Radioactive Ion beams:

Key to nuclear structure

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Outline

1.Introduction

2.Themes and Challenges:

-How are complex systems built from a few, simple ingredients?

-Shell Structure

-Pairing

-Collective modes

3.What leads to simple excitations and regularities in complex systems?

-Dynamical Symmetries

-Critical Point Symmetries

4.The Limits of nuclear existence?

-Drip-lines

-Superheavy elements?

5.Creating the beams we need-ISOL and Fragmentation.

6.Harbingers of things to come.

7.Conclusions.

Common Themes and Challenges (1)

- ***How are complex systems built from a few,simple ingredients?***

  -Our Universe seems quite complex yet it is constructed from a small number of objects.

  -These objects obey simple physical laws and interact via a handful of forces

- ***The study of nuclear structure plays a central role here.***

  -A two-fluid(neutrons and protons),finite N system interacting via strong, short-range forces.[Closely related to other systems]

- ***The Goal***

  - A comprehensive understanding of nuclear structure over all the relevant parameters [Temp.,Ang.momentum,N/Z ratio etc]

- ***The Opportunity***

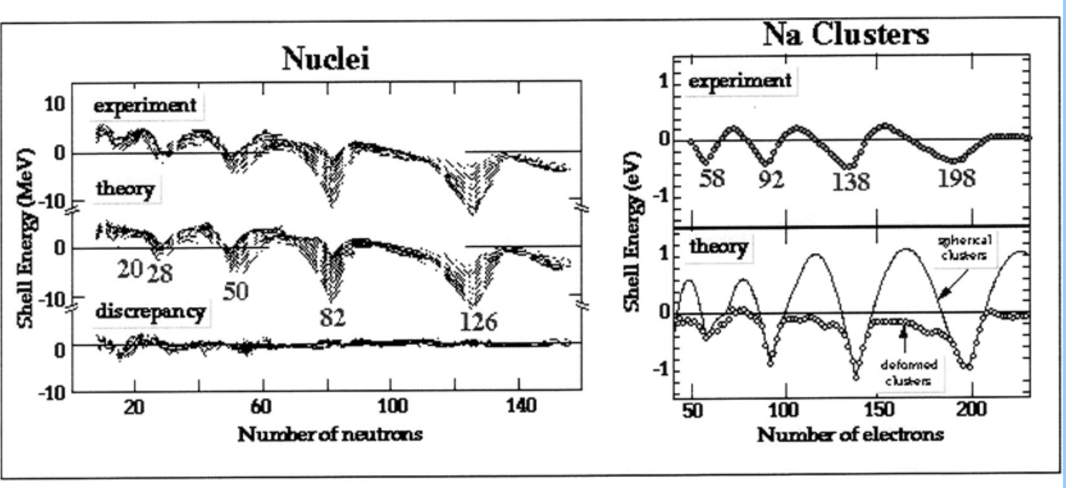
  - If we can generate high quality beams of radioactive ions we will have the ability to focus on specific nuclei from the whole of the Nuclear Chart in order to isolate specific aspects of the system

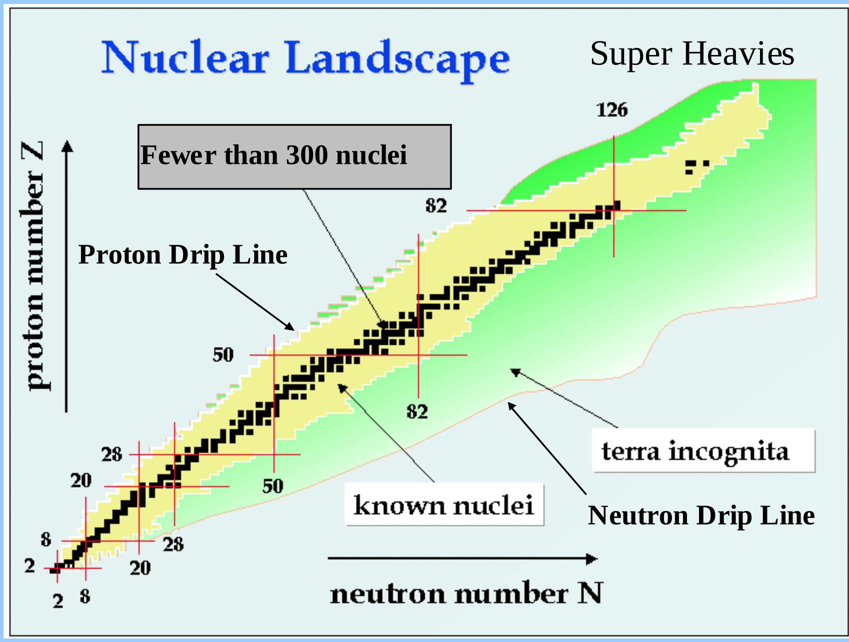
Common Themes and Challenges (2)

How are complex systems built from a few,simple ingredients?
-Specific Challenges:

A) ***Shell structure***;Key feature of all mesoscopic (finite N) systems is the occurrence of Shell structure.Loosely we can define it as the bunching of quantum levels into groups separated by gaps.

B) Originally seen in atoms and in nuclei.Now seen in metallic clusters and quantum dots as well.





C).***How is the Shell structure modified with large neutron excess?***

Quantum Nanostructures and Nuclei

- Nuclei are femtostructures - they share much in common with the quantum nanostructures which are under intense research.

- Nuclei have much in common with metallic clusters,quantum dots and grains, atom condensates, droplets and surface structures etc.

- These quantum systems share common phenomena although they are on different energy scales-nuclear MeV,molecular eV,solid state meV

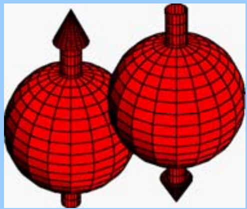
- Among the common topics we find Shell structures and the existence of collective modes of motion.

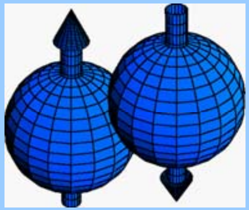
- The study of nuclei has advantages in this context. We know the no. of particles;we can simulate strong magnetic and electric fields by rotation;the temperature is zero.We have a solid technical base for the studies.

Comparison with another mesoscopic system

Atomic nuclei	Quantum dots
Two components	One component
Fixed number of particles	Variable number of particles
No thermal noise	Thermal noise
Difficult to manipulate	Easy to manipulate
Lots of observables	Few observables
3-Dimensional	1- or 2-Dimensional

Specific Challenges-Pairing





- An attractive Pairing Interaction is important in several many-body systems- s-wave pairing was discovered initially in superconductors [Cooper pairing of electrons]

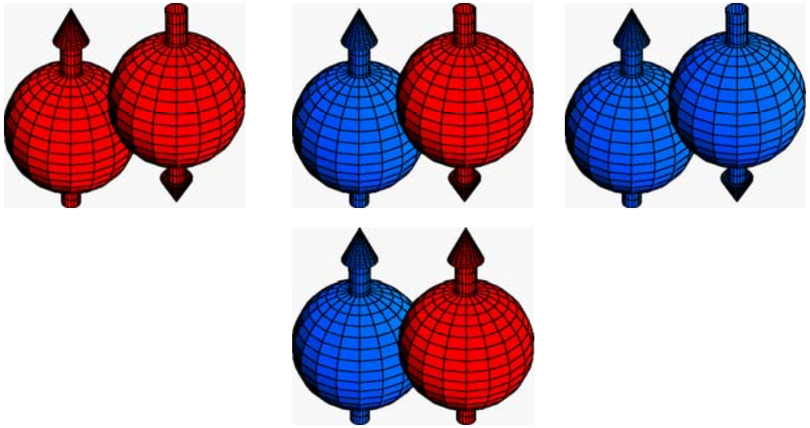
- This is an important part of the proton-proton and neutron - neutron interaction in stable nuclei. It even determines whether nuclei exist or not[e.g.^{4,6,8}He are bound and ^{5,7}He are not].It also exists in the matter in neutron stars and in the QGP[colour superconductivity].

- Later the idea was expanded to anisotropic pairing-p-wave in liquid ^{3}He and s- and d-wave in nuclei.

- Recently it has been in the news in terms of high-T_C superconductors (s- and d-wave pairing) and fermionic condensates.

Pairing with neutrons and protons

- For neutrons and protons *two* pairs and hence *two* pairing interactions are possible:
  - Isoscalar ($S=1,T=0$): $-g_{10}S_{+}^{10}\cdot S_{-}^{10}$
  - Isovector ($S=0,T=1$): $-g_{01}S_{+}^{01}\cdot S_{-}^{01}$



- Isoscalar condensate survives in N ≈ Z nuclei,if at all.

- RNB will allow the study of pairing in low-density environments

Superfluidity of $N=Z$ nuclei

- $T=0$ & $T=1$ pairing has *quartet* superfluid character with SO(8) symmetry. Pairing ground state of an $N=Z$ nucleus:

$$\left(\cos\theta\, S_{+}^{10}\cdot S_{+}^{10} - \sin\theta\, S_{+}^{01}\cdot S_{+}^{01}\right)^{n/4}|o\rangle$$

- $\Rightarrow$ Condensate of α's (θ depends on g_{01}/g_{10}).
- Observations:
  - Isoscalar component in condensate survives only in $N{\sim}Z$ nuclei, if anywhere at all.
  - Spin-orbit term *reduces* isoscalar component.

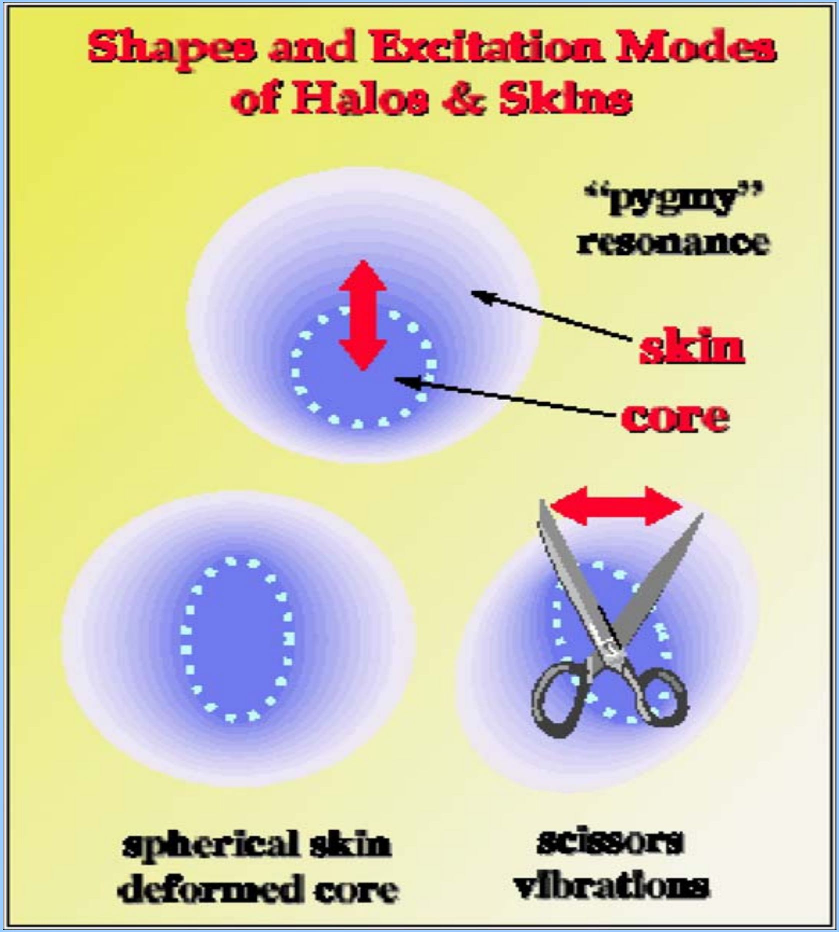
Collective Modes

- Atomic nuclei display a variety of collective modes in which an assembly of neutrons moves coherently [e.g Low-lying vibrations and rotations.

- **Challenge**:Will new types of collective mode be observed in neutron-rich nuclei in particular?

- Will the nucleus become a three-fluid system-made up of a proton and neutron core plus a skin of neutrons?

We will then get collective modes in which the skin moves relative to the core.



Common Themes and Challenges

Simple excitations and regularities in complex systems?

- Complex,many-body systems display surprising regularities and simple excitation patterns. Challenge is to understand how a nucleus containing hundreds of strongly interacting particles can display such regularities.

- Regularities are associated with symmetries, in particular symmetries of interactions, called Dynamical symmetries,based on group theory.

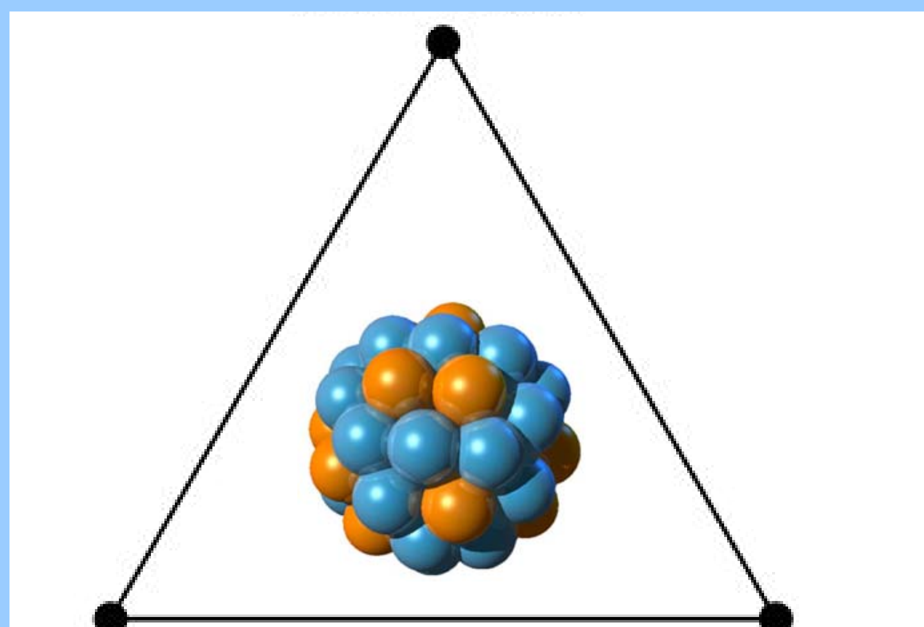
- A variety of Dynamical Symmetries have been observed in nuclei, based on the Interacting Boson Model(correlated pairs of fermions ≡ Cooper pairs in an electron gas)
- Challenge: Will these symmetries persist in nuclei far away from stability and will new symmetries appear?

Dynamical symmetries

- Within the framework of the Interacting Boson Model-a model in which nuclei consist of pairs of protons and neutrons.We can have s- and d-pairs with L = 0 and 2.We have found empirically examples of spherical, ellipsoidally deformed and asymmetric nuclei.

- This is a one-fluid system.

Gamma-soft-O(6)



Vibrator-SU(5)

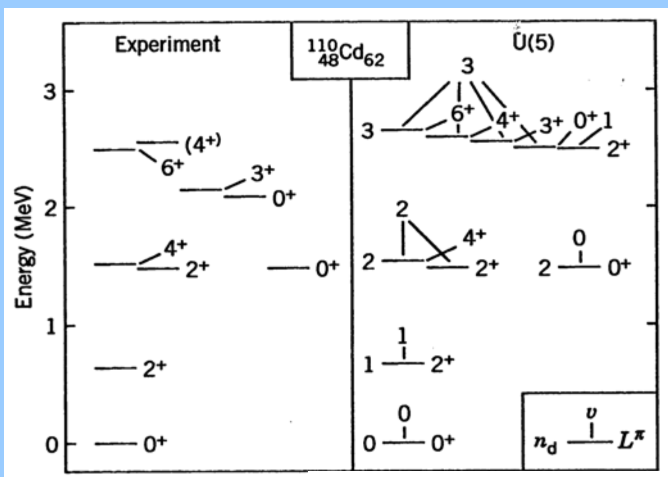
Rotor-SU(3)

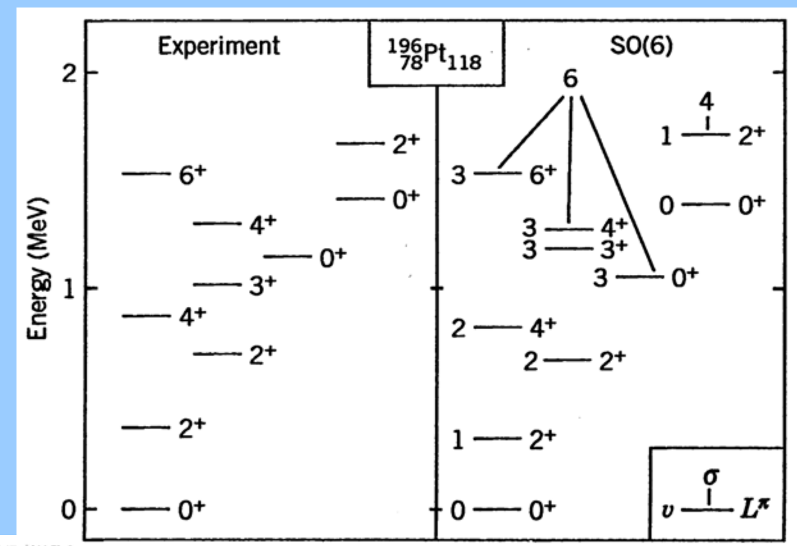
- The dynamical symmetries are shown at the vertices of the triangle.Almost all even-even nuclei can be placed in or on the triangle.

- Will we see dynamical symmetries of a 2-fluid for large n-excess?

The IBM symmetries

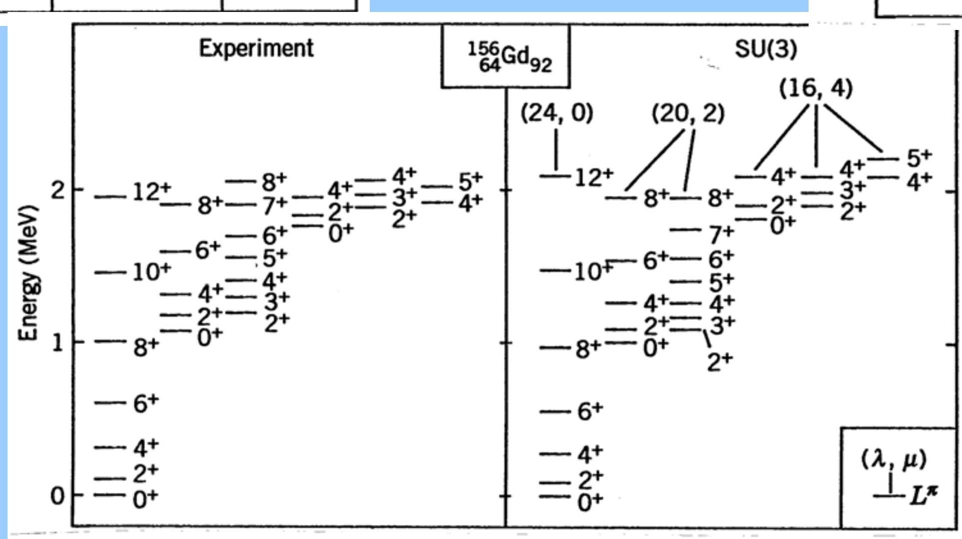
- Three analytic solutions: U(5), SU(3) & SO(6).





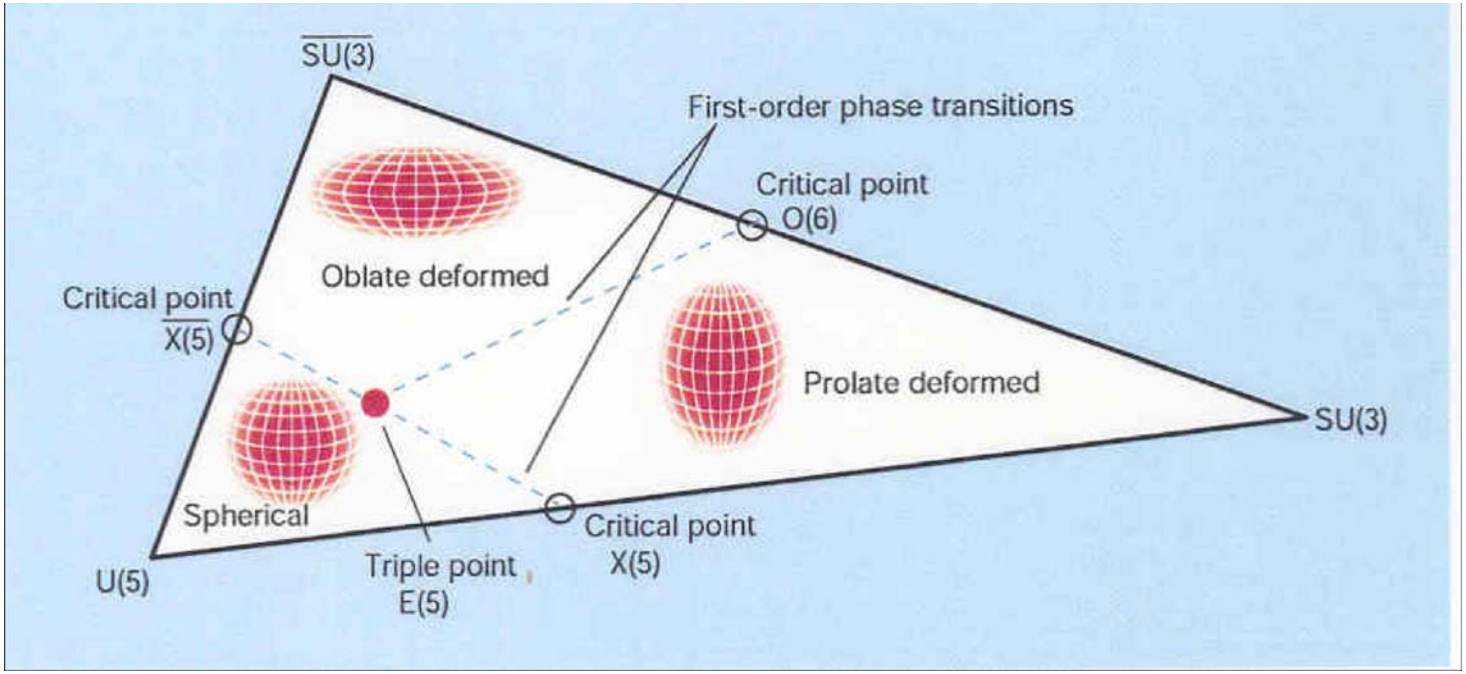
U(5)

O(6)



SU(3)

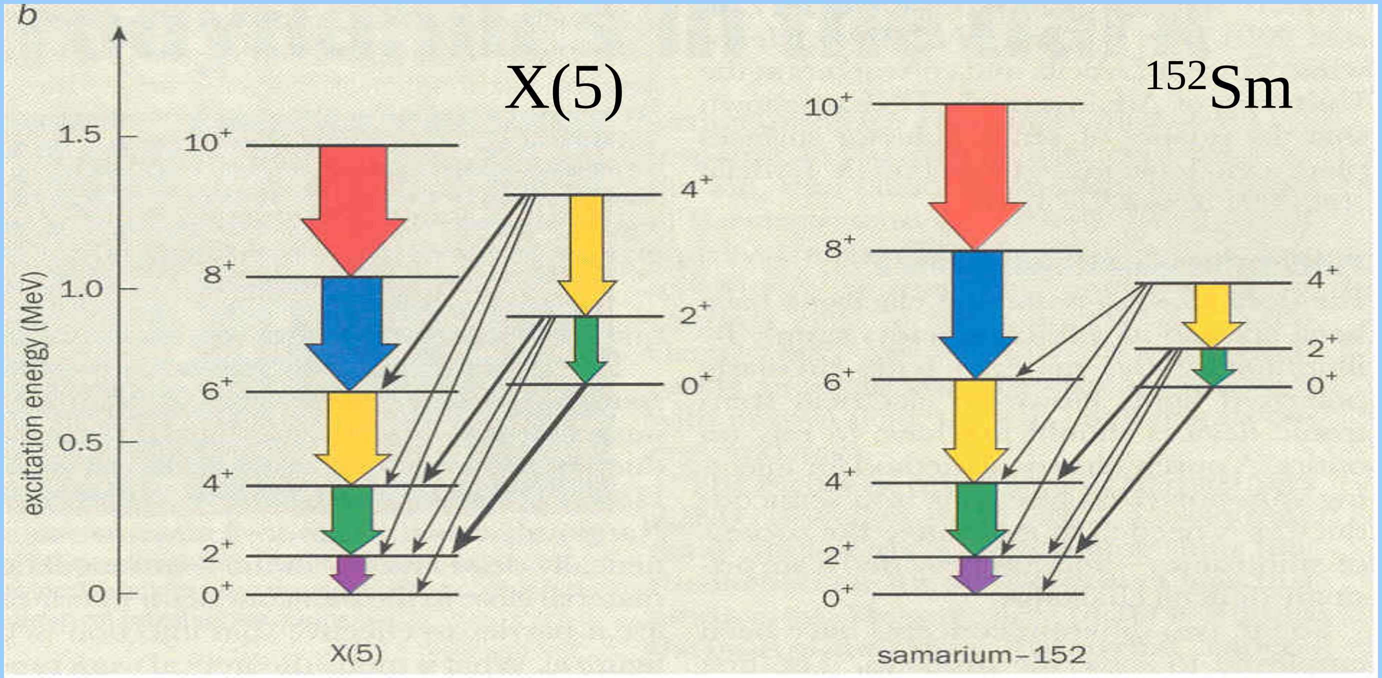
IBM symmetries and phases



- Open problems:
  - Symmetries and phases of two fluids (IBM-2).
  - Coexisting phases?
  - Existence of three-fluid systems?

D.D. Warner, Nature **420** (2002) 614

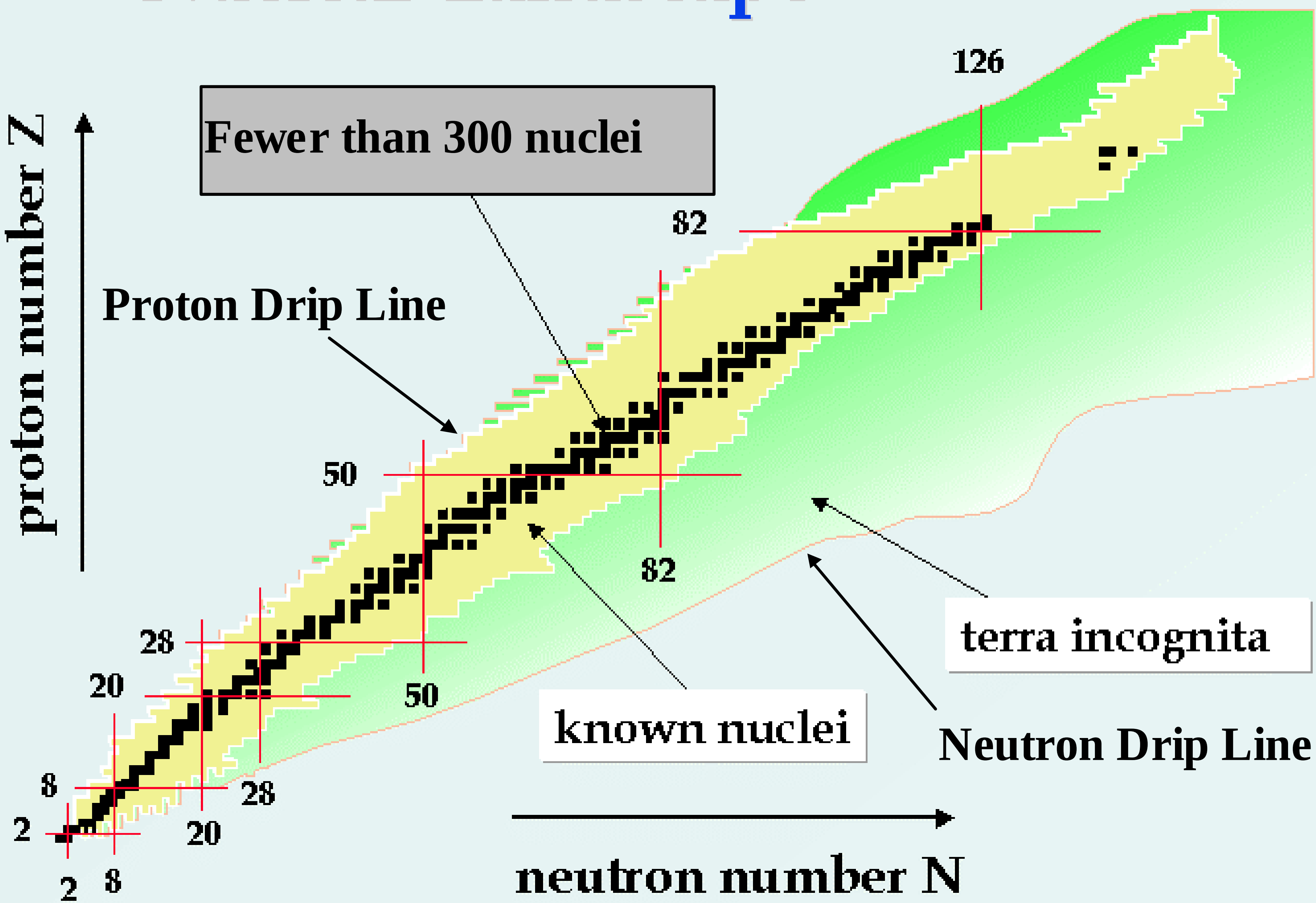
Critical Point Symmetries - an example

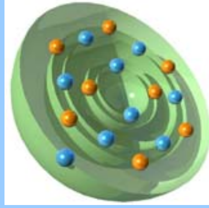


- An example of the critical point symmetries predicted by Iachello. The experimental and theoretical E(4)/E(2) ratios both equal 2.91 and the E(0)/E(2) ratios are 5.65.The measured transition probabilities also agree.This picture can be developed from Landau's theory of phase transitions[L.Landau,Phys.Sowjet 11(1937)26]

F.Iachello,PRL85(2000)3580;ibid 87(2001)052502

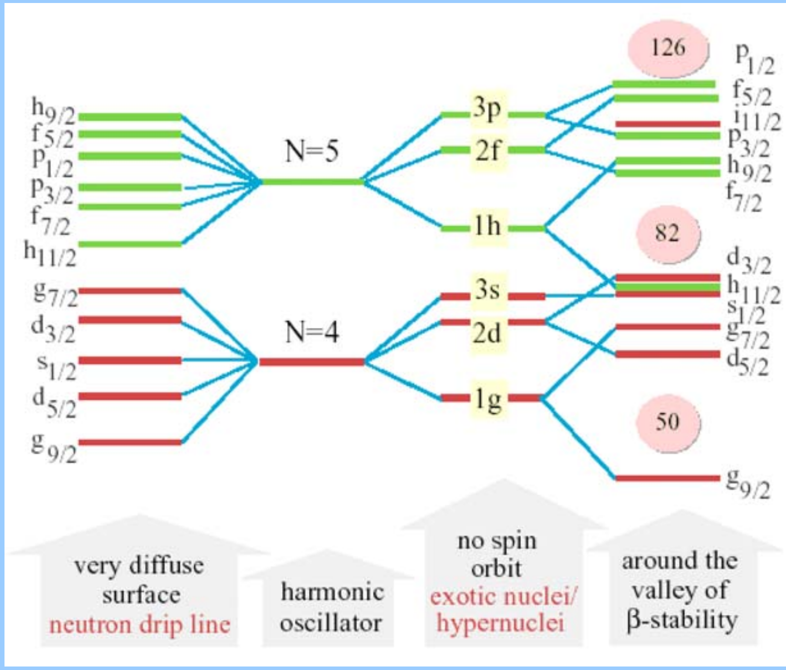
Nuclear Landscape

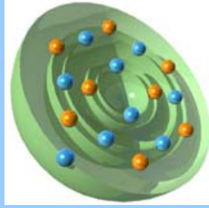




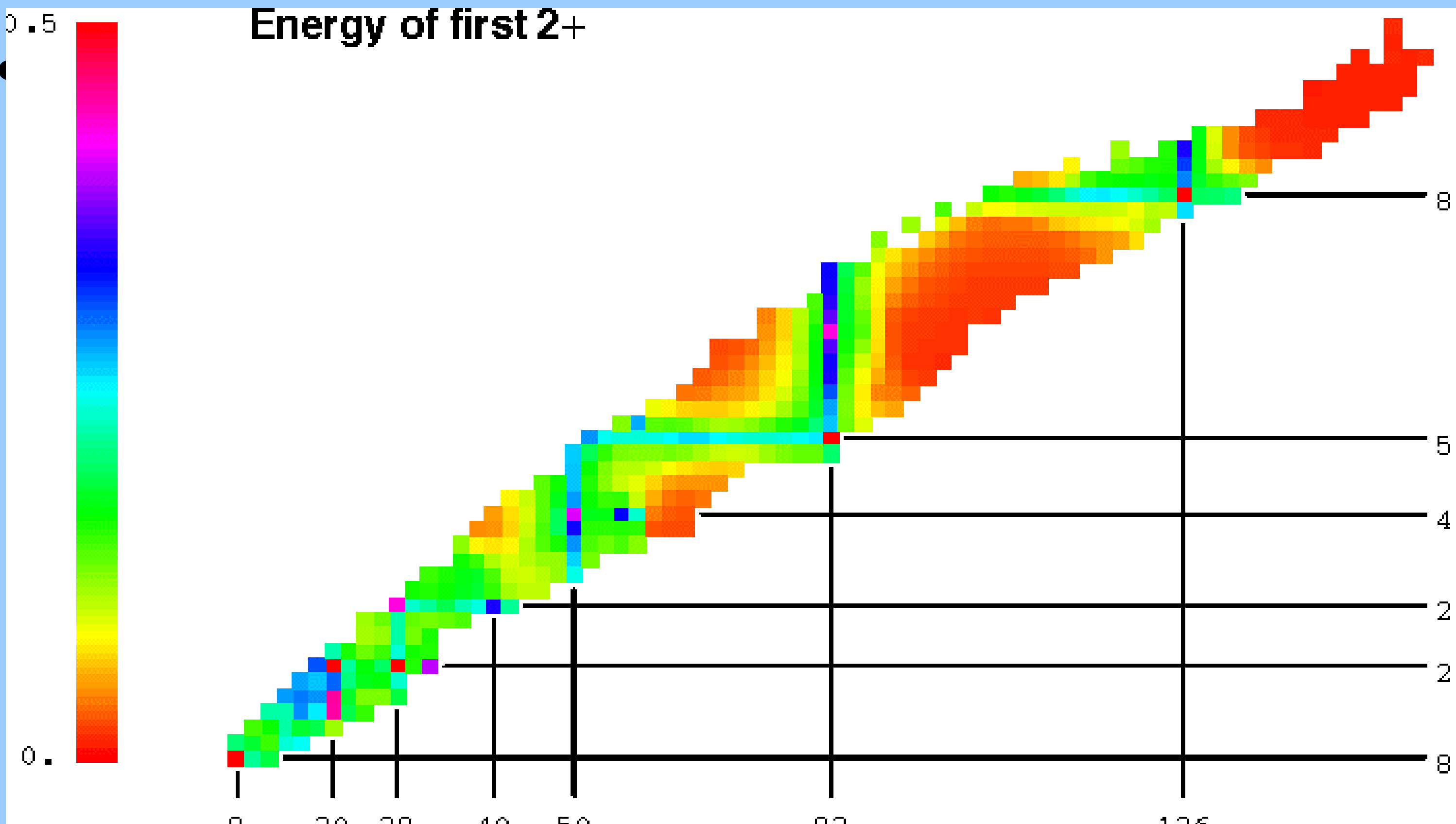
Evidence for shell structure

- Evidence for nuclear shell structure from
  - – 2^+ in even-even nuclei [E_x, $B(E2)$].
  - – Nucleon-separation energies & nuclear masses.
  - – Nuclear level densities.
  - – Reaction cross sections.
- *Is nuclear shell structure modified away from the line of stability?*

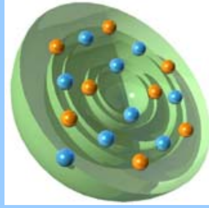


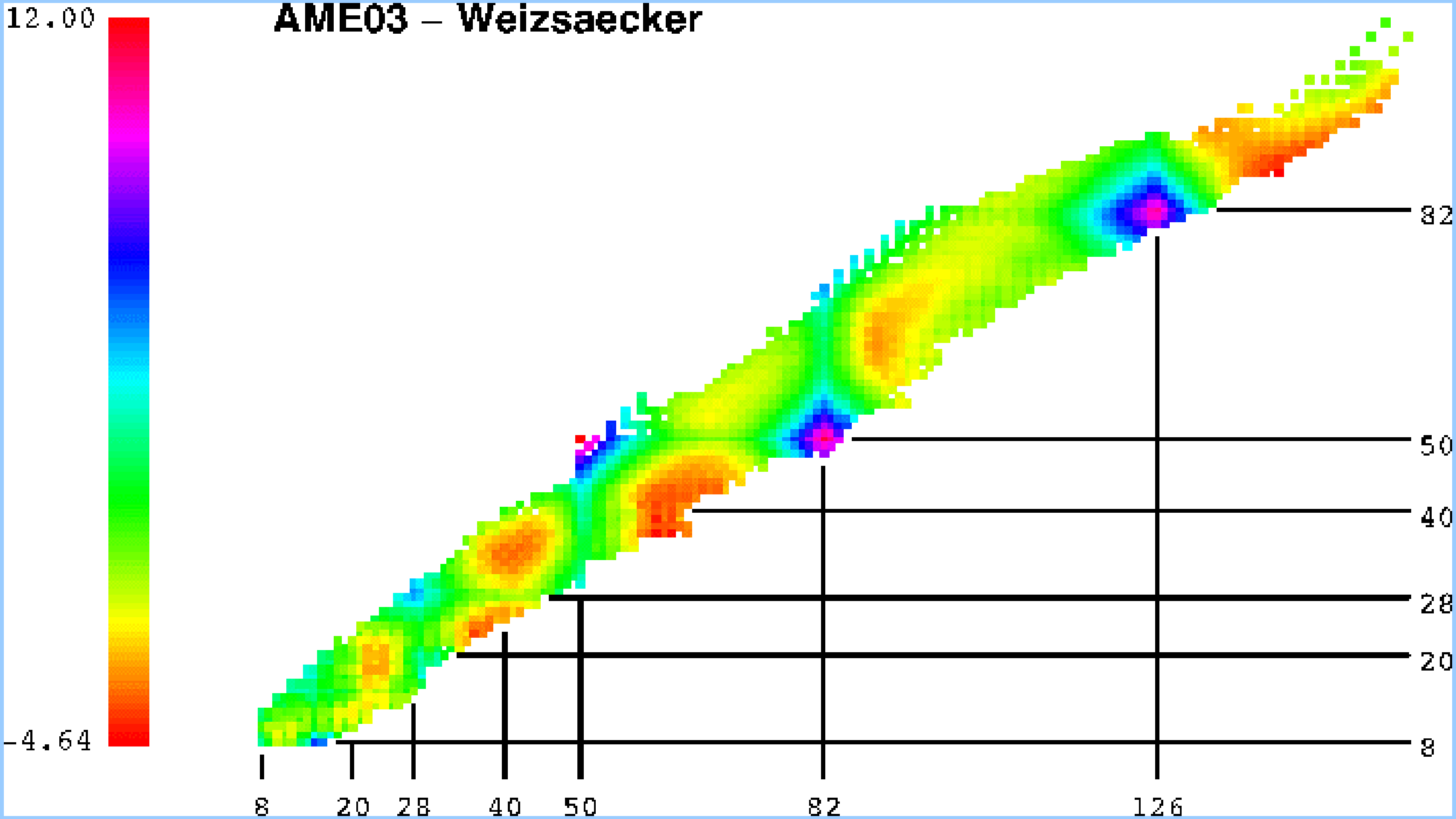


Shell structure from $E_x(2_1)$

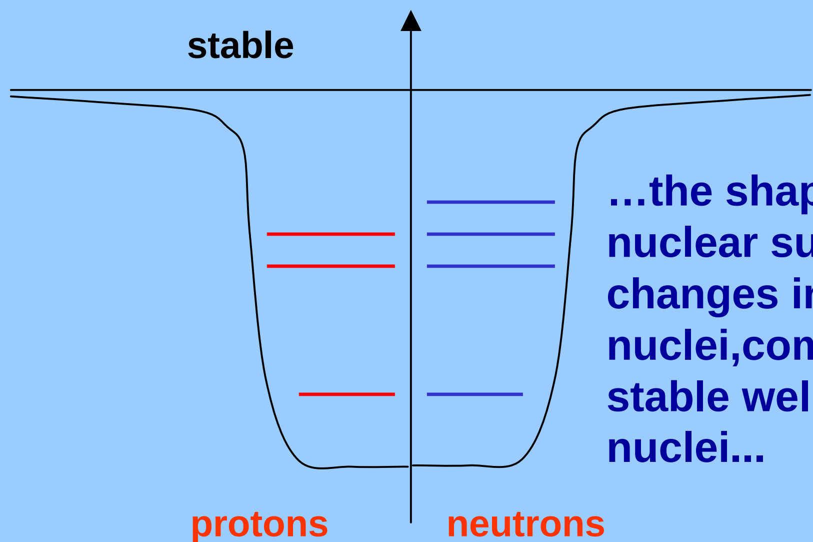


Shell structure from masses

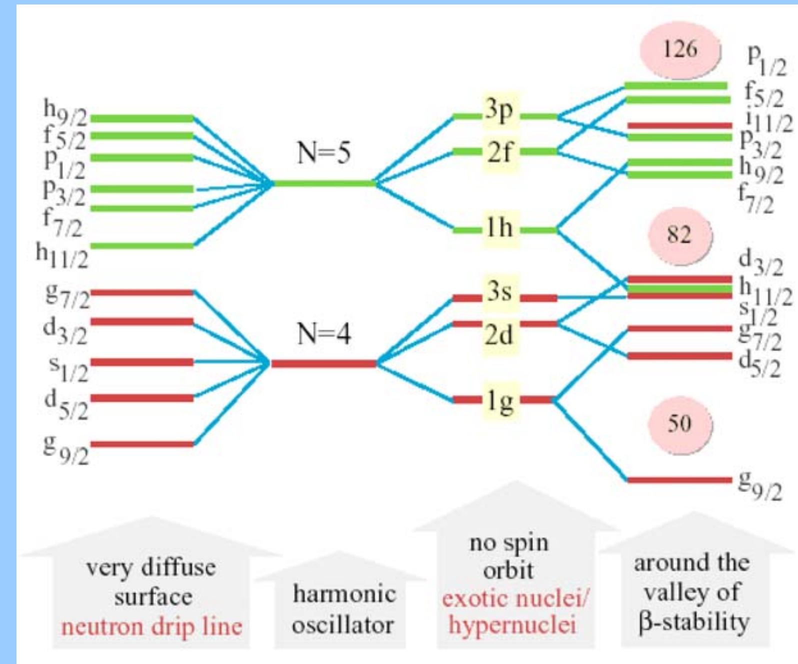




Shell Structure far from Stability

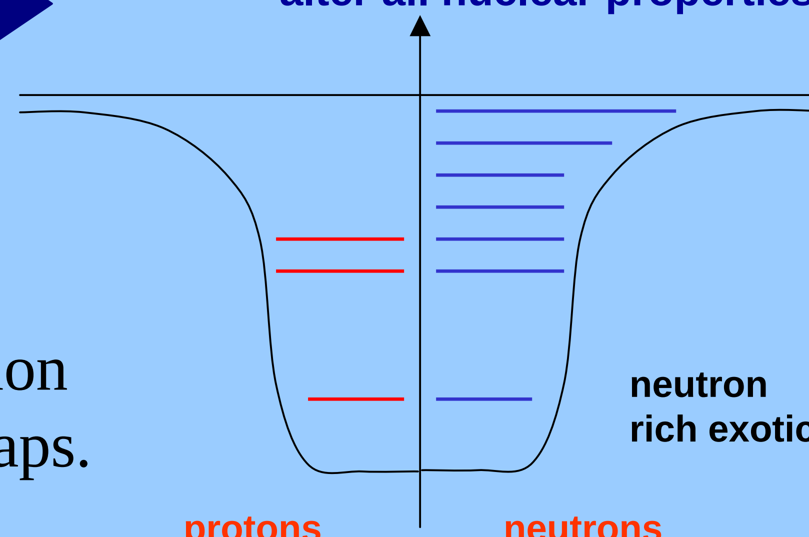


…the shape of the nuclear surface changes in exotic nuclei,compared to stable well-known nuclei...



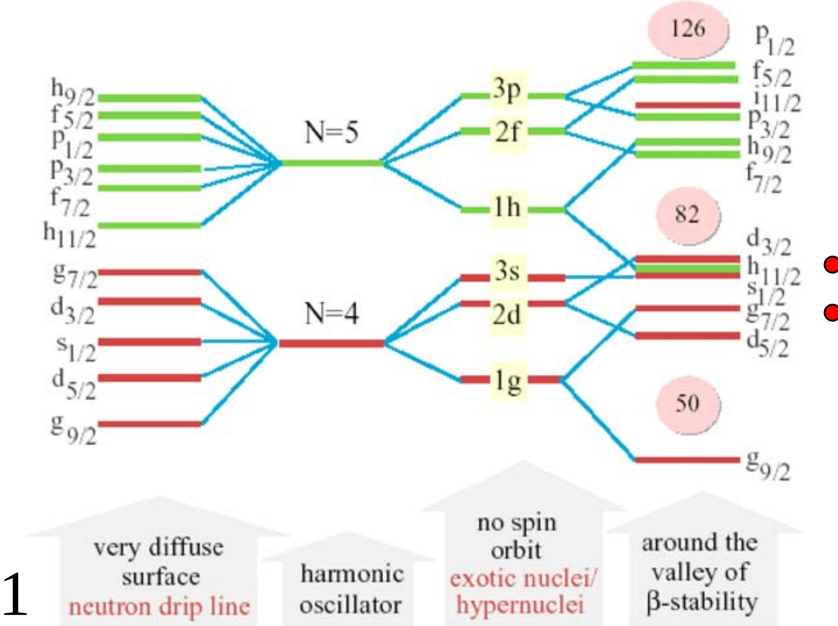
…this changes the quantum levels and hence can radically alter all nuclear properties

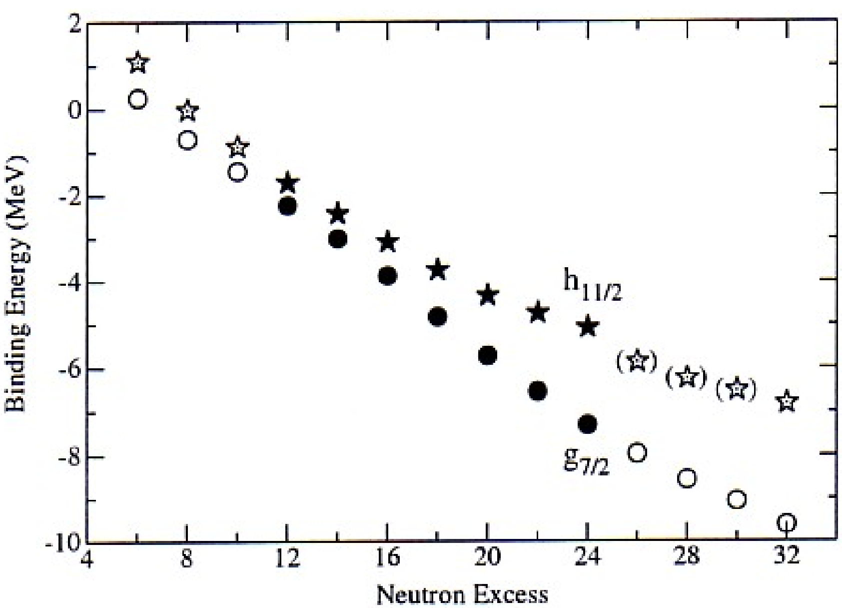
The "Magic Numbers" in heavy nuclei are due to the l.s interaction which pushes down the higher ang. mom. State. In the n-rich nuclei the lower surface density means that we anticipate a weakening of this interaction and, hence, a weakening of the shell gaps.



Shell Structure far from Stability

- Do we have any evidence for the weakening of shell structure with neutron excess?
- The Sn(Z = 50) nuclei have a long range of stable isotopes. The (α,t) reaction has been studied by J.P.Schiffer et al,PRL92(2004)162501



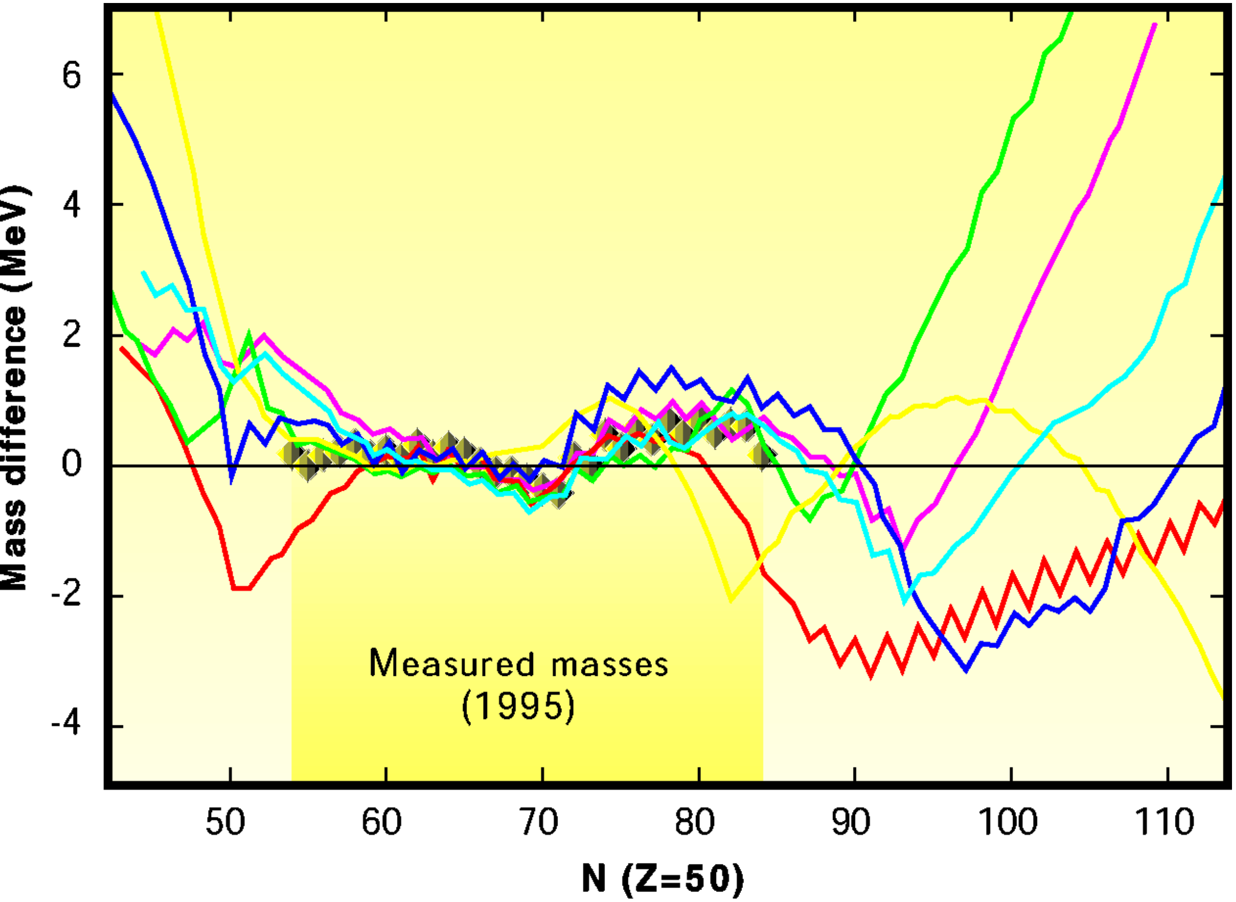


- They measured the positions and purity of the single proton states outside the ^{132}Sn doubly-closed shell.
- They observe a widening gap and hence a reduction in the shell gap.
- Challenge:Can we determine and understand the s.p. structure in n-rich nuclei?

The Drip-lines-Where are they?

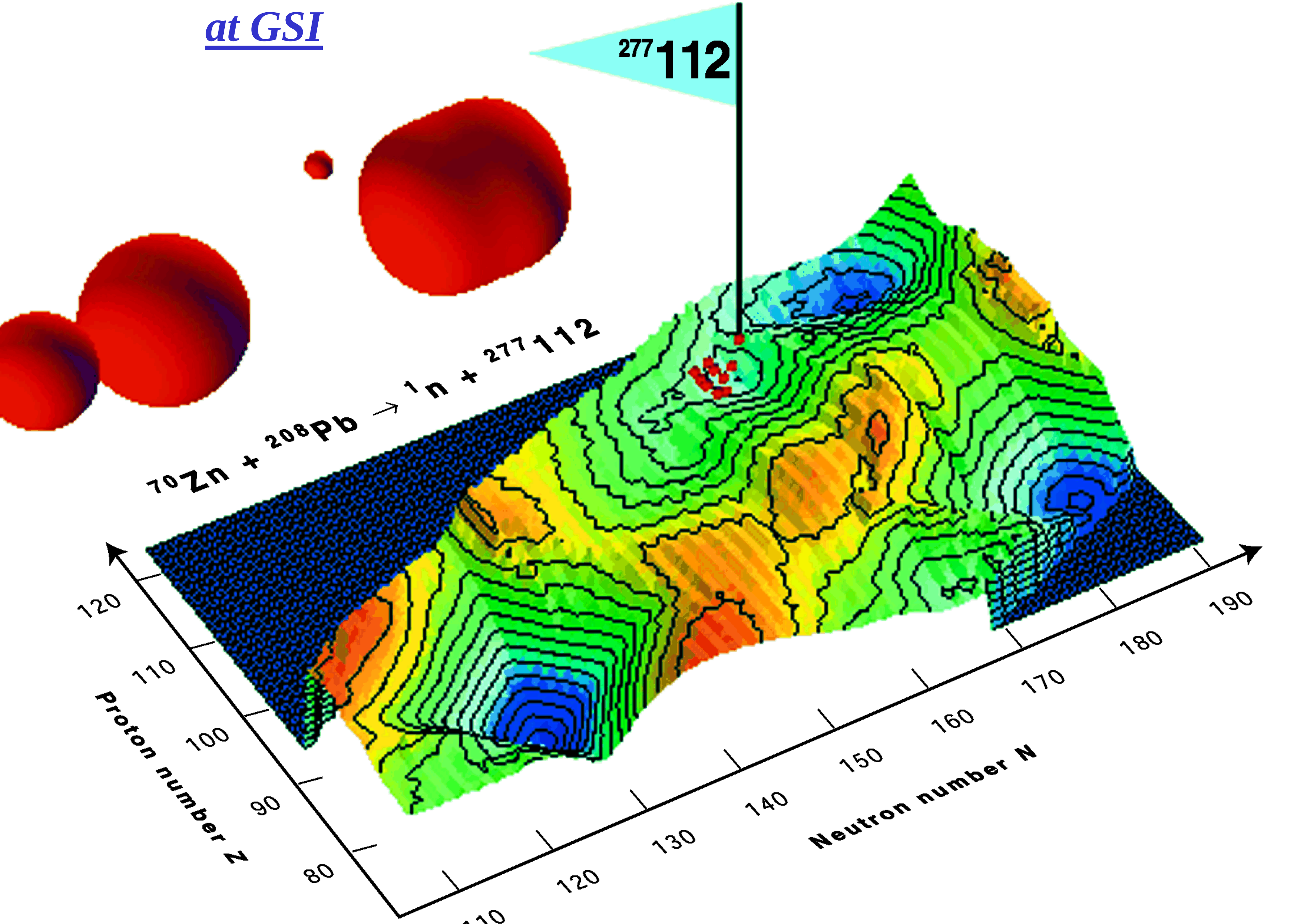
- We now have a reasonably good idea of where the proton drip-line lies but we still have little idea about the neutron drip-line.

- The figure shows the masses of the Sn(Z = 50) isotopes fitted to a range of different mass formulae.all is well where we have measured masses but we get widely differing predictions for the drip-lines.

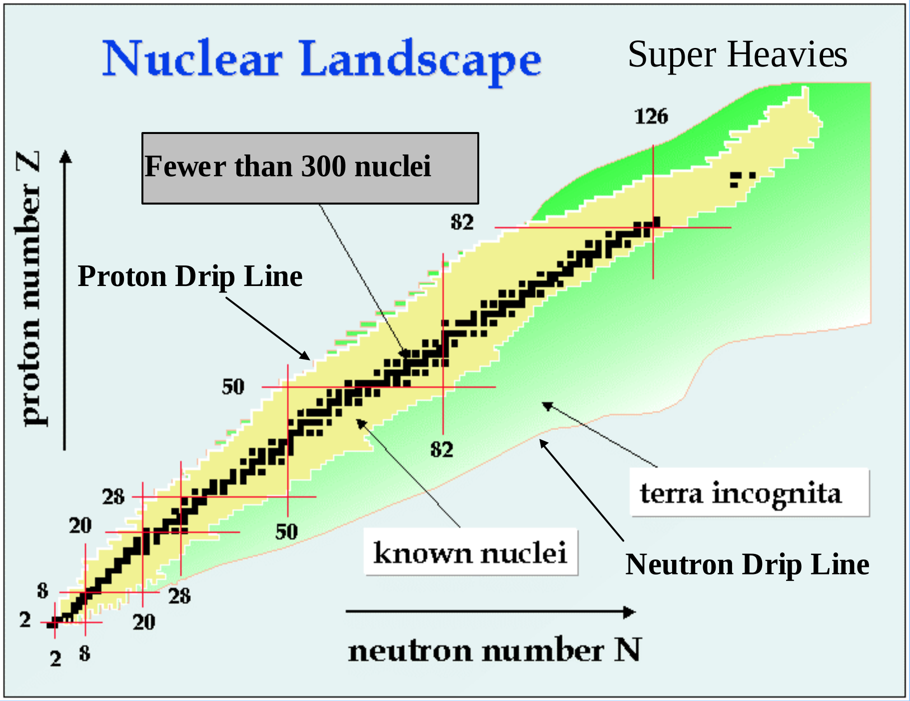


CHALLENGE:
To measure the masses as far away from stability as possible to try to determine where the drip-line lies.

Creeping up on the Superheavies at GSI



The Limits of Nuclear Existence



- Challenge: What are the limits of of nuclear existence?Where are the drip-lines? What is the last element we can make?

- We know that Shell structure stabilises the heaviest elements against fission and alpha decay.

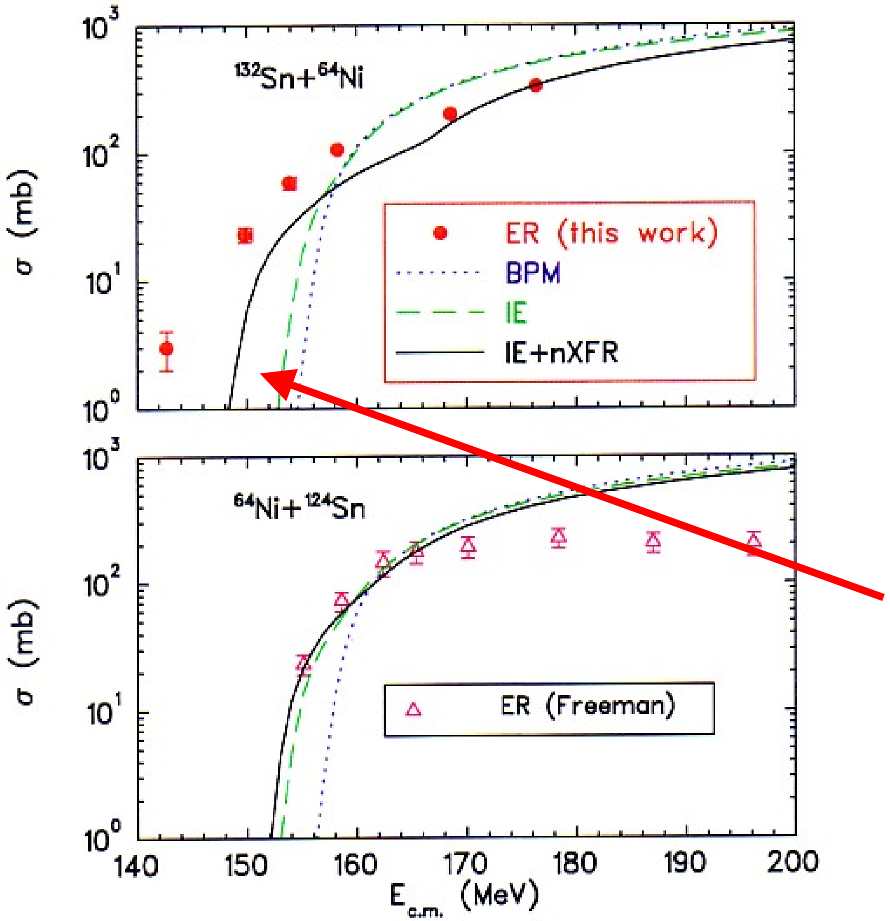
- We have solid evidence of the elements up to 112 and over the last couple of years the Russians have produced evidence of Z = 113-116 in reactions such as ^{244}Pu(^{48}Ca,xn), ^{245}Cm(^{48}Ca,xn), and ^{243}Am(^{48}Ca,xn).

- Oganessian et al.Phys.Rev.C69 (2004)054607--Z = 114 & 116

- Oganessian et al.Phys.Rev.C69 (2004)021601--Z = 113 & 115

The Limits of Nuclear Existence

- Challenge: To create elements 112-116 and beyond.



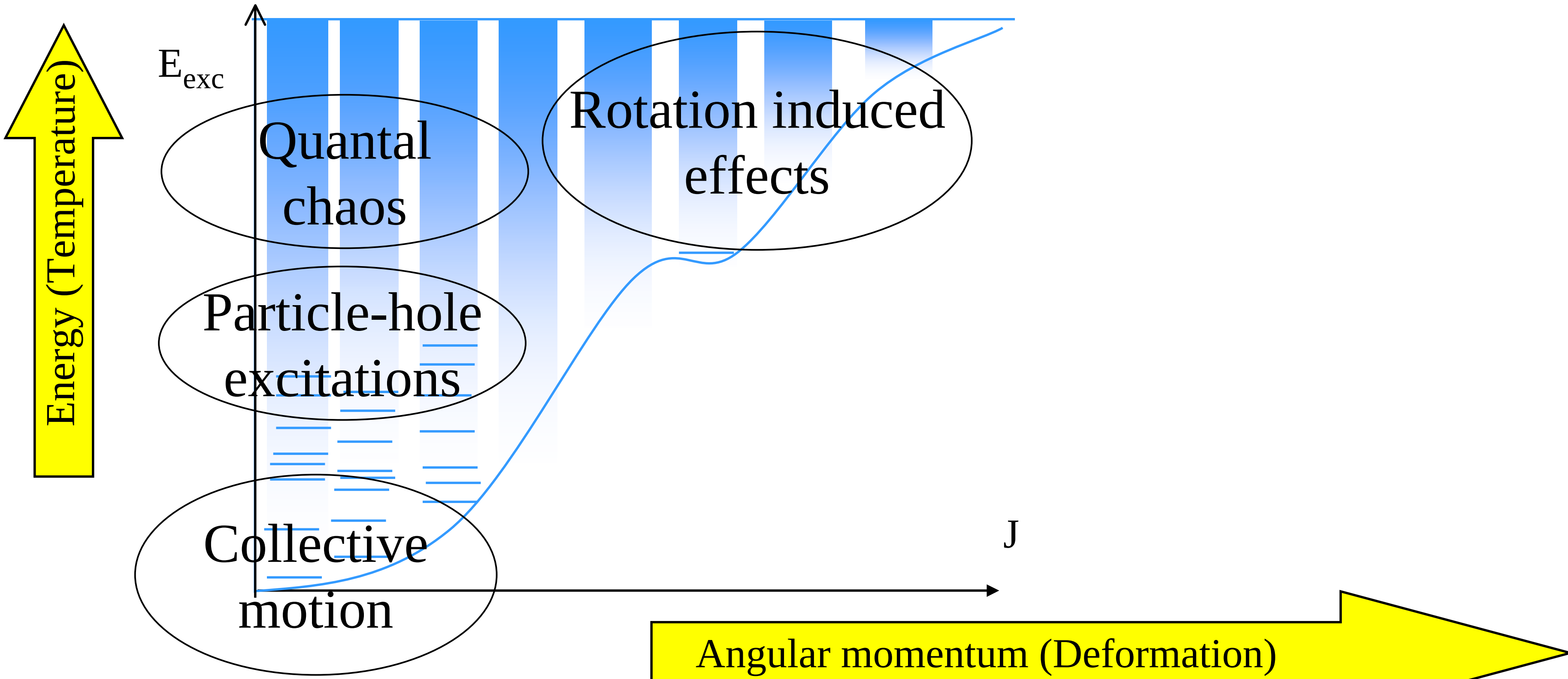
J.F.Liang et al.,PRL91(2003)152701

- Two routes:Cold and hot fusion
- Question:Will n-rich projectiles allow us to approach closer to the anticipated centre of the predicted Island of Superheavy nuclei.
- There is some evidence that extra neutrons enhance fusion below the barrier.The figure shows studies at Oak Ridge with 2 x 10^4 pps where it is clear that there is a large enhancement below the barrier.

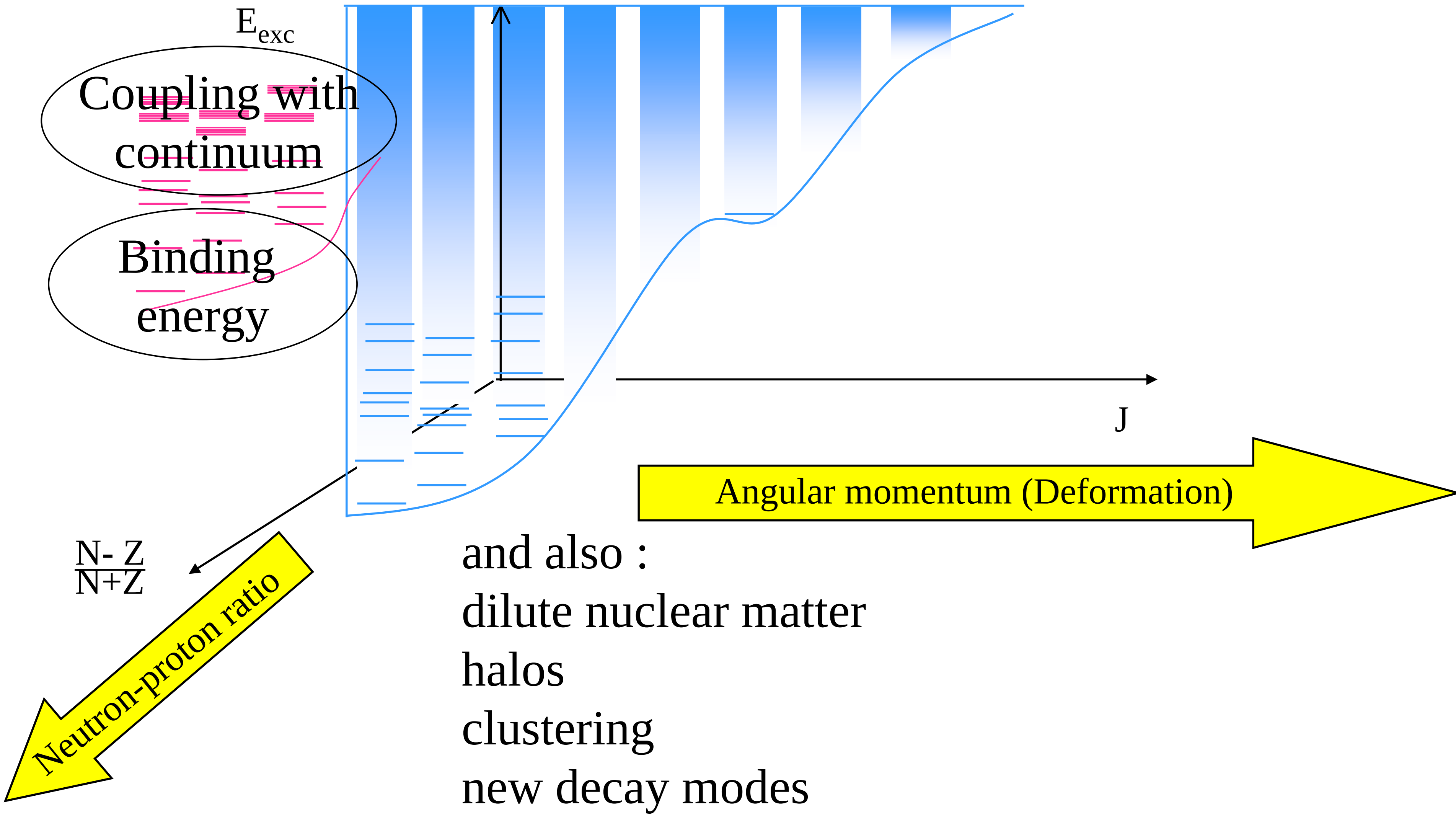
- RNBs may allow us to approach the spherical N=184 shell.

In contrast to other mesoscopic systems the atomic nucleus can be excited and observed in a very clean way.

Chart of nuclear excitations.



Radioactive Ion Beams (RIBs) add a new axis to this chart. It will allow the manipulation of one important degree of freedom in atomic nuclei.



and also :

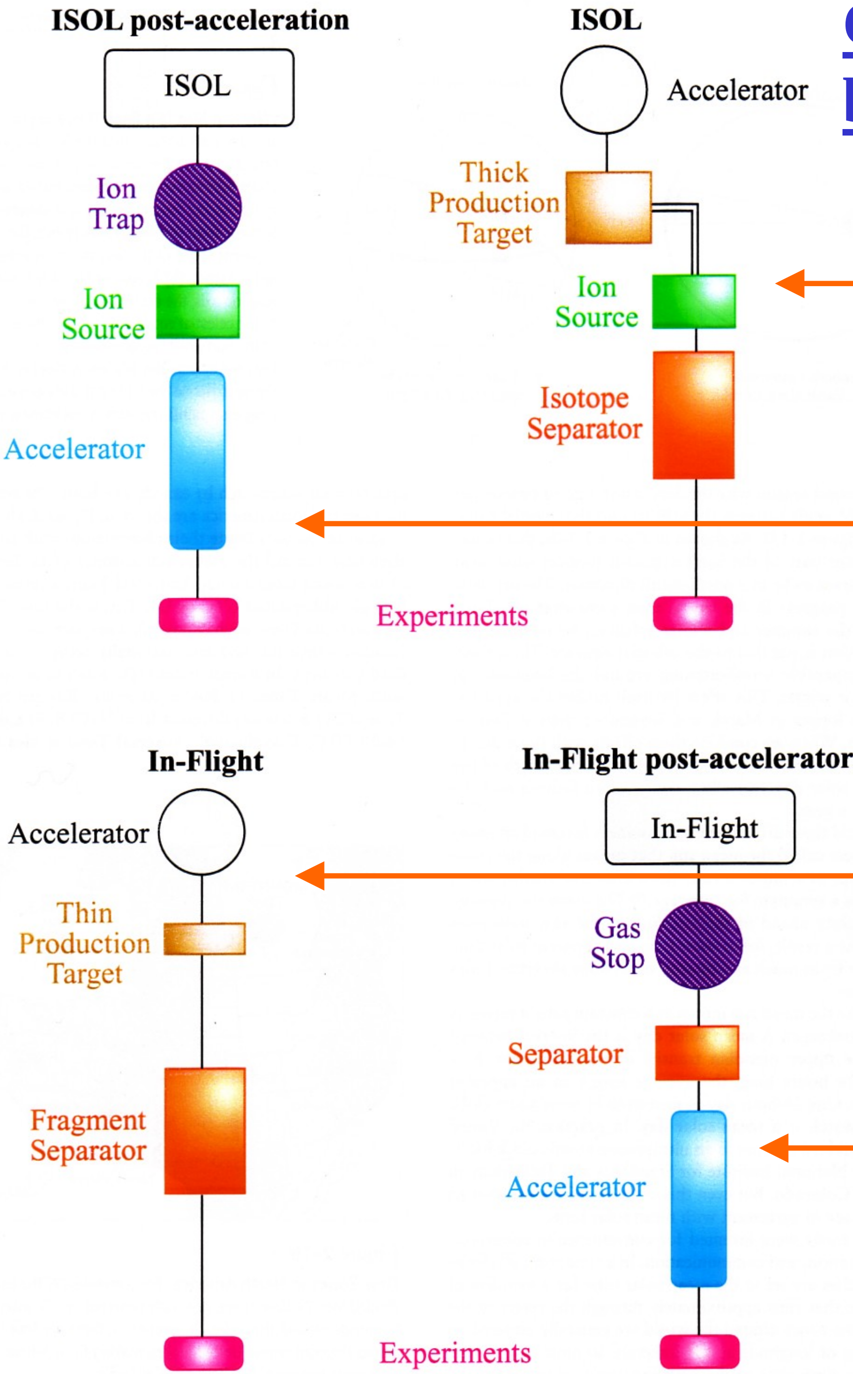
dilute nuclear matter

halos

clustering

new decay modes

Current Schemes for producing beams of radioactive nuclei



A)The classic ISOLDE scheme

B)The ISOL plus post-accelerator

C)Fragmentation -In Flight (GSI,MSU,GANIL,RIKEN)
-see talk by Juergen Kluge

D)The Hybrid-An IGISOL to replace the ISOL in B)
-The basis of RIA

ISOL and In-Flight facilities-Partners

It is probably true to say that if we worked at it, virtually all experiments could be done with both types of facility but they are complementary.

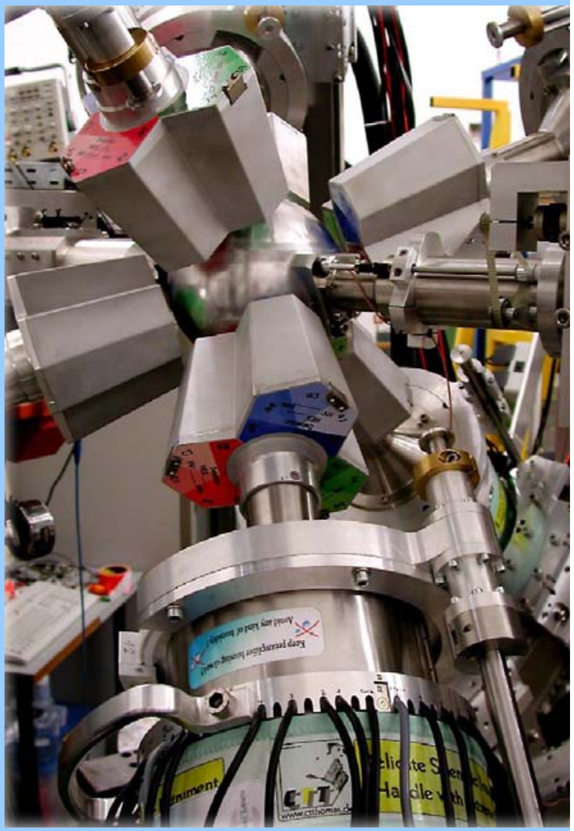
In-Flight

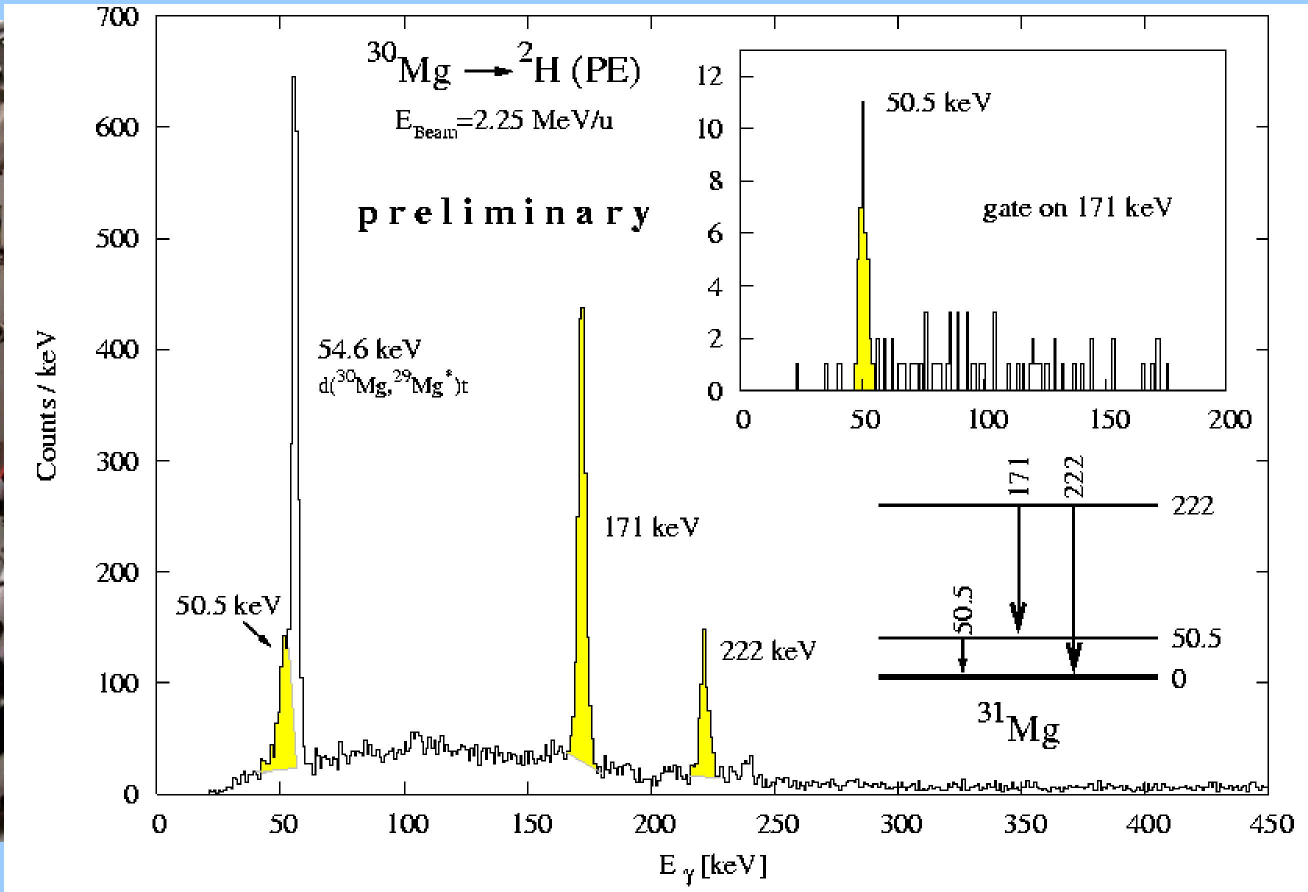
- Relativistic beams
- Universal in Z
- Down to very short $T_{1/2}$
- Easily injected into storage rings
- Leads readily to colliding beam experiments

ISOL

- High intensity beams with ion optics comparable to stable beams
- Easy to manipulate beam energies from keV to 10s of MeV
- High quality beams ideally suited to produce pencil-like beams and point sources for materials and other applied studies

Harbingers of things to come-COULEX at REX-ISOLDE





Miniball Phase 1

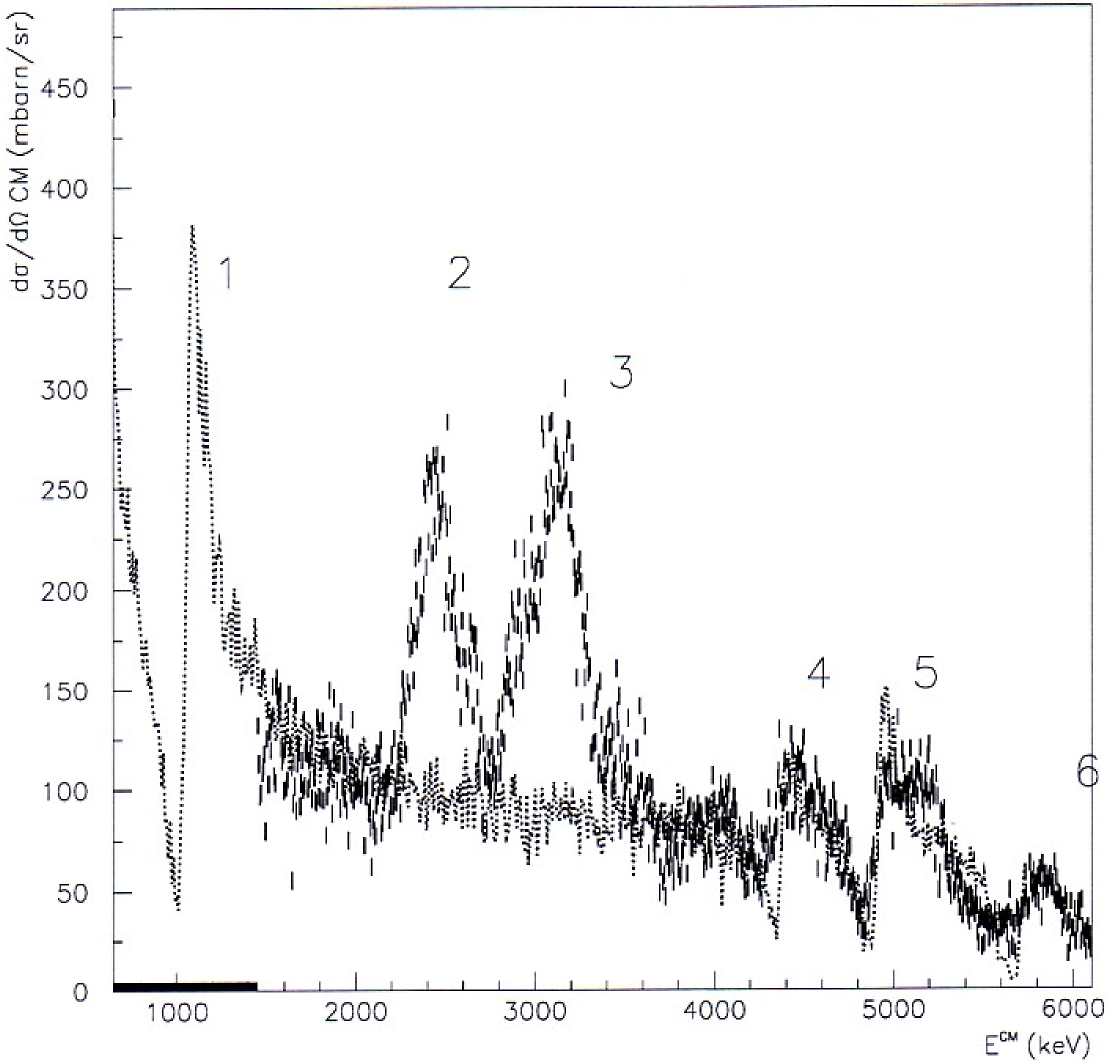
REX-ISOLDE - ^{2}H (^{30}Mg,pγ) ^{31}Mg

H.Scheit et al.,RNB6(2003)

Challenge: The target is the beam, so we have to develop new instruments

p(^{18}Ne,p) ^{18}Ne-Excitation Function at SPIRAL

Reconstructed differential cross-section for the **^{18}Ne(p,p) ^{18}Ne** elastic scattering reaction carried out with a beam of

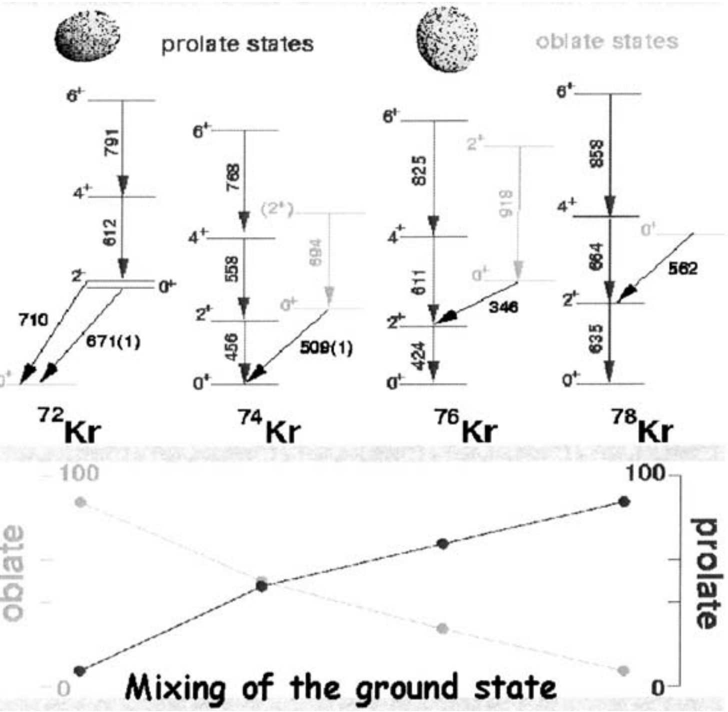


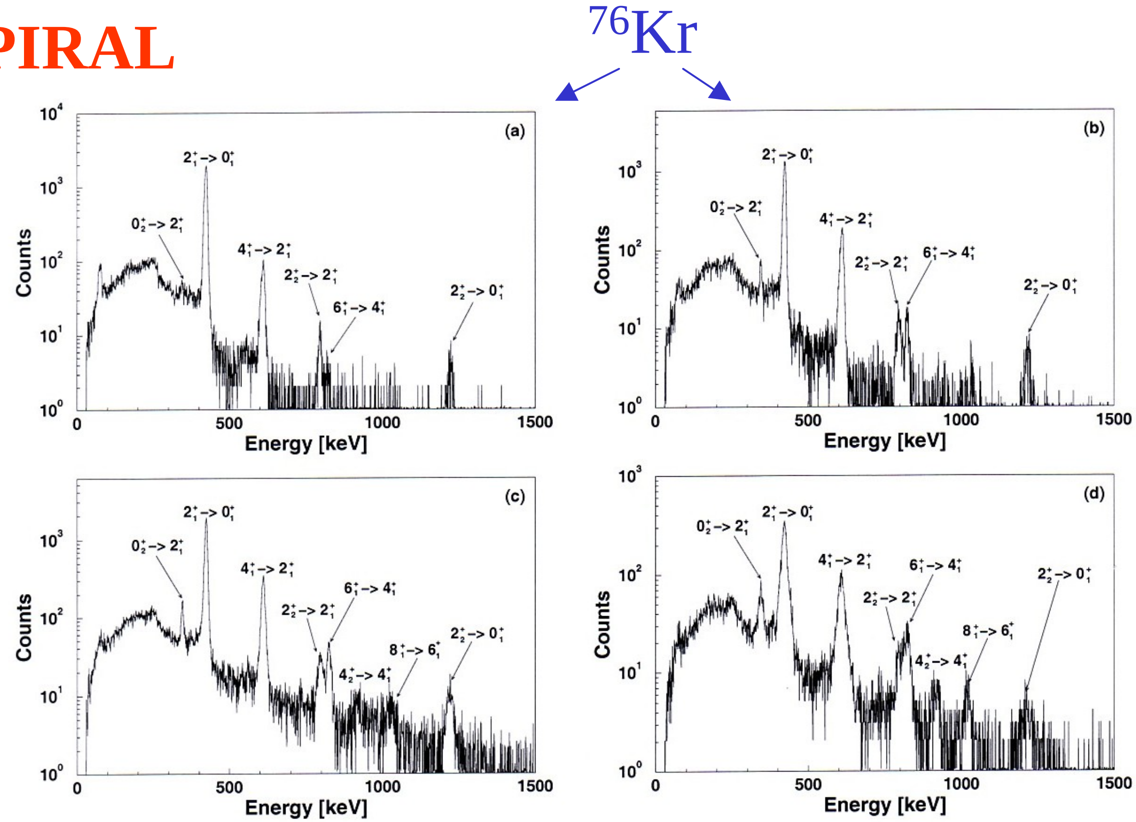
5 x 10^5 pps from SPIRAL.
The data points are exp.
The dotted line is an R-matrix calc.

The states in ^{19}Na are unbound to proton emission and were little known prior to this experiment

F.de Oliveira Santos, unpublished

Coulomb Excitation at SPIRAL





The Kr(Z=36) isotopes are expected to show shape co-existence.Mean Field calcs. show prolate and oblate deformed minima near the g.s

In this experiment Kr beams from the SPIRAL Facility were incident on a Lead target.The recoiling nuclei were detected in coincidence with γs as a function of angle.The yields and ang. distributions of the γs reveal that both states exist and how the mixing between them changes with N

E.Bouchez,Ph.D.Thesis,ULP Strasbourg,2003

Summary

- Themes:
  a)How complex systems are built from a few,basic ingredients
  b)Despite the complexity many-body systems show surprising regularities
  c)Atomic nuclei are closely linked ,on the one hand,to nanosystems such as quantum dots and metallic clusters etc and,on the other hand, to Astrophysics,Particle Physics and to many applications.

A comprehensive study of Nuclear structure is needed to answer the questions a) and b) and contribute in these other areas.

- Specific Challenges:
  a)How does shell structure change with a large neutron excess?
  b)Is Isoscalar pairing important in nuclei?
  c)How important is pairing in low-density environments?
  d)Will we see new collective modes far from stability?

Summary

- Specific Challenges(contd.):

  e)What are the limits of nuclear existence?

  -Where are the drip-lines?

  -What is the heaviest element we can make?

  f)Will we see dynamical symmetries far from stability?

  g)In nuclei with neutron skins will we see the dynamical symmetries of a two-fluid system?

  H)To what extent will the idea of "critical point symmetries" be realised in nuclei far from stability?

- The Opportunity:

  a)We need as wide a range of intense beams of radioactive ions as possible to allow us to select specific nuclei from the Segre Chart to focus on specific correlations,interactions,modes and symmetries

  b)We need new instruments and techniques to allow us to take advantage of the beams(e.g.AGATA-an advanced γ-tracking array)

Deuteron transfer in N=Z nuclei

- Deuteron intensity c_T^2 calculated in schematic model based on SO(8).
- Parameter ratio *b/a* fixed from masses.
- In lower half of 28-50 shell: *b/a*≈5.