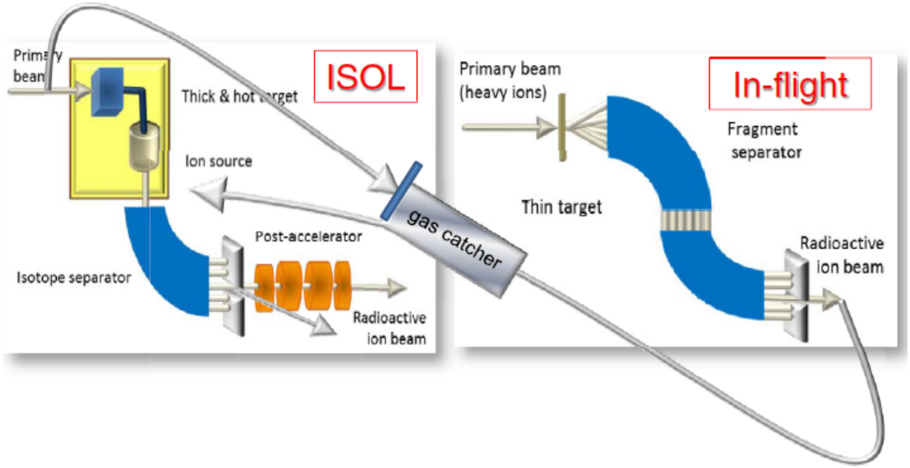
Liquid-drop and shell model describe qualitatively stable nuclei
Nowadays ab-initio nuclear-structure models from first principles

RIB enable study nuclear structure far from stability
Low intensities require new experimental techniques :
KO reactions, in-beam γ spectroscopy,...

- discovery of halo nuclei
  diffuse halo around a compact core
- shell inversions or shell collapse

RIB can be used to study reactions of astrophysical interest

Combined with a gas stopper



- can use thin target in ISOL
- can study low-energy reaction with in-flight fragmentation

$C(^{31}Ne,^{30}Ne + \gamma)X$ @ $230A$MeV

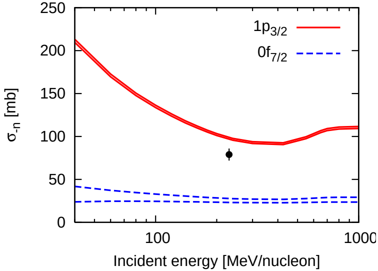
Shell model predicts ^{31}Ne ground state to be $7/2^-$ (^{30}Ne $\otimes \nu_{0f7/2}$)

One-neutron knock-out measured at RIKEN

$$^{31}\mathrm{Ne} + \mathrm{C} \rightarrow \ ^{30}\mathrm{Ne} + \mathrm{X} \text{ @ } 230A\text{MeV}$$

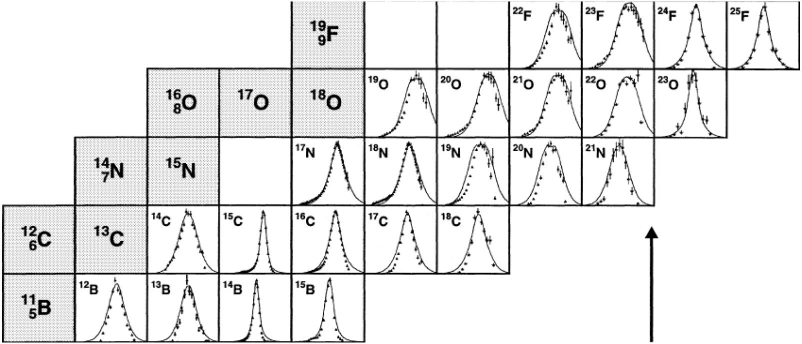
[T. Nakamura *et al.* PRL 103, 262501 (2009)]

Theoretical analysis suggests $3/2^-$ (^{30}Ne $\otimes \nu_{p3/2}$)



[W. Horiuchi *et al.* PRC 81, 024606 (2010)]

Systematic study



[Sauvan *et al.* PLB 491, 1 (2000)]