The search for exotic nuclear structure far from stability

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Introduction

Stable nuclei are qualitatively described by “simple” models

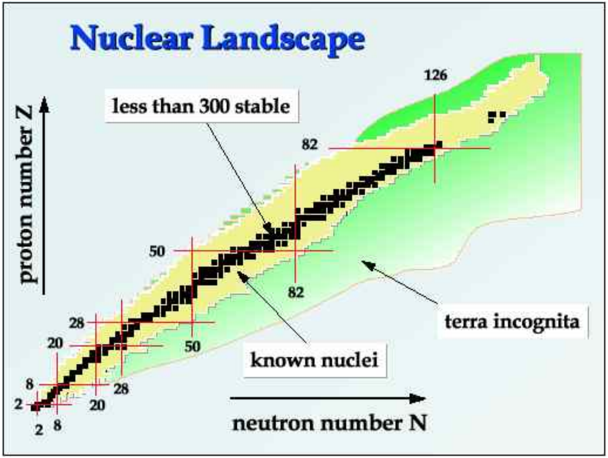
- (semi-empirical) liquid-drop model
- (basic) shell model

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

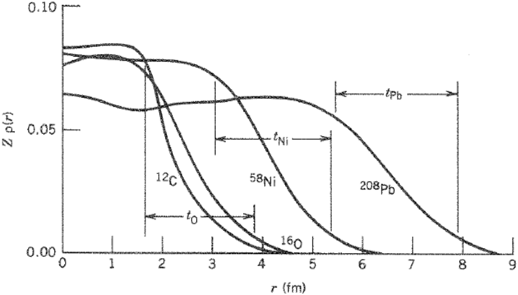
- halo nuclei
- exotic decays
- …

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 O

Charge distributions in (stable) nuclei

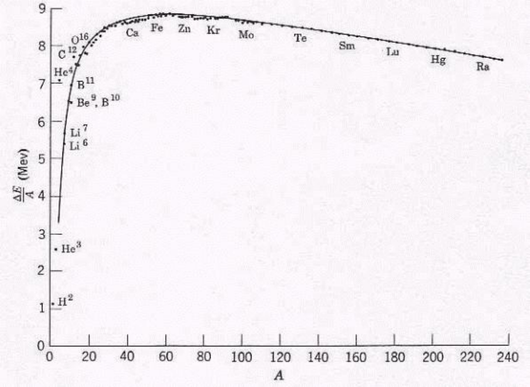


- constant density ρ_0 out to the surface (saturation)
- same skin thickness t

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

Liquid-drop model

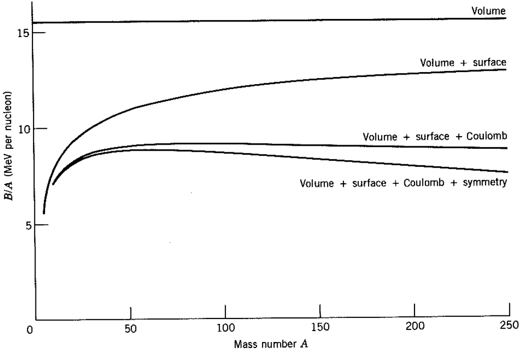
Binding energy per nucleon $B(Z, N)/A$ has smooth behaviour



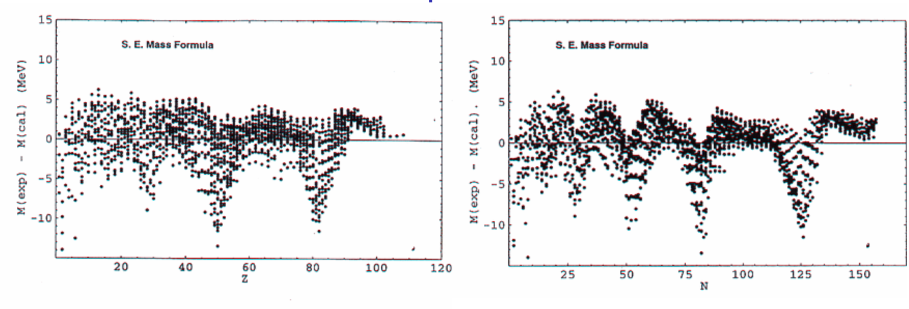
Liquid-drop model

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 ?

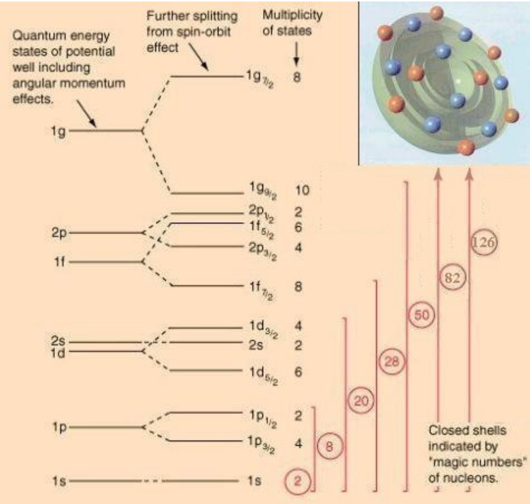
Shell model

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

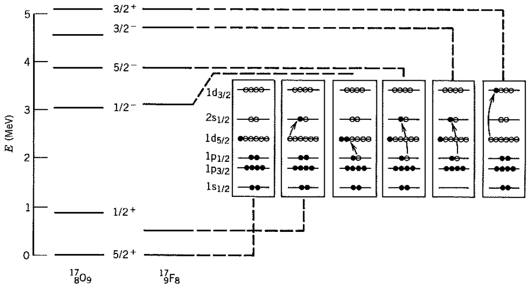
Spin-orbit coupling is crucial
to get right ordering of shells



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

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

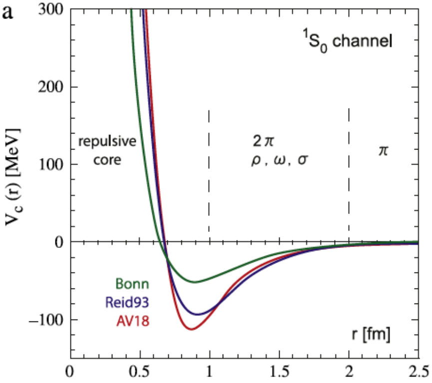
$\Rightarrow$ solve the A-body Schrödinger equation

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

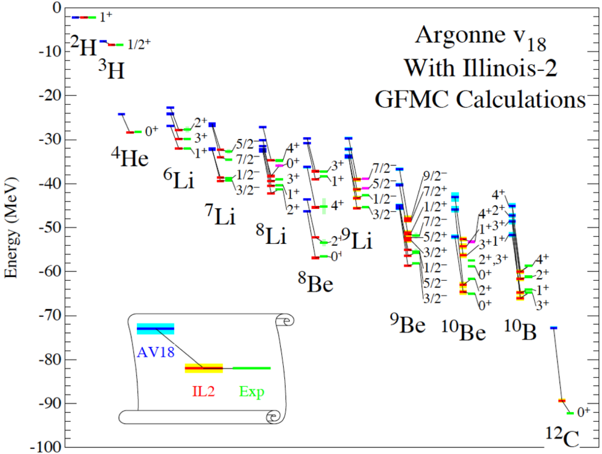
$\{E_n\}$ is the nucleus spectrum

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]

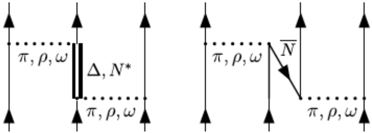
Three-body force

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, $\bar{\mathrm{N}}$...



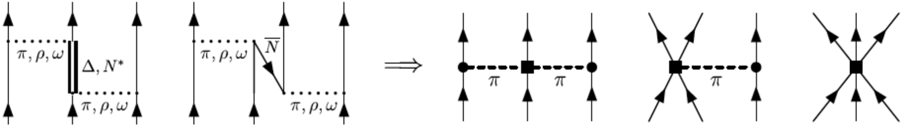
Phenomenological 3-body interaction fitted on $A > 2$ levels : IL2
Alternatively, derived from EFT

Effective Field Theory

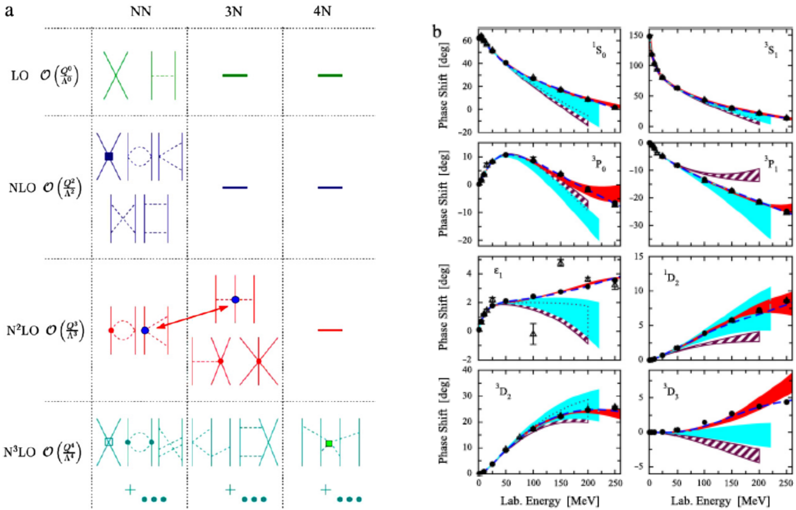
EFT is an effective quantum field theory based on QCD symmetries with resolution scale Λ that selects appropriate degrees of freedom : nuclear physics is not built on quarks and gluons, but on nucleons and mesons

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 $\{|\Phi_{[\nu]}\rangle\}$:

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

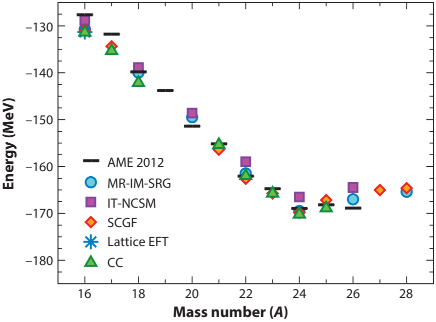
Solving the Schrödinger equation reduces to matrix diagonalisation

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

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

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

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 M. Pfützner on Tuesday & S. Zacarias on Wednesday]

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

Reactions involving radioactive nuclei useful in astrophysics

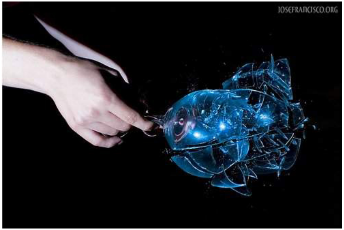
[see 2nd part,
Yu. Litvinov on Thursday and E. O'Connor on Friday]

How ?

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

- ISOL : Fire a proton at a heavy nucleus

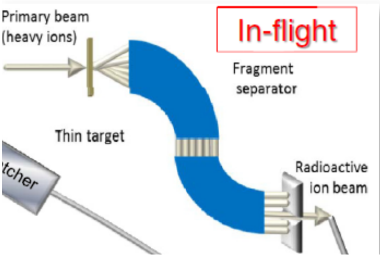
- In-flight : Smash a heavy nucleus on a target



Where ?


CANADA
UNITED STATES
NORTH PACIFIC OCEAN
NORTH ATLANTIC OCEAN
RUSSIA
CHINA
INDIA
BRAZIL
SOUTH PACIFIC OCEAN
SOUTH ATLANTIC OCEAN
INDIAN OCEAN
AUSTRALIA
SOUTHERN OCEAN
Antarctica

In-flight projectile fragmentation

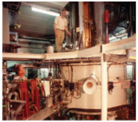


high-energy primary beam
of heavy ions (e.g. ^{18}O, ^{48}Ca, U. . .)
on thin target of light element (Be or C)
$\Rightarrow$ fragmentation/fission produces
many exotic fragments at $\approx v_{\text{beam}}$
Sorted in fragment separator

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

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

Existing NSCL @ MSU

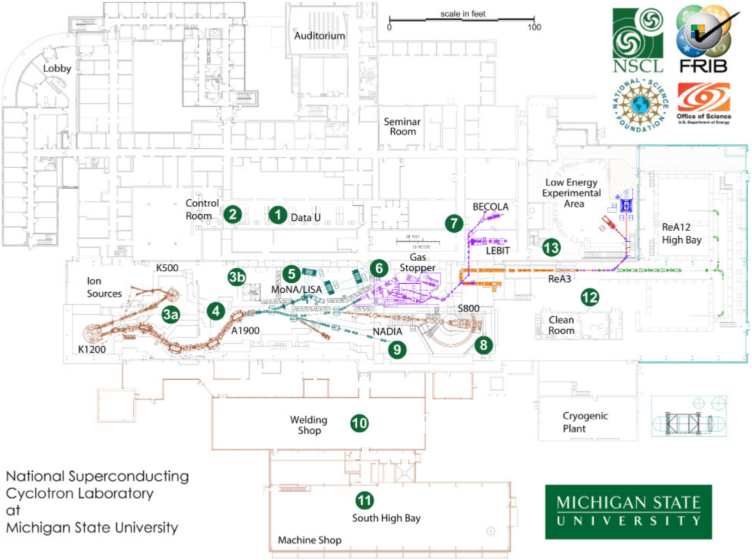


3a K500 Cyclotron

4 A1900 Fragment Separator

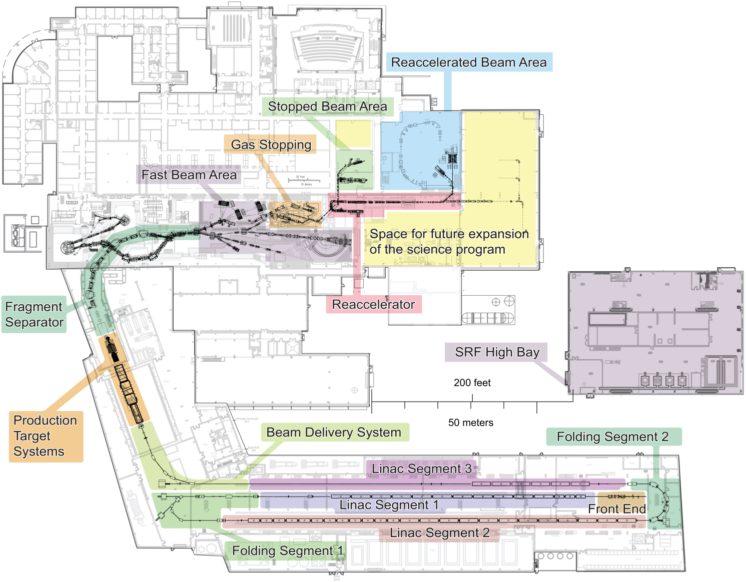
5 Modular Neutron Array

8 S800 Spectrograph



National Superconducting Cyclotron Laboratory at Michigan State University

Future : FRIB @ MSU



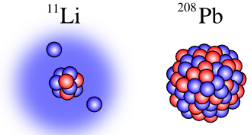
Halo nuclei

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

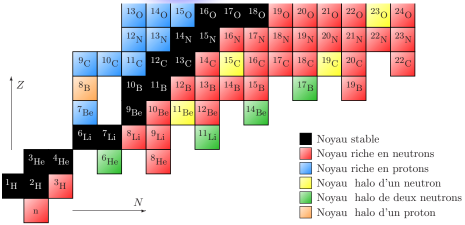
^{11}Be $\equiv$ ^{10}Be + n

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

Two-neutron halo

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

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



[M. Pfützner's talk on Tuesday & S. Zacarias' talk on Wednesday]

Two-neutron halo nuclei are Borromean...

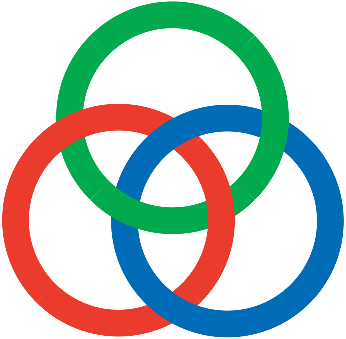
c+n+n is bound but not two-body subsystems

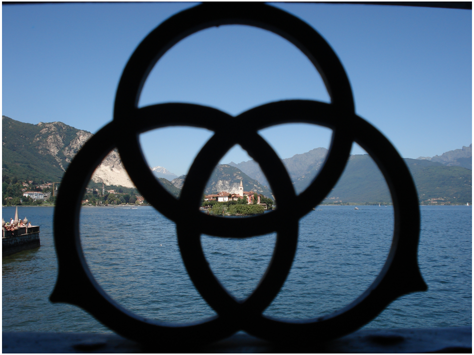
e.g. ^{6}He bound but not ^{5}He nor ^{2}n

Borromean nuclei

Named after the Borromean rings...

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



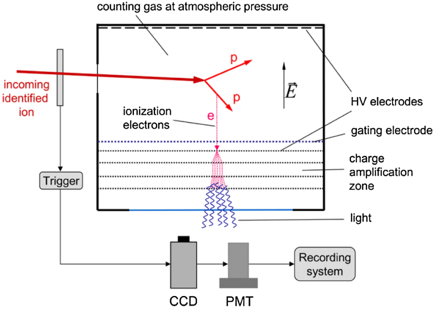


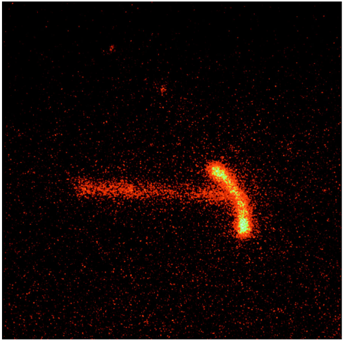
Search for exotic decays using a TPC

Close to the dripline exotic decays have been predicted

- β-delayed particle emission
- proton radioactivity

Using a Time-Projection Chamber where such events can be seen

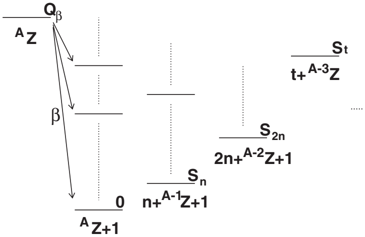




[see M. Pfützner's talk on Tuesday]

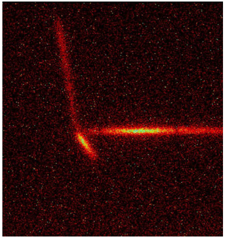
β-delayed particle emission

Away from stability, β decay can lead to emission of particles [see M. Pfützner's talk on Tuesday]



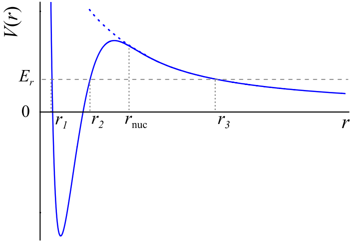
Provides structure information :

- Two-neutron halo nuclei c+n+n can decay into c+d
  e.g. ^{6}He$\rightarrow \alpha$ + d
  $\Rightarrow$ emphasises role of halo
- ^{8}He $\rightarrow \alpha$+t+n
  Depends on 3N correlations



[M. Pfützner *et al.* RMP 84, 567 (2012)]

Single-proton radioactivity



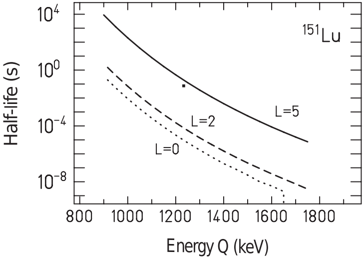
Similar process as the α decay :
the proton is held within nucleus by Coulomb barrier under which it tunnels

$$\Gamma_{\mathrm{p}} = S_{\mathrm{p}} \frac{N}{4\mu} \exp\left\{-2 \int_{r_2}^{r_3} \sqrt{2\mu\,[V(r) - Q]}dr\right\}$$

Conservation laws

- Angular-momentum : $\boldsymbol{I}_i = \boldsymbol{I}_f + \boldsymbol{l} + \boldsymbol{s}$
- Parity : $\pi_i \pi_f = (-1)^l$

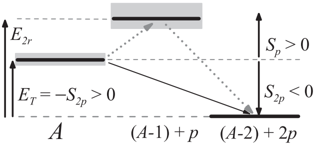
Strongly sensitive to Q value and l
$\Rightarrow$ information on structure @ dripline



[see M. Pfützner's talk on Tuesday]
[M. Pfützner *et al.* RMP 84, 567 (2012)]

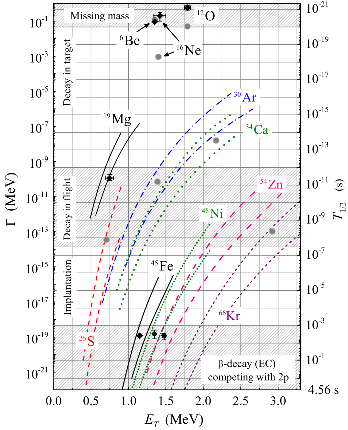
Two-proton radioactivity

At the proton dripline,
2p radioactivity is also possible
True 2p radioactivity : not sequential



Predicted in 1960s by Goldansky
Discovered in 2002 by Pfützner

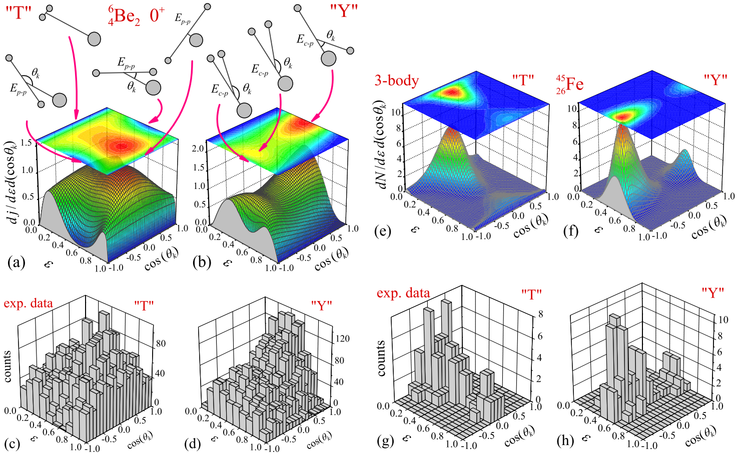
$T_{1/2}$ spans 18 order of magnitude



[see M. Pfützner's talk on Tuesday]
[Pfützner *et al.* RMP 84, 567 (2012)]

Two-proton radioactivity

A proper theoretical analysis requires a 3-body model



[see M. Pfützner's talk on Tuesday]
[Pfützner *et al.* RMP 84, 567 (2012)]

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…