Nuclei as open quantum many body systems

Witold Nazarewicz (Tennessee/Warsaw)

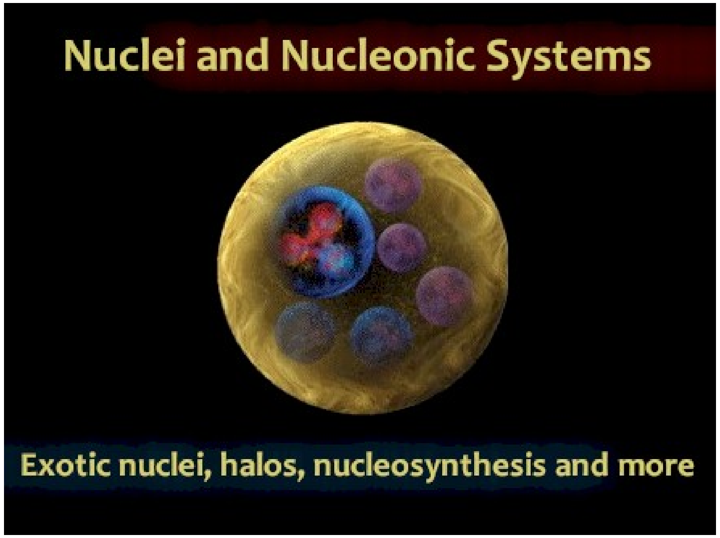
20th Chris Engelbrecht Summer School in Theoretical Physics

19 – 28 January 2009

National Institute for Theoretical Physics at Stellenbosch

Institute for Advanced Study,

Stellenbosch, Western Cape, South Africa



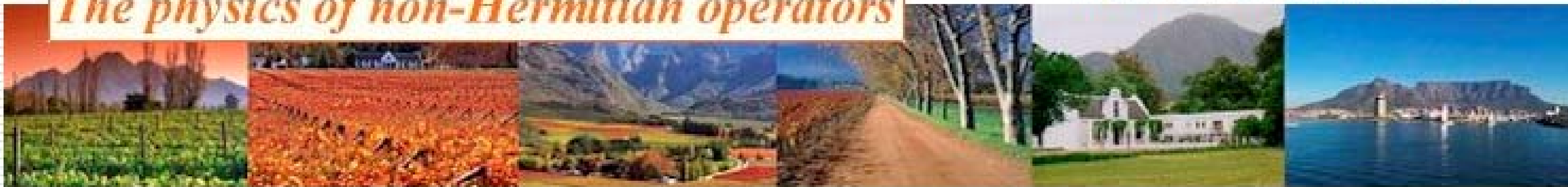
Rough Outline

- Introduction: nuclei as open systems
- Territory: nuclear landscape and the limits of nuclear existence
- Phenomena related to the openness 1
    - Coupling between structure and reactions
- Recent experimental highlights
- General comments on nuclear many-body theory 2
- Simple concepts
- Theoretical frameworks
    - Real-energy quantum mechanics (Hilbert Space) 3
        - Mean field perspective
        - Continuum shell model
    - Complex-energy quantum mechanics (Rigged Hilbert Space) 4
        - Resonant-state expansions
        - Gamow Shell Model and Complex Scaling 5
- Typical applications
    - Weakly bound and unbound nuclei
    - Fission 6
    - Hot nuclei and continuum level density
    - Other many-body systems; interdisciplinary aspects
- Perspectives

http://academic.sun.ac.za/workshop/

The 4th International Workshop

The physics of non-Hermitian operators



Pseudo-Hermitian Hamiltonians in Quantum Physics IV

Last updated: 31 July 2006

WHERE: The Workshop was held at the University of Stellenbosch, Western Cape, South Africa
WHEN: November 23-25, 2005

Also see:
Workshop series home page
The 1st Workshop (2003)
The 2nd Workshop (2004)
The 3rd Workshop (June 2005)
The 5th and upcoming Workshop (July 2006)

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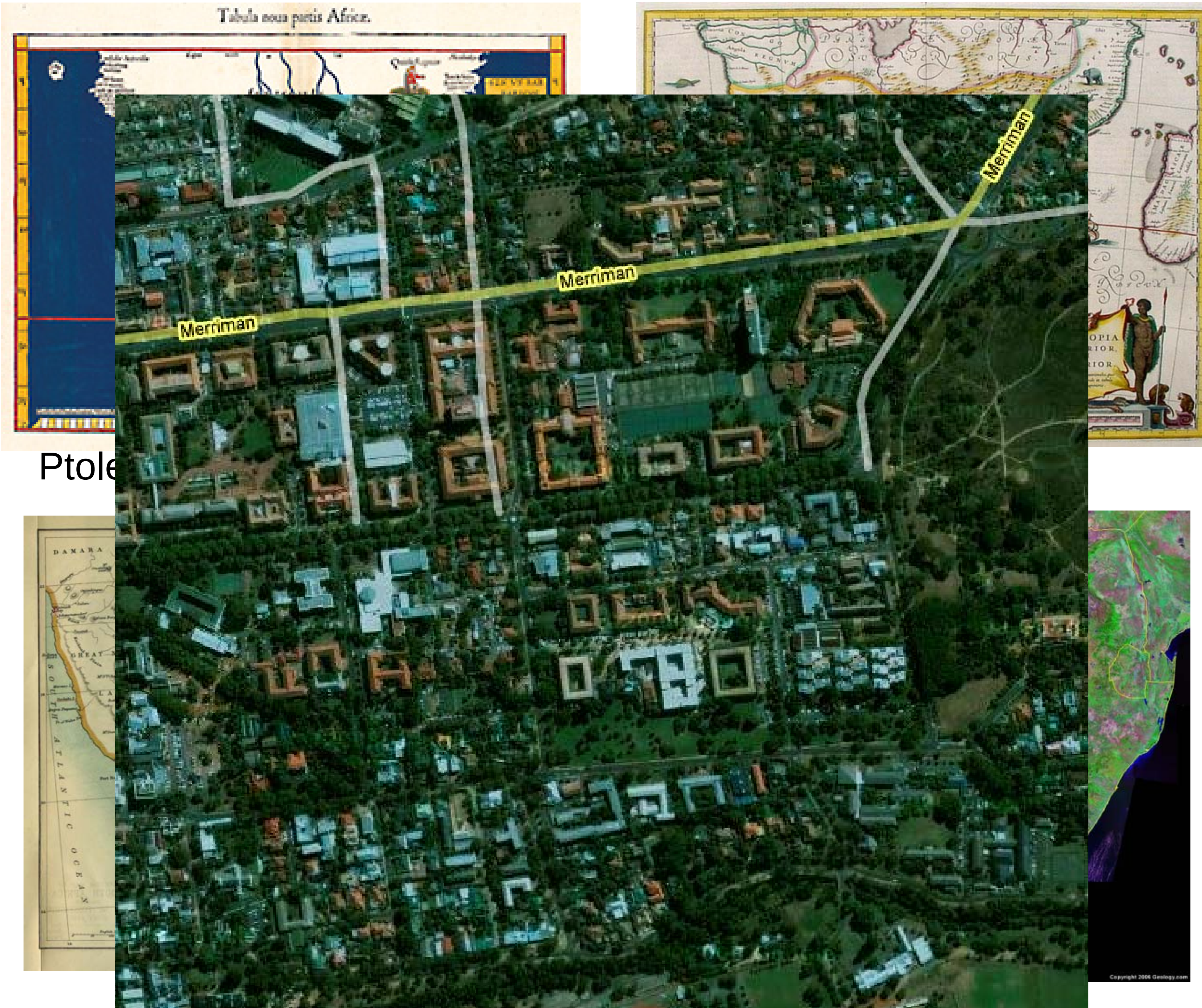
Topics

The scope of the conference:

- ALGEBRAIC, PERTURBATION AND NUMERICAL METHODS
- APPLICATIONS IN MAGNETOHYDRODYNAMICS ETC
- EFFECTIVE THEORIES IN MANY-BODY PROBLEMS
- EXCEPTIONAL POINTS
- FIELD THEORIES WITH CPT SYMMETRY
- KREIN SPACES AND RELATED RIGOROUS RESULTS
- QUASI-HERMITIAN MODELS IN QUANTUM MECHANICS
- RANDOM MATRIX MODELS AND NON-HERMITICITY IN STATISTICAL PHYSICS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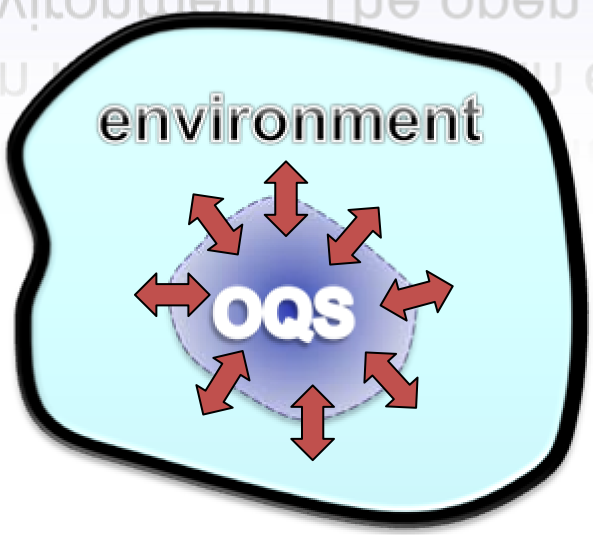
Introduction

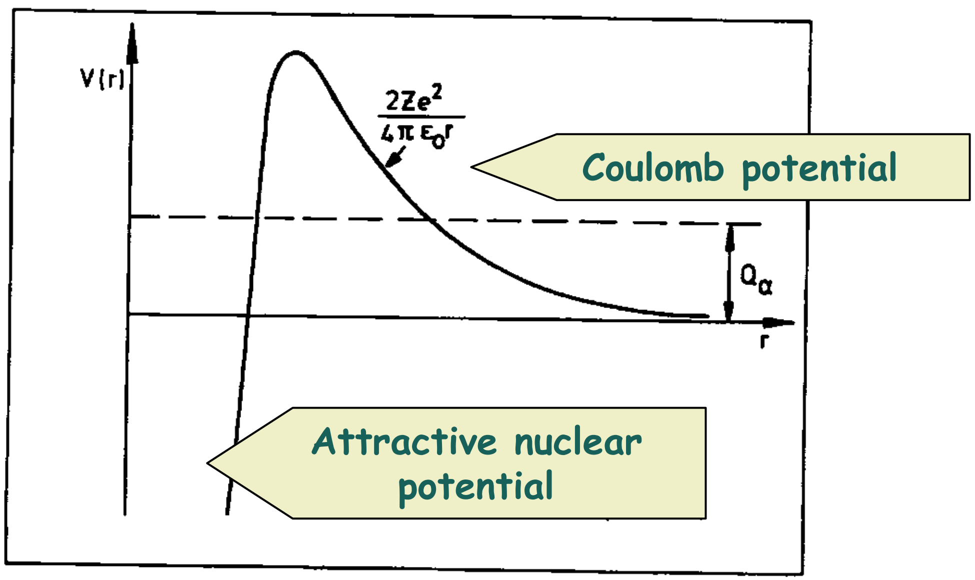
Wikipedia:

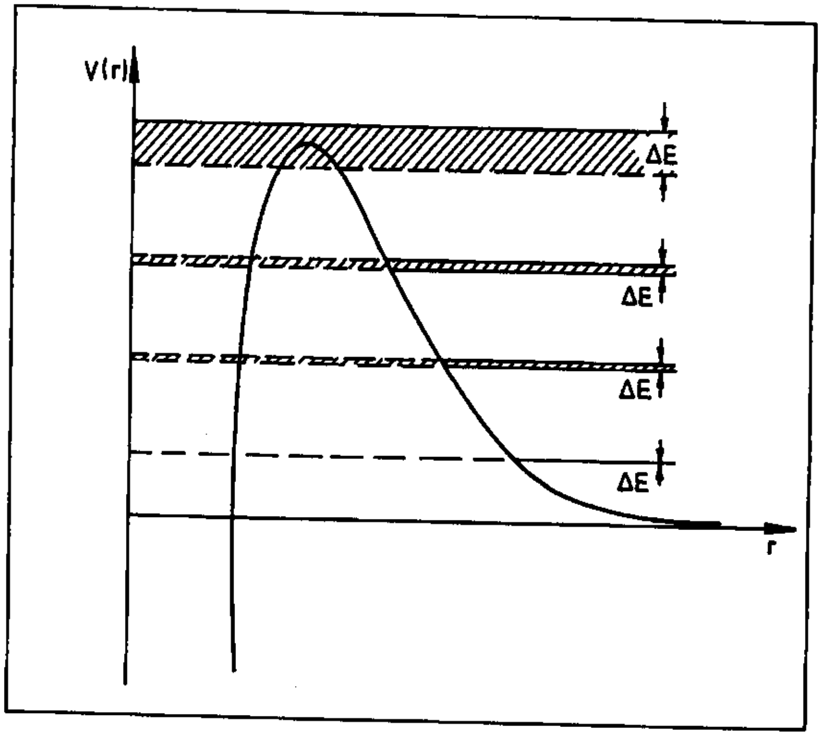
An open quantum system is a quantum system which is found to be in interaction with an external quantum system, the environment. The open quantum system can be viewed as a distinguished part of a larger closed quantum system, the other part being the environment.



Nuclear Decays

Alpha Decay

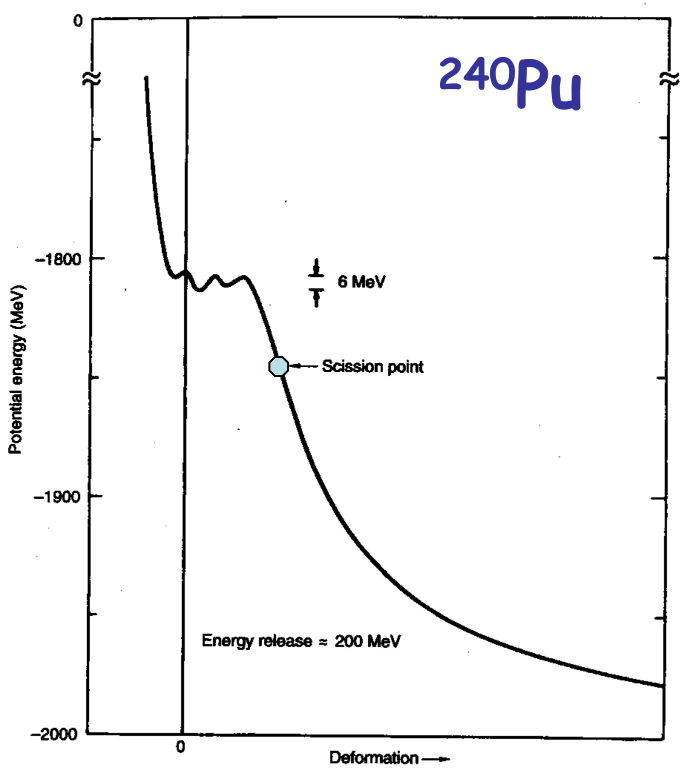


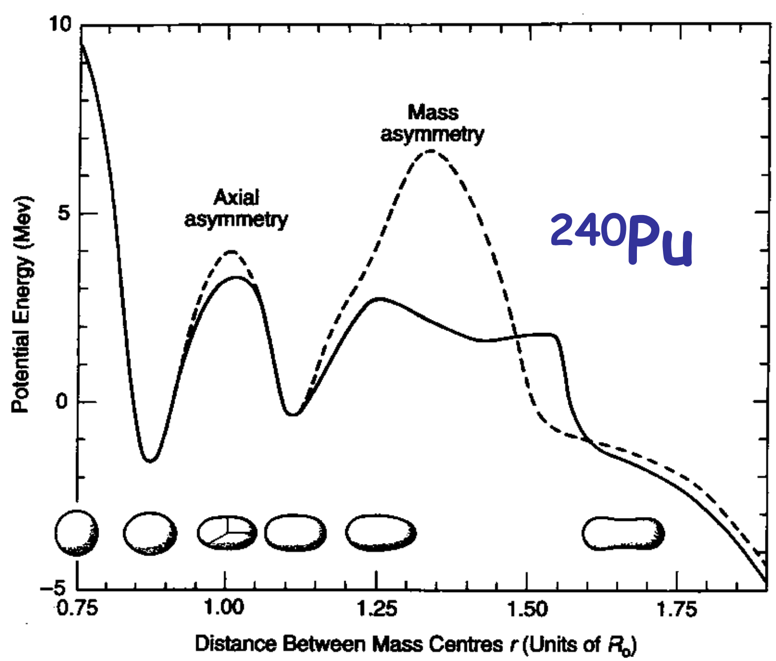


Gamow 1928

(“pre-nuclear” era)

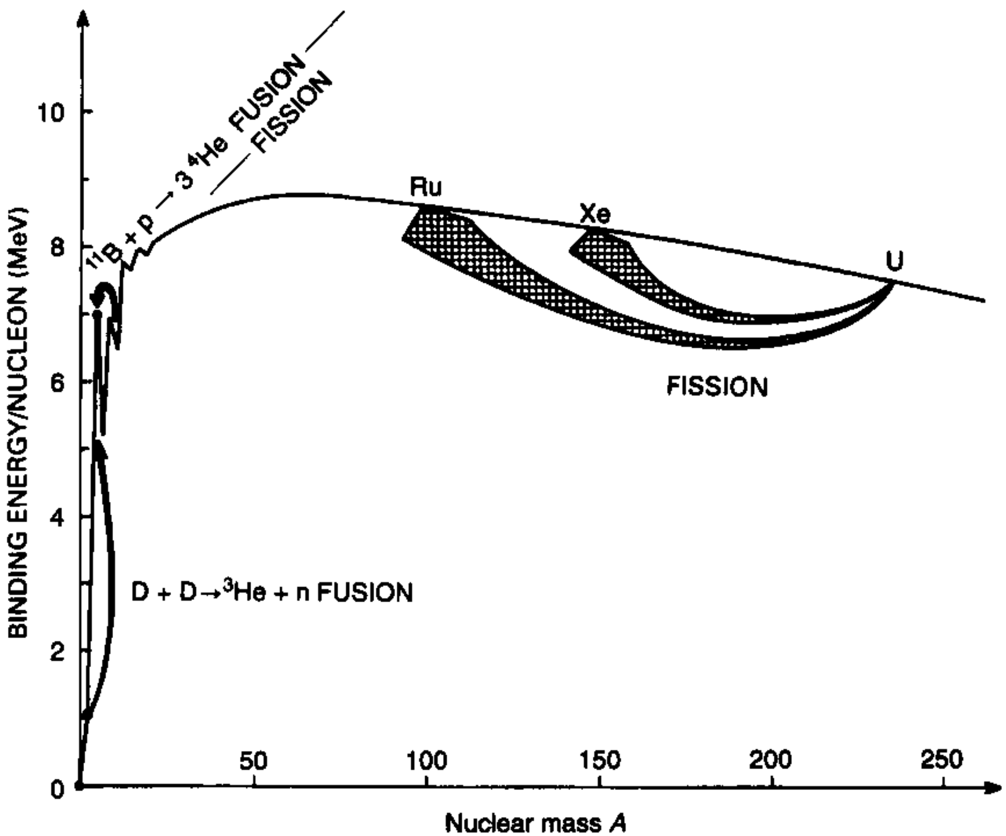
Spontaneous fission

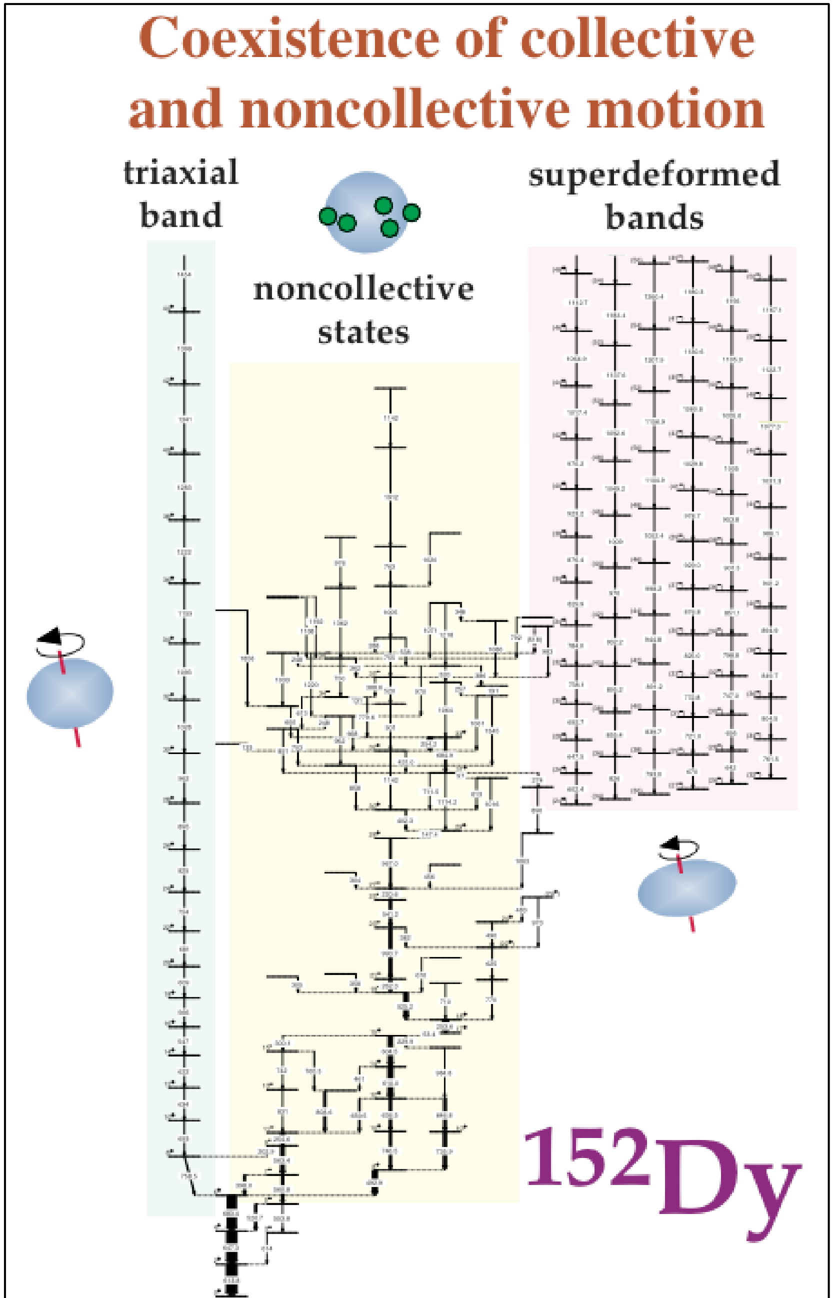




1938 - Hahn & Strassmann
1939 Meitner & Frisch
1939 Bohr & Wheeler
1940 Petrzhak & Flerov

- **All elements heavier than A=110-120 are fission unstable!**
- **But… the fission process is unimportant for nuclei with A<230. Why?**





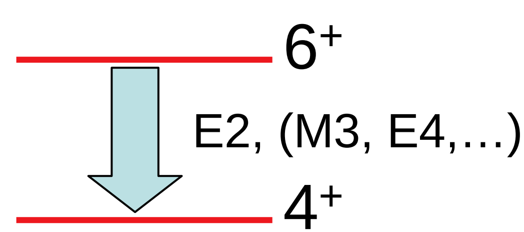
Electromagnetic Decay

Emission of a γ-ray is caused by the interaction of the nucleus with an external electromagnetic field

$$V = -\frac{1}{c} j_\mu A^\mu$$

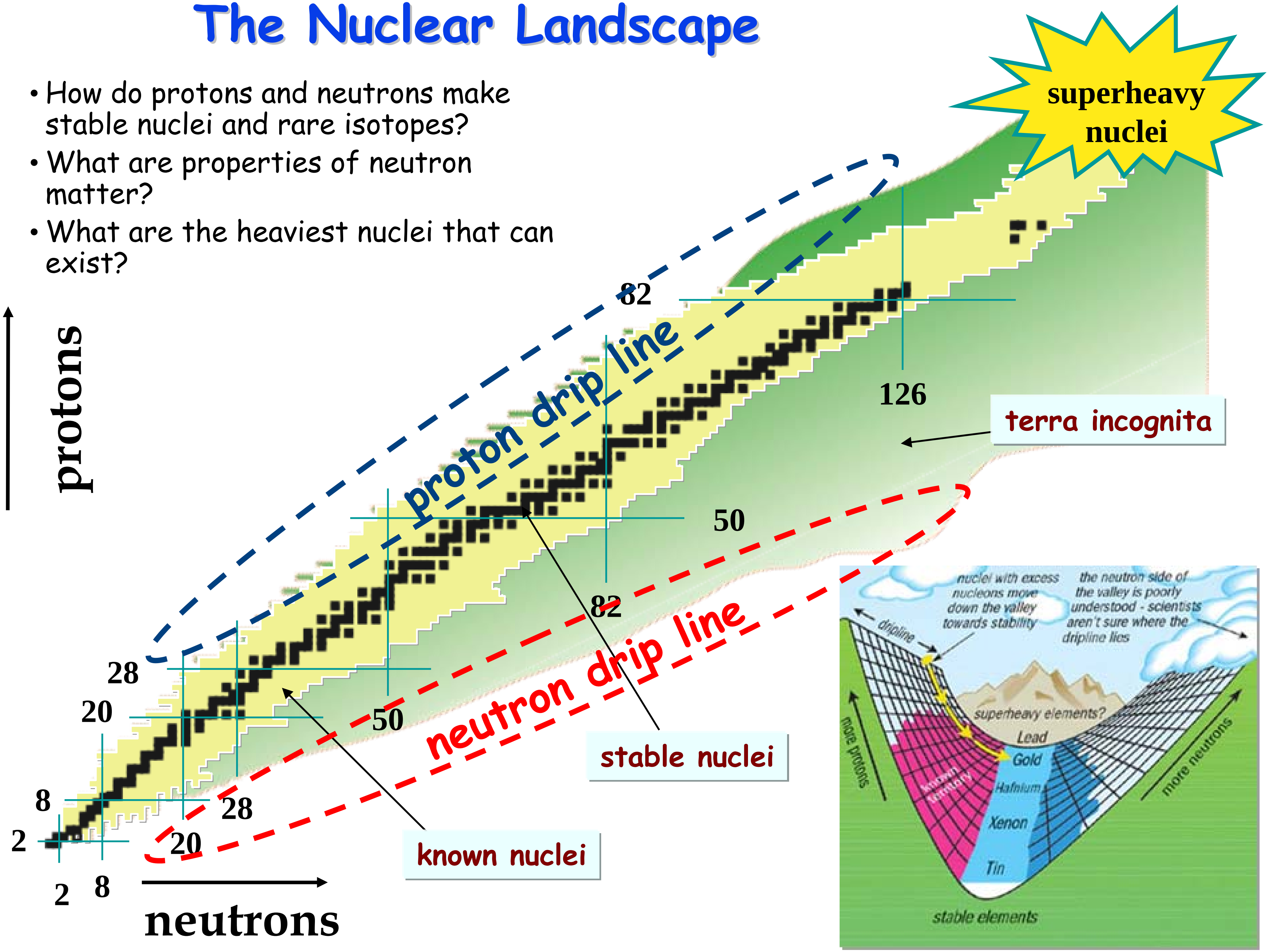
Nuclear current

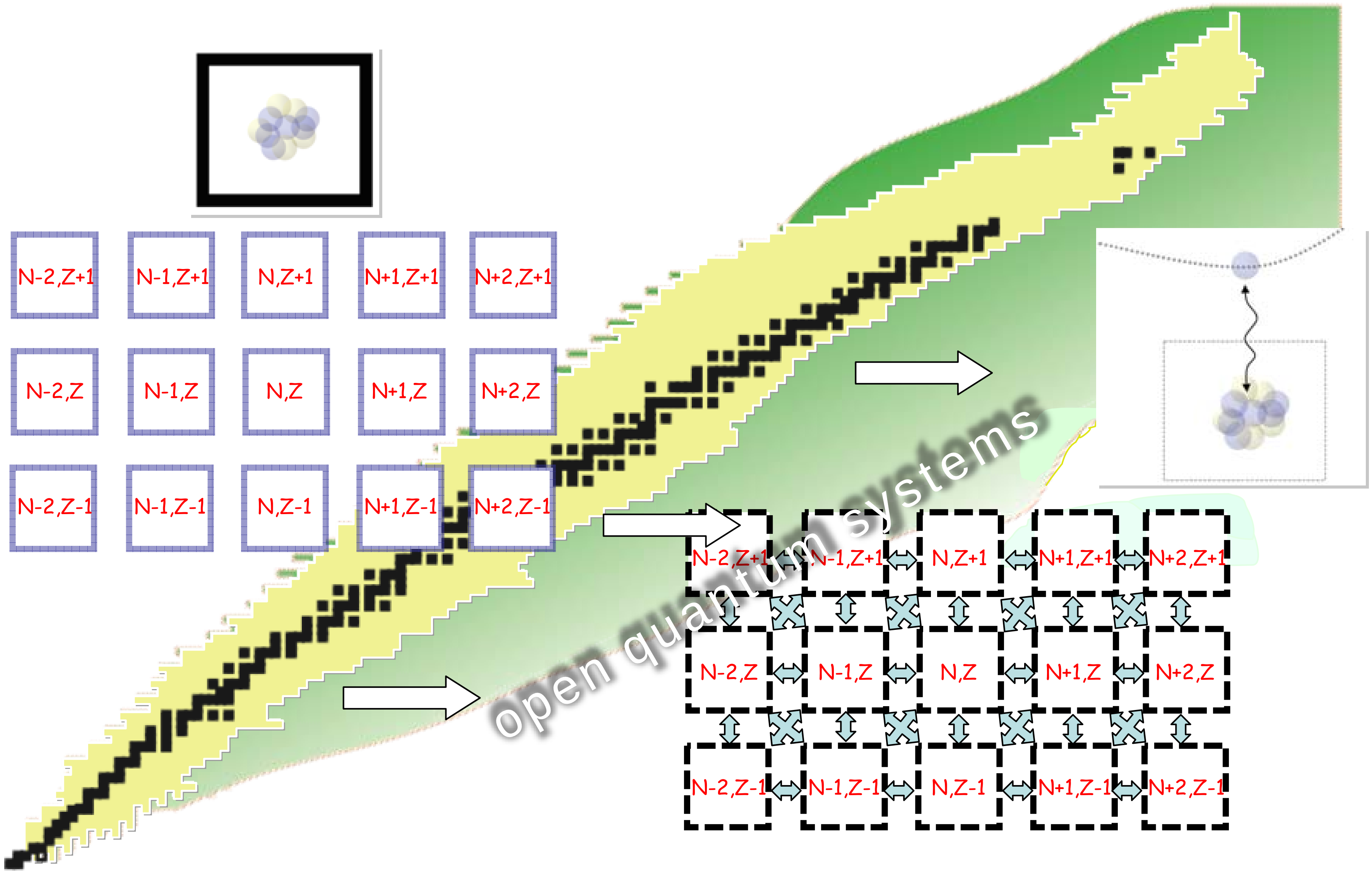
External EM filed



The Nuclear Landscape

- How do protons and neutrons make stable nuclei and rare isotopes?
- What are properties of neutron matter?
- What are the heaviest nuclei that can exist?




N-2,Z+1
N-1,Z+1
N,Z+1
N+1,Z+1
N+2,Z+1
N-2,Z
N-1,Z
N,Z
N+1,Z
N+2,Z
N-2,Z-1
N-1,Z-1
N,Z-1
N+1,Z-1
N+2,Z-1
open quantum systems
N-2,Z+1
N-1,Z+1
N,Z+1
N+1,Z+1
N+2,Z+1
N-2,Z
N-1,Z
N,Z
N+1,Z
N+2,Z
N-2,Z-1
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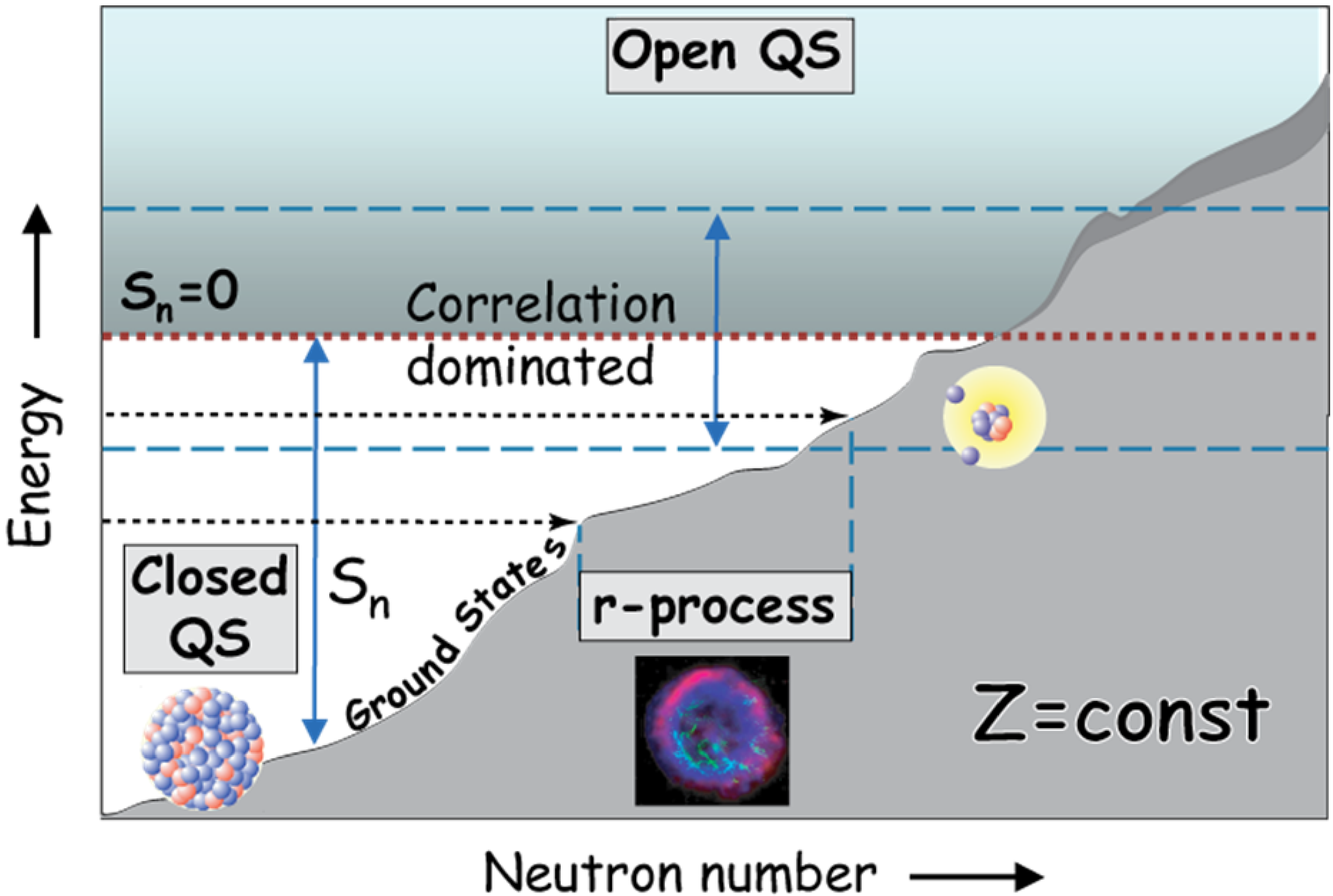
N+1,Z-1
N+2,Z-1

Prog. Part. Nucl. Phys. 59, 432 (2007)



Basic Equations

Time Dependent (Many Body) Schödinger Equation

$$i\hbar \frac{\partial \psi}{\partial t} = \hat{H}\psi$$

+ boundary conditions

Often impractical/impossible to solve but excellent starting point

Time Independent (Many Body) Schödinger Equation

$$\hat{H}\psi = E\psi$$

Box boundary conditions (w.f. vanishes at large distances)
Decaying boundary conditions
Incoming or capturing boundary conditions
Scattering boundary conditions

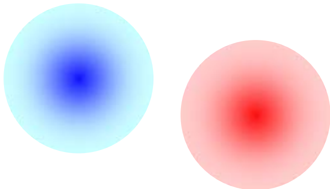
Absorbing boundary conditions

} choice depends on physics case

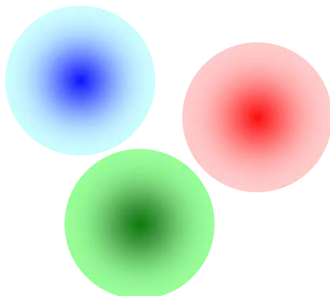
Phenomena related to the Openness

Impact of scattering space on structural properties

Halos



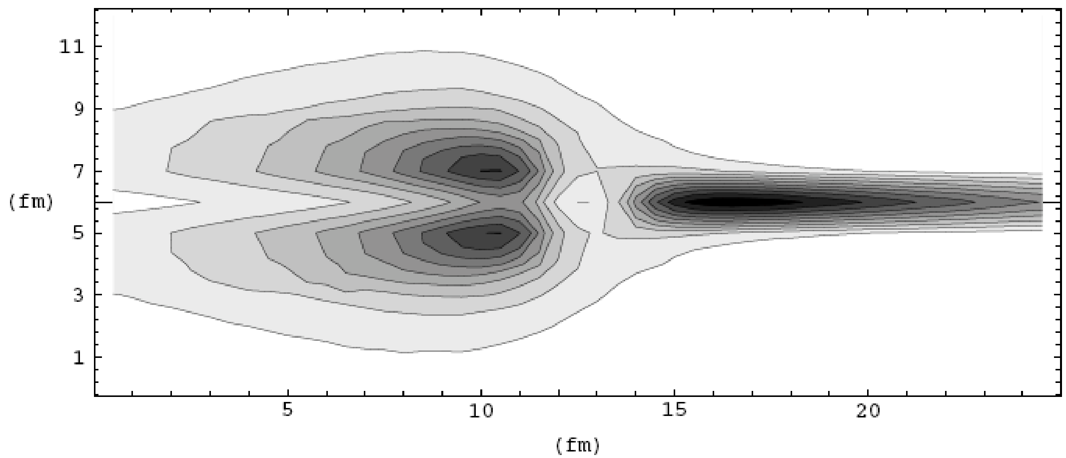
^2H (deuteron)
S_n=2.2 MeV, r_{np}=4 fm



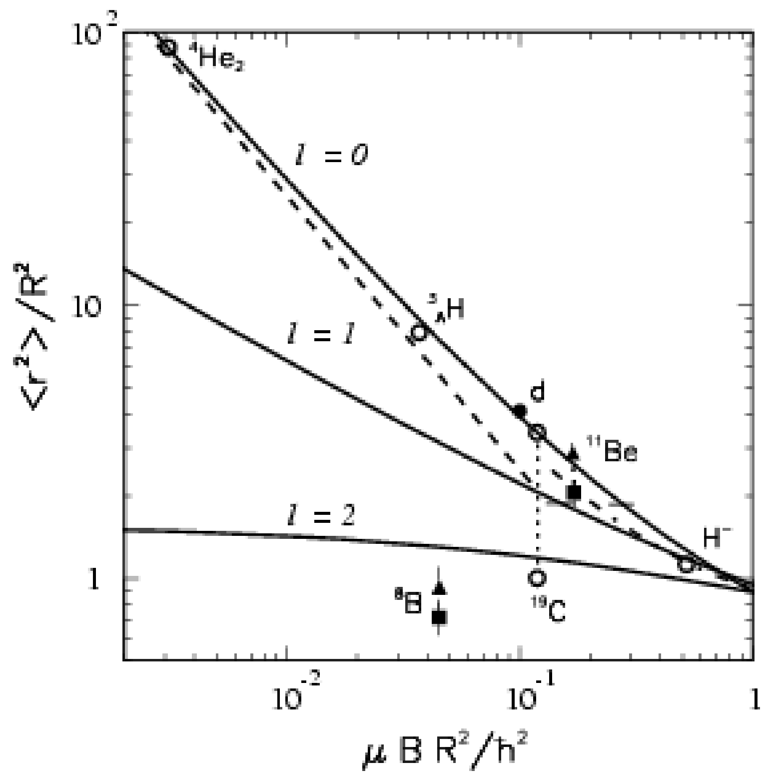
^3H_L (hypertriton)
S_Λ=0.08 MeV

Riisager, Fedorov, Jensen
Europhys. Lett. 49, 547 (2000)

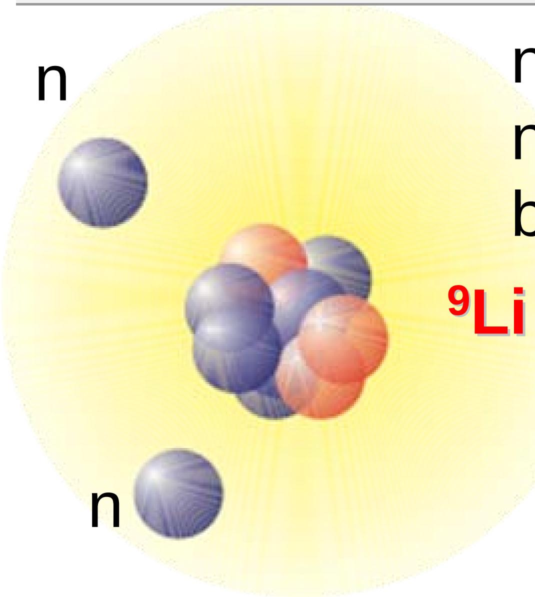
$^4He_2$ (atomic helium dimer)
S=0.13 μeV, r=100 Å



Cobis,Jensen, Fedorov
J. Phys. G23, 401 (1997)



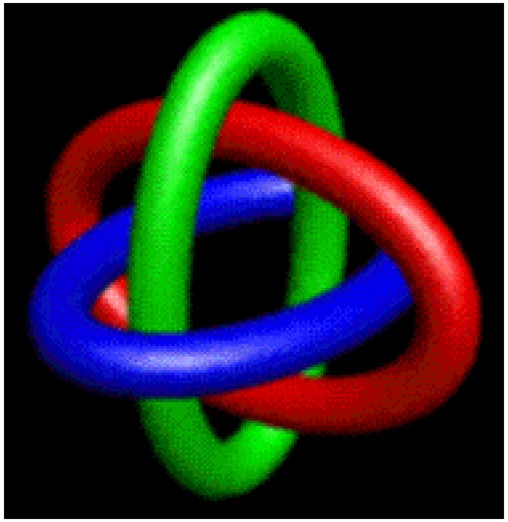
^{11}Li: Borromean halo nucleus
Z=3, N=8



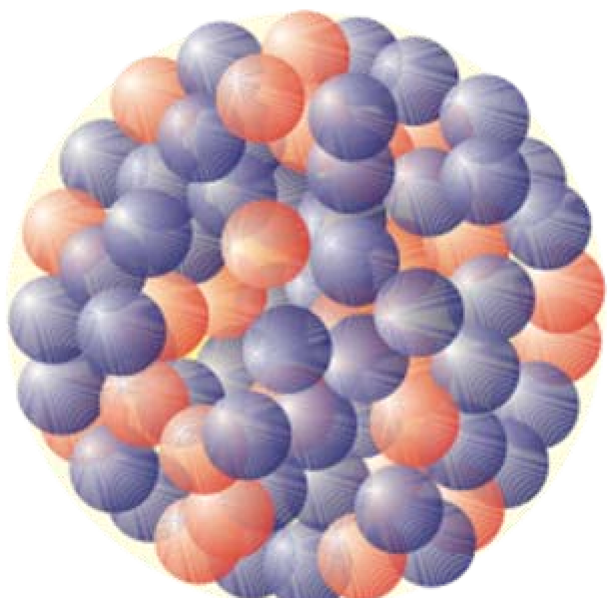
n+n is unbound
n+ ^{9}Li is unbound
but n+n+ ^{9}Li is bound !

← 0.00000000000014 cm →

The Borromean Rings



^{208}Pb: well bound heavy nucleus
Z=82, N=126

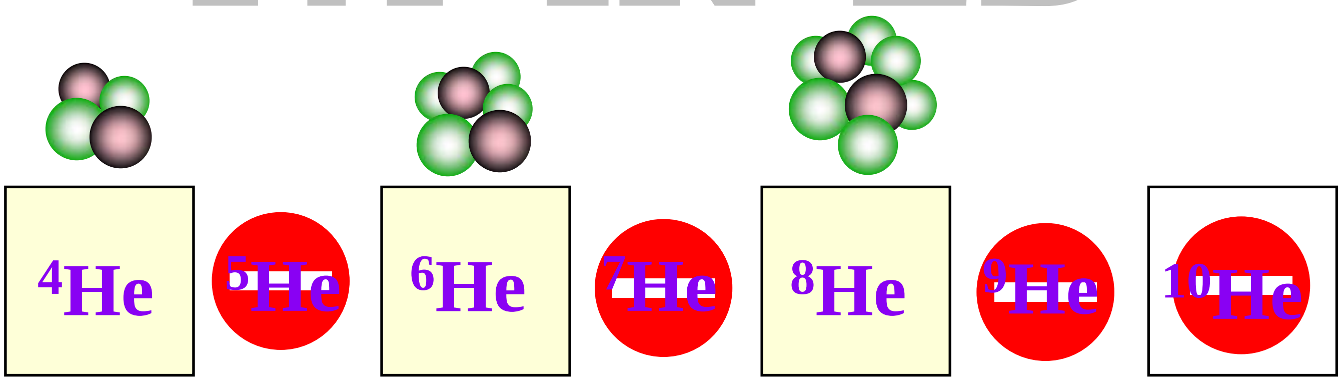


Neutron Drip line nuclei

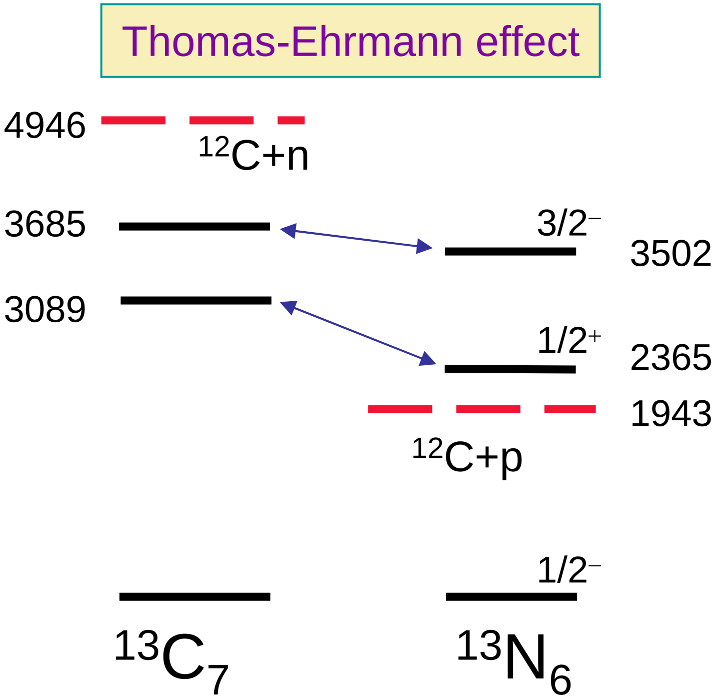
HUGE

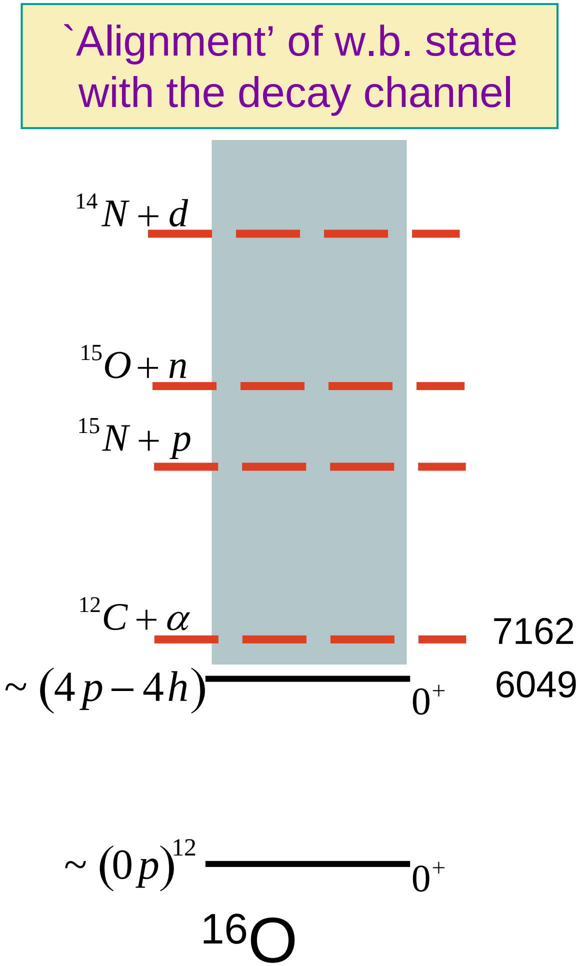
D i f f u s e d

PA IR ED

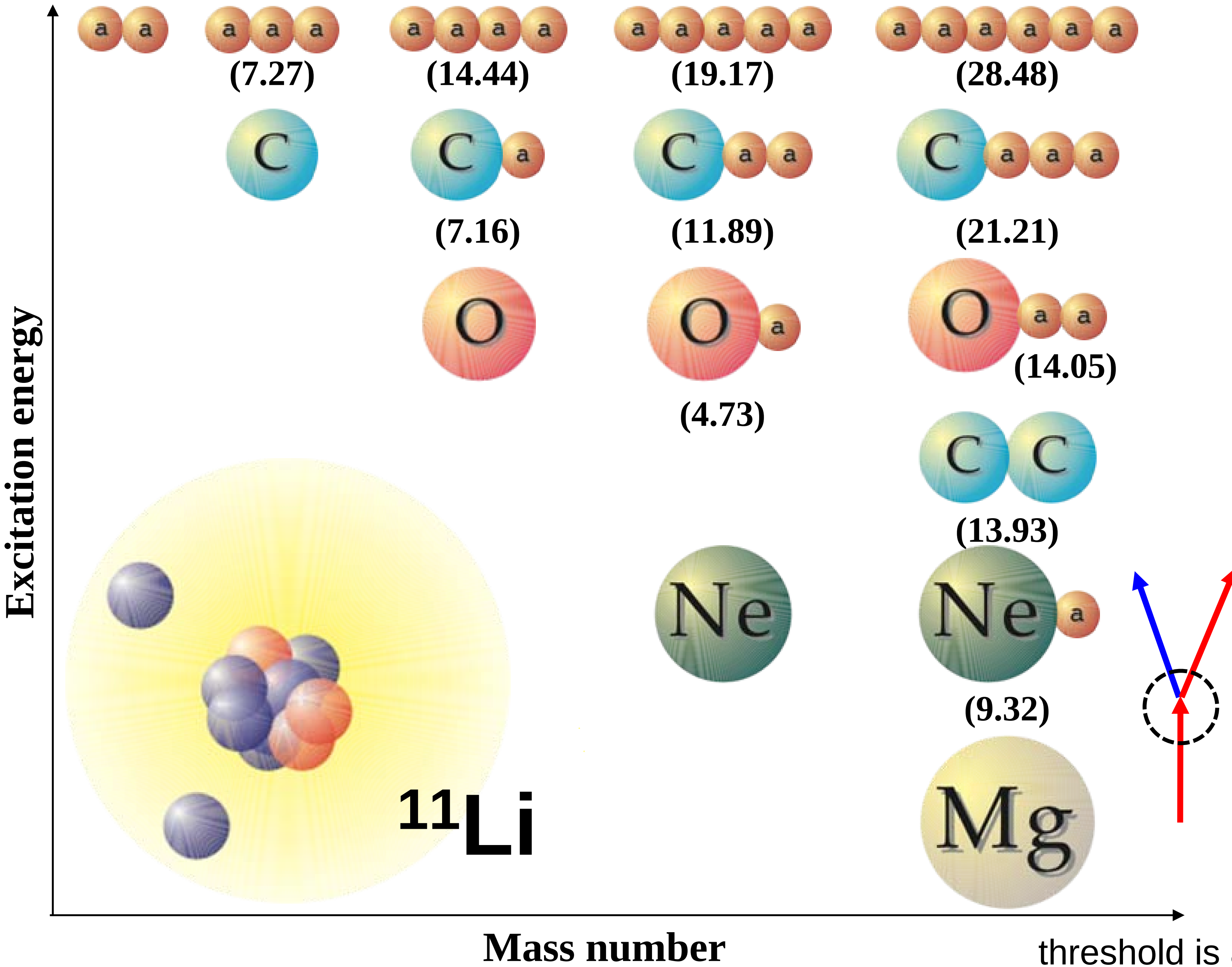


Environment: continuum of decay channels





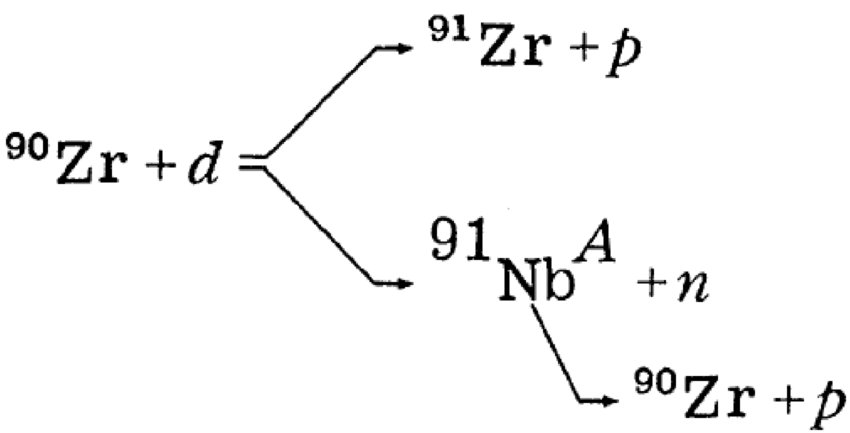
Spectra and matter distribution modified by the proximity of scattering continuum

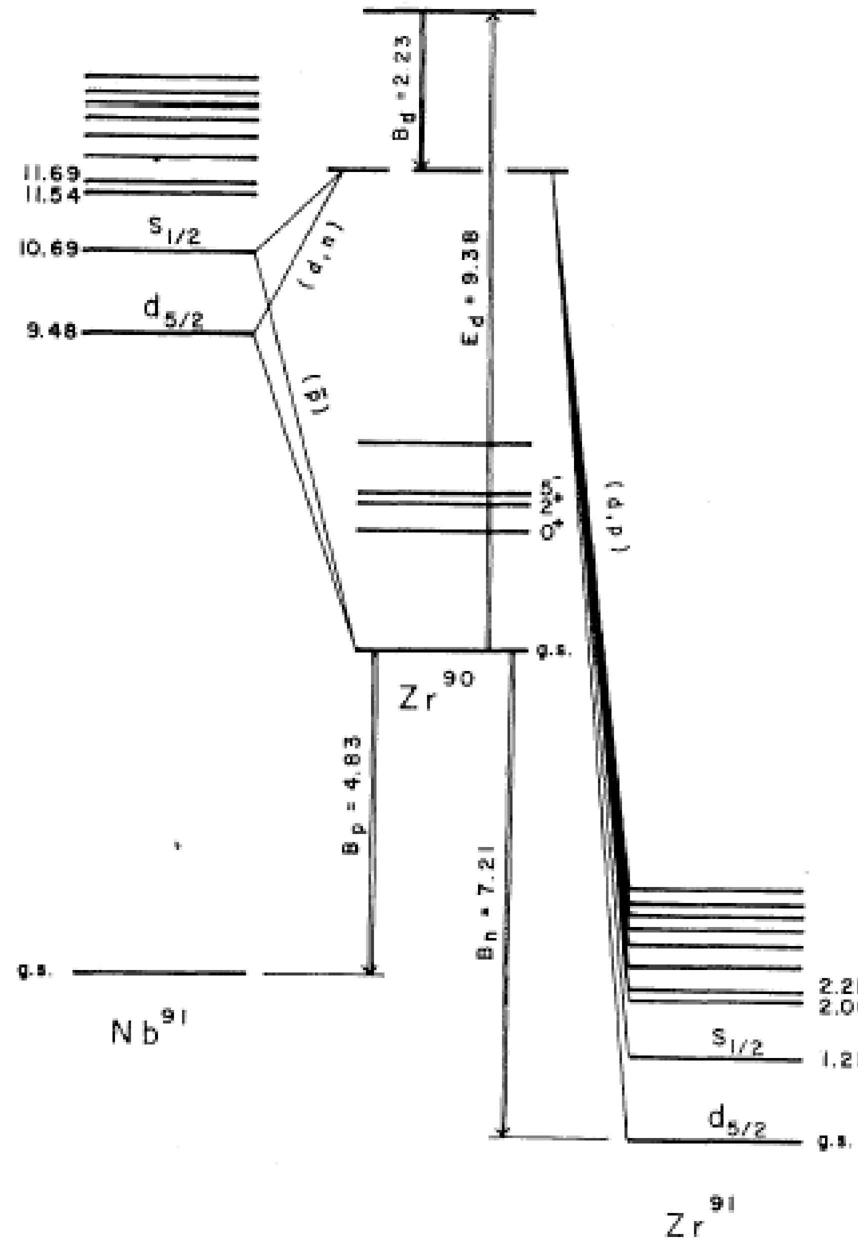


threshold is a
branching point

Coupling between analog states in (d,p) and (d,n)

C.F. Moore et al.
Phys. Rev. Lett. 17, 926 (1966)





C.F. Moore et al., Phys. Rev. Lett. 17, 926 (1966)