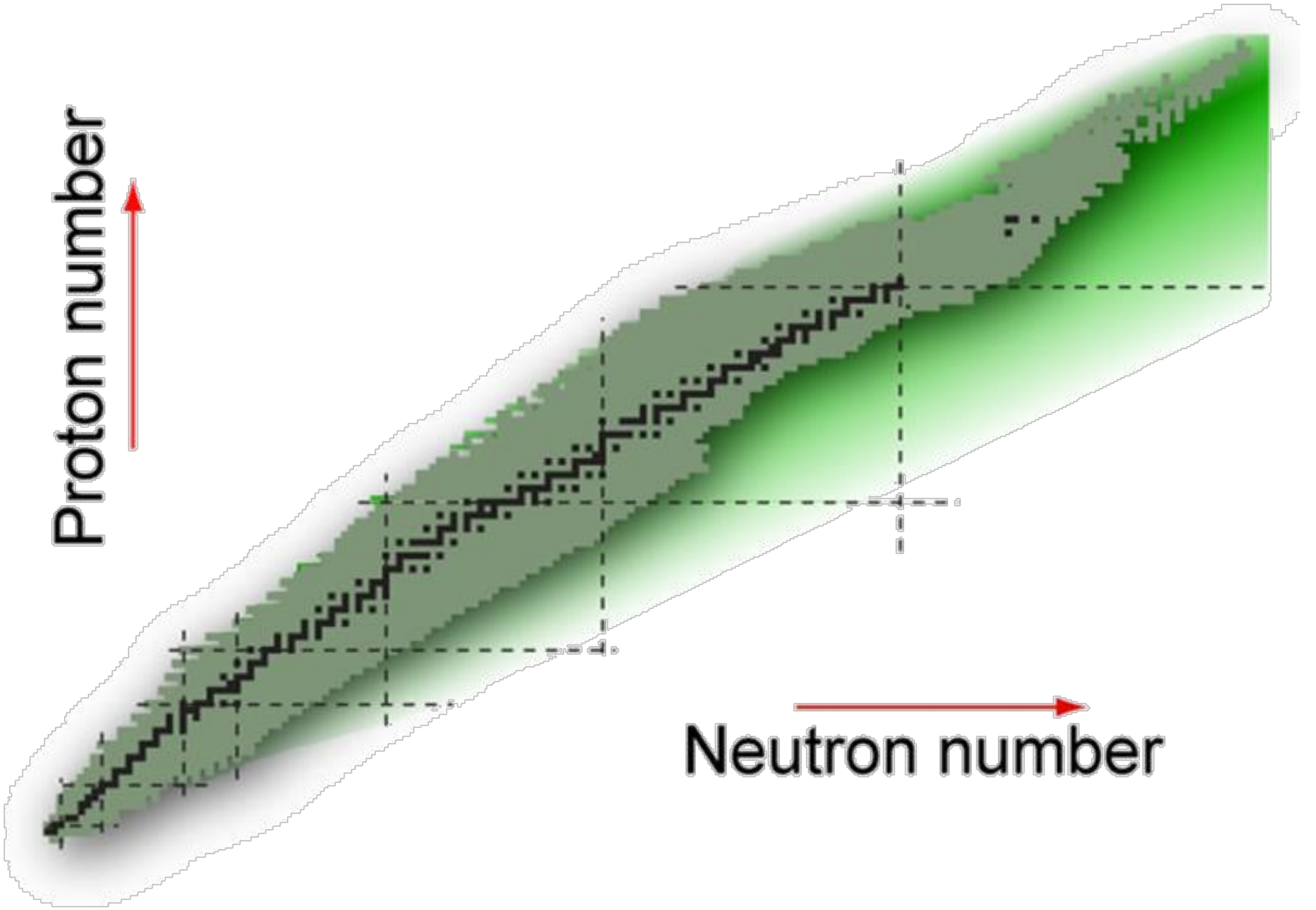
Nuclear Structure from Decay Spectroscopy

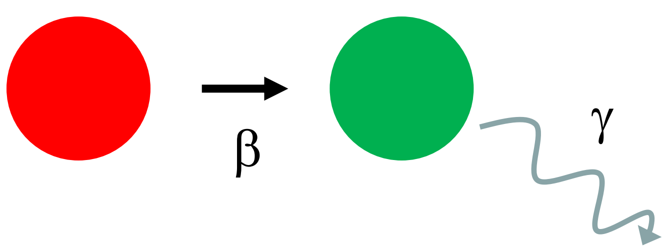
- Most nuclei decay.
- Provides complementary information to reaction studies.
- Studies can be done at the lowest count rates – access furthest from stability.
- Alpha, proton, beta, gamma.



Decay spectroscopy vs Reactions

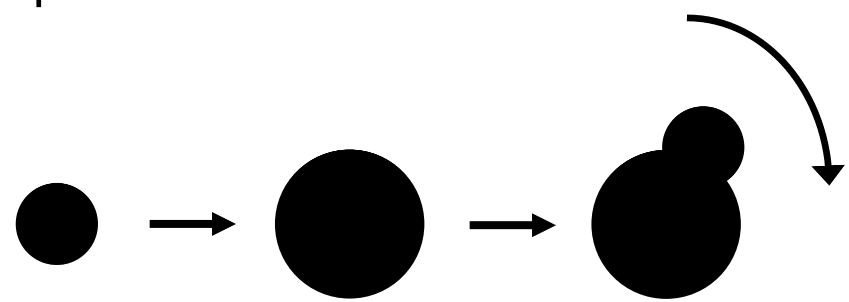
Decay Spectroscopy

- Production and observation widely separated in time.
- Difficult to change decays (not impossible)
- Relatively few channels available.
- Studies possible at rates lower than 1/day.



Reactions

- Production and observation close in time.
- Reaction mechanism provides some flexibility
- Many channels typically open.
- Typically requires 100 particles/second.



Decay Spectroscopy

Production

- High energy
  - Fragmentation
- Medium energy
  - ISOL
- Low-energy
  - Multi-nucleon transfer
- …

→

Separation

- Mass separator
- Laser spectroscopy
- Chemistry
- Energy Loss
- …

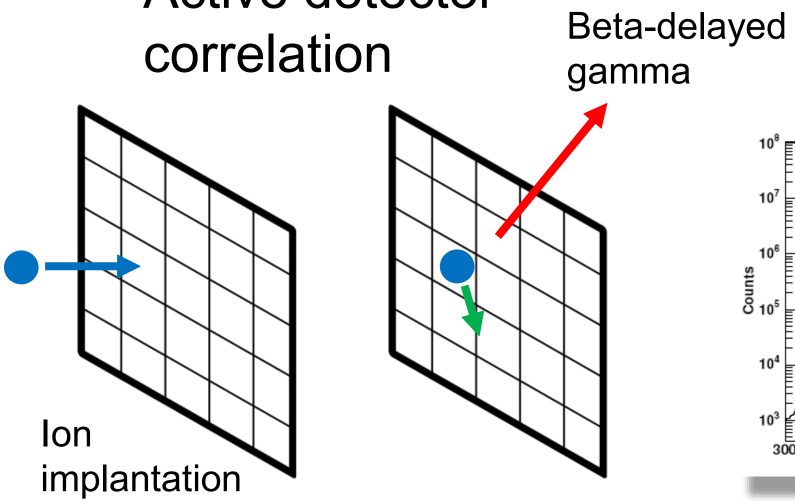
→

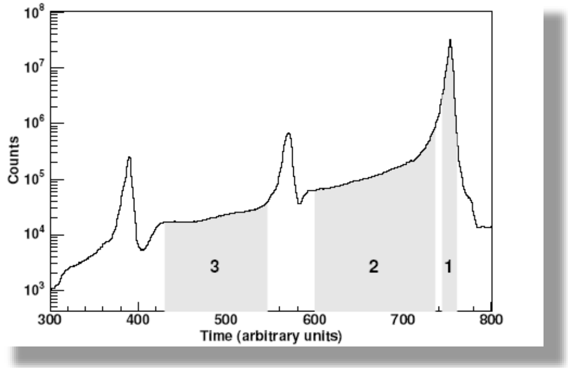
Experiment

- Semiconductor
- Moving tape
- Gas Detectors
- Passive material
- …

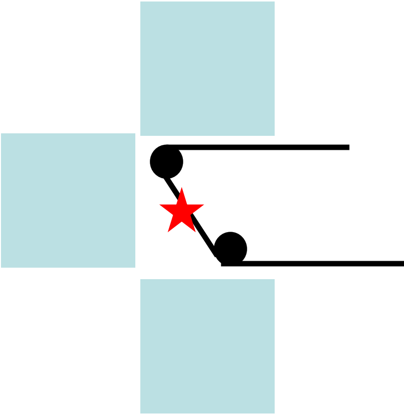
Experimental Setups

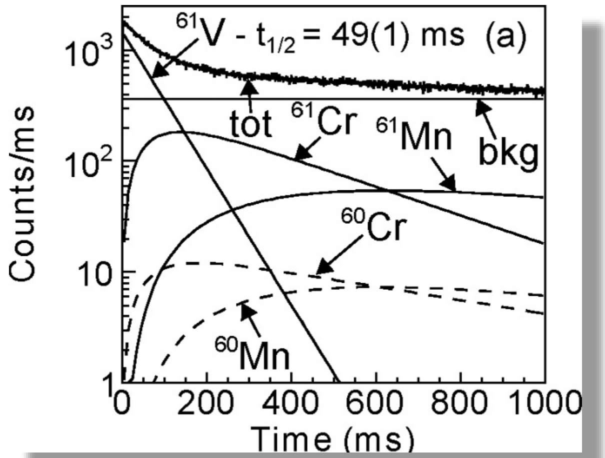
- Active detector correlation



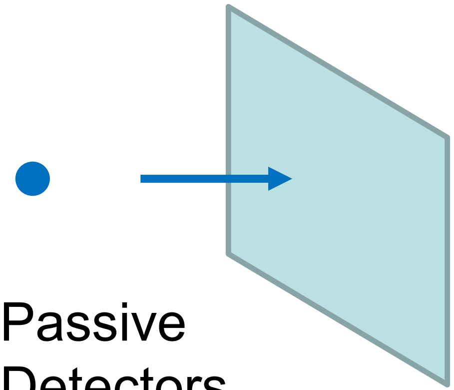


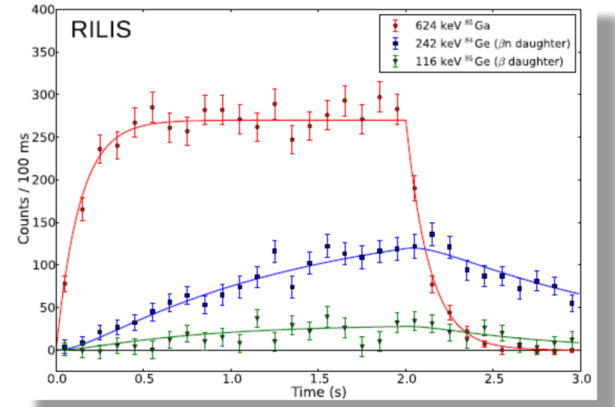
- Moving Tape Collector





- Passive Detectors

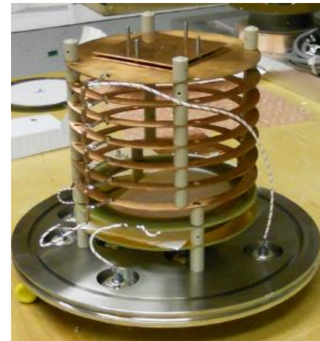




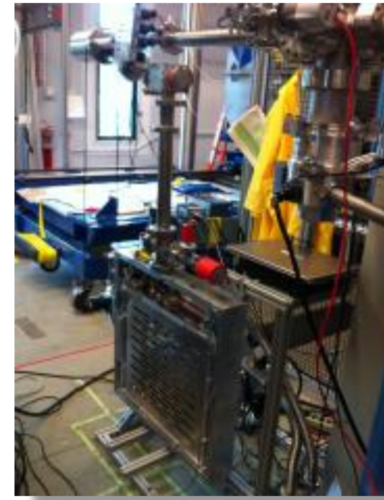
A Sample of Experimental Setups

- Active detector

Wasabi (RIKEN)



Astrobox (TAMU)

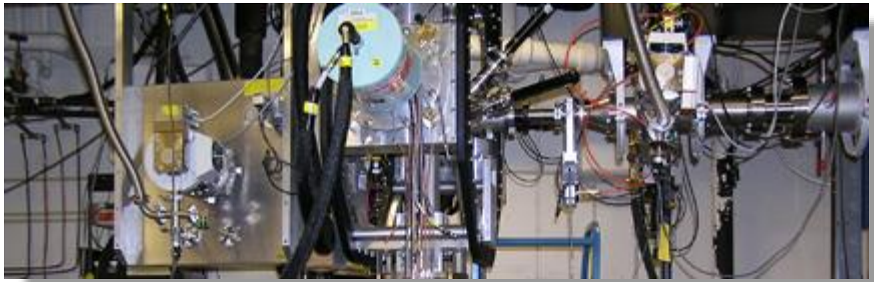


BCS (MSU)

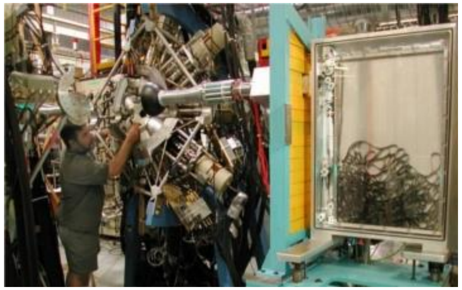
Saturn/Tape (ANL)

Rising (GSI)

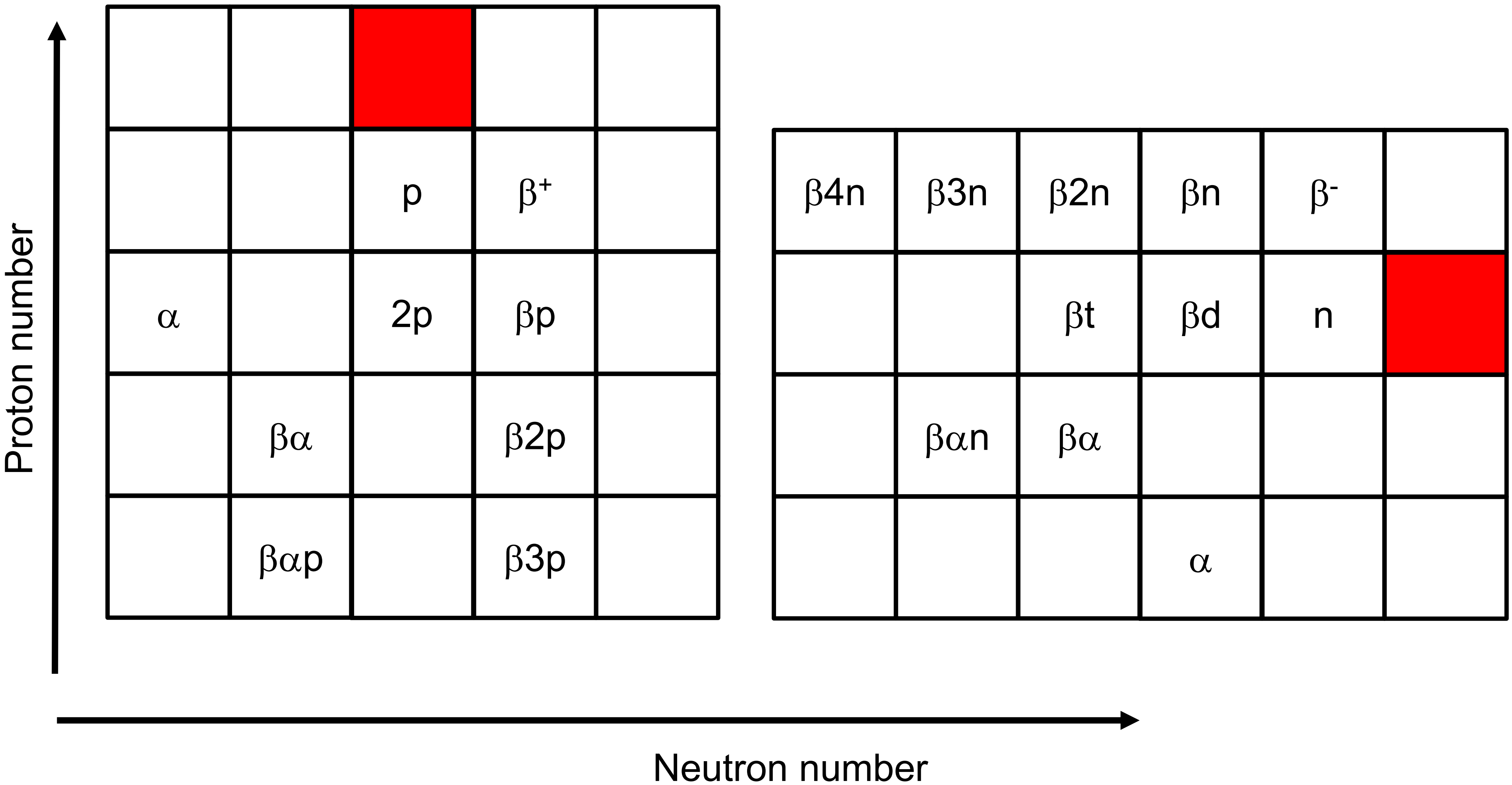
Leribss (ORNL)



Tape (TRIUMF)



What decays?

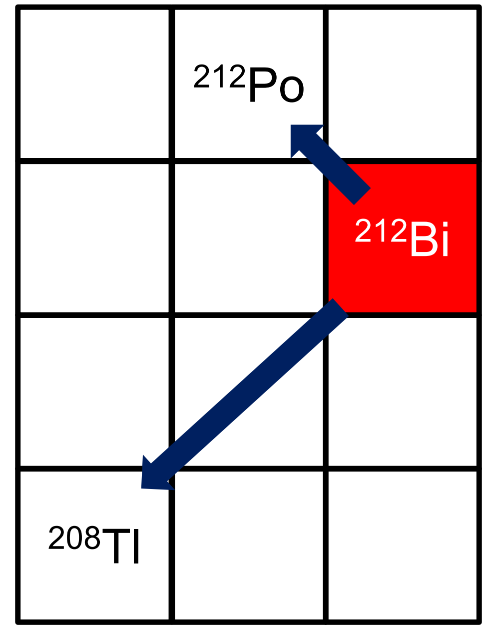

Proton number
p
β+
α
2p
βp
βα
β2p
βαp
β3p
β4n
β3n
β2n
βn
β-
βt
βd
n
βαn
βα
α
Neutron number

Experimental Observables

- Many different types of decay spectroscopy.
  - Beta-decay
  - Alpha decay
  - Proton decay
  - Isomeric decays
- Widely varying timescales
  - nanoseconds – age of universe
- Widely varying energies
  - ev to 10 MeV
- Measure three important quantities
  - energy
    - Where is the state?
  - half-lives
    - What is the time difference between creation and destruction?
  - branching ratios
    - Where does the decay go, what gets emitted?
- Selection rules
- Connect to underlying structure

Question

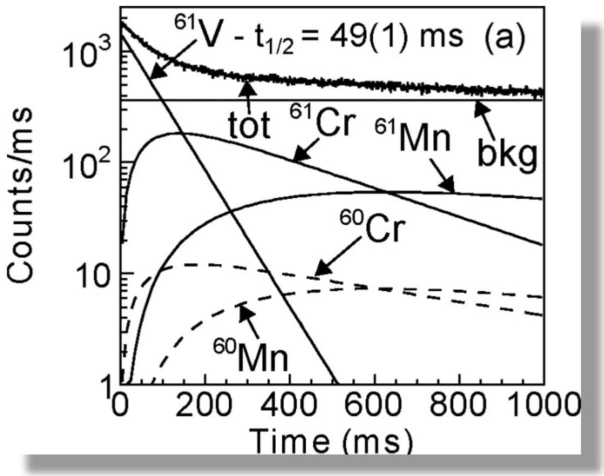
- ^{212}Bi is a member of a naturally occurring ^{232}Th radioactive decay series
- The half-life of ^{212}Bi is 61 minutes.
- The decay braches at ^{212}Bi
  - 35.94% α, $t_{1/2,\alpha}$ = 168 min.
  - 64.06% β^-, $t_{1/2,\beta}$ = 94 min.
- If your experimental setup is only sensitive to β^- what half-life do you measure?

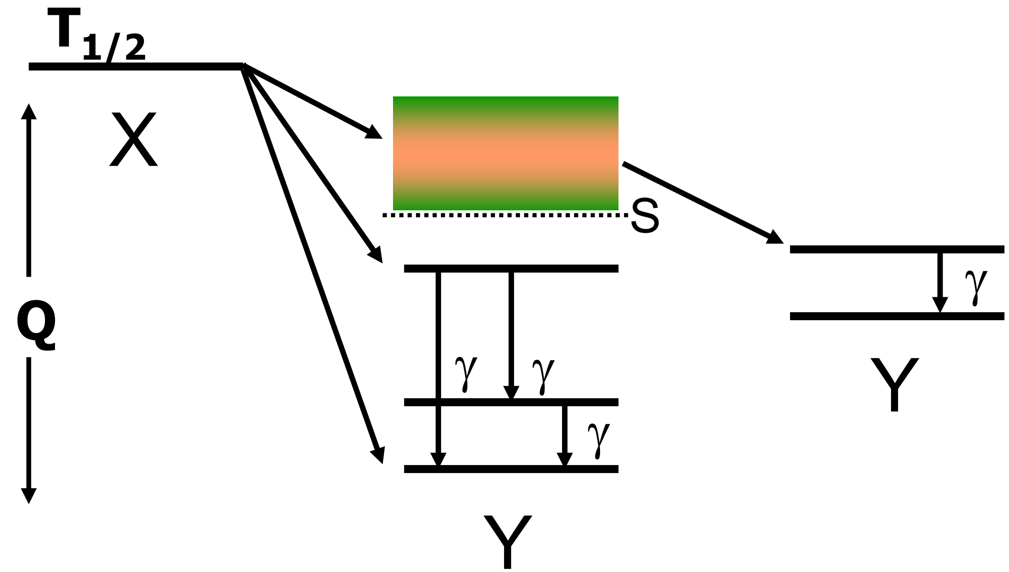


- A – 61 min
- B – 94 min
- C – 168 min
- D – 262 min
- E – not enough information

Relationships

- Measure time distribution.
- Determine $t_{1/2}/\tau/\lambda$
- Correct for branching ratios.





$$t_{1/2} = \frac{\ln 2}{\lambda} \qquad \lambda = \frac{1}{\tau}$$

$$\lambda = \Sigma_i \ \lambda_i \qquad t_{1/2,i} = \frac{\ln 2}{\lambda_i}$$

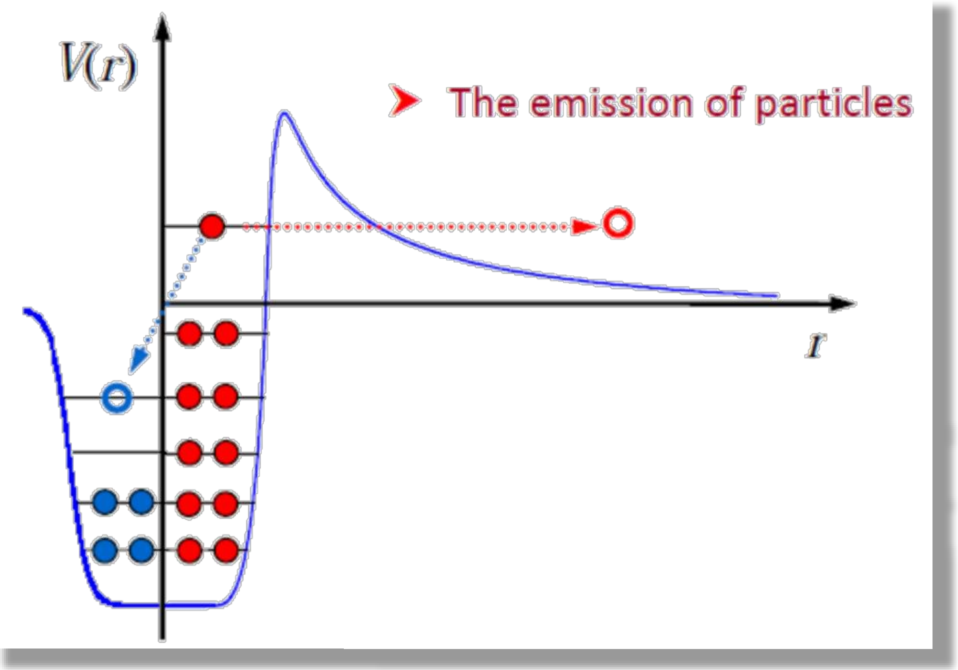
Particle Emission

- Competition between decays
  - Beta decay

$$\lambda \sim Q^5$$

  - Charged particle

$$\lambda \sim e^{\left\{-\frac{2}{\hbar}\int_{r_{in}}^{r_{out}}\sqrt{2\mu[V(r)-Q}\,dr\right\}}$$

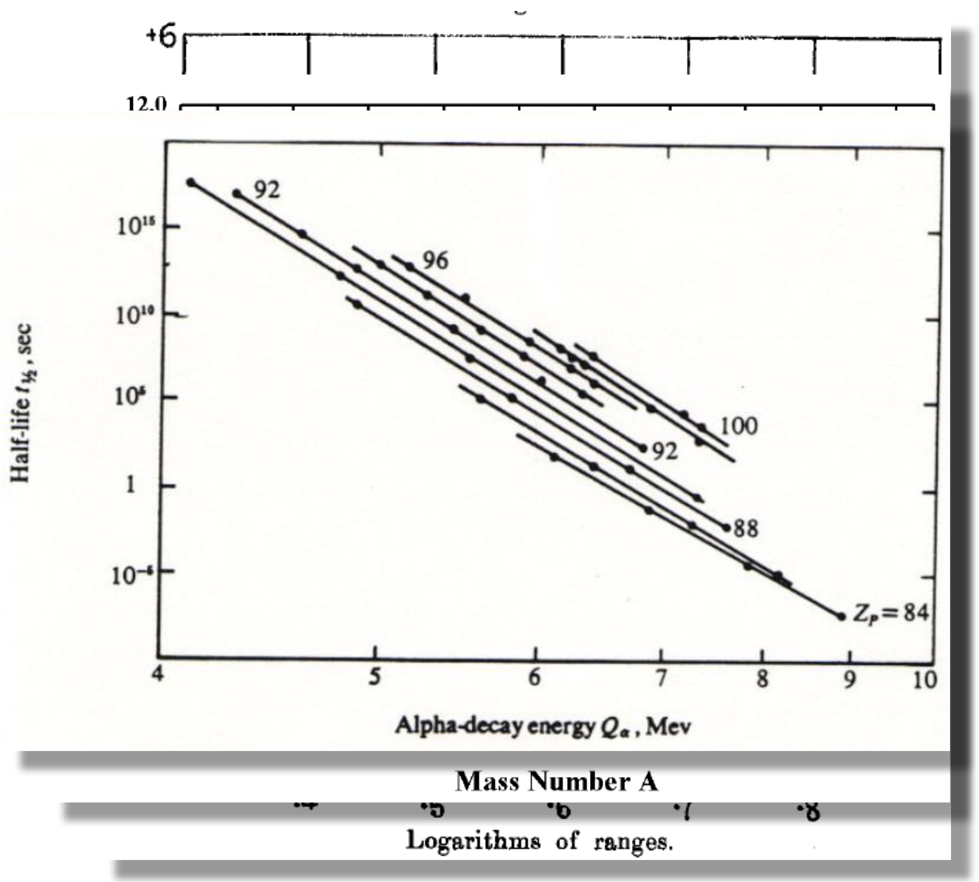


Adapted from M. Pfützner

Alpha Decay

$${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + \alpha + \text{Q}$$

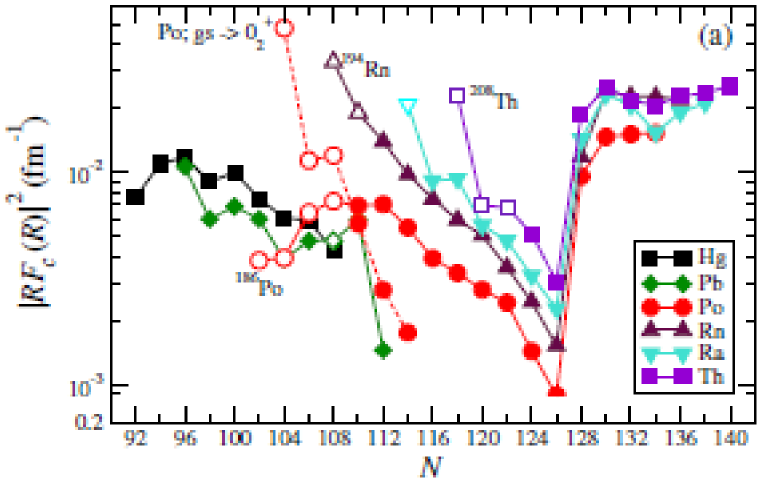
- Two body decay.
- Energy split between participants.
- Q_α influenced by shell closure.
- Gieger-Nuttal relationship between Q_α and $t_{1/2}$

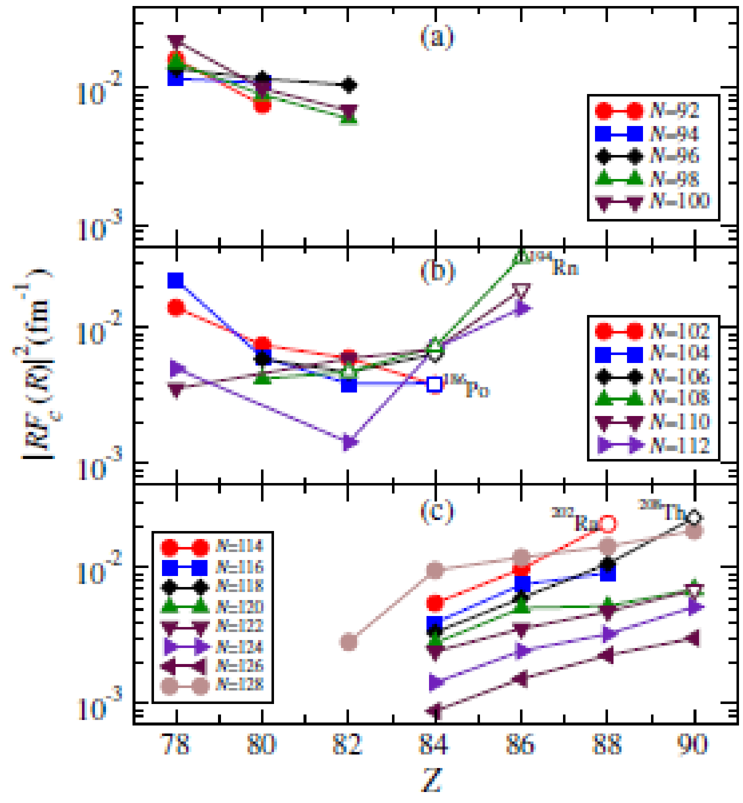


W. Loveland, D.J. Morrissey, and G.T. Seaborg. Modern Nuclear Chemistry
H. Geiger and J.M. Nuttal, Philos. Mag. 22, 613 (1911)

Alpha Decay

- Difference between theory and experiment contains nuclear structure.
- Pre-formation factor, $|RF_C(R)|^2$



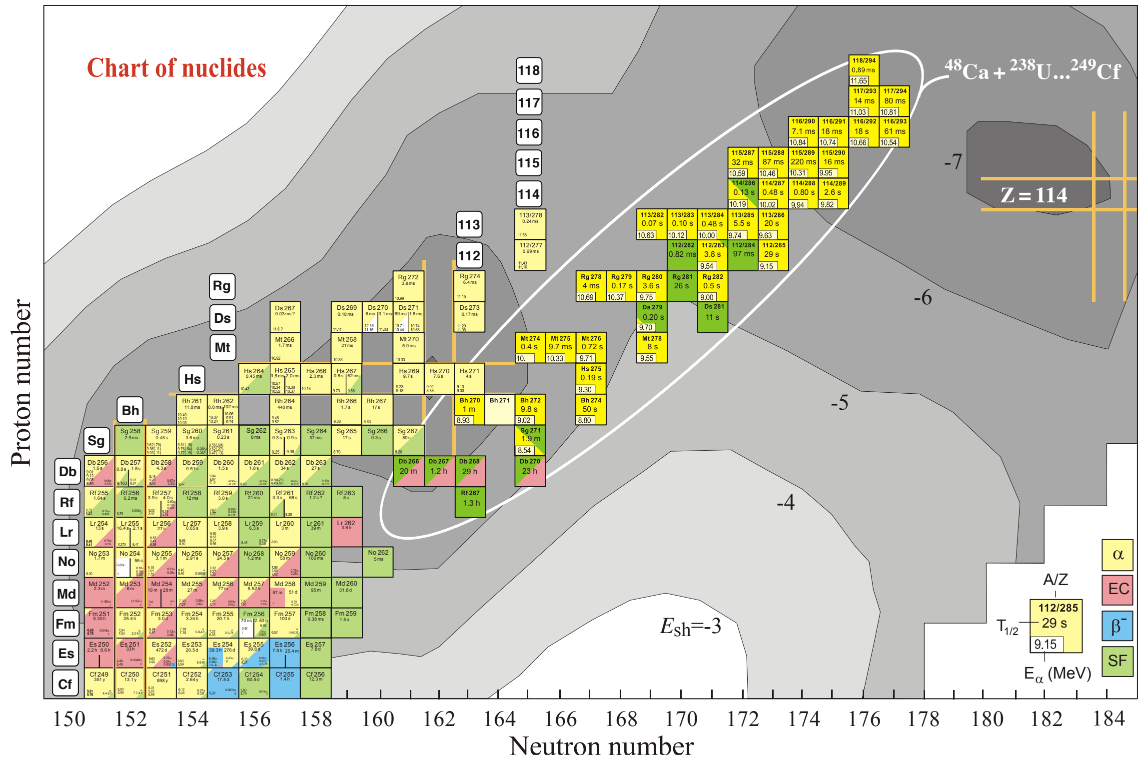


C. Qi *et al.*, Phys. Rev. Lett. 103, 072501 (2009)
A. N. Andreyev *et al.*, Phys. Rev. Lett., 110, 242502 (2014)

Superheavy Elements

Recall talk by M. Stoyer
See talk tomorrow by J. Gates

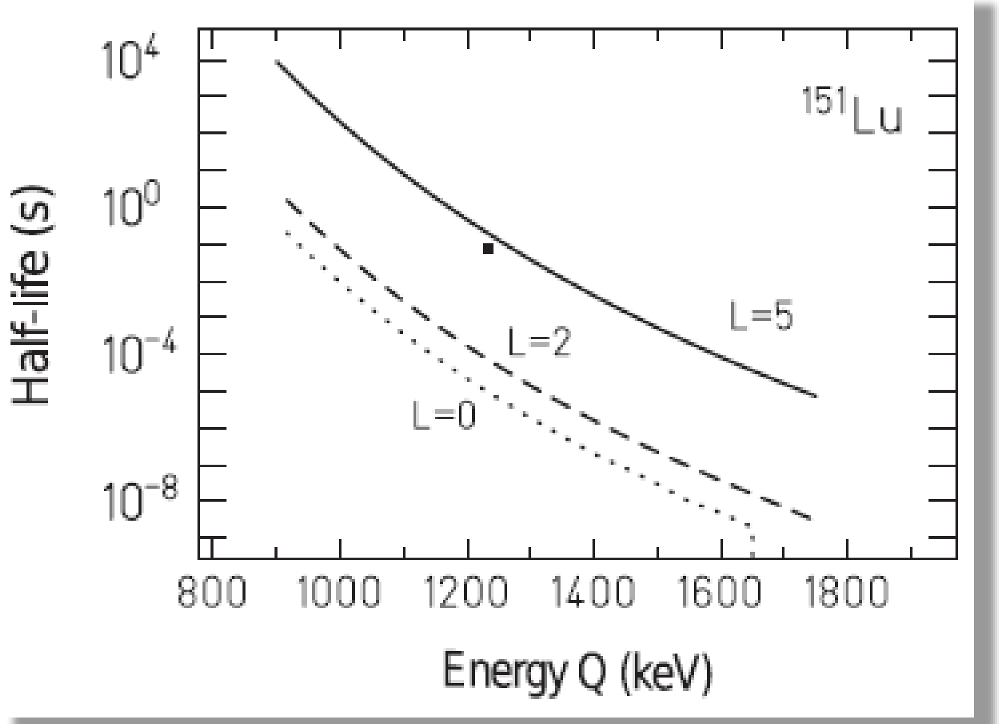
- Location of the island of (enhanced) stability.



Proton Emission

$$^{A}_{Z}X \rightarrow {}^{A-1}_{Z-1}Y + p + \mathrm{Q}$$

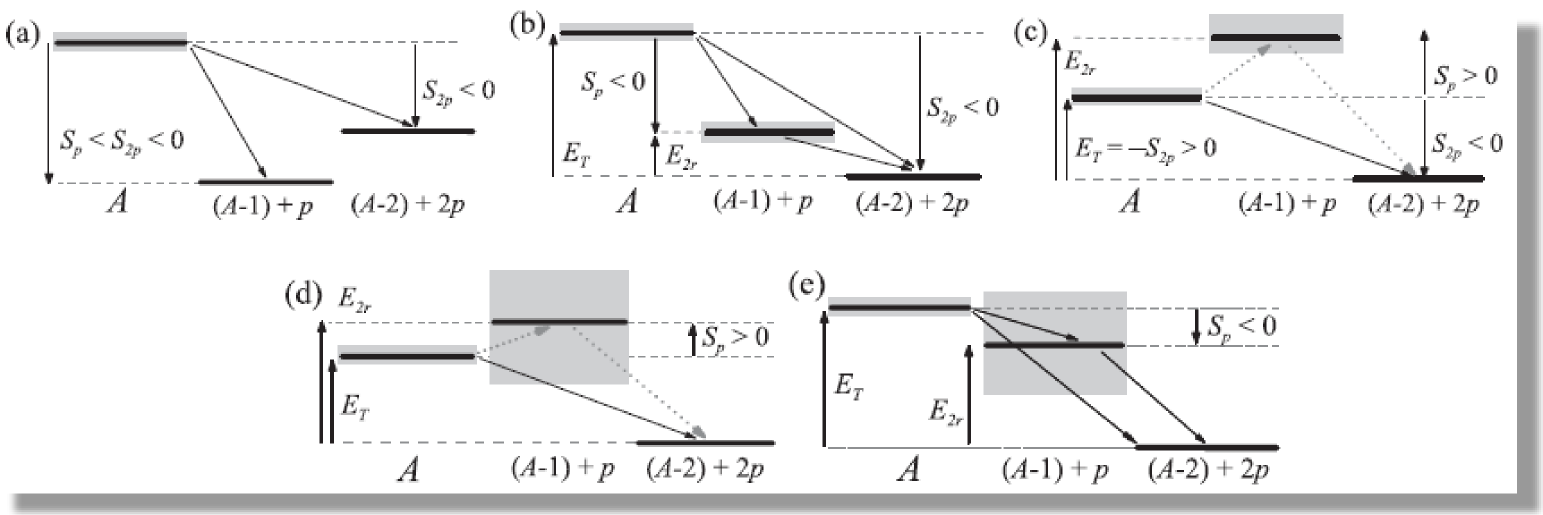
- Protons can also be emitted from nucleus.
- Conserve angular momentum and parity.
- Strong dependency between l, $t_{1/2}$, and Q_p.



Two Proton Emission

- Two protons can also be emitted from nucleus.
- Strong dependency between I, $t_{1/2}$, and Q_p.

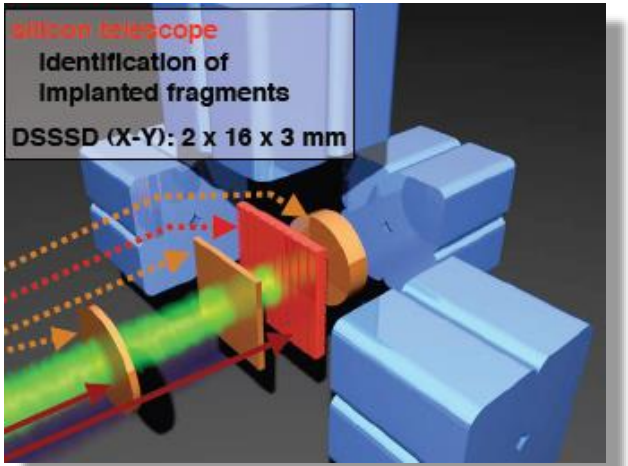
$$ {}^{A}_{Z}X \rightarrow {}^{A-2}_{Z-2}Y + 2p + \mathrm{Q} $$

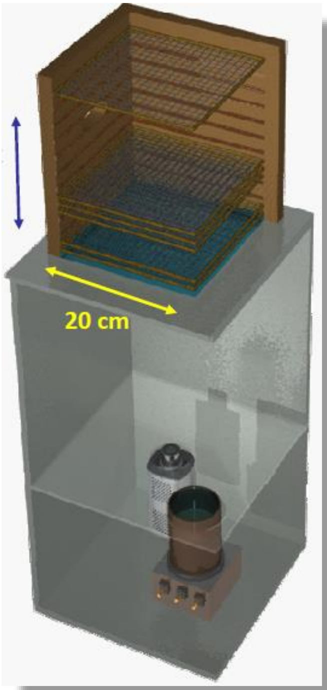


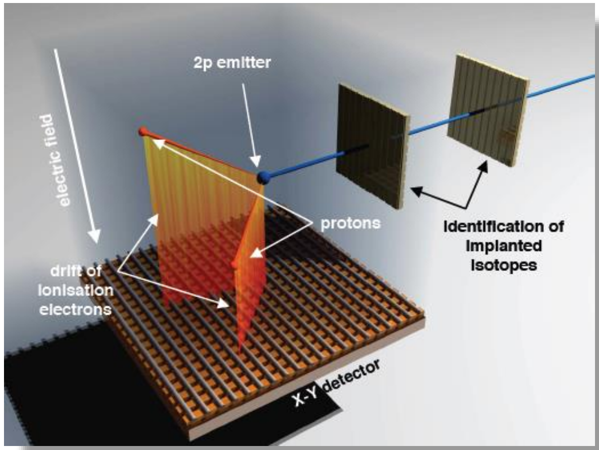
M. Pfutzner *et al.*, Rev. Mod. Phys., 84, 567 (2012)

Two Proton Emission

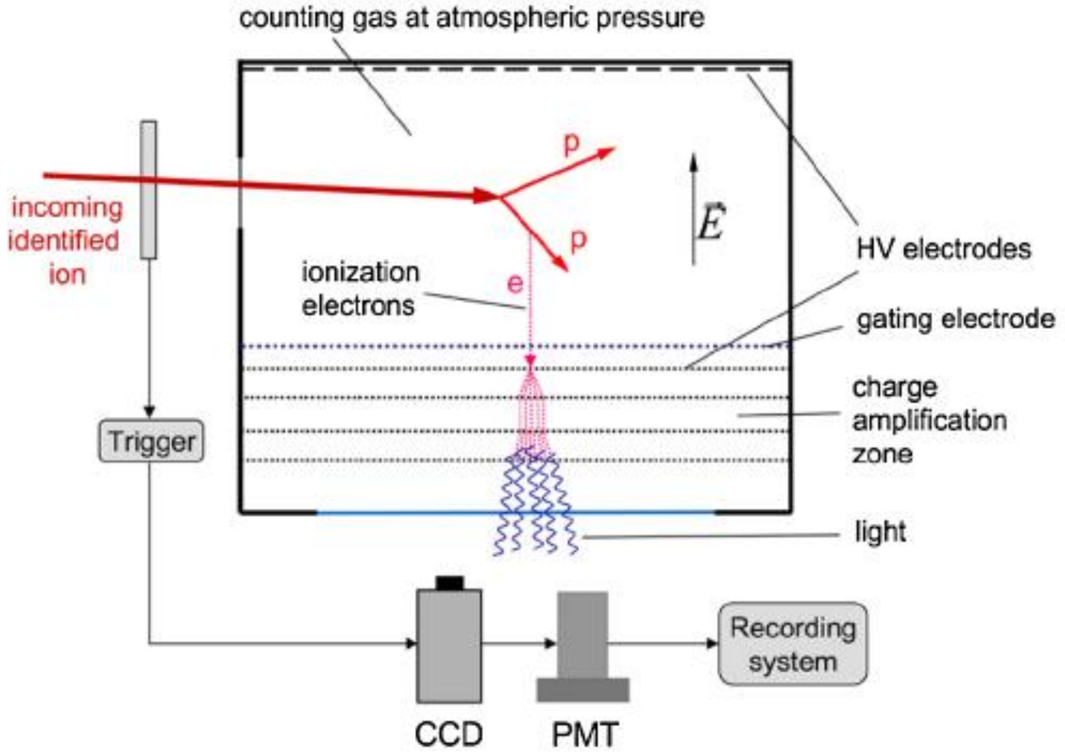
- Angle and energy dependence between two protons.

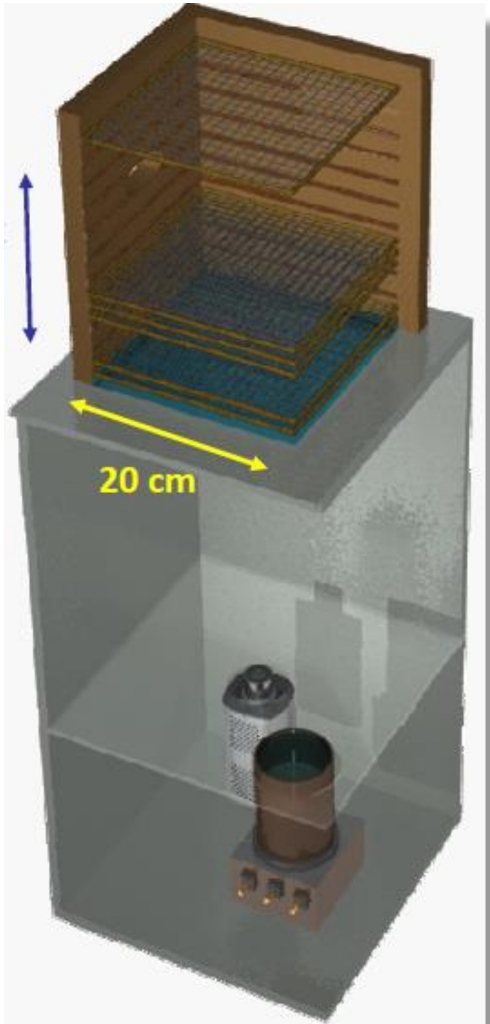






Optical Time Projection Chamber

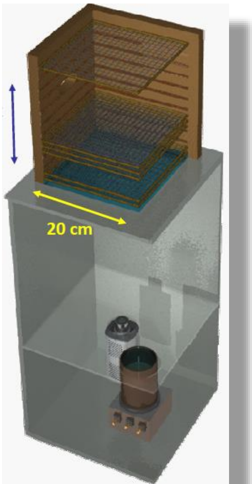




Courtesy M. Pfützner

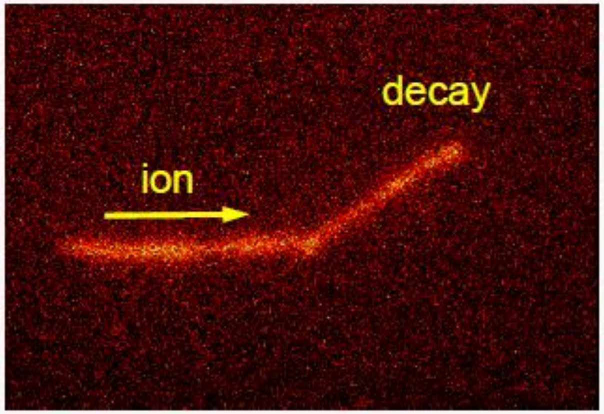
M. Ćwiok *et al.*, IEEE TNS, 52, 2895 (2005)
K. Miernik *et al.*, Nucl. Instrum. Methods. Phys. Res. A 581, 194 (2007)

Analysis

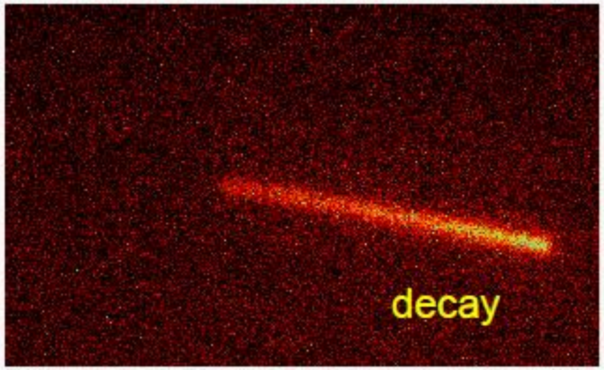


CCD image

tracks of the ion and emitted particle(s)

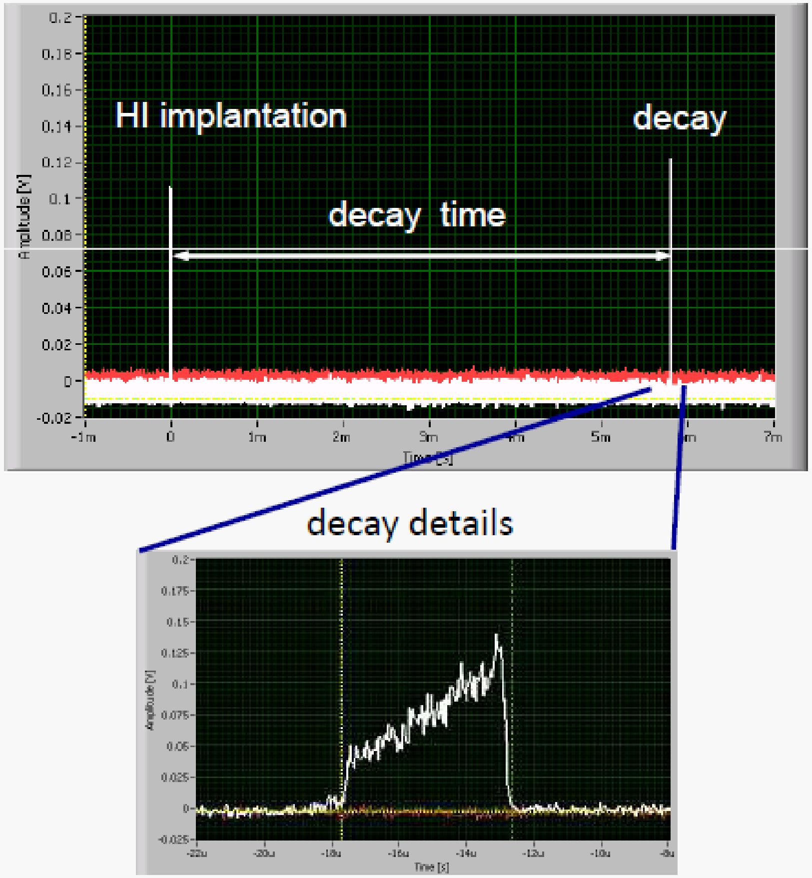


or only emitted particle(s)



PMT signal sampled

time sequence of events



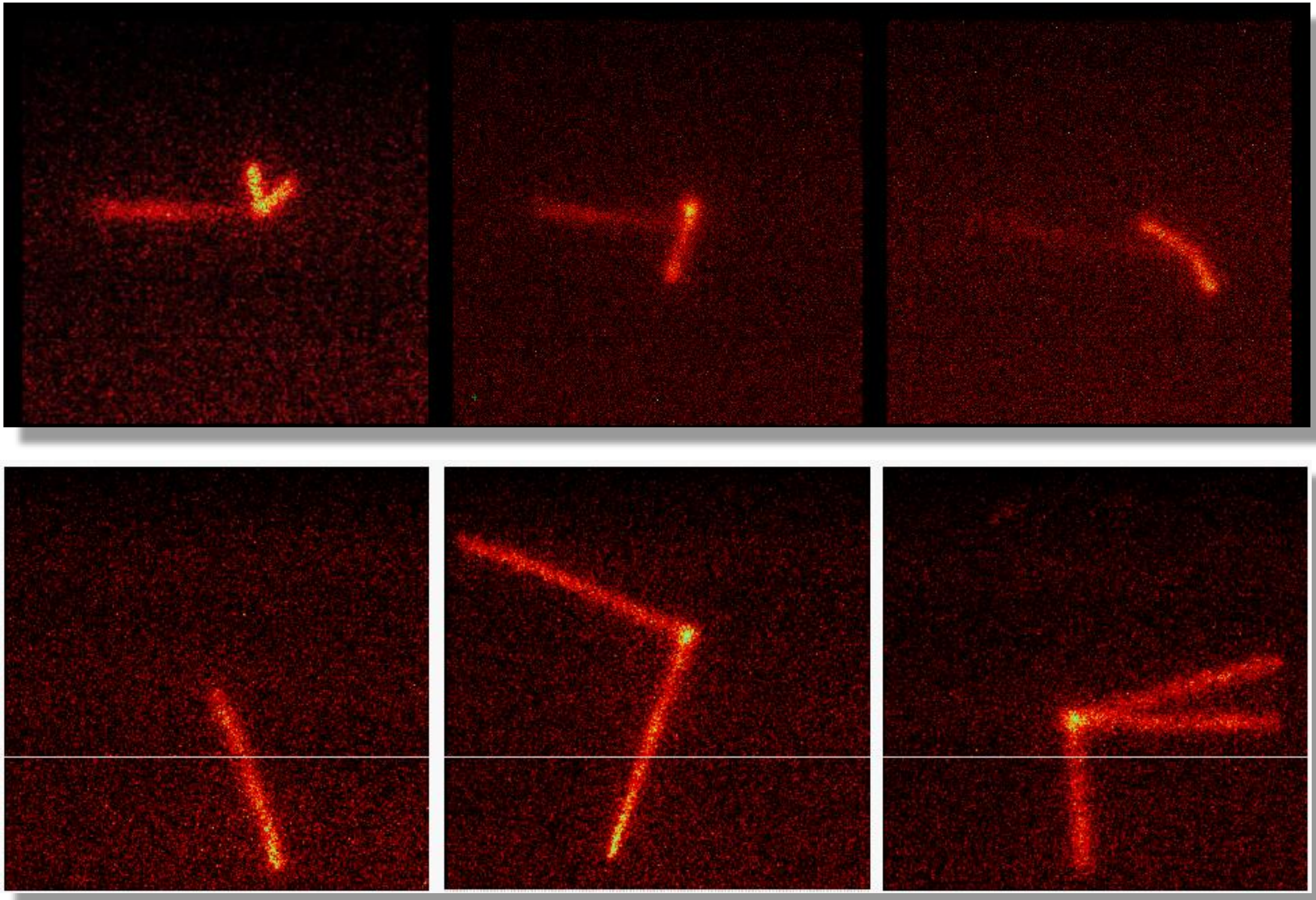
Courtesy M. Pfützner

M. Ćwiok *et al.*, IEEE TNS, 52, 2895 (2005)
K. Miernik *et al.*, Nucl. Instrum. Methods. Phys. Res. A 581, 194 (2007)

^{45}Fe

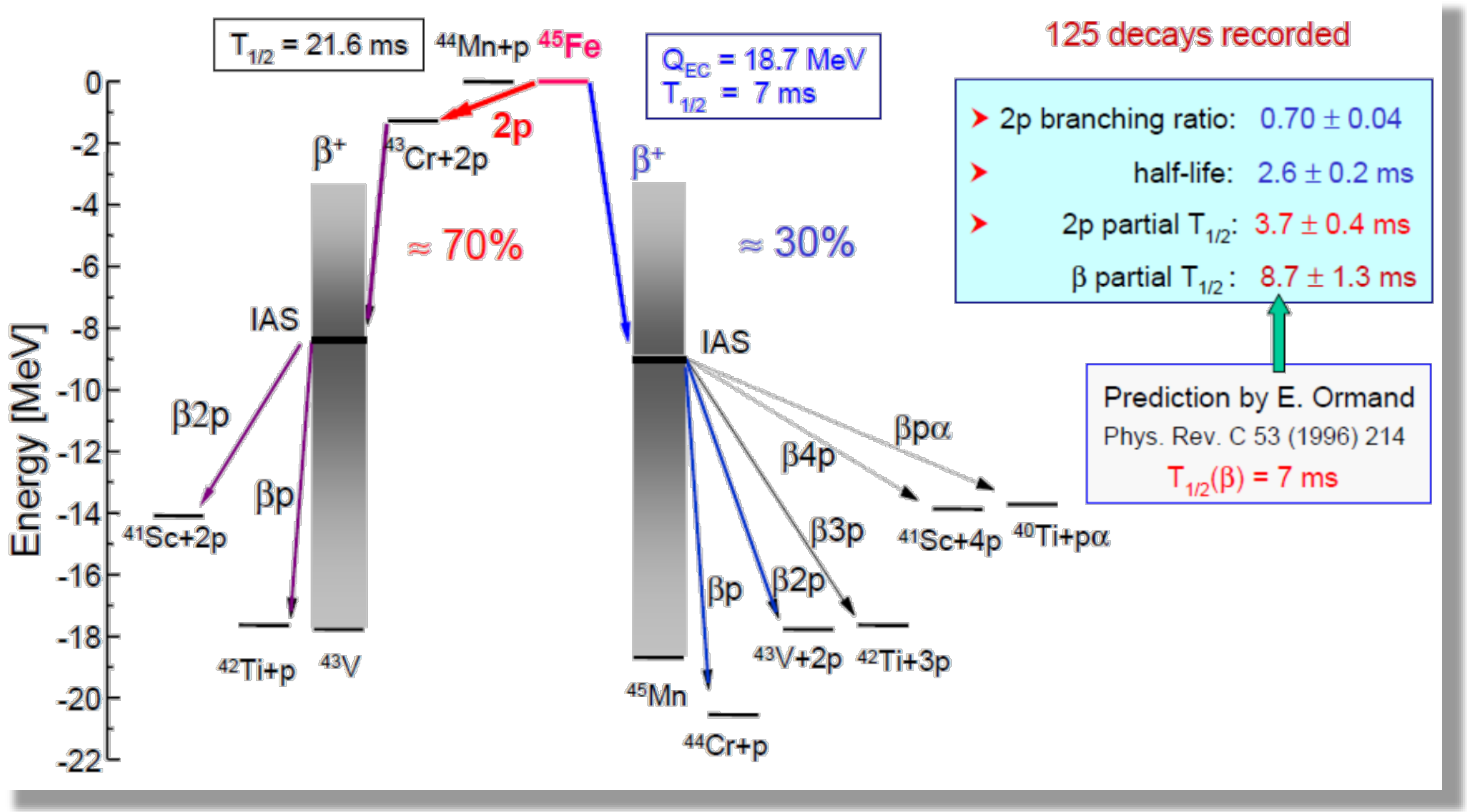
2p

βxp



Courtesy M. Pfützner

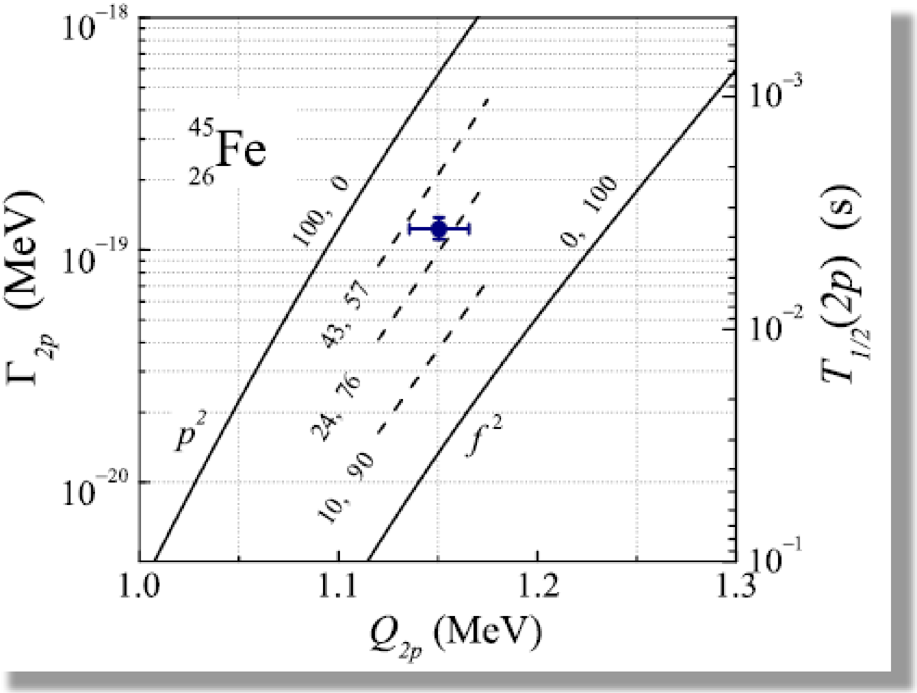
^{45}Fe

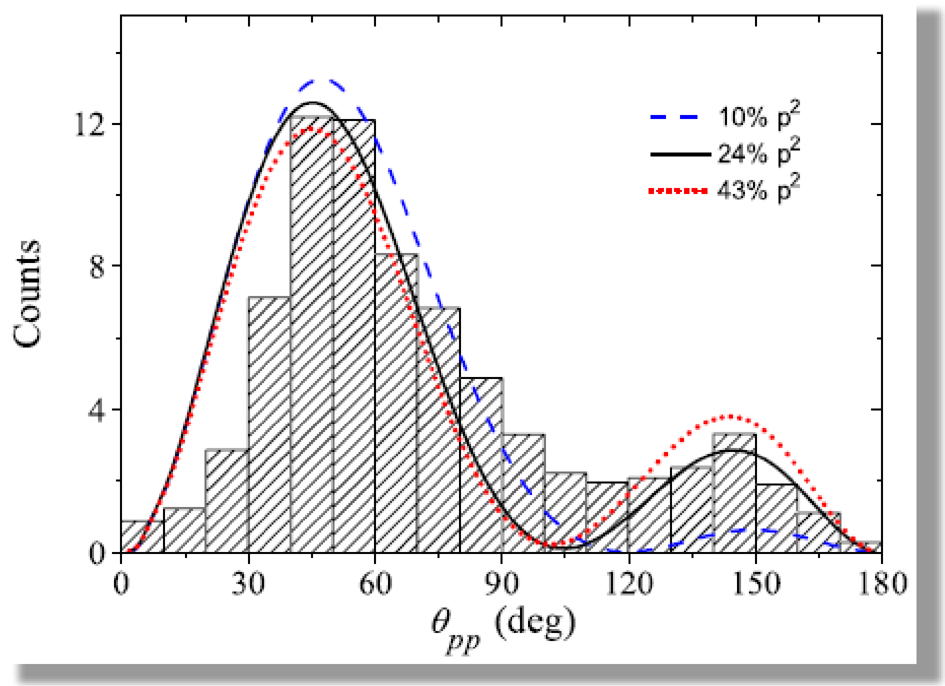


Courtesy M. Pfützner

K. Miernik *et al.*, Phys. Rev. Lett. 99, 192501 (2007)

^{45}Fe

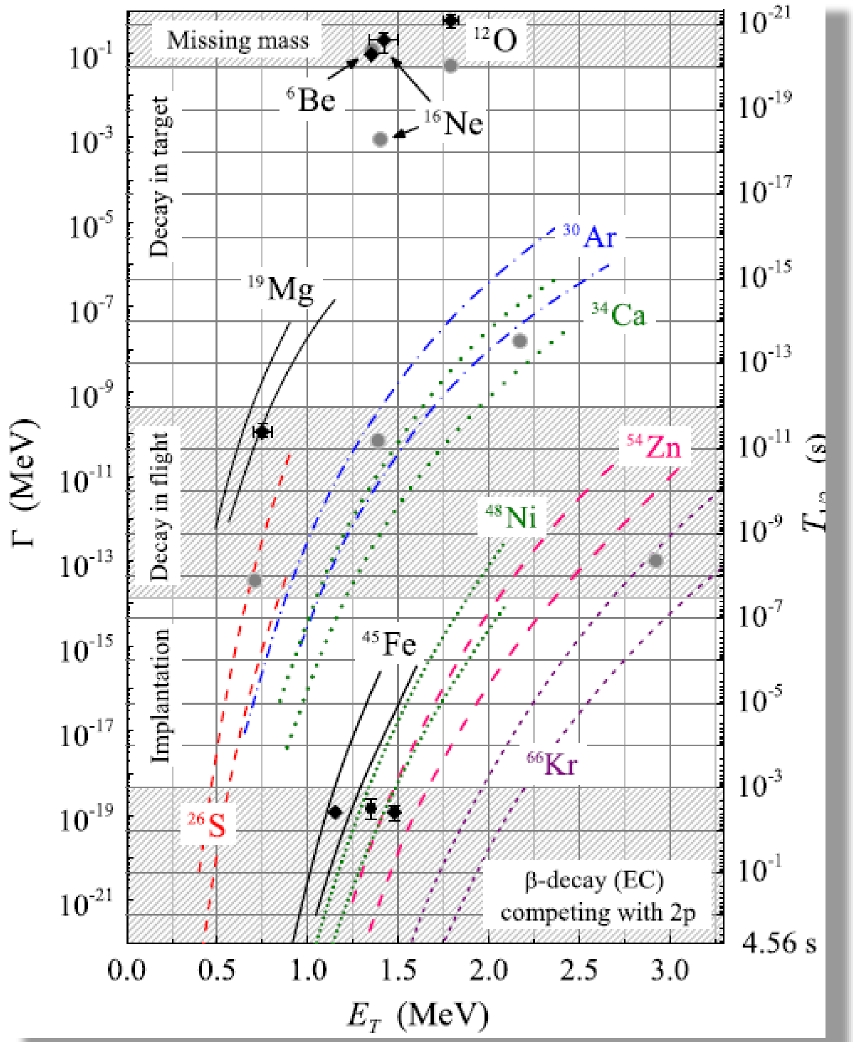




Courtesy M. Pfützner

K. Miernik *et al.*, Phys. Rev. Lett. 99, 192501 (2007)

Outlook



Courtesy M. Pfützner

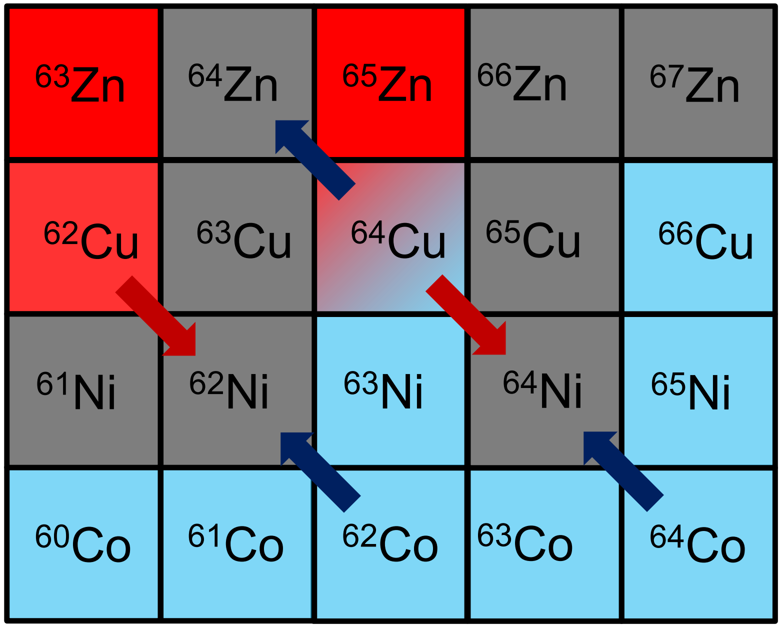
What is beta decay?

- Mediated by the weak interaction.
- Conversion of neutron into proton or vice versa
- Three different forms
  - B- decay
  - B+ decay
  - Electron Capture

$$p \rightarrow n + e^{+} + \nu_e$$

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

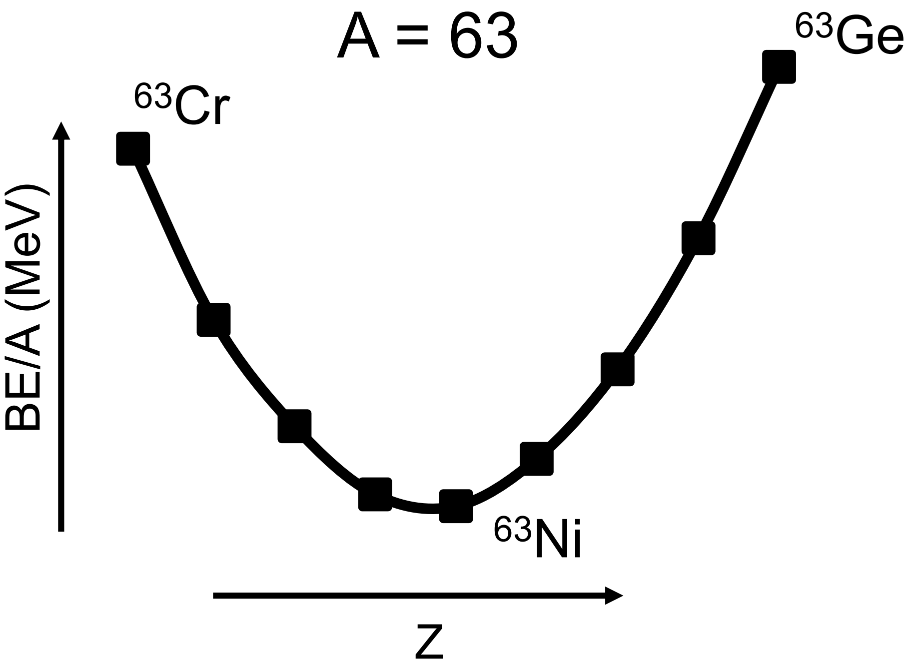
$$p + e^{-} \rightarrow n + \nu_e$$



Question

- Order the fundamental forces in order of increasing strength.
  - A – weak, strong, electromagnetic, gravitational
  - B – gravitational, weak, strong, electromagnetic
  - C – strong, weak, electromagnetic, gravitational
  - D – weak, gravitational, electromagnetic, strong
  - E – gravitational, weak, electromagnetic, strong

Q values



$$p \rightarrow n + e^{+} + \nu_e$$

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

$$p + e^{-} \rightarrow n + \nu_e$$

- Three body process
- Beta-decay Q-value determined from masses.
- $Q_{\beta-}$: Mass [^{A}Z] – Mass [^{A}(Z+1)]
- $Q_{\beta+}$: Mass [^{A}Z] – Mass [^{A}(Z+1)] – $2m_ec^2$
- Q_{EC}: Mass [^{A}Z] – Mass [^{A}(Z-1)]
- Q values can range up to many MeV
- ^{60}Fe – 0.260 MeV
- ^{63}Co – 11.2 MeV

Selection Rules

- Beta decay follows selection rules.
- Electron, neutrino are spin ½ particles.
  - S = 1 - parallel
  - S = 0 - antiparallel

$$^{A}X \rightarrow {}^{A}Y + e^{-} + \bar{\nu}_e$$

- Allowed approximation
  - Relative angular momentum of electron/neutrino is 0
- Fermi
  - S = 0
  - $\Delta J = |J_i - J_f| = 0$
- Gamow-Teller
  - S = 1
  - $\Delta J = |J_i - J_f| = 1$

Parent	**Daughter**	**Character**
^{6}He (0^+)	^{6}Li (1^+)	Gamow-Teller
^{14}0 (0^+)	^{14}N (0^+,2.313 MeV)	Fermi
n ($1/2^+$)	p ($1/2^+$)	mixed

Decay Rate

- Beta decay rate depends on three factors
  - Matrix element (nuclear structure)
  - Density of final states
  - Coulomb field from nucleus
- Fermi integral, f, is tabulated depends on
  - Daughter Z
  - End point
- Forbidden decays
  - ~ x10^{-4} per degree of forbiddeness

$$\lambda = \frac{2\pi}{\hbar}\left|M_{fi}\right|^2 \rho(E_f)$$

$$M_{fi} = \langle \varphi_f^* | V | \varphi_i \rangle$$

$$\lambda = \frac{g^2\left|M_{fi}\right|^2}{C} f(Z'E_0)$$

Matrix Elements

$$f(Z'E_0)t_{\frac{1}{2}} = \frac{K}{g^2\left|M_{fi}\right|^2}$$

$$f(Z'E_0)t_{\frac{1}{2}} = \frac{C}{B(F) \quad + B(GT)}$$

- Isospin raising/lowering operator

$$\mathrm{B(F)} \propto |\langle \varphi_f^* | \tau | \varphi_i \rangle|^2$$

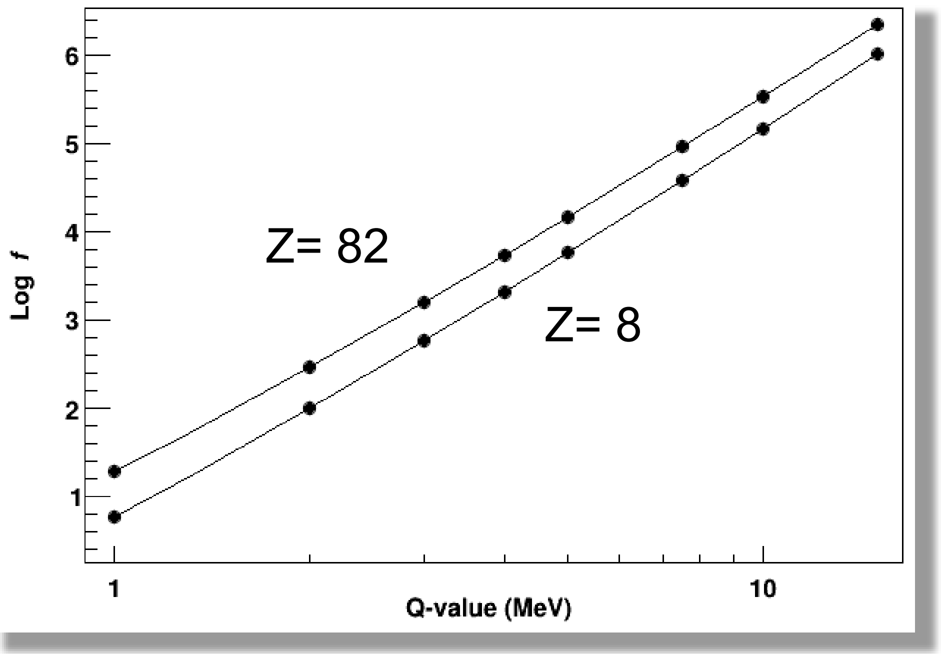
- Isospin and spin operators

$$\mathrm{B(GT)} \propto |\langle \varphi_f^* | \sigma\tau | \varphi_i \rangle|^2$$

Can be calculated

f

- Behavior of *f* as a function of Q value.
- Half-life energy dependence ~E^5
  - All things being equal
- Empirical functions can also be used.



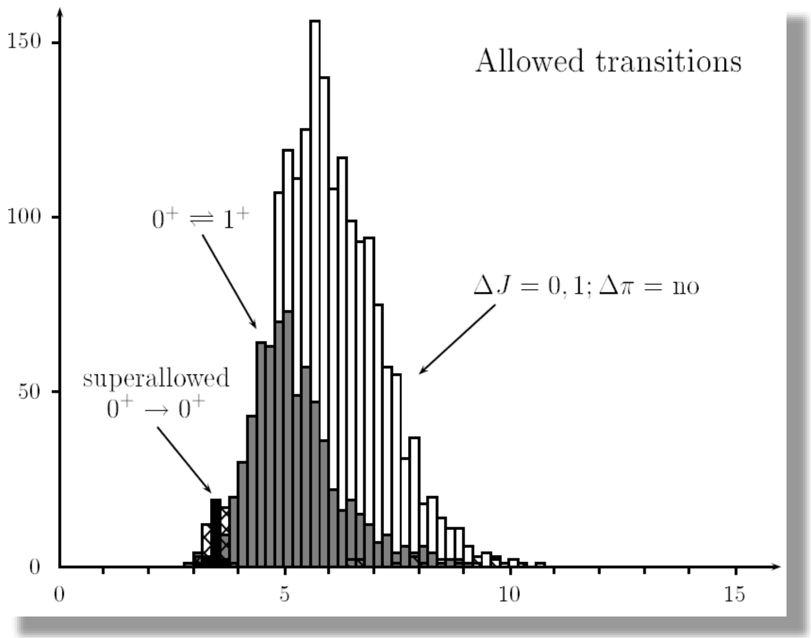
S.A. Moszkowski, Phys. Rev. 82, 35 (1951)

Log ft

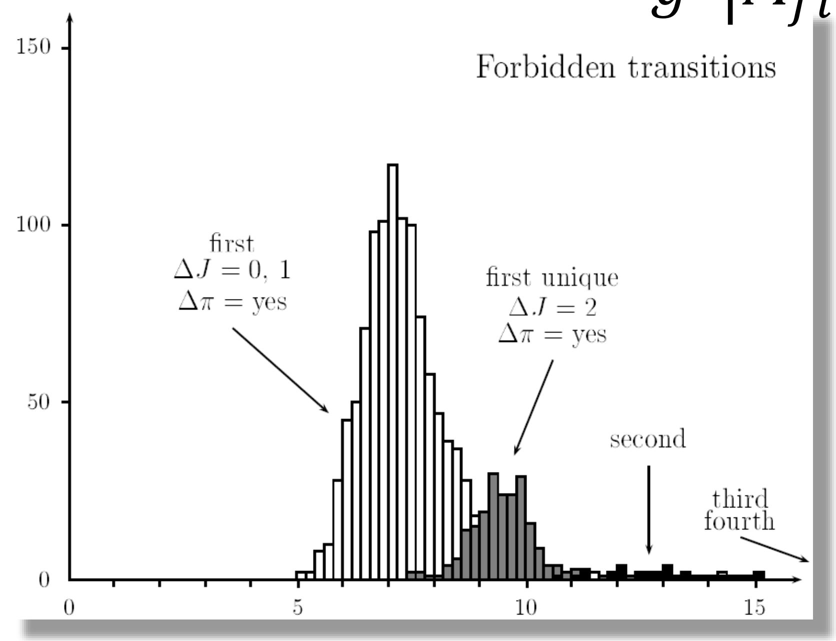
- ~ 4000 beta decays
- Known initial and final spin and parity
- Empirical classification useful as a guide

$$\lambda = \frac{g^2 |M_{fi}|^2}{C} f(Z' E_0)$$

$$f(Z' E_0) t_{1/2} = \frac{K}{g^2 |M_{fi}|^2}$$



Log *ft*

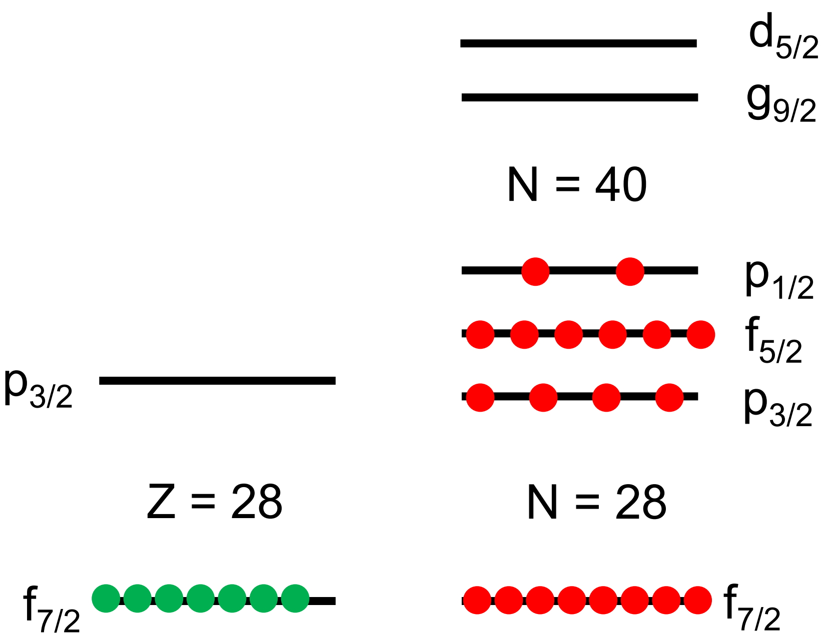


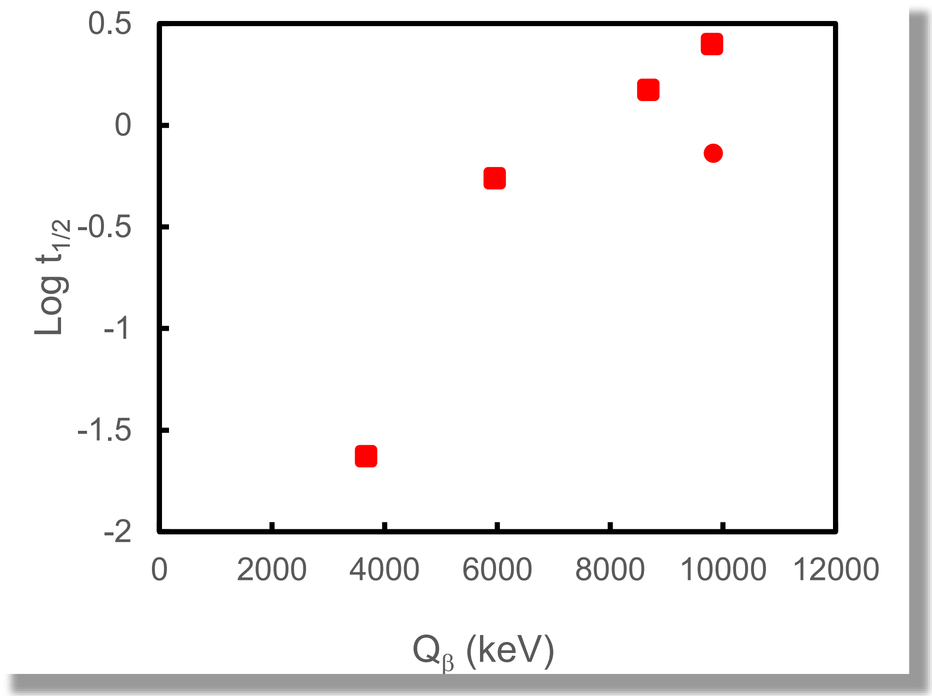
Log *ft*

B. Singh, J.L.Rodriguez, S.S.M. Wong, J.K. Tuli, NDS, 84, 487 (1998)

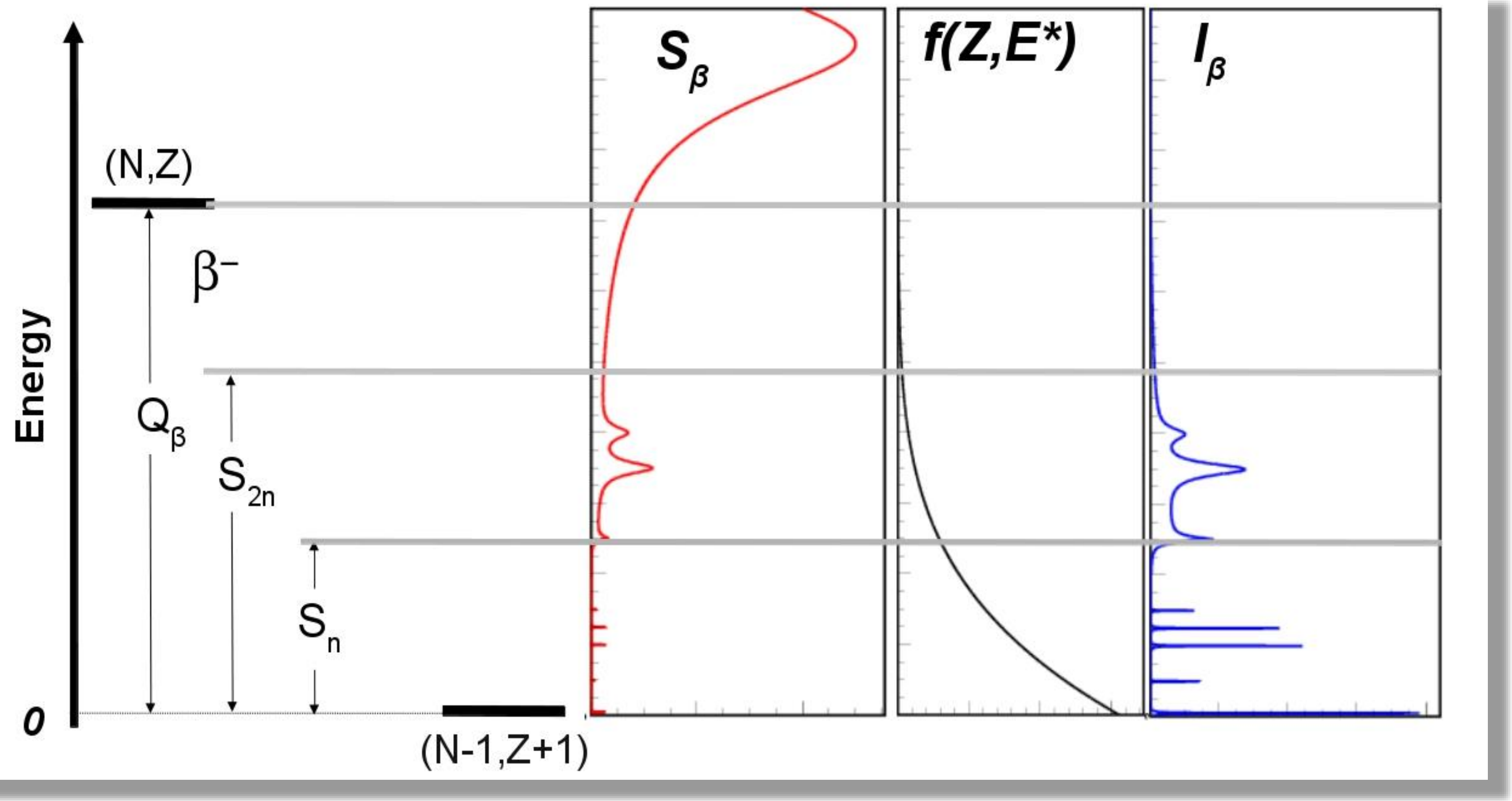
Simple Example – odd-A Co

- Odd-A $^{63,65,67,69}Co$ isotopes.
- Known half-lives and branching ratios.
- Dominated by simple $\nu f_{5/2}$ to $\pi f_{7/2}$ transition.





Beta-decay strength

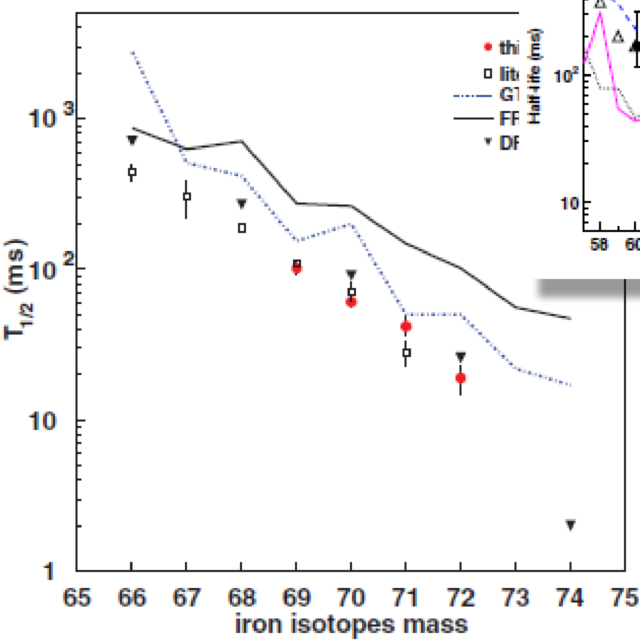


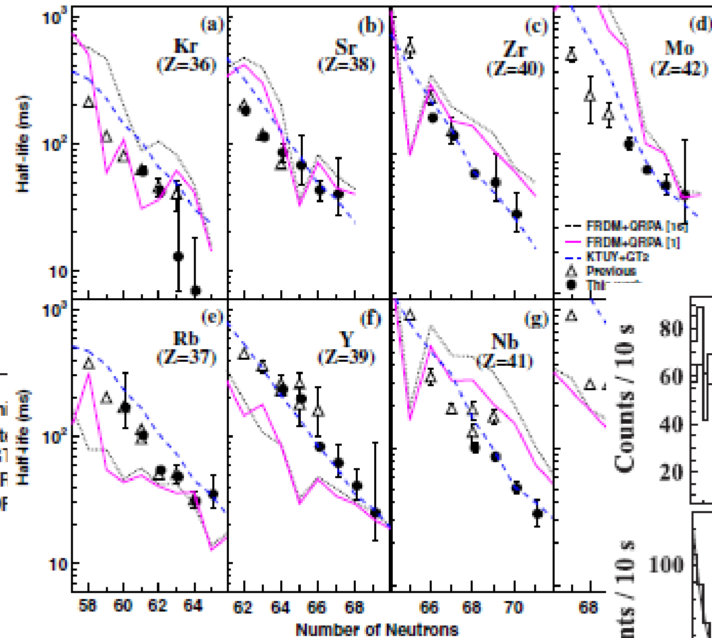
$$\frac{1}{t_{1/2}} = \sum_{0}^{Q_\beta} S_\beta(E_i) f(Z, E_o)$$

$$P_n = \frac{\Sigma_{S_n}^{Q_\beta} S_\beta(E_i) f(Z, E_o)}{\Sigma_0^{Q_\beta} S_\beta(E_i) f(Z, E_o)}$$

Half-lives

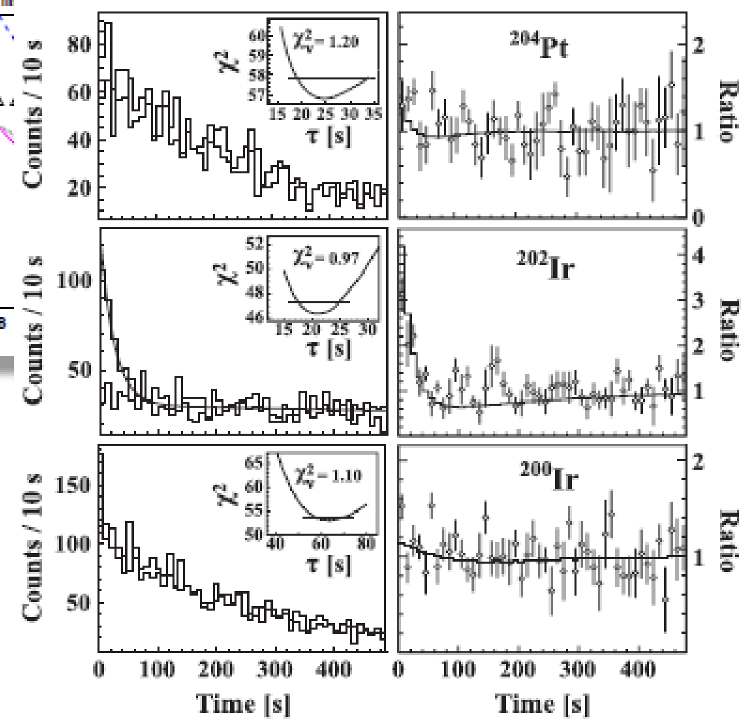
- A ~ 70





- A ~ 110

- A ~ 200



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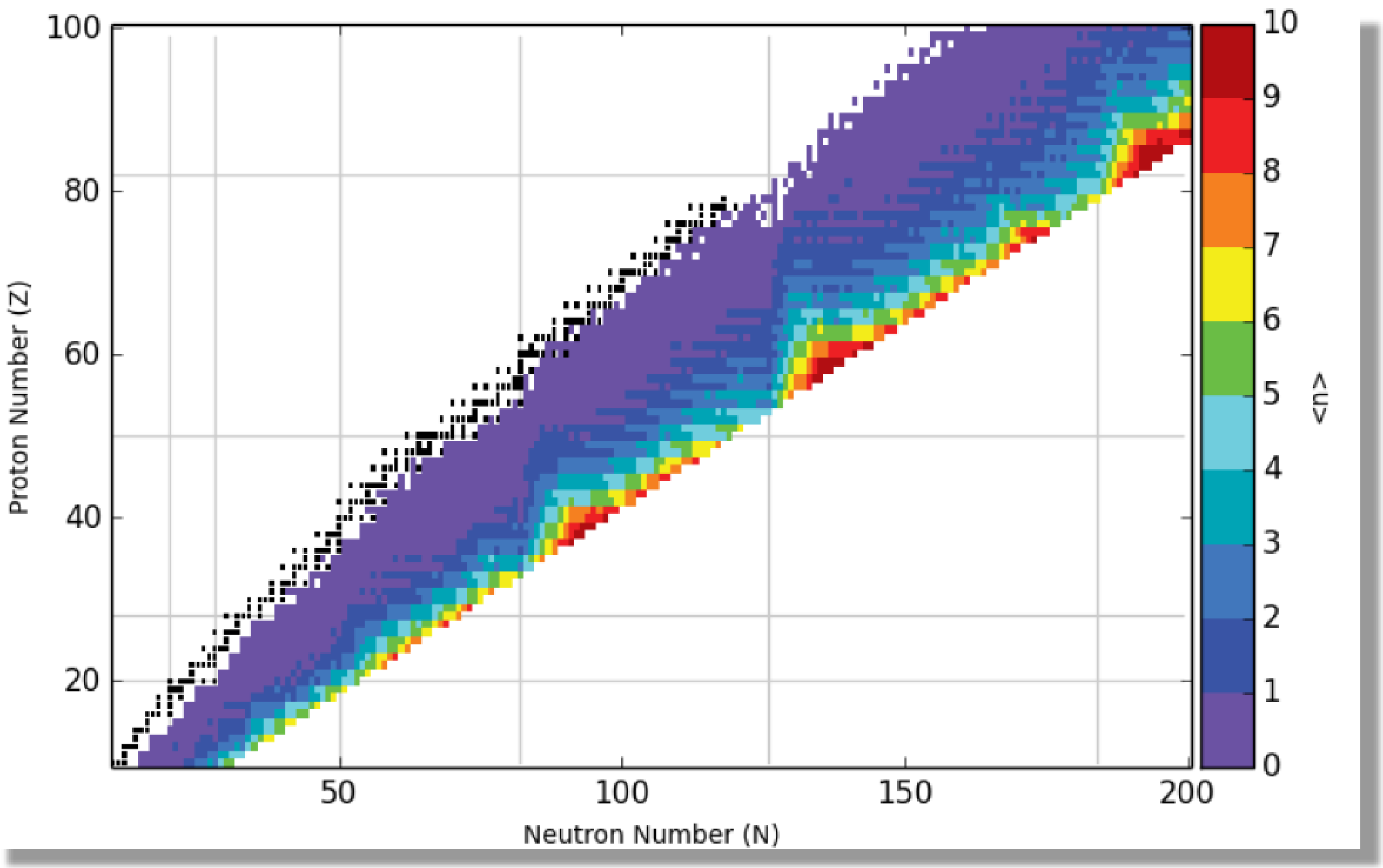
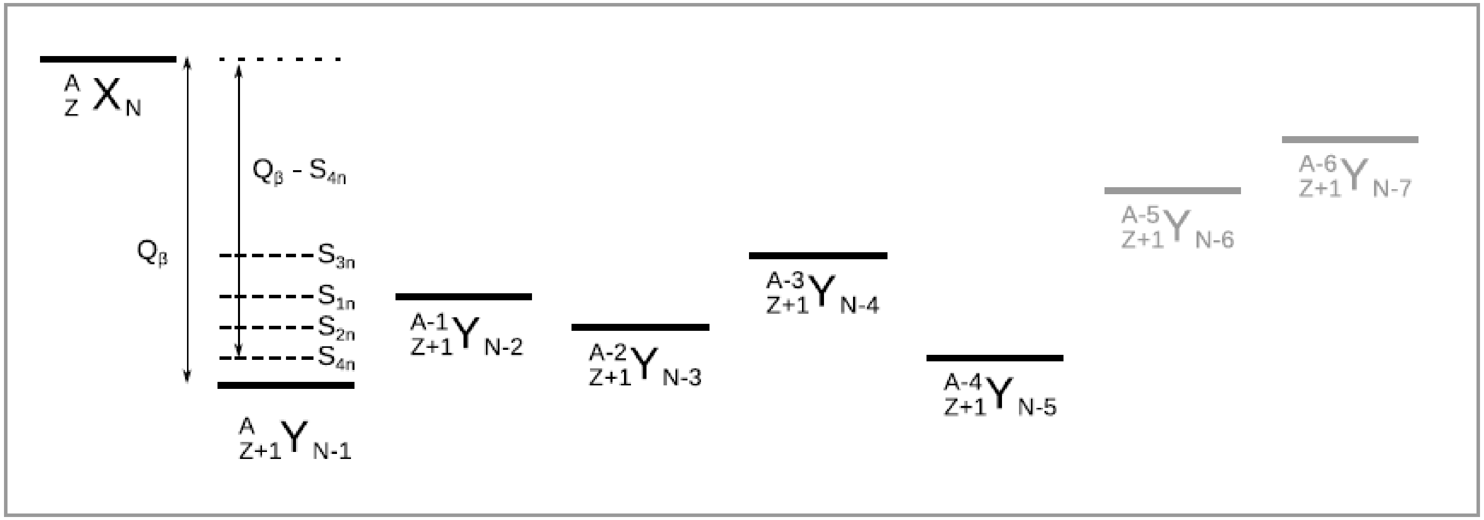
C. Mazzocchi *et al.*, Phys. Rev. C 88, 064320 (2013).

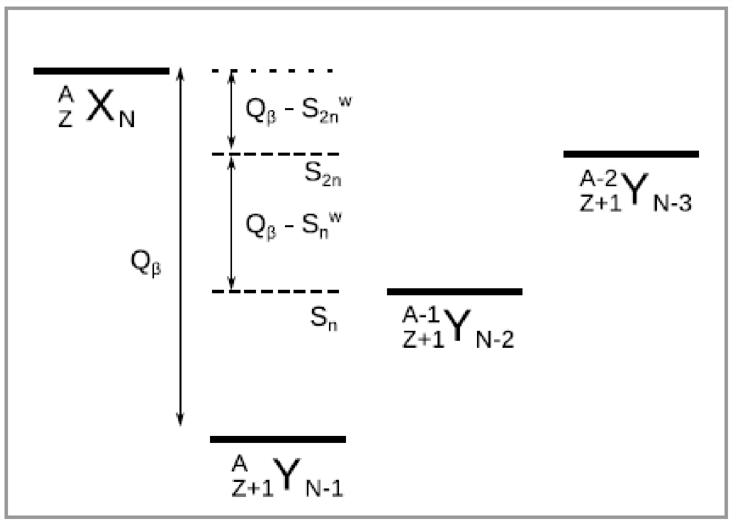
Connection to Astrophysics: βxn



Courtesy M. Mumpower

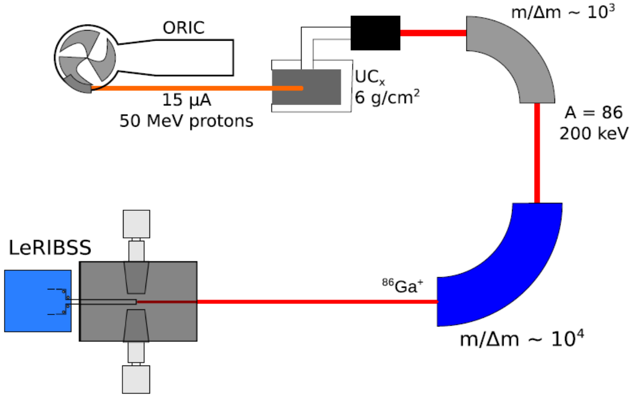
βxn

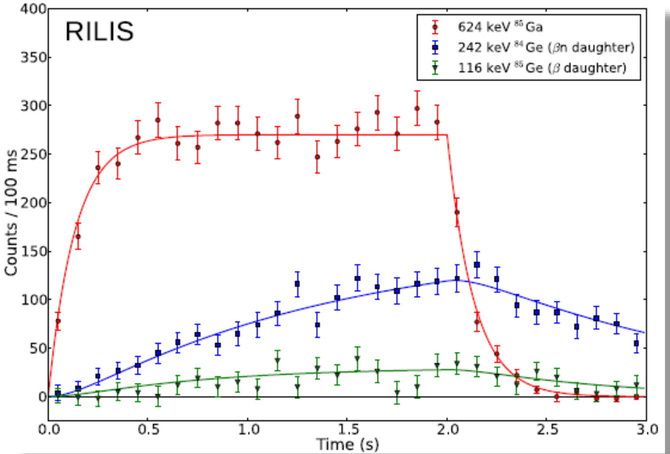


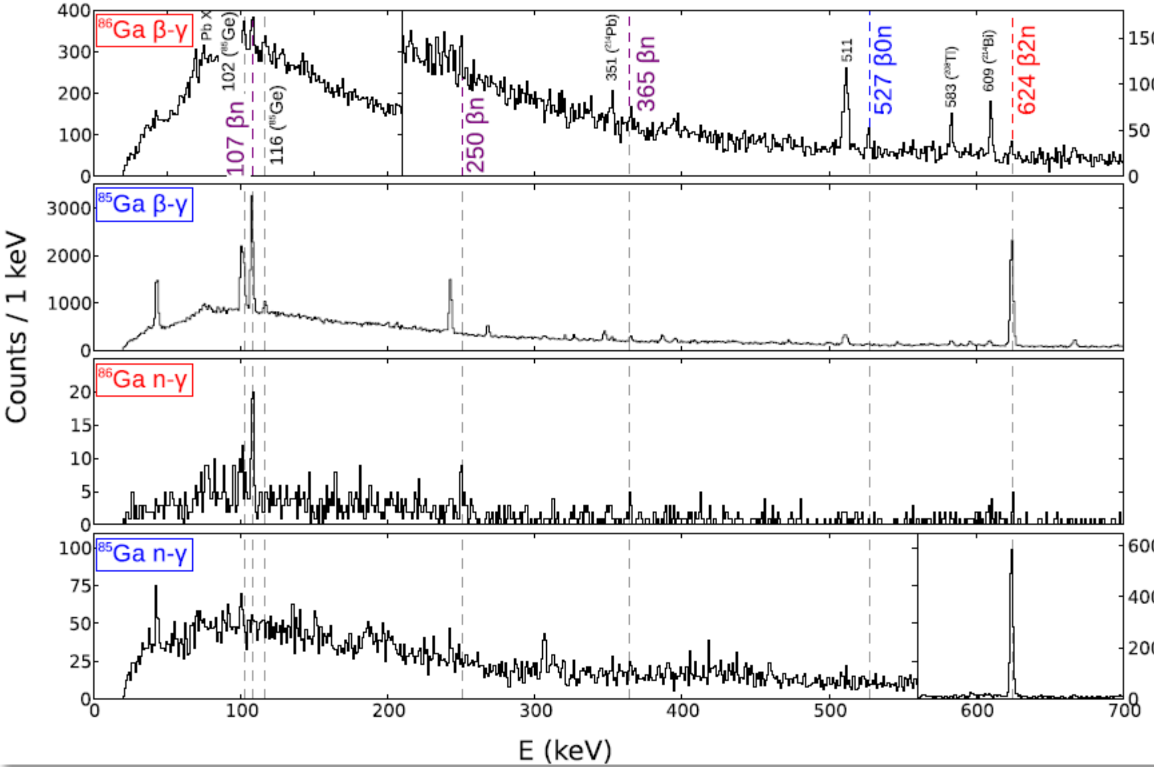


Courtesy K. Miernik

βxn

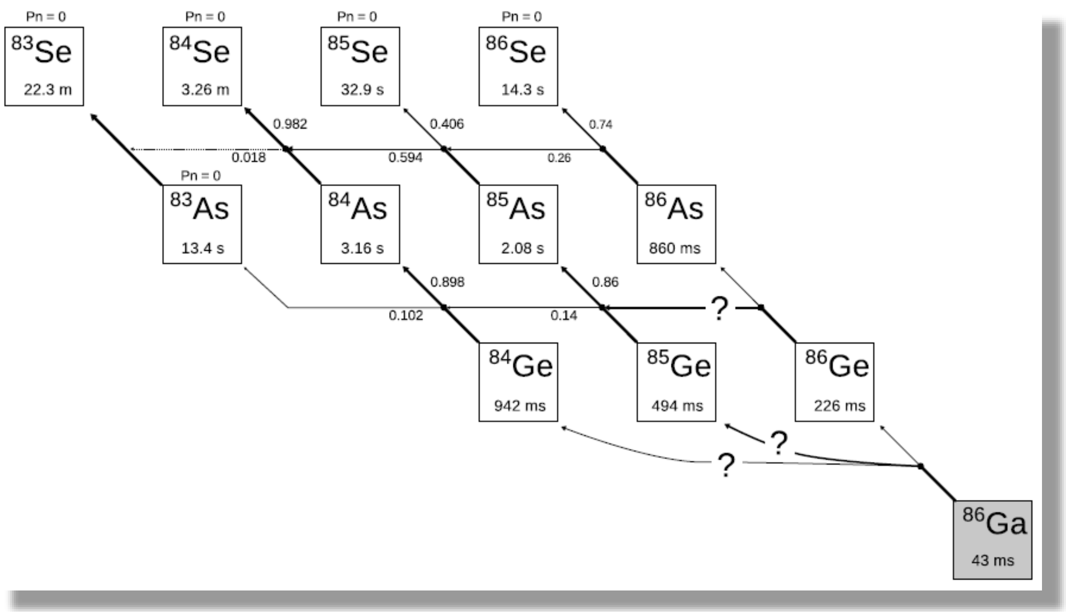


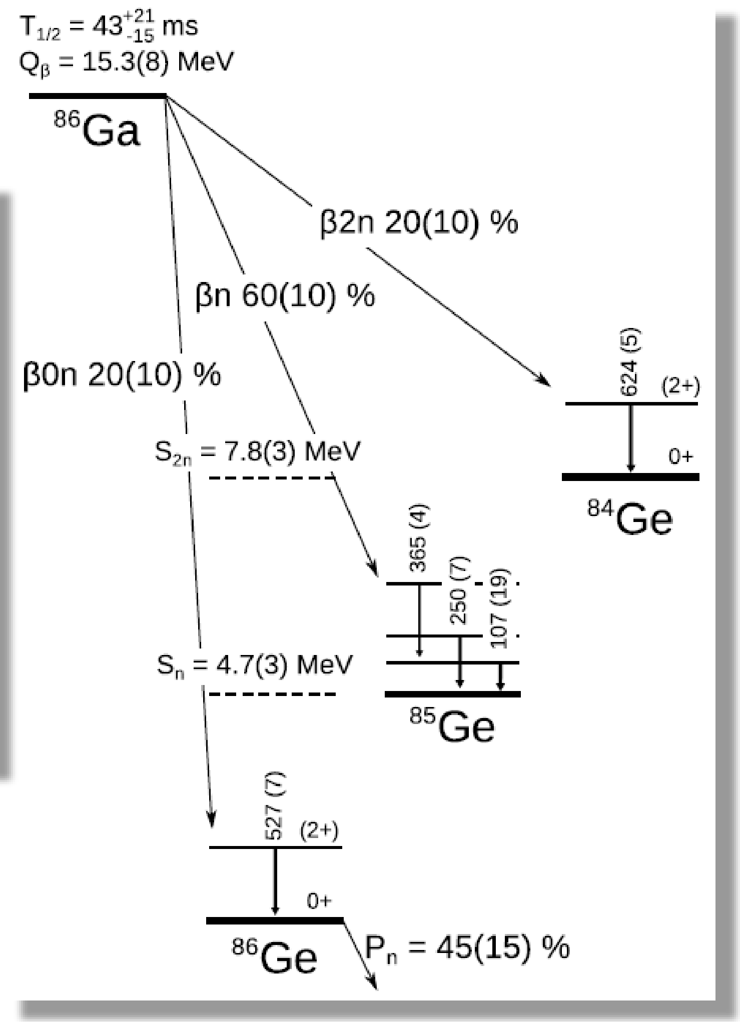




Courtesy K. Miernik

βxn

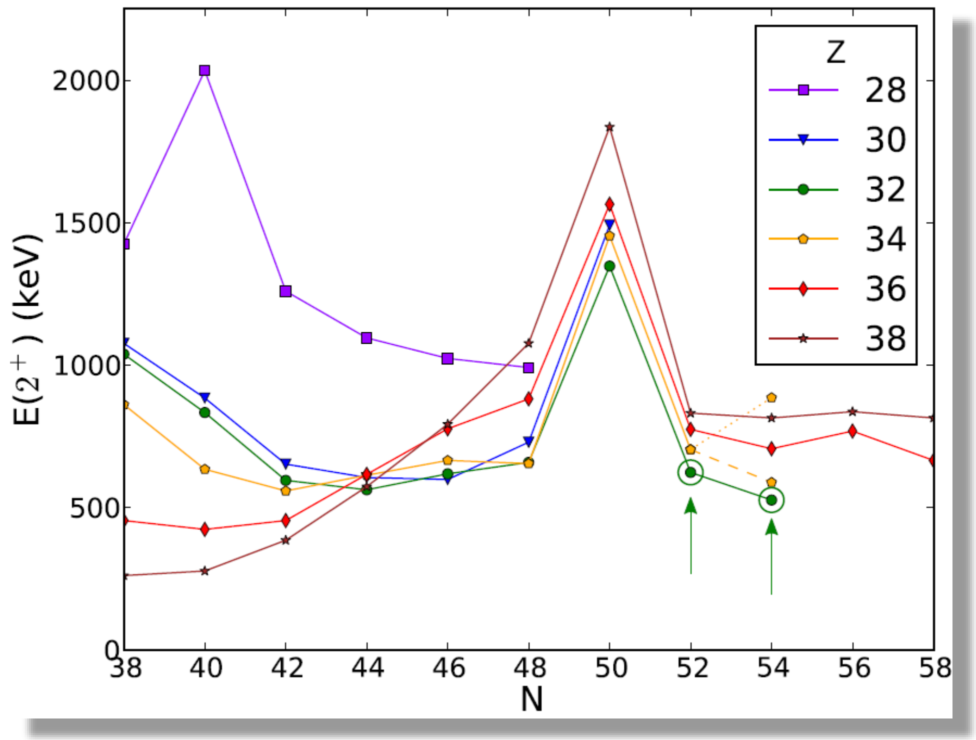


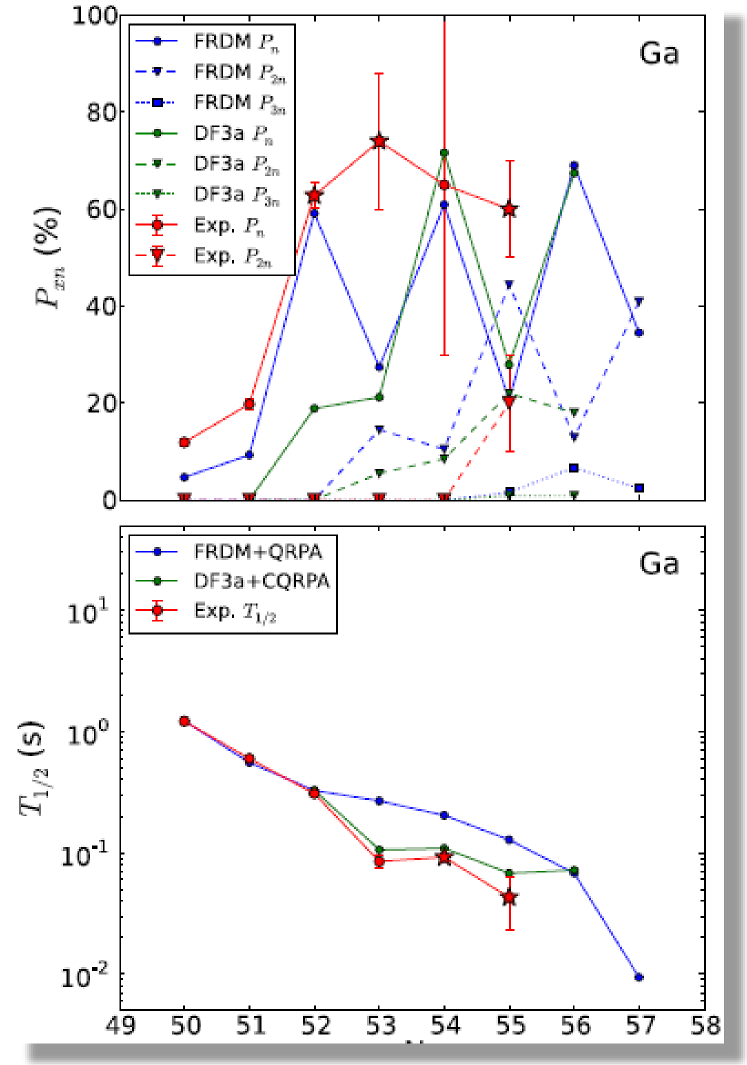


Courtesy K. Miernik

K. Miernik *et al.*, Phys. Rev. Lett. 111, 132502 (2013)

Outcomes

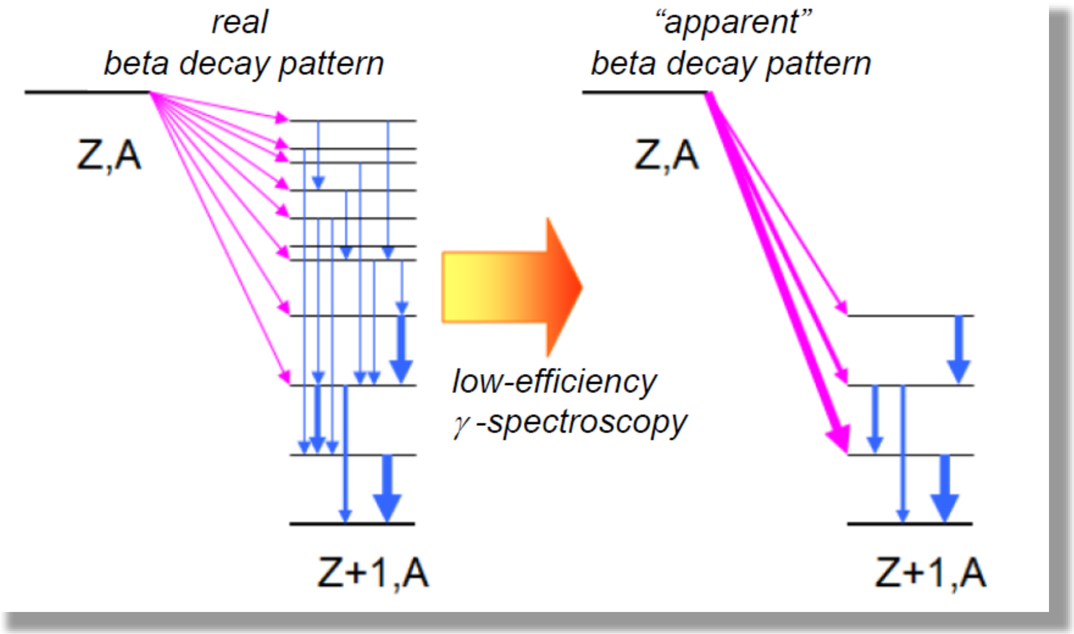


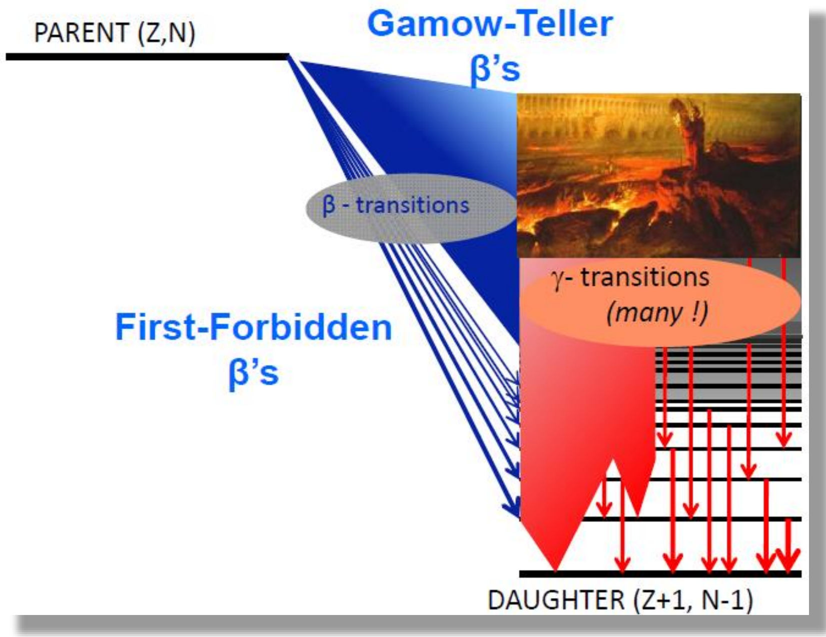


Courtesy K. Miernik

K. Miernik *et al.*, Phys. Rev. Lett. 111, 132502 (2013)
I.N. Borzov, Phhys. Rev. C, 67, 025802 (2003)
P. Möller et al., Phys. Rev. C, 67, 055802 (2003)

Pandemonium





Courtesy K. Rykaczewski

K. Rykaczewski, Physics, 3, 94 (2010).
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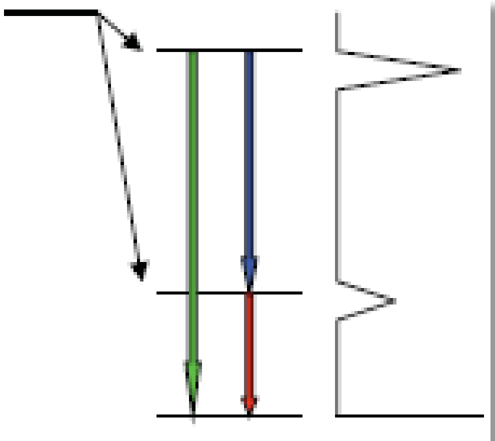
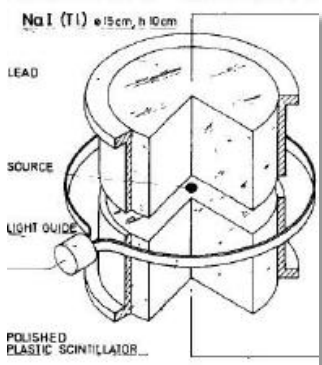
Solution: Total Absorption Spectroscopy

- Measure entire distribution

Ideal TAS



OSIRIS



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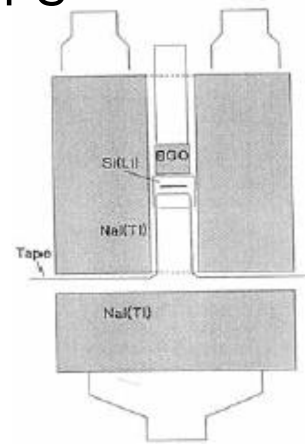
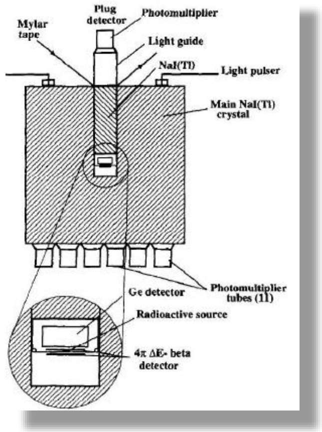
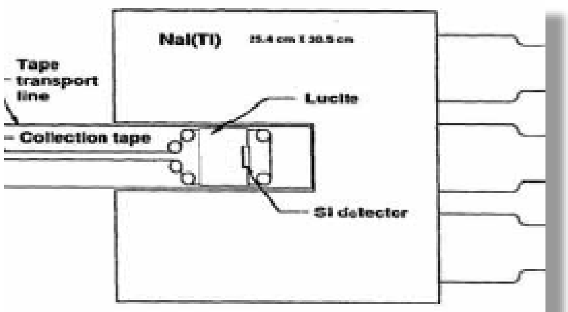


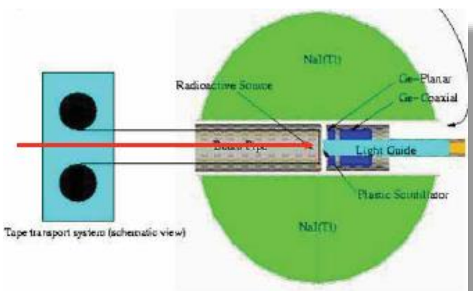
LBNL-GSI

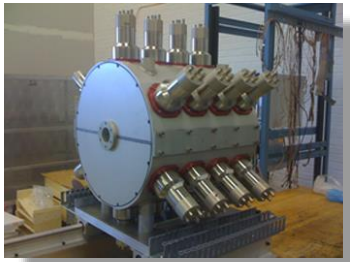




INL

Lucrecia





SuN

Adapted J.L. Tain

Don't worry Krzysztof…

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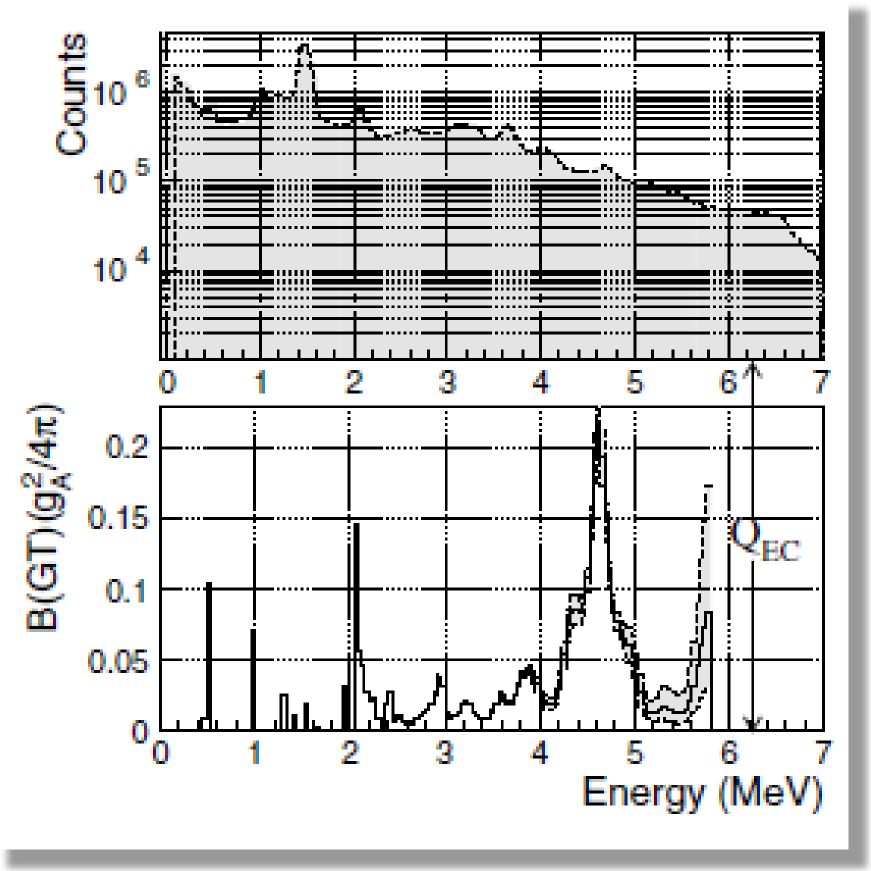
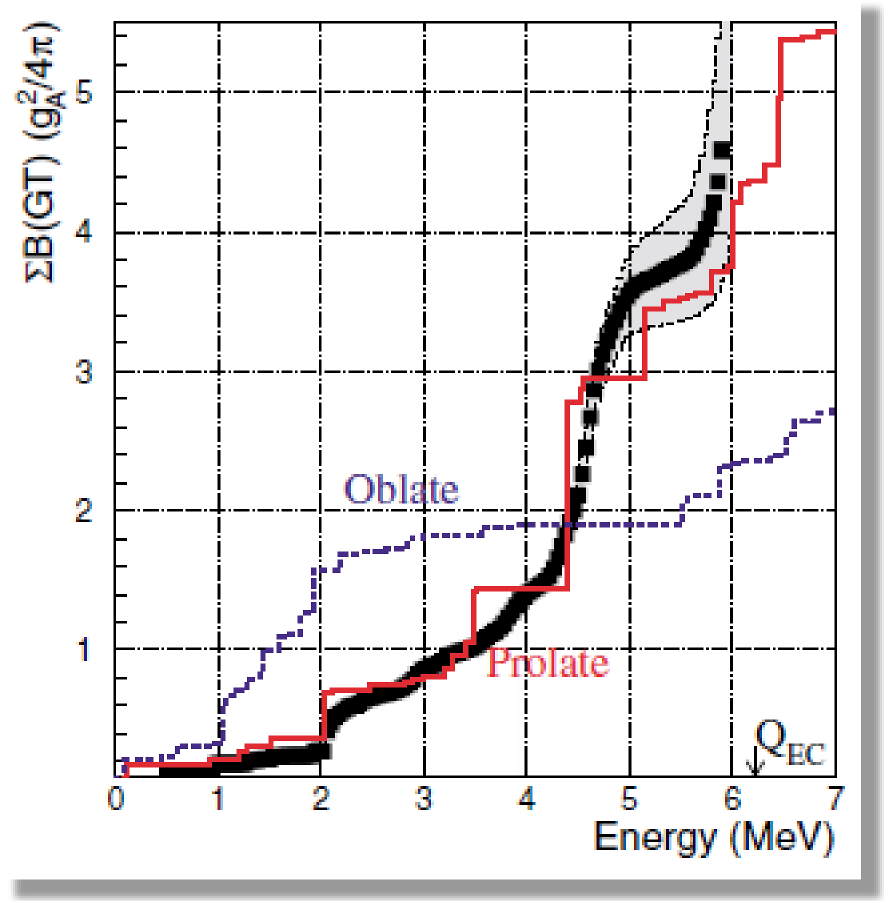
Bykov et al., IAN SSSR 44, 918 (1980)
Greenwood et al., NIMA 314, 514 (1992)
Rubio et al., JPG 31, S1477 (2005)
Karny et al., NIMB, 126, 211 (1997)

Nuclear Structure from Beta Decay: Experiment

- Shape determination – ^{76}Sr





E. Nacher et al., Phys. Rev. Lett. 92, 232501 (2004).

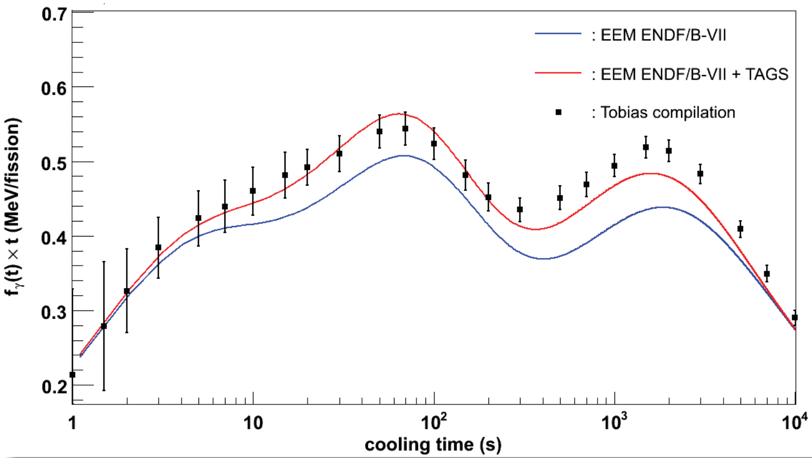
Total Absorption Spectroscopy

- Modular Total Absorption Spectroscopy

Courtesy K. Rykaczewski

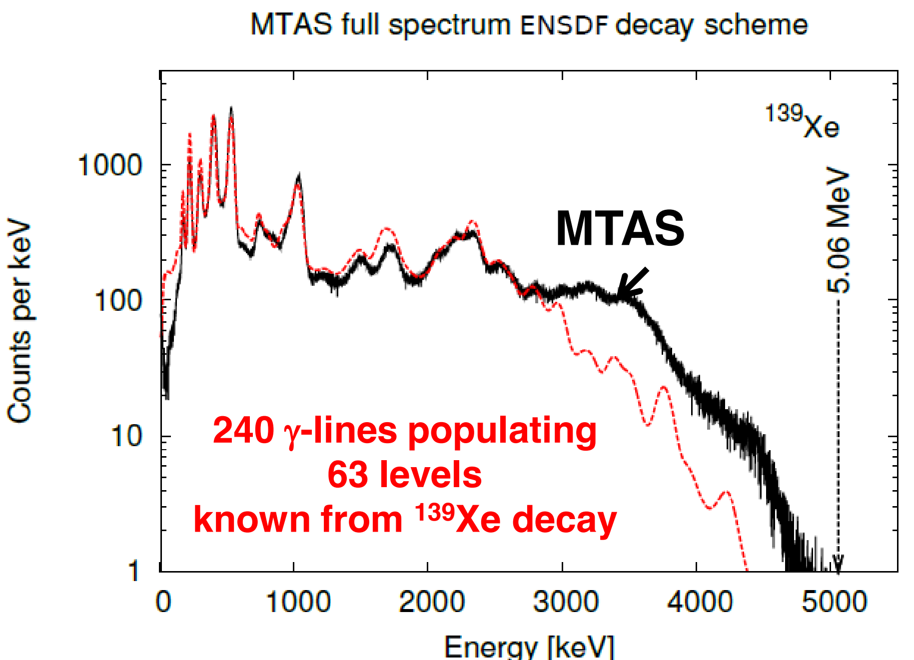
Nuclear Reactors

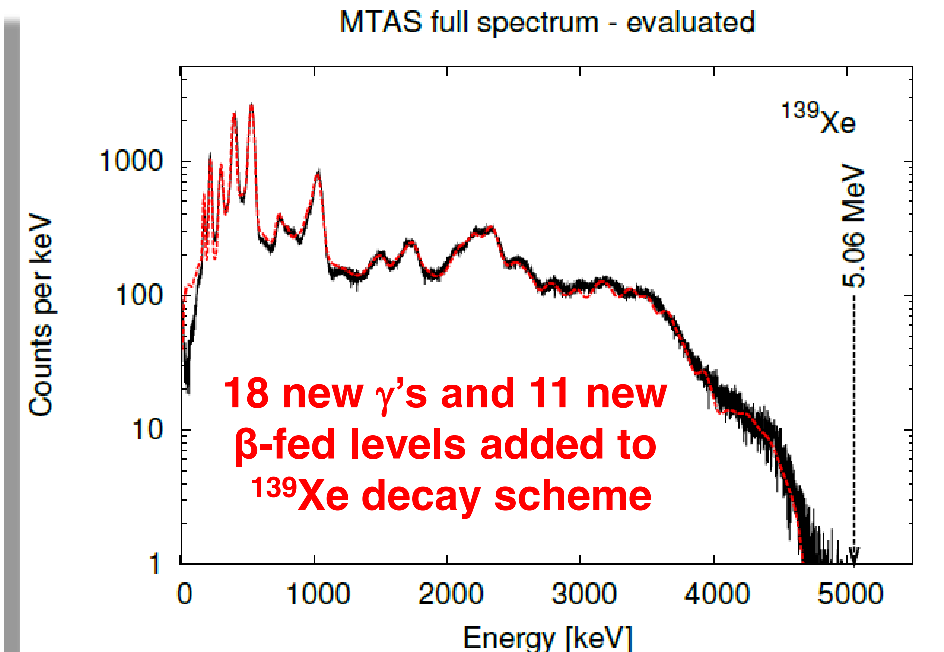
- Following the shutdown of a nuclear reactor the core is still warm. Why?
  - A – Heat from gravitational energy release following core collapse.
  - B – Heat from thermal neutron induced fission.
  - C – Heat from gamma ray emission.
  - D – Heat from neutrino induced interactions.
  - E – Heat from radioactive decay.



Connections: Decay Heat

- Priority 1 decay heat: $^{139}Xe \rightarrow {}^{139}Cs$
  - 5% cumulative yield in $n_{th}+{}^{235}U$ fission
  - 7^{th} in direct production per ^{235}U fission
- Average gamma-ray energy increase of 47%





Courtesy K. Rykaczewski