Nuclear Structure IV

experimental

MICHIGAN STATE UNIVERSITY
Advancing Knowledge. Transforming Lives.

Sunday

Monday

Thursday

Friday

Lifetimes of excited states

Population of excited states in decays

Shapes, rotations and simple patterns

The heaviest elements

Lifetimes of excited states

Lifetimes of excited 2^+ states in
even-even nuclei: picosecond range

$$\tau_\gamma = 40.81 \times 10^{13} E^{-5} [B(E2)\uparrow/\mathrm{e}^2\mathrm{b}^2]^{-1}$$

Some excited states live much longer: Isomers

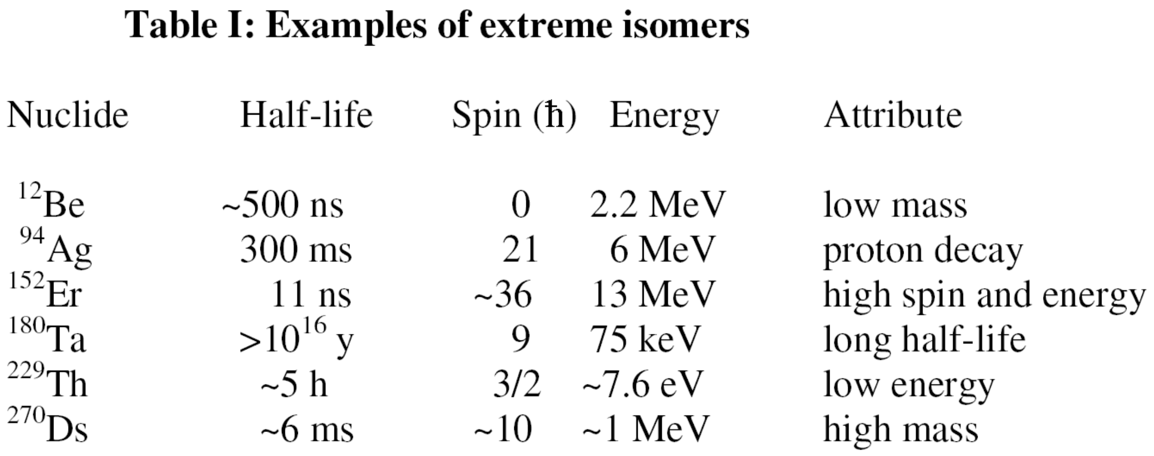


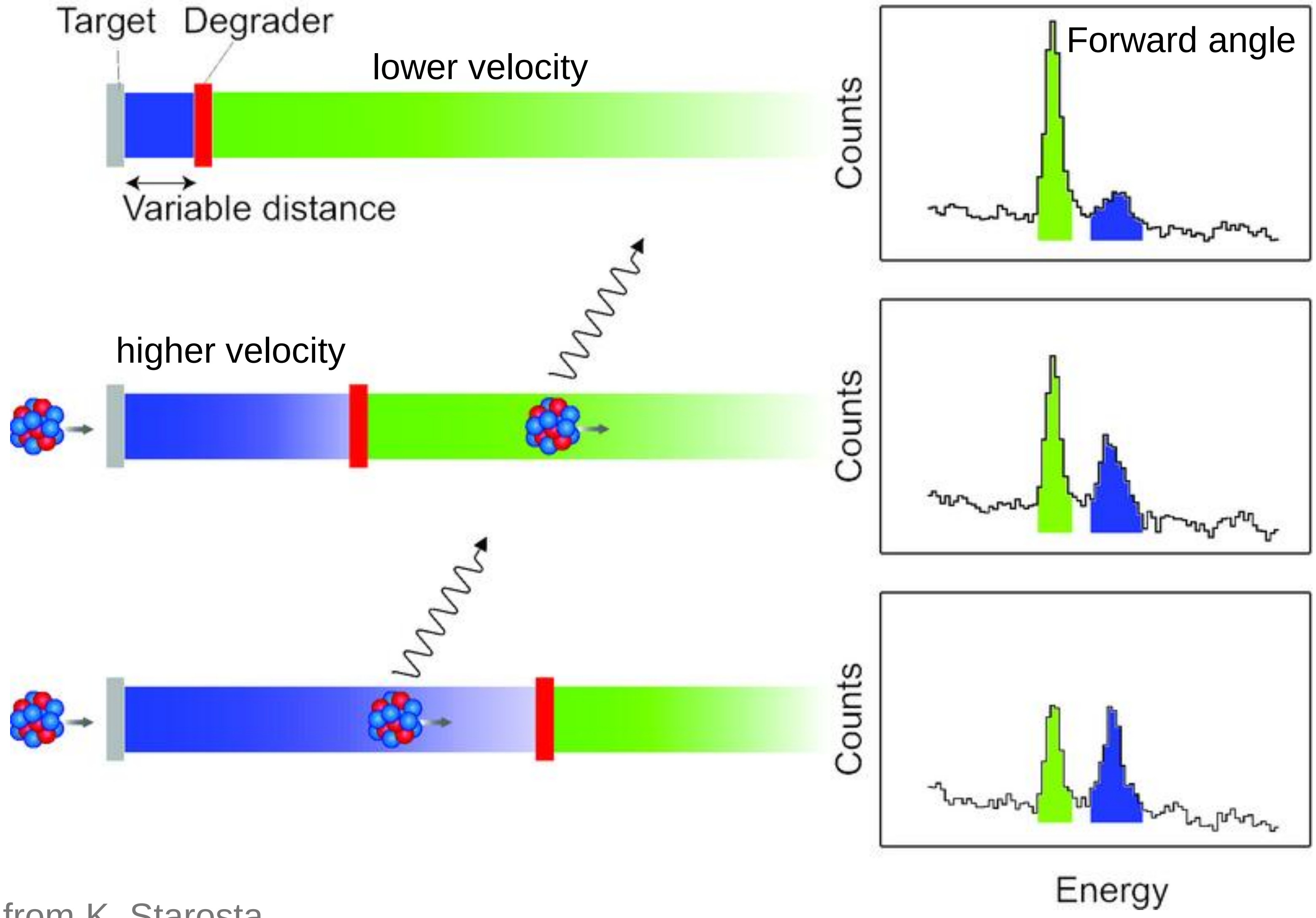
Table I: Examples of extreme isomers

Nuclide	Half-life	Spin (ħ)	Energy	Attribute
^{12}Be	~500 ns	0	2.2 MeV	low mass
^{94}Ag	300 ms	21	6 MeV	proton decay
^{152}Er	11 ns	~36	13 MeV	high spin and energy
^{180}Ta	>10^{16} y	9	75 keV	long half-life
^{229}Th	~5 h	3/2	~7.6 eV	low energy
^{270}Ds	~6 ms	~10	~1 MeV	high mass

From P.M. Walker and J. J. Carroll, Nuclear Physics News 17, 11-15 (2007)

Plunger lifetime measurements

c=300 μm/ps **β ~ 0.3c** **10 ps ~ 1mm**

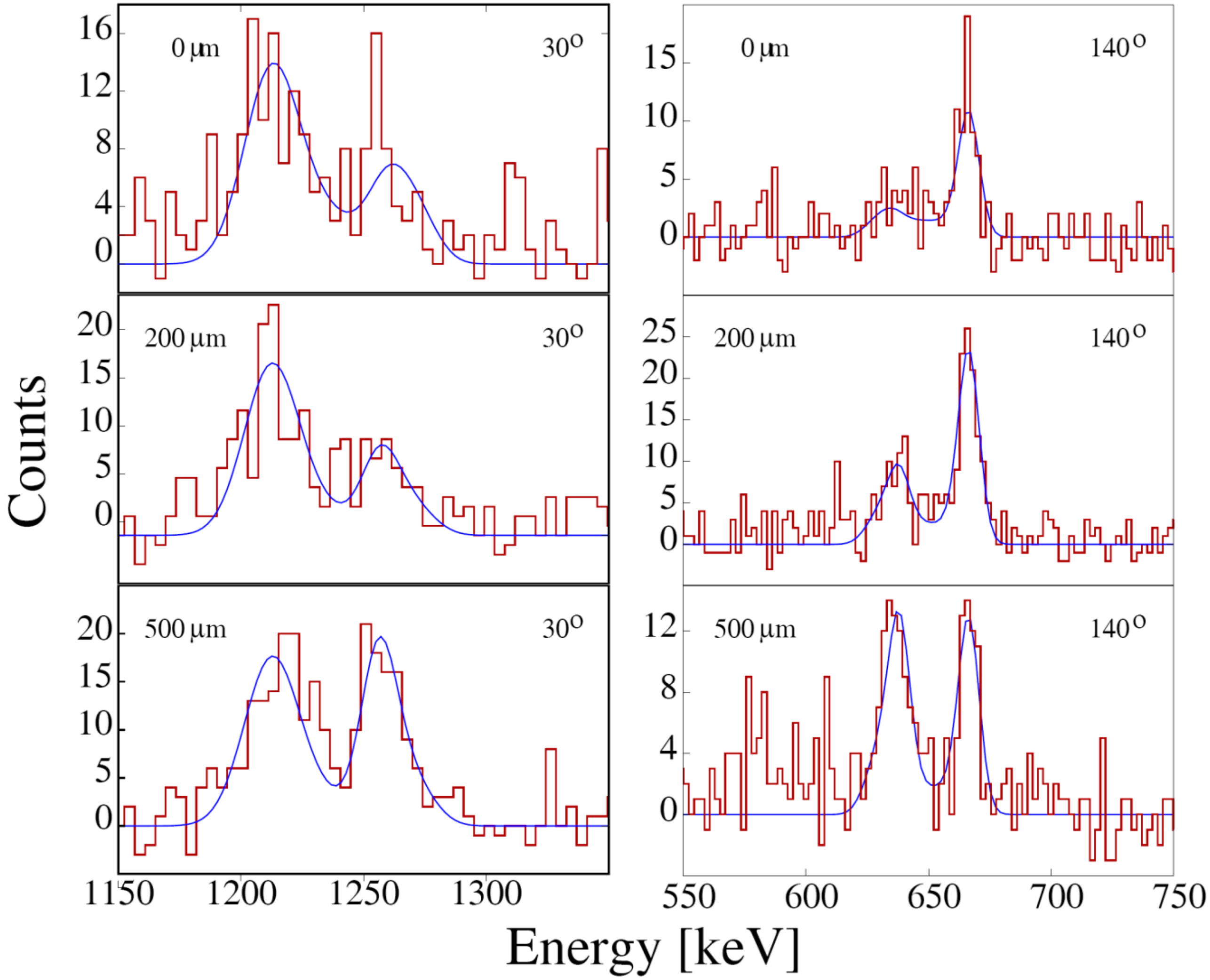


Adapted from K. Starosta

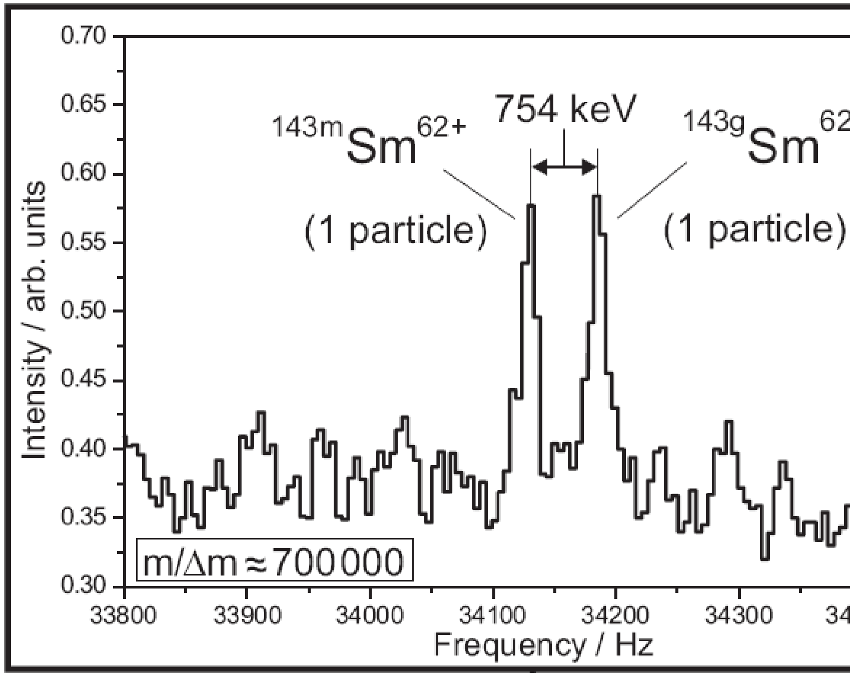
Line shapes and lifetimes

Example: ^{64}Ge $2^+_1 \rightarrow 0^+_1$

τ=3.2(5) [ps]

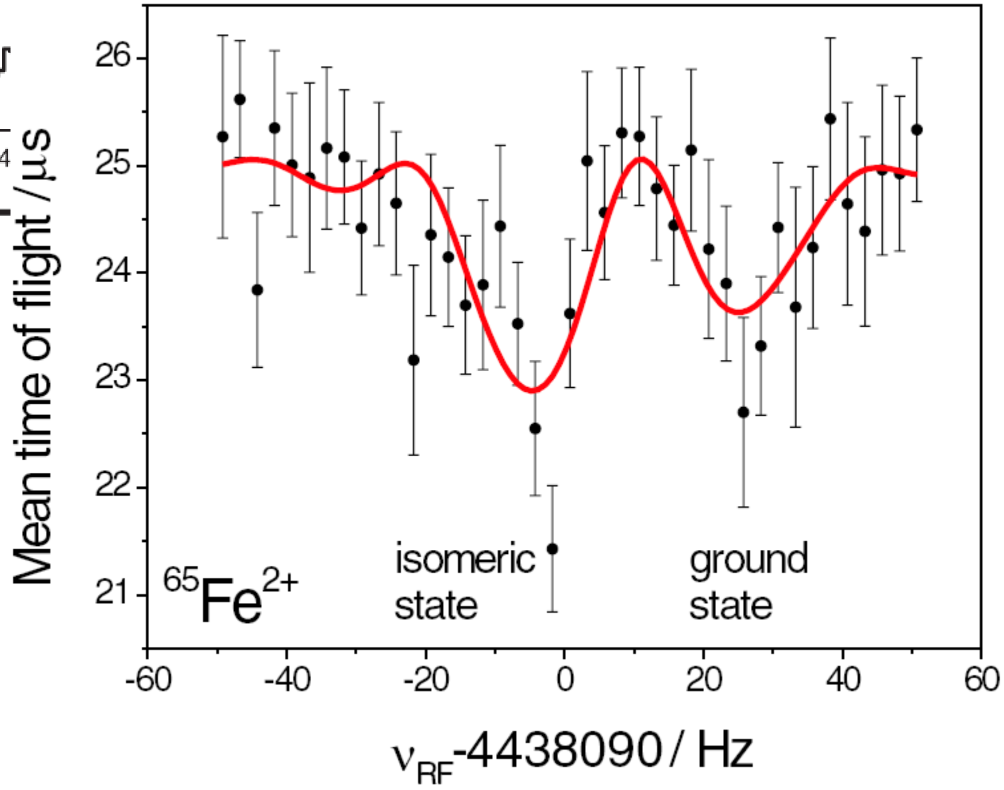


Long-lived excited states – isomers
Back to storage rings and penning traps



F. Bosch, Lect. Notes Phys. 651, 137(2004)

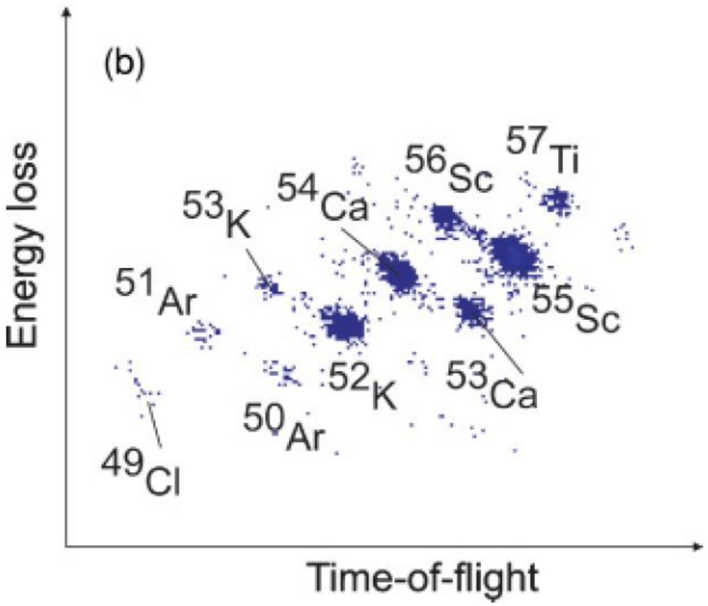
M. Block et al., PRL 100, 132501 (2008)



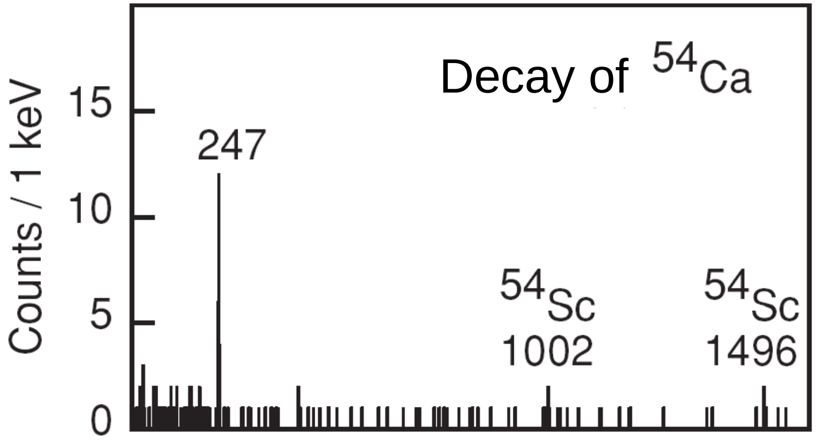
Isomers: decay hindered by nuclear structure (selection rules, energy, …) → long lifetime

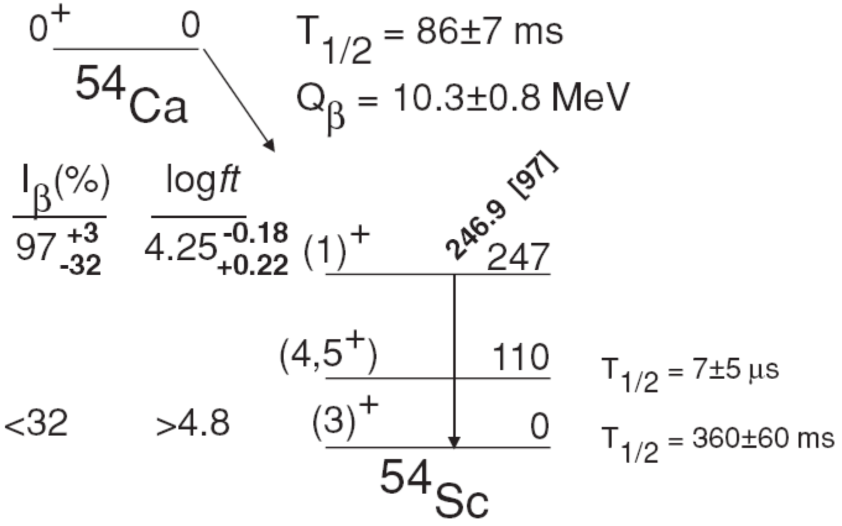
Excited states populated in decays

Excited states populated in β decay
Selectivity through selection rules



Total number of ^{54}Ca implants: 654 only



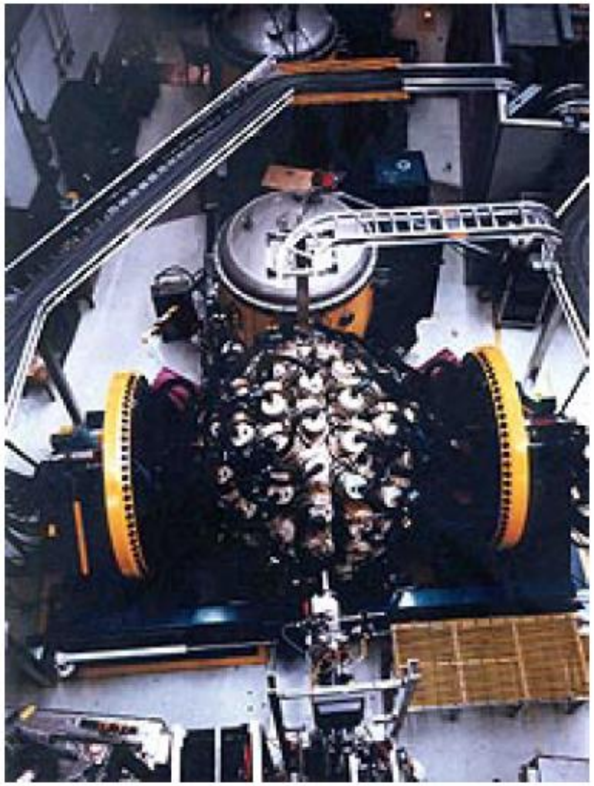


Selection rules in β decay, any textbook

Type	ΔJ	Δπ
Allowed	0,1	no
First Forbidden	0,1,2	yes
Second Forbidden	1,2,3	no
Third Forbidden	2,3,4	yes
Fifth Forbidden	3,4,5	no

P. F. Mantica et al., PRC 77, 014313 (2008)

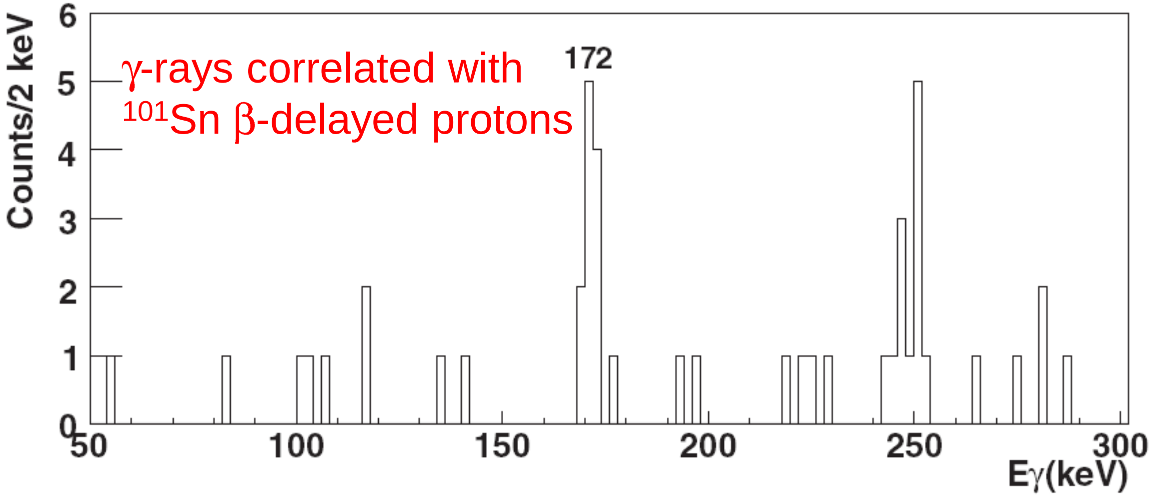
γ-ray spectroscopy tagged with β-delayed protons



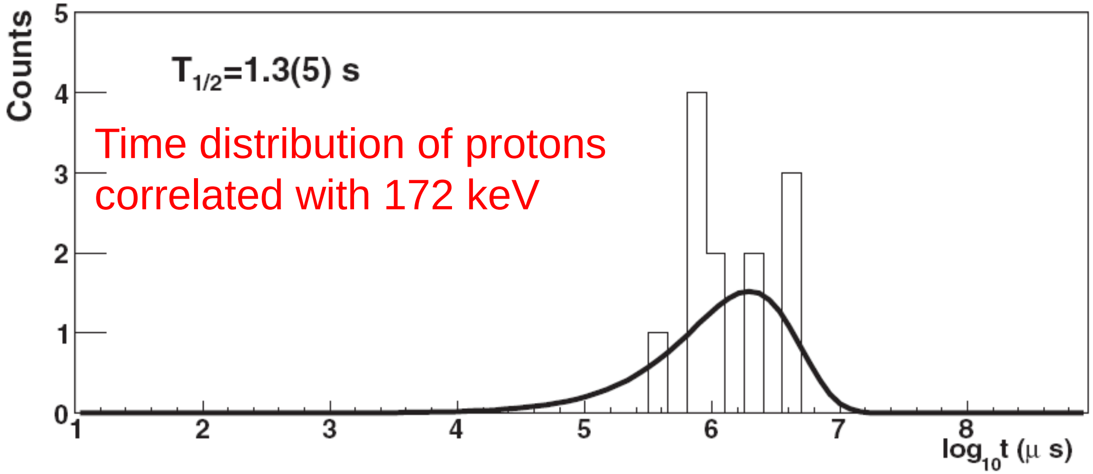
Single-neutron states above doubly magic ^{100}Sn:

$d_{5/2} – g_{7/2}$ ~ 172 keV

^{58}Ni+^{46}Ti at 192 MeV (ATLAS/ANL)



γ-rays correlated with ^{101}Sn β-delayed protons

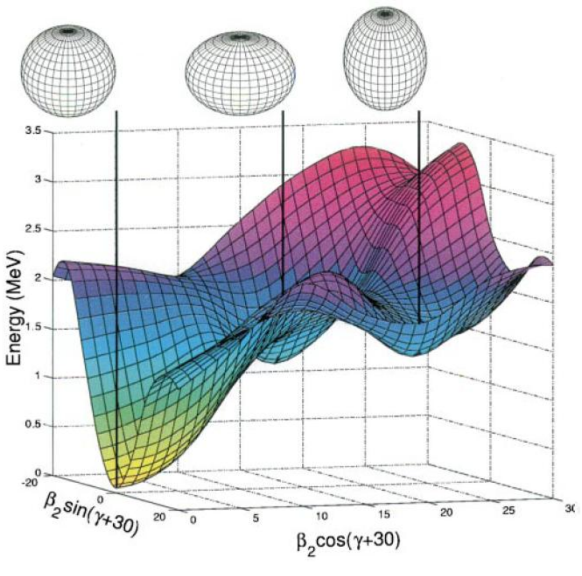


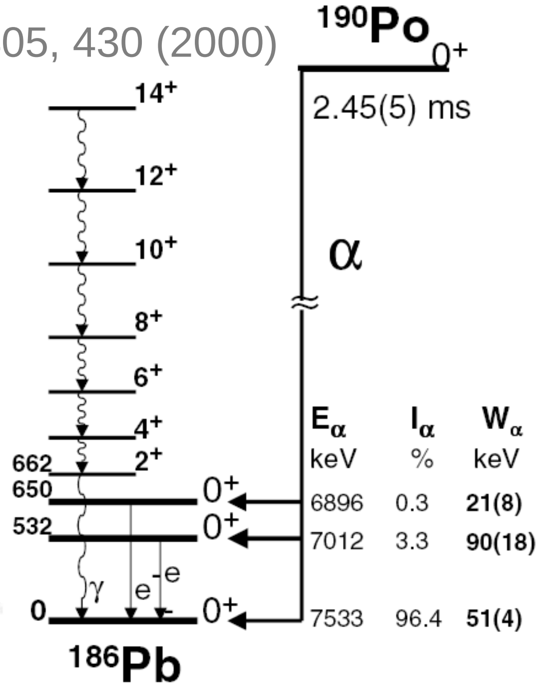
Time distribution of protons correlated with 172 keV

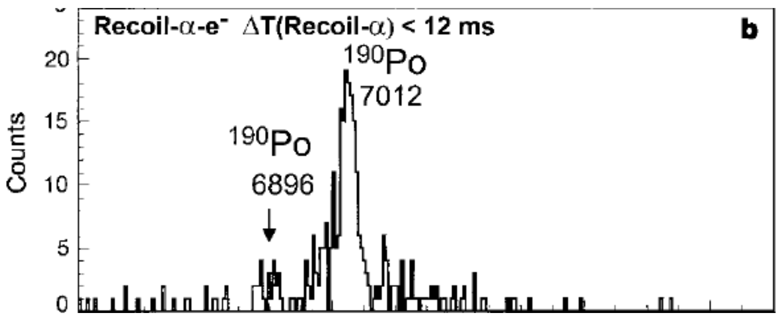
D. Seweryniak et al., PRL 101, 022504 (2007)

Excited states populated following α and proton emission

A. N. Andreyev et al., Nature 405, 430 (2000)

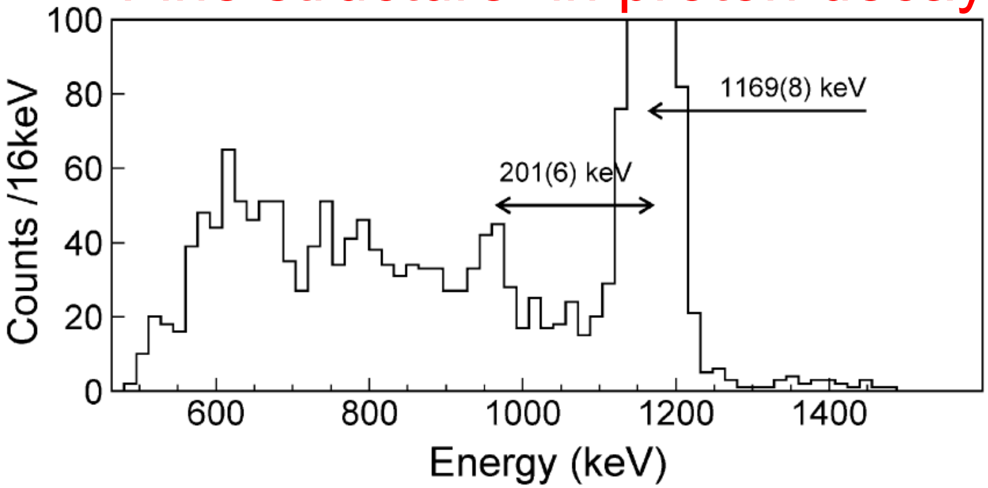






“Fine structure” in proton decay

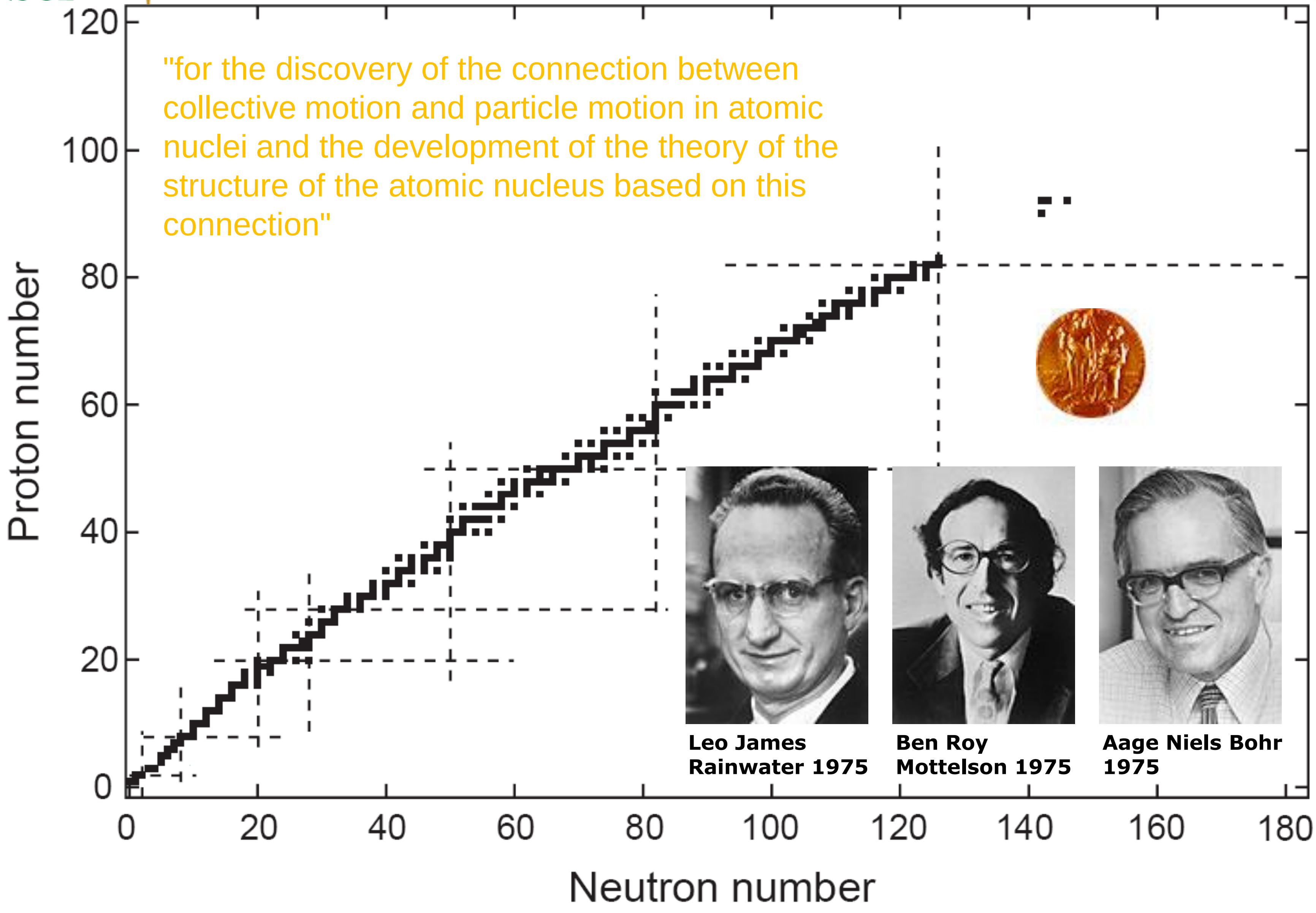
Ground state and first excited state (201 keV) of ^{140}Dy populated in proton decay of ^{141}Ho



M. Karny et al., PLB 664, 52 (2008)

Follow-up on collectivity

Nuclear structure - Collectivity



"for the discovery of the connection between collective motion and particle motion in atomic nuclei and the development of the theory of the structure of the atomic nucleus based on this connection"

Leo James Rainwater 1975

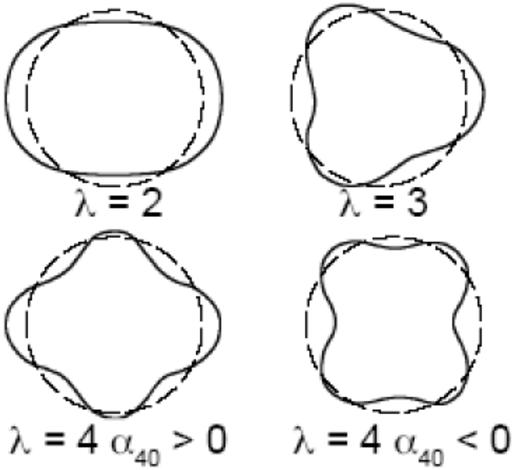
Ben Roy Mottelson 1975

Aage Niels Bohr 1975

Shapes of nuclei

- The general shape of a nucleus can be expressed as an expansion of spherical harmonics:

$$R = R_0\left[1+\sum_{\lambda=0}^{\infty}\sum_{\mu=-\lambda}^{\lambda} a_{\lambda\mu}Y_{\lambda\mu}(\theta,\phi)\right]$$



- λ=2 is the most important term and describes quadrupole deformations.

$$R = R_0\left[1+\sum_{\mu=-2}^{2} a_{2\mu}Y_{2\mu}(\theta,\phi)\right]$$

Symmetry: all but α_{20} and α_{22} parameters are 0

Quadrupole deformation

- We define:

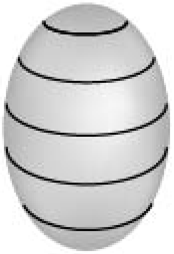
$$a_{20} = \beta \cos \gamma$$

$$a_{22} = \frac{1}{\sqrt{2}} \beta \sin \gamma$$

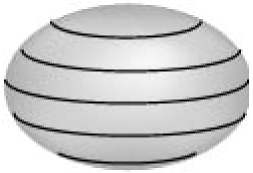
- β is a measure of the quadrupole deformation, while γ is a measure of the degree of triaxiality.
- By convention (the Lund convention):

  $\beta > 0$, $\gamma = 0^{\circ}$ is axially symmetric prolate deformation

  $\beta < 0$, $\gamma = -60^{\circ}$ is axially symmetric oblate deformation

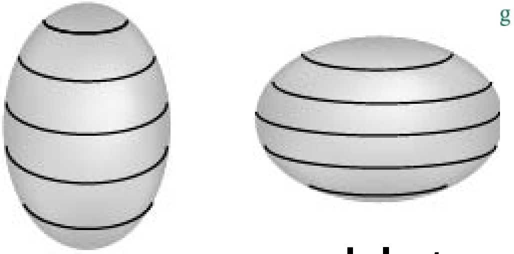


prolate



oblate

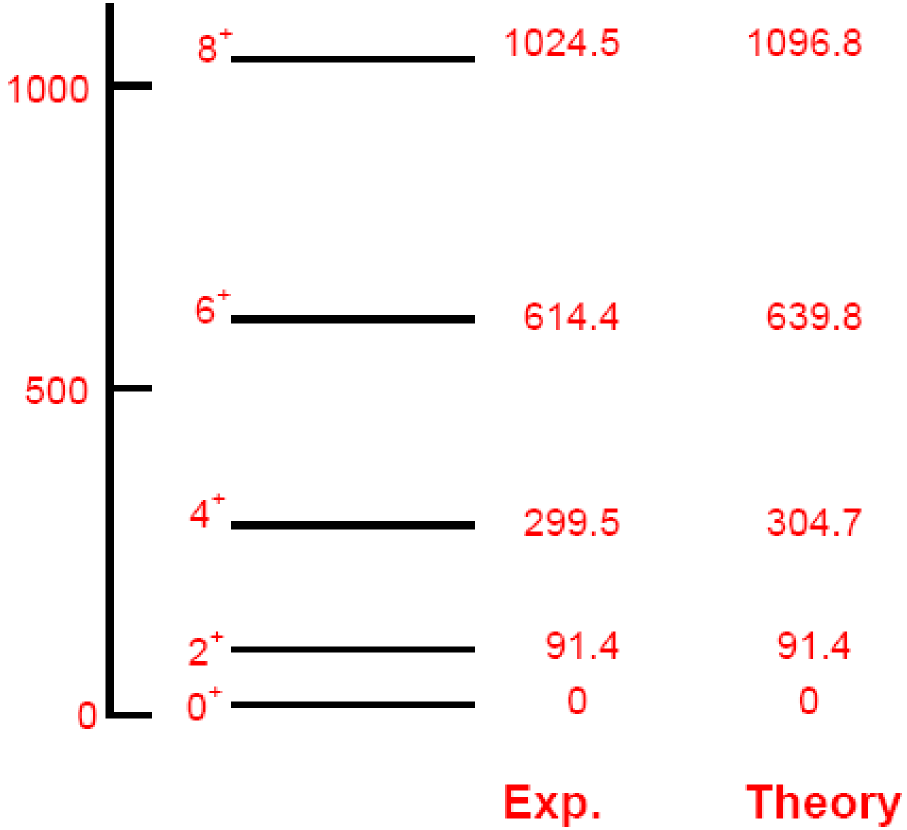
Deformed nuclei can rotate – rotational bands



prolate

oblate

Example: ^{164}Er



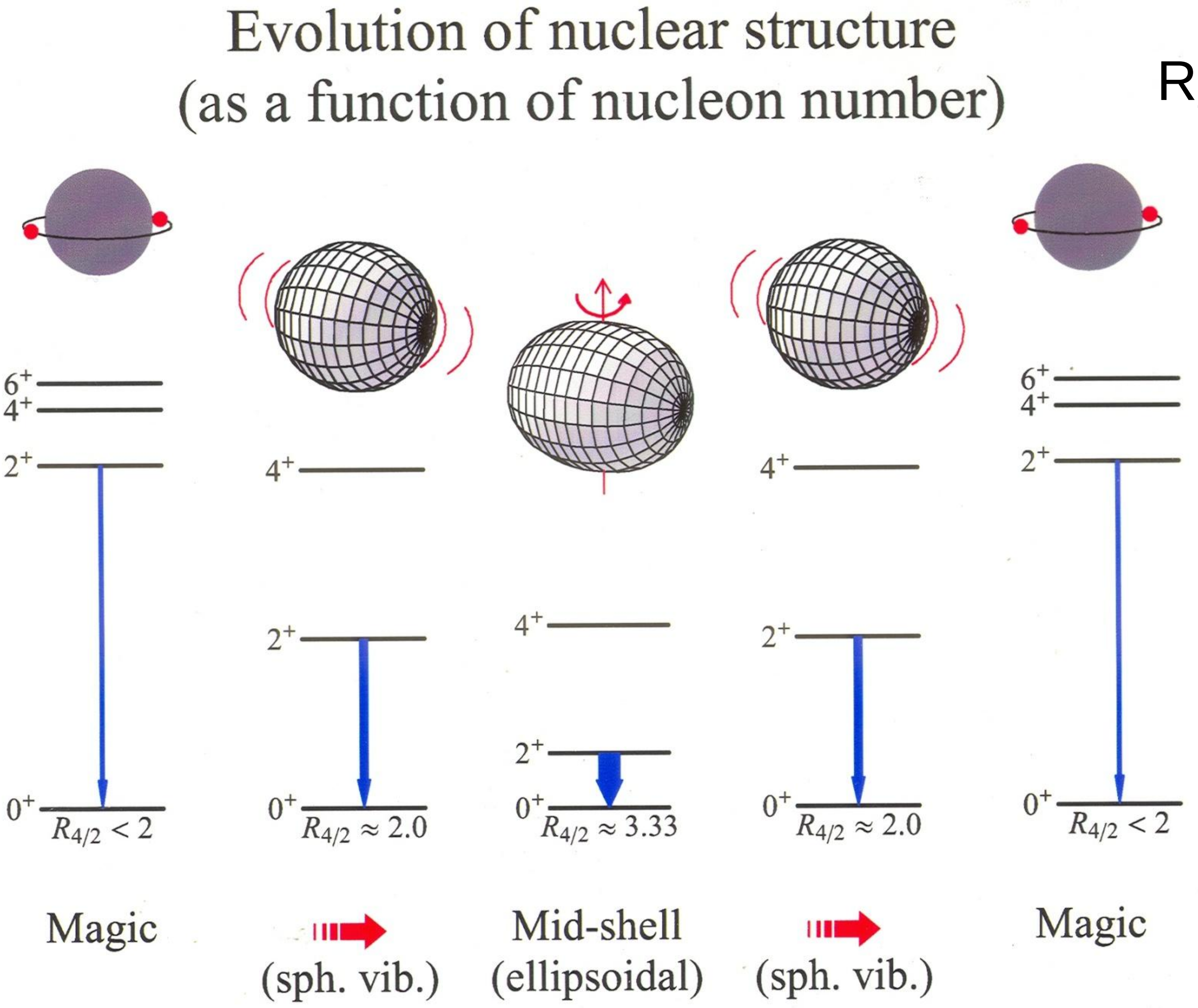
E=

$$E_{\mathrm{rot}}(J) = \frac{\hbar^2}{2I} J(J+1)$$

I: moment of inertia

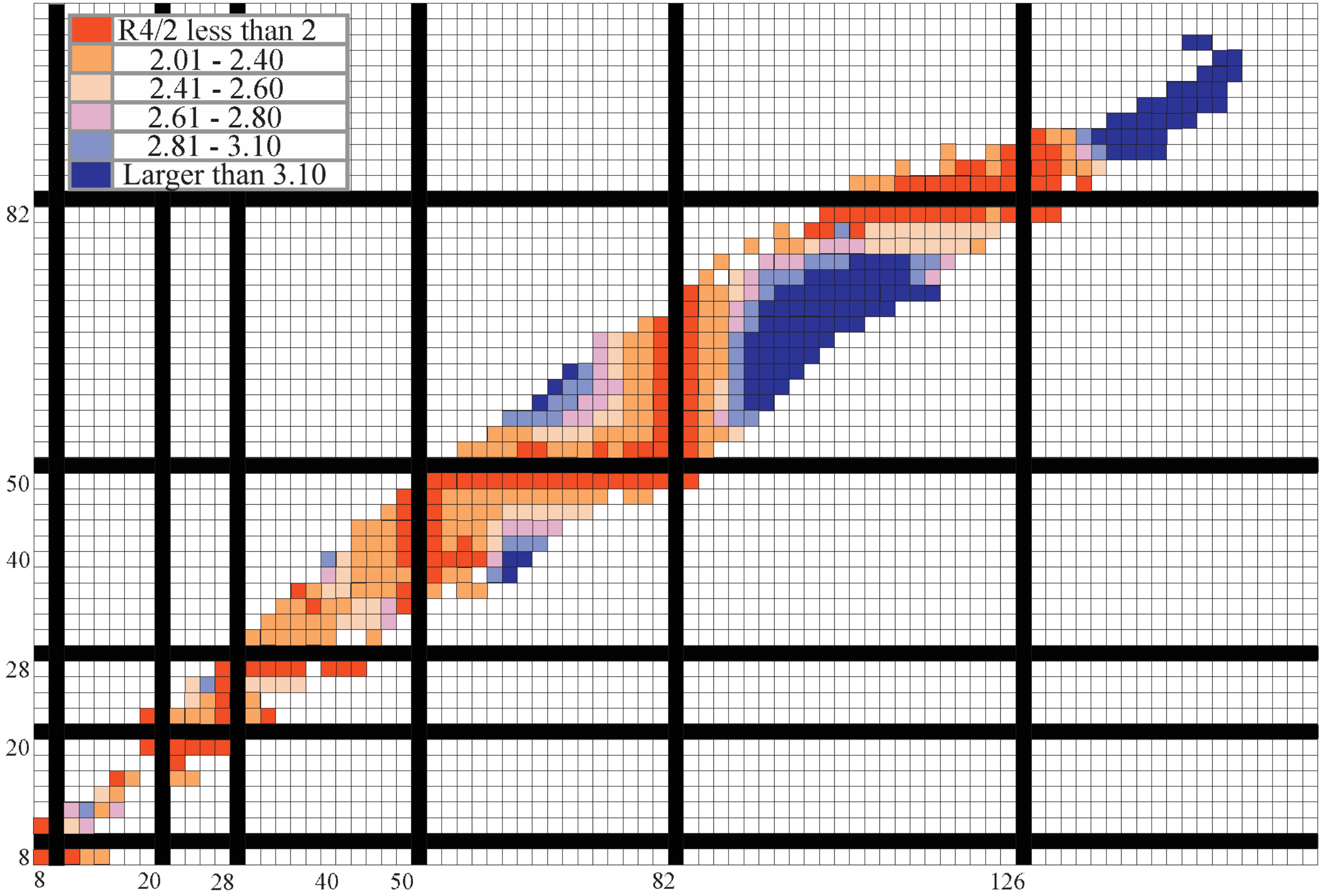
$R_{4/2}$ and simple patterns

$R_{4/2}=E(4^+)/E(2^+)$

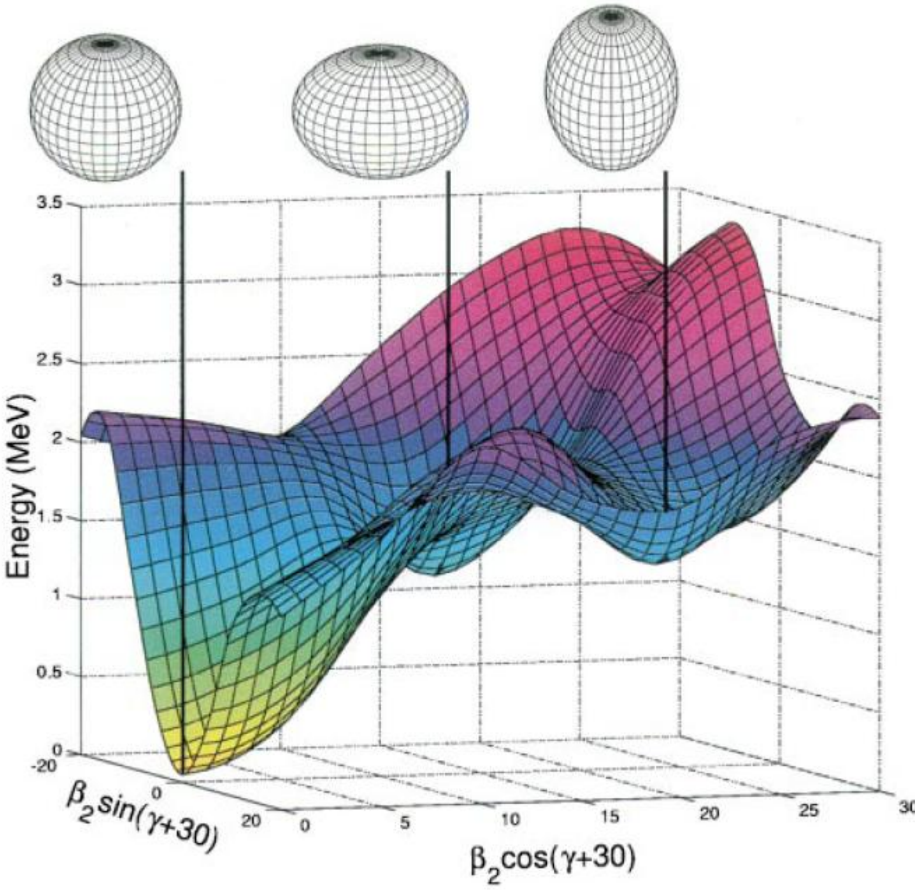


Evolution of nuclear structure
(as a function of nucleon number)

Simple but powerful: $R_{4/2}$



Shape coexistence



- A nucleus can take on more than one shape and several shapes can coexist at nearly the same energies.
- This phenomenon is known as shape coexistence and one well known example is ^{186}Pb.
- There are three low-lying 0^+ states corresponding to different shapes; spherical ($\beta=0$), oblate ($\beta<0$), and prolate ($\beta>0$).
- The figure shows a calculated potential energy surface which shows the minima associated with each shape.

A.Andreyev et al., Nature 405 (2000) 430

Nuclear radii and spatial extent

Nuclear radii - definitions

Nuclear mean square charge radius (take square root: rms charge radius $\langle r_c^2 \rangle^{1/2}$)

$$\langle r_c^2 \rangle = \frac{\int_0^R \rho(r) r^2 \, dr}{\int_0^R \rho(r) \, dr}$$

Mathematically:
Second radial moment of the charge distribution ρ(r)

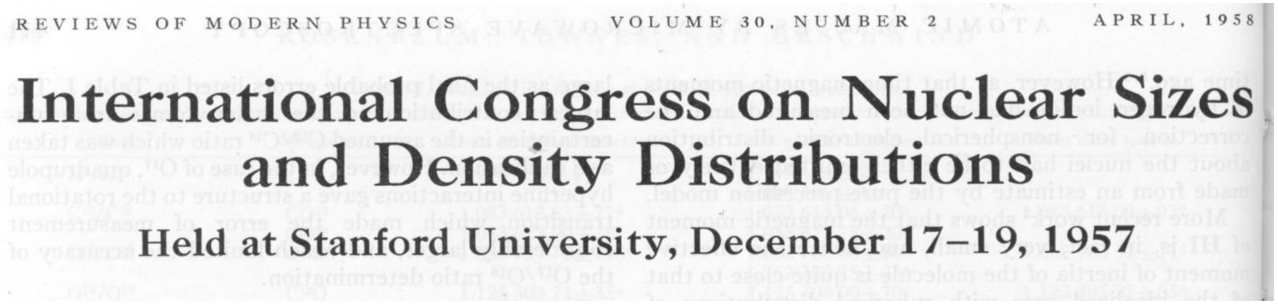
$\langle r_m^2 \rangle^{1/2}$ rms matter radius

$\langle r_n^2 \rangle^{1/2}$ rms neutron radius

Sometimes: point proton radius $<r^2_p>=<r^2_c> - 0.64 \text{ fm}^2$

proton ms radius

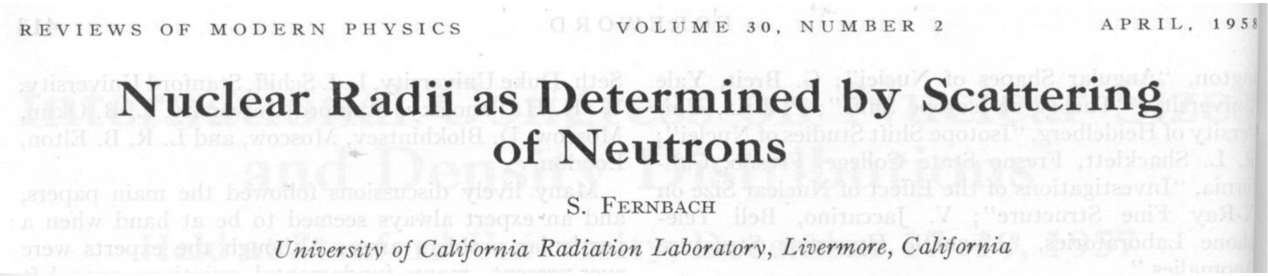
The common wisdom from stable nuclei



REVIEWS OF MODERN PHYSICS VOLUME 30, NUMBER 2 APRIL, 1958

International Congress on Nuclear Sizes and Density Distributions

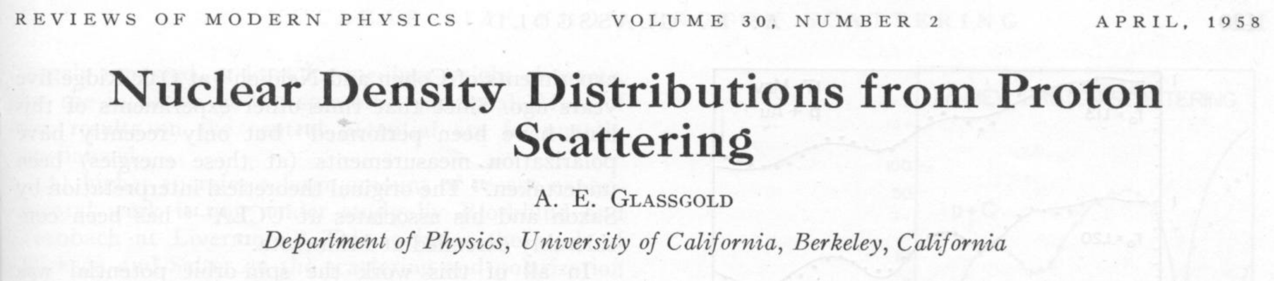
Held at Stanford University, December 17–19, 1957



REVIEWS OF MODERN PHYSICS VOLUME 30, NUMBER 2 APRIL, 1958

Nuclear Radii as Determined by Scattering of Neutrons

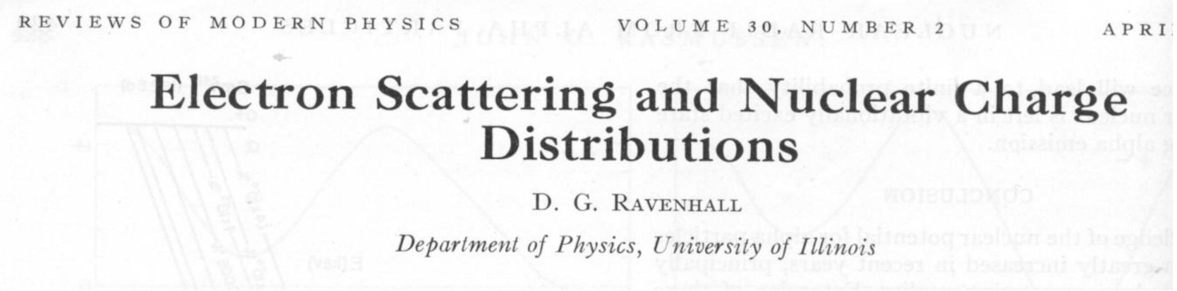
S. Fernbach
University of California Radiation Laboratory, Livermore, California



REVIEWS OF MODERN PHYSICS VOLUME 30, NUMBER 2 APRIL, 1958

Nuclear Density Distributions from Proton Scattering

A. E. Glassgold
Department of Physics, University of California, Berkeley, California



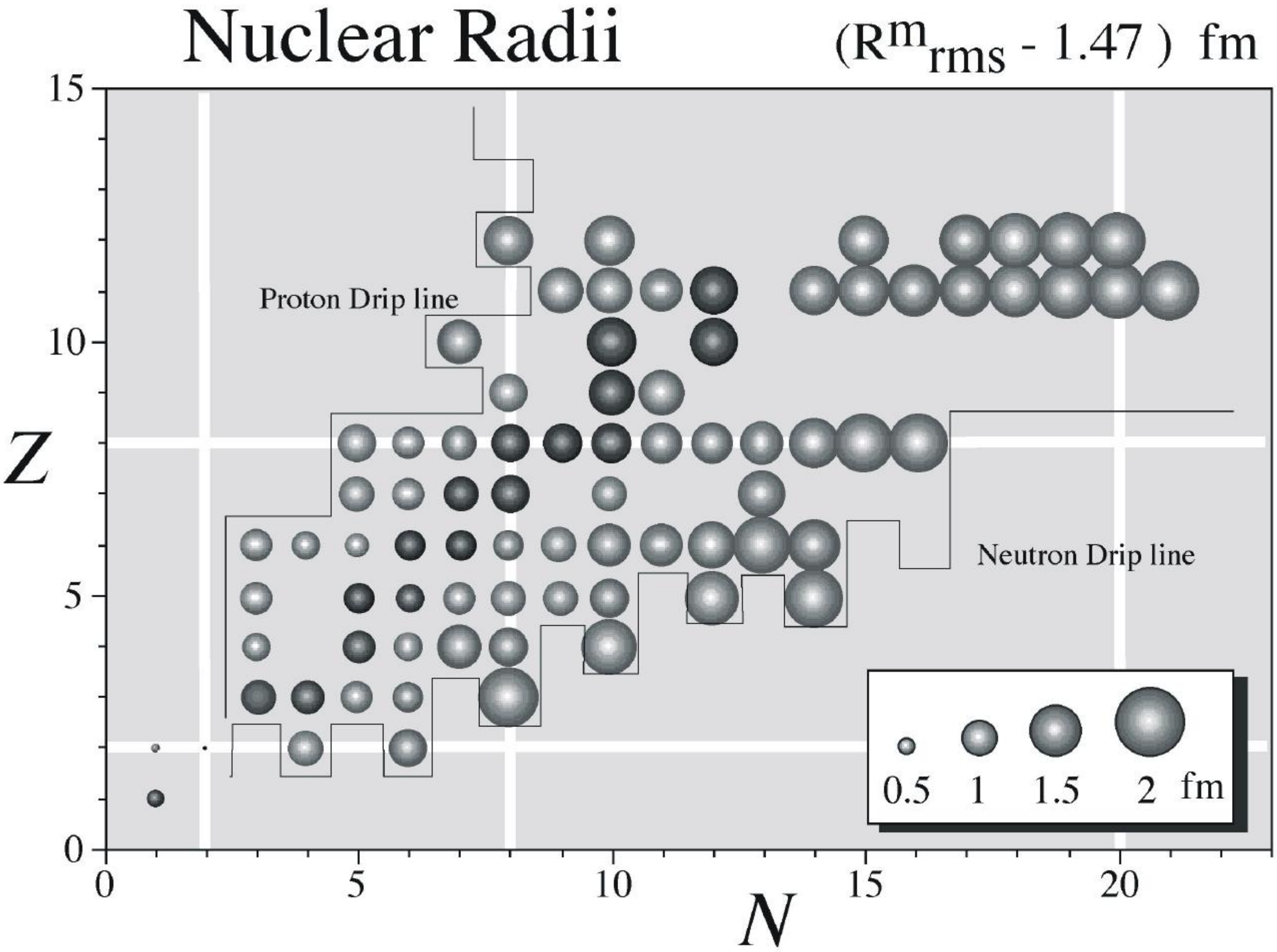
REVIEWS OF MODERN PHYSICS VOLUME 30, NUMBER 2 APRI

Electron Scattering and Nuclear Charge Distributions

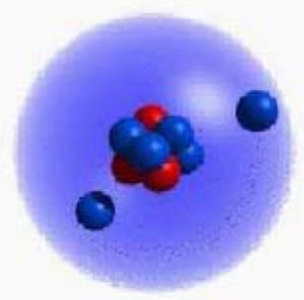
D. G. Ravenhall
Department of Physics, University of Illinois

$$R = r_0\, A^{1/3}$$

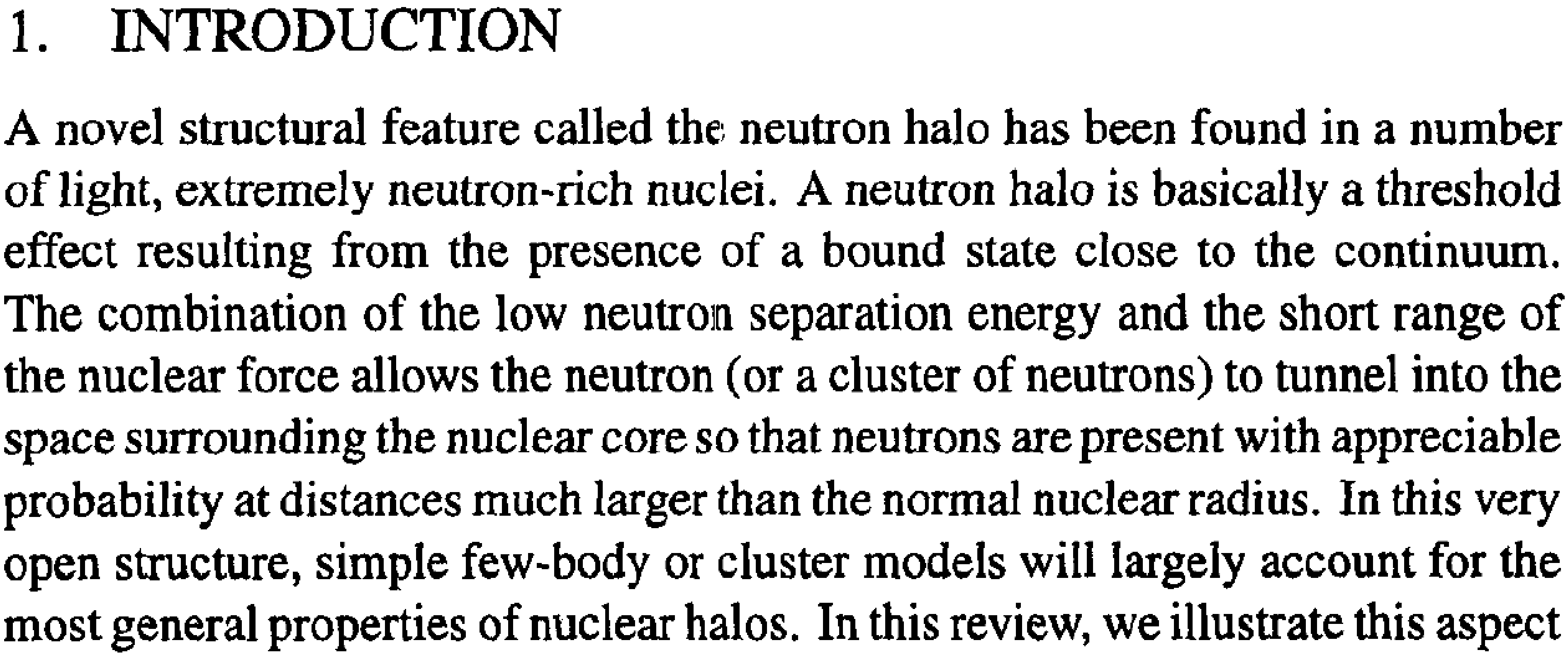
Nuclear radii: R = r_0 $A^{1/3}$?



I. Tanihata, Nucl. Phys. A 654, 235c (1999)



Nuclear halos, P.G. Hansen, A.S. Jensen, and B. Jonson, Annu. Rev. Part. Sci. 45, 591 (1995)

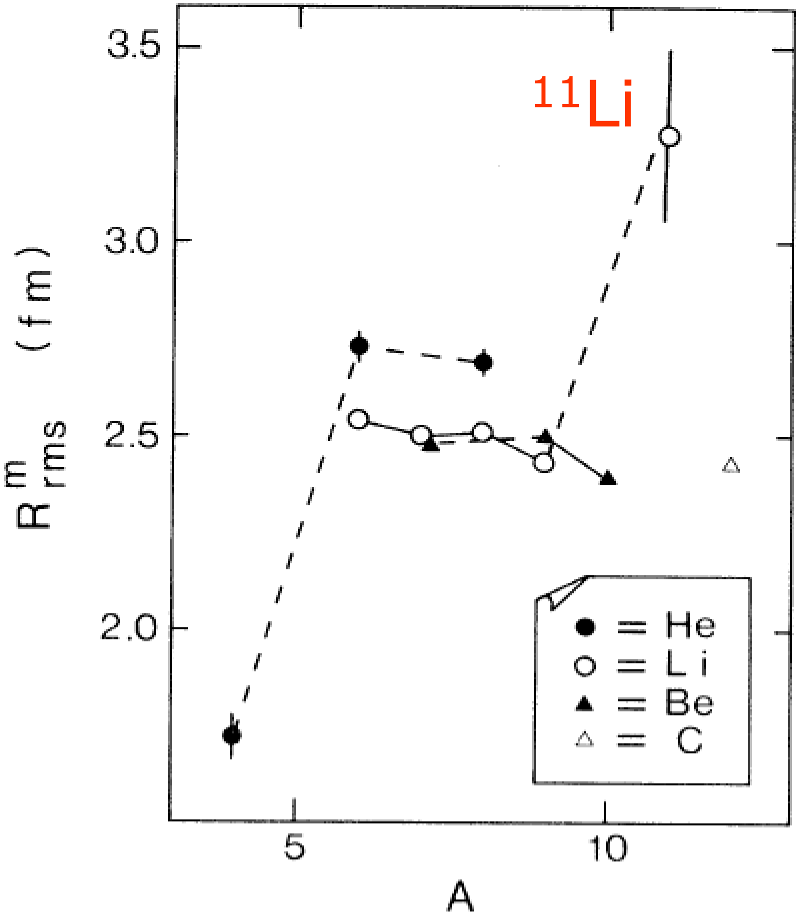


1. INTRODUCTION

A novel structural feature called the neutron halo has been found in a number of light, extremely neutron-rich nuclei. A neutron halo is basically a threshold effect resulting from the presence of a bound state close to the continuum. The combination of the low neutron separation energy and the short range of the nuclear force allows the neutron (or a cluster of neutrons) to tunnel into the space surrounding the nuclear core so that neutrons are present with appreciable probability at distances much larger than the normal nuclear radius. In this very open structure, simple few-body or cluster models will largely account for the most general properties of nuclear halos. In this review, we illustrate this aspect

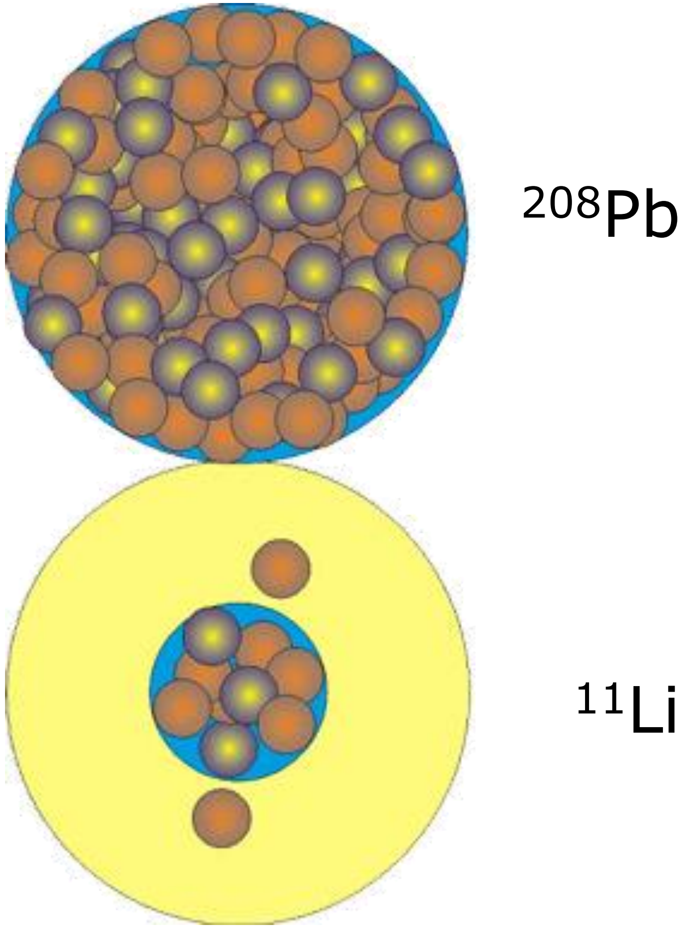
2-Neutron Halo in ^{11}Li 1985

First experiments done at the Bevalac at Berkeley



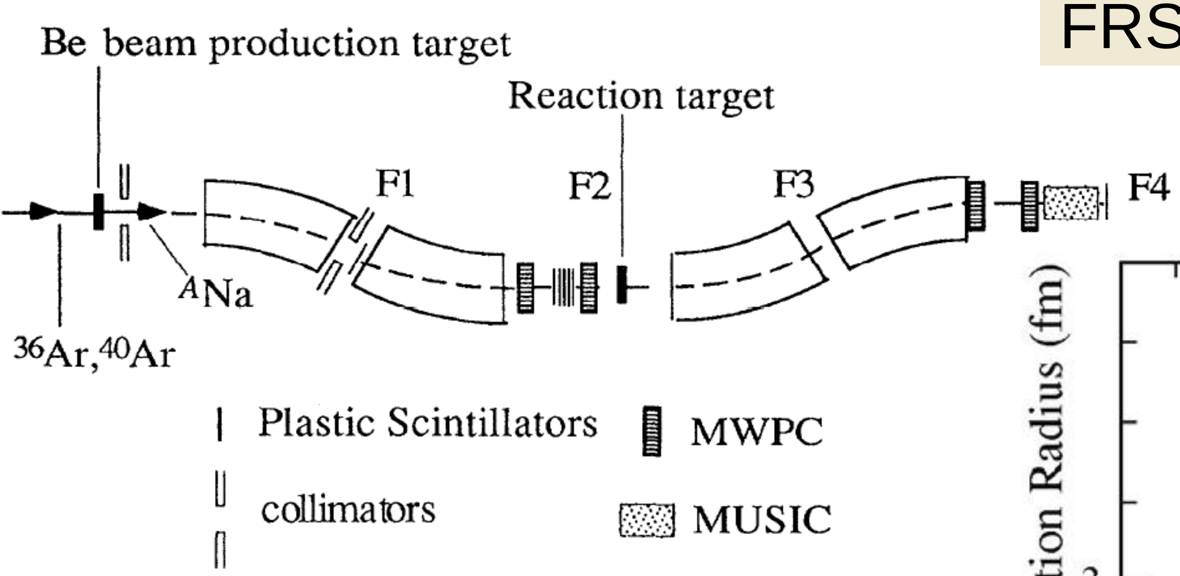
I. Tanihata et al., PRL 55, 2676 (1985)

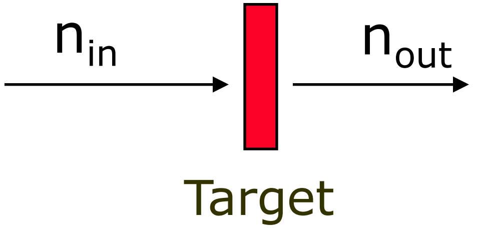
$r_{RMS}(^{11}\mathrm{Li}) = r_{RMS}(^{208}\mathrm{Pb})$



Total interaction cross sections
Matter radii

FRS at GSI



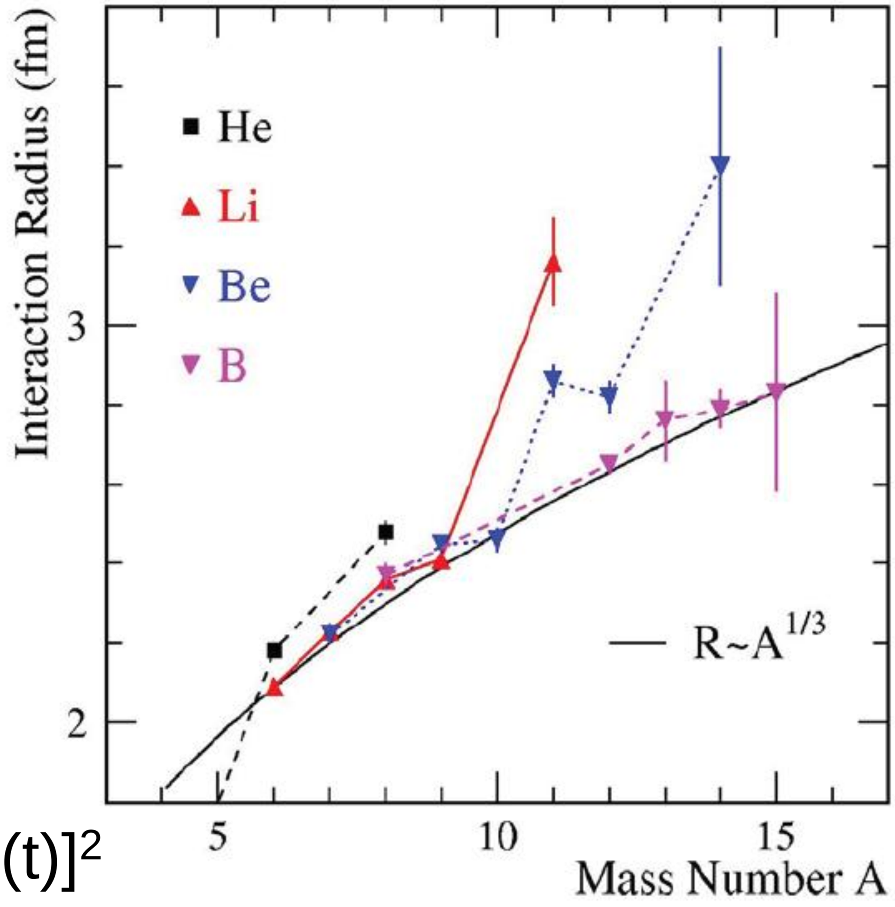


$$n_{out}=n_{in}\, e^{-N_t \sigma_i}$$

N_t: number of target nuclei per unit area

$$\sigma_i = 1/N_t \ln(n_{out}/n_{in})$$

I. Tanihata, J. Phys. G 22, 157 (1996)

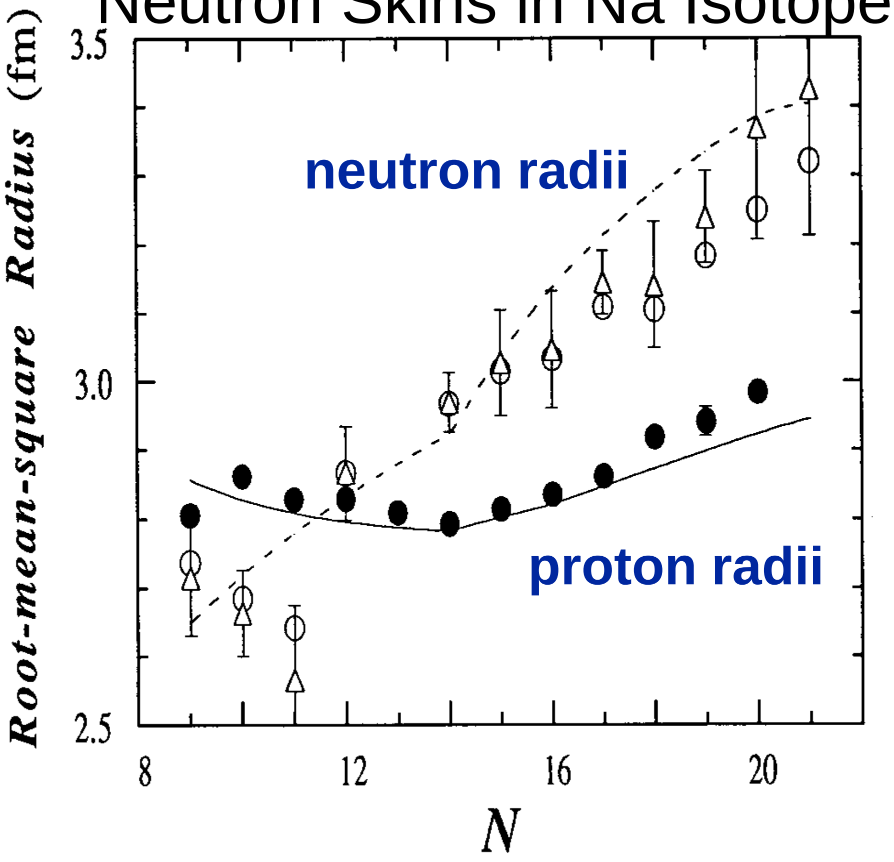


Theoretical model: $\sigma_i = \pi[R_i(p) + R_i(t)]^2$

Extraction of matter radius assuming density distributions

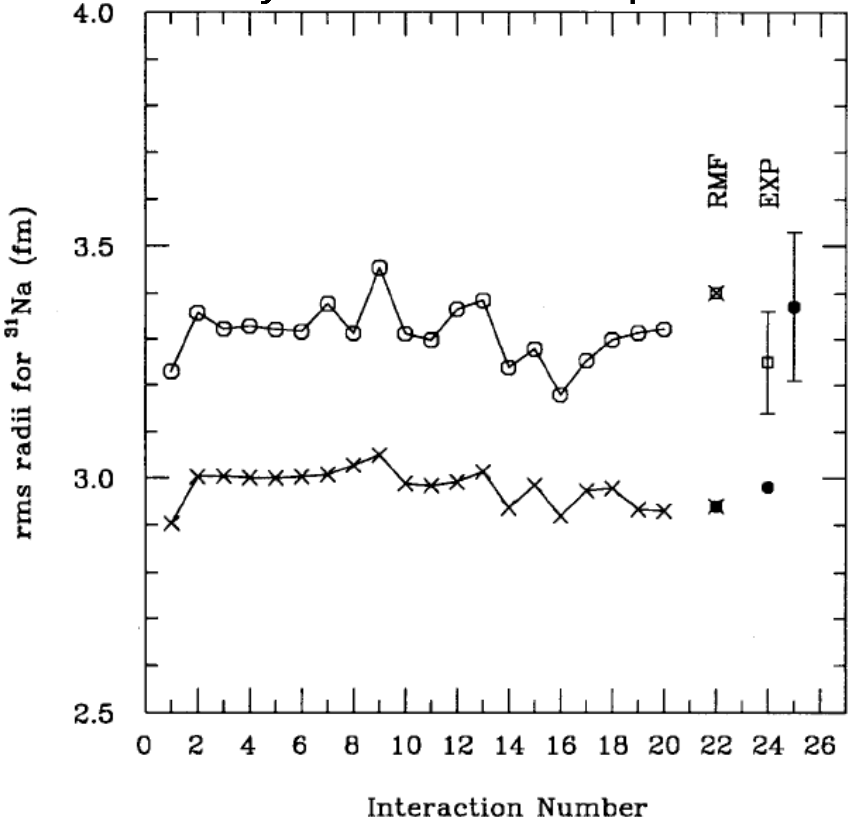
Evidence for a neutron skin in neutron-rich Na isotopes

Neutron Skins in Na Isotopes



T. Suzuki et al., PRL 75, 3241 (1995).

Study of the model dependence



B.A. Brown and W.A. Richter,
PRC 54, 673 (1996).

Extended spatial distributions – Halo systems

nature

NUCLEAR PHYSICS

A shattered halo

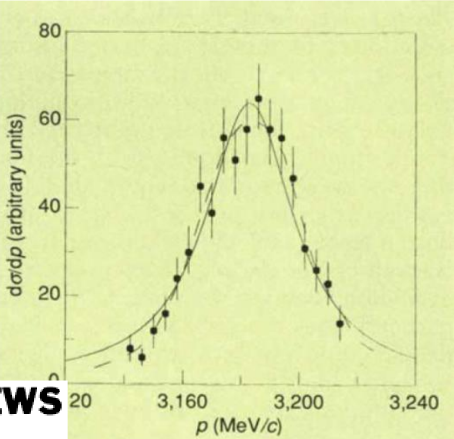
P. G. Hansen

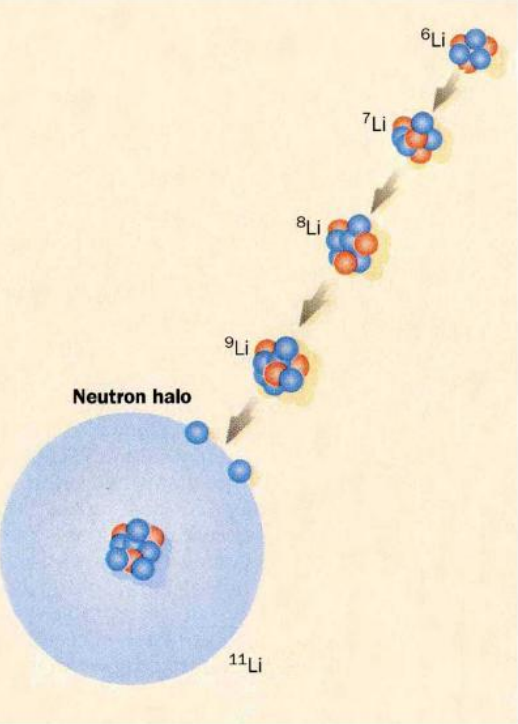
NEWS AND VIEWS

NUCLEAR STRUCTURE

Broken halo reveals all

W. Gelletly



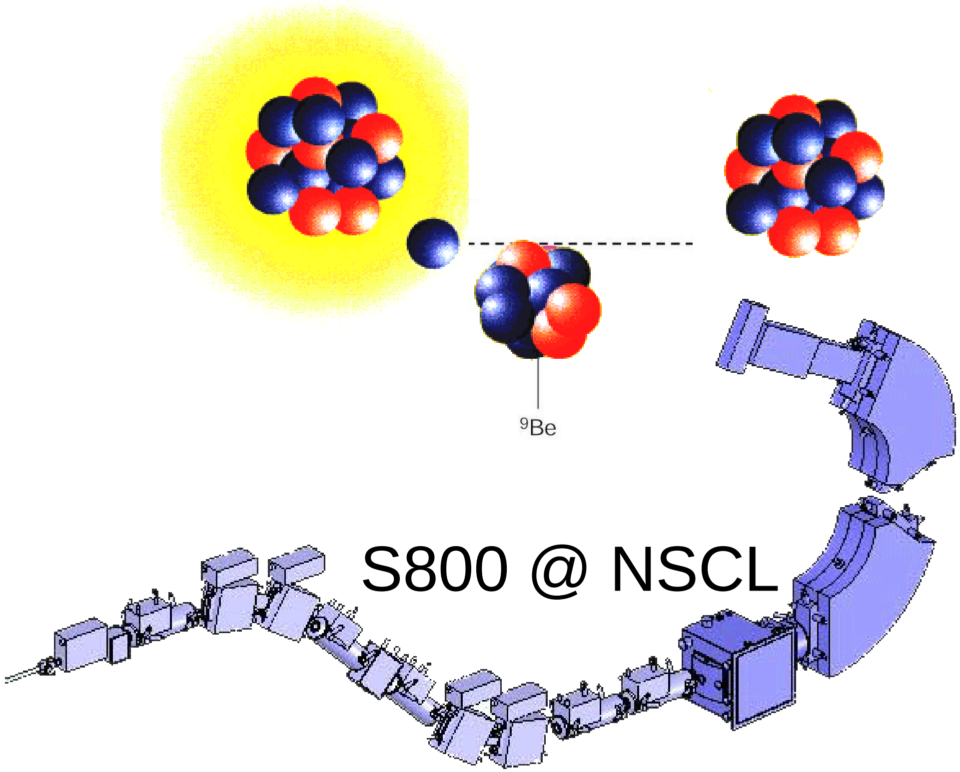


narrow momentum distribution
→ large spatial extent

Quantum mechanics also links the size of the halo, through Heisenberg's uncertainty principle, to the momenta of the constituents, which is the easier quantity to measure. This is what has been done in the pair of new experiments at Michigan State University[1,2], looking at the ^{9}Li fragments and neutrons produced by the dissociation of ^{11}Li.

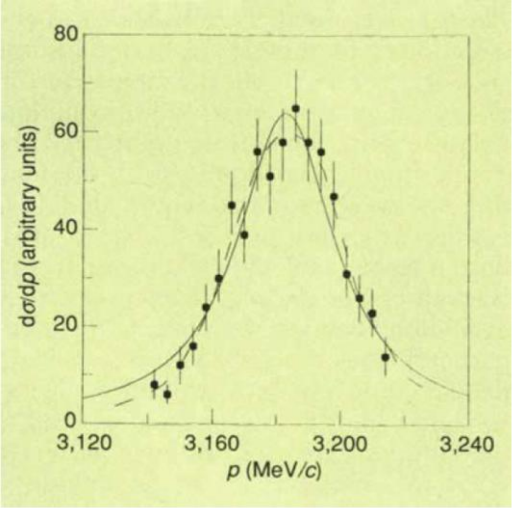
Not that the experiments are straightforward. First, the radioactive ^{11}Li isotopes have to be made by slamming ^{18}O ions into a beryllium foil. They then have to be selected from the debris of the collision by magnetic analysis and directed at a second metal target. The intensity of the secondary beam is a mere 300–1,500 ^{11}Li atoms per second, depending on the requirements.

Extended spatial distributions – Halo systems



S800 @ NSCL

narrow momentum distribution
→ large spatial extent



- S800 (NSCL)
- FRS (GSI)
- SPEG (GANIL)
- Momentum from time of flight (RIKEN)

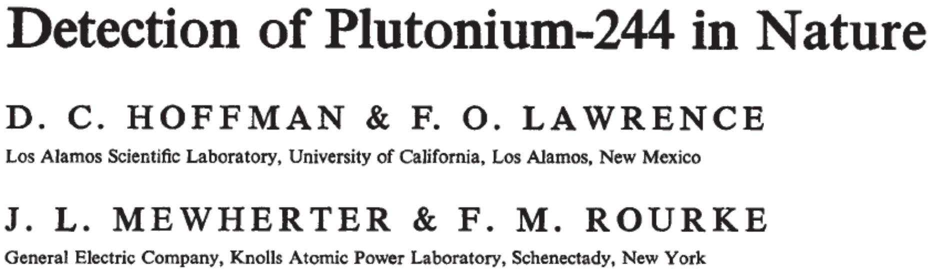
The heaviest nuclei

In transactinide nuclei (Z≥104), the liquid-drop contribution to the binding decreases and only stabilizing shell effects remain

Relativistic effects impact the electron structure and the chemistry of the heaviest elements

The heaviest elements found in nature:
U (Z=92) and ^{244}Pu (Z=94)

Nature, 234 Nov. 19 1971



Detection of Plutonium-244 in Nature

D. C. HOFFMAN & F. O. LAWRENCE
Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

J. L. MEWHERTER & F. M. ROURKE
General Electric Company, Knolls Atomic Power Laboratory, Schenectady, New York

NSCL

NSF

The periodic table

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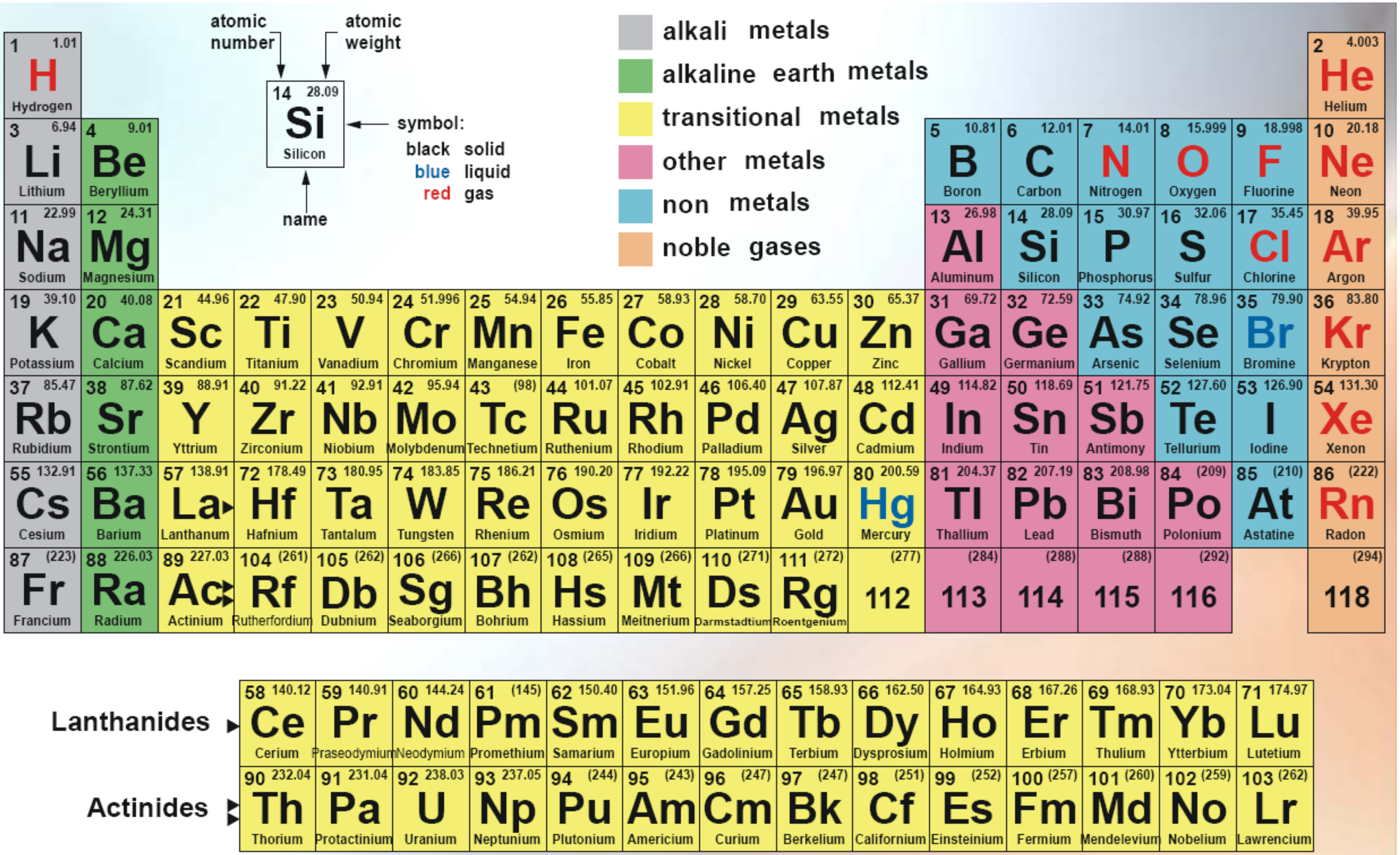
Transforming Lives.



atomic number → 14

atomic weight → 28.09

symbol: → Si

name → Silicon

symbol:
black solid
blue liquid
red gas

⬜ alkali metals

🟩 alkaline earth metals

🟨 transitional metals

🟪 other metals

🟦 non metals

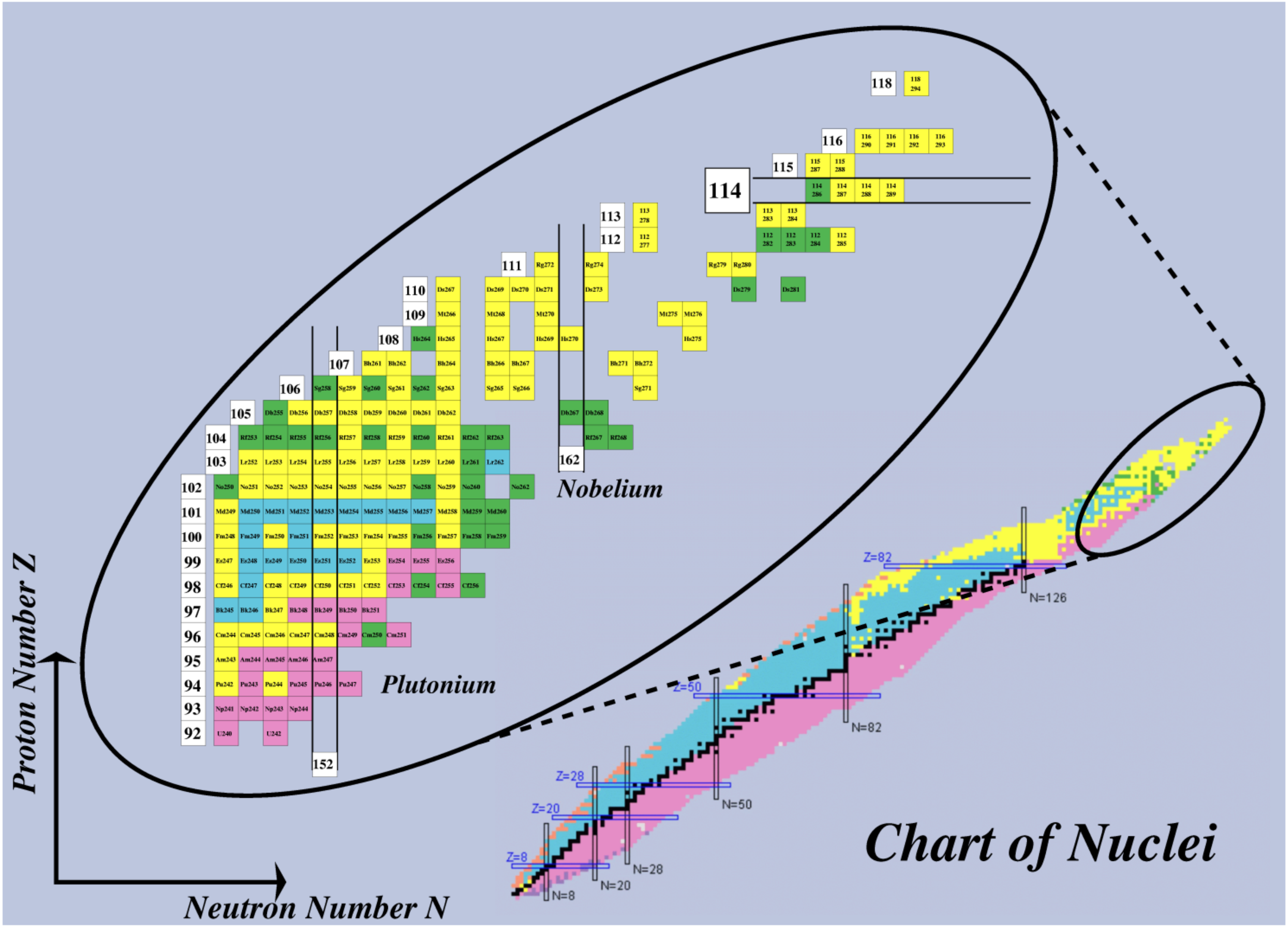
🟧 noble gases

1 1.01 H Hydrogen																	2 4.003 He Helium
3 6.94 Li Lithium	4 9.01 Be Beryllium											5 10.81 B Boron	6 12.01 C Carbon	7 14.01 N Nitrogen	8 15.999 O Oxygen	9 18.998 F Fluorine	10 20.18 Ne Neon
11 22.99 Na Sodium	12 24.31 Mg Magnesium											13 26.98 Al Aluminum	14 28.09 Si Silicon	15 30.97 P Phosphorus	16 32.06 S Sulfur	17 35.45 Cl Chlorine	18 39.95 Ar Argon
19 39.10 K Potassium	20 40.08 Ca Calcium	21 44.96 Sc Scandium	22 47.90 Ti Titanium	23 50.94 V Vanadium	24 51.996 Cr Chromium	25 54.94 Mn Manganese	26 55.85 Fe Iron	27 58.93 Co Cobalt	28 58.70 Ni Nickel	29 63.55 Cu Copper	30 65.37 Zn Zinc	31 69.72 Ga Gallium	32 72.59 Ge Germanium	33 74.92 As Arsenic	34 78.96 Se Selenium	35 79.90 Br Bromine	36 83.80 Kr Krypton
37 85.47 Rb Rubidium	38 87.62 Sr Strontium	39 88.91 Y Yttrium	40 91.22 Zr Zirconium	41 92.91 Nb Niobium	42 95.94 Mo Molybdenum	43 (98) Tc Technetium	44 101.07 Ru Ruthenium	45 102.91 Rh Rhodium	46 106.40 Pd Palladium	47 107.87 Ag Silver	48 112.41 Cd Cadmium	49 114.82 In Indium	50 118.69 Sn Tin	51 121.75 Sb Antimony	52 127.60 Te Tellurium	53 126.90 I Iodine	54 131.30 Xe Xenon
55 132.91 Cs Cesium	56 137.33 Ba Barium	57 138.91 La ▸ Lanthanum	72 178.49 Hf Hafnium	73 180.95 Ta Tantalum	74 183.85 W Tungsten	75 186.21 Re Rhenium	76 190.20 Os Osmium	77 192.22 Ir Iridium	78 195.09 Pt Platinum	79 196.97 Au Gold	80 200.59 Hg Mercury	81 204.37 Tl Thallium	82 207.19 Pb Lead	83 208.98 Bi Bismuth	84 (209) Po Polonium	85 (210) At Astatine	86 (222) Rn Radon
87 (223) Fr Francium	88 226.03 Ra Radium	89 227.03 Ac ▸ Actinium	104 (261) Rf Rutherfordium	105 (262) Db Dubnium	106 (266) Sg Seaborgium	107 (262) Bh Bohrium	108 (265) Hs Hassium	109 (266) Mt Meitnerium	110 (271) Ds Darmstadtium	111 (272) Rg Roentgenium	(277) 112	(284) 113	(288) 114	(288) 115	(292) 116		(294) 118

Lanthanides ▸	58 140.12 Ce Cerium	59 140.91 Pr Praseodymium	60 144.24 Nd Neodymium	61 (145) Pm Promethium	62 150.40 Sm Samarium	63 151.96 Eu Europium	64 157.25 Gd Gadolinium	65 158.93 Tb Terbium	66 162.50 Dy Dysprosium	67 164.93 Ho Holmium	68 167.26 Er Erbium	69 168.93 Tm Thulium	70 173.04 Yb Ytterbium	71 174.97 Lu Lutetium
Actinides ▸	90 232.04 Th Thorium	91 231.04 Pa Protactinium	92 238.03 U Uranium	93 237.05 Np Neptunium	94 (244) Pu Plutonium	95 (243) Am Americium	96 (247) Cm Curium	97 (247) Bk Berkelium	98 (251) Cf Californium	99 (252) Es Einsteinium	100 (257) Fm Fermium	101 (260) Md Mendelevium	102 (259) No Nobelium	103 (262) Lr Lawrencium

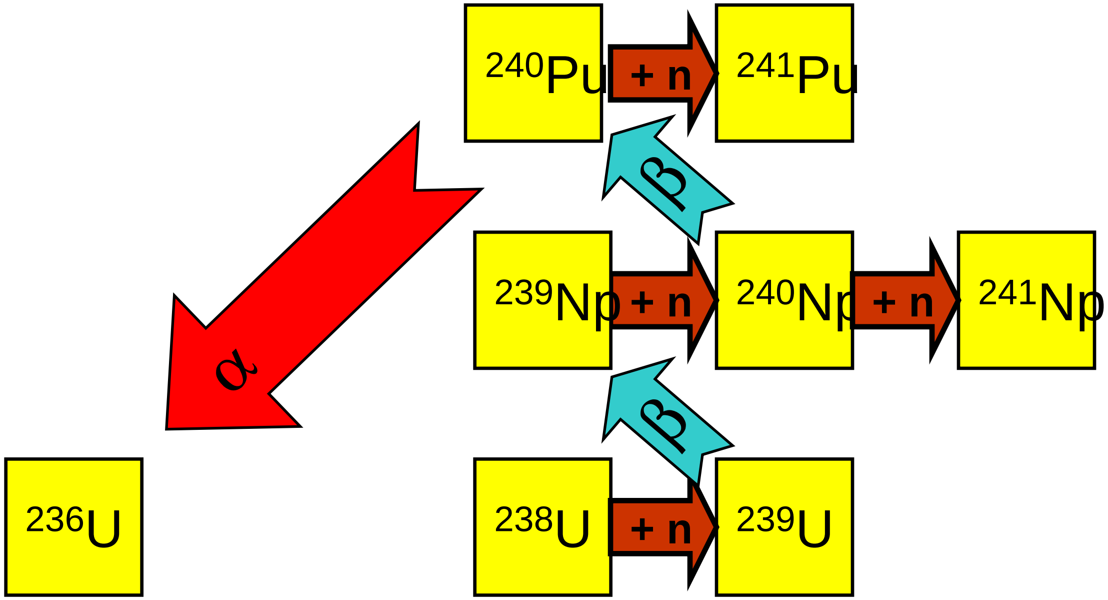
Transactinides: $Z \geq 104$

The limit of charge



Creation of new elements in an environment with high neutron flux

- Neutron capture (up to Z=100)
  - in reactors
  - in bombs
  - in stars?



Adapted from R.-D. Herzberg

The discovery of Fermium and Einsteinium

Fermium and **Einsteinium** was discovered in the debris from the thermonuclear explosion of the hydrogen bomb “Mike” in the Pacific Ocean – detonated 3,000 miles west of Hawaii on the 1st of November 1952 (Operation “Ivy”).

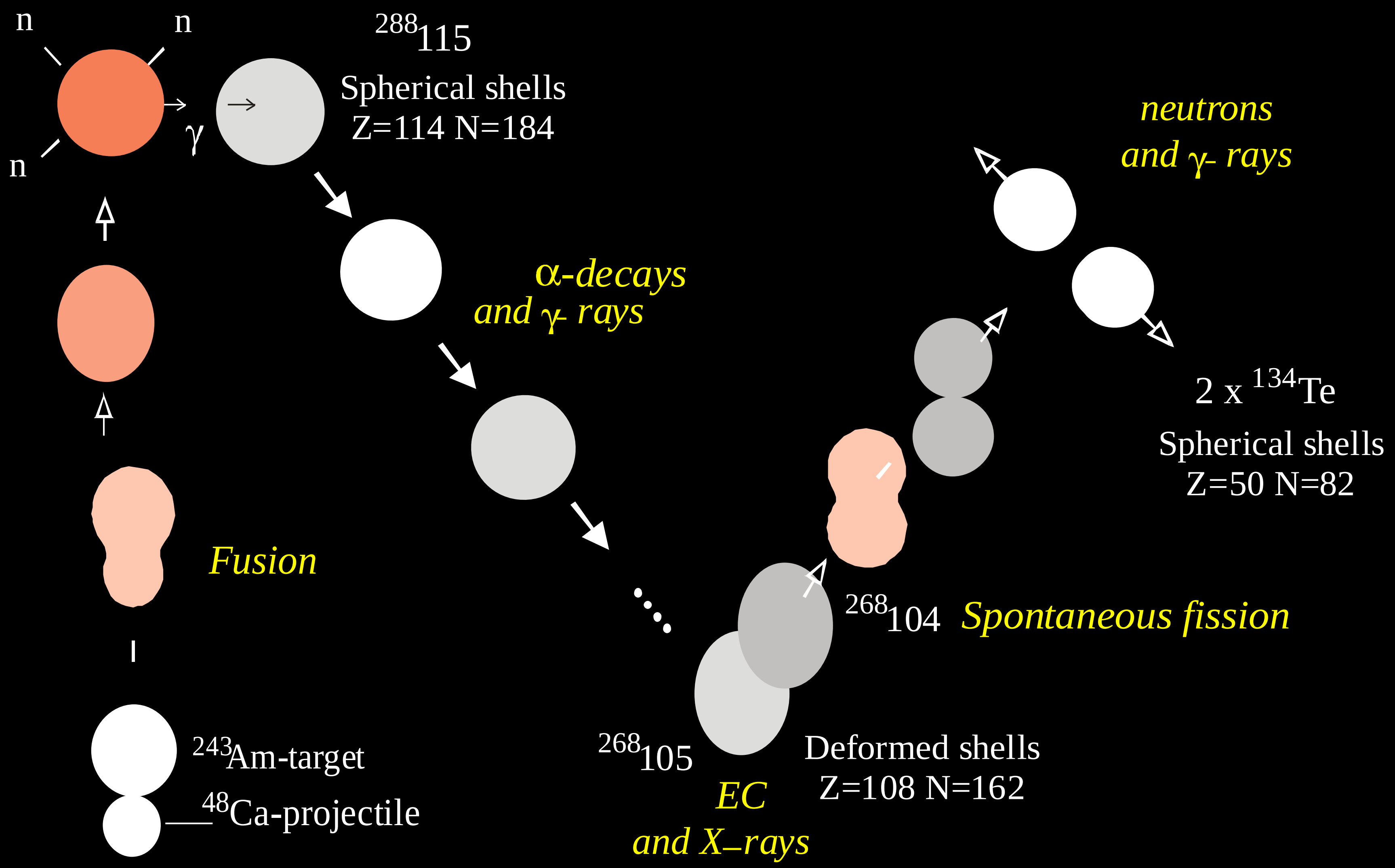
Hundreds of kilograms of explosion matter were collected and investigated. Hundreds of atoms of the **elements 99 (Einsteinium)** and **element 100 (Fermium)** could be chemically separated.

It is estimated that some of the **uranium-238** nuclei captured 17 neutrons creating ^{255}**U** which, after a chain of beta-decay reactions, created Es (Z=99) and Fm (100).

Hydrogen bomb “Mike”

http://pubs.acs.org/cen/80th/einsteiniumfermium.html

Formation of heavy elements



^{288}115

Spherical shells
Z=114 N=184

α-decays
and γ- rays

Fusion

^{243}Am-target

^{48}Ca-projectile

^{268}105

EC
and X–rays

Deformed shells
Z=108 N=162

^{268}104 *Spontaneous fission*

neutrons
and γ- rays

2 x ^{134}Te

Spherical shells
Z=50 N=82

Adapted from R.-D. Herzberg

Production of the heaviest elements

"Cold fusion": E_{CN}=10 MeV
$^{50-70}X$+Pb, Bi
$^{70}Zn + ^{208}Pb$ (n-poor isotopes)
1n evaporation channel
σ(113)=0.05pb → 1 atom/month
Long lifetimes: µs-ms
GSI (Germany), RIKEN (Japan)

Heavy projectile on Pb/Bi targets

Pb+Cr -> Sg Pb+Fe -> Hs
Pb+Zn -> 112

"Hot fusion": E_{CN}=45 MeV
$^{20-48}X$+Actinide targets
^{48}Ca + U … Cm (n-rich isotopes)
4-5n evaporation channel
σ(114)=5pb → 2 atoms/day
Long lifetimes: ms-d
FLNR Laboratory in Dubna

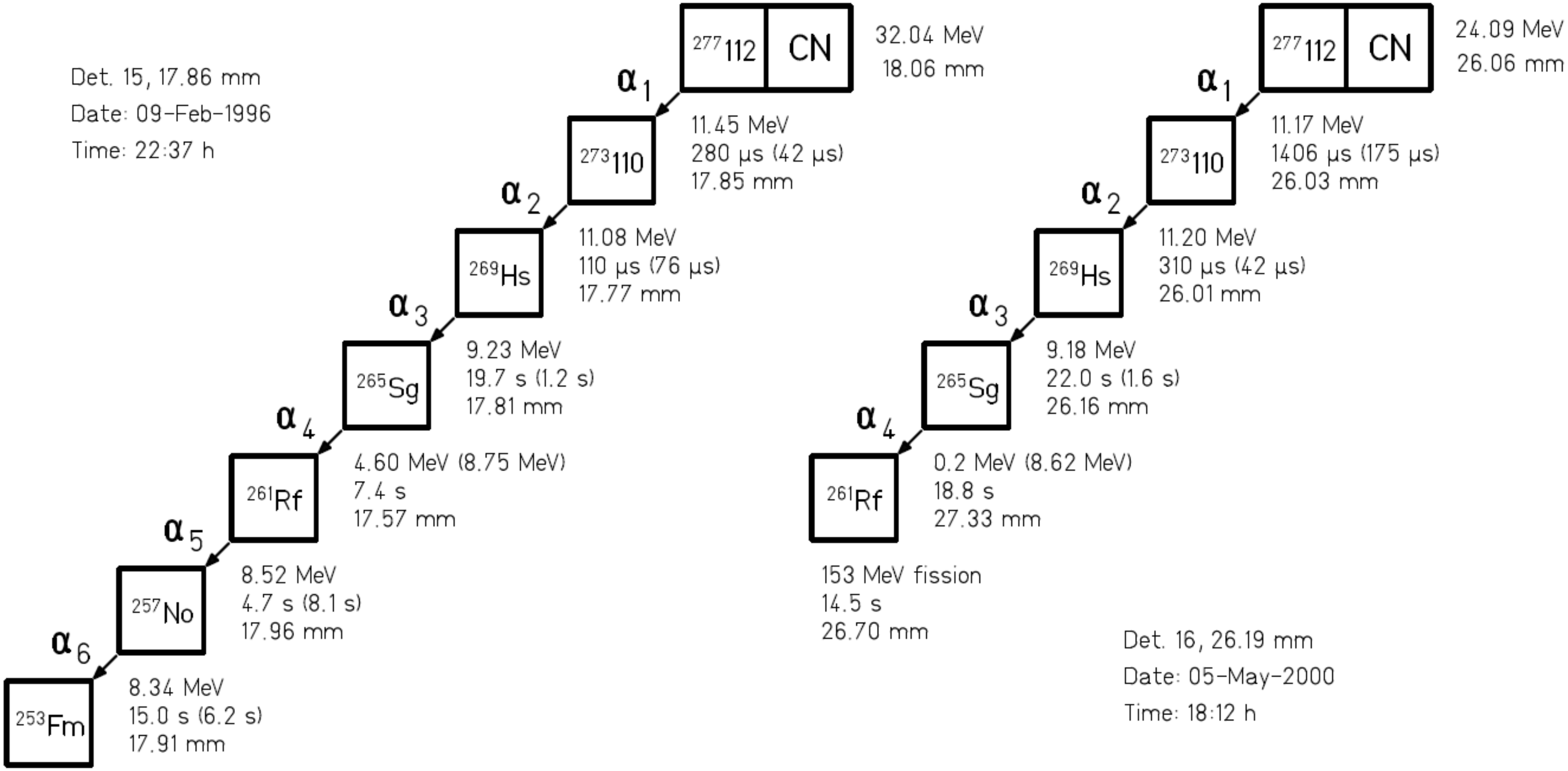
Light projectile on radioactive target

U+Mg->Rf (104)
Ca+Cf->118

Element 112 – 1996 and 2000 at GSI

$^{208}_{82}\mathrm{Pb} + ^{70}_{30}\mathrm{Zn} \rightarrow ^{278}112 \rightarrow ^{277}112 + n$

S. Hofmann et al., Z. Phys. 354 (1996) 229.



Det. 15, 17.86 mm
Date: 09-Feb-1996
Time: 22:37 h

$^{277}112$ CN
32.04 MeV
18.06 mm

α_1
$^{273}110$
11.45 MeV
280 µs (42 µs)
17.85 mm

α_2
$^{269}\mathrm{Hs}$
11.08 MeV
110 µs (76 µs)
17.77 mm

α_3
$^{265}\mathrm{Sg}$
9.23 MeV
19.7 s (1.2 s)
17.81 mm

α_4
$^{261}\mathrm{Rf}$
4.60 MeV (8.75 MeV)
7.4 s
17.57 mm

α_5
$^{257}\mathrm{No}$
8.52 MeV
4.7 s (8.1 s)
17.96 mm

α_6
$^{253}\mathrm{Fm}$
8.34 MeV
15.0 s (6.2 s)
17.91 mm

$^{277}112$ CN
24.09 MeV
26.06 mm

α_1
$^{273}110$
11.17 MeV
1406 µs (175 µs)
26.03 mm

α_2
$^{269}\mathrm{Hs}$
11.20 MeV
310 µs (42 µs)
26.01 mm

α_3
$^{265}\mathrm{Sg}$
9.18 MeV
22.0 s (1.6 s)
26.16 mm

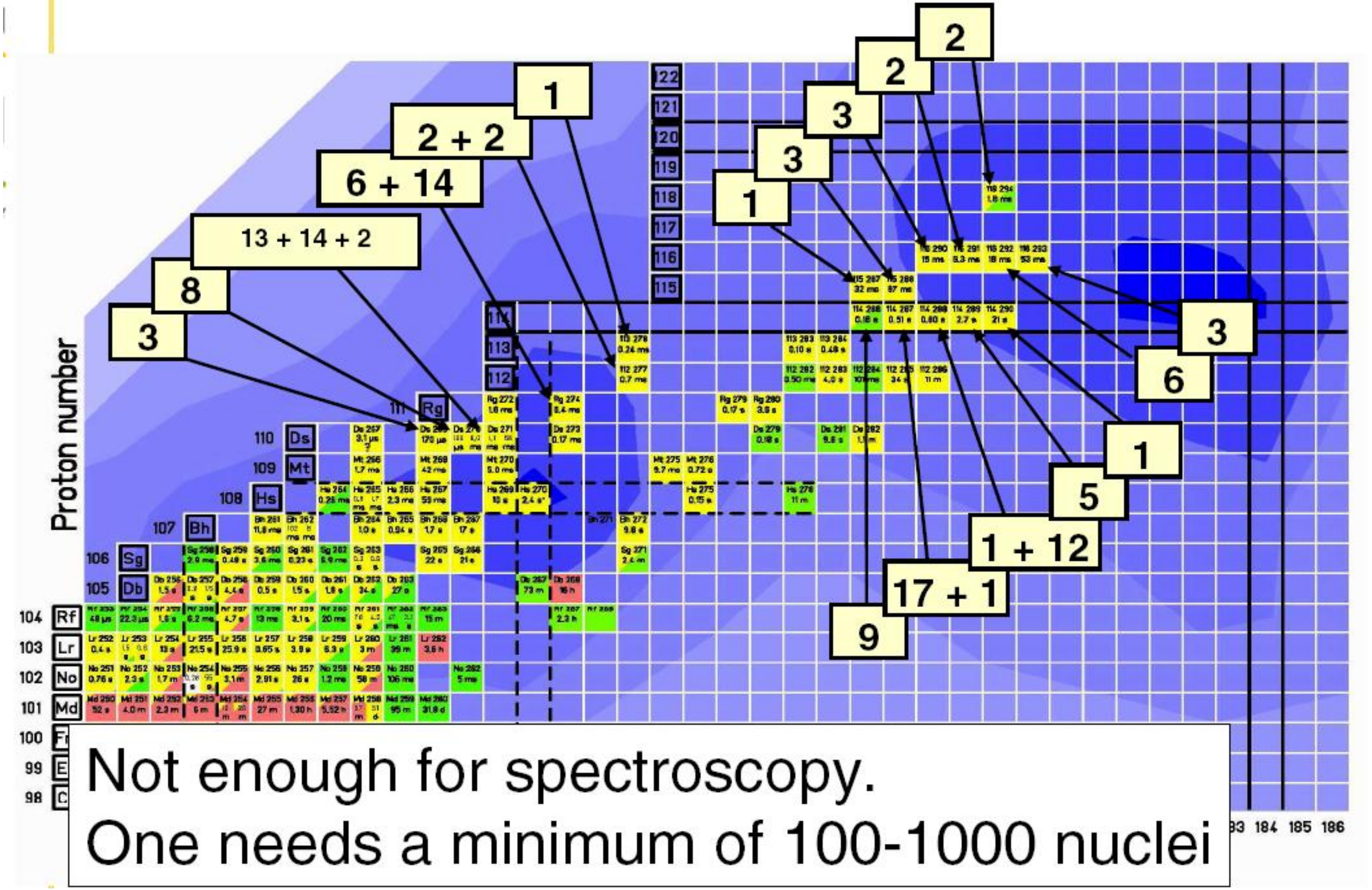
α_4
$^{261}\mathrm{Rf}$
0.2 MeV (8.62 MeV)
18.8 s
27.33 mm

153 MeV fission
14.5 s
26.70 mm

Det. 16, 26.19 mm
Date: 05-May-2000
Time: 18:12 h

Confirmed measurements also at RIKEN (Japan) in 2004 and the latest new element officially recognized by the International Union of Pure and Applied Chemistry (IUPAC)

Spectroscopy?



Not enough for spectroscopy.
One needs a minimum of 100-1000 nuclei

Adapted from Ch. Theisen (2008)

Example

$^{48}\text{Ca} + ^{238}\text{U} \rightarrow Z=112$, $\sigma \approx 1\text{pb}$

→ Reaction rate ~ 1/month

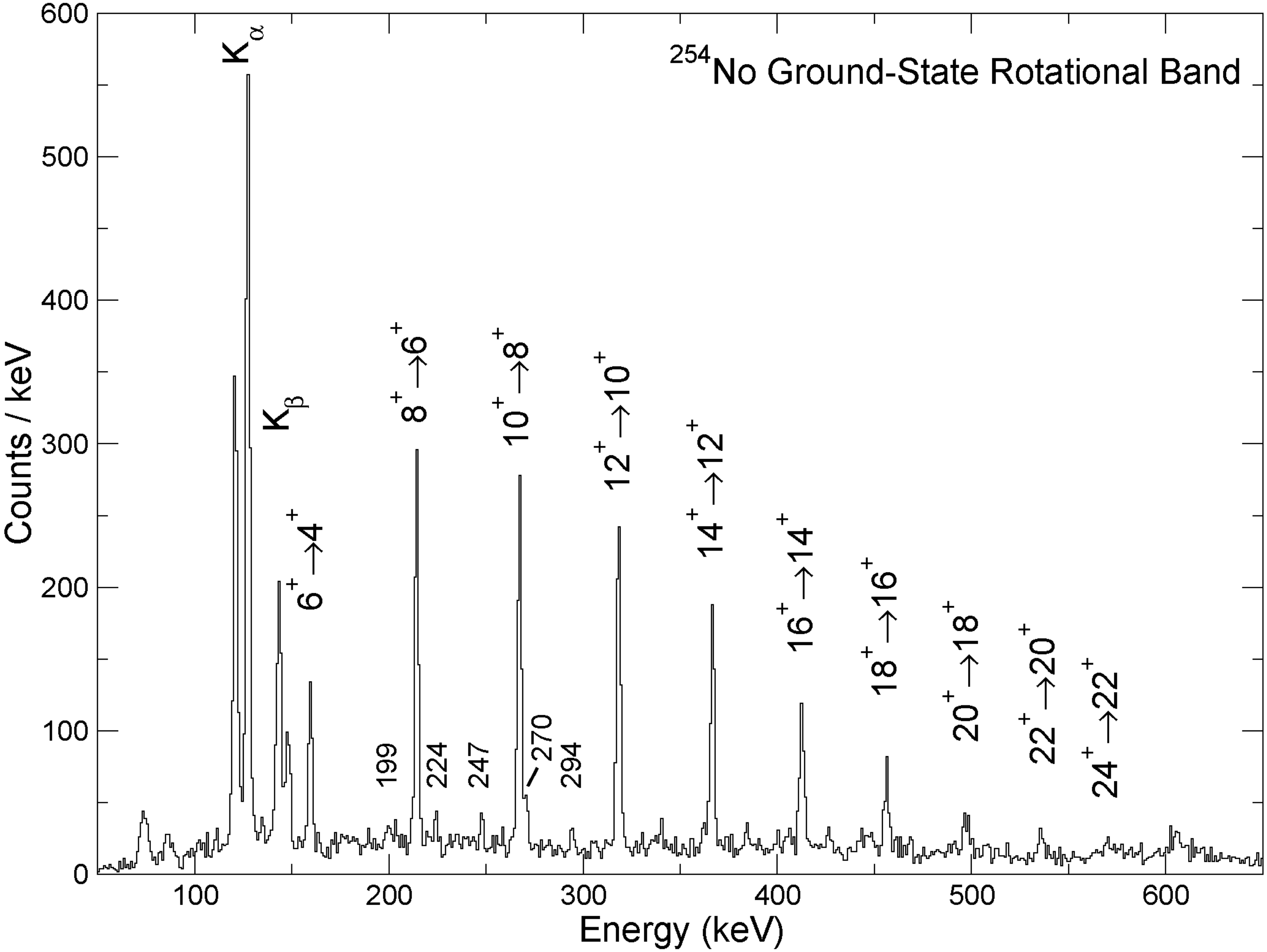
Example : $^{208}\text{Pb}(^{48}\text{Ca},2n)^{254}\text{No}$

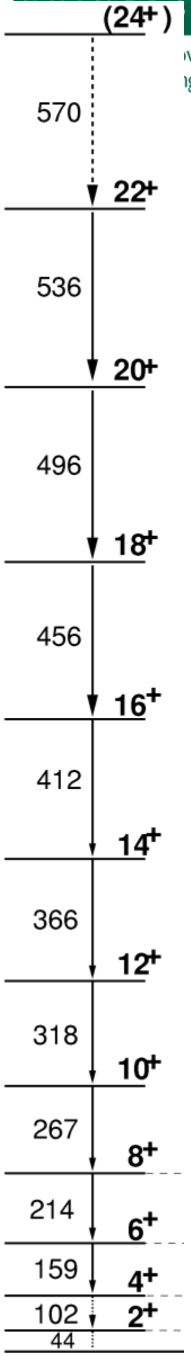
- Beam intensity
  $100 \text{ pnA} = 10^{-7}/1.6\ 10^{-19}\ \text{s}^{-1} = 0.625\ 10^{12}\ \text{s}^{-1}$
- Target Thickness
  $300\ \mu\text{g/cm}^2 = 300\ 10^{-6} \times N_A/208\ \text{cm}^{-2} = 8.68\ 10^{17}\ \text{cm}^{-2}$
- Cross section
  $\sigma = 2\mu\text{b} = 2\ 10^{-6} \times 10^{-24}\ \text{cm}^2 = 2\ 10^{-30}\ \text{cm}^2$

→ Reaction rate ~ 1/s

Adapted from Ch. Theisen

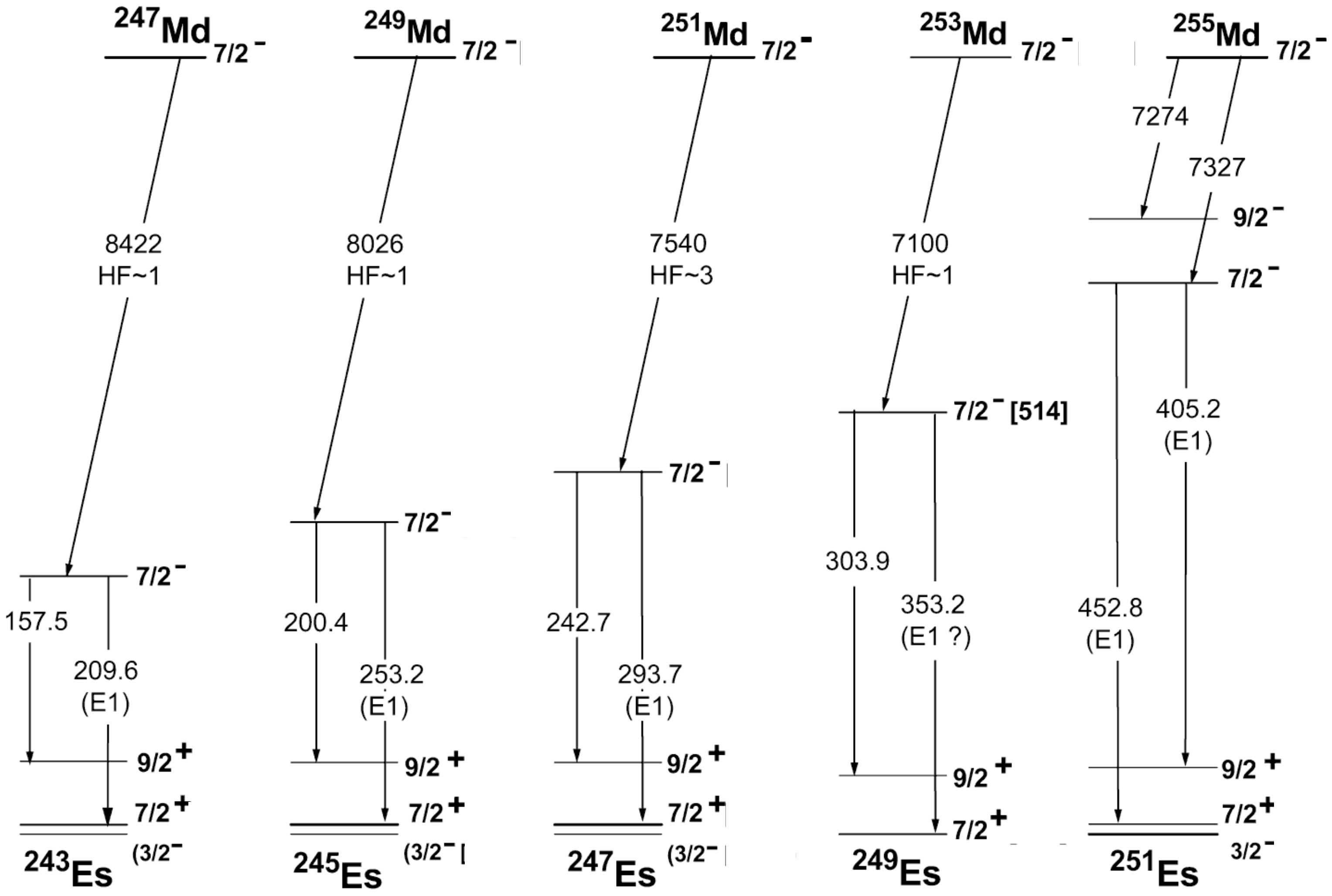
^{254}No





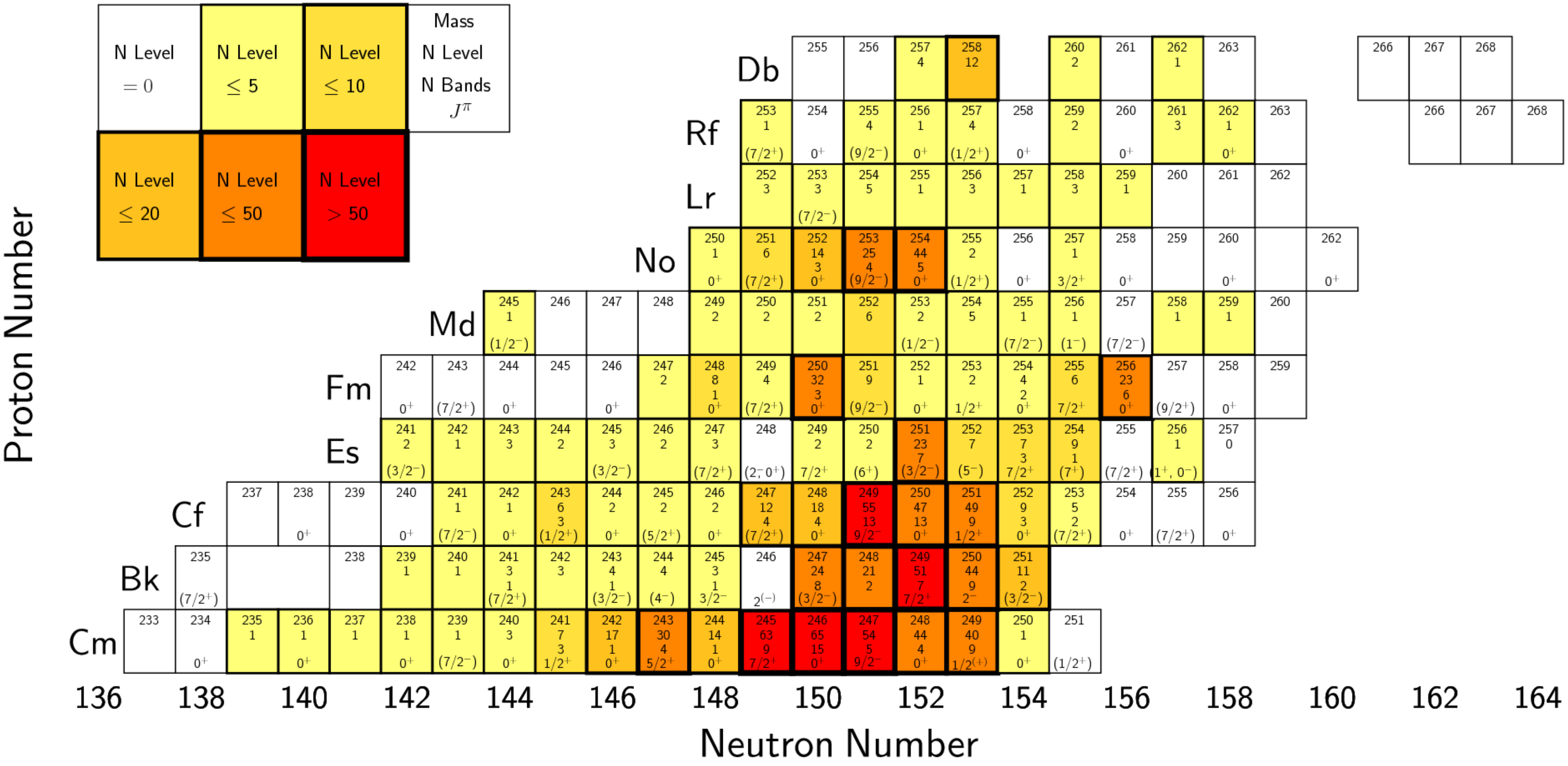
R.-D. Herzberg and P. T. Greenlees, Prog. Part. Nucl. Phys. 61 (2008) 674

Level schemes: Example



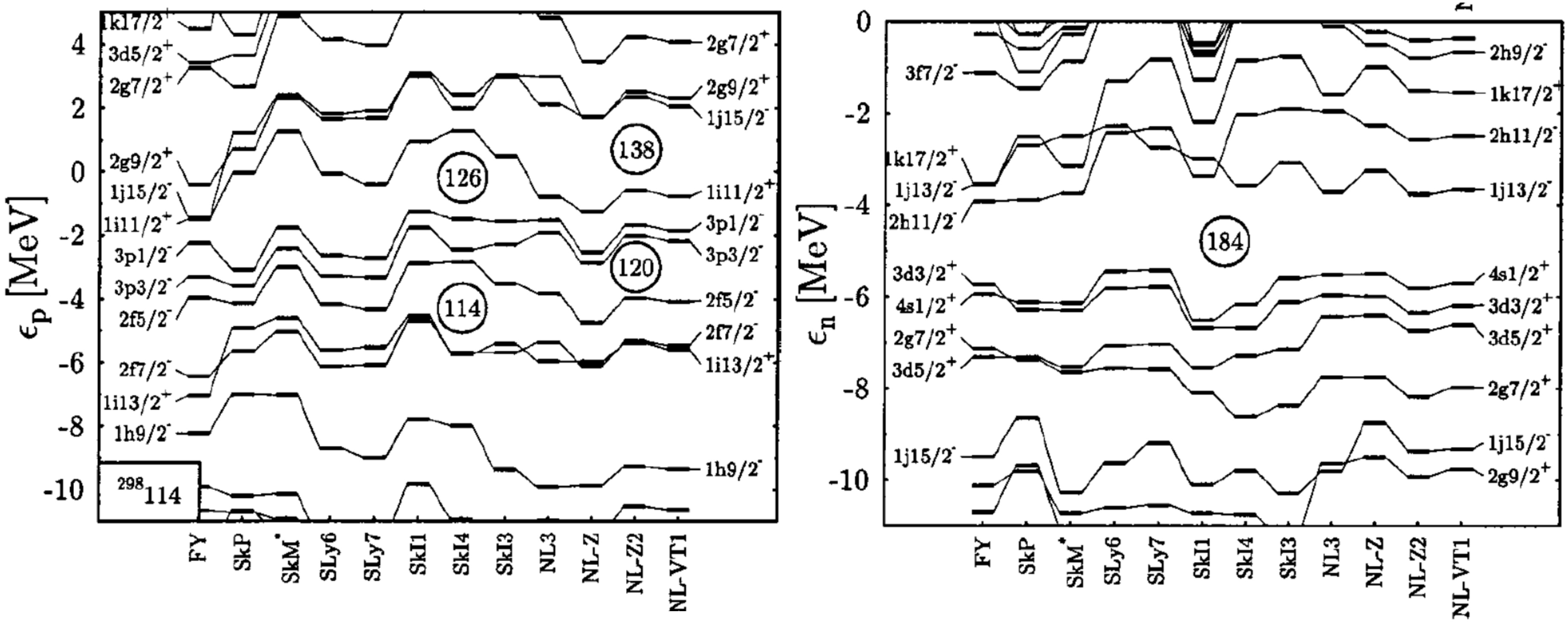
F.P. Hessberger et al., EPJA 26 (2005) 233

Spectroscopic information



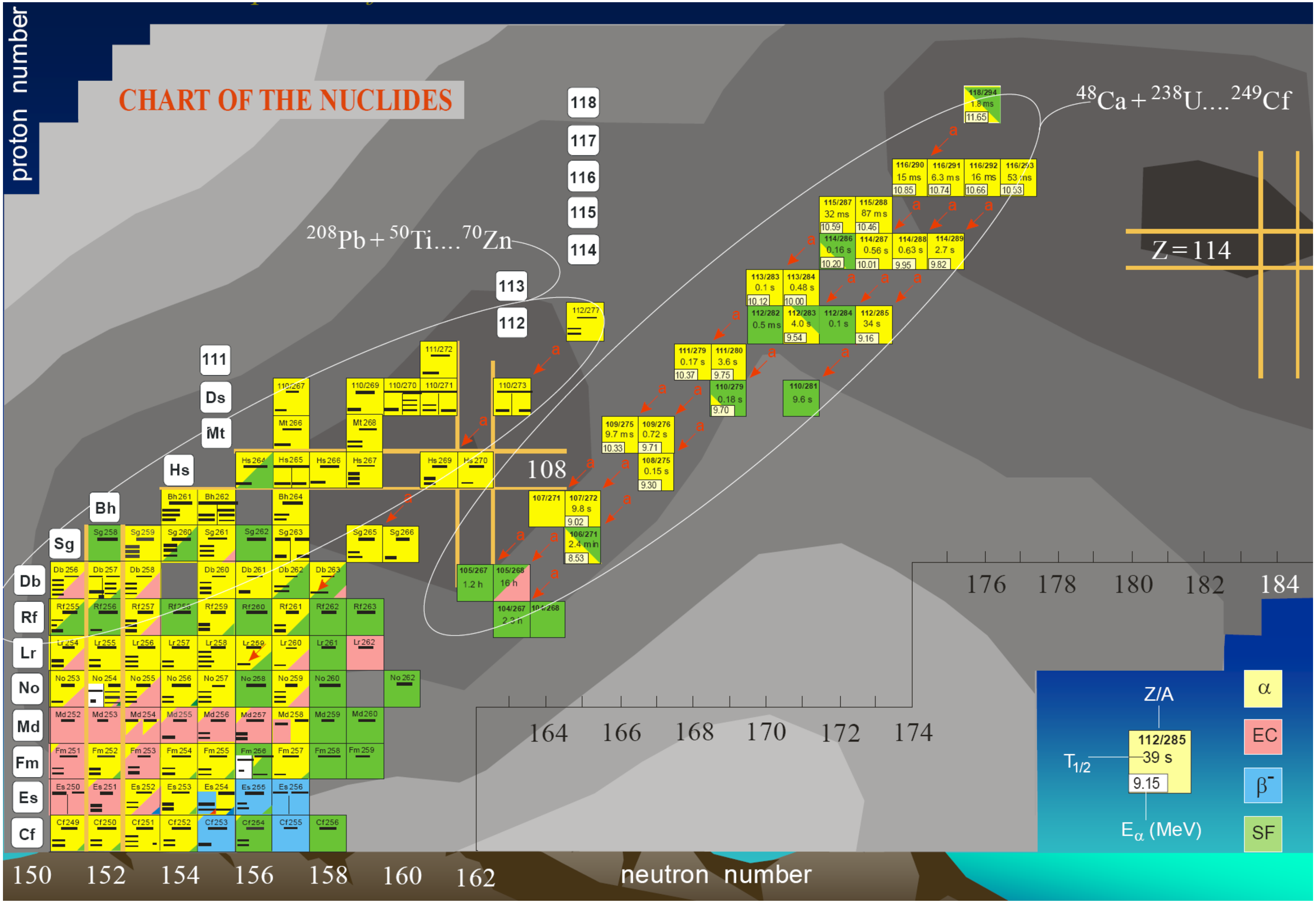
R.-D. Herzberg and P. T. Greenlees, Prog. Part. Nucl. Phys. 61 (2008) 674

Shell Positions for $^{298}114$



From M. Bender et al., PRC 60 (1999) 034304

Possibilities



Changes in the electron configurations: Relativistic effects at high Z

Bohr radius: $a_0 = \frac{\hbar}{m_e c\alpha}$

$$m_{rel} = \frac{m_e}{\sqrt{1-(v_e/c)^2}}$$

Electron velocity: $v_e/c = Z\alpha = Z/137$ (s electrons)

For the s electrons in Sg (106): $v_e/c = 0.77$

$m_{rel} \sim 1.57 m_0$ increases

$r = 0.64 r_0$ decreases

Take away

- Life-times of excited states
  - Different experimental approaches
- Population of excited states in decays (selectivity)
- Neutron halo structures emerge in the regime of weak neutron binding
- The heaviest elements (hard to produce, rates can be as low as atom/month)
  - Last confirmed new element: Z=112
  - Production: “cold” vs. “hot” fusion
  - Detailed spectroscopy possible in quite a few cases
  - Electron structure and thus chemistry might be altered for the heaviest nuclei (relativistic effects on electron mass and radius)

Further reading

Radii and halos

- Neutron halo nuclei, I. Tanihata, J. Phys. G: Nucl. Part. Phys. 22, 157 (1996)
- Nuclear halos, P.G. Hansen, A.S. Jensen, and B. Jonson, Annu. Rev. Part. Sci. 45, 591 (1995)
- Nuclear halo states, K. Riisager, Rev. Mod. Phys. 66, 1105 (1994).

Heavy elements

R.-D. Herzberg
Spectroscopy of Superheavy Nuclei,
Topical Review, JPG 30 (2004), R123.

Y.Oganessian
Heaviest nuclei from ^{48}Ca-induced reactions
Topical Review, JPG 34 (2007) R165.

S. Hofmann and G. Muenzenberg
The discovery of the heaviest elements,
Rev. Mod. Phys. 72 (2000) 733.

Collectivity and simple patterns

Rick Casten, Nuclear structure from a simple perspective, 2nd edition, Oxford science publications (2000)

http://nobelprize.org/nobel_prizes/physics/laureates/1975/mottelson-lecture.pdf