Westcott Building, Florida State University, Tallahassee.
Kirby Kemper 2013

Florida State University in 1851-First as a seminary for men then in 1904 as a women's college and then in 1947 became a co-ed university.

Today has 39,000 students.

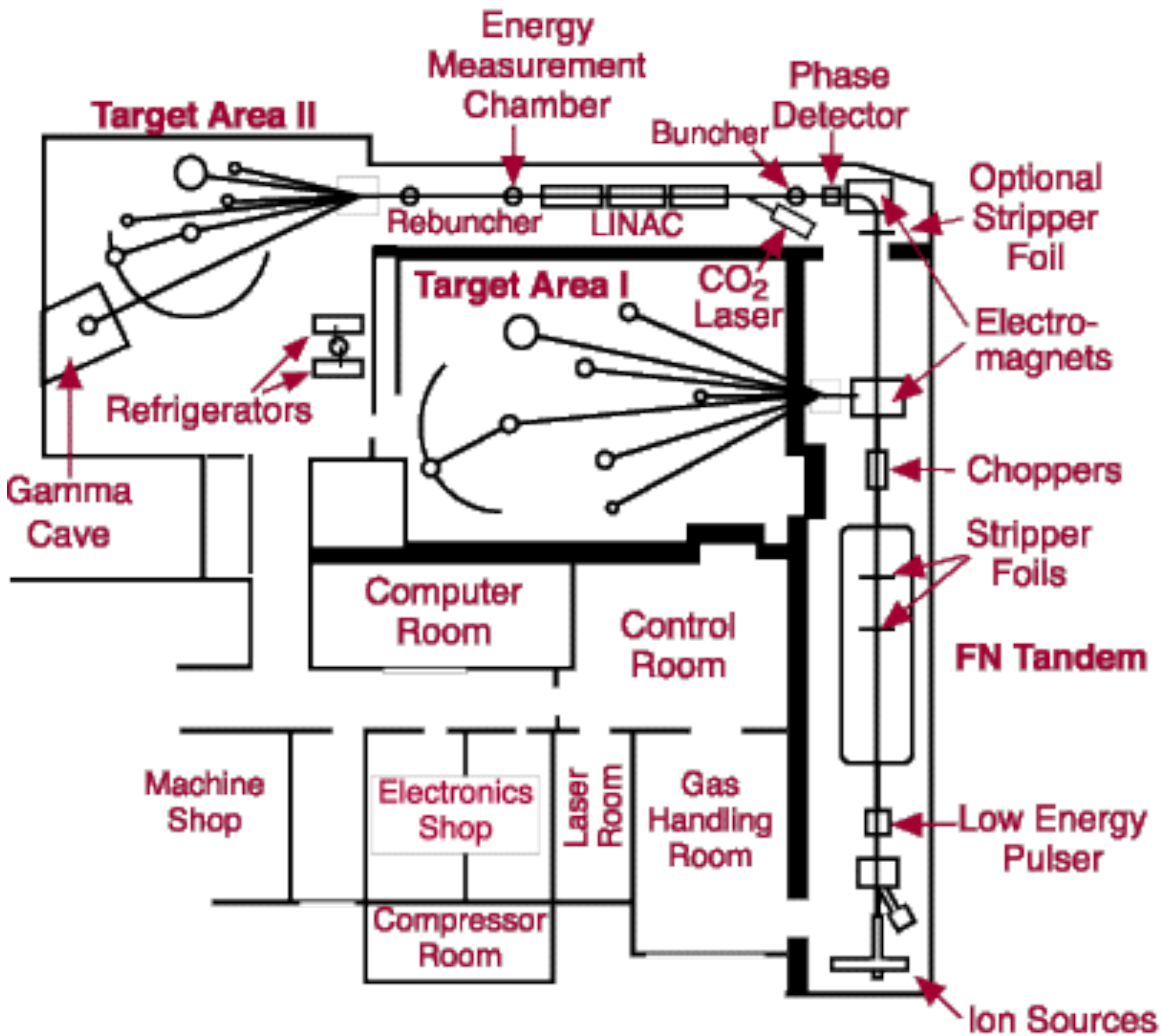
Map of Florida

The first European "discovery" of Florida was by Ponce de Léon- April 7, 1513

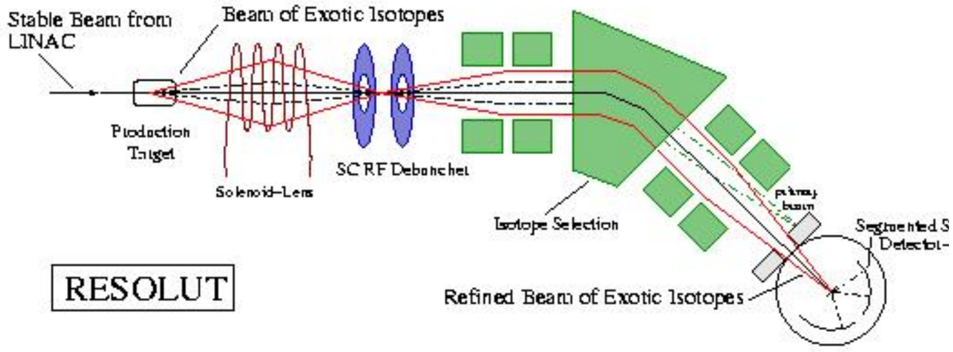
He gave it the name La Pascula de la Florida (Passion of the Flowers)

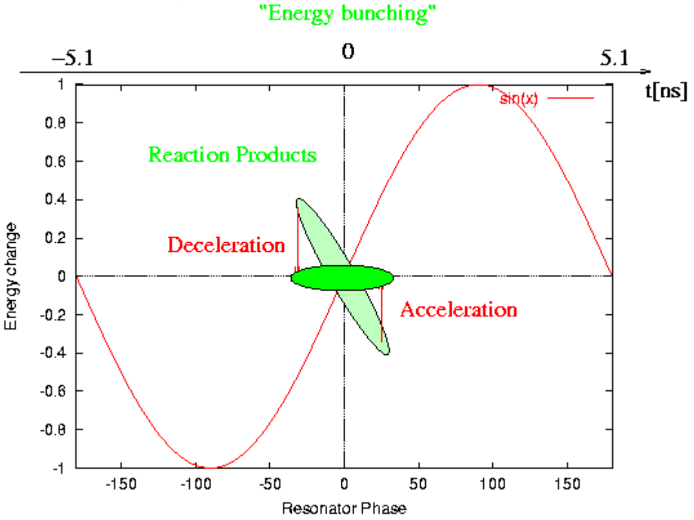
Florida was ruled by the Spanish from 1513-1763,
then British from 1763-1783
and Spanish again from 1783-1821
Became a state in 1855

Accelerator Laboratory at Florida State

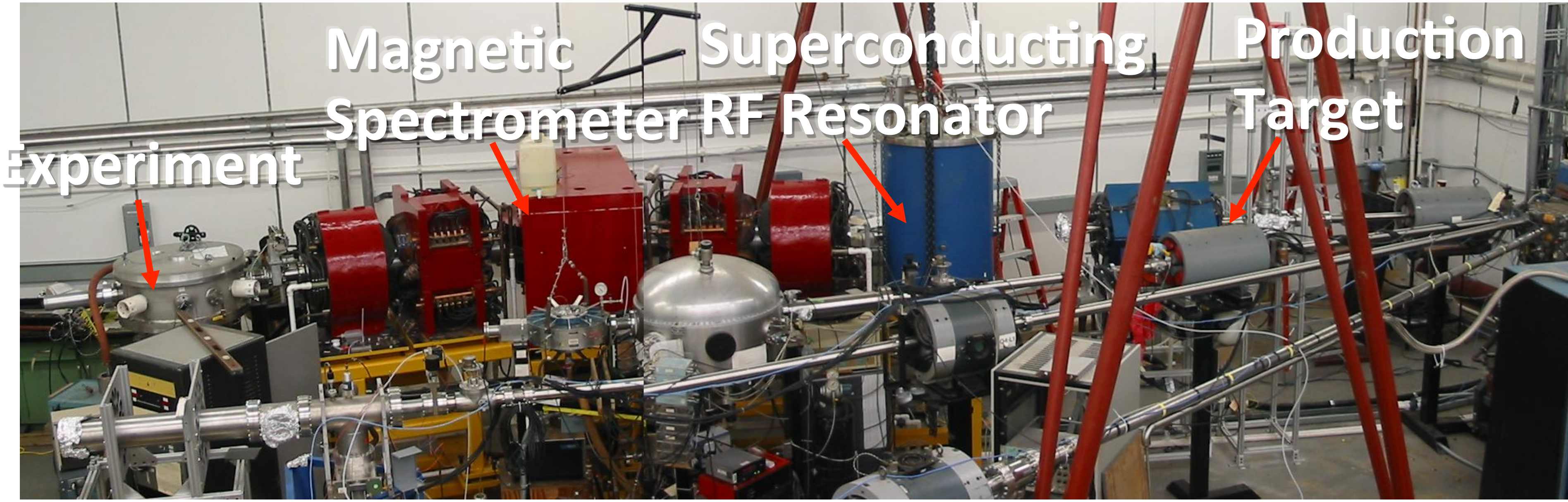


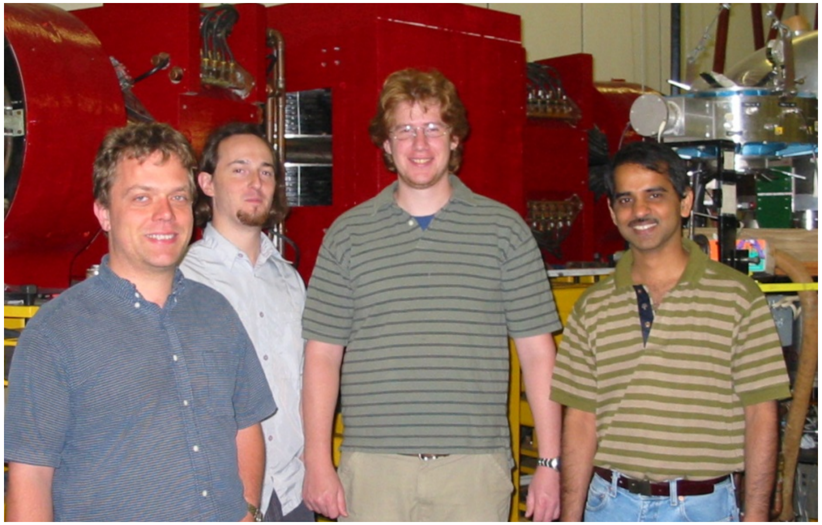
The next step: RESOLUT





- Exotic Isotope Beams at FSU:
  RESonator SOLenoid with UpscaleTransmission
- Active energy-bunching of exotic isotope beams with superconducting RF
- A mini-Accelerator Mass Spectrometer

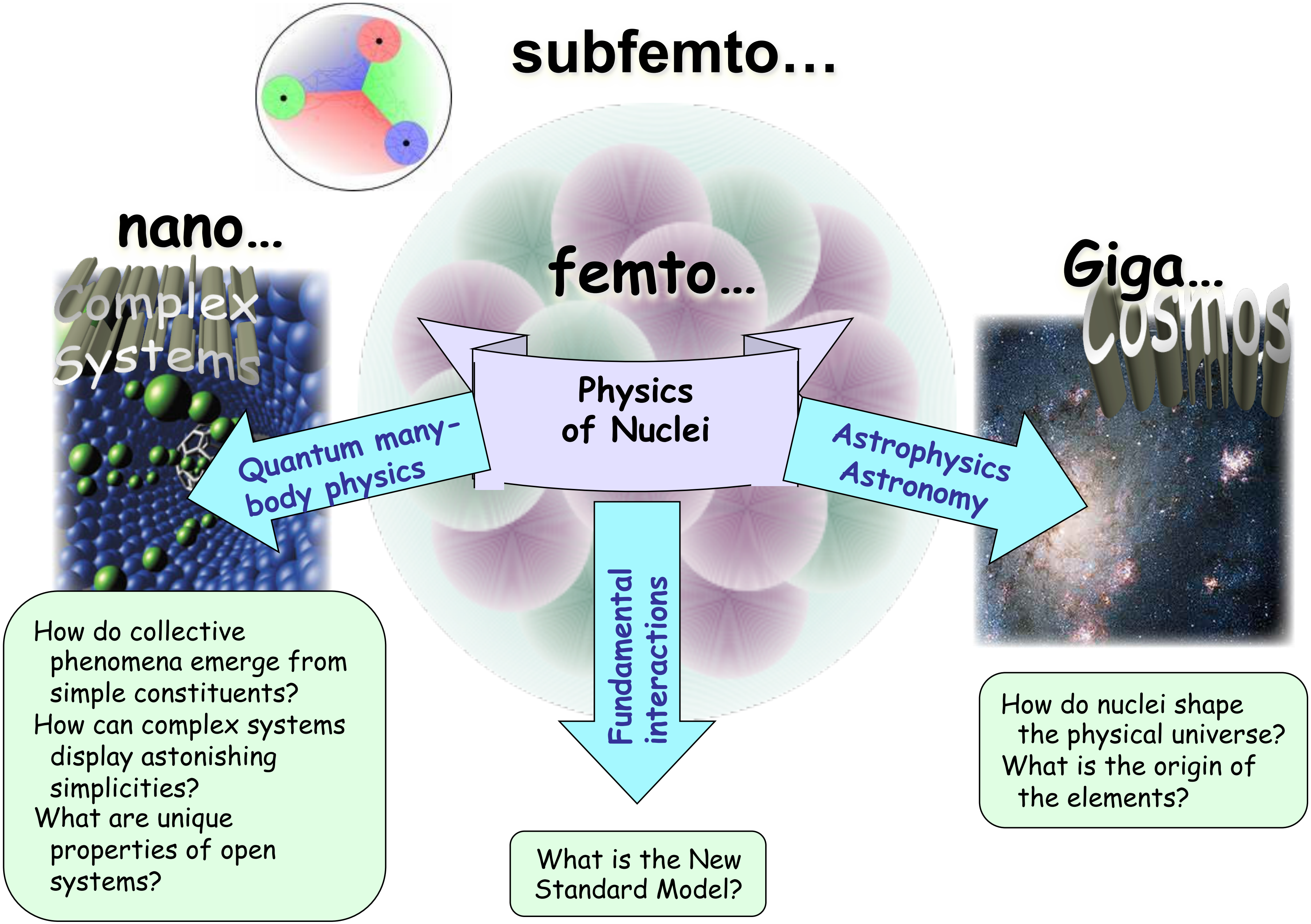

Magnetic Spectrometer
Superconducting RF Resonator
Production Target
Experiment



Energy of beam=K Q^2/A

where Q is the charge state of the beam and A is its mass

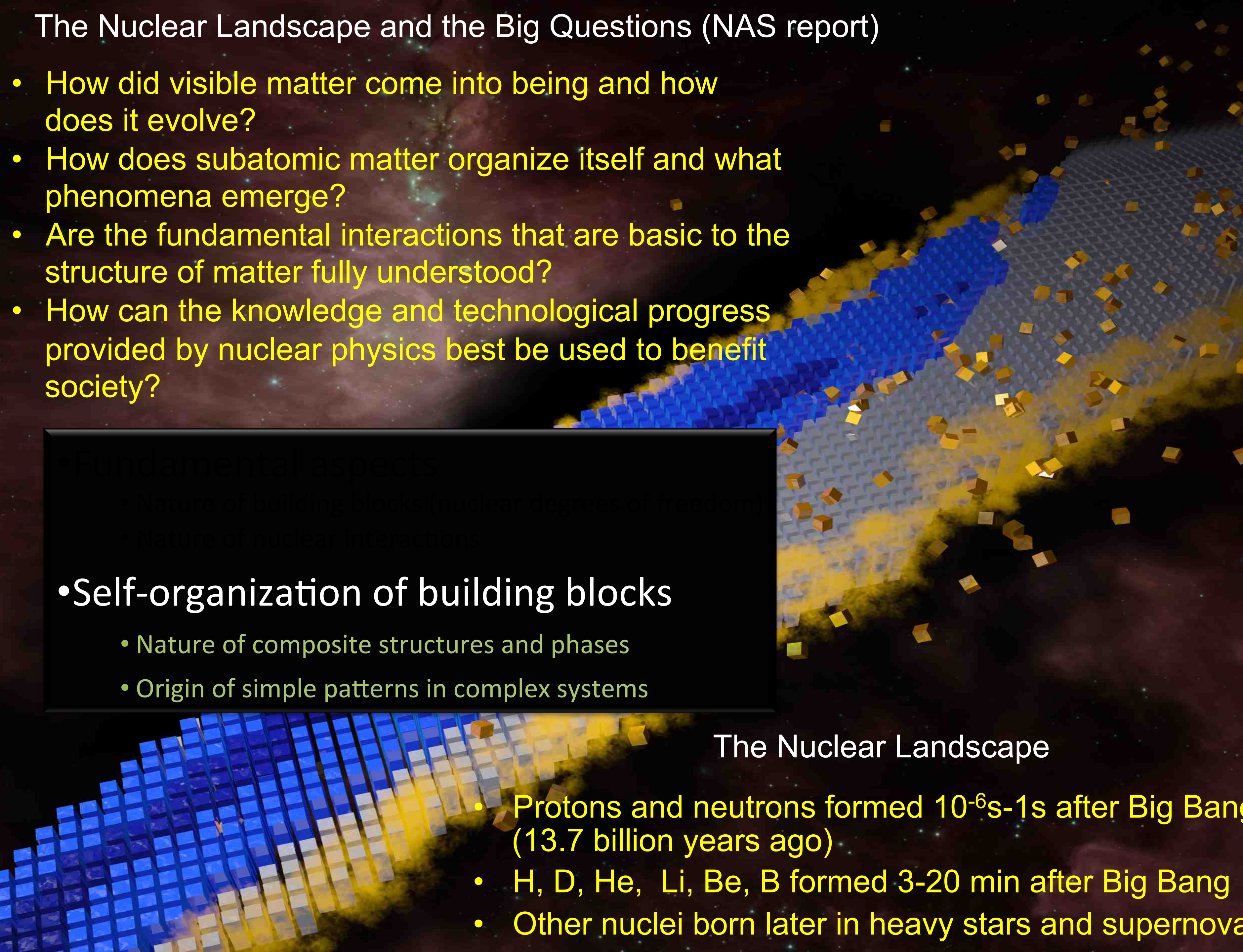
Profound intersections




NIELS BOHR INSTITUTET
1920

The Nuclear Landscape and the Big Questions (NAS report)

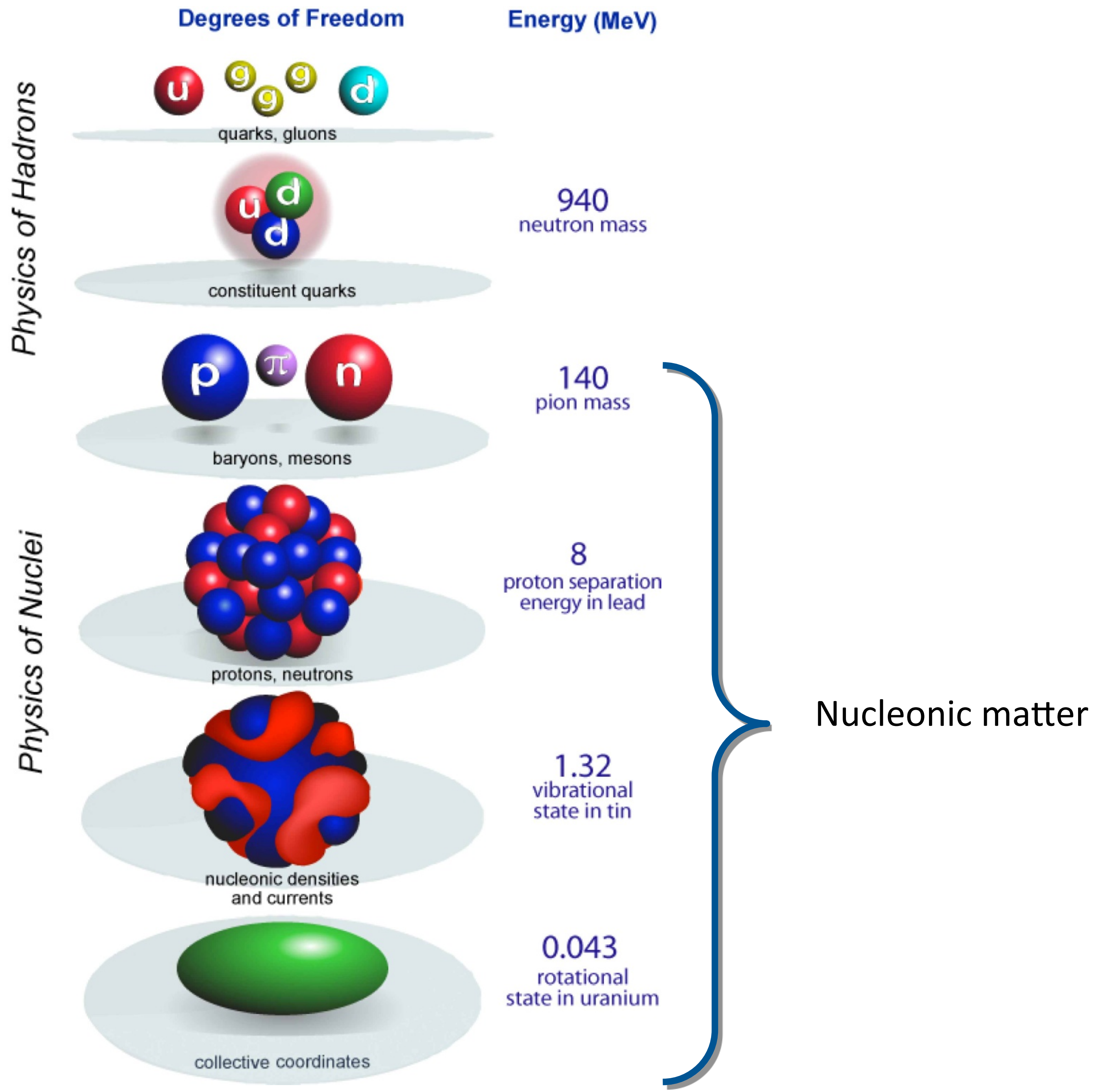
- How did visible matter come into being and how does it evolve?
- How does subatomic matter organize itself and what phenomena emerge?
- Are the fundamental interactions that are basic to the structure of matter fully understood?
- How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?



- Fundamental aspects
  - Nature of building blocks (nuclear degrees of freedom)
  - Nature of nuclear interactions
- Self-organization of building blocks
  - Nature of composite structures and phases
  - Origin of simple patterns in complex systems

The Nuclear Landscape

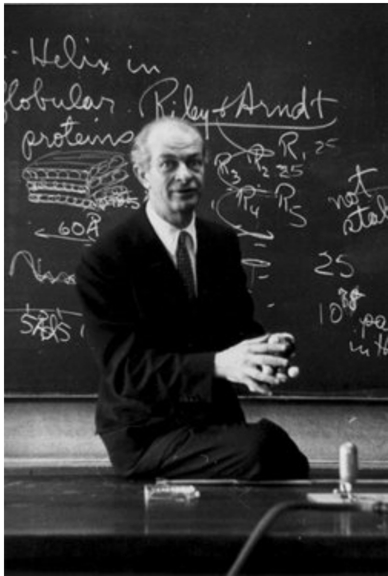
- Protons and neutrons formed 10^{-6}s-1s after Big Bang (13.7 billion years ago)
- H, D, He, Li, Be, B formed 3-20 min after Big Bang
- Other nuclei born later in heavy stars and supernovae



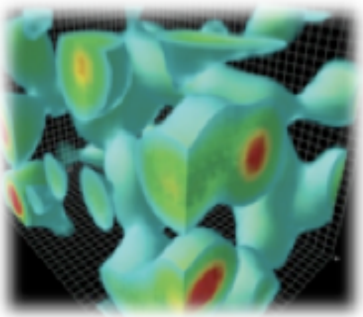
Degrees of Freedom
Energy (MeV)
Physics of Hadrons
Physics of Nuclei
u
g
g
g
d
quarks, gluons
u
d
d
constituent quarks
940
neutron mass
p
π
n
baryons, mesons
140
pion mass
protons, neutrons
8
proton separation
energy in lead
nucleonic densities
and currents
1.32
vibrational
state in tin
collective coordinates
0.043
rotational
state in uranium
Nucleonic matter

Linus Pauling (1901 – 1994): (He is one of only two people to have been awarded a Nobel Prize in two different fields (the Chemistry and Peace prizes), the other being Marie Curie (the Chemistry and Physics prizes))

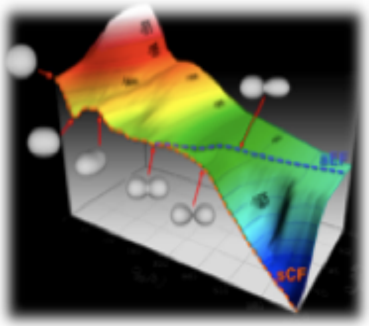
"I like everything about the world. I like the mesons and the hadrons, and the electrons and the protons and the neutrons; and the atoms, the molecules, the self-replicating molecules; the microorganisms, the plants and animals; the minerals; the zunyite and cuprite; the oceans and mountains, and the forests; the stars and the nebulae and the blacks holes, the Big Bang 18 billion years ago. I like it all!"



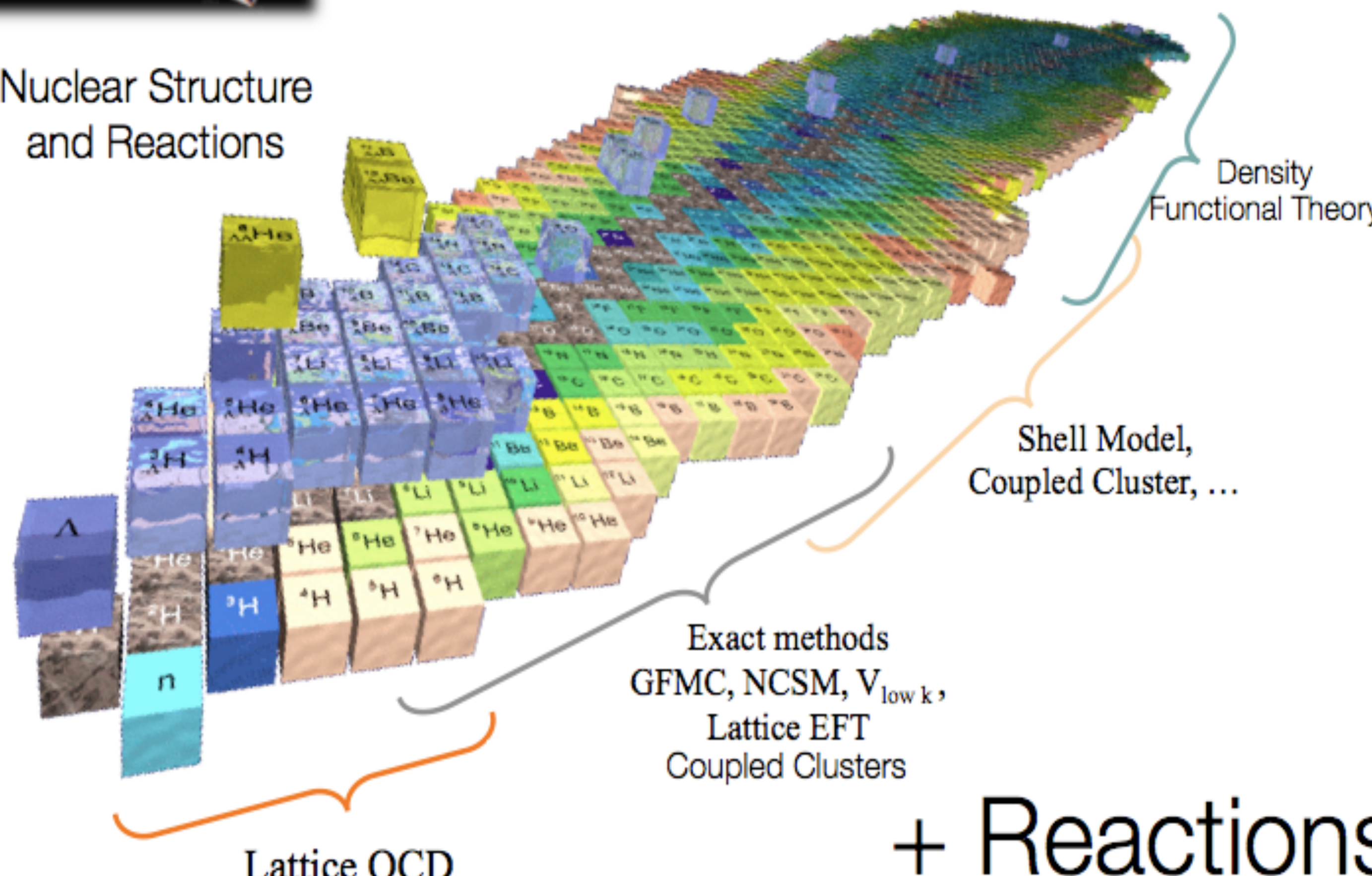
Exa-scale computing will unify Nuclear Physics



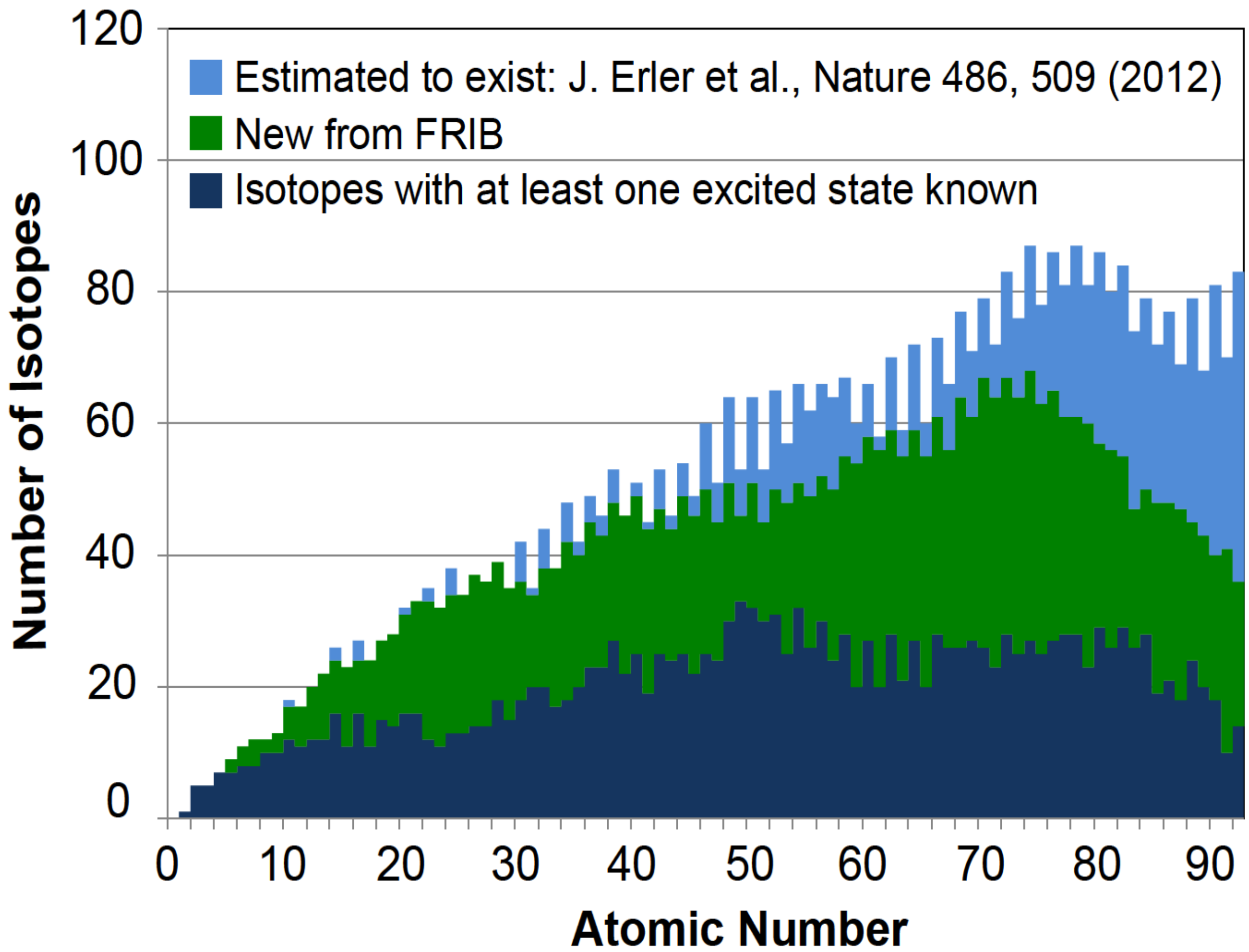
Cold QCD and Nuclear Forces



Nuclear Structure and Reactions



+ Reactions



Estimated to exist: J. Erler et al., Nature 486, 509 (2012)
New from FRIB
Isotopes with at least one excited state known
Number of Isotopes
Atomic Number
0
20
40
60
80
100
120
0
10
20
30
40
50
60
70
80
90

Now focus specific processes

Can one observe the properties of a projectile such as its breakup threshold, presence of low-lying excited bound and resonant states, continuum structure or ground state quadrupole moment in scattering and reactions?

Lets' focus on heavy ion scattering and reactions since those are the beams that can be produced here at the HIL

Hope to convince you YES if you take precise data

First need some history and theoretical guidance

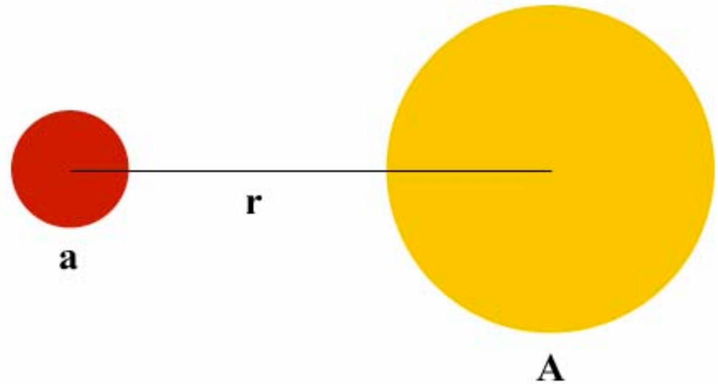
Worldwide push in heavy-ion physics began in early 1970s (Generally a heavy ion beam is considered one whose mass Is greater than that of the alpha particle)

Work was driven by in beam gamma-ray work and Ge detectors, sputter and ECR ion sources (dial a beam), higher voltage tandems, revitalized cyclotrons, interest in multiparticle transfer reactions such as (^{6}Li,d) , (^{12}C,α) where new structures could form and realization that you could unravel structure of long studied single particle states by controlling angular momentum mismatch.

Most data taken at 5 MeV/amu or so

Elastic scattering taken mostly to get parameters for distorted wave Born approximation analysis-not interesting

Optical Model for Elastic Scattering



$$\left(\frac{d^2}{dr^2} + k^2 - \frac{L\,(L+1)}{r^2} - 2\,\mu\,\frac{V_{opt}\,(r)}{\hbar^2}\right) u_L\,(r_\alpha) = 0$$

where $V_{opt}\,(r)$ is :

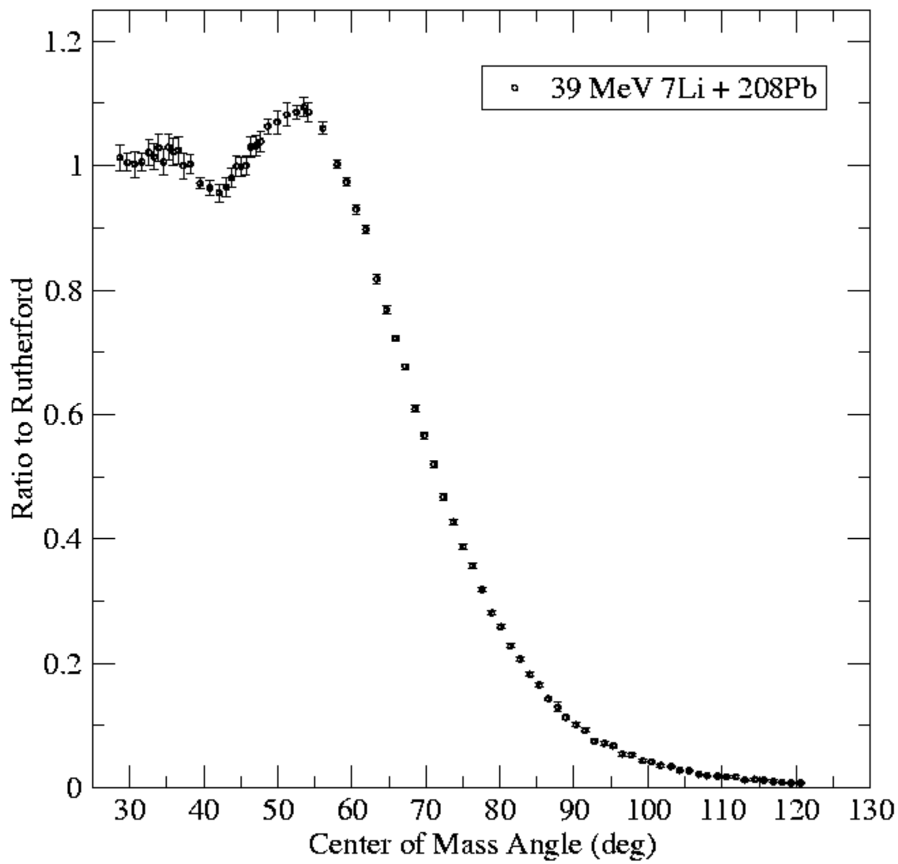
$$V_{opt}\,(r) = V_N\,(r) + V_C\,(r)$$

$$V(r) = -V_R f(x_R) - i\left\{W_V f(x_V) - 4W_S \frac{d}{dx_S} f(x_S)\right\} + 4\frac{V_{SO}}{r}\frac{d}{dr} f(x_{SO})\ell\cdot s + 4i\frac{W_{SO}}{r}\frac{d}{dr} f(x_W)\ell\cdot s$$

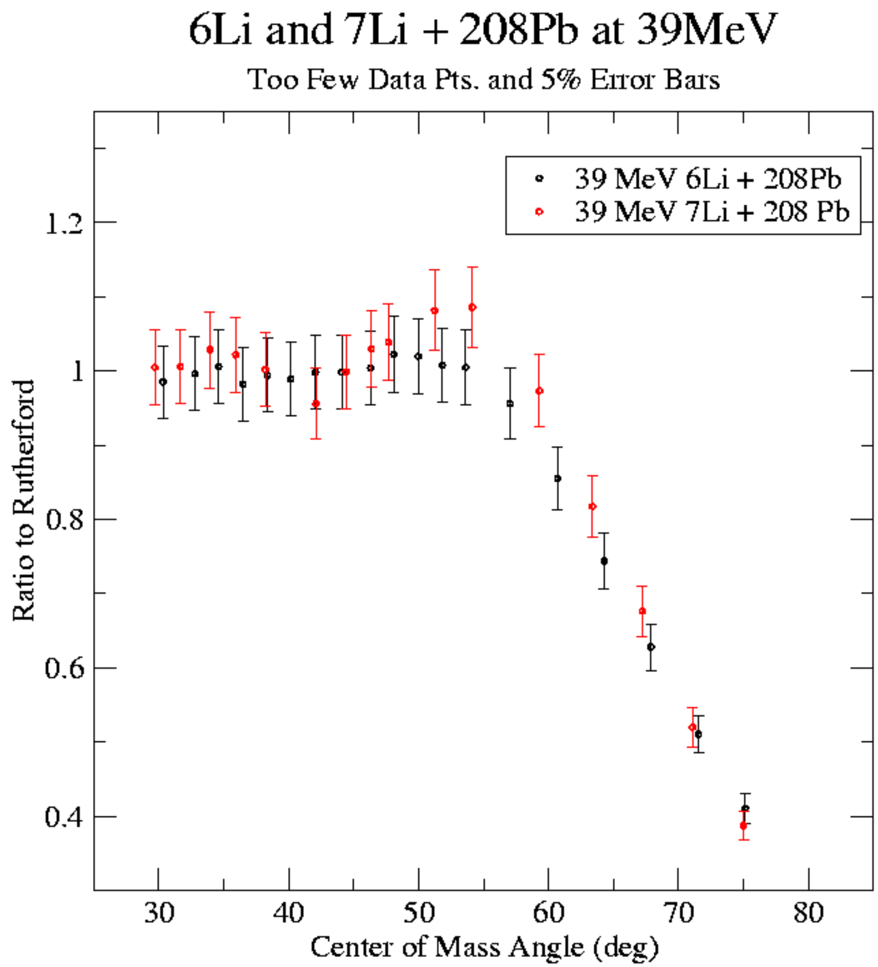
where $f(x_i) = (1 + \exp x_i)^{-1}$ and $x_i = (r - r_i \times A^{1/3})/a_i$.

Note, no where does the structure of the interacting nuclei enter

208Pb(7Li,7Li)208Pb Elastic Scattering at 39MeV



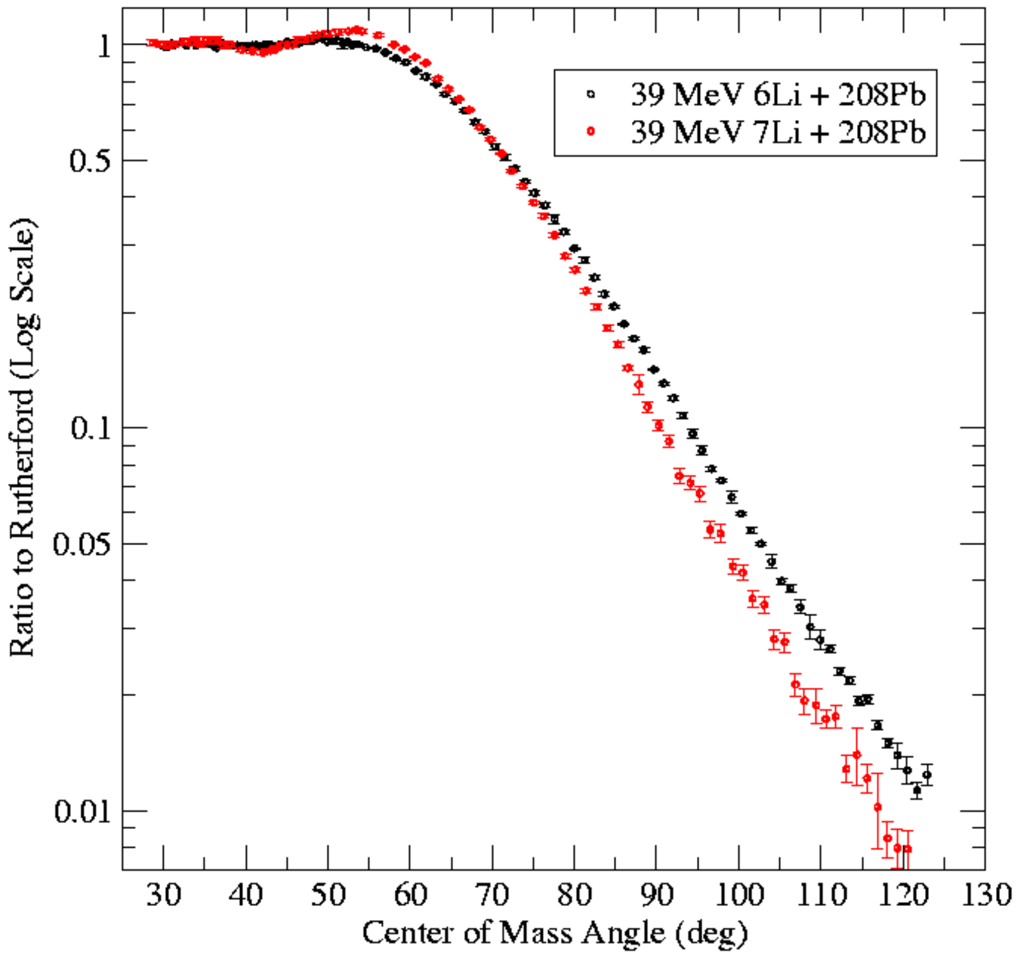
Classic Fresnel scattering problem



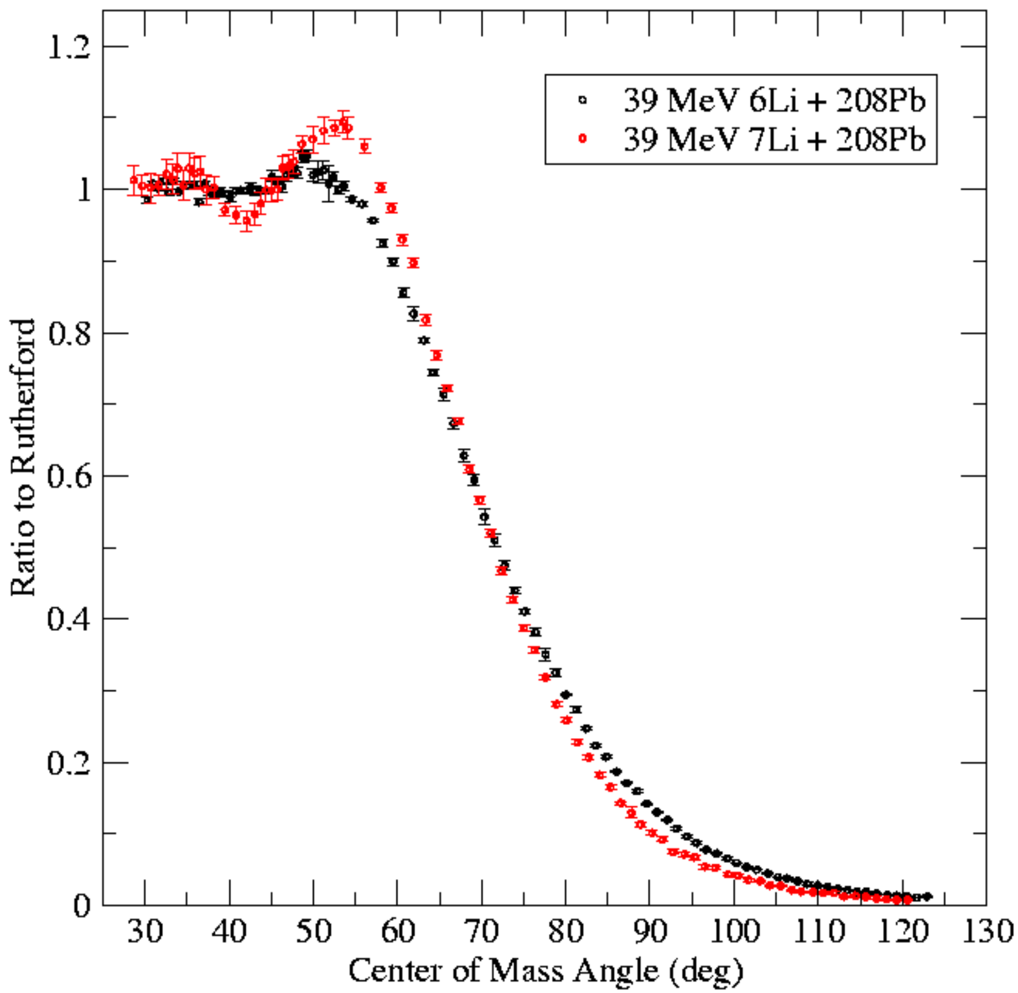
6Li and 7Li + 208Pb at 39MeV
Too Few Data Pts. and 5% Error Bars
39 MeV 6Li + 208Pb
39 MeV 7Li + 208 Pb
Ratio to Rutherford
Center of Mass Angle (deg)
1.2
1
0.8
0.6
0.4
30
40
50
60
70
80

6Li and 7Li + 208Pb Elastic Scattering at 39MeV

Log vs. Linear Scale

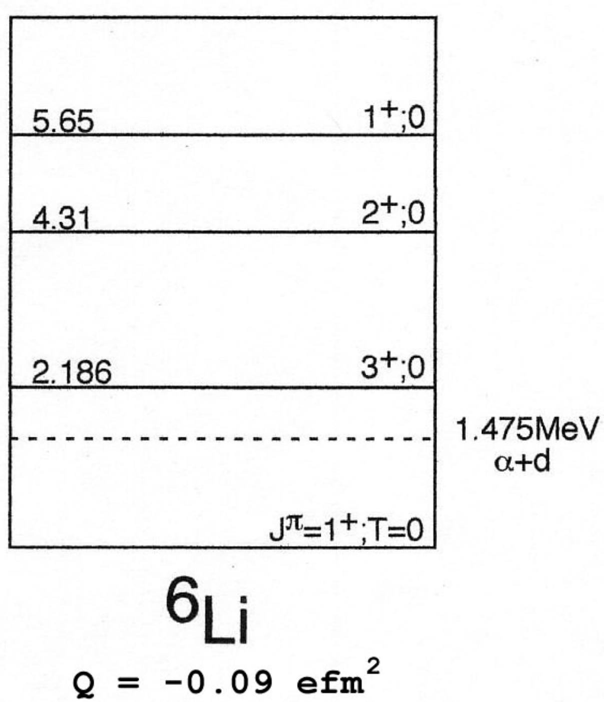


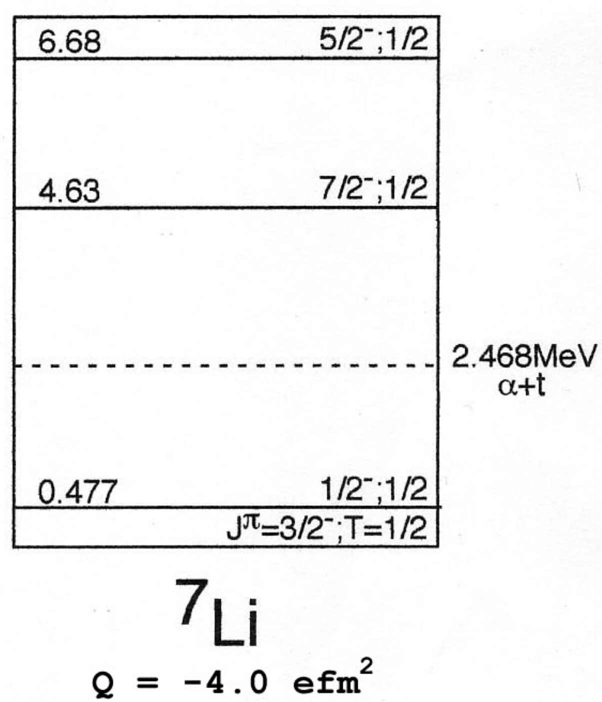
6Li and 7Li + 208Pb Elastic Scattering at 39MeV



N. Keeley et al Nucl Phys **A571** (1994) 326.

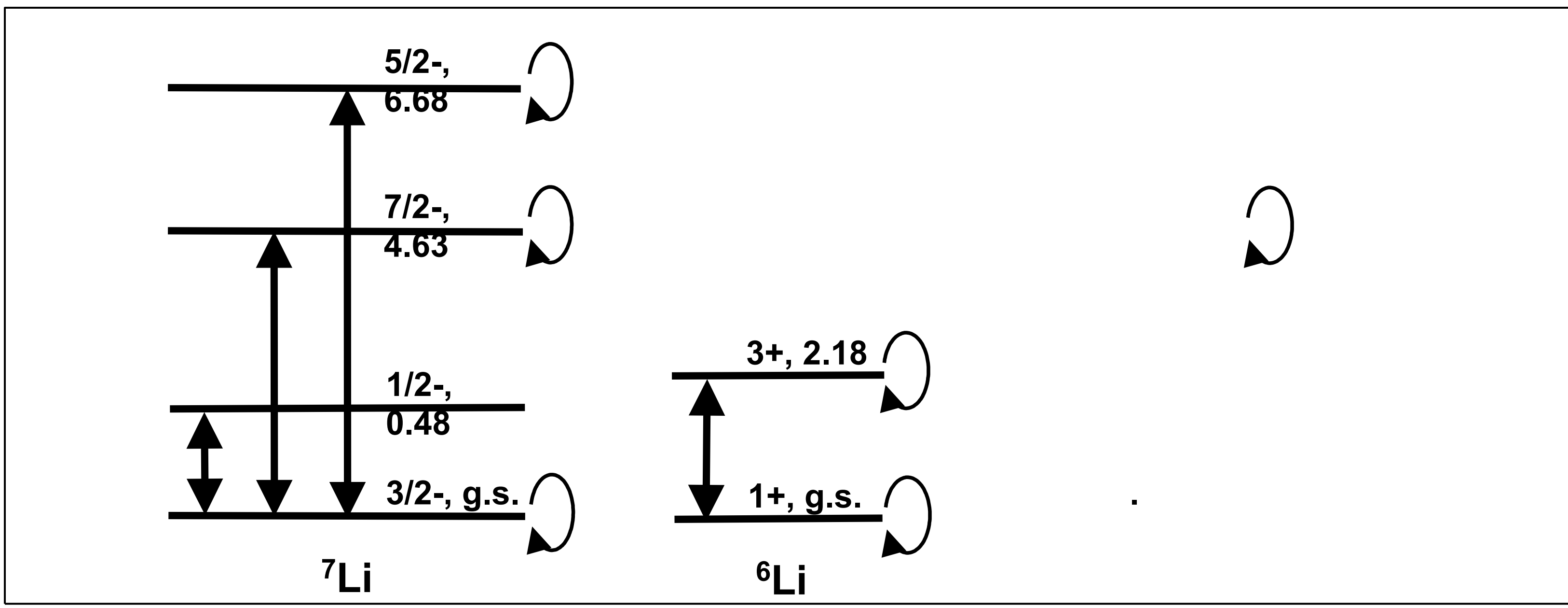
- 6Li and 7Li targets have different properties that can allow to study target effects when extracting the properties of loosely bound nuclei.



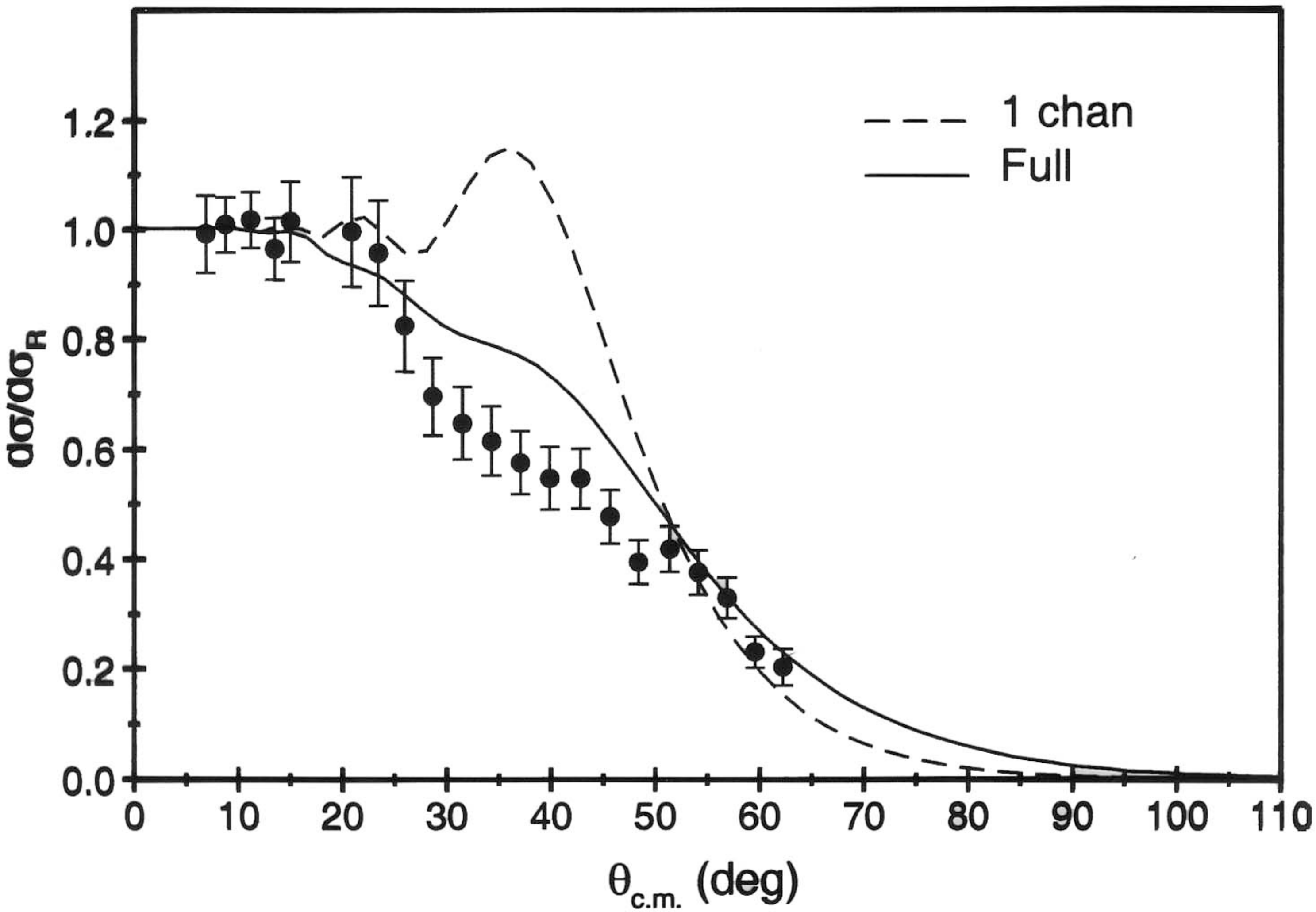


CC ANALYSIS

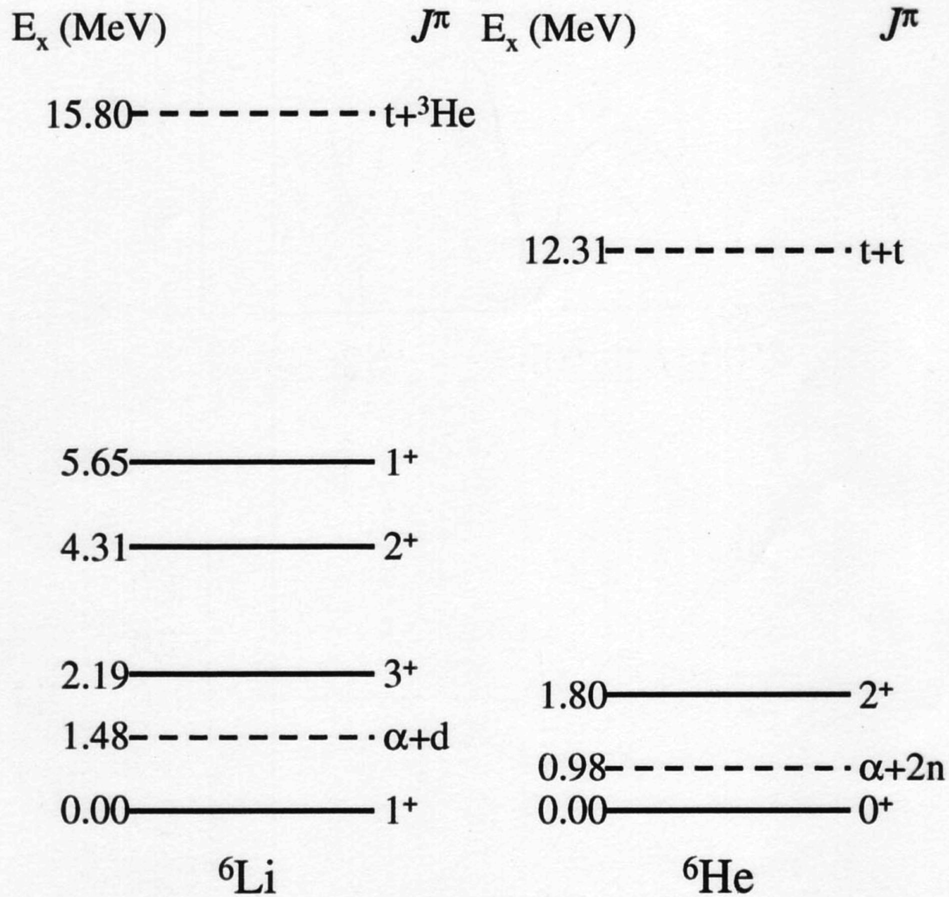
The experimental data were analyzed using the coupled channels (CC) approach. The CC calculations were performed using the latest version of code FRESCO. Final coupled – channels scheme :



29.6 MeV $^{6}He + ^{208}Pb$
R. Raabe et al.



Comparison of ^{6}Li and ^{6}He



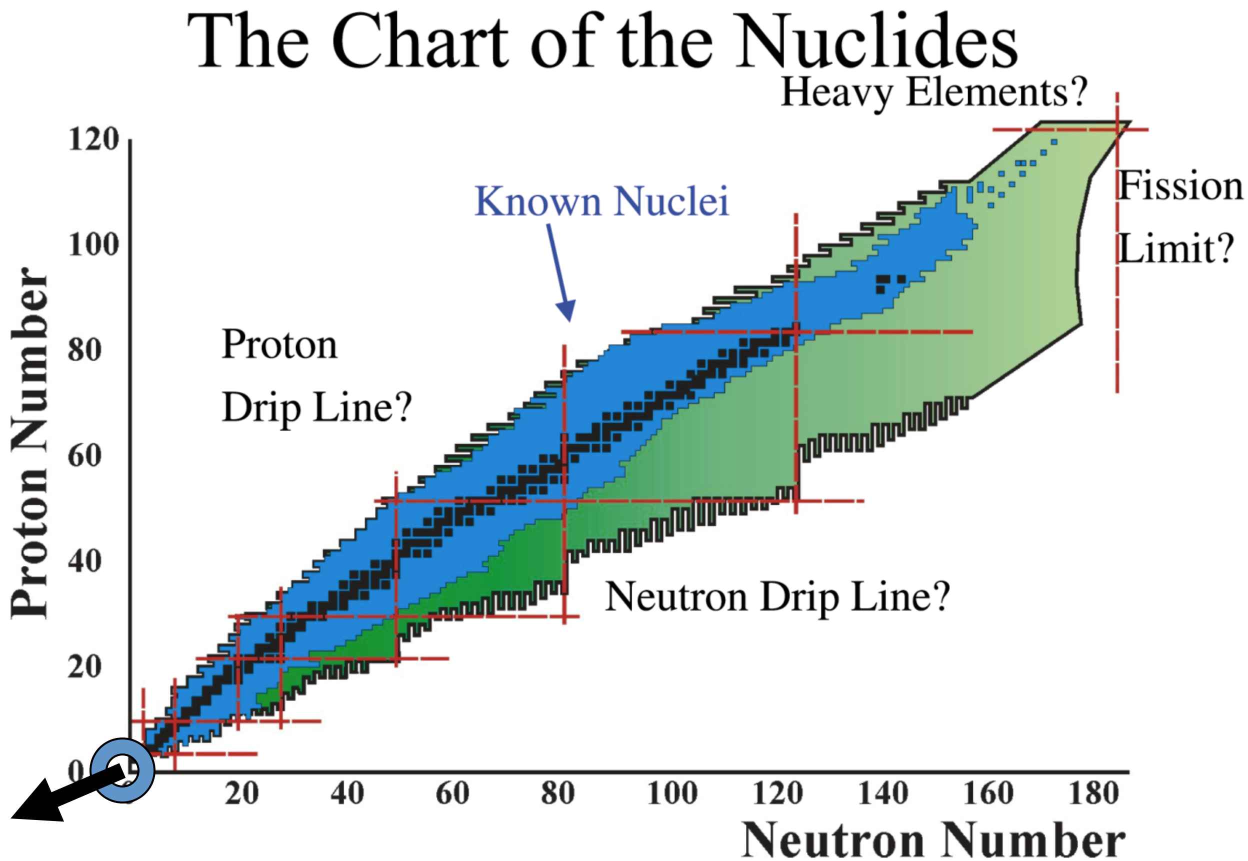
rms radius: 2.46 fm(*) 2.52 fm(*)

(*) I. Tanihata *et al.*, PL**B206**, 592 (1988)

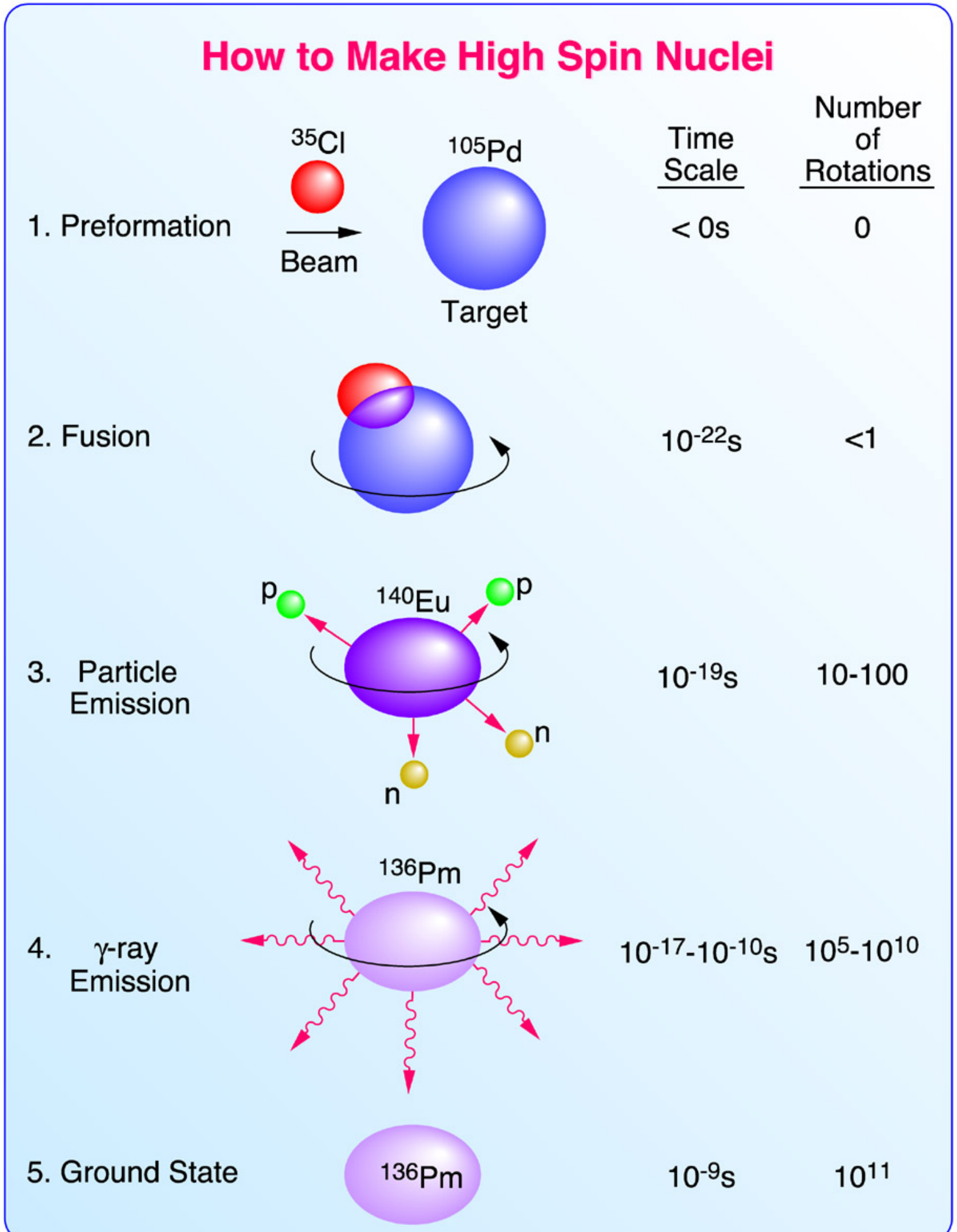
Take away message- Even in something as simple as elastic scattering, New things are learned when “careful” data are taken

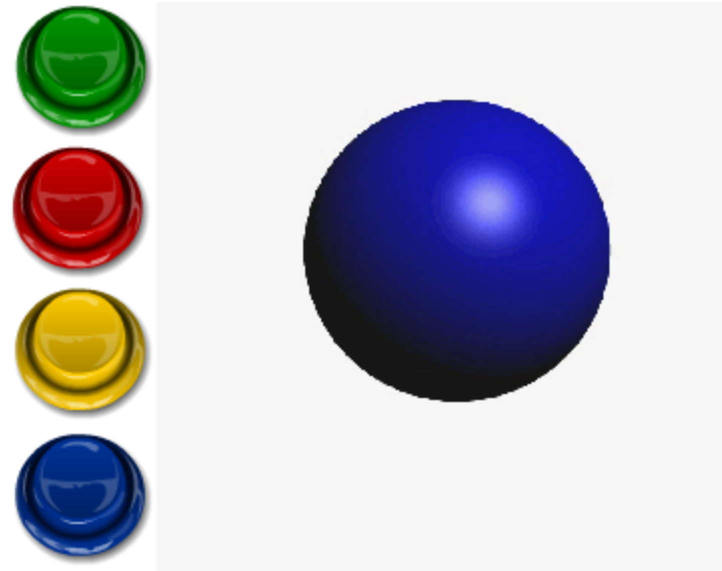
Now shift gears and look at other properties of nuclear matter

We want to know where are the limits and what happens on the way?



Increasing Angular Momentum and Excitation Energy: An excellent way to investigate nuclear structure, especially to see what the intruder orbitals are doing.

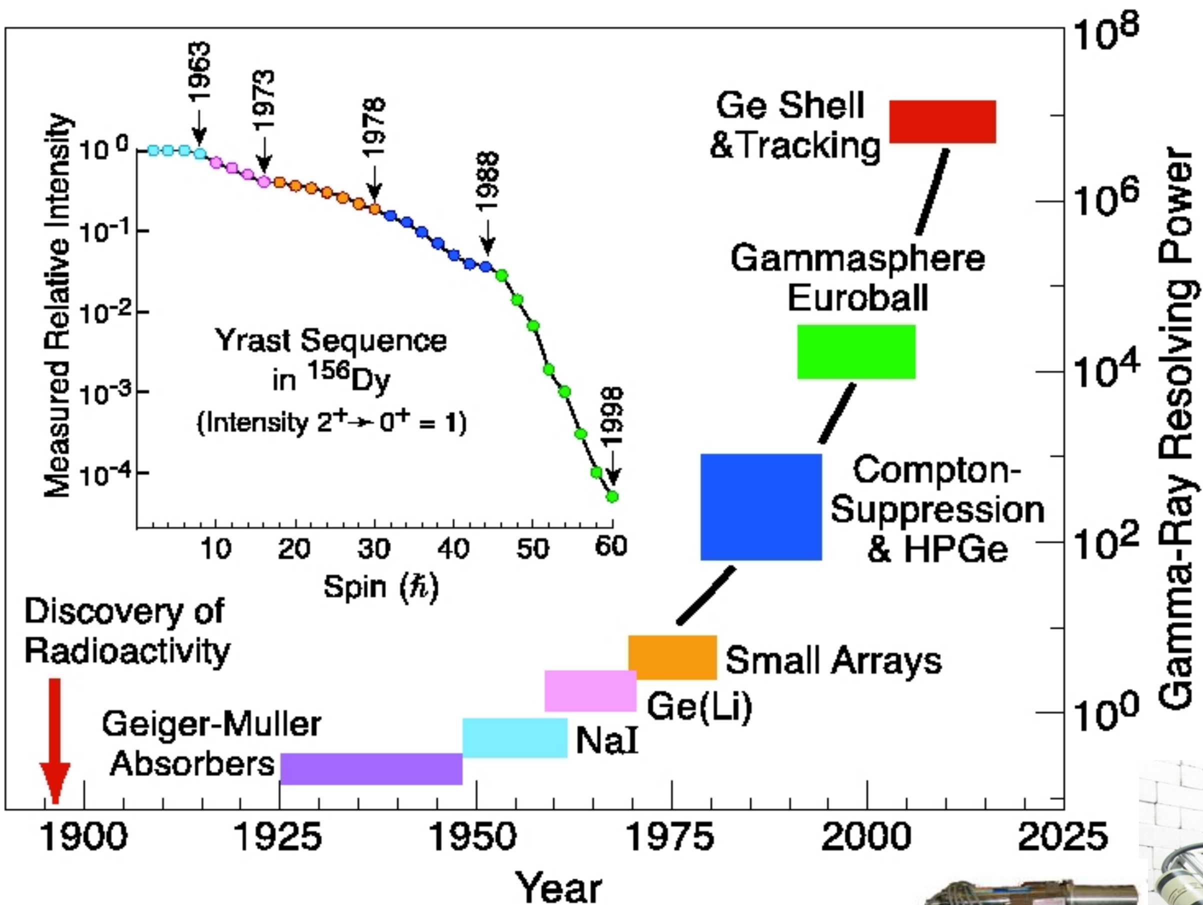


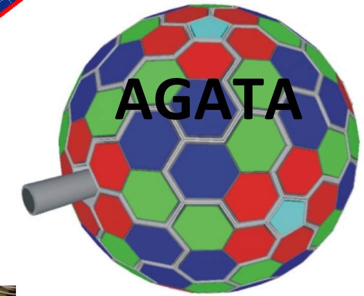


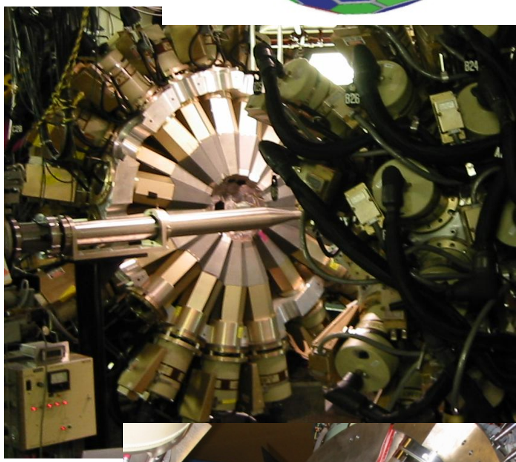
- Need to catch as many of the γ rays in each cascade as possible.

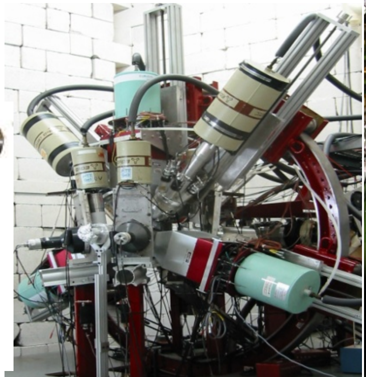
- Need efficient detector systems!

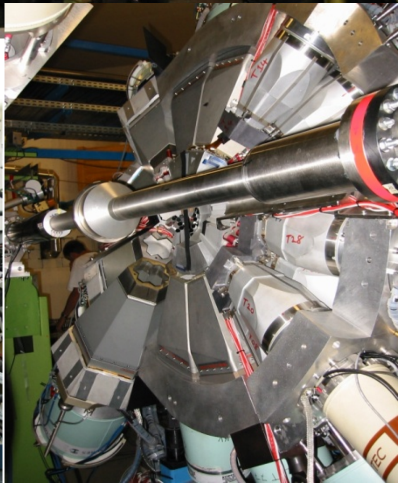
Gamma-Ray Detection Evolution



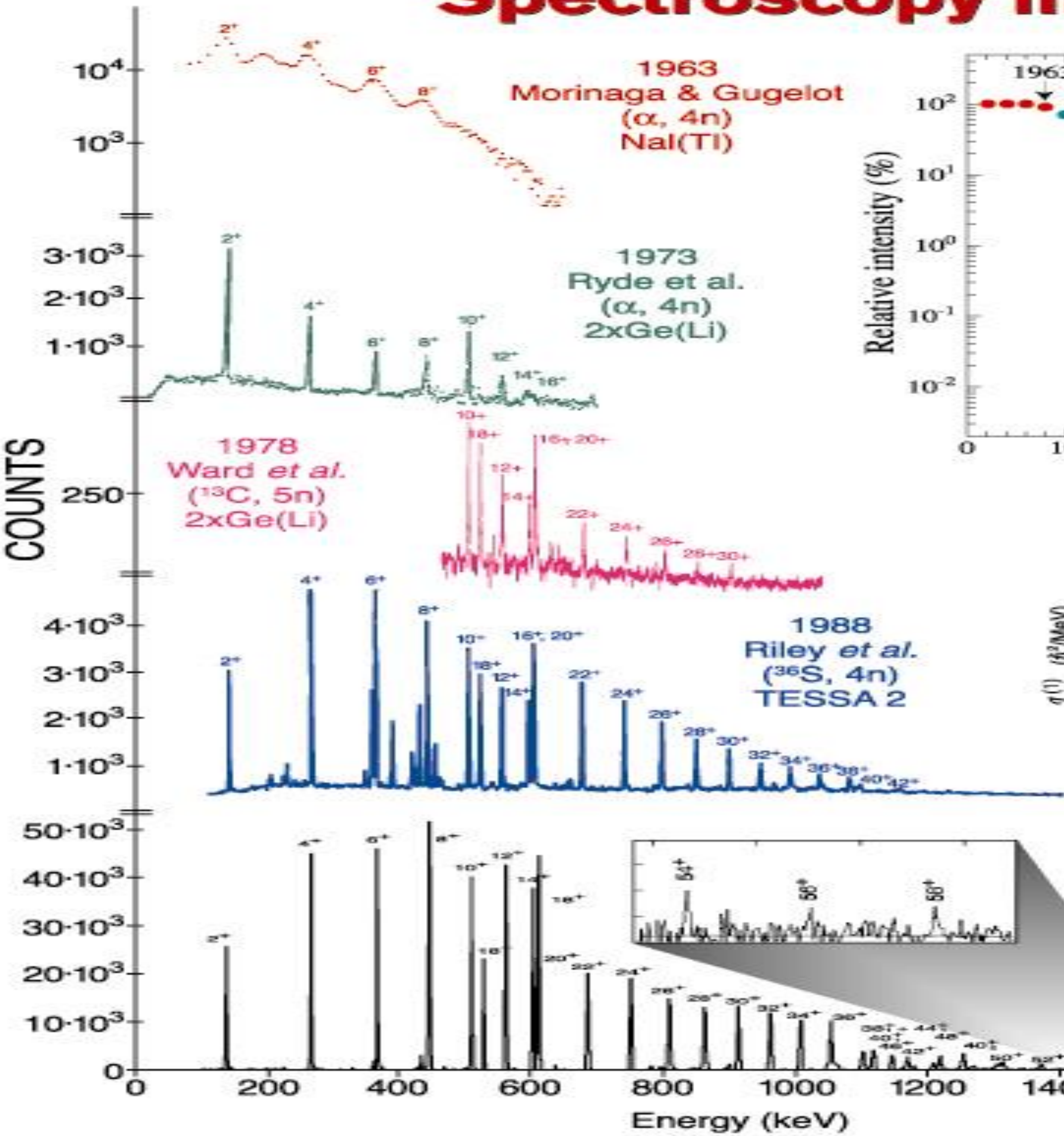


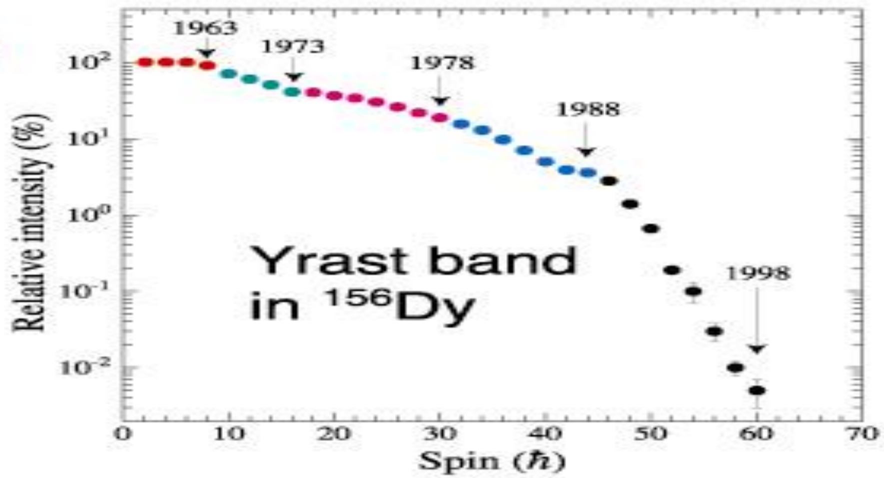


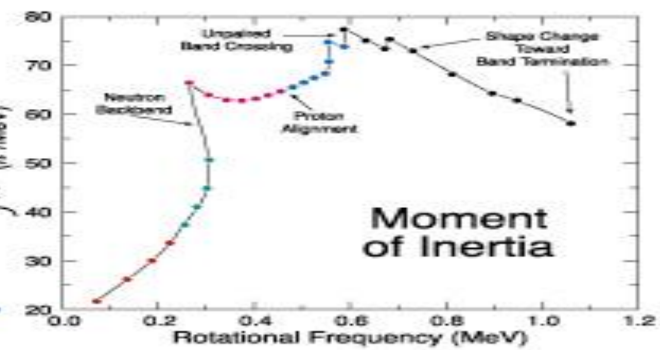




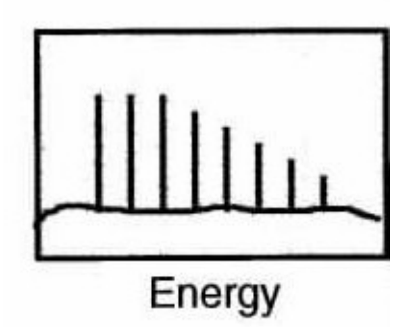
Evolution of High-Spin γ-ray Spectroscopy in ^{156}Dy





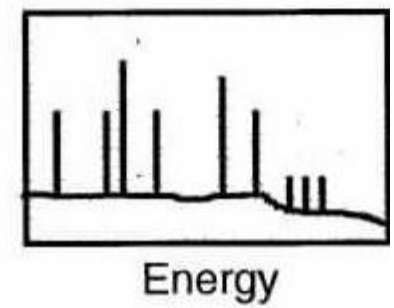


What can we infer from the γ-ray spectra?



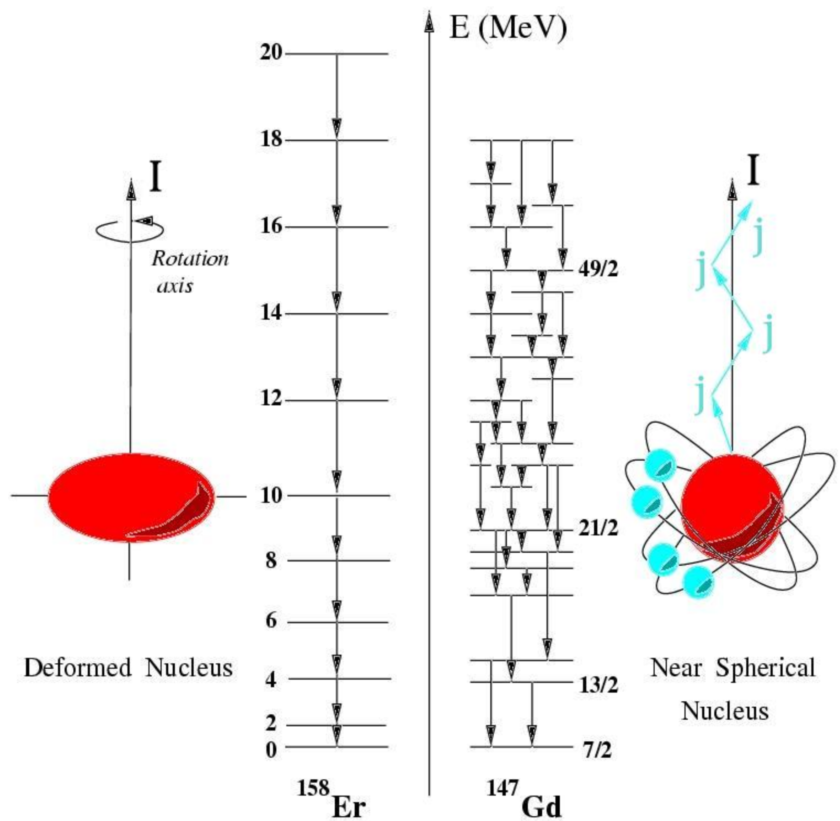
Collective Rotation

Single Particle Alignment



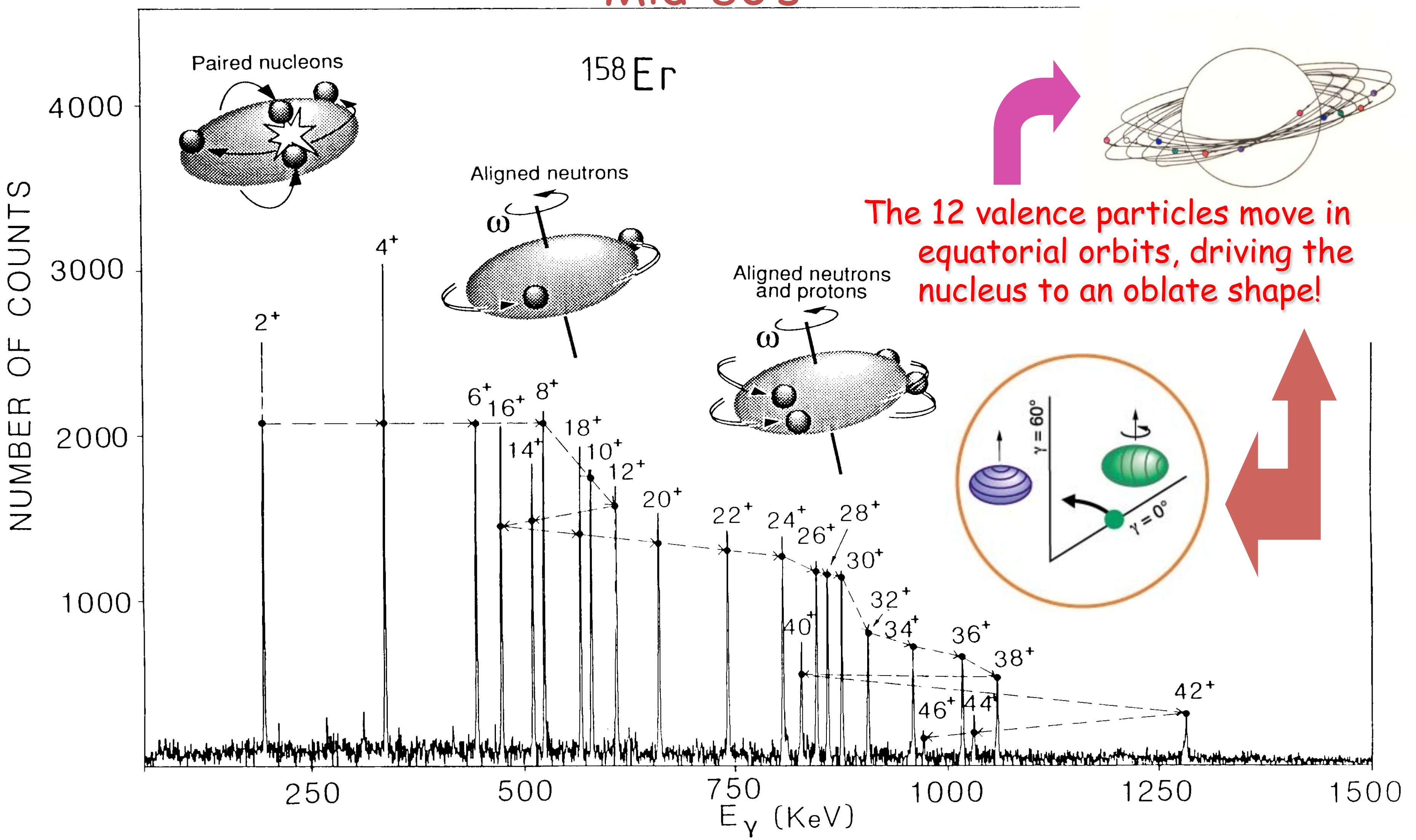
Level Schemes Contain Structural Information

Deformed nucleus rotating about an axis perpendicular to the symmetry axis.



Excitation energy and angular momentum are generated by single particle excitations and continually changing configurations.

^{158}Er expt at Daresbury - Riley/Simpson/Sharpey-Schafer - Mid-80's



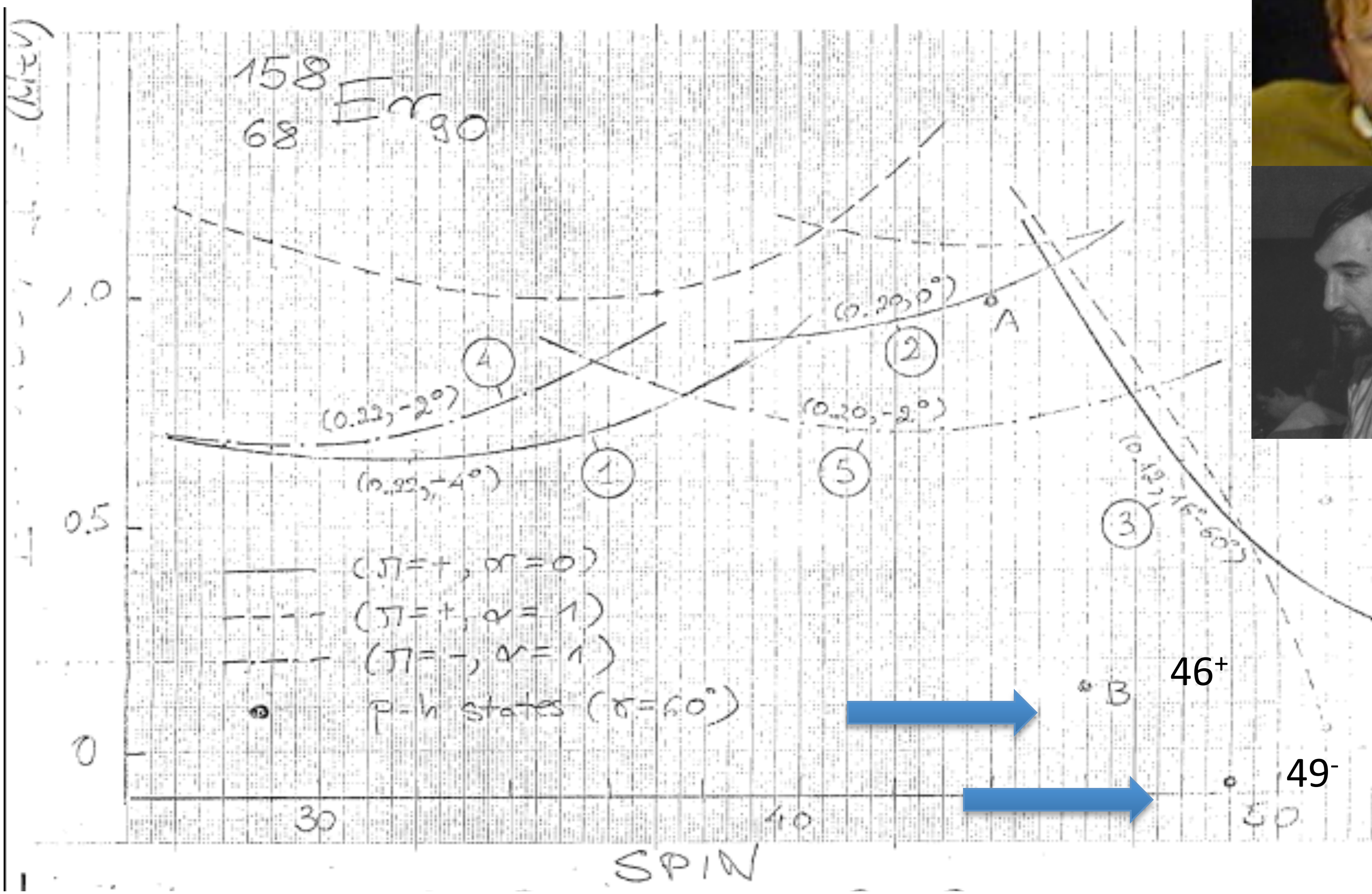
The 12 valence particles move in equatorial orbits, driving the nucleus to an oblate shape!

Simpson et al., Phys. Rev. Lett. (1984) – prolate-oblate shape change
LBL group, P.O.Tjom et al., PRL 55 (1985) 2405 – beautiful lifetime measurements
T.Bengtsson and I.Ragnarsson, Physica Scripta T5 (1983) 165
Ragnarsson, Xing, Bengtsson and Riley, Phys. Scripta 34 (1986) 651

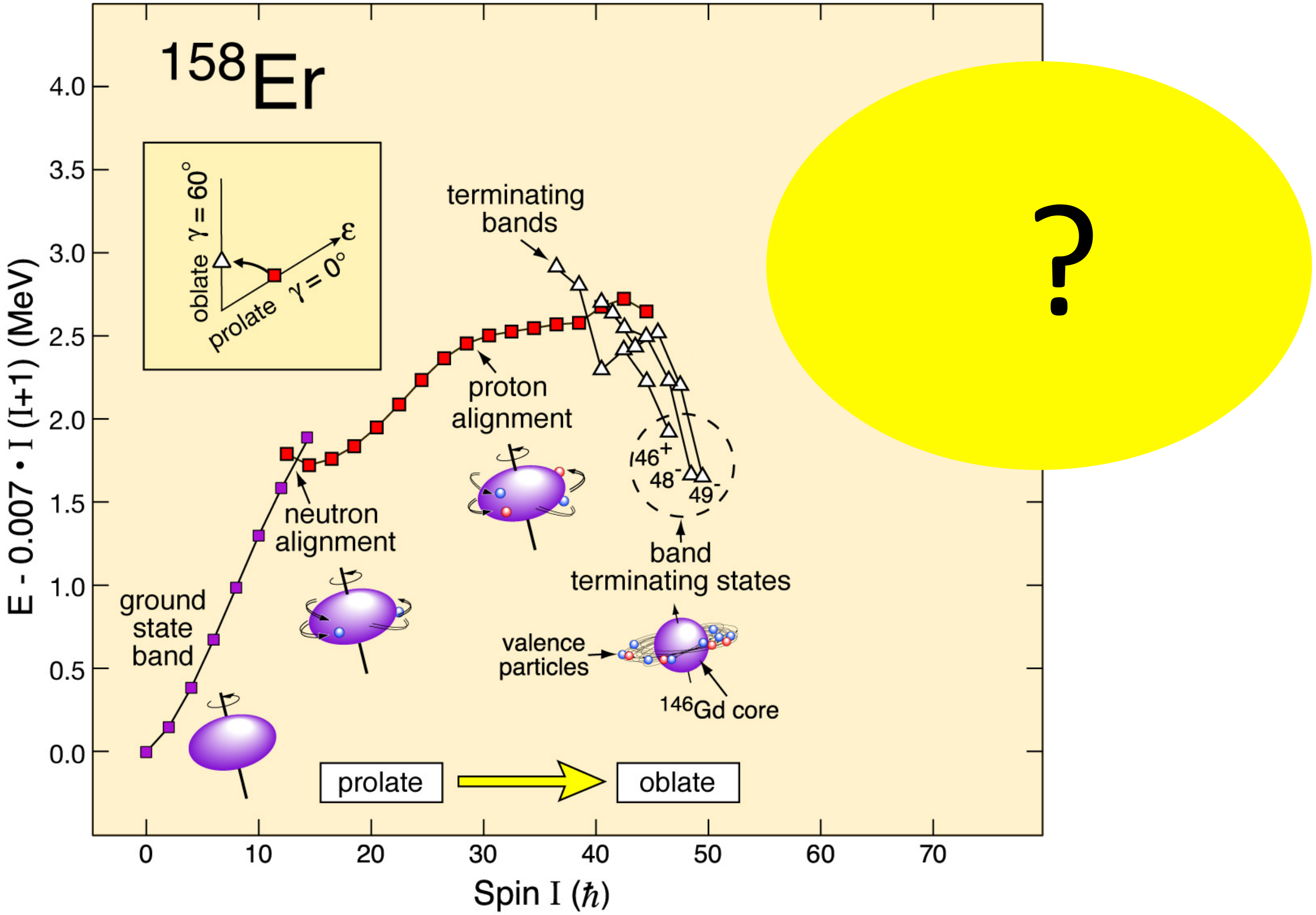
1985: Witek and Jerzy fabulous calculations on ^{158}Er too!

Original hand drawings for the famous 1985 article

Phys. Rev. C31 (1985) 298

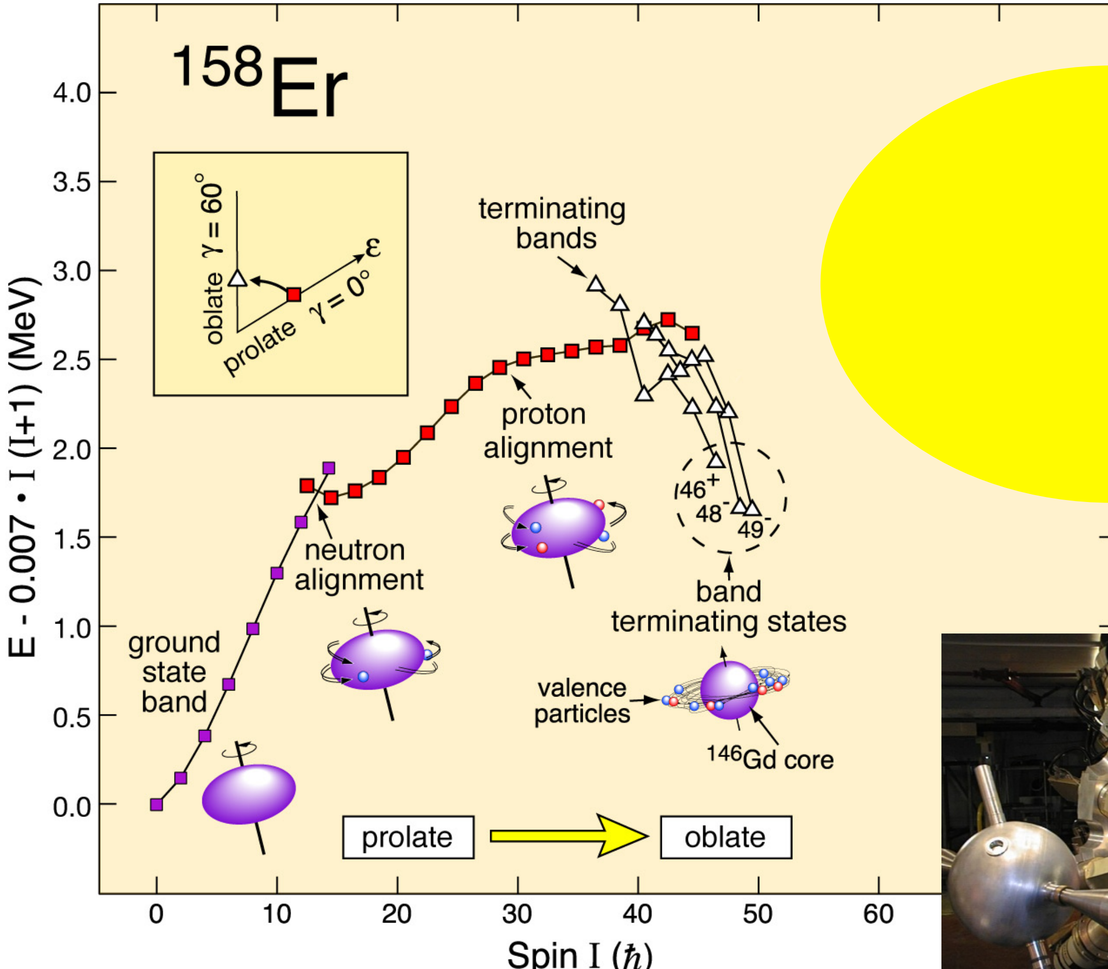


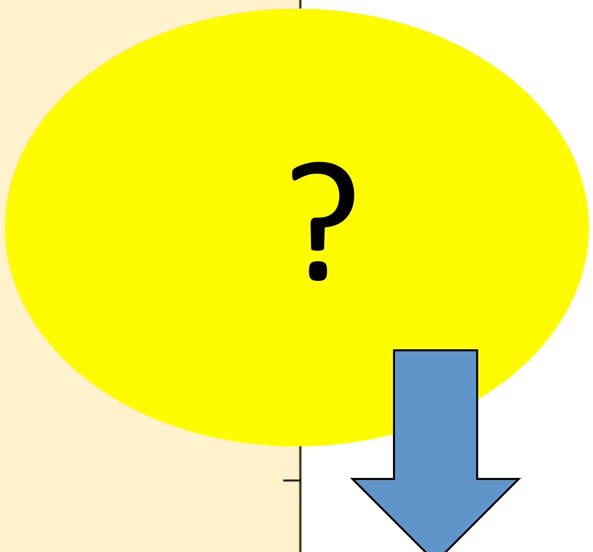
In 90's (EUROGAM 1 – 55 ESS's) more BT states found. BUT WHAT LIES ABOVE BAND TERMINATION?

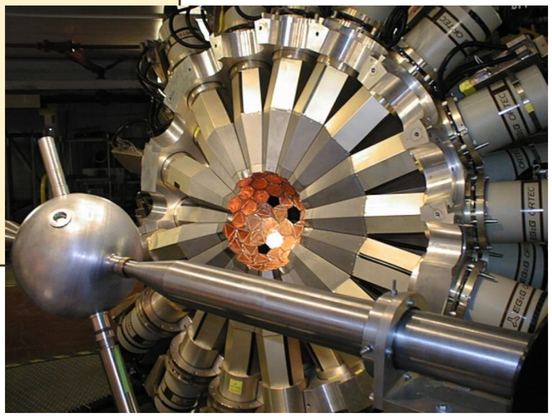


Simpson, Riley et al., Phys. Lett. B 327, 187 (1994)

In 00's…WHAT LIES ABOVE BAND TERMINATION? … Gammasphere at LBL!

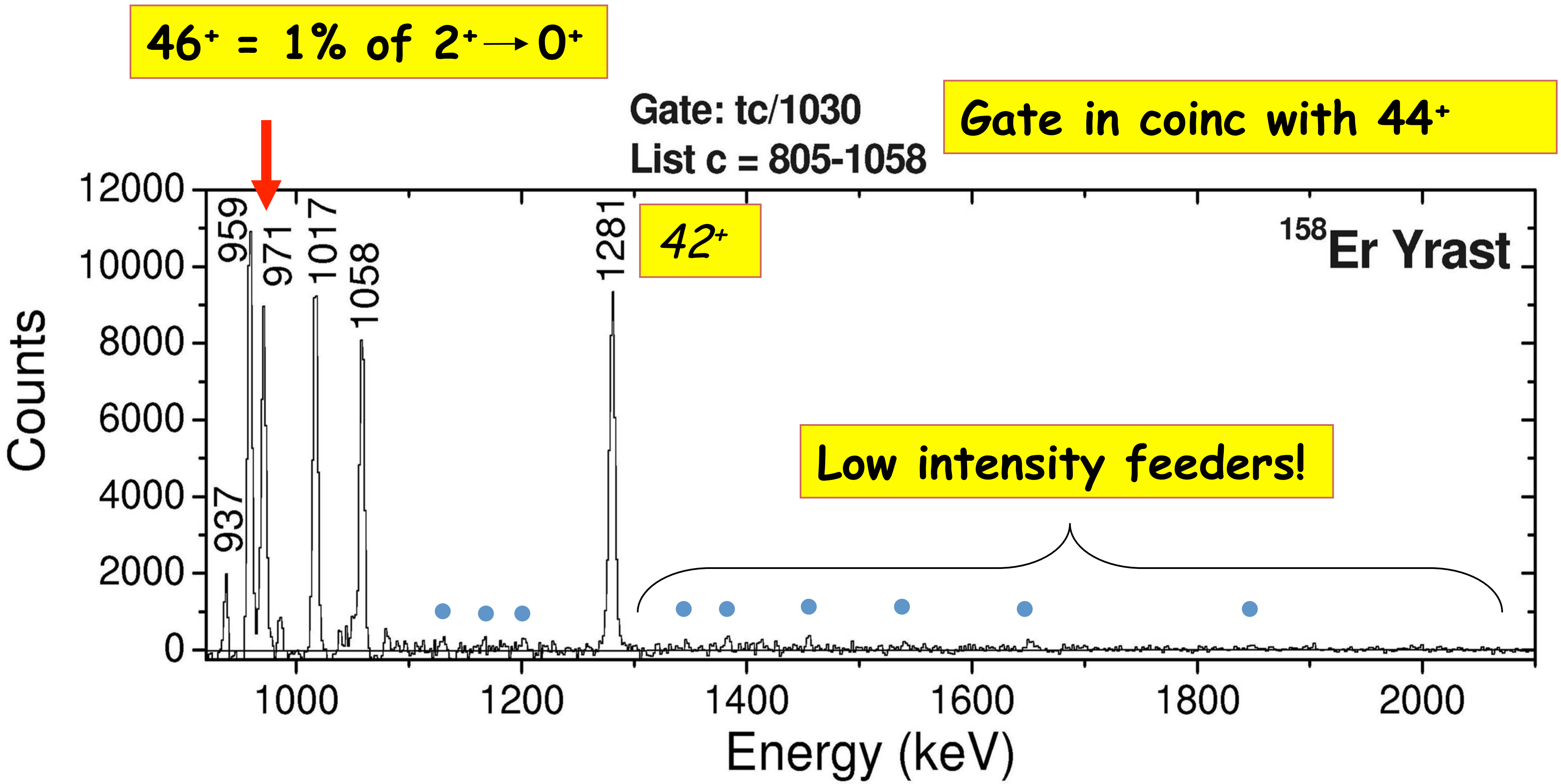






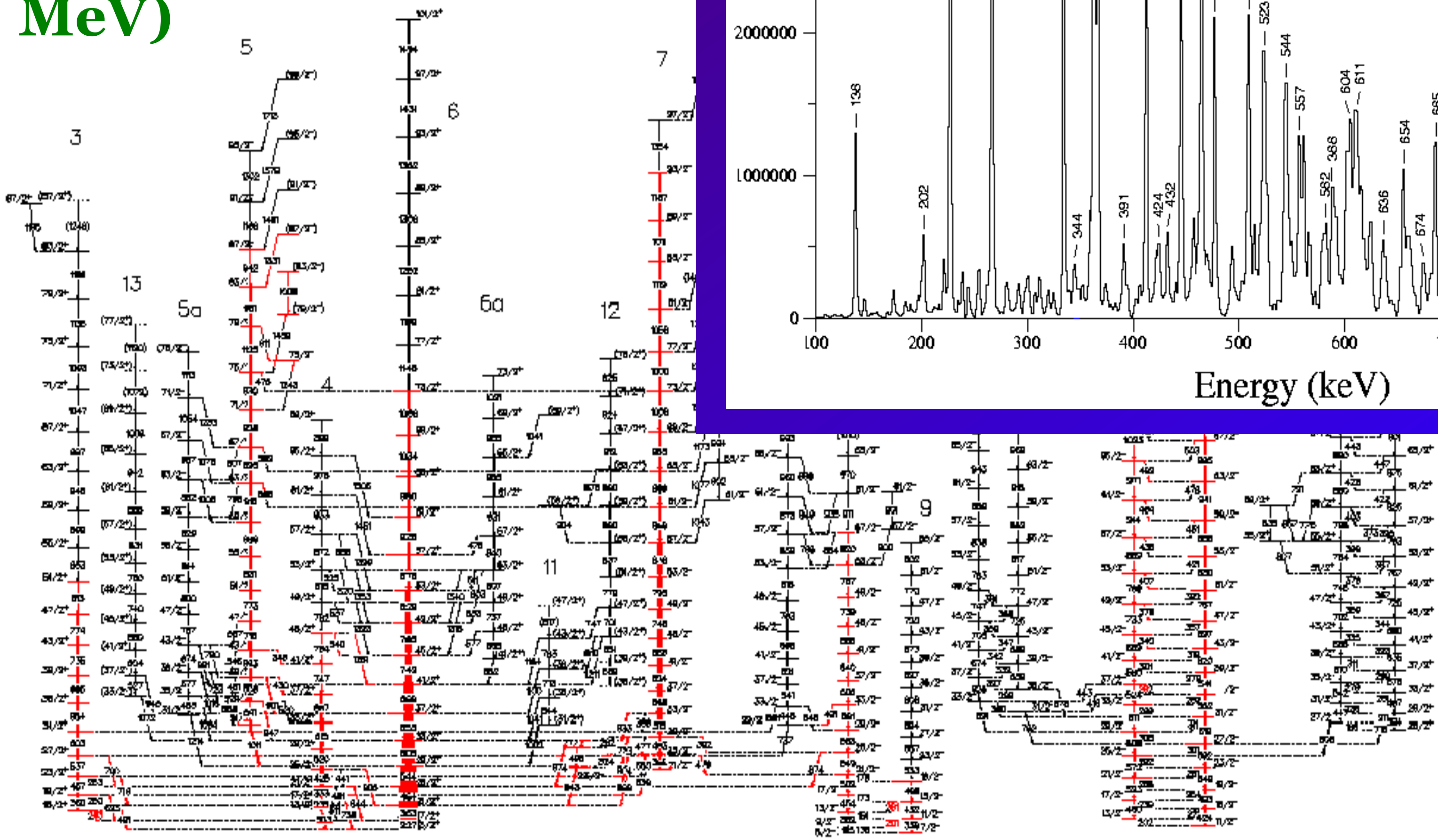
What about ^{158}Er above 46^+?

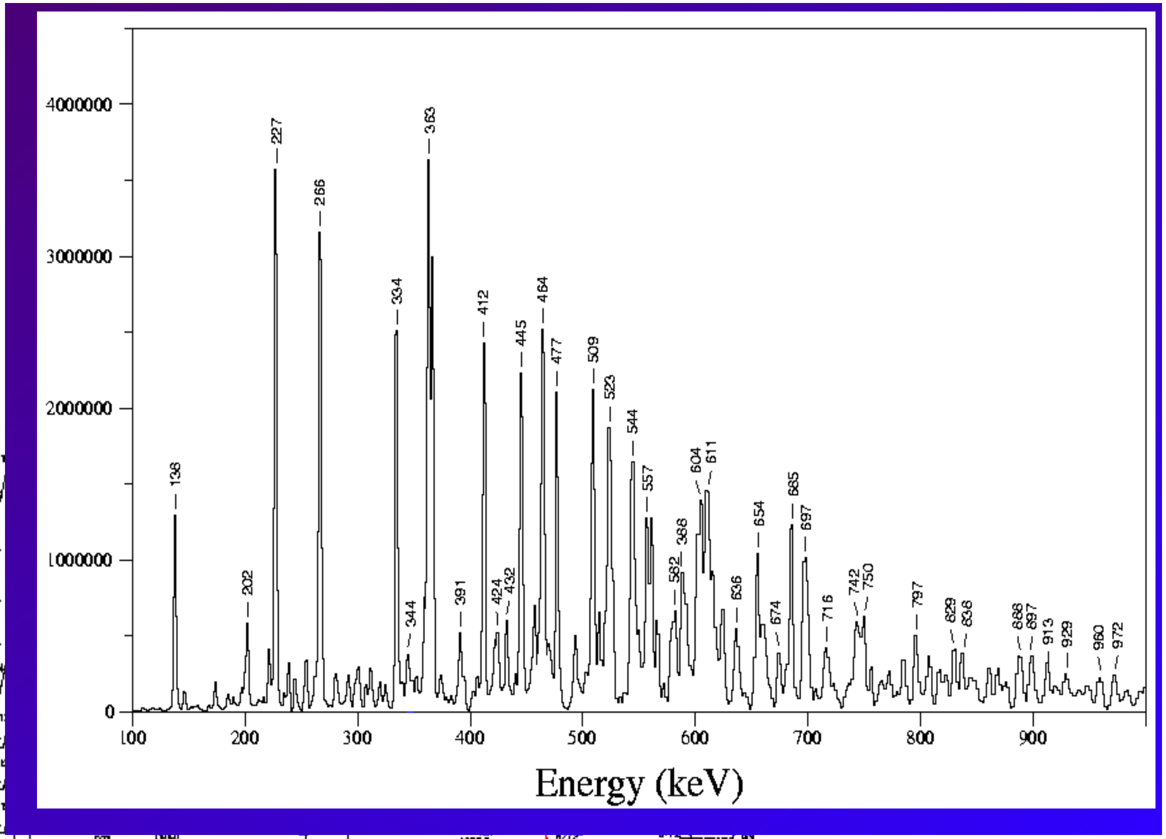
No wonder we could not see it before!



Real Energy Level Schemes and the Total γ-Ray Spectrum

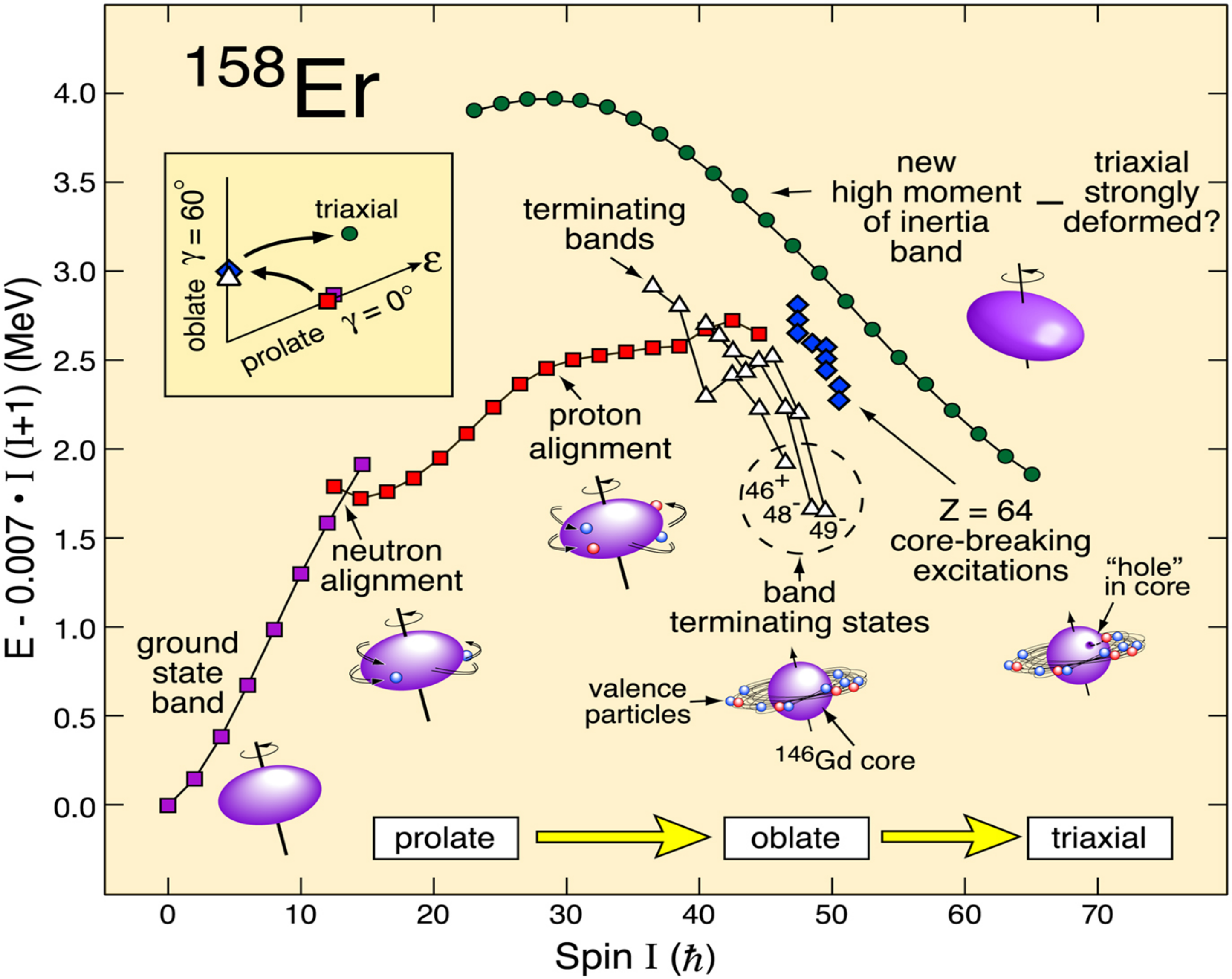
100's & 100's of γ 's
Many open channels
High Spins (60 h)
High Excitations (30 MeV)





Along the Yrast Line ^{158}Er

Paul *et al.*, PRL **98**, 012501 (2007)




LET IT BE
ERBIUM
PORSCHE

Return of Collective Rotation in ^{157}Er and ^{158}Er at Ultrahigh Spin

E. S. Paul,[1] P. J. Twin,[1] A. O. Evans,[1] A. Pipidis,[2] M. A. Riley,[2] J. Simpson,[3] D. E. Appelbe,[3] D. B. Campbell,[2,*] P. T. W. Choy,[1] R. M. Clark,[4] M. Cromaz,[4] P. Fallon,[4] A. Görgen,[4,†] D. T. Joss,[3,‡] I. Y. Lee,[4] A. O. Macchiavelli,[4] P. J. Nolan,[1] D. Ward,[4] and I. Ragnarsson[5]

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(Received 5 September 2006; published 5 January 2007)

A new frontier of discrete-line γ-ray spectroscopy at ultrahigh spin has been opened in the rare-earth nuclei ^{157,158}Er. Four rotational structures, displaying high moments of inertia, have been identified, which extend up to spin $\sim 65\hbar$ and bypass the band-terminating states in these nuclei which occur at $\sim 45\hbar$. Cranked Nilsson-Strutinsky calculations suggest that these structures arise from well-deformed triaxial configurations that lie in a valley of favored shell energy which also includes the triaxial strongly deformed bands in $^{161-167}$Lu.

SUGGESTION

NuPECC REPORT
JULY 2007
High Intensity Stable Beams
In Europe

http://www.nupecc.org/ecos/ECOS-Final.pdf

Research using stable ion beams

1. The quest for super-heavy nuclei

1-a Synthesis
1-b In-beam spectroscopy
1-c Decay studies and isomers
1-d Coulomb and atomic excitation
1-e Chemical studies

2. Nuclear structure studies at low, medium and high-spin

2-a Exotic shapes and decay modes.
2-b Structure of neutron-rich nuclei
2-c Structure of nuclei at and beyond the proton drip-line
2-d Clusters and molecules in nuclei

3. Ground-state properties

3-a Atomic masses
3-b Charge radii and moments

4. Near barrier transfer and fusion reactions

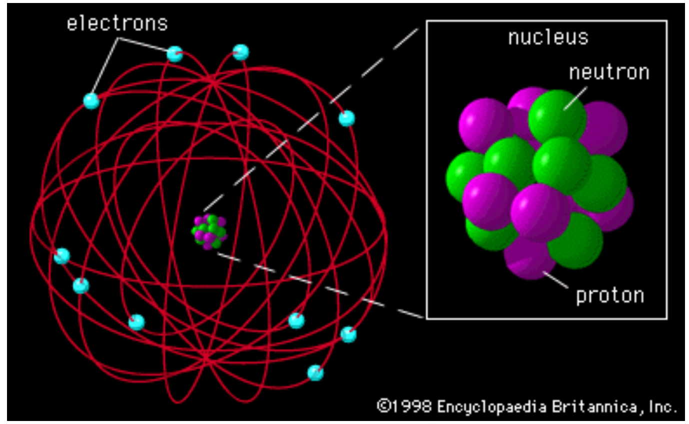
4-a Transfer reactions
4-b Sub-barrier fusion

5. Nuclear astrophysics

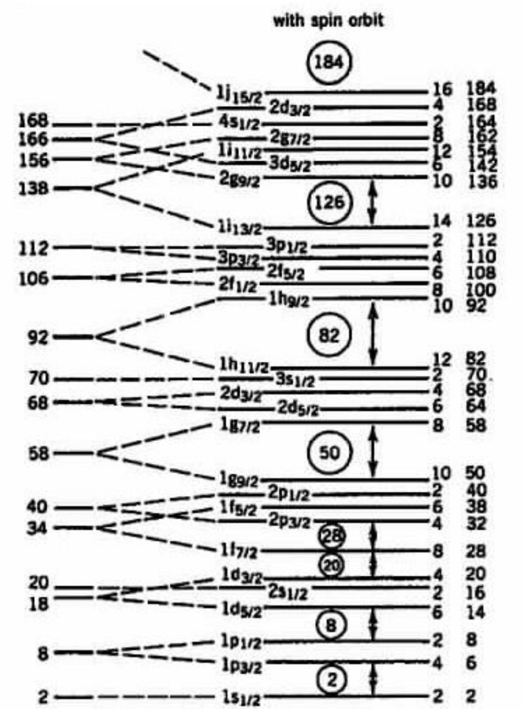
Shell Structure

Atomic

Nuclear



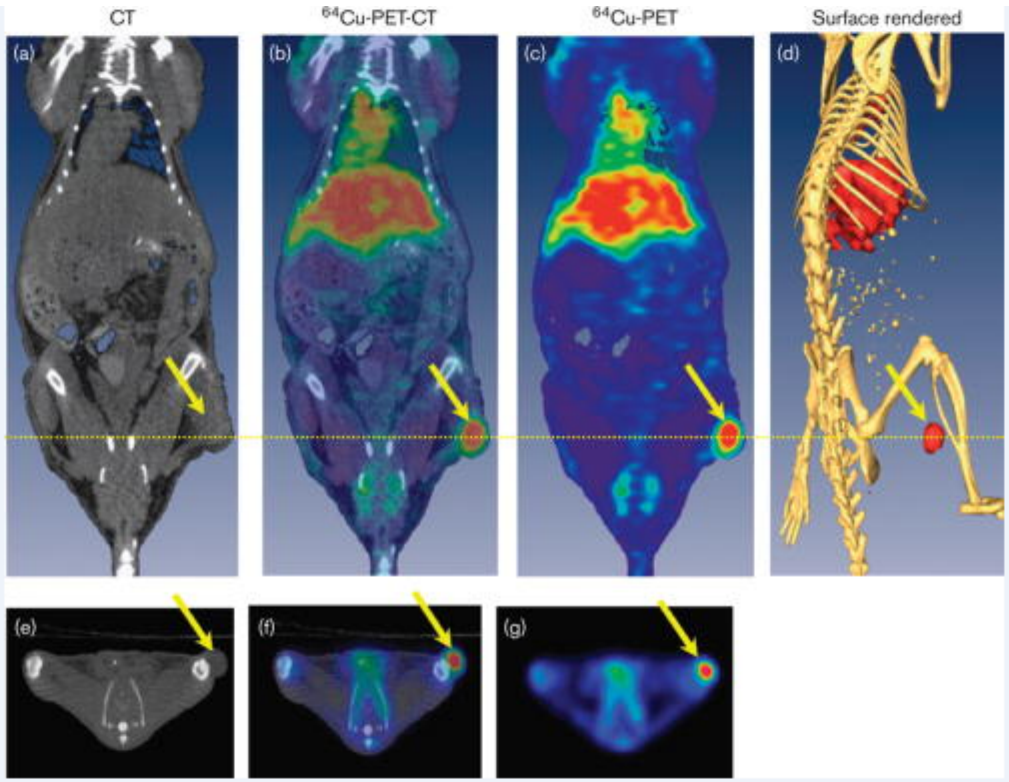
Nucleons



We still have a long way to go before we can say we understand the nucleus. It is a wild and mysterious place!

One example of isotopes for medicine

- ^{64}Cu is presently used to image tumors BUT not therapy.
- ^{67}Cu – could be used to both imaging AND therapy. Listed in *Report on Isotopes for the Nation's Future* as a research priority.



Coronal positron emission tomography /computed tomographic (PET/CT)-slices using ^{64}Cu of a mouse bearing MDA-MB-468 tumor.

(d) Surface-rendered indicating the location of the tumor.

For ^{67}Cu to be attractive to medicine, it must be available throughout the year. (Remember the ^{99m}Tc story.) Production methods can be explored at FRIB and the technology transferred subsequently to a dedicated facility.

Other examples already identified

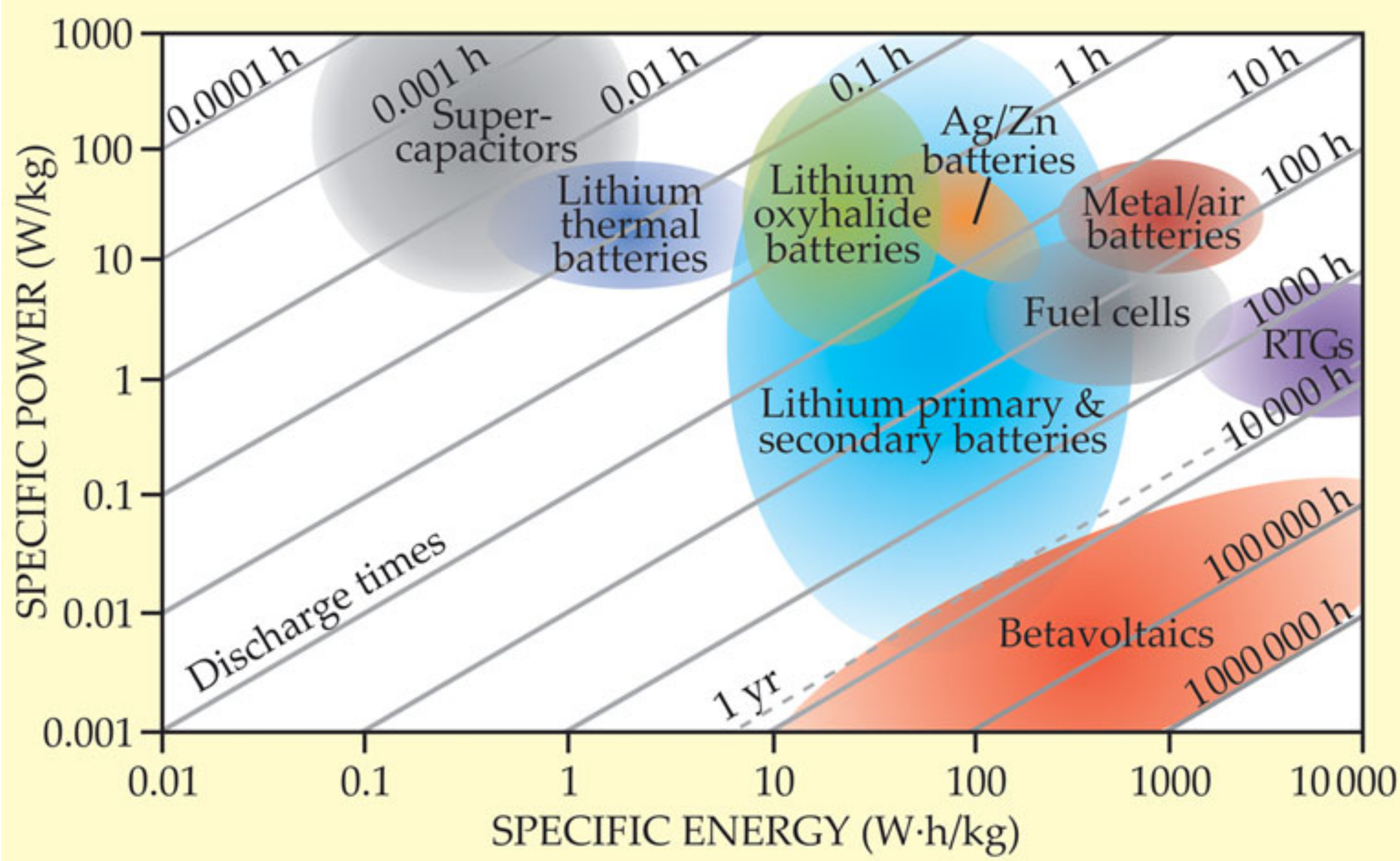
- ^{149}Tb and ^{211}At – targeted radiotherapy using alpha emitters.
- ^{44}Ti -^{44}Sc mother-daughter pair (can be used to image ^{47}Sc used for therapy).

Applied nuclear physics
Betavoltaic power supplies use in things like heart pace makers
(Long life time needed)
December -Physics Today 2012

Idea is to have the beta make an electron-hole pairs that are drawn off as current. If betas too energetic they damage crystal structure and so battery deteriorates over time.
Can operate at low temperatures.

Beta source candidates

Isotope|	Beta energy (keV) average |	Beta energy (keV) maximum |	Half-life (yr) |	Price
Tritium	5.7	18	12.3	~$3.50/ curie
Nickel-63	18	67	92	~$4000/ curie
Promethium-147	62	225	2.6	N/A

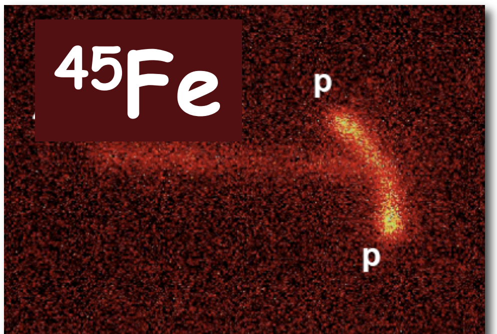


Betavoltaics supply low power over a long lifetime, making them unique among energy-storage devices, including chemical batteries, fuel cells, supercapacitors, and radioisotope thermoelectric generators. RTGs use more aggressive radioisotopes, such as polonium-210 or plutonium-238, to generate heat, which is then converted into electricity via the Seebeck effect. (For more on chemical batteries and supercapacitors, see the article by Héctor Abruña, Yasuyuki Kiya, and Jay Henderson in *Physics Today*, December 2008, page 43 .)

Some nuclei are more important than others

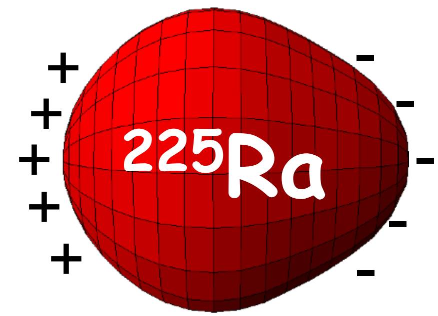
Over the last decade, tremendous progress has been made in techniques to produce and describe *designer nuclei*, rare atomic nuclei with characteristics adjusted to specific research needs and applications

nuclear structure

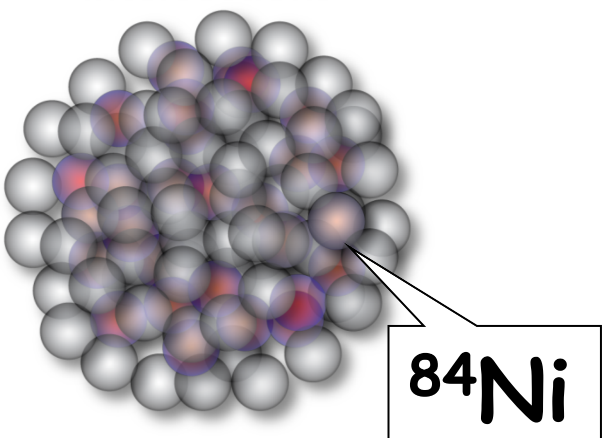


astrophysics

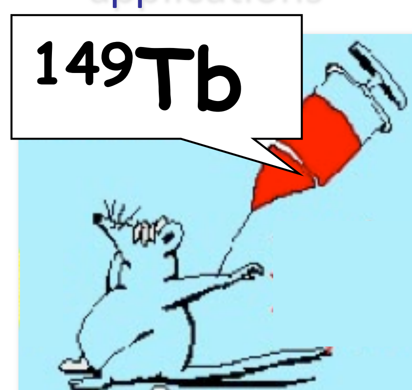
tests of fundamental laws of nature



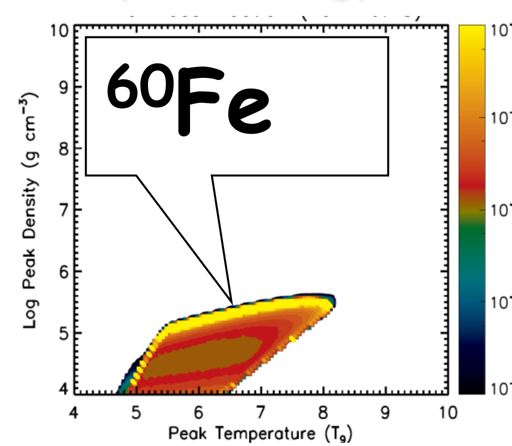
intersections



applications



paleontology



The Alchemist's Dream Come True: nuclear physicists can transmute the elements (designer nuclei)

^{45}Fe: decays by emitting a pair of protons thus telling us about proton superconductivity

^{26}Al, ^{44}Ti: rare isotopes synthesized in Nova explosions

^{80}Ni – skins, neutron stars

^{225}Ra: Why More Matter than Antimatter? CP violation through EDM searches

^{149}Tb: an "alpha knife" radionuclide that kills cancer cells

Thank you for your attention-
you face a wonderfully bright future

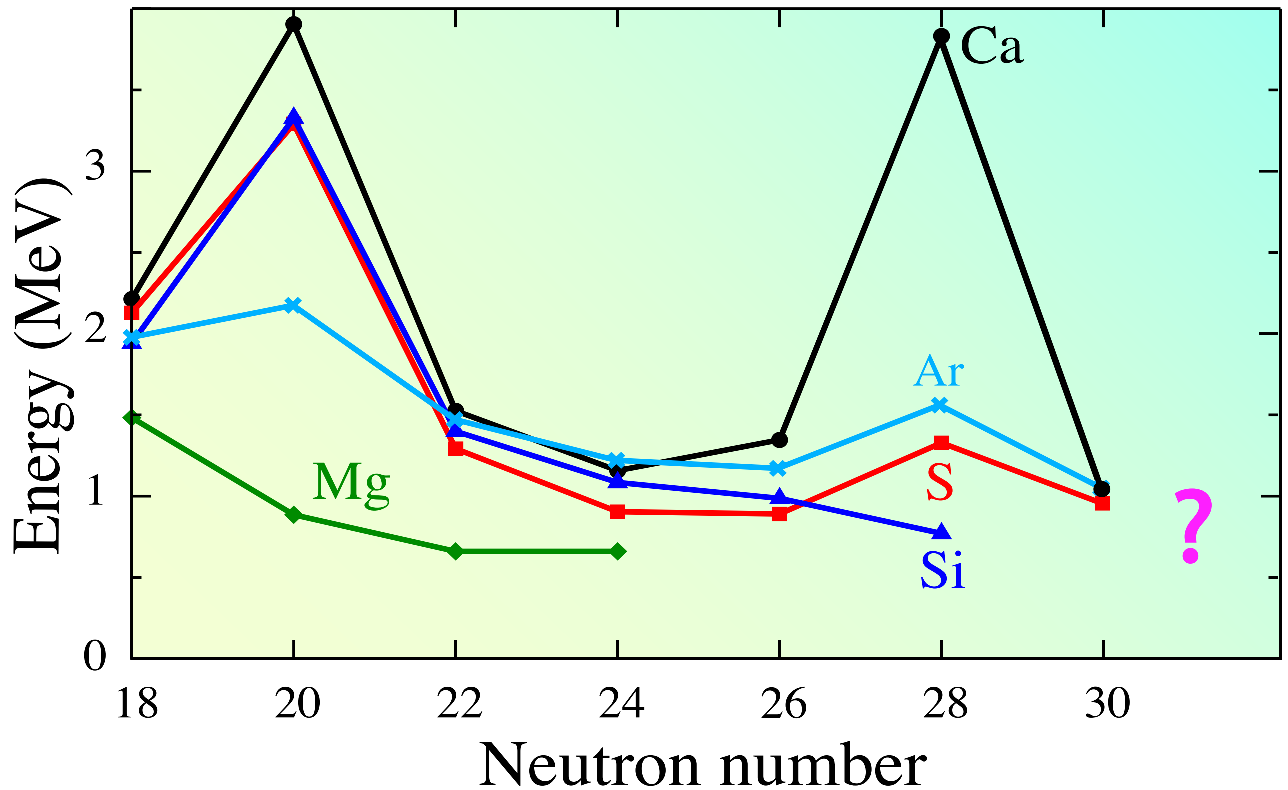


Figure 4: Measured energies of the lowest 2^+ states in the neutron-rich even-even Mg, Si, S, Ar, and Ca isotopes. A high value indicates a magic number. Low values signal the development of collective behavior**.** The plot indicates that the traditional N=20 and 28 magic numbers vanish in rare isotopes. (Courtesy of A. Gade.)

How does subatomic matter organize itself and what phenomena emerge?

How can finite nuclei exhibit phase transitional behavior?

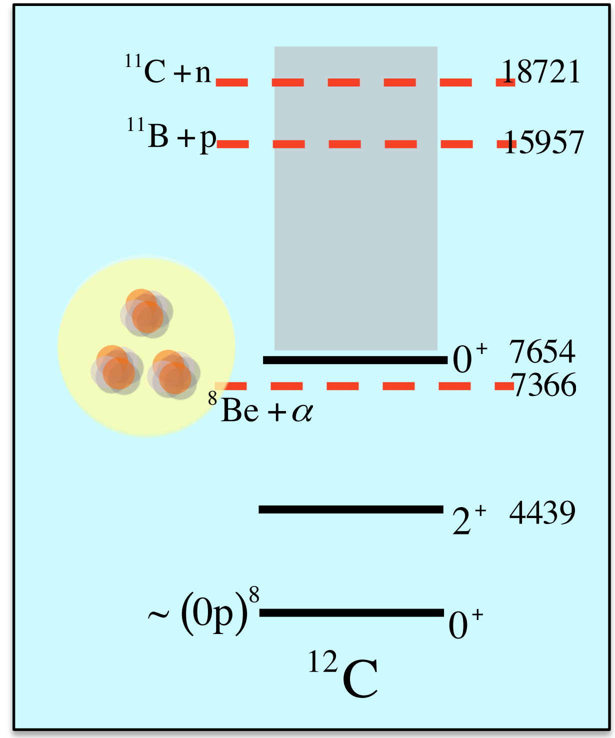
- Studies of phase transitions between regions characterized by different many-body symmetries. Critical- and triple point searches as a function of particle number, spin, and temperature. Re-entrant phenomena.

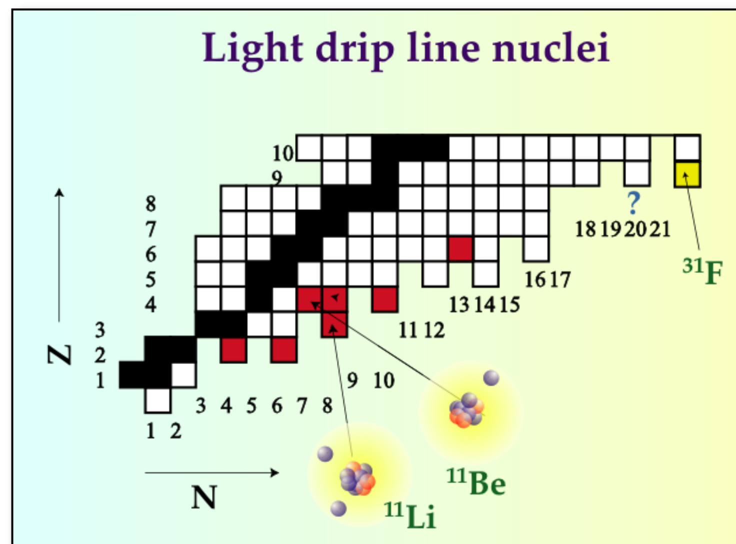
What is the nature of emergent phenomena in atomic nuclei?

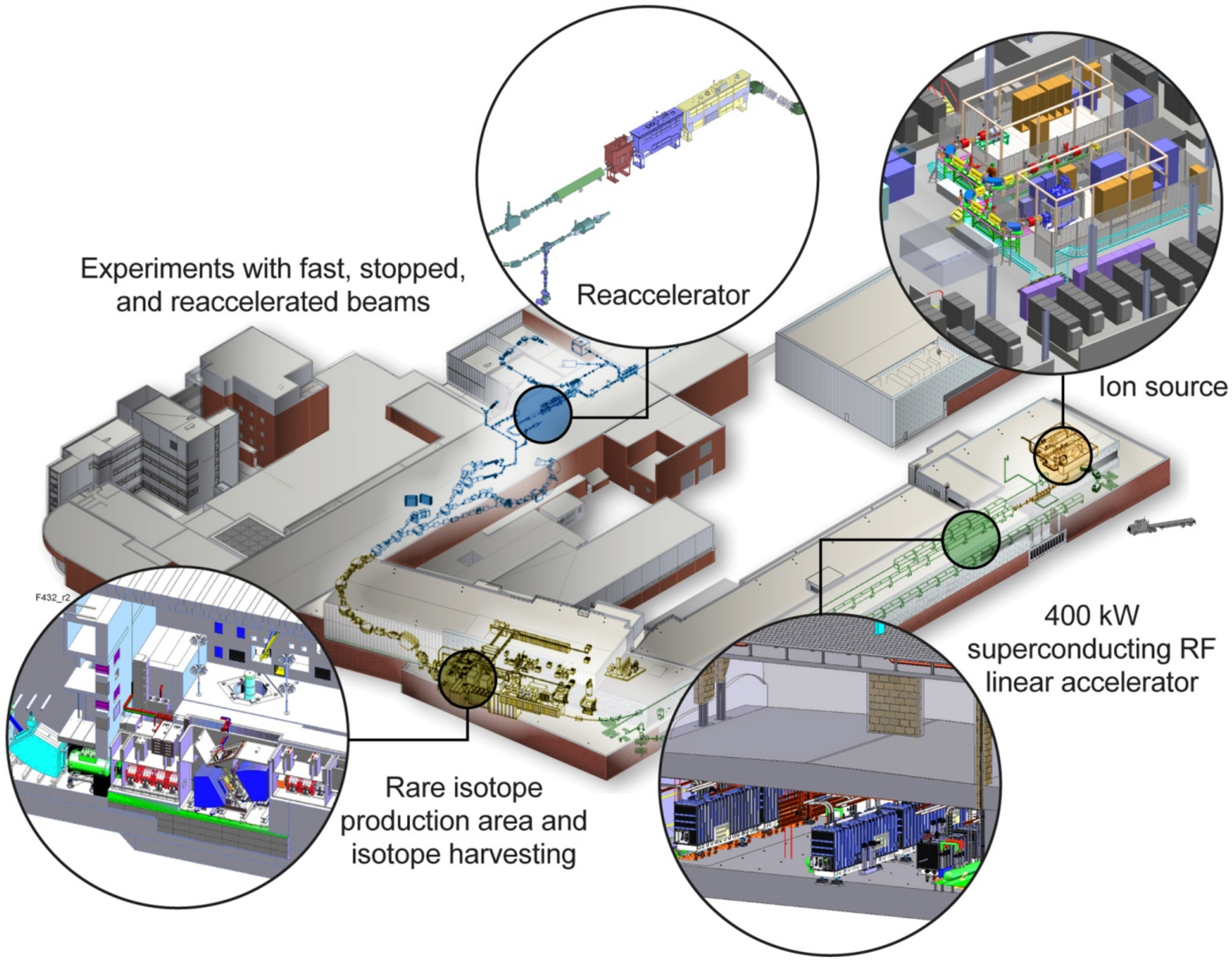
- Studies of nucleonic pairing in various spin and isospin channels, in finite nuclei and extended nucleonic matter.
- Studies of new collective modes related to skins and angular momentum (magnetic modes).
- Studies of the large-amplitude collective motion, such as fission and shape coexistence.

How can nuclear structure and reactions be described in a unified way?

- Understanding the role of the particle continuum on properties of weakly bound and unbound nuclear states, including halos. Elucidating the role of reaction thresholds on appearance of collective cluster states.







New facility for making intense radioactive beams at Michigan State University, Lansing, Michigan-The facility goes by FRIB