SCIENTIFIC OPPORTUNITIES AT RADIOACTIVE BEAM FACILITIES (RBF)

Francesco Iachello

Yale University

Legnaro, May 26, 2014

The nucleus: a unique many-body system with strong (and short-range) interactions

A mesoscopic system (2-250 particles) intermediate between a few-body system (2-4 particles) and a condensed matter system (10^{23} particles)

A strongly correlated Fermi liquid

METHODS USED TO STUDY NUCLEAR STRUCTURE

Very light	2-8	Few-body
Light	8-20	Cluster Shell
Medium	20-50	Shell Collective
Heavy	50-250	Collective

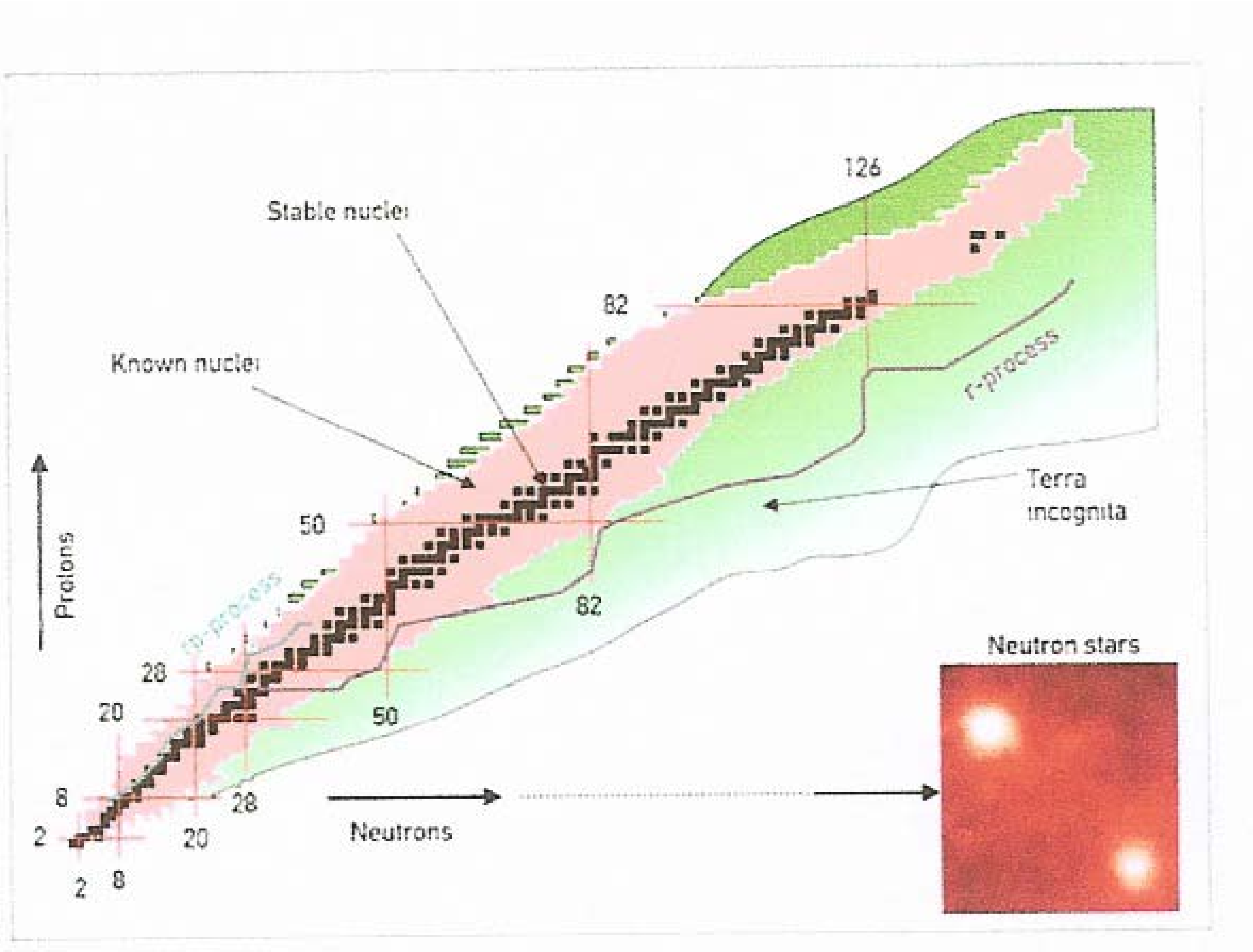
MODELS OF NUCLEAR STRUCTURE

The shell model (1948)
The collective model (1952)
The cluster model (1958)
The interacting boson model (1974)

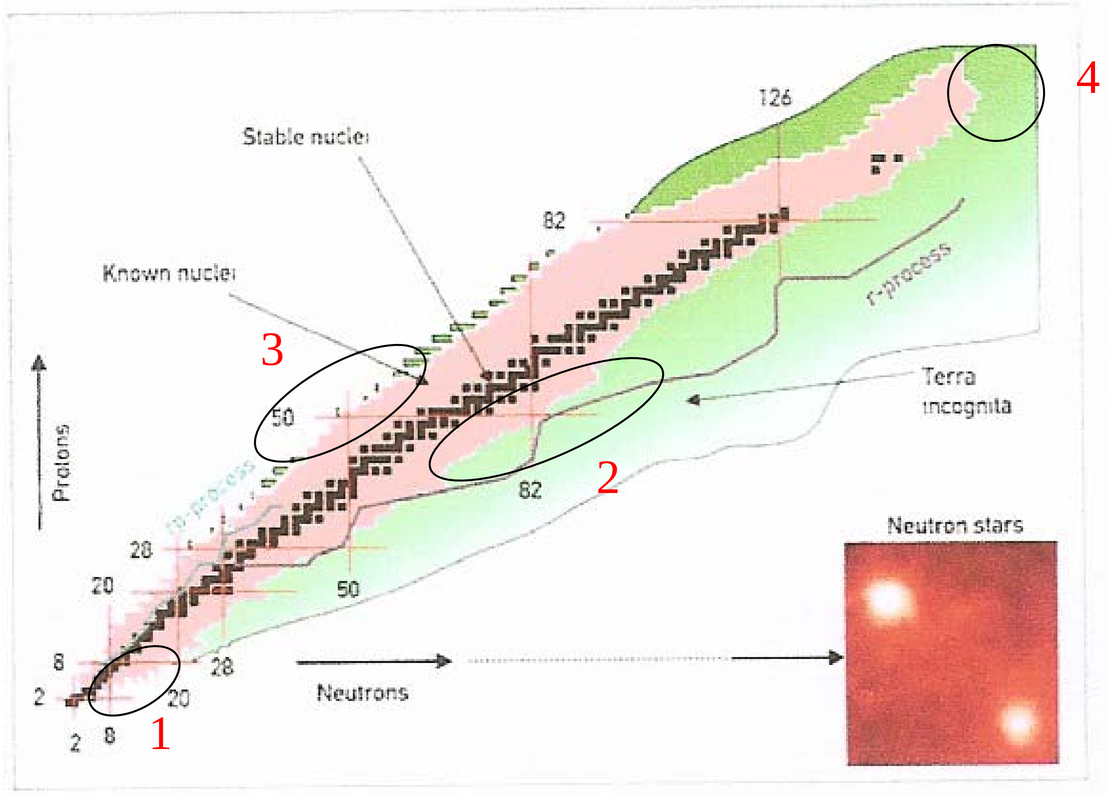
In recent years, with increasing computing capabilities, *ab initio* calculations of nuclear structure have become possible:

Quantum Monte Carlo
Density Functional Theory (DFT)
Large Scale Shell Model
No-core Shell Model
Molecular Dynamics Theory
Lattice Effective Field Theory (EFT)

THE NUCLEAR LANDSCAPE



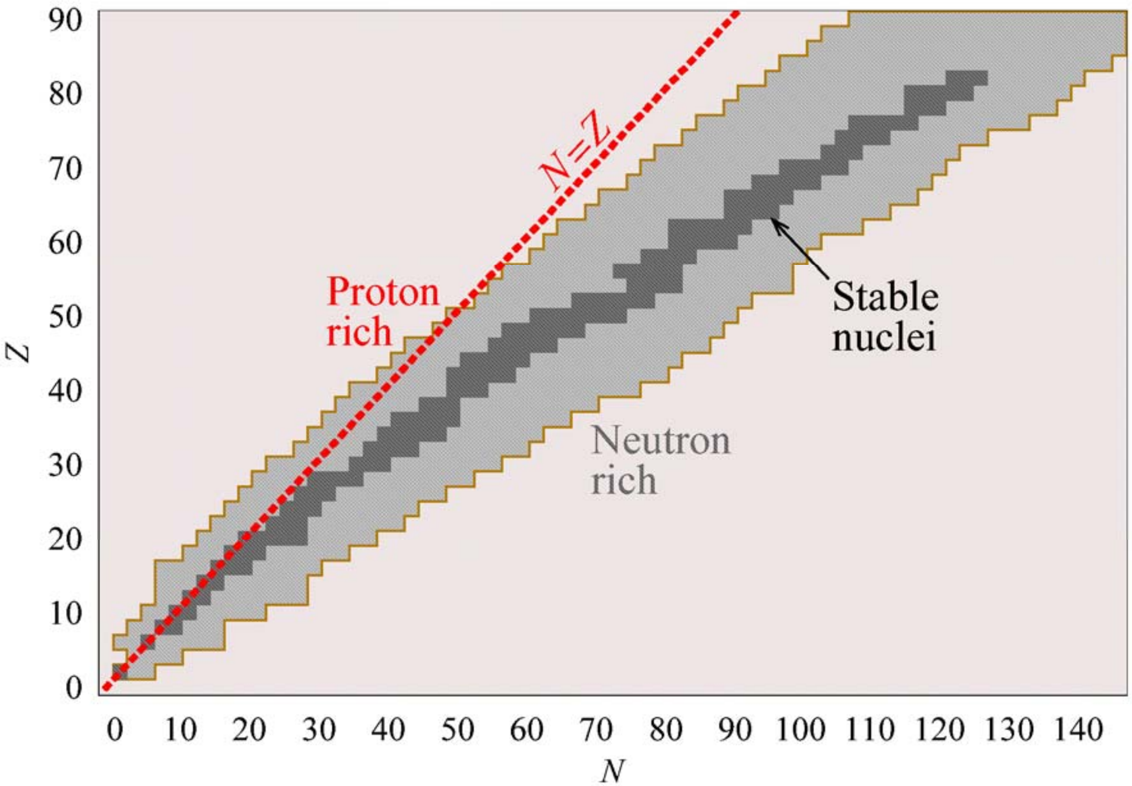
Courtesy of Witek Nazarewicz



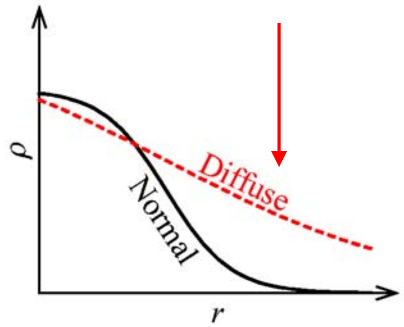
Frontiers

1 Light neutron-rich nuclei
2 Heavy neutron-rich nuclei
3 Heavy proton-rich nuclei
4 Super-heavy nuclei

Different physics questions at different frontiers



Neutron skin



Nomenclature:

Proton-rich (N/Z)~1 Dense systems

Neutron-rich (N/Z)~1.6-2.0 Diffuse systems

In addition to testing *ab initio* calculations, RBF offer some other scientific opportunities:

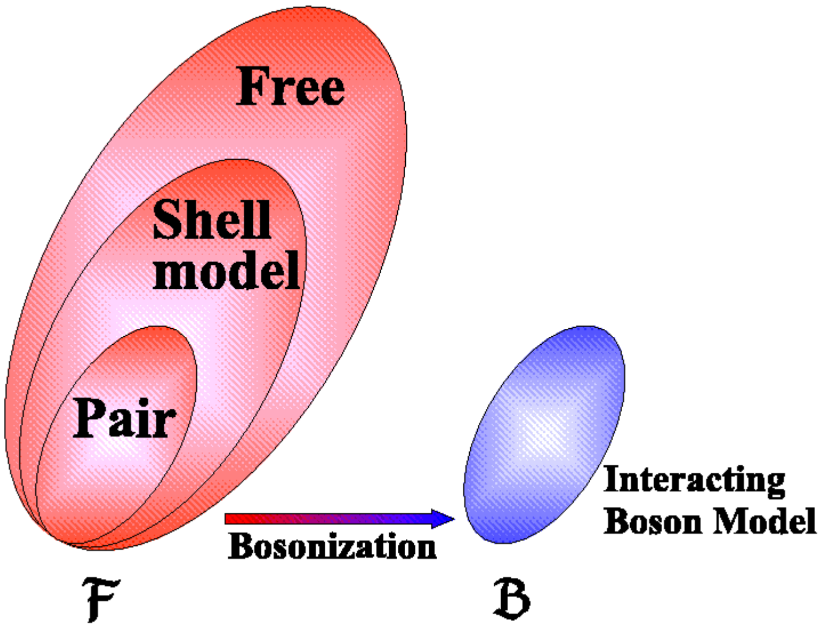
- EFFECTIVE INTERACTIONS IN MEDIA

- DYNAMIC SYMMETRIES AND SUPERSYMMETRIES

- QUANTUM PHASE TRANSITIONS

EFFECTIVE INTERACTIONS IN MEDIA

When going from free space to a medium the interactions are modified (density dependent forces).
When going from an infinite to a finite Hilbert space the interactions are further modified (truncation schemes).



EFFECTIVE INTERACTIONS IN MEDIA

Shell model:
Ab initio from free nucleon-nucleon?
Role of spin-orbit, spin-spin and tensor forces?
⇨ Medium neutron rich nuclei (for example Ni with N>28)

Cluster model:
Alpha-alpha interaction?
Role of neutron-alpha interaction?
⇨ Very-light and light nuclei (for example C with N>6)

Interacting boson model:
Is there p-n T=0 pairing?
⇨ N=Z nuclei (for example Sn with N~50)
Is there n-n (and p-p) quadrupole interaction?
⇨ Heavy neutron rich nuclei (for example Sn with N>82)

Comment: Particularly important is the question of T=0 pairing

A major component of the effective interaction in the nuclear medium is pairing.
In the last 50 years it has been found that n-n and p-p S- and D-wave pairing plays a crucial role in nuclear structure.
p-n T=1 pairing must be present because of the isospin invariance of nuclear forces.
What about p-n T=0 pairing?

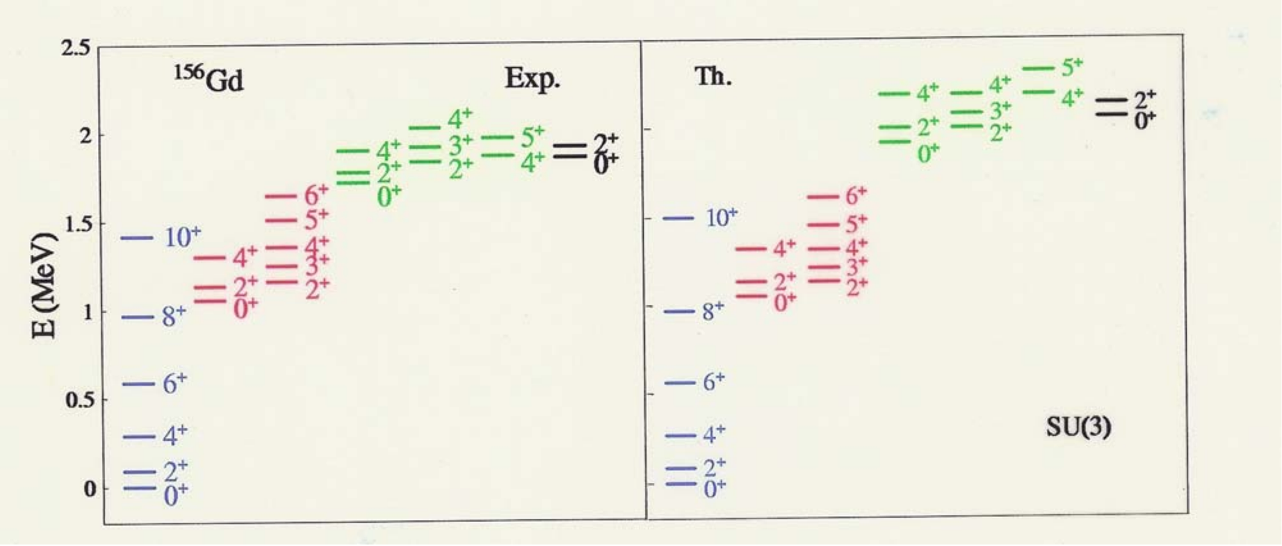
Pairing is a pervasive phenomenon of great importance in all fields of physics: superconductivity (condensed matter), color superconductivity (particle physics), BCS atomic condensates,…

DYNAMIC SYMMETRIES AND SUPERSYMMETRIES

Complex systems often display an astonishing simplicity in their spectral properties (simplicity in complexity).
The manifestation of simplicity is symmetry, in particular symmetry of the interactions, called dynamic symmetry.

Symmetry is a guiding principle in all of physics. Nuclei have provided the best examples so far of dynamic symmetries in nature.

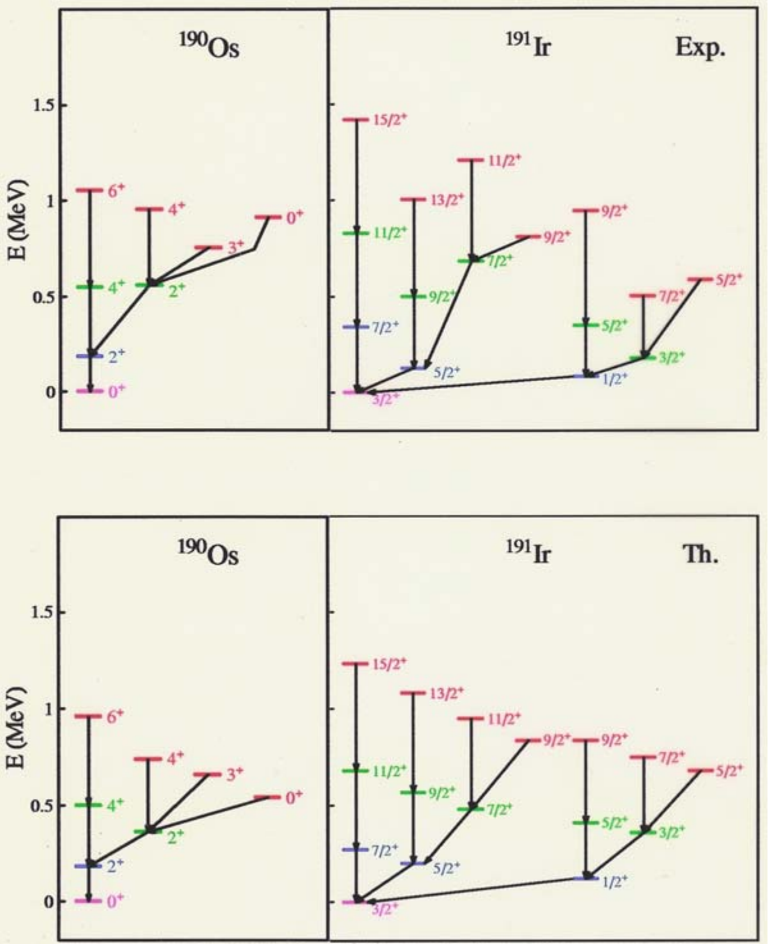
Evidence for IBM-SU(3) symmetry in nuclei: ^{156}Gd



Dynamic symmetries apply to purely fermionic or purely bosonic systems. In 1974 a new concept was introduced in physics called supersymmetry that applies to mixed systems of bosons and fermions.

Nuclei have provided so far the only example of supersymmetry experimentally observed. (The bosons are the collective excitations and the fermions are the single-particles.)

Evidence for U(6/4) supersymmetry in nuclei: ^{190}Os-^{191}Ir



SYMMETRIES AND SUPERSYMMETRIES

Shell model:

Restoration of harmonic oscillator SU(3) symmetry in diffuse systems?

Elliott SU(3) is broken in normal nuclei by the spin-orbit interaction and lack of degeneracy of the single particle orbitals. In diffuse systems, the spin-orbit interaction, proportional to the derivative of the density, vanishes.

⇨ Medium-heavy and heavy neutron rich nuclei (for example Sn with N>82)

Restoration of spin-isospin SU(4) symmetry in dense systems?

Wigner SU(4) is broken in light nuclei for the same reasons. In heavy nuclei, a pseudo-SU(4) symmetry may appear.

⇨ N=Z proton rich nuclei (for example odd-odd Rb)

Comment: Particularly important is the restoration of Elliott SU(3) symmetry

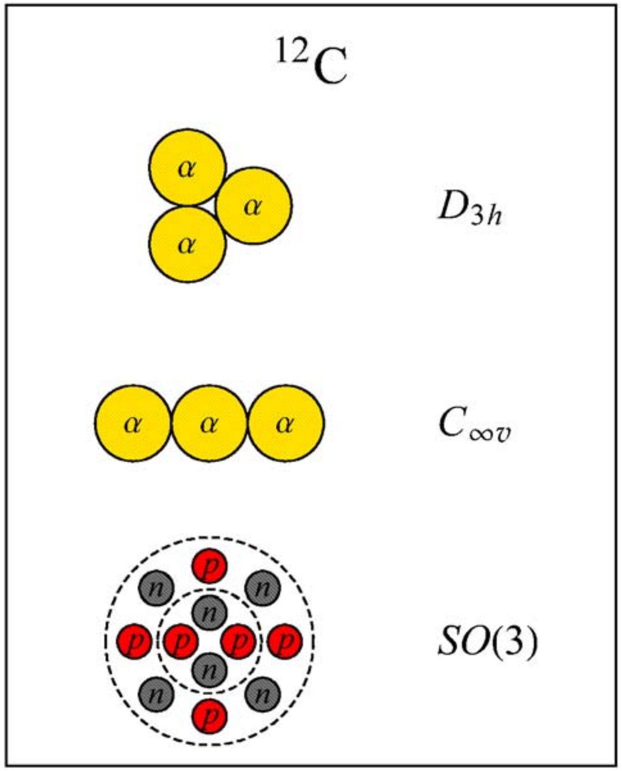
SU(3) is the degeneracy symmetry of the three-dimensional harmonic oscillator. Its restoration will imply a change in the shell-structure.

Similar phenomena are encountered in quantum dots.

Cluster model:

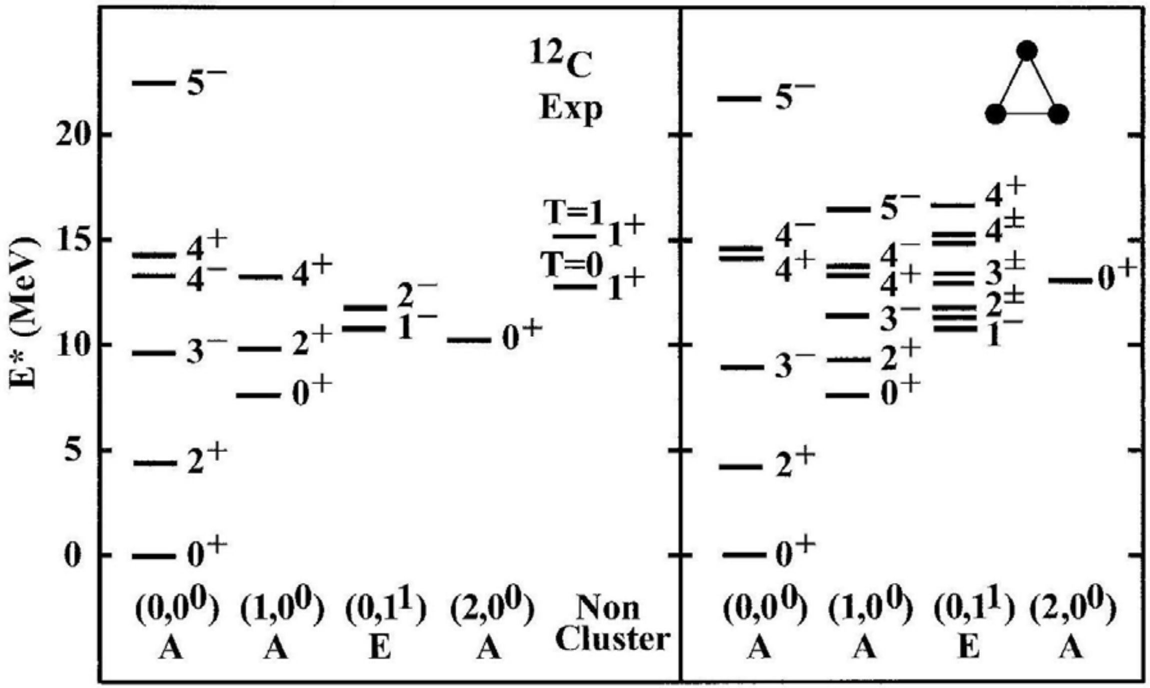
Role of discrete symmetries (D_{3h},T_d….) in dense systems?
Motion of neutrons in a mean field with discrete symmetry in diffuse systems?

⇨ Light nuclei (for example C and O)

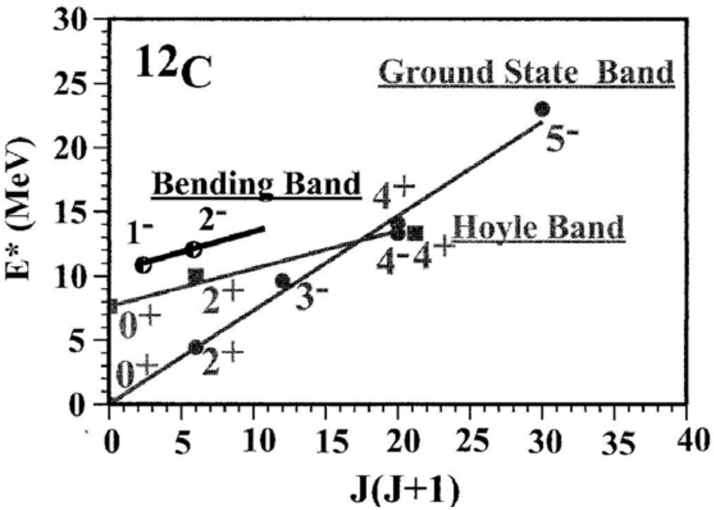


Comment: This question is important for nuclear astrophysics

Evidence of D_3 symmetry in ^{12}C

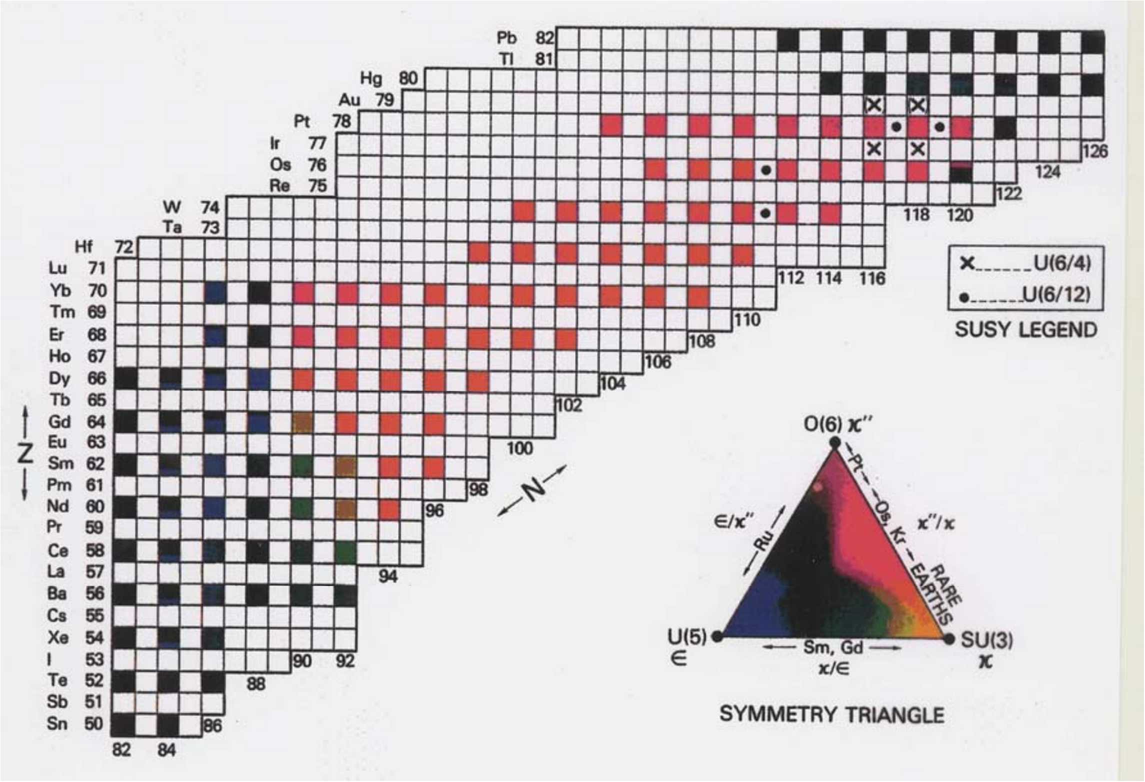


Observed cluster rotational bands



Interacting Boson Model:
New symmetries in addition to U(5), SU(3) and SO(6)?
New supersymmetries in addition to U(6/4) and U(6/12)?
⇨ Medium-heavy and heavy neutron rich nuclei (for example the region of heavy Sm-Gd)

Symmetry classification of nuclei



Comment: Particularly important are supersymmetries

The occurrence of supersymmetries requires that bosons and fermions and their interactions are related by a supersymmetry transformation. This condition is not met everywhere. The large pool of new nuclei provided by RBF will allow access to regions where supersymmetry is most likely.

Supersymmetry is of interest to many areas of physics. In particular in particle physics (fundamental supersymmetry), in gravitation (supergravity) and, very recently, in high-T_c superconductors. Supergravity and supersymmetric superconductors have a mathematical structure similar to that of nuclear supersymmetry.

QUANTUM PHASE TRANSITIONS

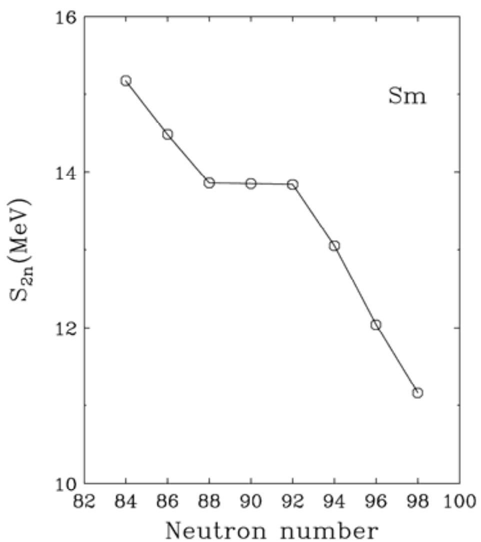
Quantum phase transitions were introduced in nuclear physics in the 1970's and called 'ground state phase transitions'. They are also encountered in condensed matter physics where they are named 'quantum phase transitions'.

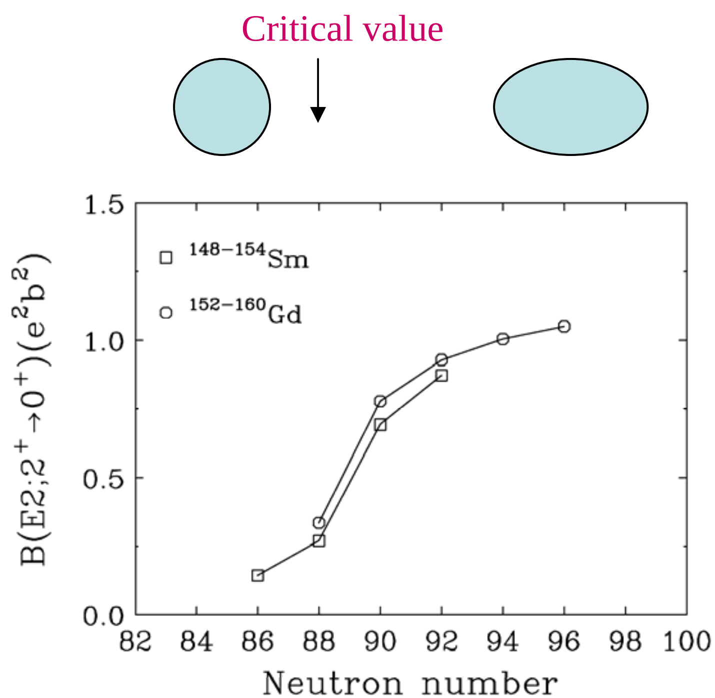
A QPT is a phase transition in which the control parameter is not the temperature T as in thermodynamic phase transitions, but rather the coupling constant, g, appearing in the quantum Hamiltonian

$$H = (1-g)H_1 + gH_2$$

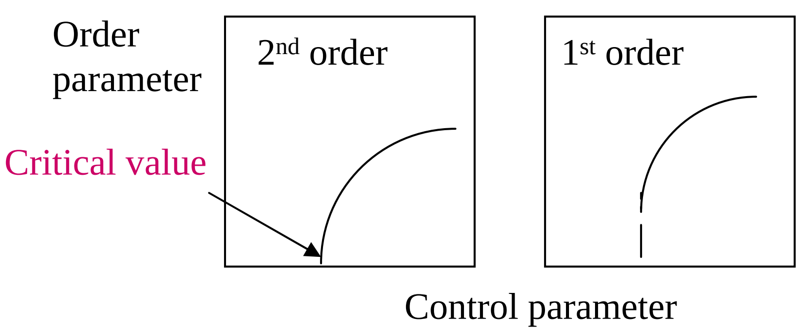
Nuclei have provided some of the best examples of QPT in physics. The phase transitions here are between different shapes (spherical, axially deformed, …)

Evidence for QPT:





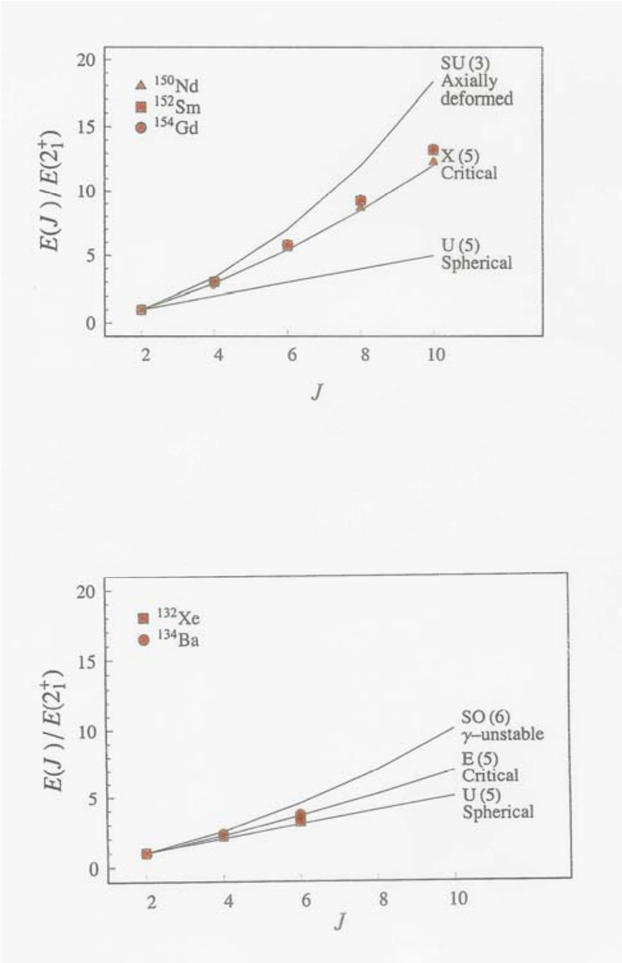
Other phase transitions?



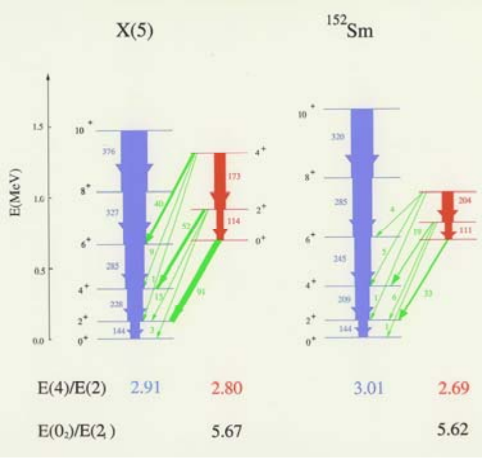
Nuclei are ideal systems to study quantum phase transitions: They are finite systems in which the number of particles can be tuned, thus allowing a study of scaling behavior.
They display both first and second order transitions (Erhenfest classification).
(They are almost unique. While second order transitions are pervasive, first order transitions are rare.)

In addition, recently (2000), signatures of critical behavior have been suggested, called “critical symmetries”.

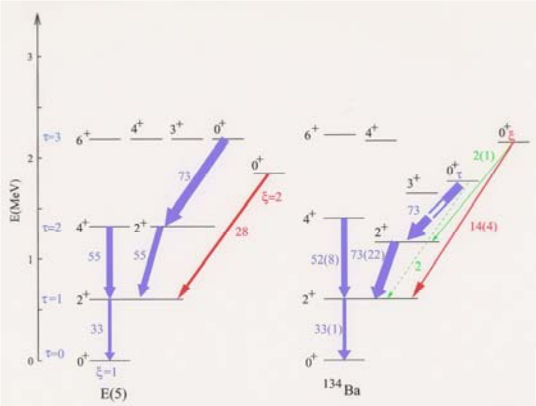
Several examples of critical symmetry have been found



X(5)



E(5)



⇨ Other examples?

These signatures are important for understanding the approach to criticality.
(Conformal invariance in quantum field theory.)

Even more recent (2005) is the suggestion of signatures of critical behavior in Bose-Fermi systems, called “critical supersymmetries”.

QUANTUM PHASE TRANSITIONS

New shape phase transitional regions?

⇨ Medium-heavy and heavy nuclei

Approach to criticality and role of "critical symmetries" E(5), …

Approach to criticality in Bose-Fermi systems and role of "critical supersymmetries" E(5/4),…

⇨ Scaling behavior (finite N effects)

Medium-heavy and heavy nuclei both even-even and odd-even

SUMMARY OF SYMMETRIES AND PHASE TRANSITIONS IN NUCLEI

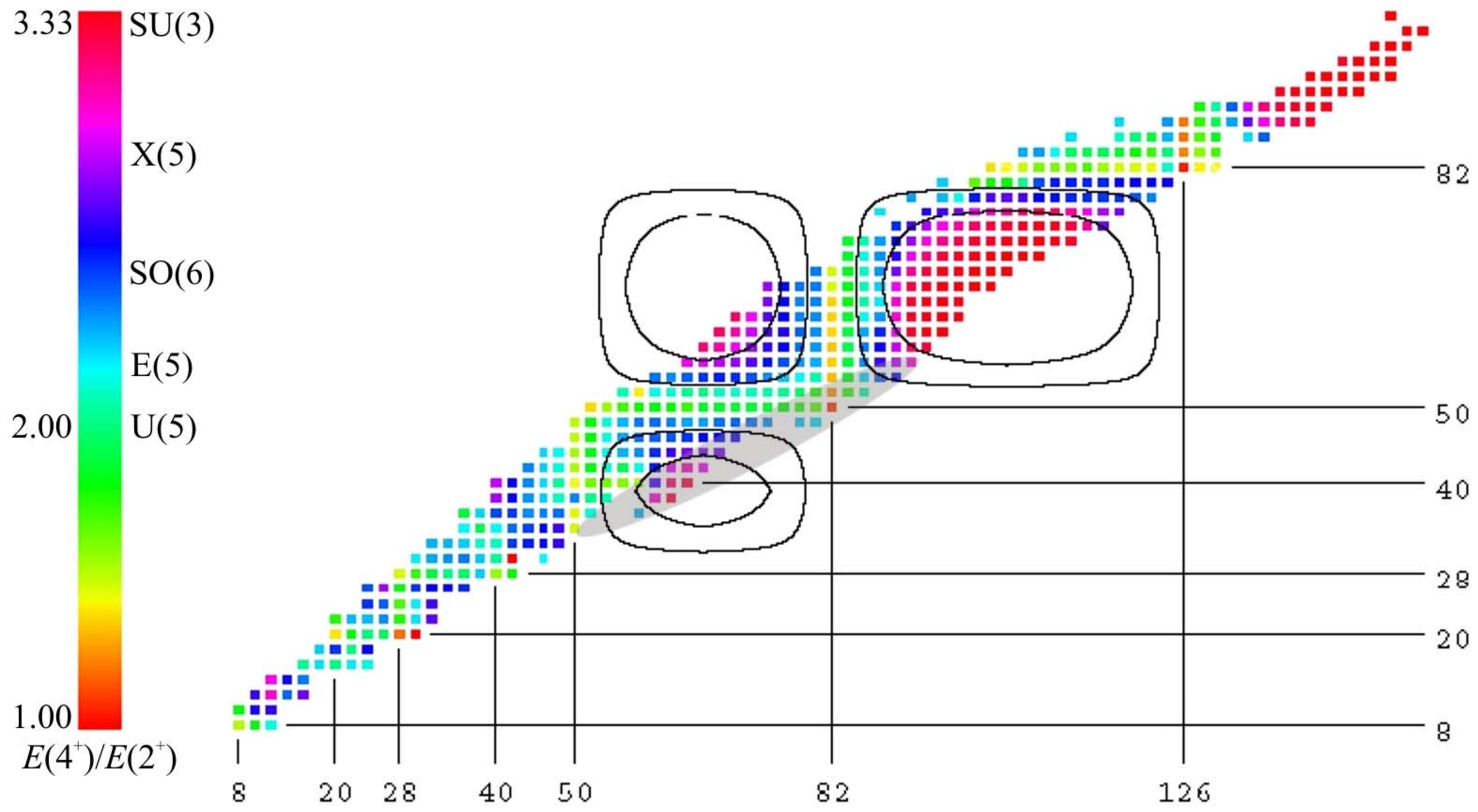


Figure courtesy of P. van Isacker

CONCLUSION

SPES: May provide the testing ground for some of the most important concepts in physics:

- FROM LARGE TO SMALL HILBERT SPACES (EFFECTIVE INTERACTION)
- SYMMETRIES AND SUPERSYMMETRIES
- QUANTUM PHASE TRANSITIONS