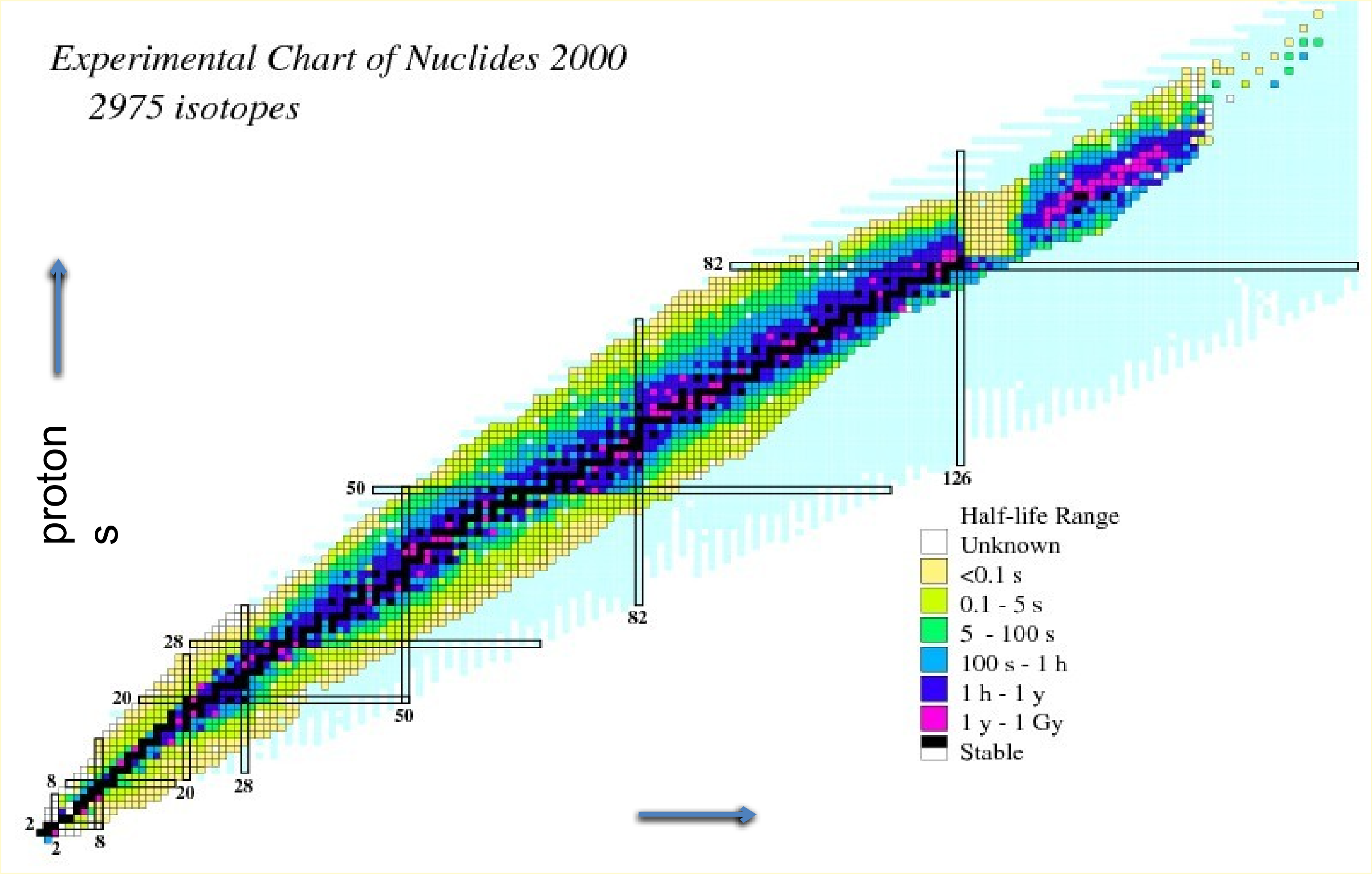
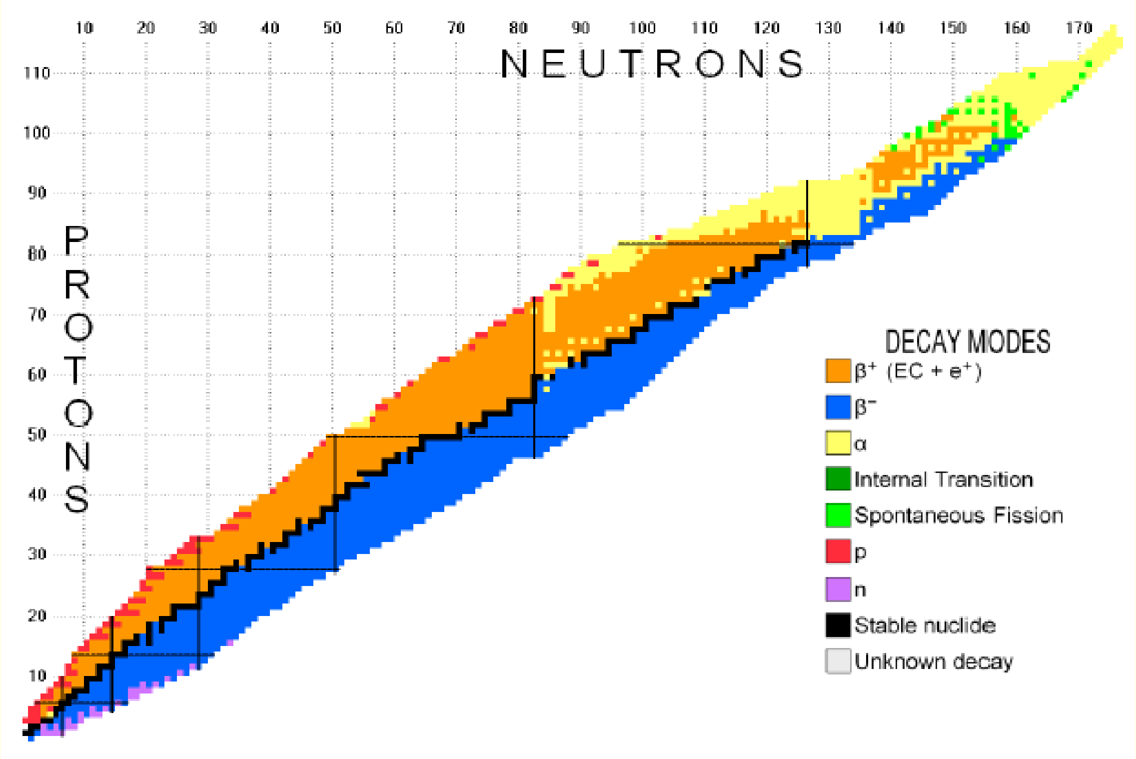
Nuclear chart, “magic” proton and neutron numbers, measured half-life ranges



NUBASE evaluation: exp. decay modes

Audi et al., Nucl. Phys. A 729 (2003) 3-128



History of radioactivity

- Henri Becquerel (1890's) discovers that various uranium salts emit unknown "rays" that penetrate paper and expose photographic plate

- Marya Sklodovska ↔ Marie Curie (1896) works with "pitchblende" (mixture of uranium ore and others), isolates two new chemical elements that are highly "ray-producing" (= radioactive):

  radium (Z=88), this element is a million times more radioactive than natural uranium, and

  polonium (Z=84), named after her home country Poland

History of radioactivity

Marie Curie won two Nobel prizes:
 1903 in physics (radioactivity), with husband Pierre Curie
 1911 in chemistry (two new elements, Po and Ra)

Her daughter Irène Joliot-Curie and her son-in-law Frédéric Joliot-Curie also also won Nobel prize, in chemistry (1935)

Nuclear decay modes: α decay (helium-4 emission)

- in heavy nuclei, α particles form in nuclear surface region
- α particles tunnel through potential barrier formed by Coulomb + strong nuclear interaction

Example:

$$^{238}_{92}U \rightarrow \; ^{234}_{90}Th + \; ^{4}_{2}He$$

uranium thorium α

"parent" nucleus (Z,N) → "daughter" nucleus (Z-2,N-2) + α

Note: total numbers of A, Z, and N conserved in α decay

The radioactive decay law

See related notes in section 2.1a

Topics:
decay rate, half-life, mean life, level width
activity A(t) of radioactive substance

Theory of α decay: George Gamov (1928)
tunneling through a potential barrier

See related notes in section 2.1a

Nuclear decay modes: β^- decay (electron emission)

Basic weak interaction decay (note charge conservation):

neutron → proton + electron + anti-neutrino

Example:

$^{234}_{90}$Th → $^{234}_{91}$Pa + e^- + anti-neutrino

thorium protactinium

"parent" nucleus (Z,N) → "daughter" nucleus (Z+1,N-1) + …

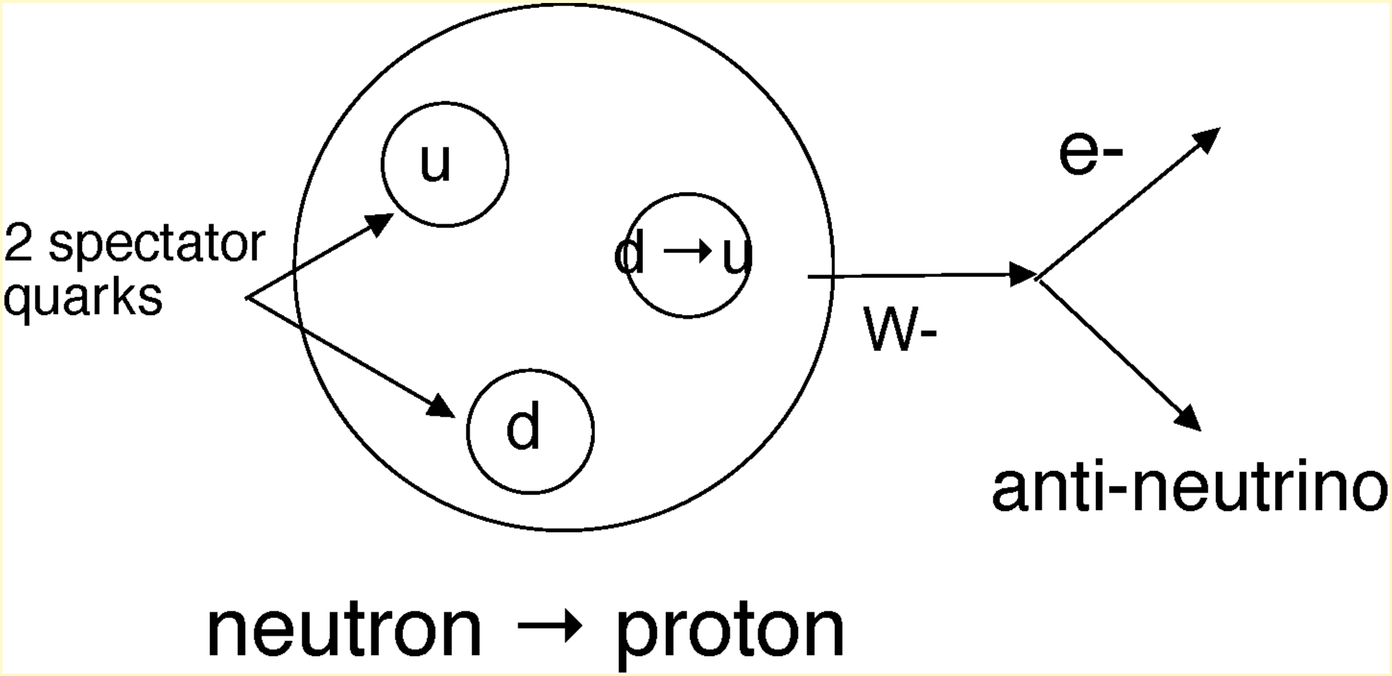
Note: total number of A is conserved in β^- decay

β^- decay: interpretation in terms of quarks and W boson

neutron = (u d d), proton = (u u d)

$$d \rightarrow u + W^-$$

charges: $-1/3 \rightarrow +2/3 \; -1$



Nuclear decay modes: β^+ decay (positron emission)

Basic weak interaction decay (note charge conservation):

proton → neutron + positron + neutrino

Example:

$^{13}_{7}N \rightarrow {}^{13}_{6}C + e^+$ + neutrino

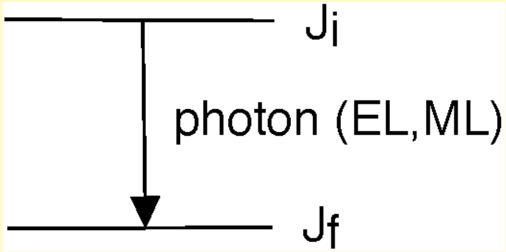
nitrogen → carbon

"parent" nucleus (Z,N) → "daughter" nucleus (Z-1,N+1) + …

Note: total number of A is conserved in β^+ decay

Practical application: positron emission tomography (PET)

Nuclear decay modes: gamma decay



Spontaneous photon emission is explained by quantum electrodynamics (QED). Even in the vacuum state, there are always zero-point vibrations of the electromagnetic fields which couple to the electric charges and currents of the nucleons, thus producing EM radiation.

Classical treatment : J.D. Jackson, Classical Electrodynamics, 3rd edition, chapter 9.11
QED treatment (brief summary): Shankar, QM, 2nd edition, p. 506-521

Angular momentum selection rules are determined by Clebsch-Gordan Coefficients (Wigner-Eckart theorem, see e.g. Shankar p. 420)

spontaneous fission: example Californium-252

$$^{252}_{98}\text{Cf} \rightarrow \; ^{132}_{50}\text{Sn} + \; ^{117}_{48}\text{Cd} + 3n$$

heavy fission fragment — light fission fragment

Sizable spontaneous fission is observed in heavy transuranic isotopes.
For ^{252}Cf one finds (Nuclear Wallet Cards, BNL, 2005):

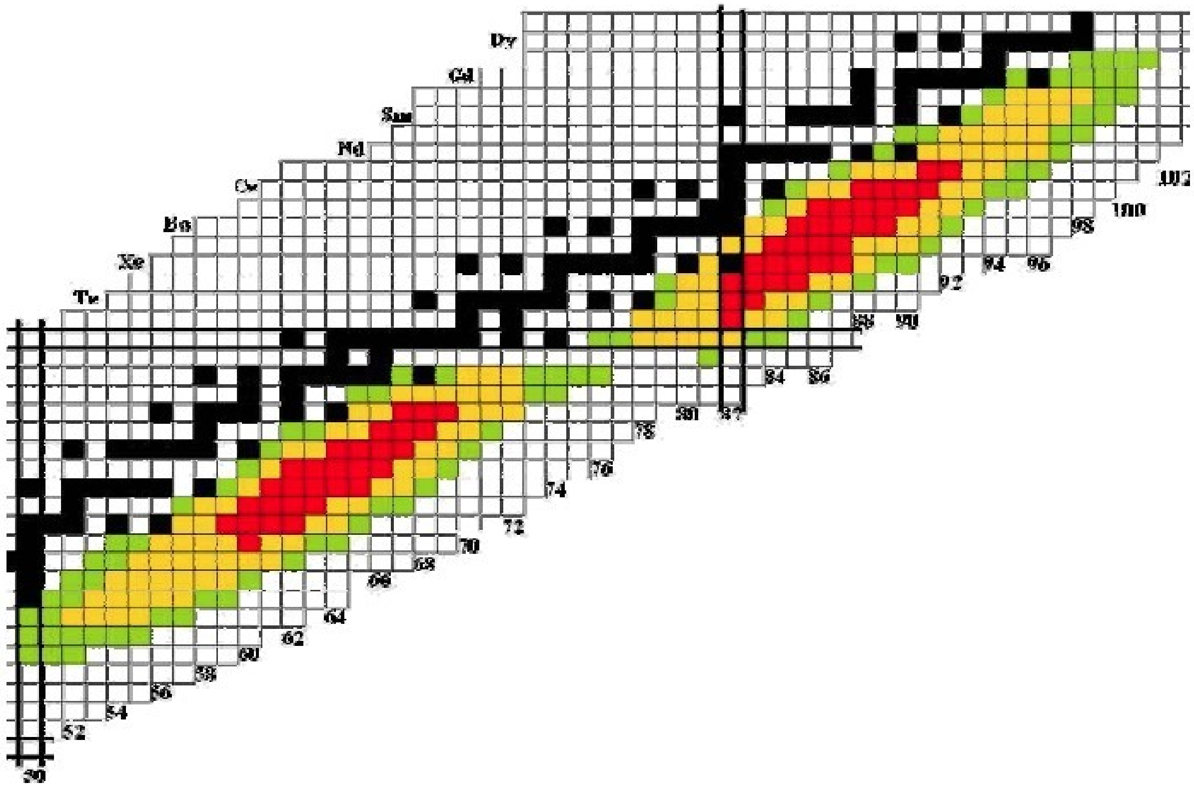
α-decay probability = 96.91 %
spontaneous fission probability = 3.09 %

Total half-life (mostly α) = 2.645 years
Spontaneous fission half life ≈ 100 years

Fission products from spontaneous fission of ^{252}Cf

http://www.phy.anl.gov/atlas/caribu/Cf252_upgrade_proposal_final_Rev4.pdf

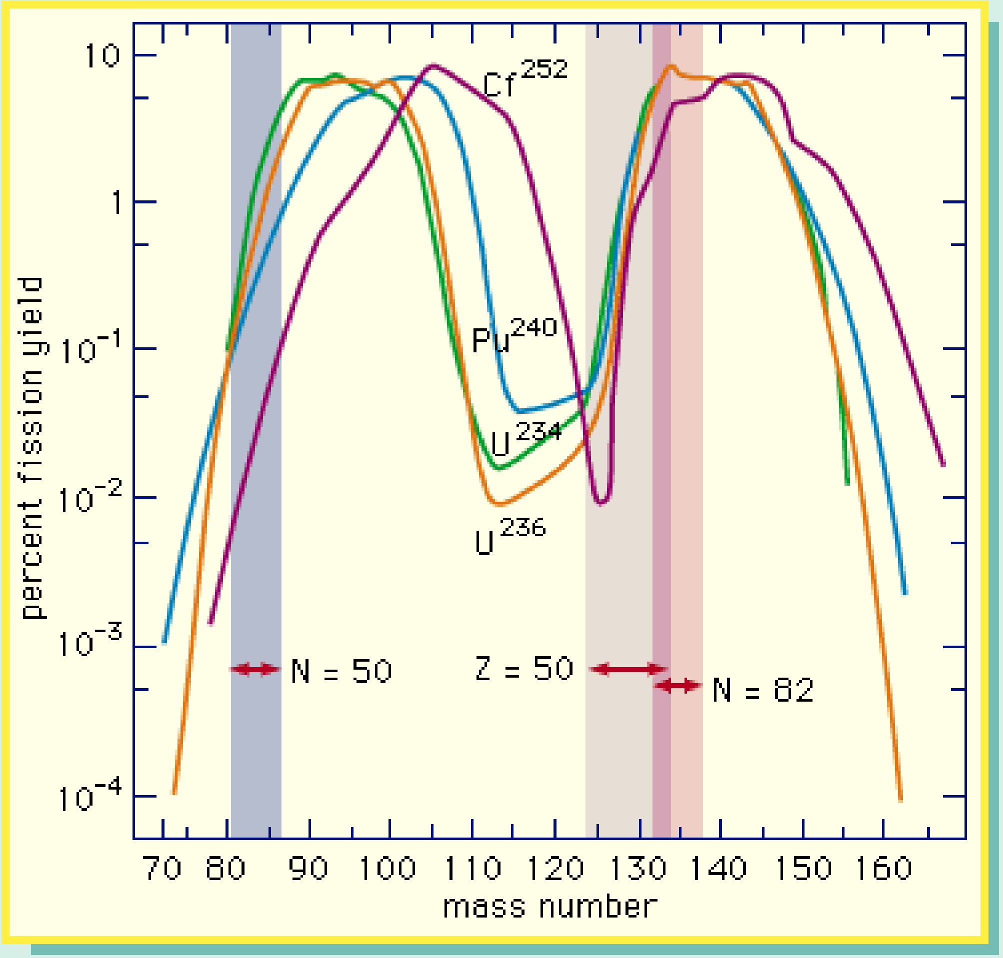
Figure 6. Distribution of the fission products from the spontaneous fission of ^{252}Cf. Both peaks are centered on heavier mass than the equivalent peaks in uranium fission.



Fission mass distributions

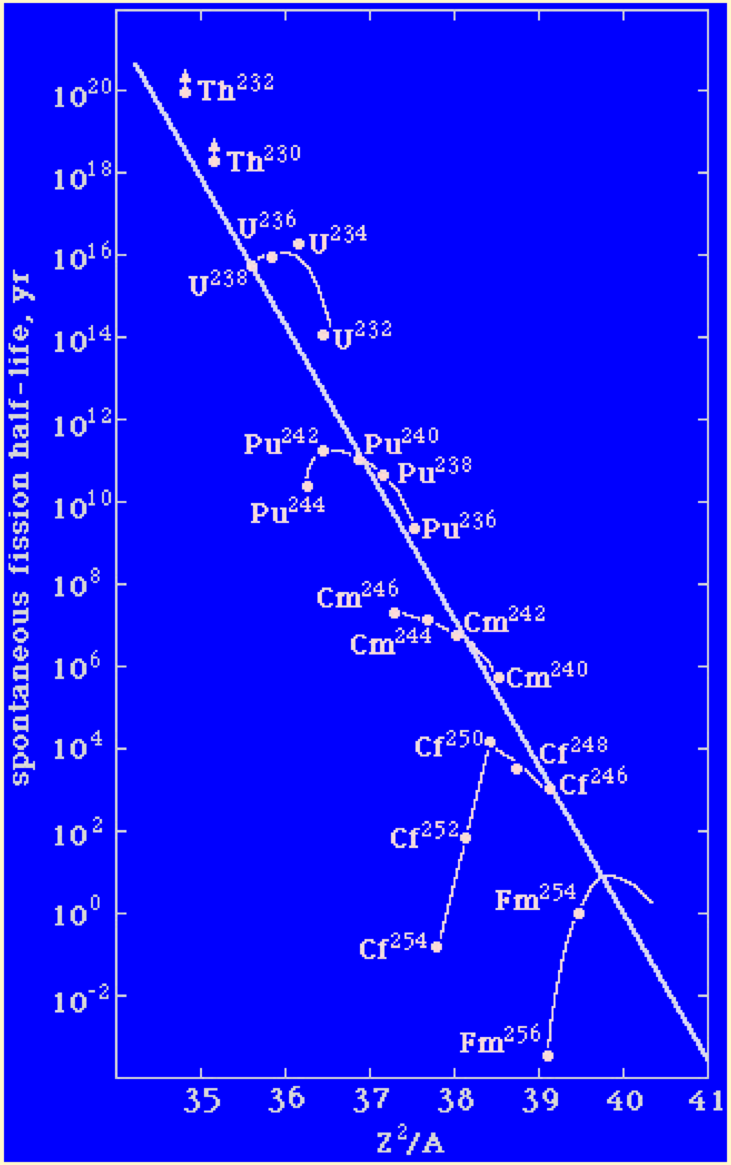
spontaneous fission of ^{252}Cf; thermal neutron fission of U and Pu

Ref: A.C. Wahl, Symposium on Physics and Chemistry of Fission (1965), IAEA, Vienna



The light mass group shifts to higher masses as the mass of the fissioning nucleus increases, while the heavy group remains nearly stationary. The shaded areas show the location of the closed shells of 50 protons, 50 neutrons, and 82 neutrons (see text).

spontaneous fission: half-lives



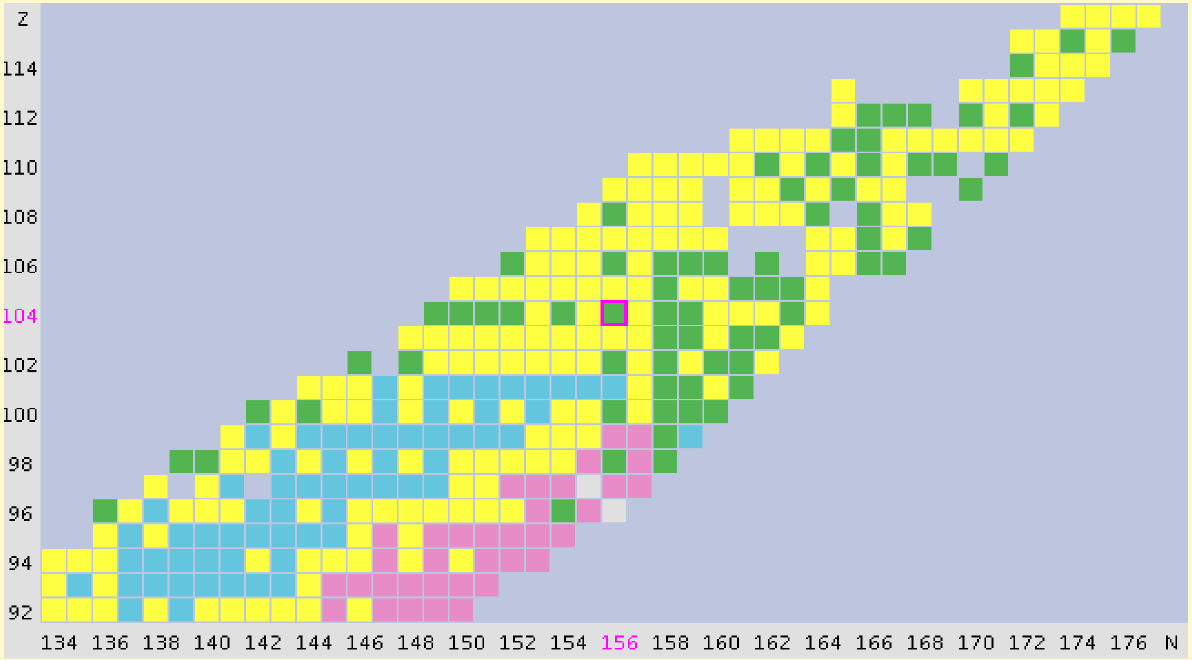
Spontaneous fission half-lives of actinide isotopes vary by 22 orders of magnitude.

For ^{252}Cf one obtains about 100 years.

Second frontier: superheavy elements in heavy-ion fusion reactions

Ref: National Nuclear Data Center, Brookhaven

http://www.nndc.bnl.gov/index.jsp



Exp. discovery of superheavy element Z=117 at Dubna (Russia)

Vanderbilt physicists involved: Professors Hamilton and Ramayya

Phys. Rev. Lett. 104, 142502 (2010)

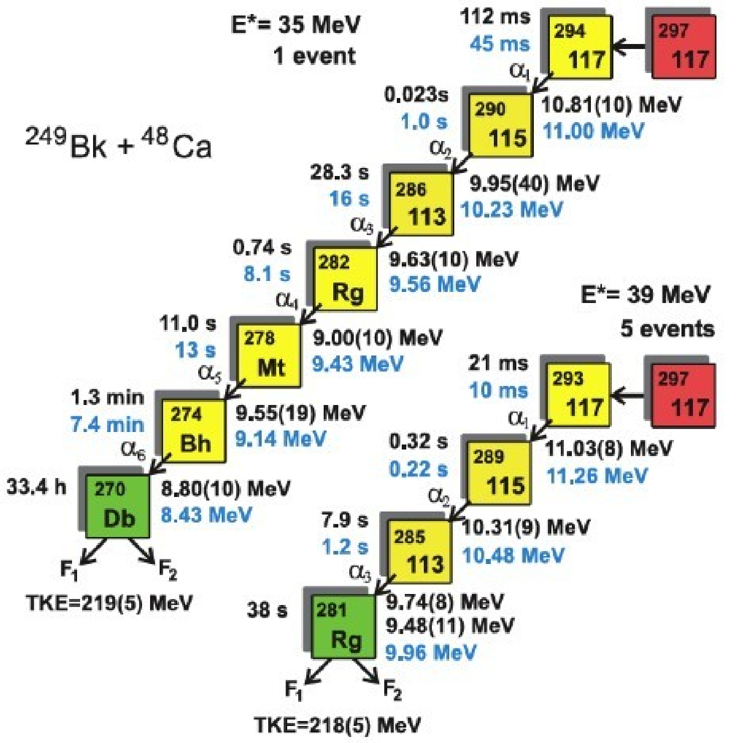


FIG. 1 (color). Observed decay chains interpreted as originating from the isotopes $A = 294$ (single event) and $A = 293$ (average of five events) of the new element $Z = 117$. The deduced and predicted [9] lifetimes ($\tau = T_{1/2}/\ln 2$) and α-particle energies are shown in black and blue, respectively.

The isotopes $^{293}117$ and $^{294}117$ were produced in fusion reactions between $^{48}_{20}$Ca and $^{249}_{97}$Bk. Decay chains involving 11 new nuclei were identified by means of the Dubna gas-filled recoil separator. The measured decay properties show a strong rise of stability for heavier isotopes with Z ≥111, validating the concept of the long sought island of enhanced stability for superheavy nuclei.

Nuclear decay modes: exotic

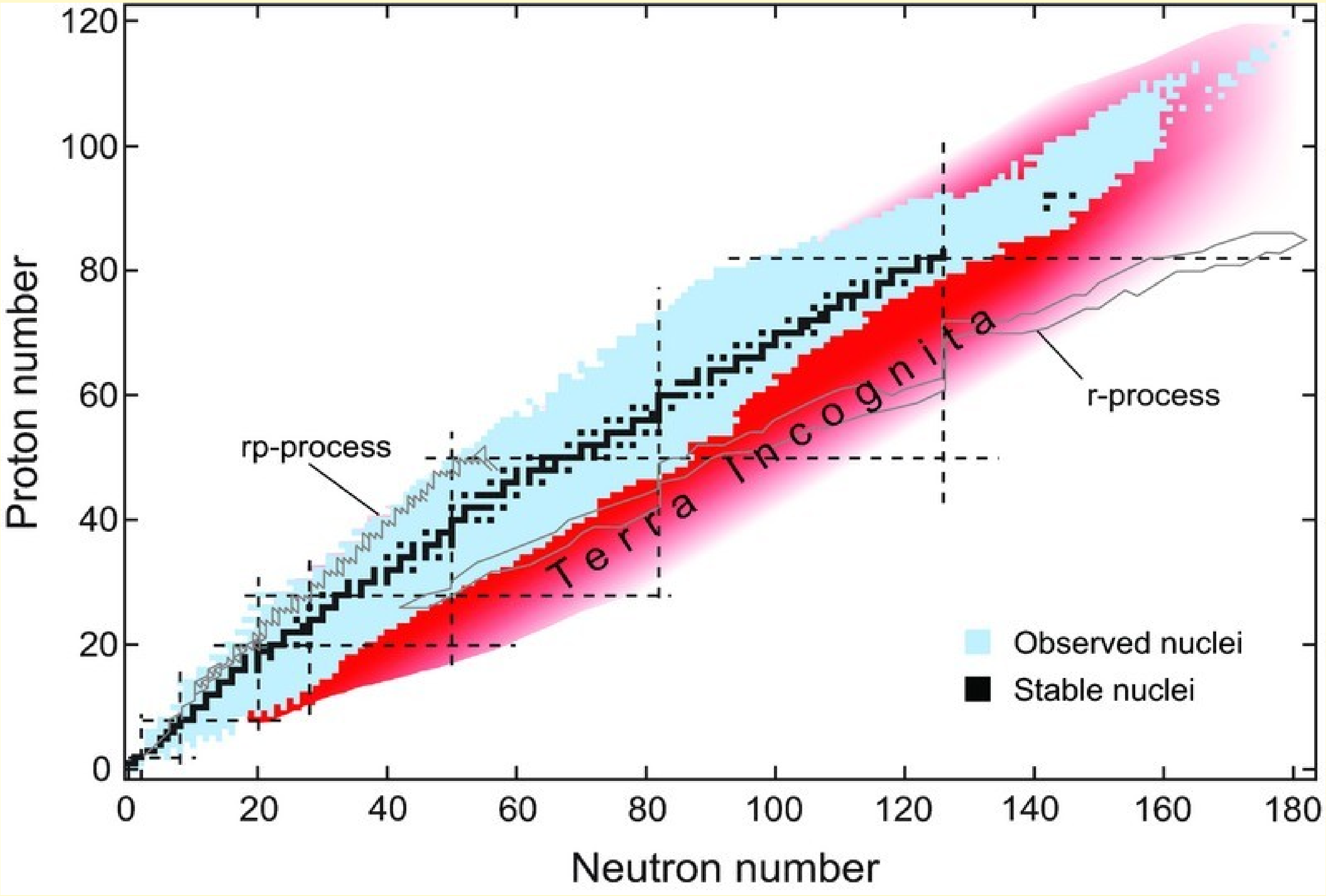
Proton radioactivity: spontaneous p and 2p emission at proton dripline

Neutron radioactivity: spontaneous n and 2n emission at neutron dripline

“cluster emission” of heavier ions, e.g. ^{14}C, ^{24}Ne, …

Nuclear chart and the frontier of neutron-rich nuclei

Ref: Isotope Science Facility proposal, MSU (Nov. 2006)



Exp. data: neutron dripline for light nuclei (up to Z=8)

Ref: RIA Physics White Paper, Raleigh, NC conference (2000)

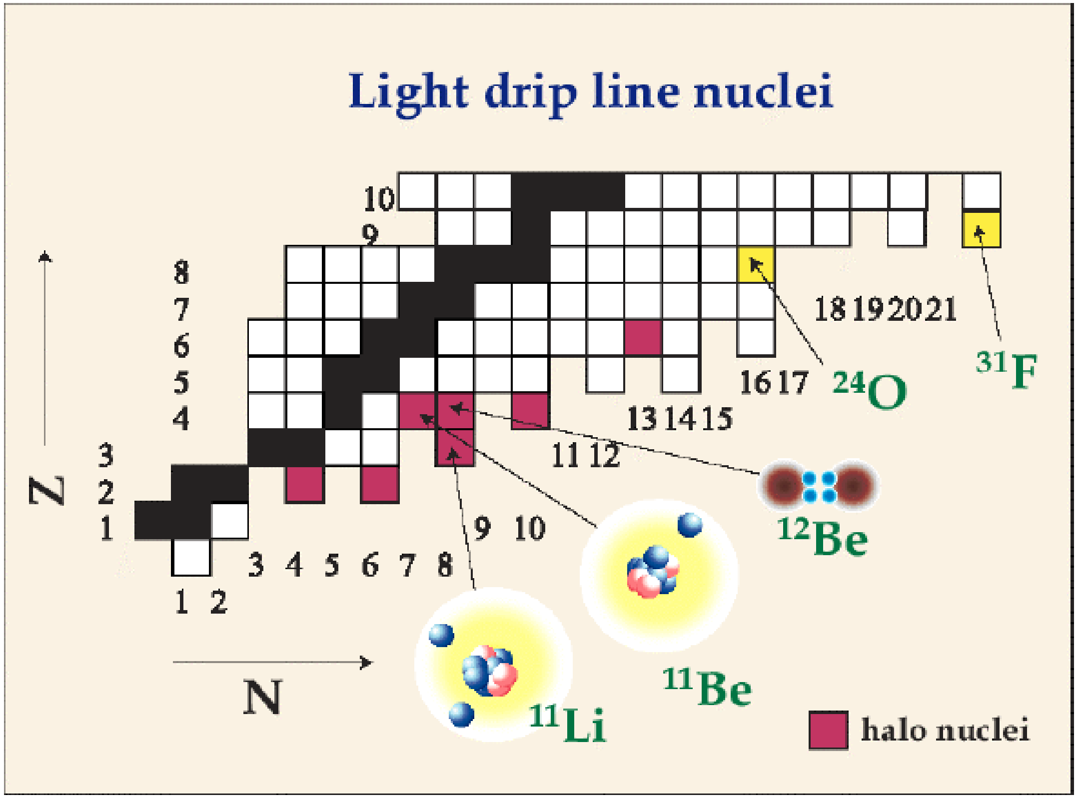


Figure 5: The part of the (N,Z) chart for the lightest nuclei. The neutron drip line has been reached only up to oxygen (Z = 8) where the heaviest particle-stable isotope has 16 neutrons. Interestingly, the heaviest isotope of flourine (Z=9) known has 22 neutrons. That is, one additional proton binds at least six neutrons. Known halo nuclei are marked by red squares. A very elongated "dimer" configuration in ^{12}Be has recently been found at higher excitation energies.