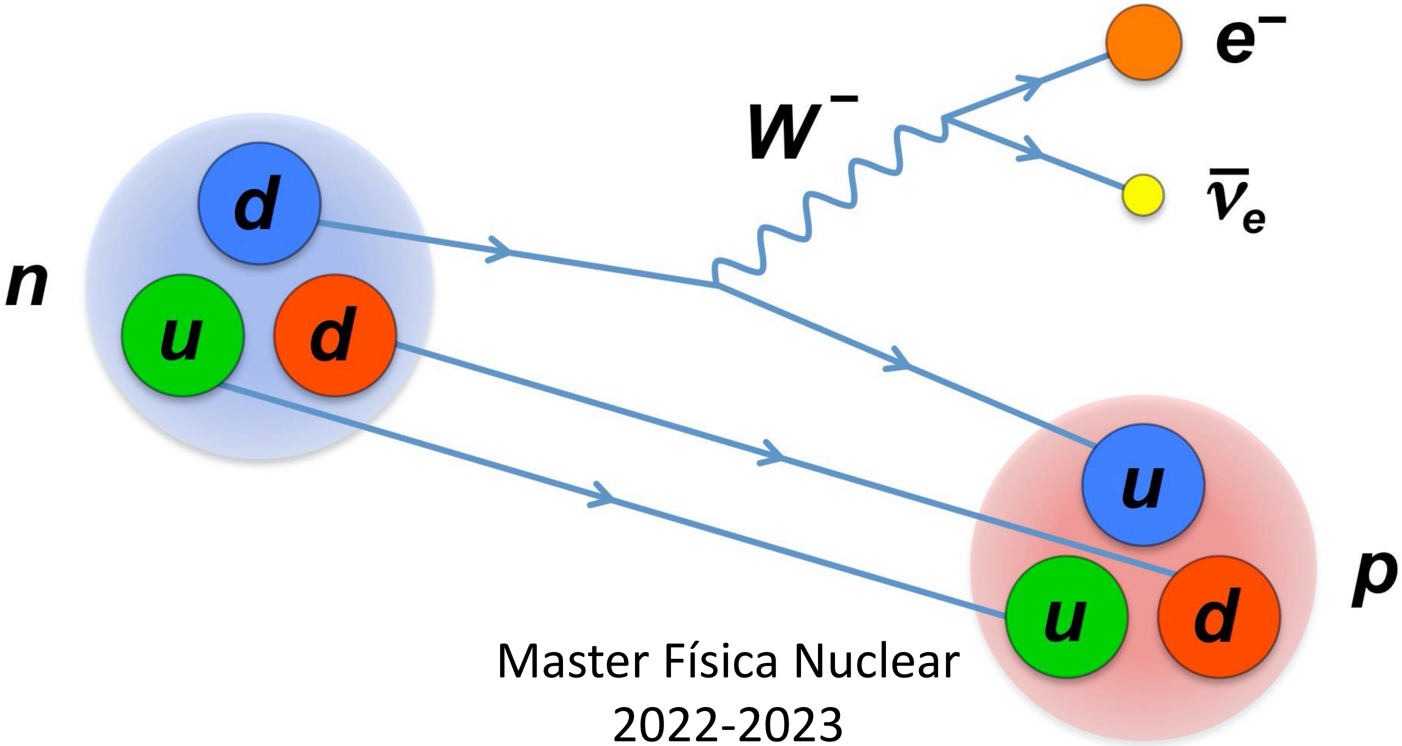
Beta decay experiments



Master Física Nuclear
2022-2023
Bruno Olaizola
CSIC-IEM

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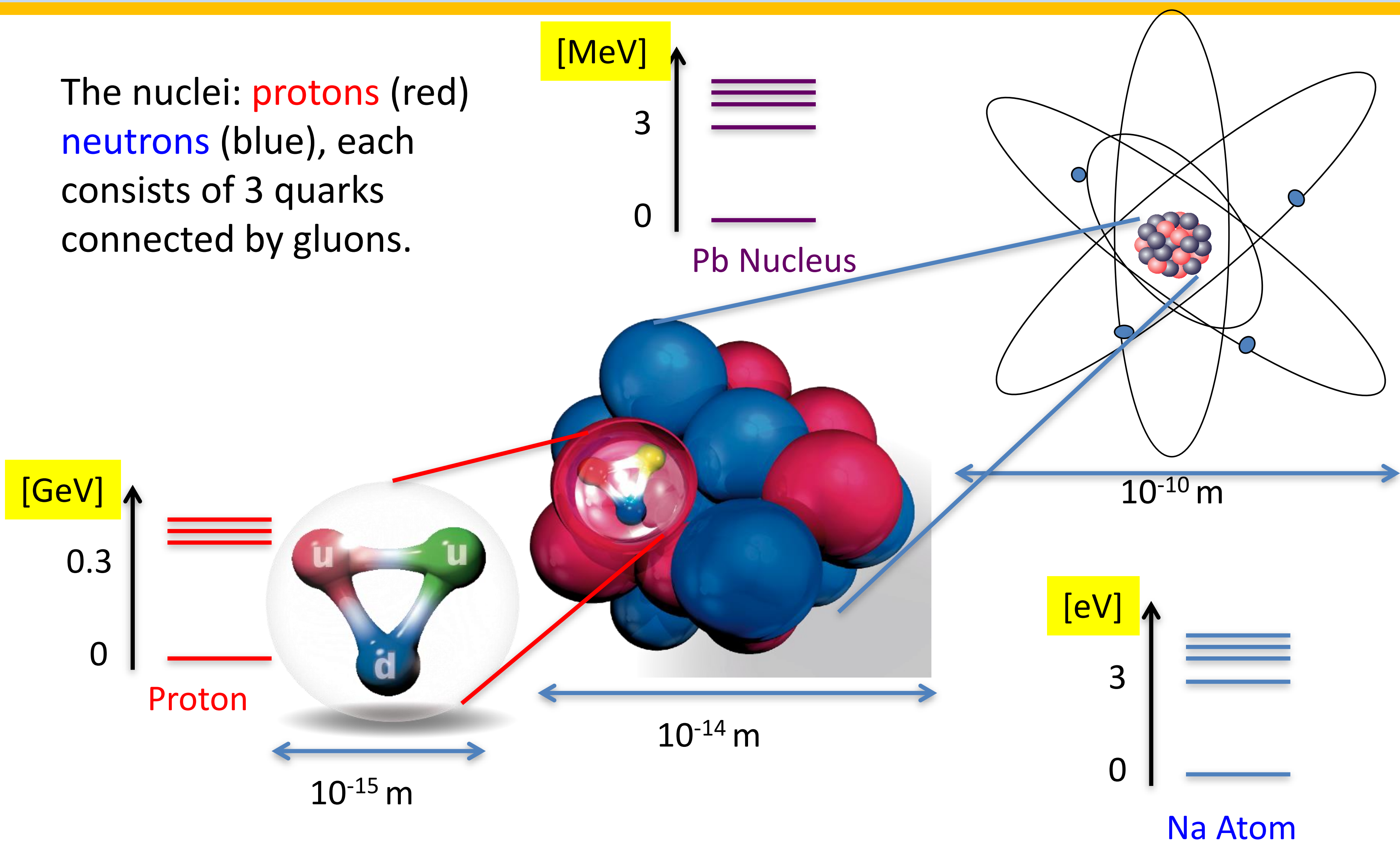
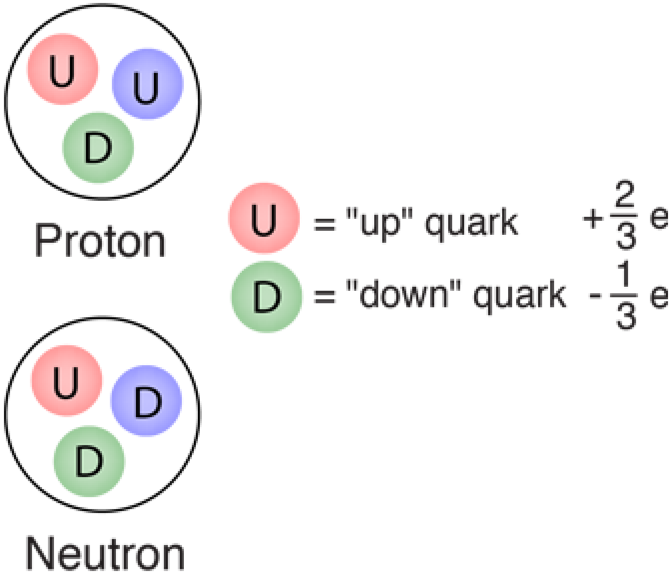
Subatomic Structure

The nuclei: protons (red) neutrons (blue), each consists of 3 quarks connected by gluons.



Particle masses

- Mass 938.3 MeV*

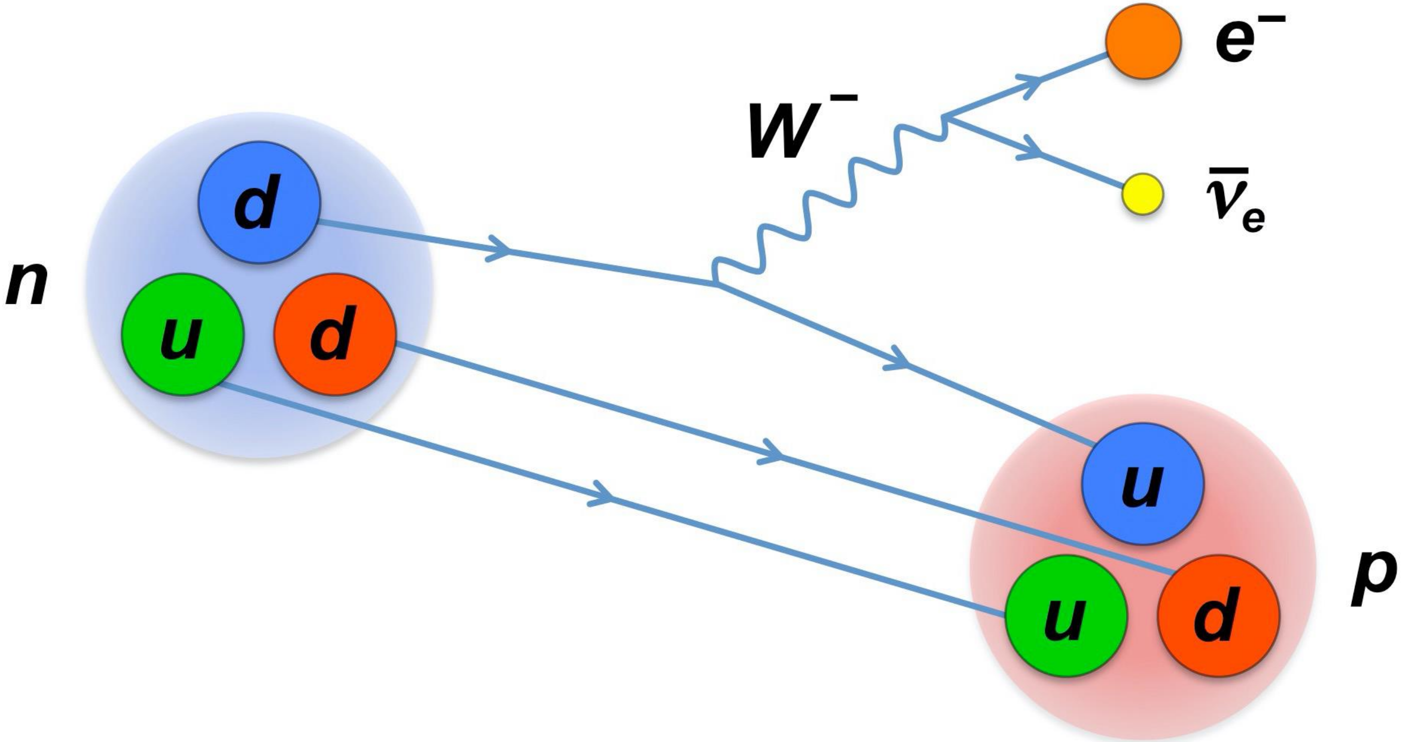


- Mass 1.7-3.3 MeV*
- Mass 4.1-5.8 MeV*

- Mass 939.6 MeV*

*Independent particle rest mass which, in the case of quarks, is meaningless

Beta decay



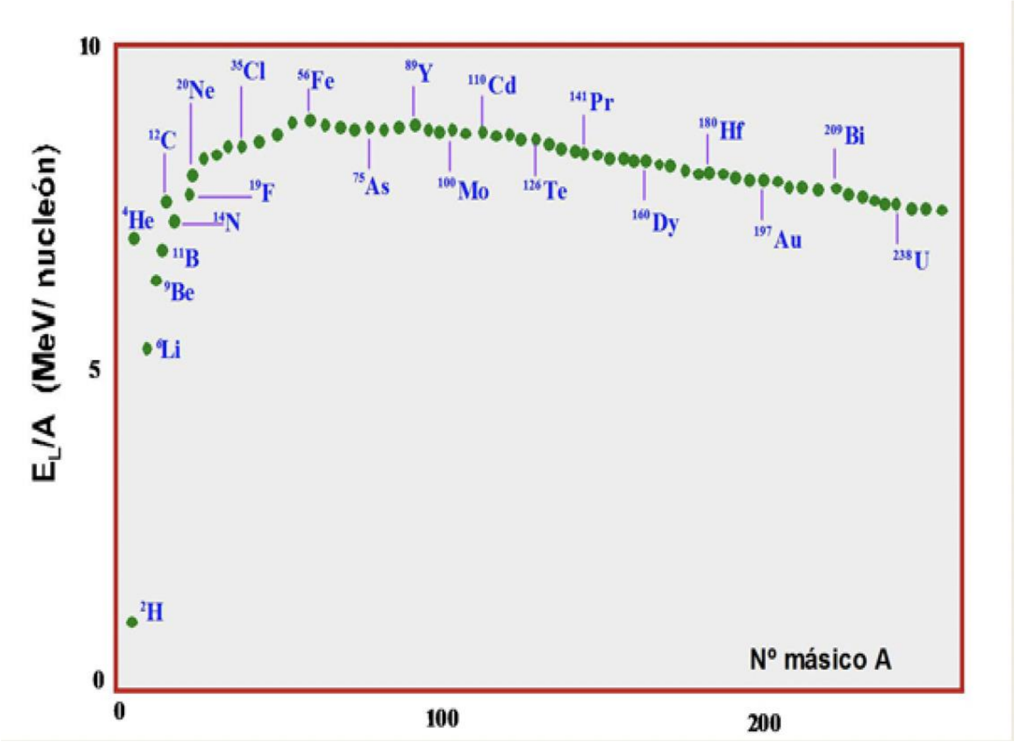
- Free neutrons decay into protons with τ~900 s
- Due to charge conservation, an electron is emitted e^-
- Due to lepton number conservation, and antineutrino is also emitted $\overline{\upsilon_e}$
- Free protons are stable

Nuclear mass

$$m_N < Z \cdot m_p + \mathrm{N} \cdot m_n$$

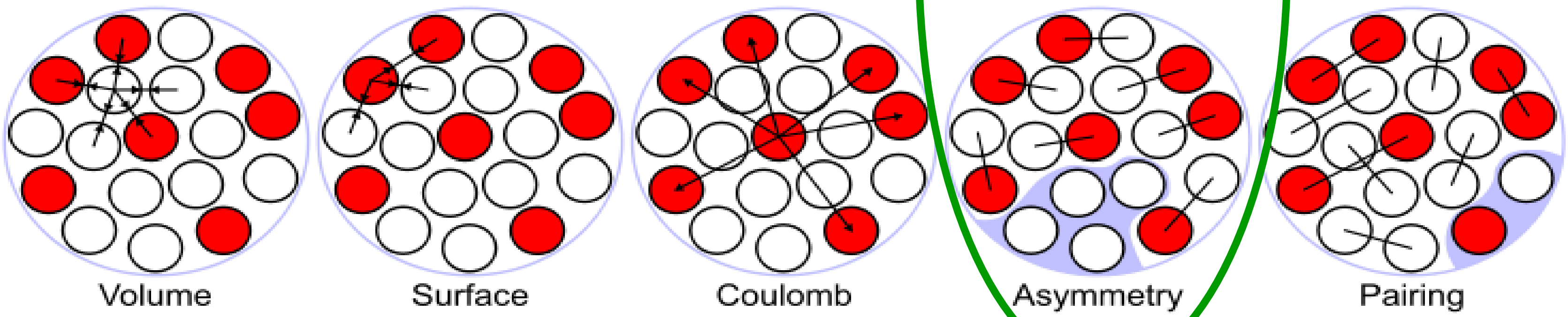
$$m_N = Z \cdot m_p + \mathrm{N} \cdot m_n - \mathrm{B}/c^2$$

- B is the nuclear binding energy
- It is a residue of the strong interaction between quarks
- B/A~8 MeV on average
- Maximum around ^{62}Ni
- Explains stellar nuclear reactions
  - Element abundance
- Nuclear reactors



Semi-empirical mass formula

$$\boxed{B(A,Z) = \underset{\overset{\nearrow}{\text{volume}}}{a_v A} - \underset{\overset{\uparrow}{\text{surface}}}{a_s A^{2/3}} - \underset{\overset{\uparrow}{\text{Coulomb}}}{a_c Z(Z-1)A^{-1/3}} - \underset{\overset{\uparrow}{\text{symmetry}}}{a_{sym}\frac{(A-2Z)^2}{A}} + \underset{\overset{\nwarrow}{\text{pairing}}}{\delta a_p A^{-3/4}}}$$



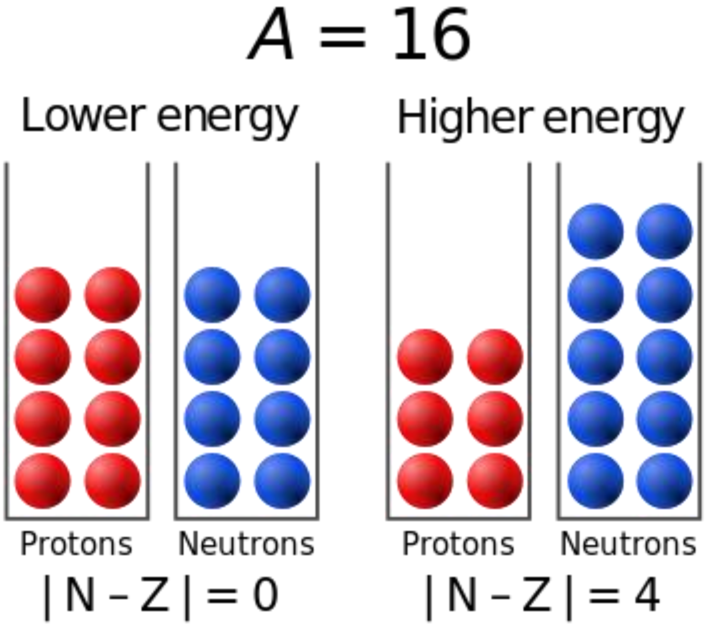
https://en.wikipedia.org/wiki/Semi-empirical_mass_formula

Assymetry term

- Also known as *Pauli term*
- It originates from the Pauli exclusion principle and the Shell structure
- An excess of neutrons would need to occupy higher energy orbitals
- It can be expressed as:

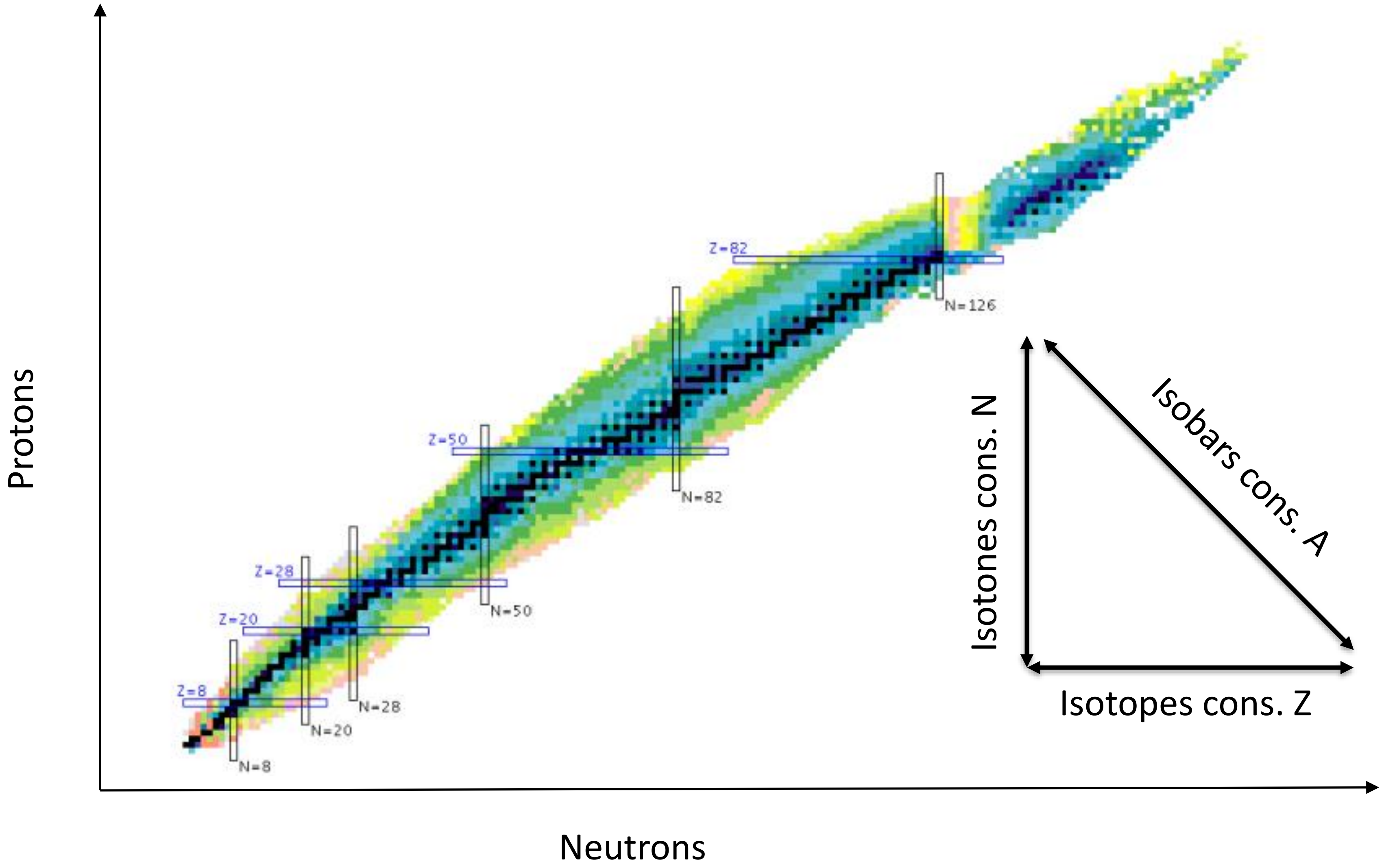
$$a_A \frac{(N-Z)^2}{A}$$

- Notice the square dependence with the difference between protons and neutrons
- This can also be derived by modeling the nucleus as a Fermi ball of nucleons



https://en.wikipedia.org/wiki/Semi-empirical_mass_formula

Nuclear chart



https://www.nndc.bnl.gov/

Nuclear stability

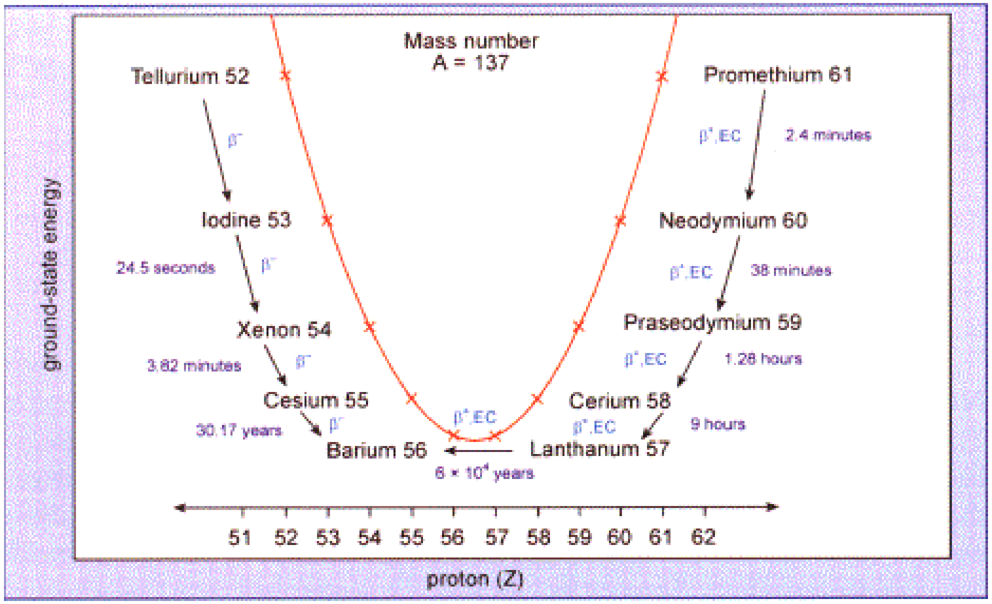
- Due to the asymmetry term, in isobar lines the masses will follow a parabola
- Nuclei will decay into the valley of stability
- This valley is not at N=Z mainly due to the Coulomb repulsion between protons
- Protons inside the nucleus can be unstable, they decay into a neutron by β^+

Thus for each A-value one can calculate the nucleus with lowest mass (largest binding energy):

For a given A a parabolic behaviour of the nuclear masses show up.

odd-A only one stable nucleus. The rest $\beta^\pm$ decay towards the only stable nucleus.

even A both even-even and odd-odd $\Rightarrow$2 parabolas implied by the mass equation.



Beta Decay: definition

Beta Decay: **universal term for all weak-interaction transitions between two neighboring isobars**

Takes place in 3 different forms

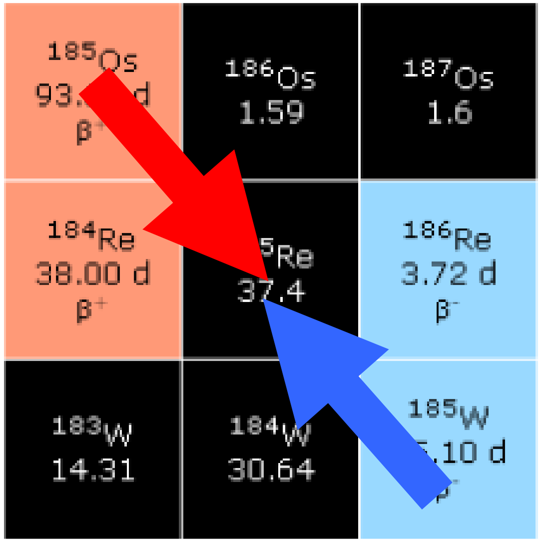
β^-, β^+ & EC (capture of an atomic electron)

β^+: $p \rightarrow n + e^+ + \nu$

$${}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z-1}X^{*}_{N+1} + e^{+} + \nu_{e}$$

EC: $p + e^- \rightarrow n + \nu$

$${}^{A}_{Z}X_{N} + e^{-} \rightarrow {}^{A}_{Z-1}X^{*}_{N+1} + \nu_{e} + X_{ray}$$



β^-: $n \rightarrow p + e^- + \tilde{\nu}$

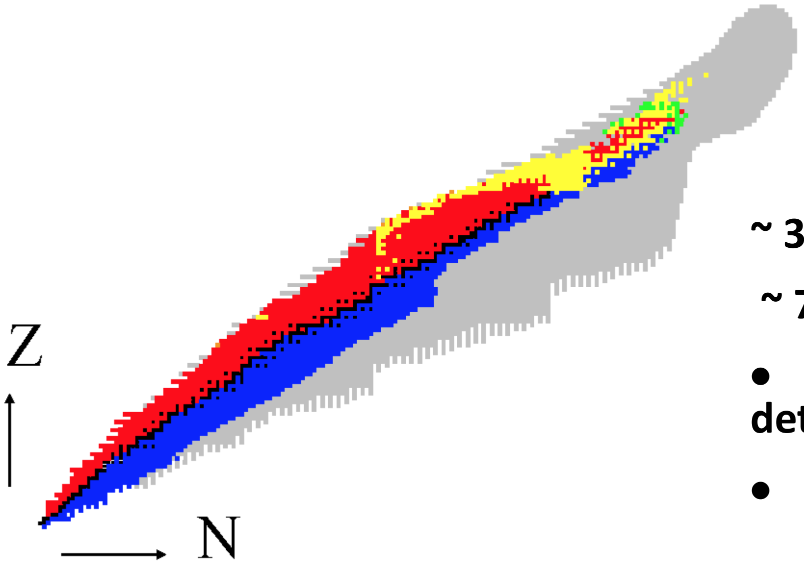
$${}^{A}_{Z}X_{N} \rightarrow {}^{A}_{Z+1}X^{*}_{N-1} + e^{-} + \bar{\nu}_{e}$$

a nucleon inside the nucleus is transformed into another

No preformation!

Atomic Mass Model

Relationship with Nuclear Decay Models



254 Stable nuclei

- 167 e-e
- 4 o-o (2H, 6Li, 10B, ^{14}N)
- 83 e-o

34 Primordial ($T_{1/2} > 10^9$y)

~ 3000 produced in nuclear reactions

~ 7000 predicted to be bound

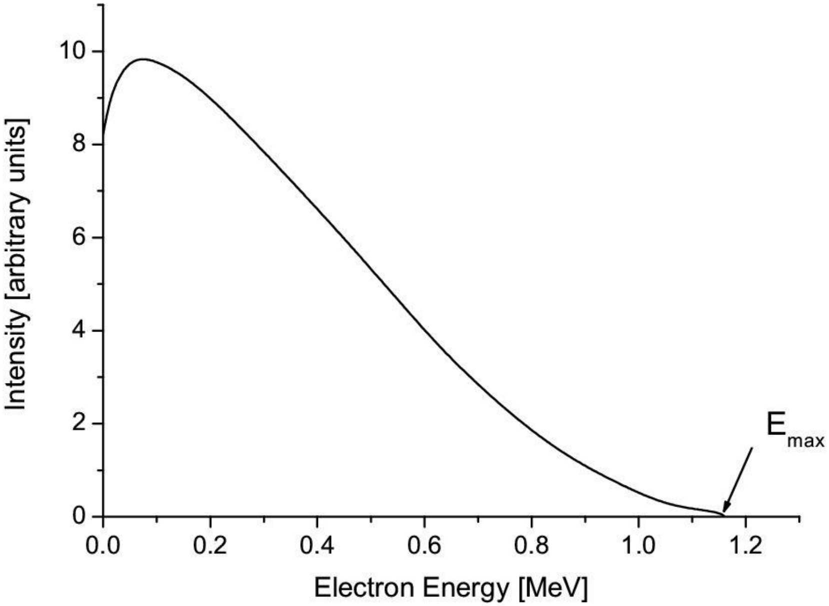
- **Decay characteristics of most radioactive nuclei determined by β-decay i.e. weak interaction**
- **For heavier nuclei → Electromagnetic interaction important →**
  - **α-decay**
  - **fission**

- **Moving away from stable nuclei by adding protons or neutrons → until the particle drip-lines (S_p = 0 or S_n = 0).**

Nuclei beyond drip-line are unbound to nucleon emission, i.e. Strong interaction cannot bind one more nucleon to the nucleus

Beta decay energy spectrum

- Energy spectrum of beta particle is continuous
- No discrete peaks
- This is why neutrinos were suggested
- 3-body decay: beta, (anti)neutrino and recoiling nucleus
- Energy mass difference is split among the 3 products
- Total energy available:



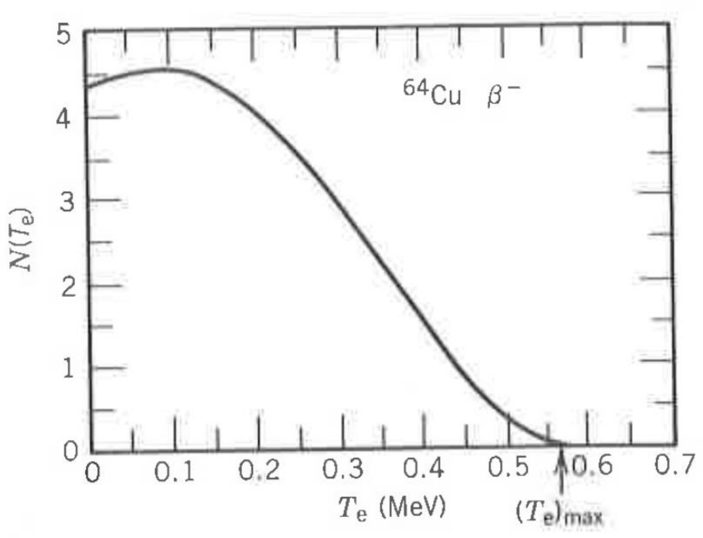
$$Q = (m_X - m_{X'} - m_\nu - m_e)c^2 = E_{X'} + E_\nu + E_e$$

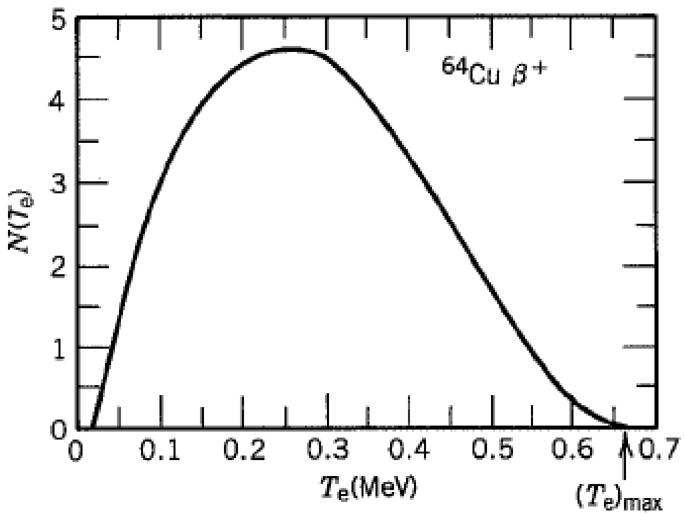
Typical Q is few MeV

Energy spectra features

- $E_{max} \sim Q_\beta$, the β particle takes all the available energy; daughter nucleus and neutrino at rest
- There is a most likely value for the β particle energy $0.3\text{-}0.4 Q_\beta$
- β^- can be emitted at ~0 energy
- β^+ can not be emitted at ~0 energy
  - The attraction or repulson of the protons in the nucleus is not negligible

$$N\left(T_e\right) = \frac{C}{c^5} F(Z,Q) |V_{fi}|^2 [Q - T_e]^2 \sqrt{T_e^2 + 2T_e m_e c^2}\left(T_e + m_e c^2\right)$$

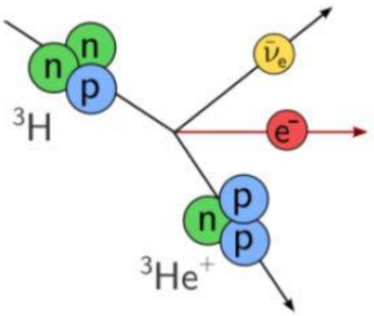




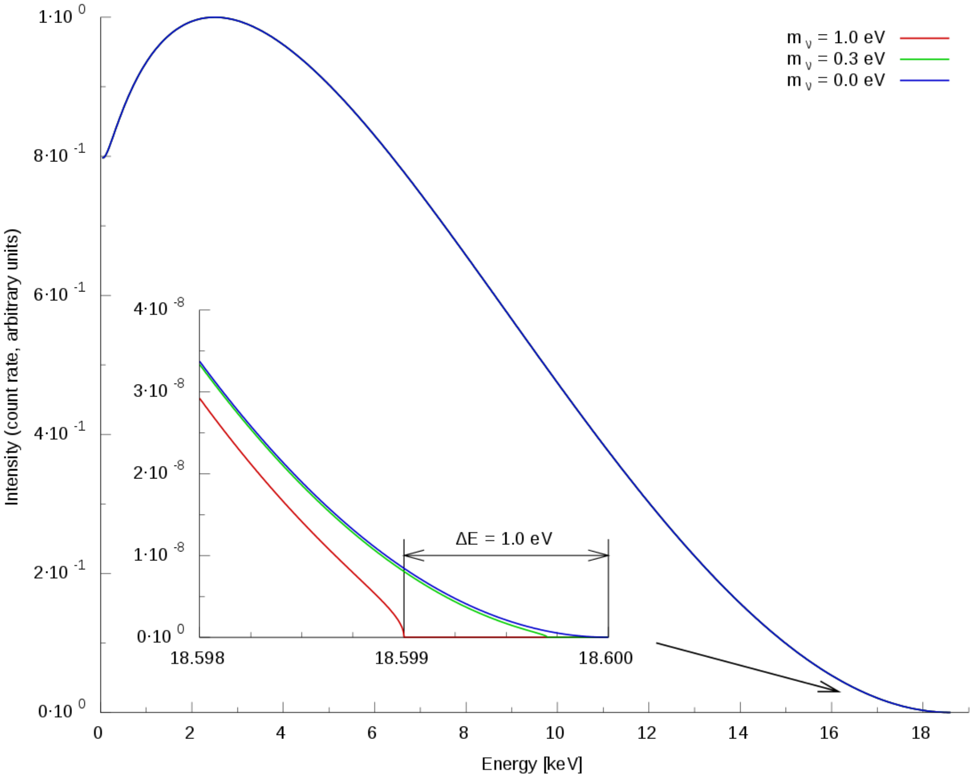
Neutrino mass measurement

$$\frac{dN}{dE} = C \cdot F(E,Z) \cdot p(E + m_e) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_\nu^2}$$

$$\boxed{m_{\nu_e}^2 = \sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$



- If we know with great precision the nuclear masses, we know Q_β
- A precise measurement of the end point is sensitive to m_ν
- Model independent method



https://indico.cern.ch/event/572149/contributions/2488095/attachments/1446803/2228876/ALPS2017_fraenkle.pdf

KATRIN (Karlsruhe Tritium Neutrino Experiment)

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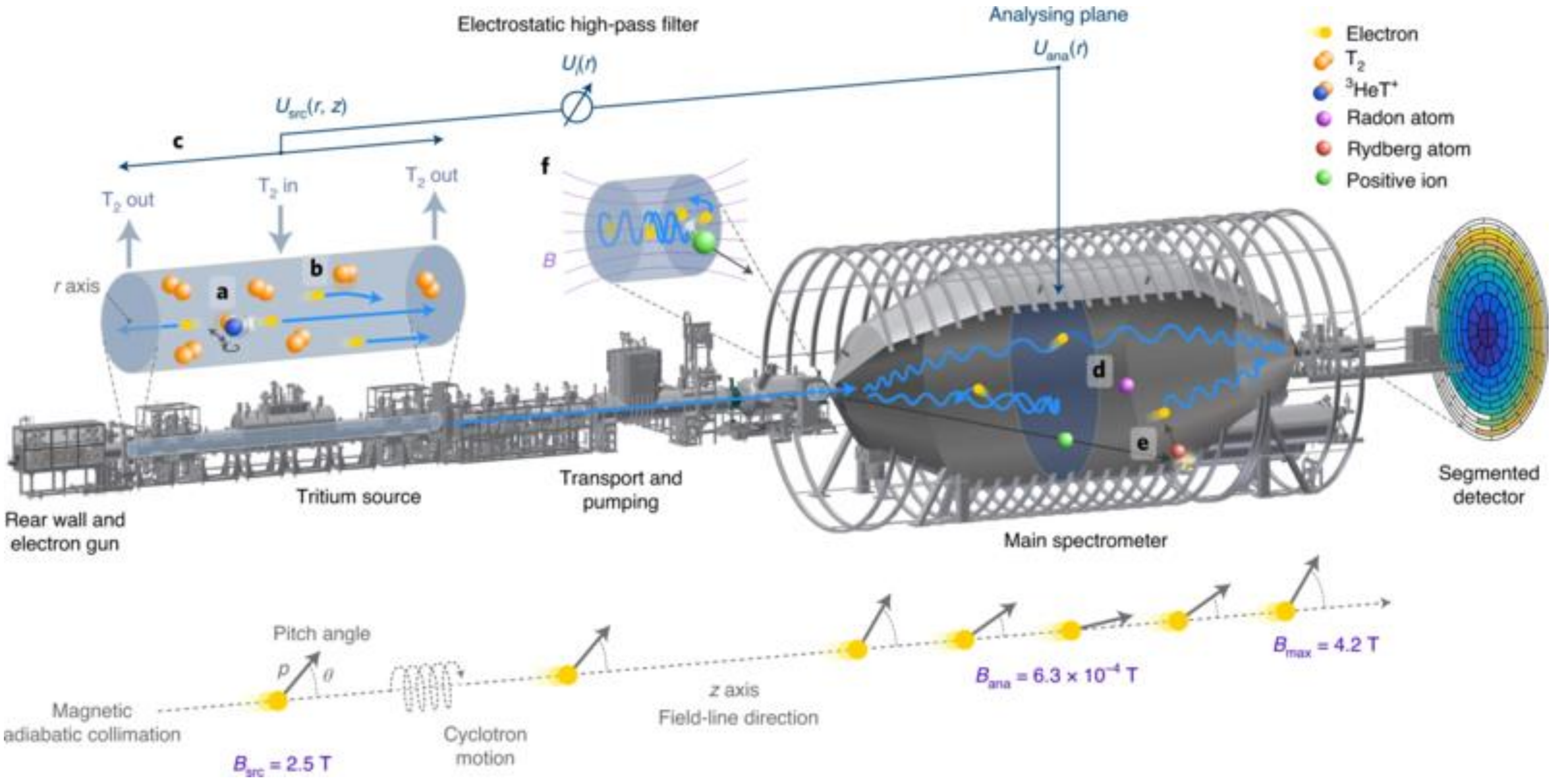
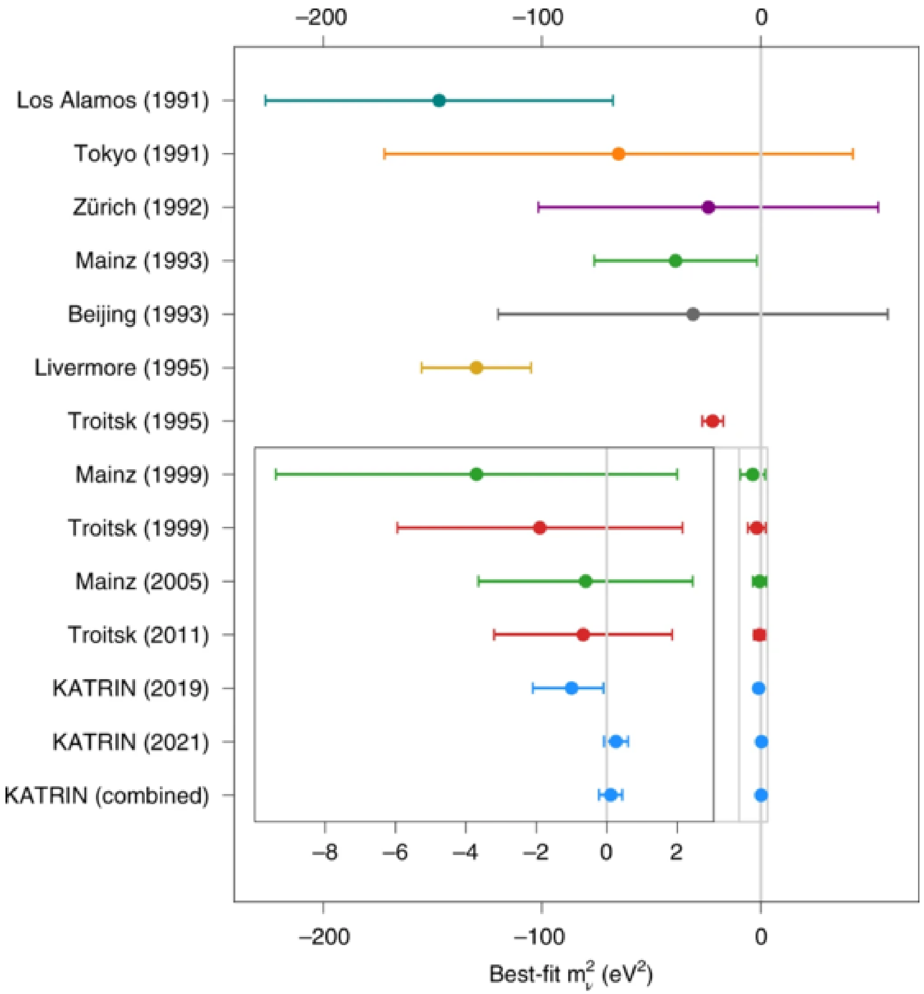


- Molecular tritium source ($T_{1/2}$=12.3 years and Q_β=18.59202 (6) keV)
- Electric field to filter low energy β particles
- Magnetic field to conduct them to the detector

KATRIN (Karlsruhe Tritium Neutrino Experiment)

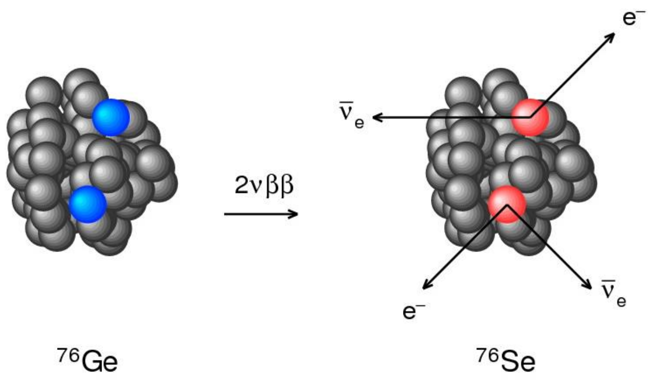
- Up to now ~65 days of measurement
- Out of ~1000 days planned
- Current upper limit of $m_\nu<0.8$ eV
- Plan to reach $m_\nu<0.2$ eV
- Model independent measurement, but relies on theoretical calculation
  - i.e. molecular dynamics

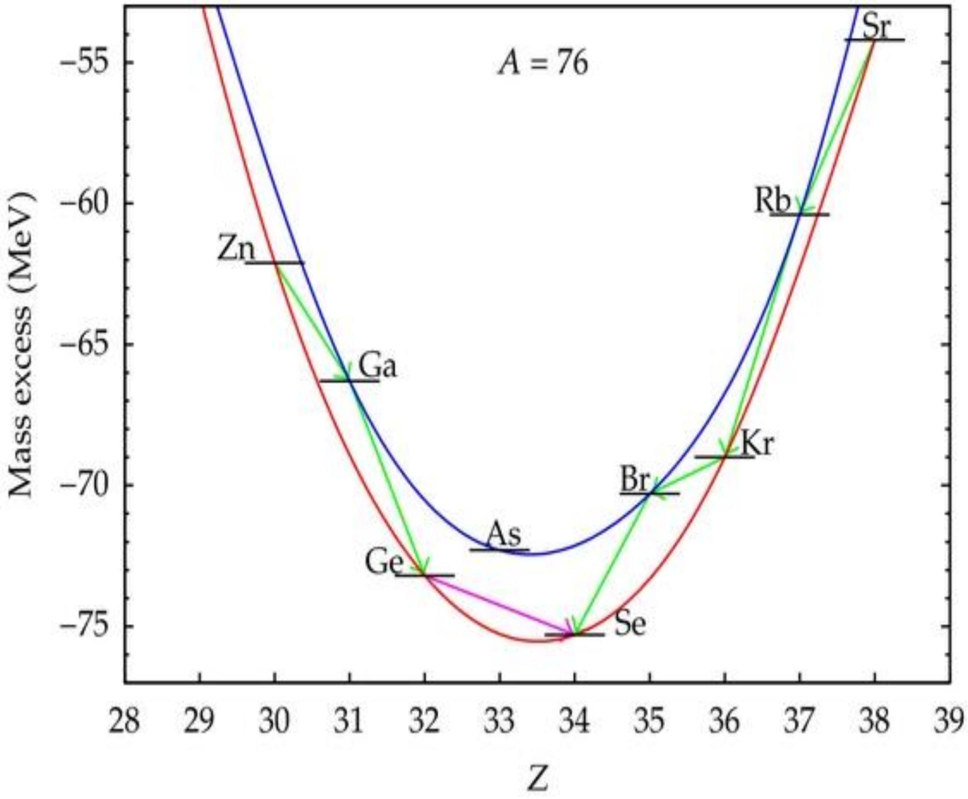


Nat. Phys. **18**, 160–166 (2022). https://doi.org/10.1038/s41567-021-01463-1

Double beta decay

- There are a few cases for which simple β decay is not energetically allowed, but double β decay is.
- Has been observed in about dozen cases, i.e., ^{76}Ge → ^{76}Se
- $T_{1/2}$~10^{18}-10^{21} years

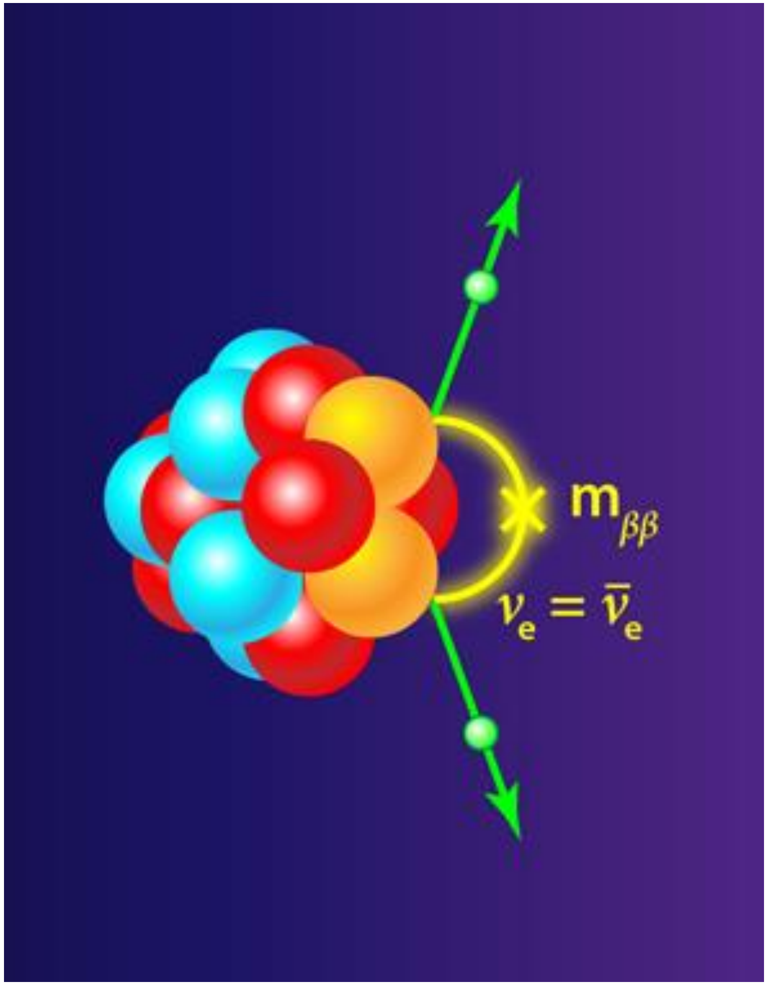




J. Mendez PhD thesis

Neutrinoless double beta decay

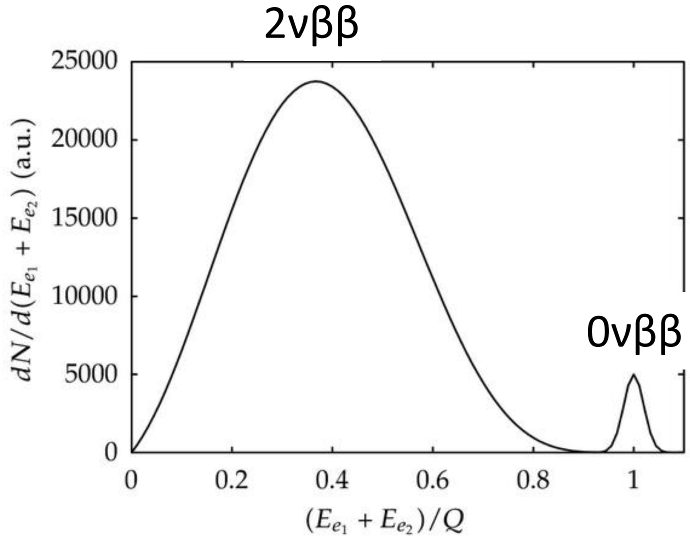
- If neutrinos have masses (they oscillate, so yes) they could be Majorana particles
- Neutrinos would be their own antiparticle $\nu_e = \overline{\nu_e}$
- This decay would violate lepton number conservation (+2 from the emitted e^-)
- Would allow for absolute measurement of m_ν
- Imply physics beyond the standard model

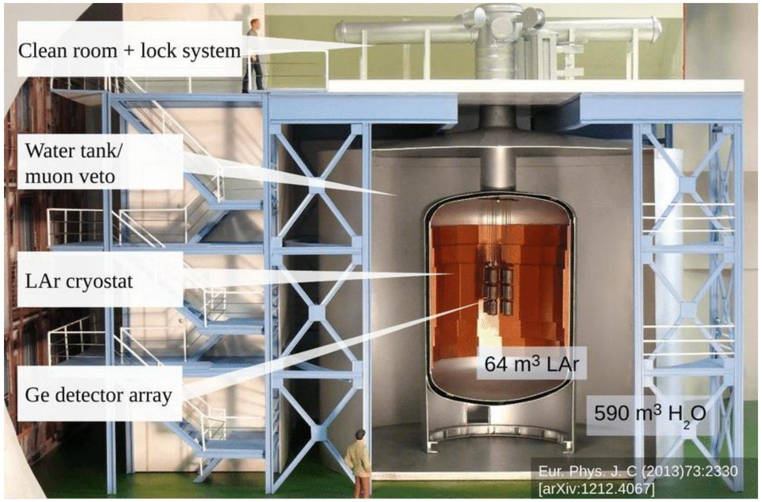


Physics 11, 30 (2018)

Neutrinoless double beta decay

- In neutrinoless double beta decay, both electrons carry all the energy
  - Sum of both energies=total energy
- Very low probability
  - Large amount of radioactive material
  - Superb sensitivity and efficiency
  - Long collection time
- Ultra low background (i.e. underground)
- No event has been observed so far
  - $T_{1/2}>10^{26}$ years (universe age ~10^{10} years)





https://www.mpi-hd.mpg.de/gerda/

Beta decay process

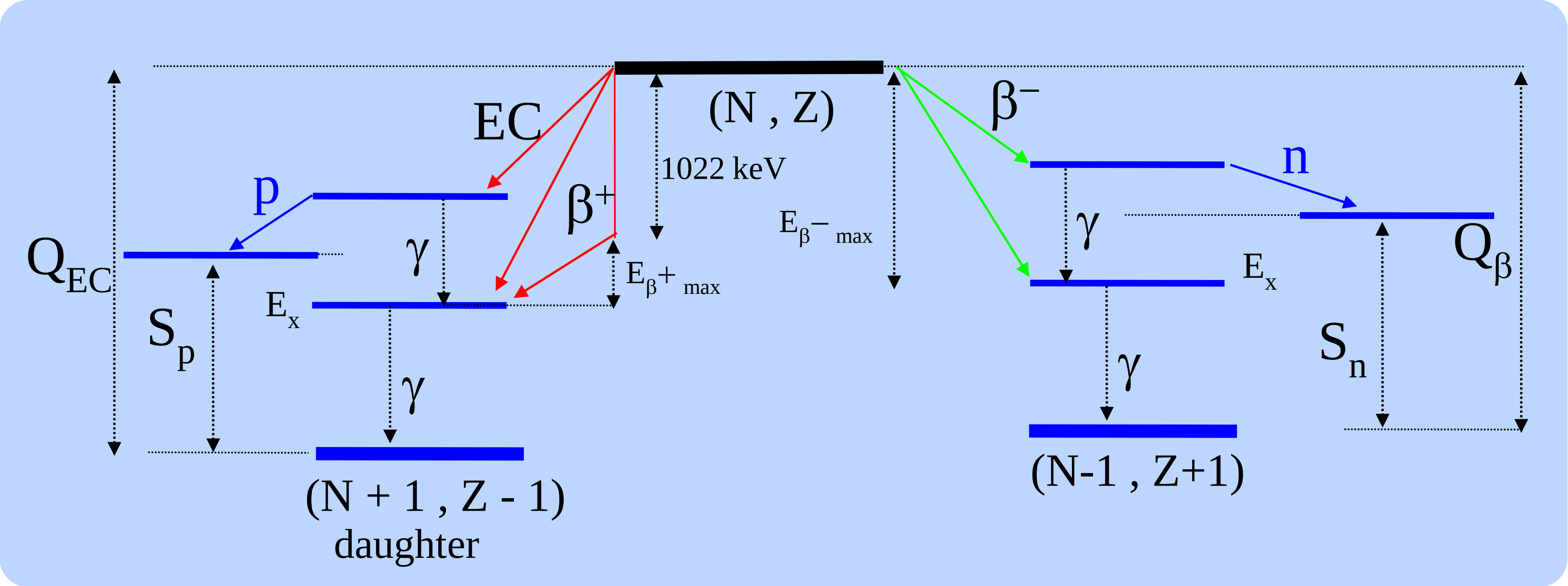
Process mediated by the weak interaction between two isobars

$(N , Z) \xrightarrow{\beta^-} (N-1, Z+1) + e^- + \nu$

$M(Z) - M(Z+1) = E_{\beta} + E_{\nu} + Ex$

$(N , Z) \xrightarrow{\beta^+ + EC} (N+1, Z-1) + e^+ + \nu$

$M(Z) - M(Z-1) = E_{\beta\square} + E_{\nu} + 1022 + Ex$



Fermi´s golden rule

$$\lambda_{if} = \frac{2\pi}{\hbar}\left|M_{if}\right|^2 \rho_f$$

Transition rate or probability of decay per second

Matrix element for the (weak) interaction

Density of final states

$$M_{if} = \langle f|M|i\rangle = \int \psi_f^* \psi_e^* \psi_v^* M \psi_i \, dV$$

Beta decay *ft* value

$$ft = f(Q)\,\frac{t_{1/2}}{BR} = \frac{2\pi^3\hbar^7\ln(2)}{g^2 m_e^5 c^4 \left|\overline{M'_{if}}\right|^2} = \frac{K}{g^2\left|\overline{M'_{if}}\right|^2}$$

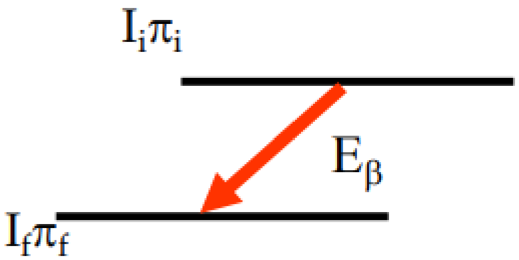
- *f* is the phase-space integral, which is related to the statistical rate factor, and is a function of the Q value. It is tabulated. It favours populating low energy states.

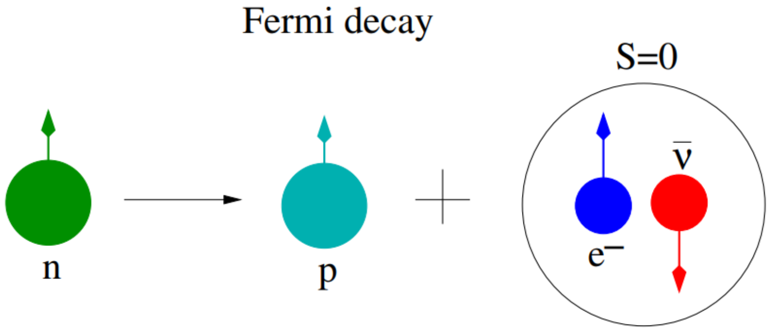
- Partial half-life of a specific decay branch $t_{1/2}^{\beta_i} = \frac{T_{1/2}^{exp}}{P_{\beta_i}}$

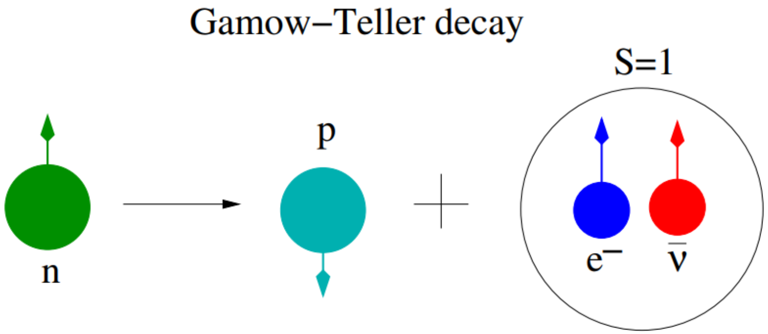
- If we measure Q, BR and $t_{1/2}$, we have log(*ft*).

Beta decay momentum conservation

- $\vec{L}_\beta = \vec{l}_e + \vec{l}_\nu$, $\vec{S}_\beta = \vec{s}_e + \vec{s}_\nu$ and $\vec{J}_\beta = \vec{L}_\beta + \vec{S}_\beta$
- $\vec{J}_i = \vec{J}_f + \vec{L}_\beta$
- J is the total angular momentum
- L is the orbital angular momentum
- S is the spin
  - Fermi $\vec{S}_e + \vec{S}_\nu = 0$ (antiparallel)
  - Gamow-Teller $\vec{S}_e + \vec{S}_\nu = 1$ (parallel)







Beta decay selection rules

L Classification

$$\begin{array}{lc} L_\beta = 0 \rightarrow & \text{Allowed} \\ L_\beta = 1 \rightarrow & \text{First Forbidden} \\ L_\beta = 2 \rightarrow & \text{Second Forbidden} \\ L_\beta = 3 \rightarrow & \text{Third Forbidden} \end{array}$$

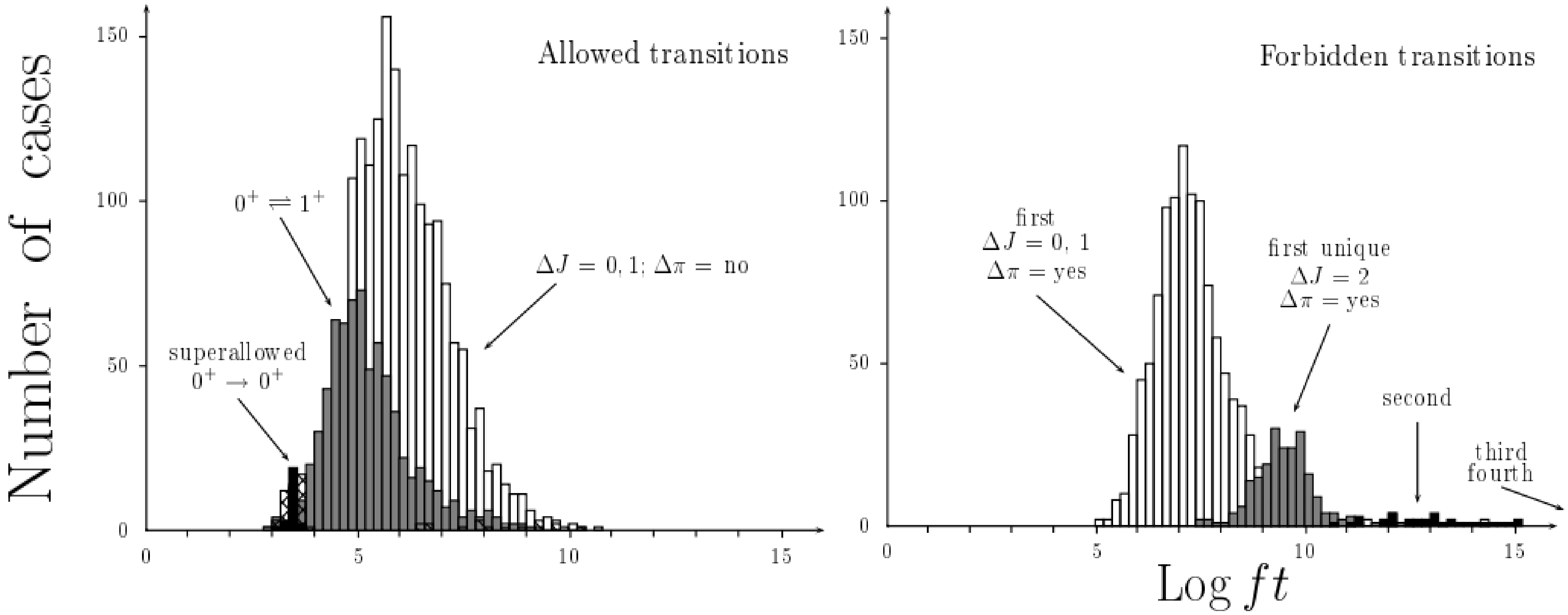
S Classification

$$\vec{S}_\beta = \vec{S_{e^+}} + \vec{S_{\nu_e}} = \begin{cases} 0 & \uparrow\downarrow \text{ or } \downarrow\uparrow \quad V\,(F) \\ 1 & \uparrow\uparrow \text{ or } \downarrow\downarrow \quad A\,(GT) \end{cases}$$

- $0^+ \rightarrow 0^+$ not allowed in GT, because $S_\beta=1$ and therefore $\Delta L \neq 0$

Beta decay selection rules

B. Singh et al., Nucl. Data Sheets 84, 487 (1998)



- We can use log(*ft*) to infer the spin-parity of daughter nucleus states
- Learn about nuclear structure

Beta decay experiment

- Selection rules tell us which states we will “most likely” populate in the daughter nucleus
- Log(*ft)* favours populating low energy states
- No need to re-accelerate beams
  - Higher intensity
  - No Doppler corrections
  - Easier experiment

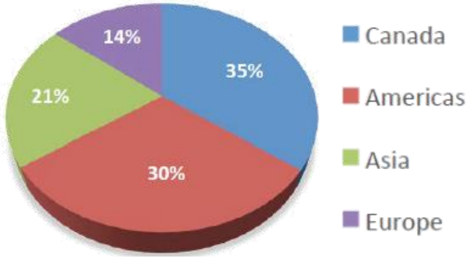
Beta decay experiment

- Now we have all the ingredients to perform beta decay experiments and learn nuclear structure
- I will use GRIFFIN at TRIUMF as example, current state-of-the-art spectrometer
- More facilities are following its design

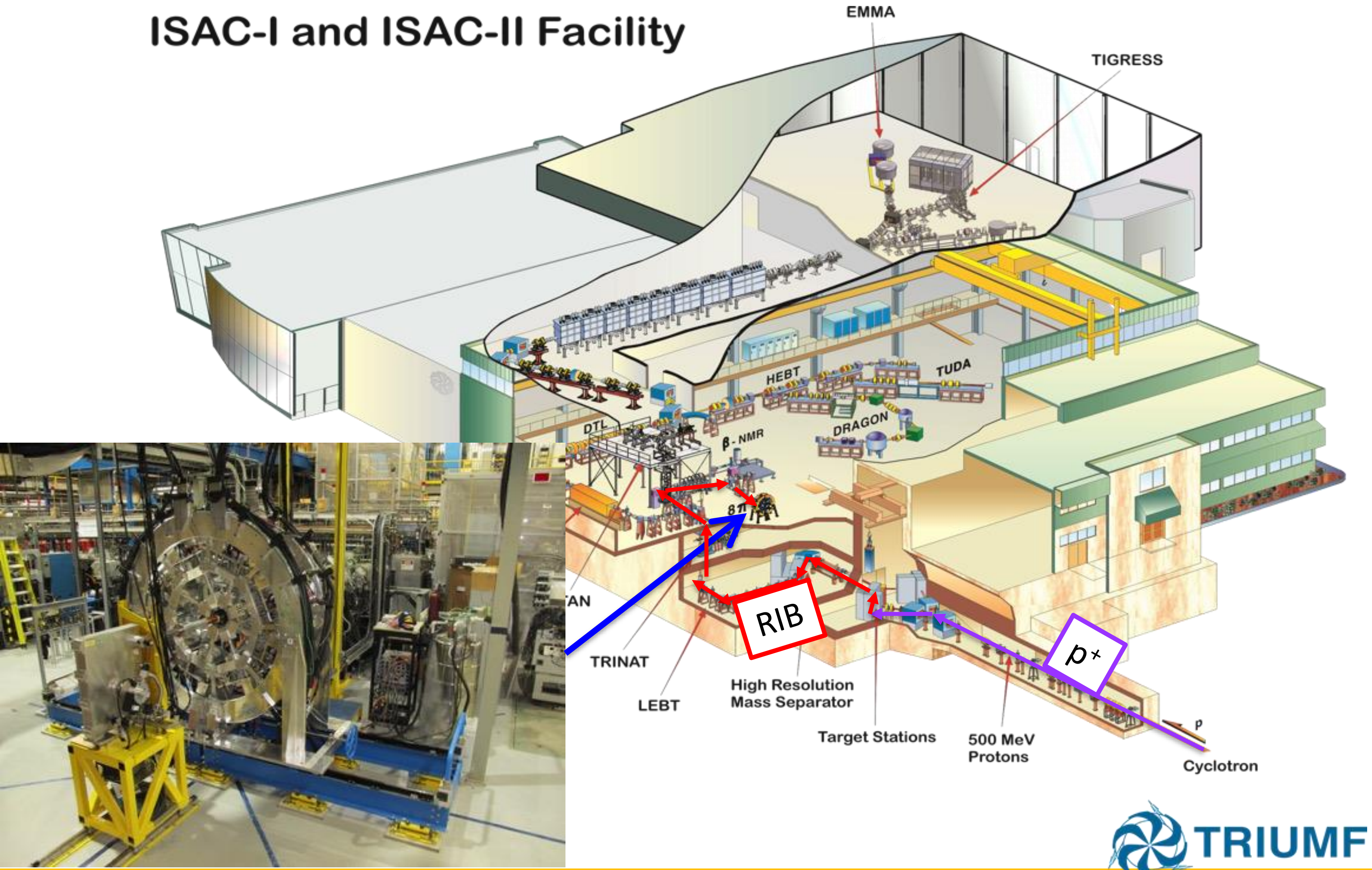
400 staff

200 students & post-doctoral researchers

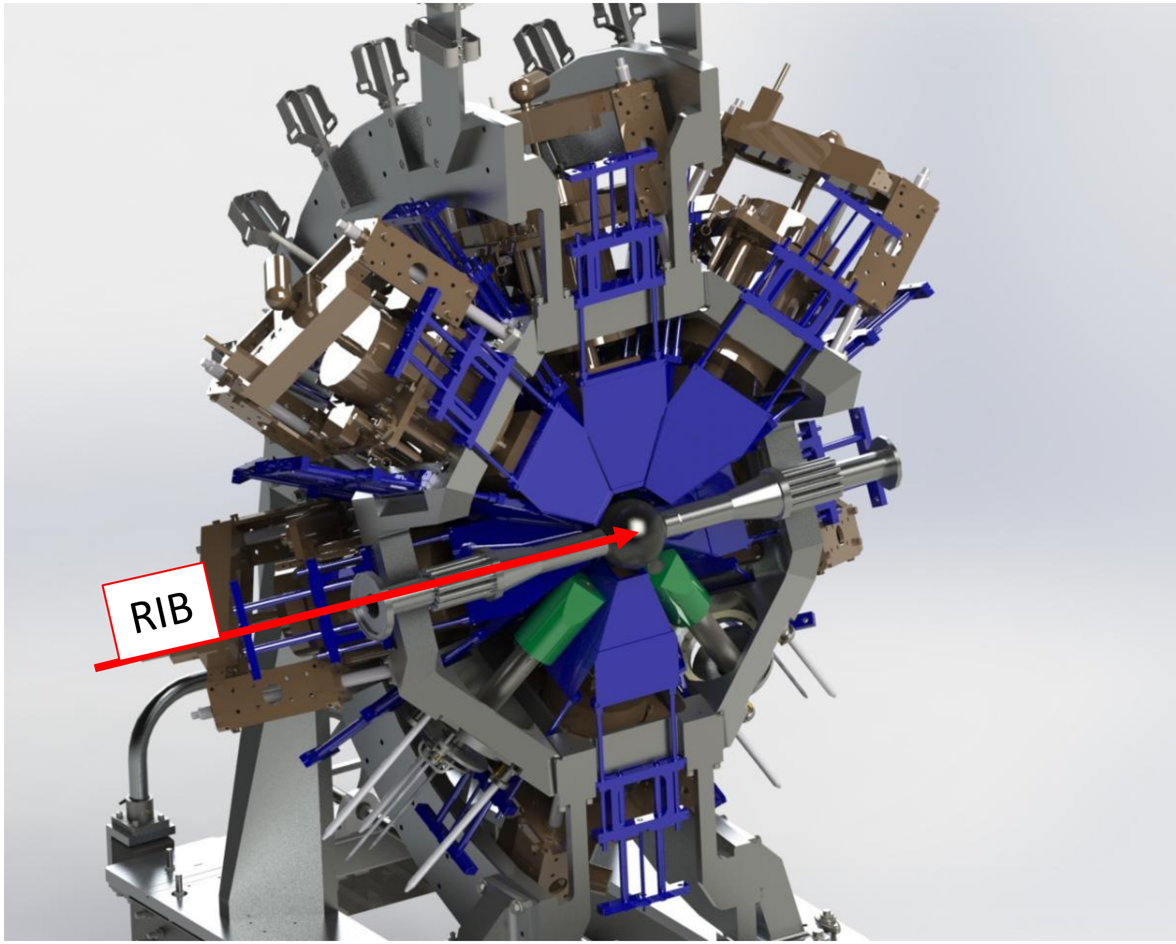
650 scientist & student researcher visits per year



ISAC@TRIUMF

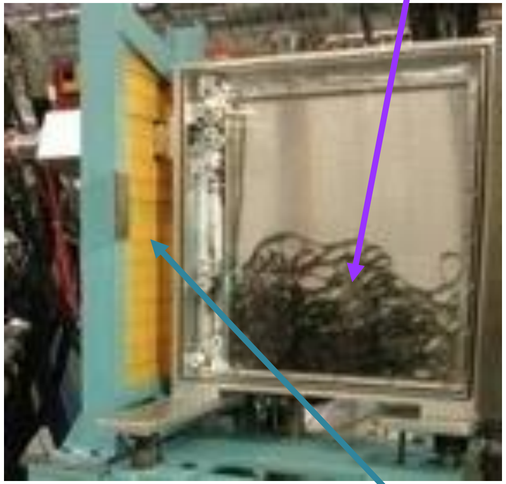

ISAC-I and ISAC-II Facility
EMMA
TIGRESS
HEBT
TUDA
DTL
β-NMR
DRAGON
8π
AN
RIB
p+
TRINAT
LEBT
High Resolution Mass Separator
Target Stations
500 MeV Protons
p
Cyclotron
TRIUMF

GRIFFIN

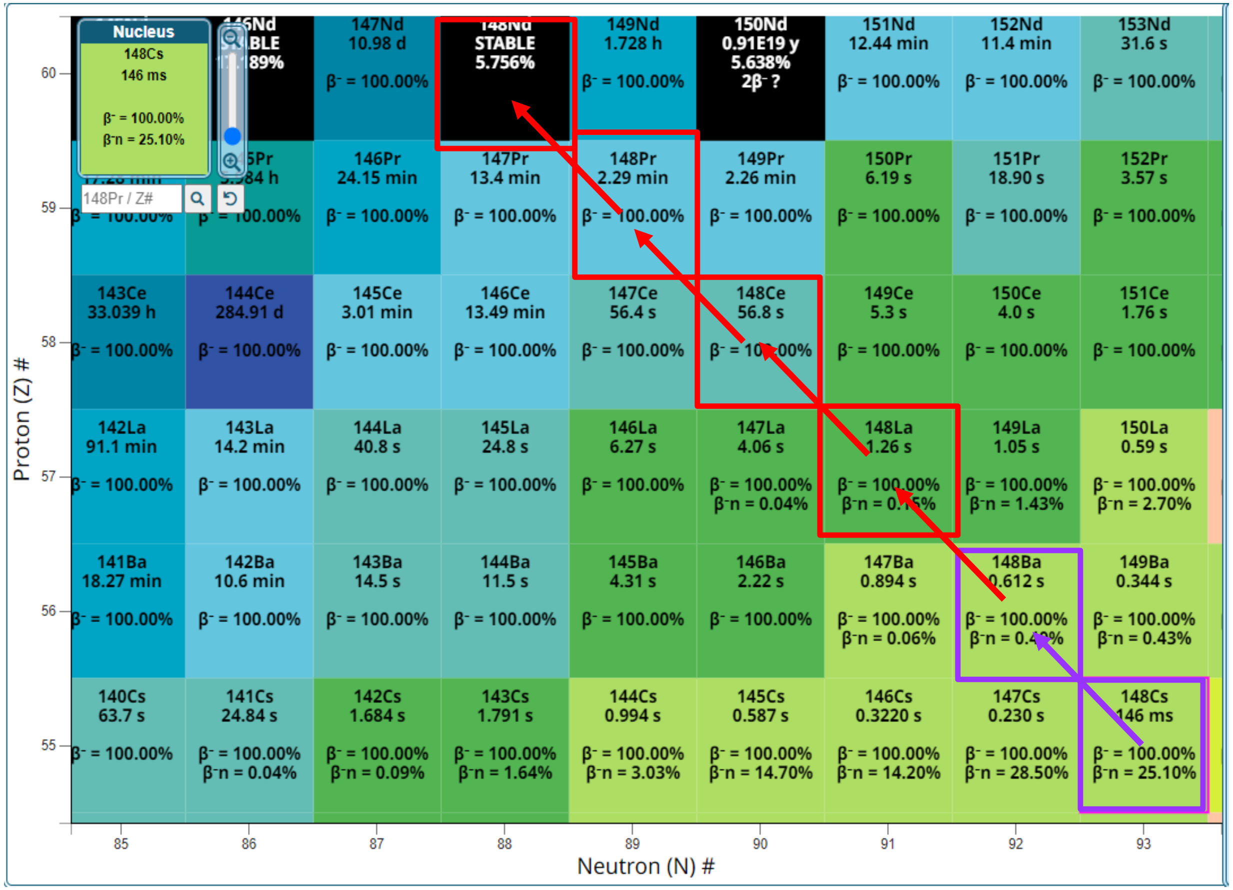


Moving tape

Mylar tape



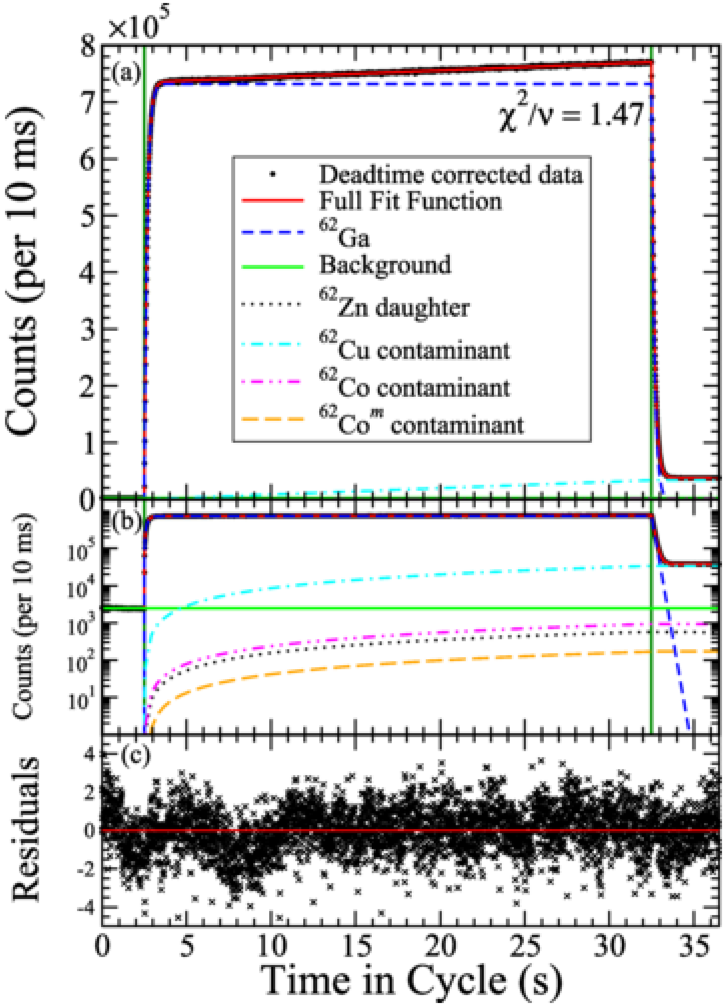
Lead wall



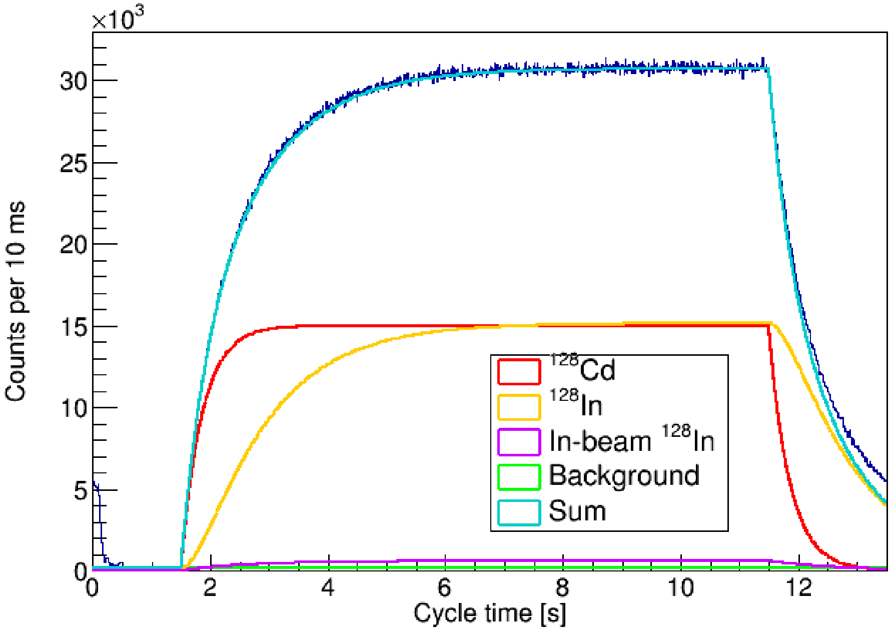
Nucleus
148Cs
146 ms
$\beta^- = 100.00\%$
$\beta^-n = 25.10\%$

Proton (Z) # \ Neutron (N) #	85	86	87	88	89	90	91	92	93
60		146Nd STABLE 17.189%	147Nd 10.98 d $\beta^- = 100.00\%$	148Nd STABLE 5.756%	149Nd 1.728 h $\beta^- = 100.00\%$	150Nd 0.91E19 y 5.638% $2\beta^-$?	151Nd 12.44 min $\beta^- = 100.00\%$	152Nd 11.4 min $\beta^- = 100.00\%$	153Nd 31.6 s $\beta^- = 100.00\%$
59	17.28 min $\beta^- = 100.00\%$	145Pr 5.984 h $\beta^- = 100.00\%$	146Pr 24.15 min $\beta^- = 100.00\%$	147Pr 13.4 min $\beta^- = 100.00\%$	148Pr 2.29 min $\beta^- = 100.00\%$	149Pr 2.26 min $\beta^- = 100.00\%$	150Pr 6.19 s $\beta^- = 100.00\%$	151Pr 18.90 s $\beta^- = 100.00\%$	152Pr 3.57 s $\beta^- = 100.00\%$
58	143Ce 33.039 h $\beta^- = 100.00\%$	144Ce 284.91 d $\beta^- = 100.00\%$	145Ce 3.01 min $\beta^- = 100.00\%$	146Ce 13.49 min $\beta^- = 100.00\%$	147Ce 56.4 s $\beta^- = 100.00\%$	148Ce 56.8 s $\beta^- = 100.00\%$	149Ce 5.3 s $\beta^- = 100.00\%$	150Ce 4.0 s $\beta^- = 100.00\%$	151Ce 1.76 s $\beta^- = 100.00\%$
57	142La 91.1 min $\beta^- = 100.00\%$	143La 14.2 min $\beta^- = 100.00\%$	144La 40.8 s $\beta^- = 100.00\%$	145La 24.8 s $\beta^- = 100.00\%$	146La 6.27 s $\beta^- = 100.00\%$	147La 4.06 s $\beta^- = 100.00\%$ $\beta^-n = 0.04\%$	148La 1.26 s $\beta^- = 100.00\%$ β^-n = 0.[illegible]5%	149La 1.05 s $\beta^- = 100.00\%$ $\beta^-n = 1.43\%$	150La 0.59 s $\beta^- = 100.00\%$ $\beta^-n = 2.70\%$
56	141Ba 18.27 min $\beta^- = 100.00\%$	142Ba 10.6 min $\beta^- = 100.00\%$	143Ba 14.5 s $\beta^- = 100.00\%$	144Ba 11.5 s $\beta^- = 100.00\%$	145Ba 4.31 s $\beta^- = 100.00\%$	146Ba 2.22 s $\beta^- = 100.00\%$	147Ba 0.894 s $\beta^- = 100.00\%$ $\beta^-n = 0.06\%$	148Ba 0.612 s $\beta^- = 100.00\%$ β^-n = 0.4[illegible]%	149Ba 0.344 s $\beta^- = 100.00\%$ $\beta^-n = 0.43\%$
55	140Cs 63.7 s $\beta^- = 100.00\%$	141Cs 24.84 s $\beta^- = 100.00\%$ $\beta^-n = 0.04\%$	142Cs 1.684 s $\beta^- = 100.00\%$ $\beta^-n = 0.09\%$	143Cs 1.791 s $\beta^- = 100.00\%$ $\beta^-n = 1.64\%$	144Cs 0.994 s $\beta^- = 100.00\%$ $\beta^-n = 3.03\%$	145Cs 0.587 s $\beta^- = 100.00\%$ $\beta^-n = 14.70\%$	146Cs 0.3220 s $\beta^- = 100.00\%$ $\beta^-n = 14.20\%$	147Cs 0.230 s $\beta^- = 100.00\%$ $\beta^-n = 28.50\%$	148Cs 146 ms $\beta^- = 100.00\%$ $\beta^-n = 25.10\%$

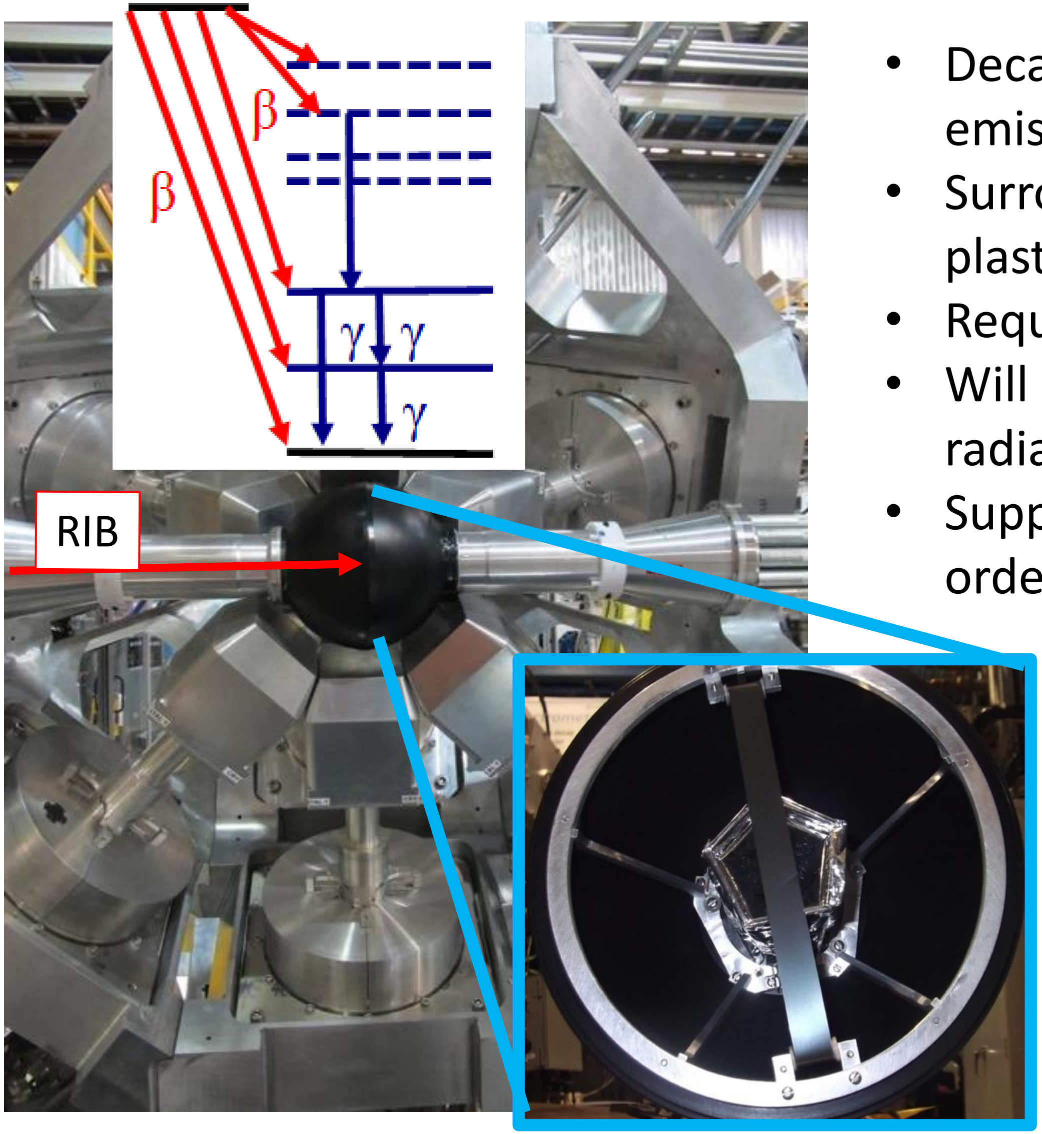
Moving tape



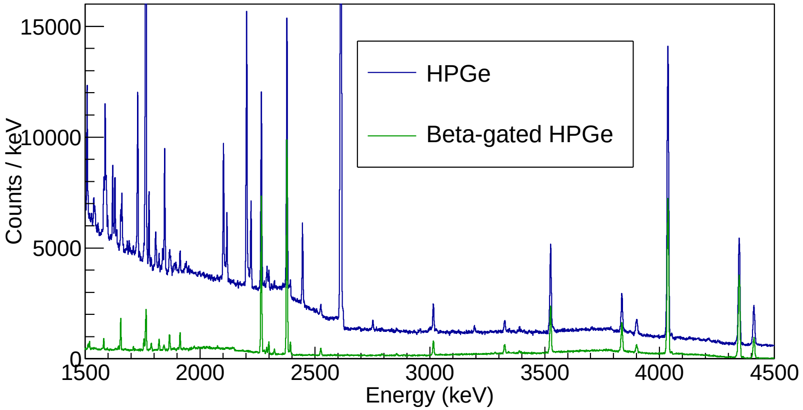
- You implant RIB for some time until your activity saturates
- Block RIB and measure decay
- Thanks to very different lifetimes, you observe different decay curves
- Move tape behind lead wall
- Start fresh implantation



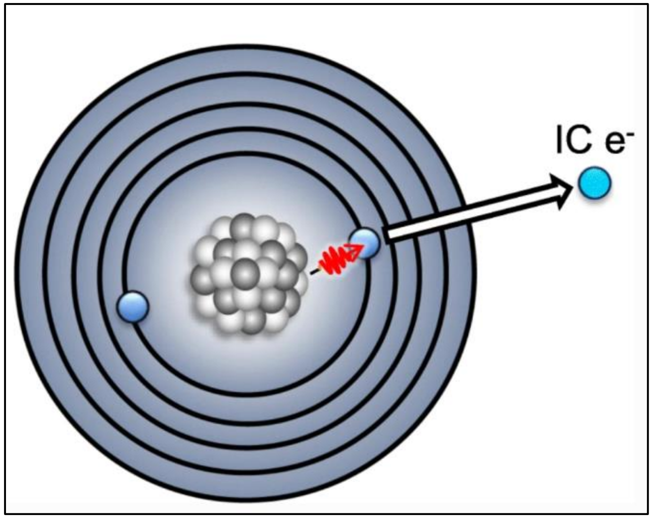
Beta tagging

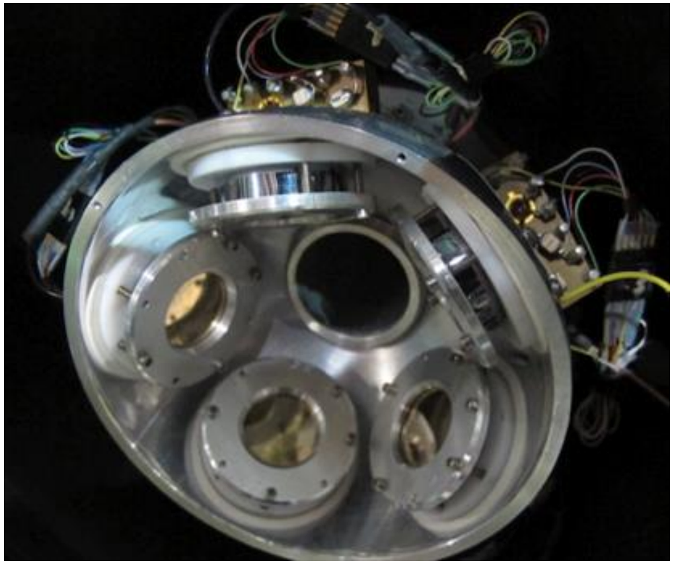


- Decay of interest begins with a β emission
- Surround point of implantation with plastic scintillators
- Require detection of a β particle
- Will not detect β particle from ambient radiation
- Suppresses room background by 5 orders of magnitude



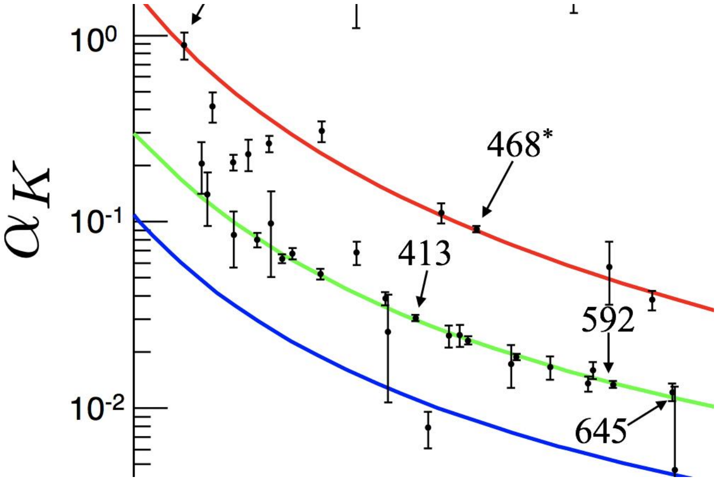
Conversion electrons



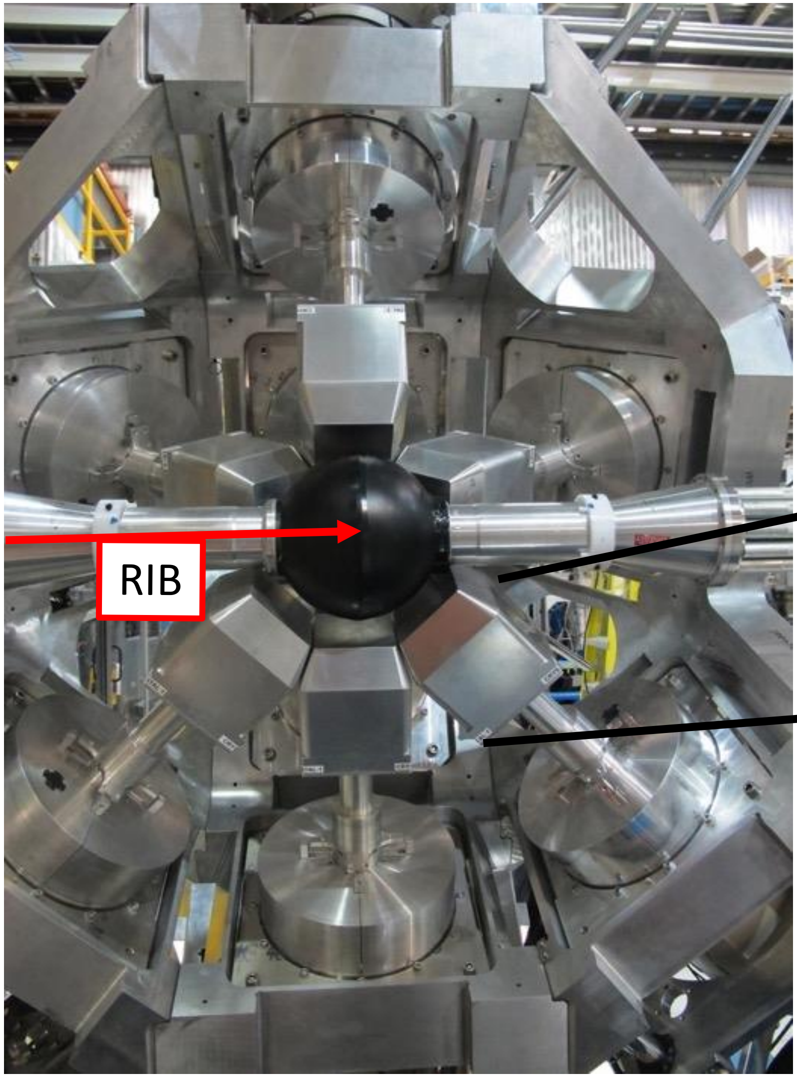


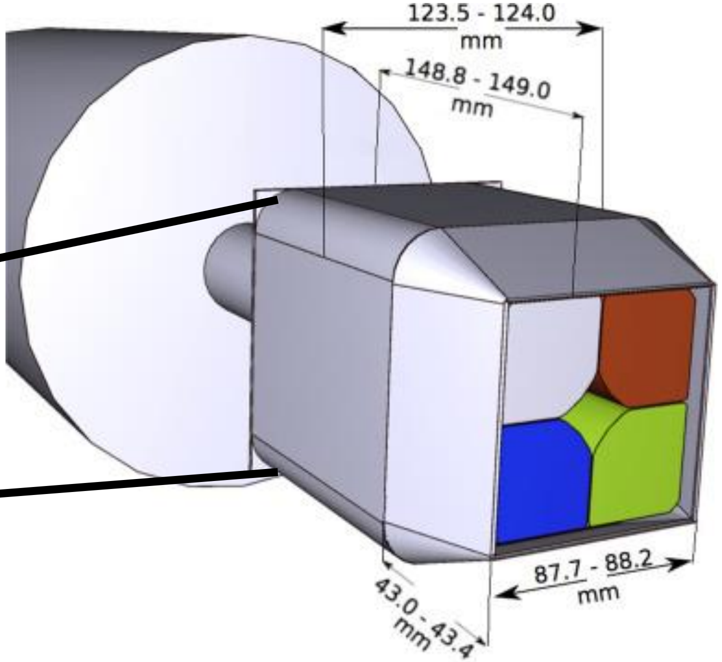
J. Park *et al.*, PRC 96, 014315 (2016).

- Whenever a low energy gamma is emitted, an inner shell atomic orbital can absorb it
- Probability depends on multipolarity of gamma and energy
- Electron emitted with discrete energy
- Si detectors, cooled to reduce electronic noise
- PACES in GRIFFIN, SPEDE in IDS



HPGe clovers

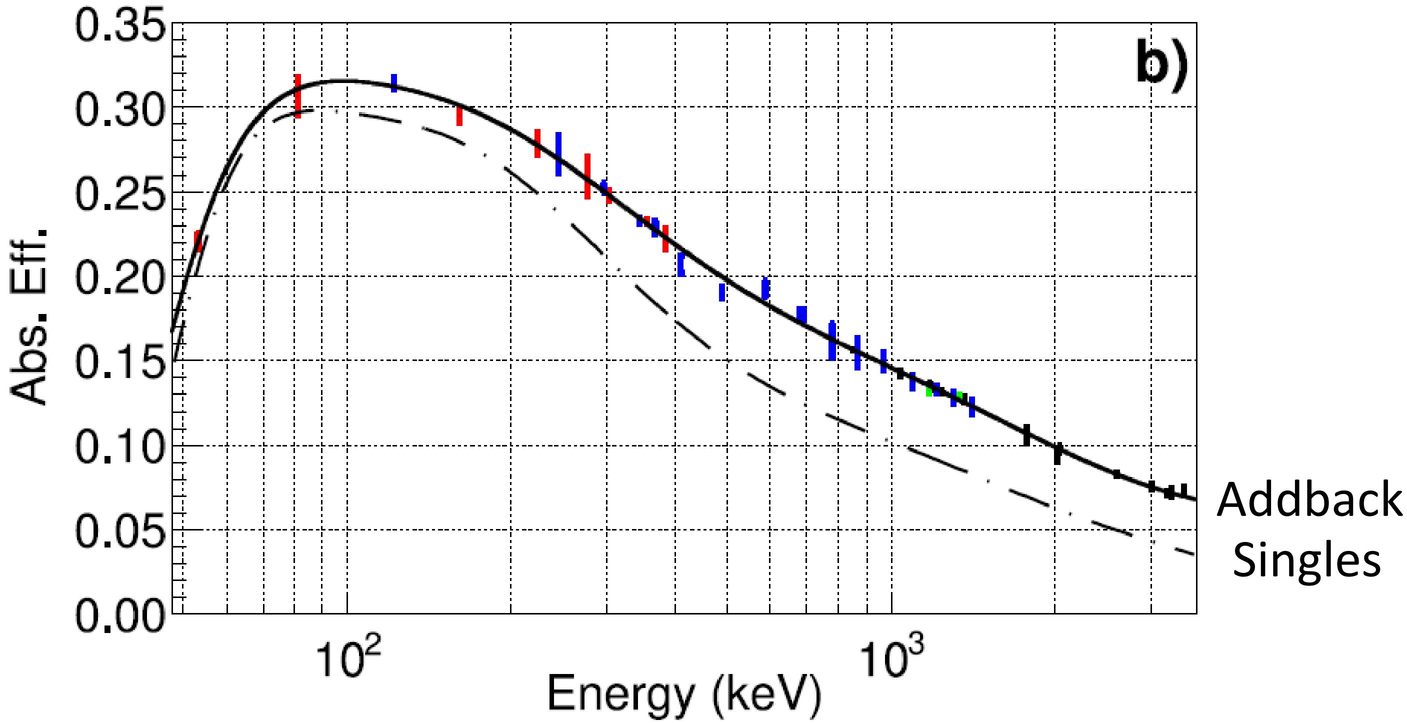




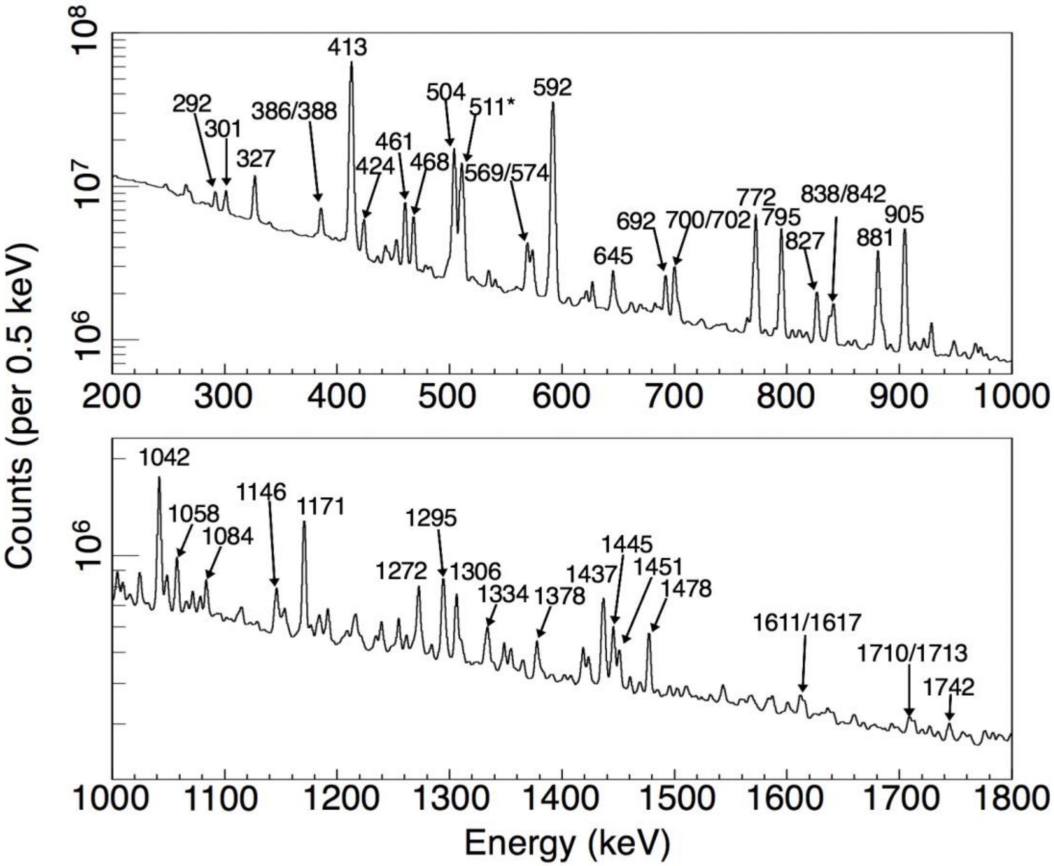
A.B. Garnsworthy, C.E. Svensson, M. Bowry et al. Nuclear Inst. and Methods in Physics Research, A 918 (2019) 9–29

HPGe clovers

- 16 clovers, 4 crystal each, 64 total
- ~30% efficiency at ~120 keV
- Energy resolution@ 1.3MeV = 1.89(6) keV



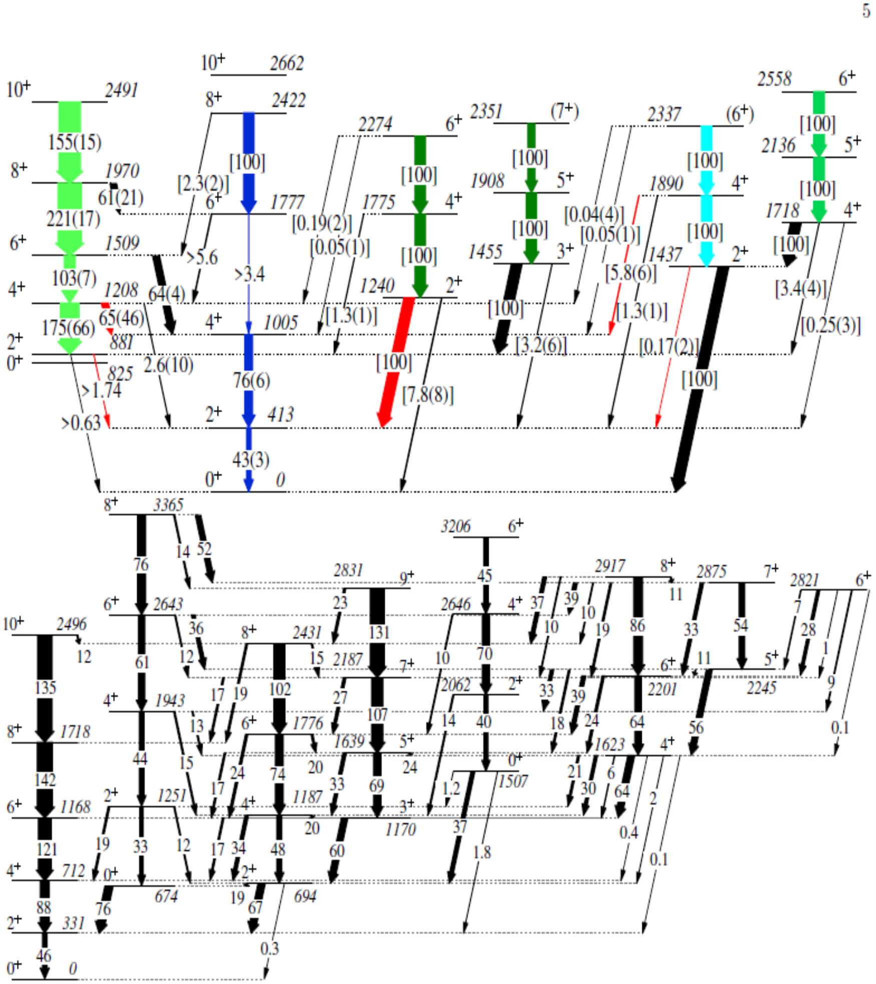
Statistics



- High efficiency allows for high statistics
- Detects more and weaker γ rays
- Wealth of information, but more complex analysis

A. MacLean PhD thesis, UoGuelph 2021

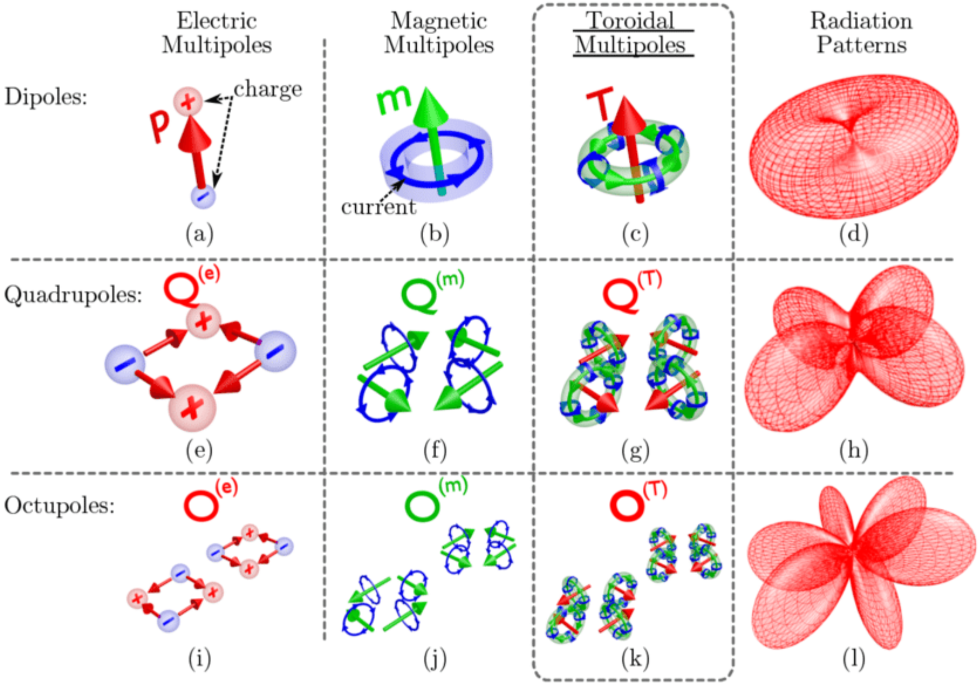
Build complex level scheme



A. MacLean PhD thesis, UoGuelph 2021

- Use γ- γ coincidences to build level scheme
- Coincidences require large statistics and efficiency
- This is a small fraction of a level scheme, can get a lot more complex
- Reveals inner structure of the nucleus

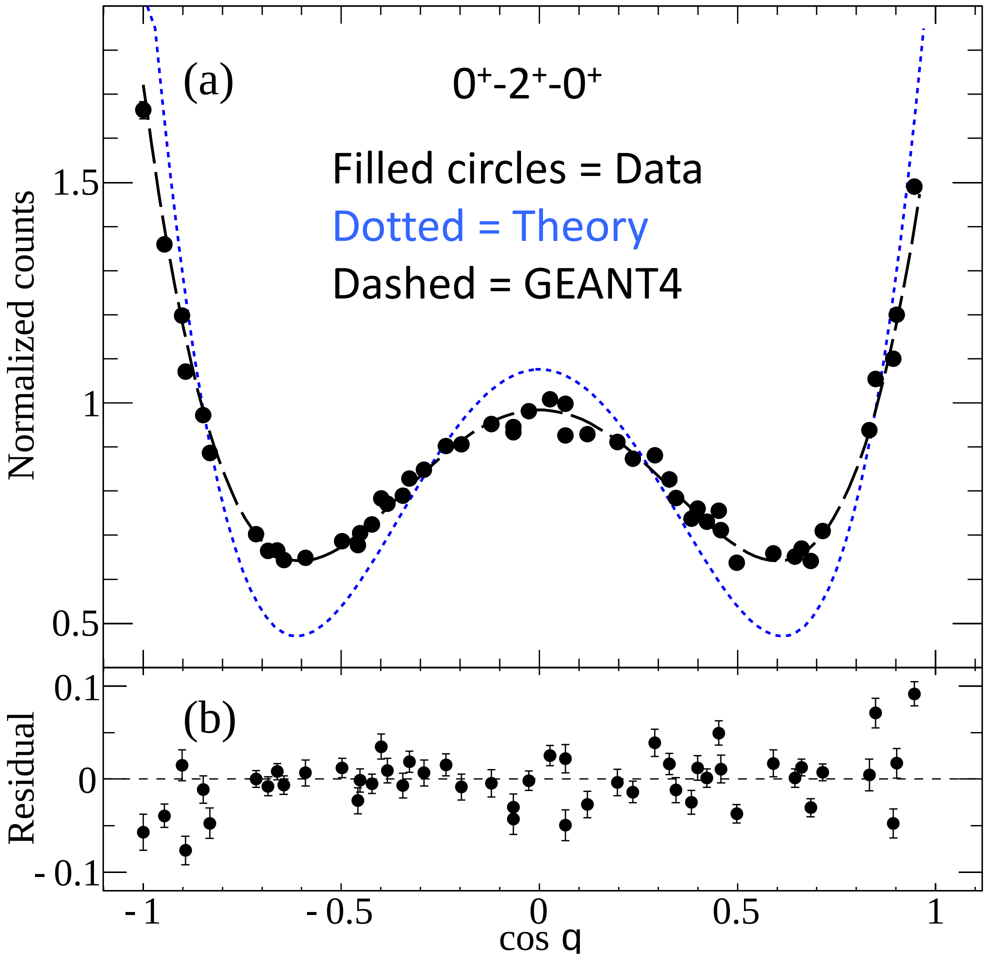
γ emission



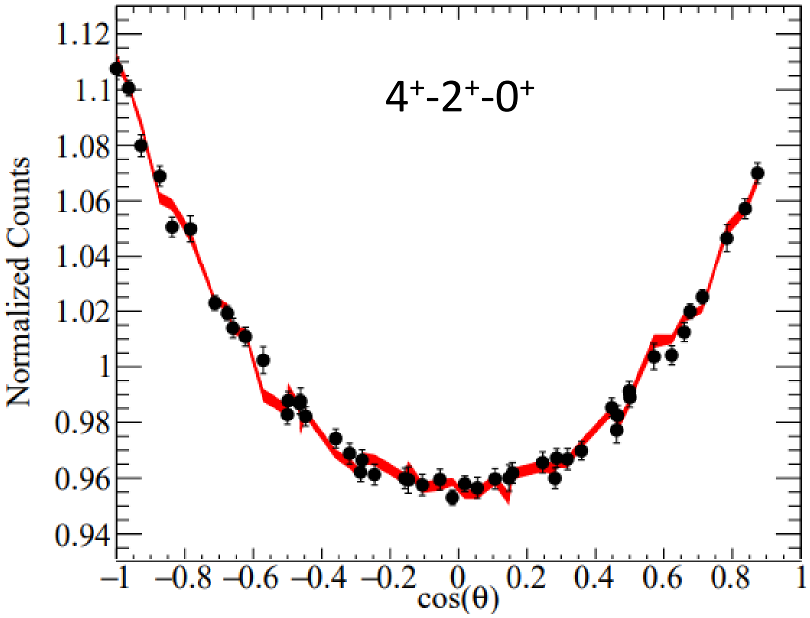
N. Papasimakis Nature Materials volume 15, pages263–271 (2016)

- γ-ray emission is not isotropic
- Different for a dipole than a quadrupole
- Depends on J_i, J_f and E/ML involved
- Powerful tool to firmly assign *J* to levels and E/ML to γ-rays

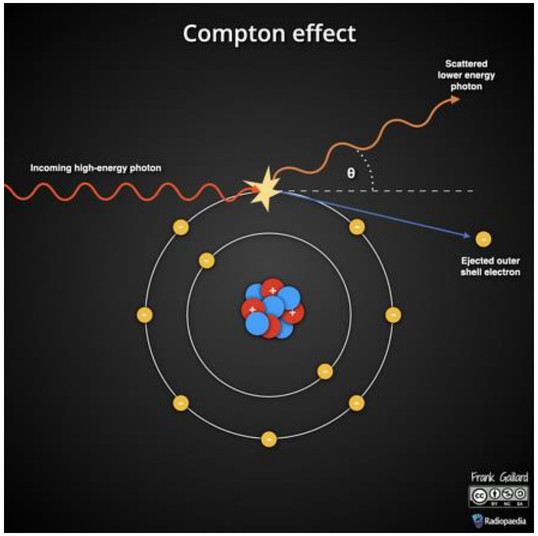
γ-γ angular correlations



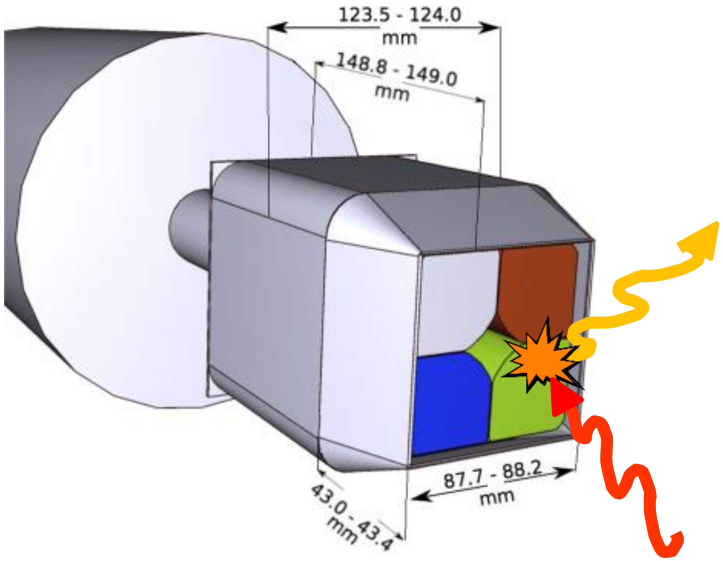
- With 64 crystals, there are 4096 pair combinations
- Very high granularity
- 52 unique angles
- Great angular resolution
- Precise angular correlations

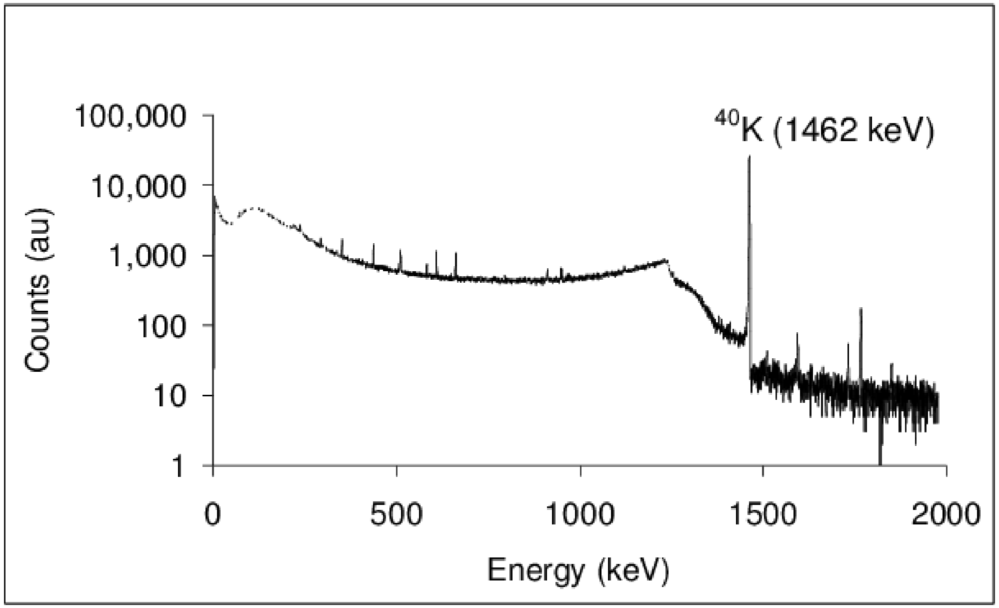


Compton scattering

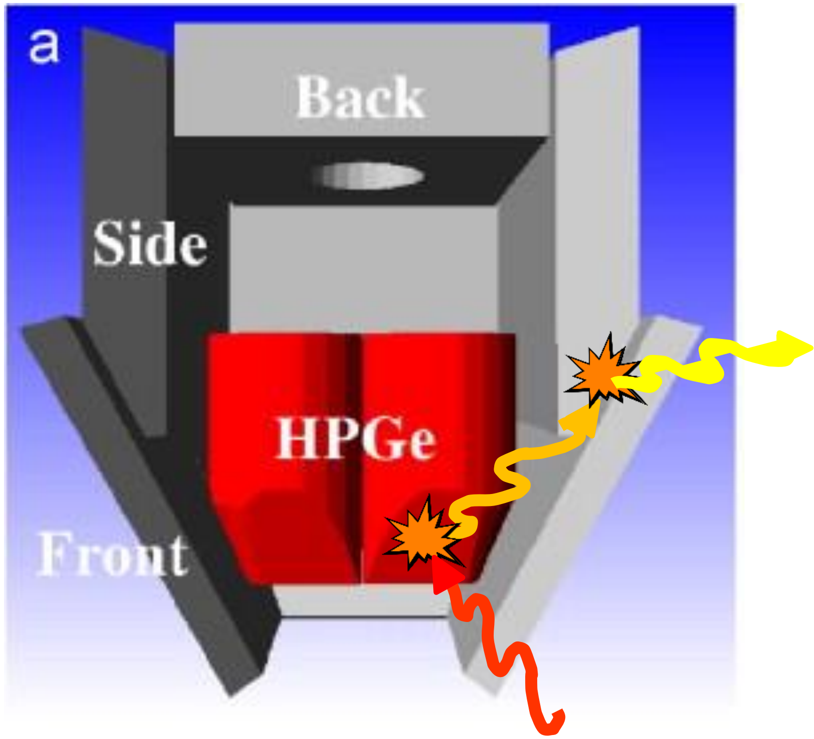


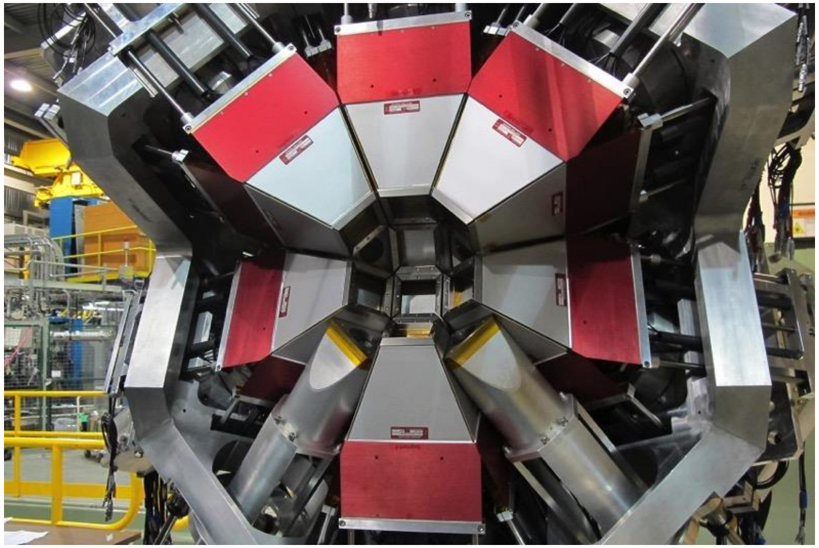
- A photon interacts with an atom depositing a fraction of its energy (not all)
- If after the Compton event, it escapes the detector, we will not detect the full energy
- Compton background difficults measurement of weaker gammas

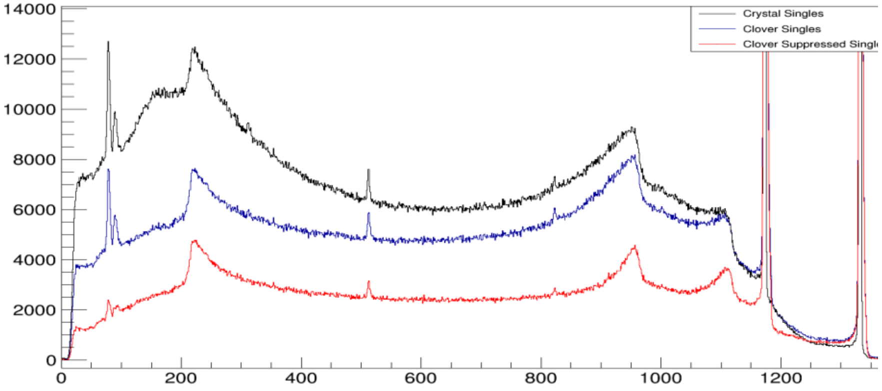


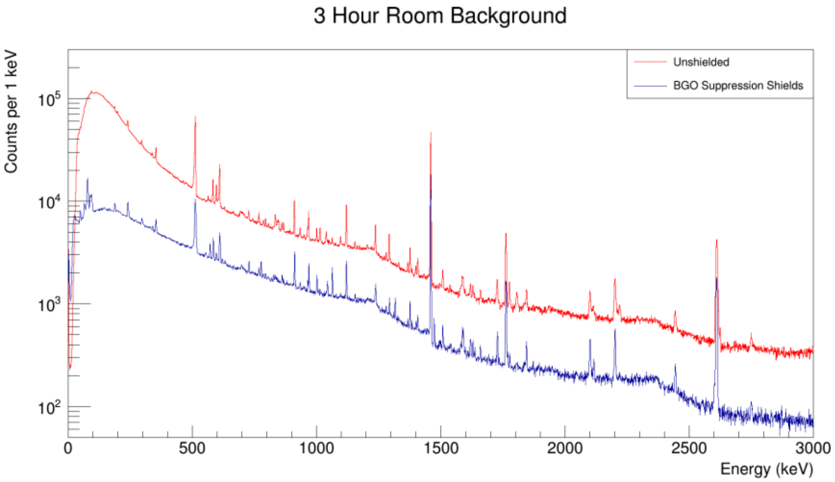


BGO Compton suppressors

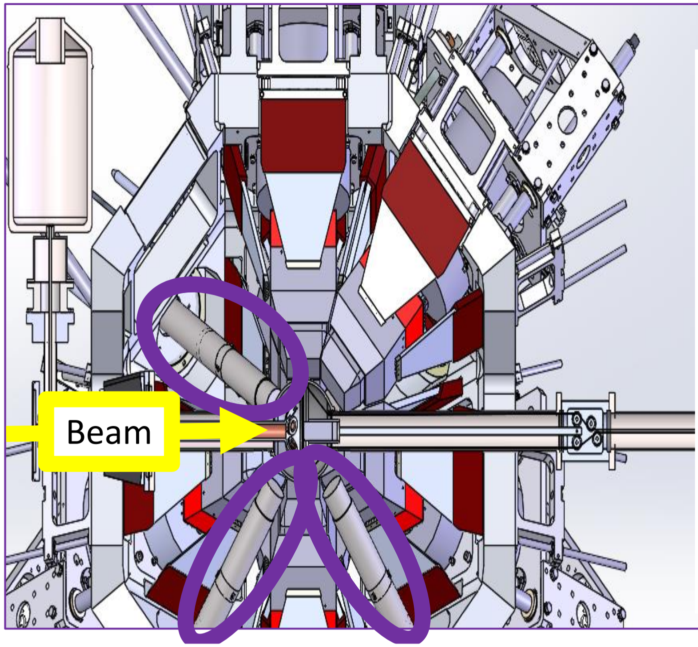


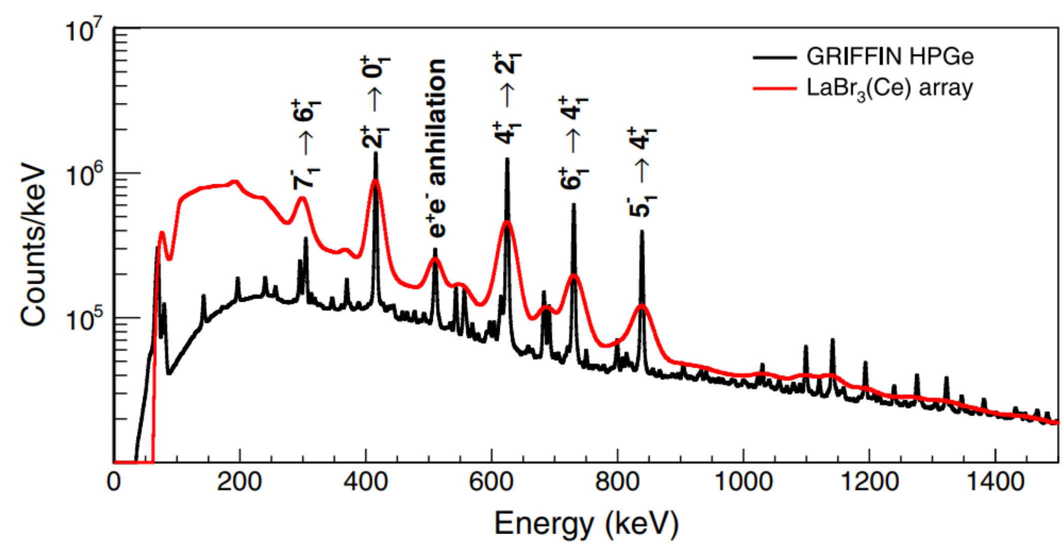


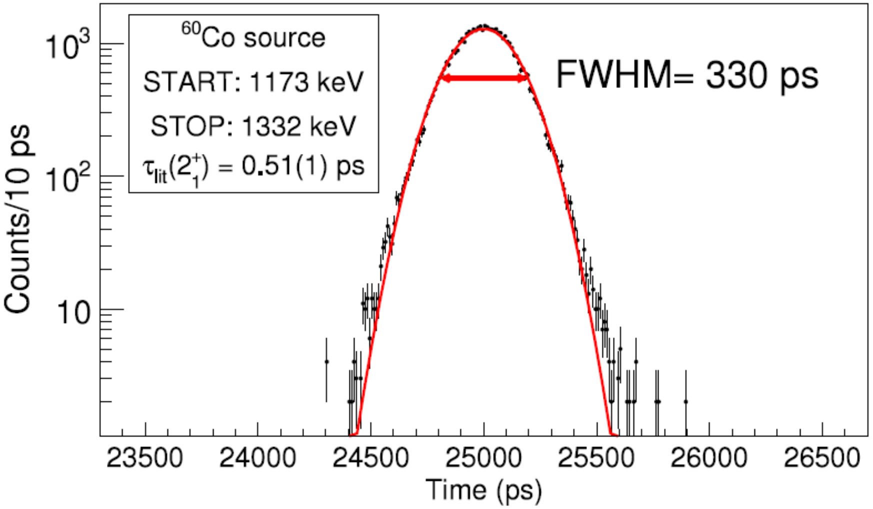




Timing with scintillators

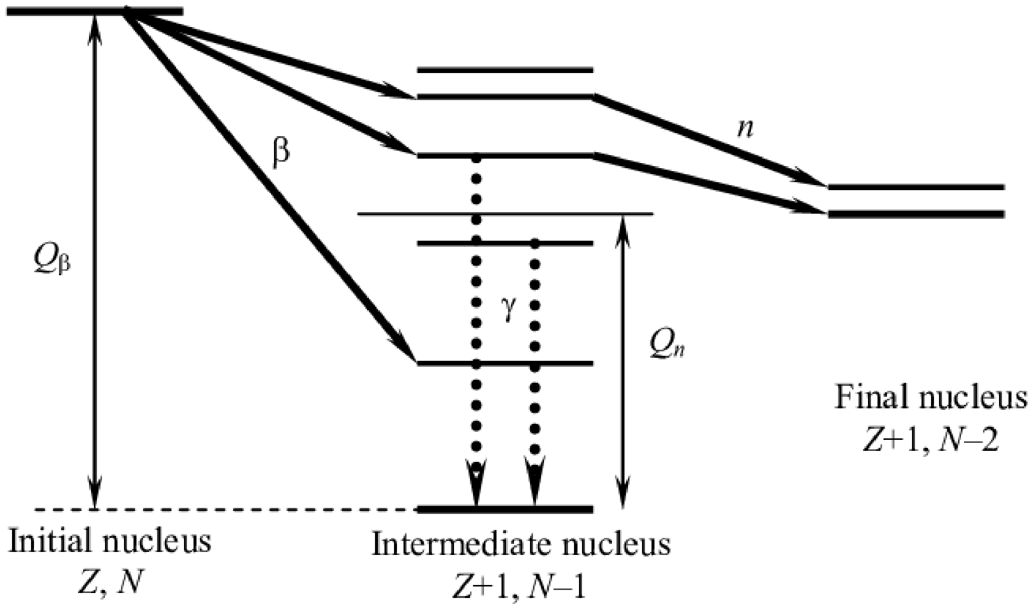






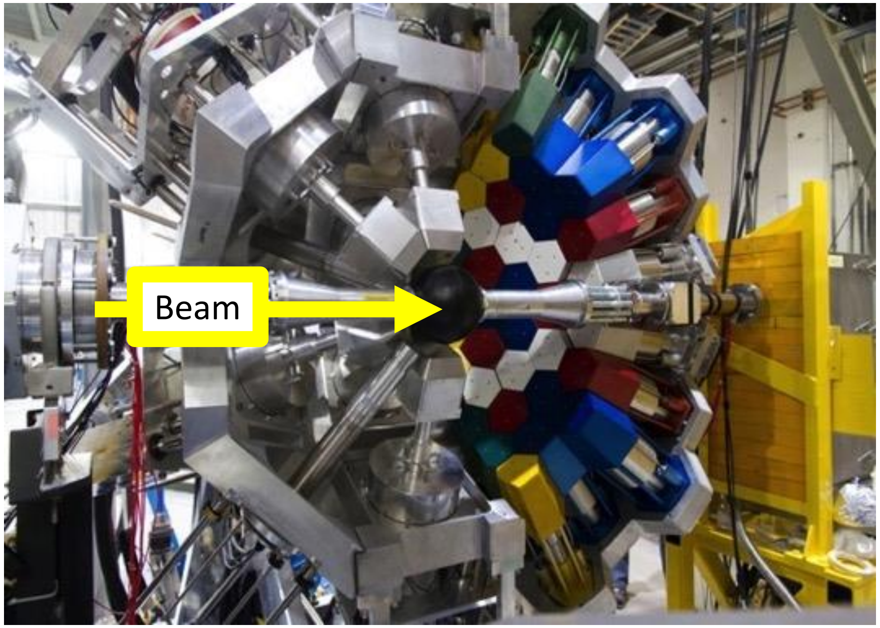
- We can add scintillators, such as LaBr$_3$(Ce)
- Worse energy resolution, superb timing properties
- Lifetime measurements down to ps

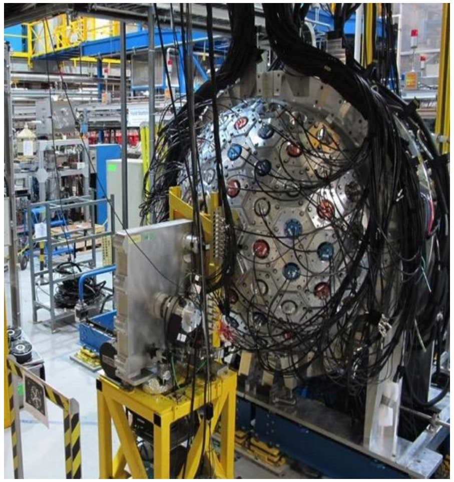
Beta delayed neutron emission



- After a beta decay, the daughter nucleus can be left in a state above the neutron separation energy
- The intermediate nucleus can emit a neutron instead of a gamma.

Neutron measurment



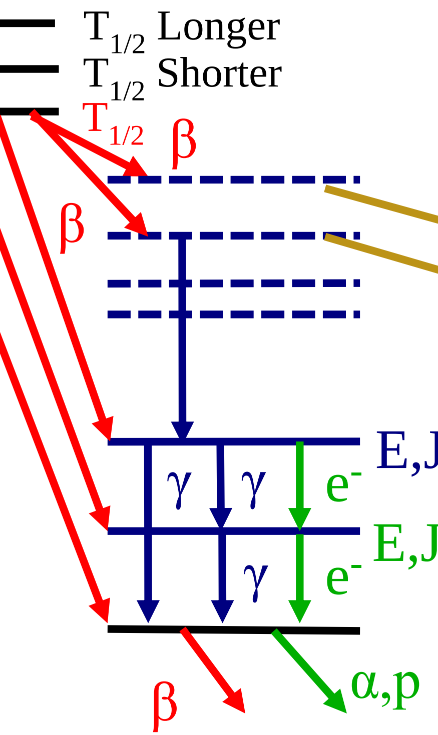


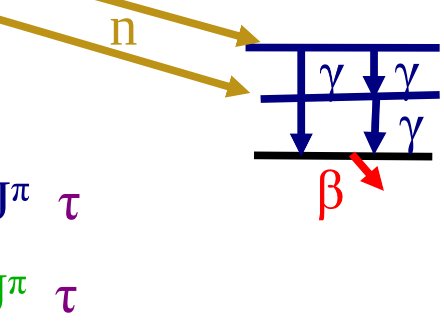
- We can use DESCANT to detect neutrons
- Liquid scintillators
- VANDLE (at ISOLDE) are plastic scintillators strips
- By neutron coincidences, we can distinguish if we are populating the N-1 nucleus or the N-2
- Without neutron detection, is not always trivial

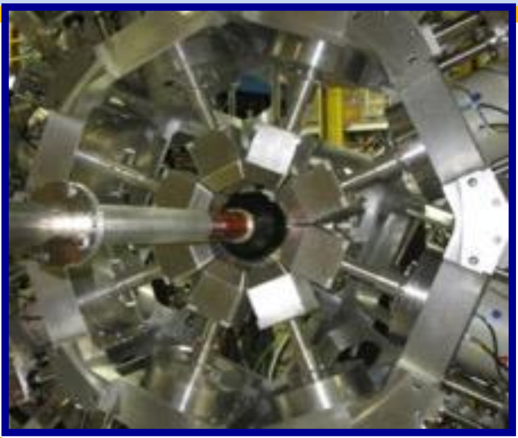
Beta decay experiment

Fast, in-vacuum tape system

Enhances decay of interest







HPGe: 16 Clovers

Detect gamma rays and determines branching ratios, multipolarities and mixing ratios

$LaBr_3$:

8x$LaBr_3$

Fast-timing to measure level lifetimes

SCEPTAR: 10+10 plastic scintillators

Detects beta decays and determines branching ratios

PACES: 5 Cooled Si(Li)s

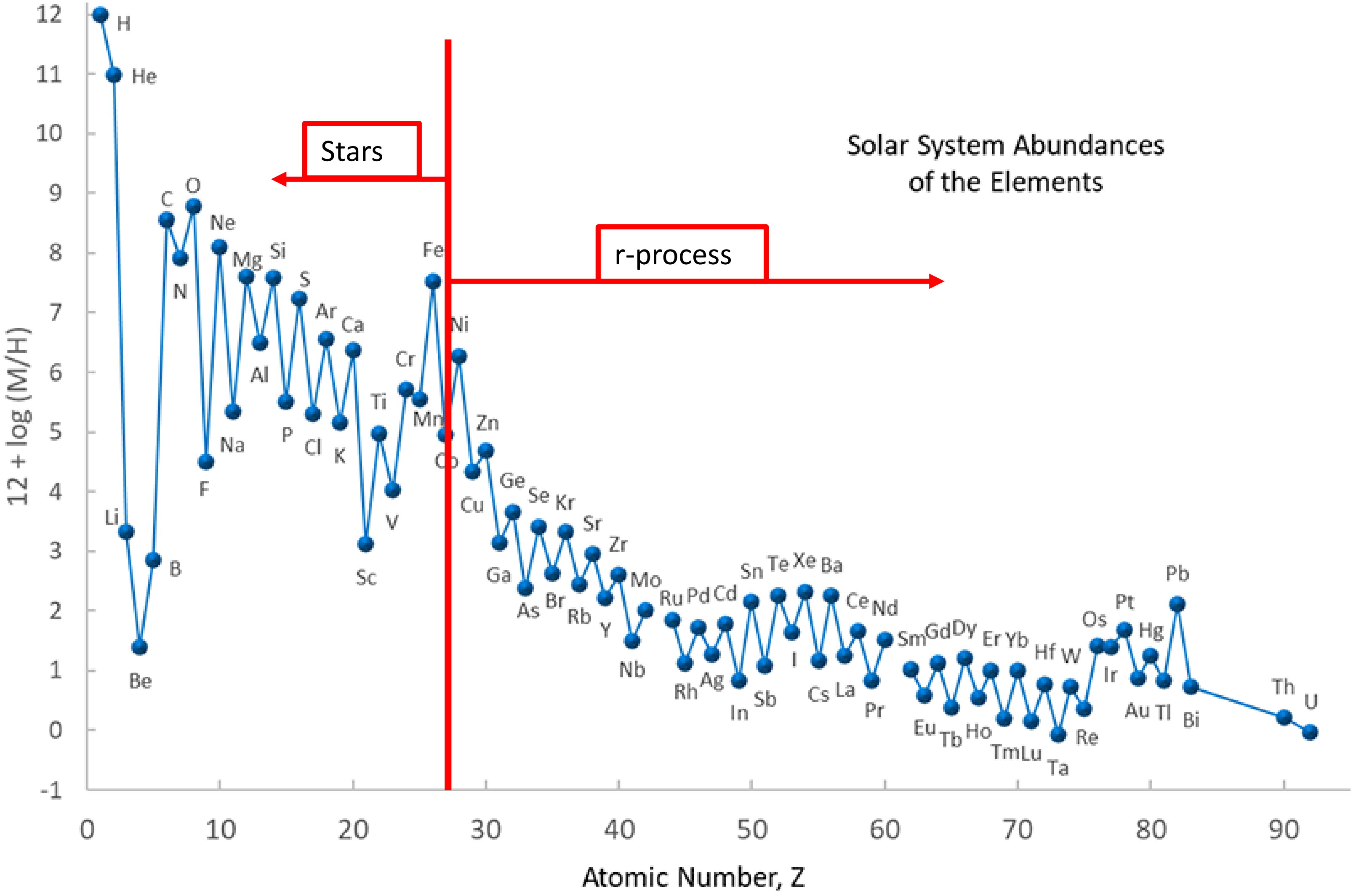
Detects Internal Conversion Electrons and alphas/protons

Beta decay experiment

Nuclear structure

- Measure beta decay half-life
- Construct level scheme with γγ coincidences
- Assign J^{π} to excited states using:
  - Log(ft) from beta decay
  - γγ angular correlations
  - α from conversion electrons
  - B(XL) from lifetime measurements
- Firmly assigning J^{π} is key to understand the structure of a nucleus
- **NOTE:** none of this techniques is exclusive from beta decay experiments, but, in general, it would be the simplest and cleanest experiment to use them

Beta decay experiment

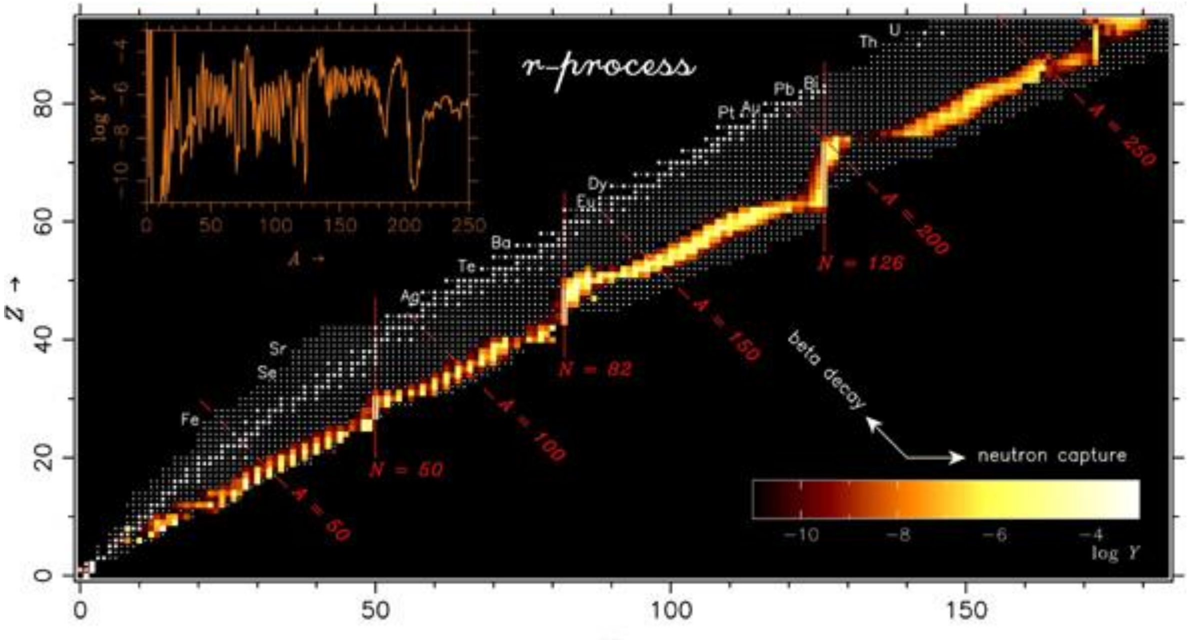


Stars

r-process

Solar System Abundances of the Elements

r-process

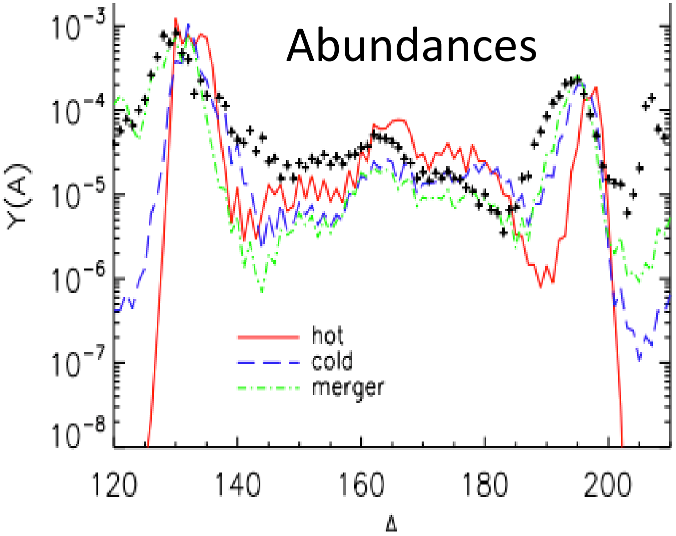


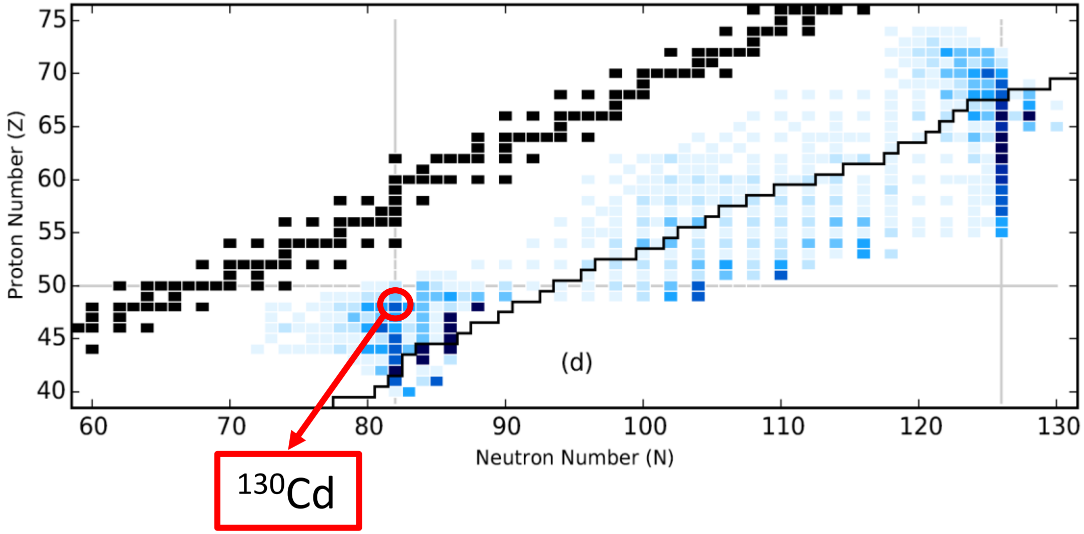
- Rapid neutron-capture process
- Supernovae explosions
- Competition between beta decay and neutron absorption
- Most relevant observables:
  - Beta decay half life (g.s. and isomers)
  - Neutron emission
  - Neutron capture cross section

http://www.ph.sophia.ac.jp/~shinya/research/research.html

Half-Lives of Neutron-Rich $^{128\text{-}130}$Cd

Nuclei near N = 82 are responsible for the A ~ 130 r-process abundance peak. These ‘waiting point’ nuclei are important in calculations of all astrophyical environments.

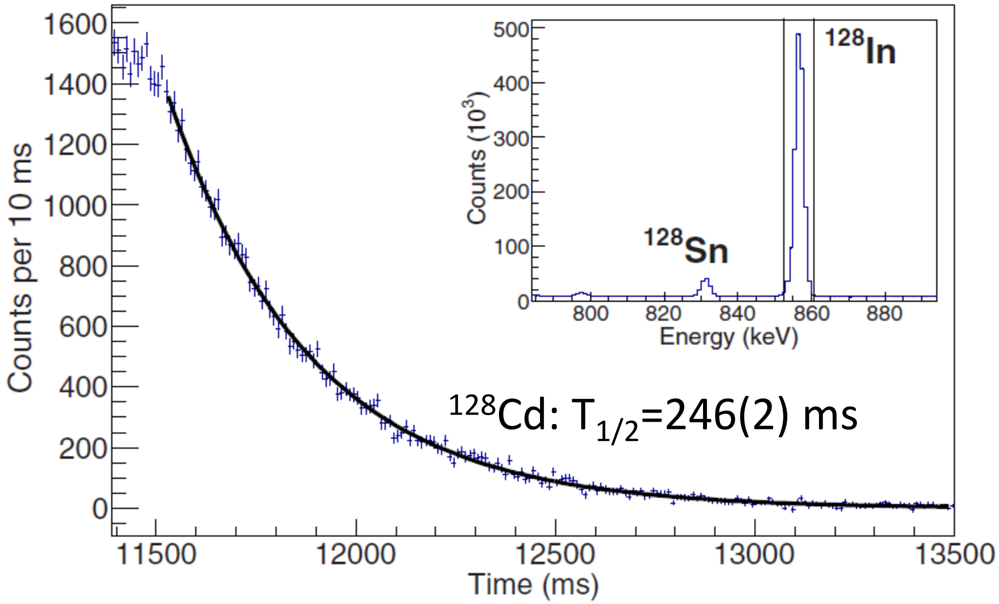


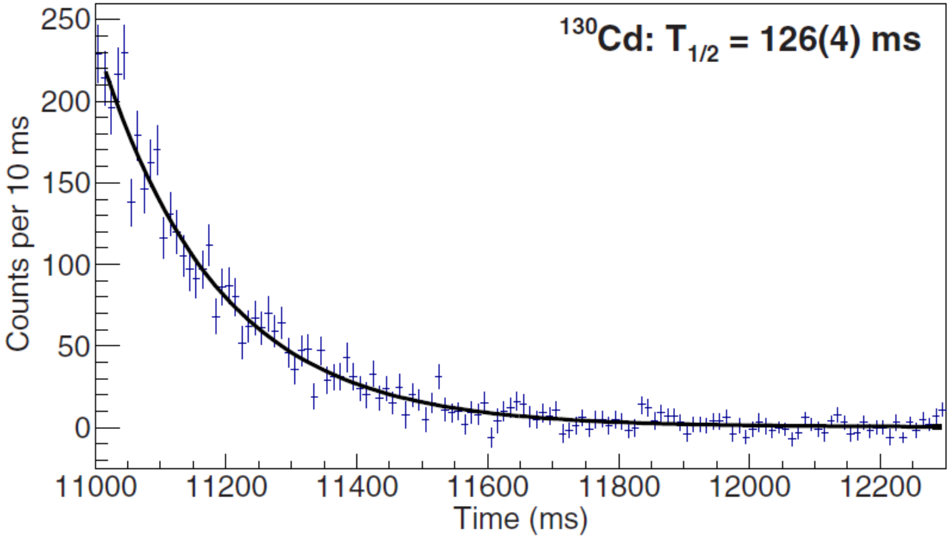


^{130}Cd

G. Lorusso et al. PRL 114 192501 (2015)
M. Mumpower et al., Prog. Part. Nucl. Phys. 86, 86 (2016)

Half-Lives of Neutron-Rich $^{128\text{-}130}$Cd

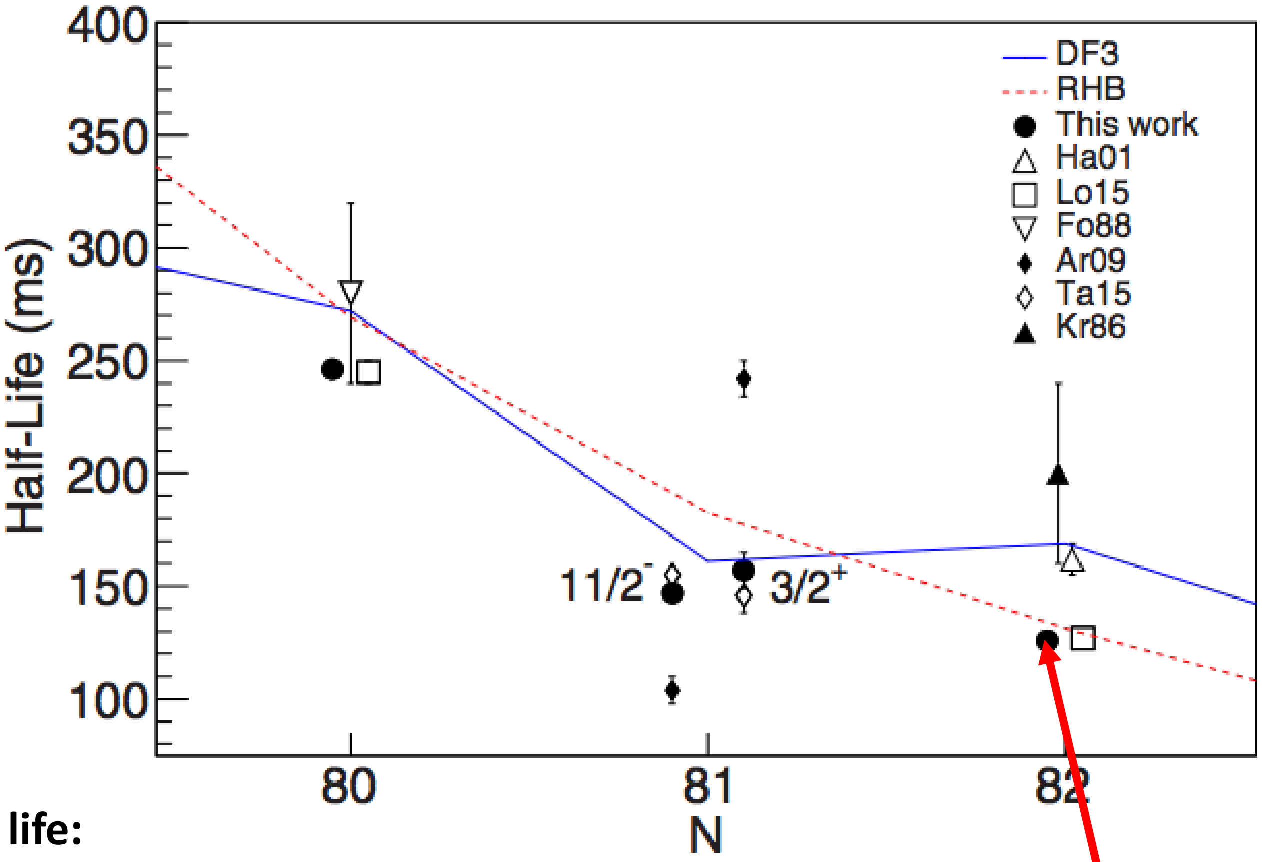




- Lifetimes were measured in β-γ coincidences
- HPGe gate cleans the spectra
- Lifetime is extracted from SCEPTAR (β) activity

R. Dunlop et al., PRC 93, 062801(R) (2016).

Beta decay experiment



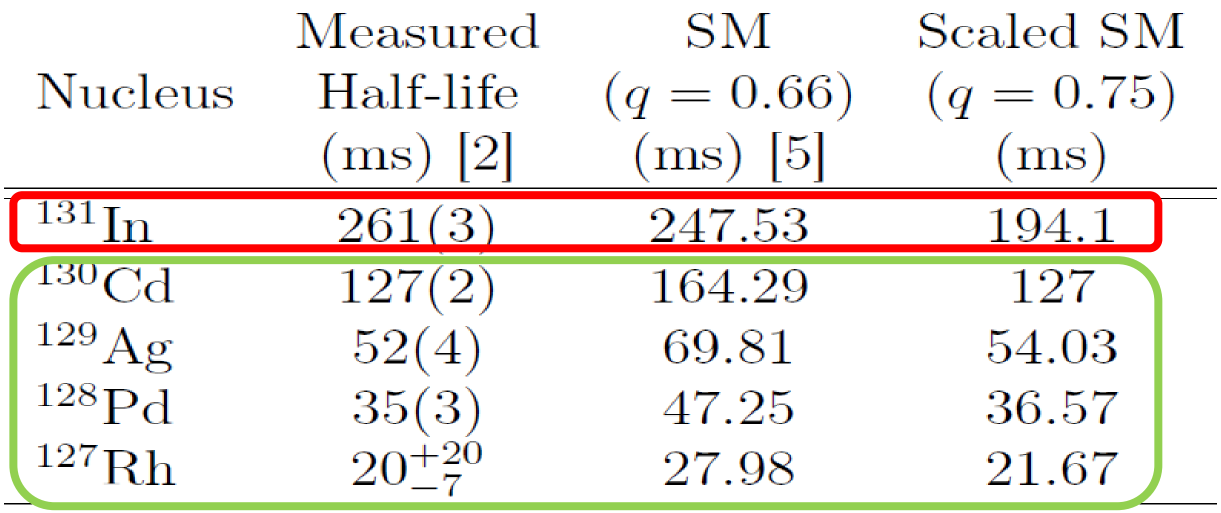
This work

^{130}Cd half life:

195 (35) ms K.-L. Kratz *et al.*, Z. Phys.A325, 489 (1986).
162 (7) ms M. Hannawald *et al.*, NPA 688, 578 (2001).

127 (2) ms G. Lorusso *et al.* PRL 114 192501 (2015).
126 (4) ms R. Dunlop *et al.*, PRC 93, 062801(R) (2016).

SM half-lives prediction below N=82



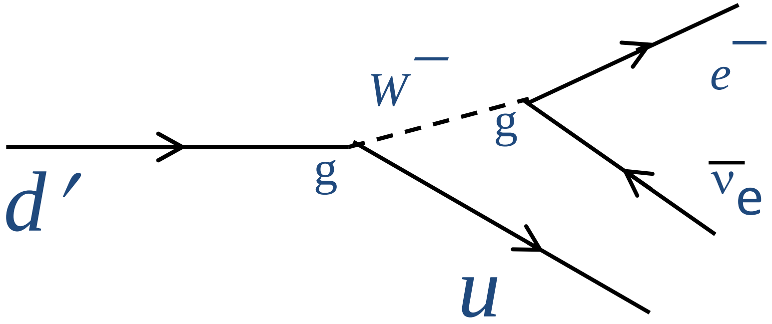
Nucleus	Measured Half-life (ms) [2]	SM ($q = 0.66$) (ms) [5]	Scaled SM ($q = 0.75$) (ms)
^{131}In	261(3)	247.53	194.1
^{130}Cd	127(2)	164.29	127
^{129}Ag	52(4)	69.81	54.03
^{128}Pd	35(3)	47.25	36.57
^{127}Rh	20^{+20}_{-7}	27.98	21.67

- Previous SM prediction were ~25% off
- New quenching precisely reproduces lifetimes
- Affects the N=82 waiting point and the A~130 peak abundance
- Creates significant discrepancy for ^{131}In
- R. Dunlop *et al.* Phys. Rev. C **93**, 062801(R) (2016)

The Standard Model of particle physics

The CKM matrix plays a central role in the Standard Model and underpins all quark flavour-changing interactions:

→ weak interaction eigenstates ≠ quark mass eigenstates



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

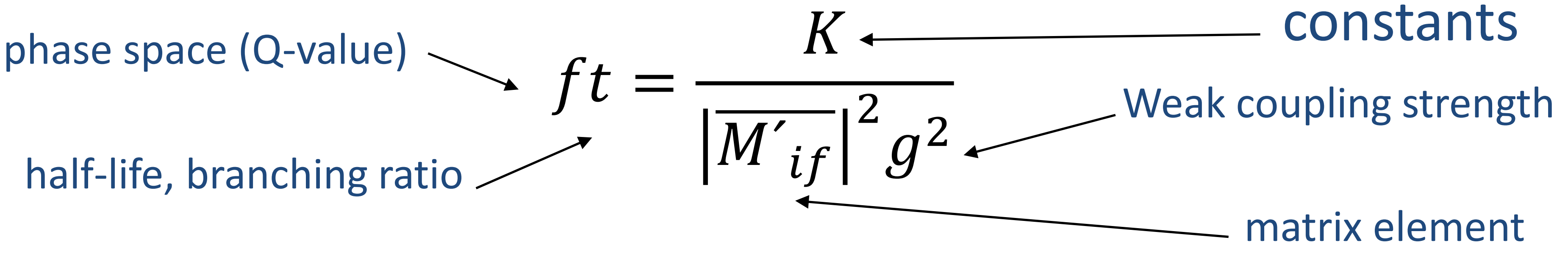
$$|d'\rangle = V_{ud}|d\rangle + V_{us}|s\rangle + V_{ub}|b\rangle$$

In the Standard Model the CKM matrix describes a unitary transformation:

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1$$

The first row of the CKM matrix provides the most demanding experimental test of the unitarity condition.

Superallowed Fermi β Decay



phase space (Q-value)

half-life, branching ratio

$$ft = \frac{K}{\left|\overline{M'_{if}}\right|^2 g^2}$$

constants

Weak coupling strength

matrix element

For the special case of $0^+ \rightarrow 0^+$ (pure Fermi) β decays between isobaric analogue states (superallowed) the matrix element is that of an isospin ladder operator:

$$|M_{fi}|^2 = (T - T_Z)(T + T_Z + 1) = 2 \quad \text{(for } T=1\text{)}$$

Strategy: Measure superallowed ft-values, deduce G_V and V_{ud}:

$$ft = \frac{K}{2\,G_V^2}$$

$$|V_{ud}| = G_V / G_F \leftarrow$$

Fermi coupling constant

Vector coupling constant

Superallowed Fermi β Decay

$$Ft = ft\left(1+\delta'_{\mathrm{R}}\right)\left(1+\delta_{\mathrm{NS}}-\delta_{\mathrm{C}}\right) = \frac{K}{2G_{\mathrm{V}}^{2}\left(1+\Delta_{\mathrm{R}}^{\mathrm{V}}\right)} = \text{constant}$$

“Corrected”
ft value

Experiment

Calculated corrections (~1%)
(nucleus dependent)

Inner radiative correction (~2.4%)
(nucleus independent)

CVC Hypothesis

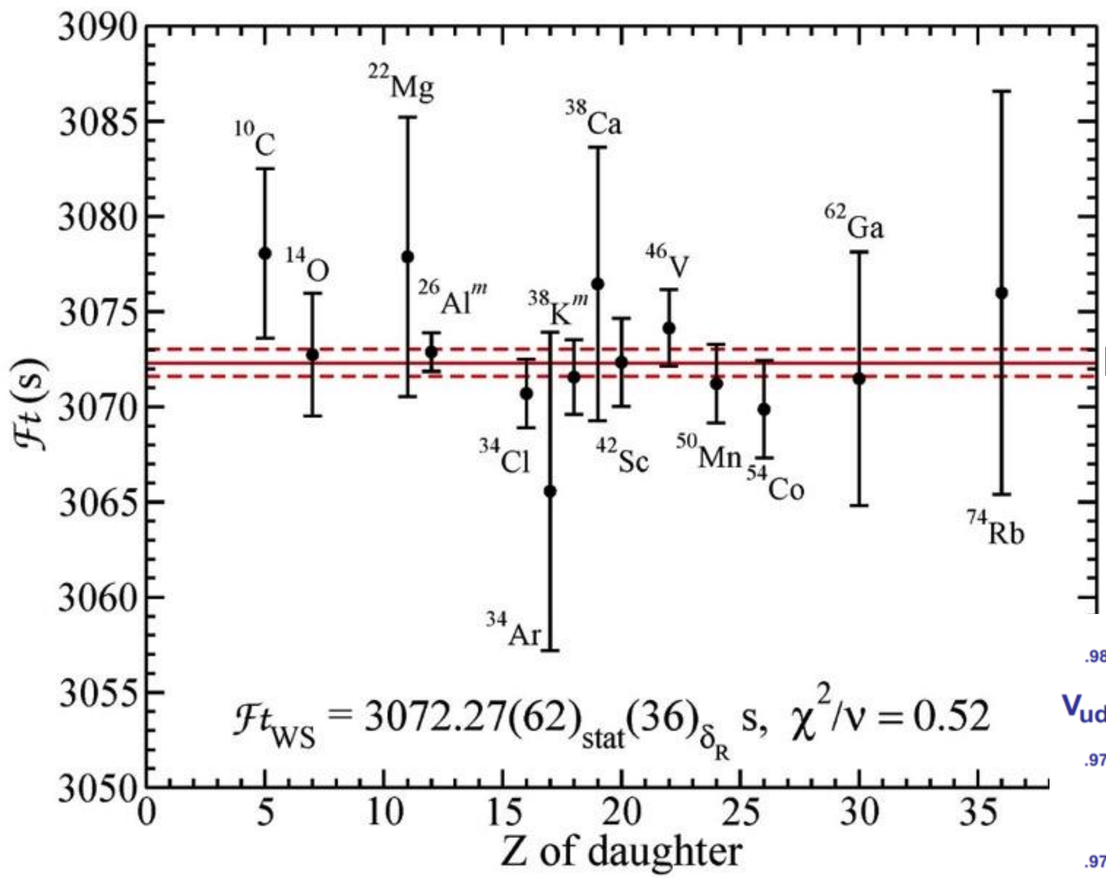
$\Delta_{\mathrm{R}}^{\mathrm{V}}$ = nucleus independent inner radiative correction: 2.361(38)%

δ_{R} = nucleus dependent radiative correction to order $Z^2\alpha^3$: ~1.4%
- depends on electron’s energy and *Z* of nucleus

δ_{NS} = nuclear structure dependent radiative correction: -0.35% – 0.05%

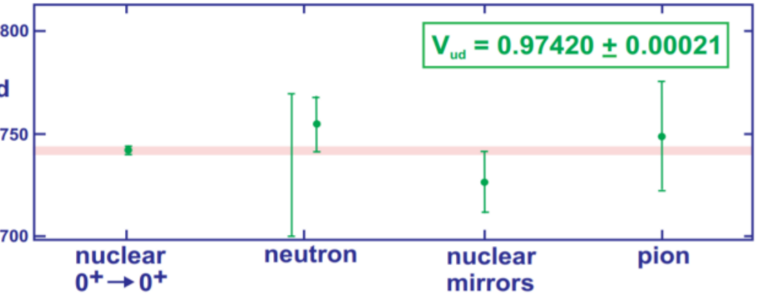
δ_{C} = nucleus dependent isospin-symmetry-breaking correction: 0.2% – 1.6%
- strong nuclear structure dependence

Superallowed Fermi β Decay

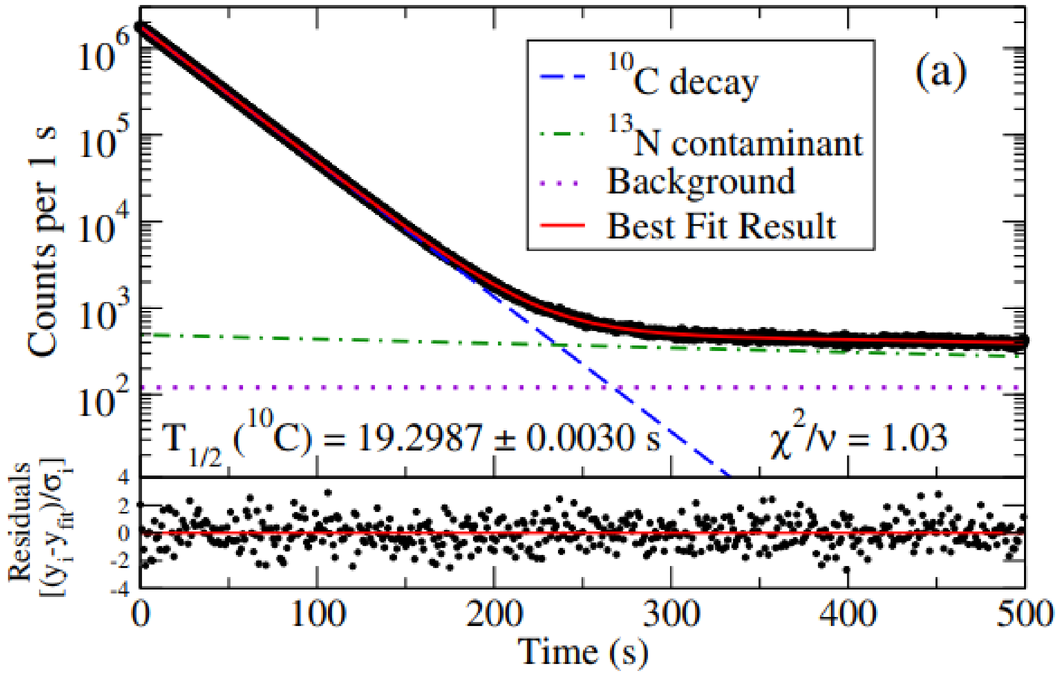


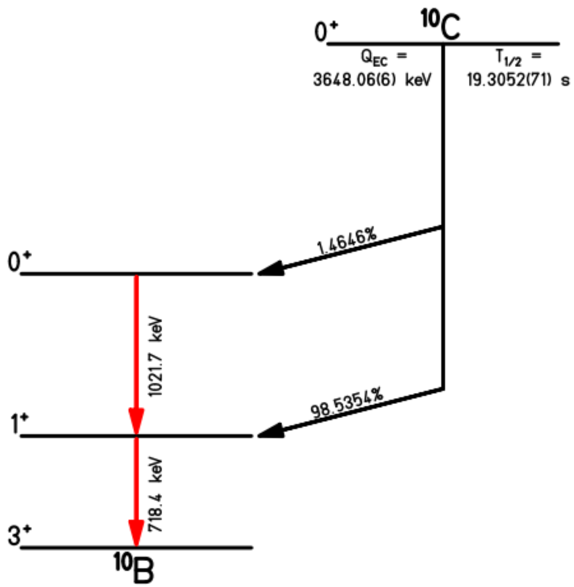
$|V_{ud}| = 0.97417 \pm 0.00021$

Hardy and Towner,
Phys. Rev. C ***91****, 025501 (2015)*



Beta decay experiment





- The job of nuclear physics is to precisely measure Q_β, $T_{1/2}$ and branching ratio
- Extract Ft better than 1 part in 10^4
- If $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \neq 1$ would imply physics beyond the standard model

M. R. Dunlop et al. Phys. Rev. Lett. 116, 172501 (2016)

Beta decay experiments

- One of the cleanest and most precise probes we have in nuclear physics
- Versatile experiments able to measure multiple observables simultaneously
- Relevant for astrophysics
- Powerful tool to search for physics beyond the Standard Model

Useful References

Books

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- ✓ G. Benzoni, Eur. Phys. J plus 131 (2016) 99
- ✓ A. Algora et al., Eur. Phys A 57 (2021) 85
- ✓ École Joliot-Curie de Physique Nucleaire, 2002

Bibliography courtesy of MJ Borge

Plenty of information available on the Web

Any questions?

Beta decay experiment