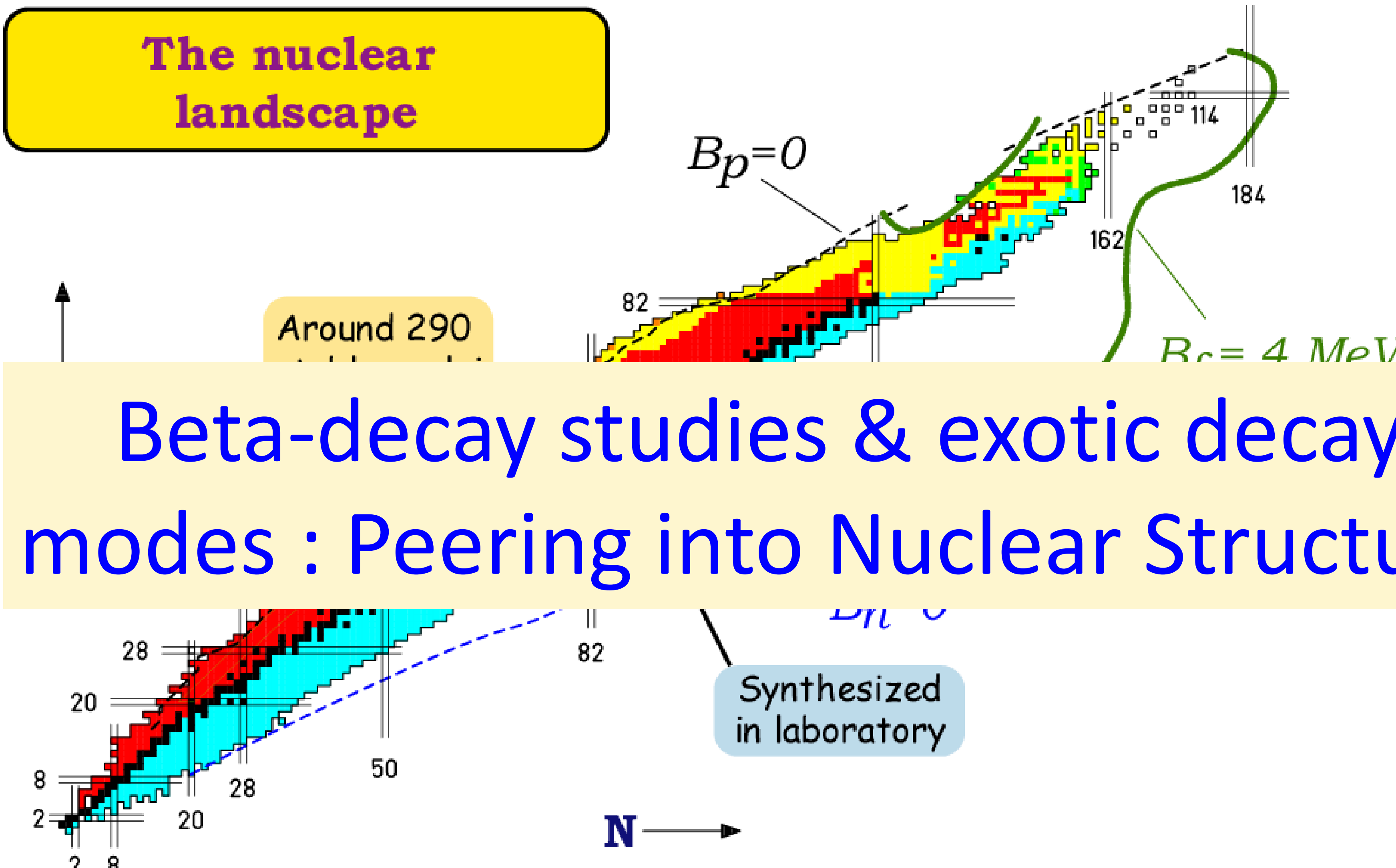
Beta-decay studies & exotic decay modes : Peering into Nuclear Structure



Useful References

Books

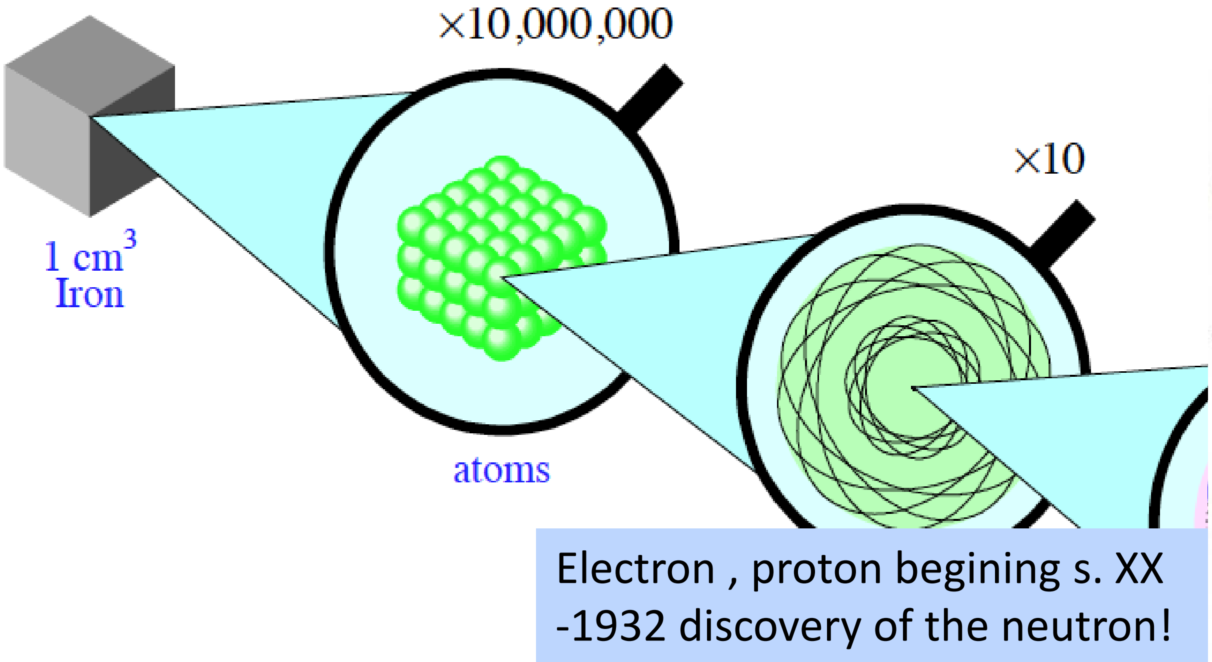
- ✓ "Handbook of nuclear spectroscopy", J. Kantele, 1995
- ✓ "Radiation detection and measurements", G.F. Knoll, 1989
- ✓ "Alpha-, Beta- and Gamma-ray Spectroscopy", Ed. K. Siegbahn, 1965
- ✓ "Introductory Nuclear Physics", K. S. Krane, 1988
- ✓ "Basic Ideas and Concepts in Nuclear Physics" K. Heyde IOP Publ. Ltd. 1994
- ✓ "Particle Emission from Nuclei" Ed. D.N. Poenaru & M.S. Ivaçcu CRD 1989 Vol I, II, III

Journal Articles

- ✓ Euroschool on Exotic Beams, Lectures Notes: "Decay Studies of N~Z Nuclei", E. Roeckl, Vol I, "Beta "Decay of exotic Nuclei", B. Rubio & W. Gelletly, Vol III
- ✓ B. Blank and M.J.G. Borge, Prog Part and Nuc. Phys 60 (2008) 403
- ✓ M. Pfützner, L.V. Grigorenco, M. Karny & K. Riisager, Rev. Mod. Phys,ArXiV:1111.0482
- ✓ V.I. Goldanskii , Ann. Rev. Nucl. Sci. 16 (1966)1
- ✓ P.I. Woods, C.N. Davids, Ann.Rev.Nucl.Part.Sci 47 (1997)541
- ✓ P. Buford Price, Ann.Rev.Nucl.Part.Sci. **39** (1989) 19

Plenty of information available on the Web

The structure of the Matter

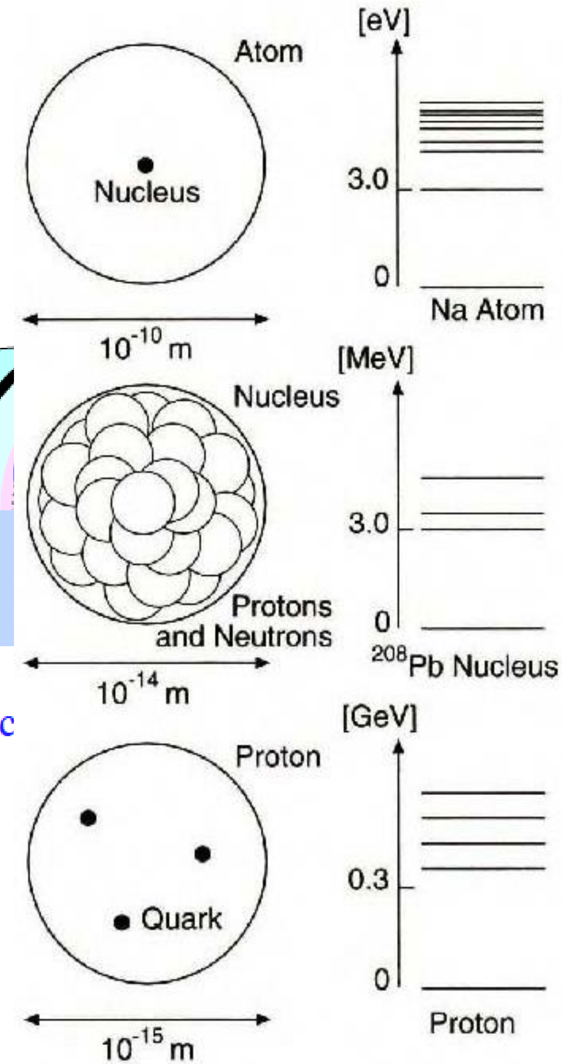


Electron , proton begining s. XX
-1932 discovery of the neutron!

- 1 cm^3 Iron = 7.9 g
  - 85,000,000,000,000,000,000,000 atoms !
  - 99.9999999999% of matter is empty !
  - 1 cm^3 of nuclei = 300 million tons !

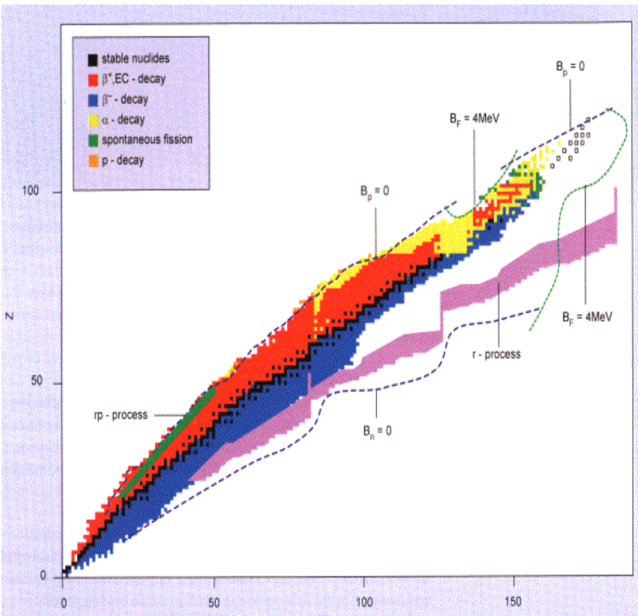
50/60's Accelerators➔ hadron zoo(100)
Hadrons combination of 2-3 quarks

Energy Scale!



Atomic Mass Model

Relationship with Nuclear Decay Models



- **265 Stable nuclei**
  - **157 e-e**
  - **4 o-o**
  - **104 e-o**

  60 radioactive ($T_{1/2}$ > 109y)

~ 2200 produced in nuclear reactions

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

- **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

Binding Energy (I)

- Strong interaction acts at very short distance.
- Naively one would expect A(A-1)/2 bonds and each E_{bond} ~constant thus giving:

  BE($^{A}_{Z}X_{N}$)/A $\propto E_2$ (A-1) / 2

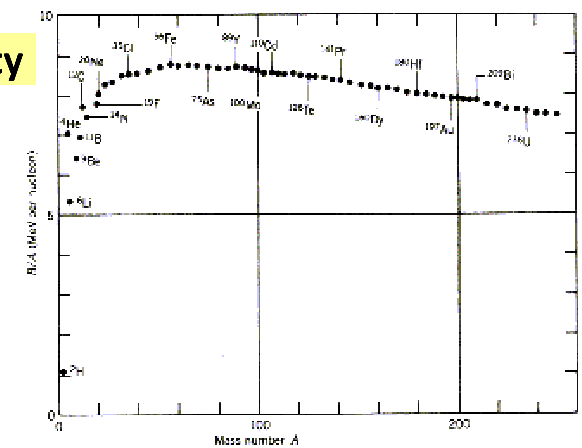
- Experimentally **BE($^{A}_{Z}X_{N}$)/A** $\propto$ 8 MeV over the full region indicating
  - Nuclear and charge independent
  - Saturation of Nuclear Forces: $\rho_o \approx 0.17$ N/fm^3
  - The less bound nucleon has an energy of ~ 8 MeV independent of the number of nucleons

  → **The independent particle picture holds : nucleons move in an average potential**

Nuclear density is independent of A and 10^{14} times normal density

- **BE/A as function of A has its maximum around A = 56-60 (^{62}Ni)**

  → Source of energy production
  - **Fission of heavy nuclei**
  - **Fusion of light nuclei**



Nuclear stability

$BE(A,Z) = ZMpc^2 + NMnc^2 – M'({}^A{}_Z X_N)c^2$

Using the Bethe-Weizsäcker mass equation for BE(A,Z)

$$M'({}^A{}_Z X_N)c^2 = ZMpc^2 + NMnc^2 - a_v A + a_s A^{2/3} + a_c Z(Z-1)A^{-1/3} + a_A (A-2Z)^2/A - a_p A^{-1/2}$$

For each A value this represents a quadratic equation in Z

$$M'({}^A{}_Z X_N)c^2 = xA + yZ + zZ^2 + 0(\pm\delta)$$

$$x = Mnc^2 - a_v + a_A + a_s A^{1/3}$$

$$y = (Mp-Mn)c^2 - 4a_A - a_c A^{1/3}$$

$$z = a_c A^{1/3} + 4a_A/A$$

$$\frac{\partial M'}{\partial Z} = 0$$

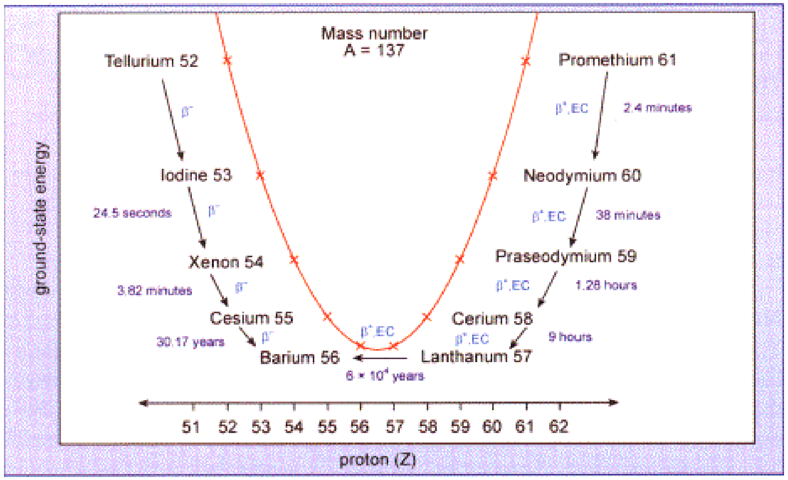
$$Z_0 \approx \frac{A/2}{1+0.007A^{2/3}}$$

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.

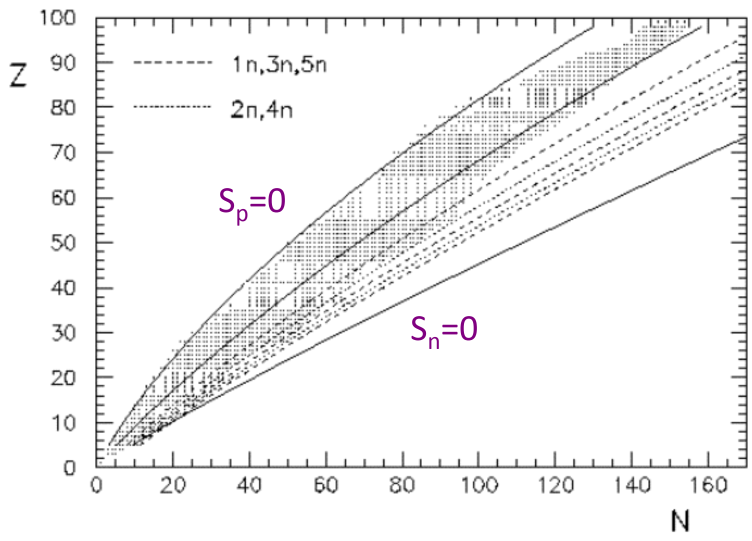
odd-A only one stable nucleus. The rest $\beta^{\pm}$ decay towards the only stable nucleus.

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



Stability Against Radioactive Decay

Last stable nuclei A≈210



Spontaneus α-decay ($S_\alpha = 0$) correspond to

$BE({}^{A}_{Z}X_{N}) - [\, BE({}^{A-4}_{Z-2}X_{N-2}) + BE({}^{4}He)\,] = 0$

The half-lives becomes short in the actinide region A ≈ 210

The conditions $S_n = 0$ and $S_p = 0$ establishes the drip-lines

The energy release in nuclear fission:

$$E_{fission} = M^1\left({}^{A}_{Z}X_N\right)c^2 - 2M'\left({}^{A/2}_{Z/2}X_{N/2}\right)c^2$$

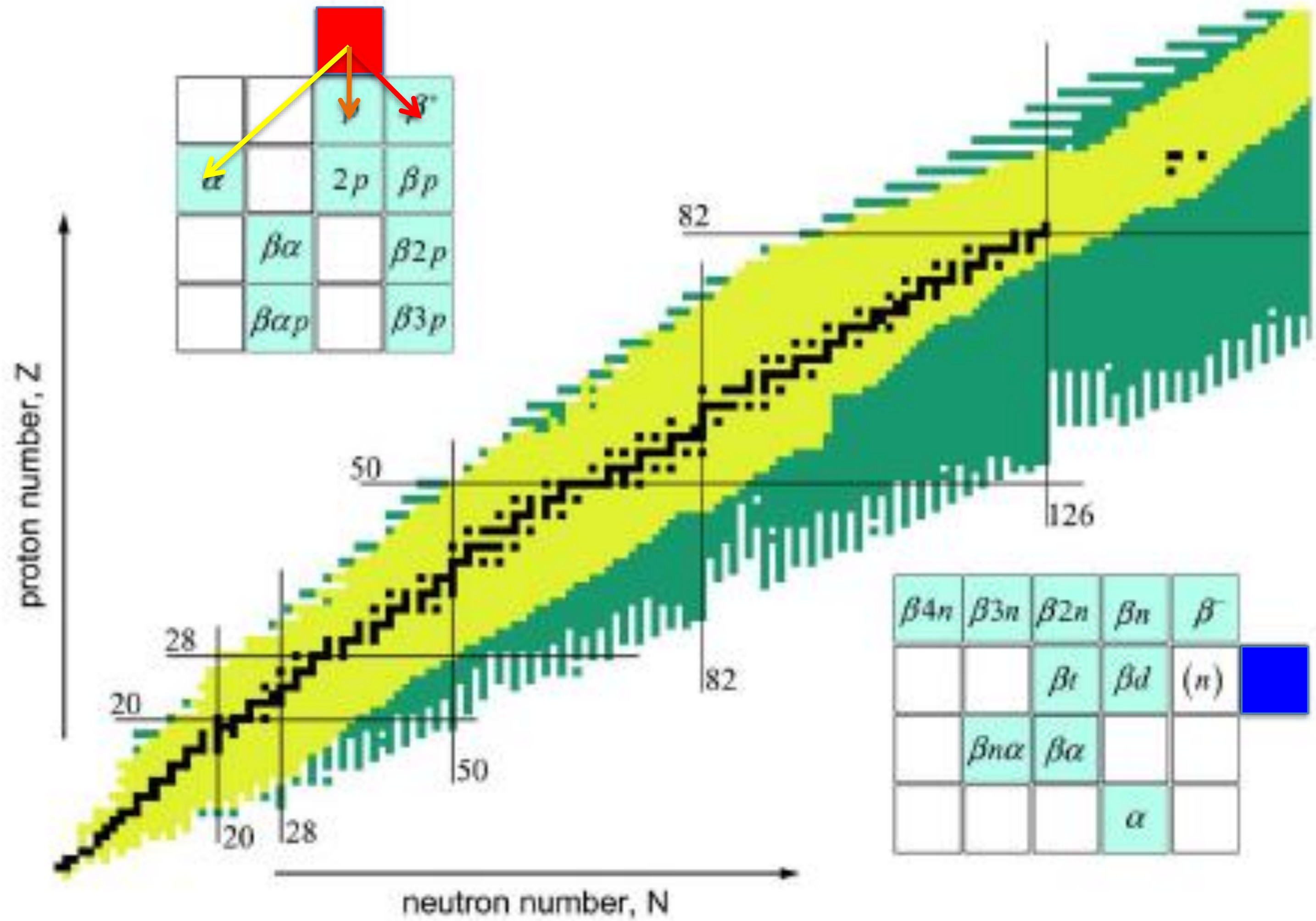
Using a simplified mass eq. where Z(Z-1) ≈ Z^2 and neglecting the pairing corrections δ:

$$E_{fission} = [\, -5.12\, A^{2/3} + 0.28\, Z^2 A^{-1/3}\,]\, c^2$$

$E_{fission} > 0$ for A≈ 90 and $E_{fission}$ = 185 MeV for ^{238}U.

The fission products, neutron rich nuclei, mainly β^- ⇒ good source of electron anti-neutrinos.

Different decay modes



Alpha decay

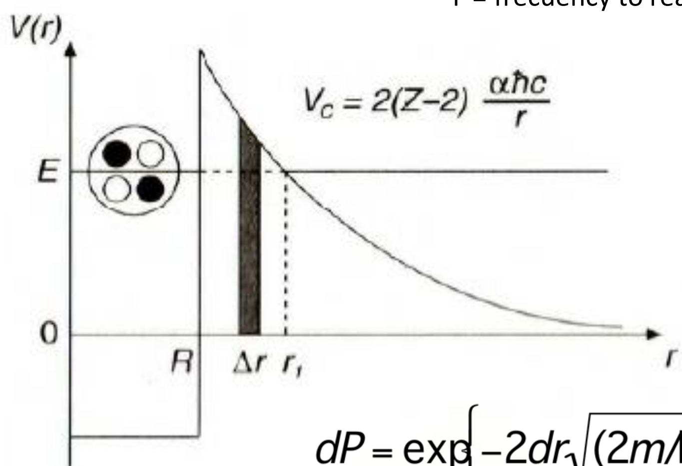
Spontaneus α-decay ($S_\alpha = 0$) correspond to

$BE({}^{A}_{Z}X_{N}) - [\,BE({}^{A-4}_{Z-2}X_{N-2}) + BE({}^{4}He)\,] = 0$

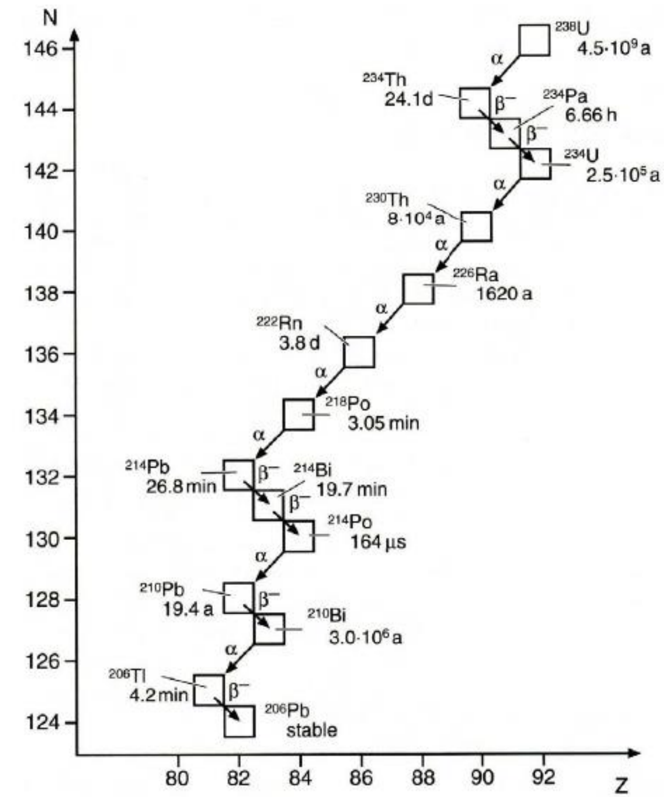
${}^{A}_{Z}X_{N} \rightarrow {}^{A-4}_{Z-2}X_{N-2} + \alpha$

▶ α tunnelling : $\lambda = FP$

P = Prob Transmission
F = frecuency to reach the barrier



$$dP = \exp\left\{-2dr\sqrt{(2m/\hbar)[V(r) - E]}\right\}$$



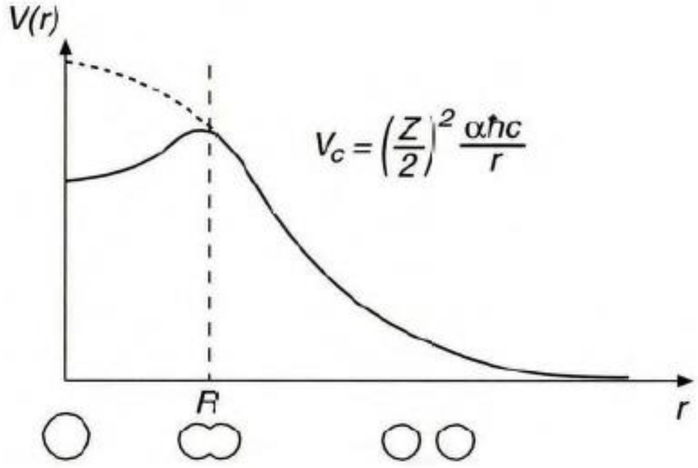
P = exp(-2G) and; G = Gamow factor

$$G = \sqrt{\frac{2m}{\hbar^2}}\int_R^{r_1}[V(r) - E]^{1/2}dr = \sqrt{\frac{2m}{\hbar^2 E}}\,\frac{zZe^2}{4\pi\varepsilon_0}\left[\arccos\sqrt{x} - \sqrt{x(1-x)}\right]$$

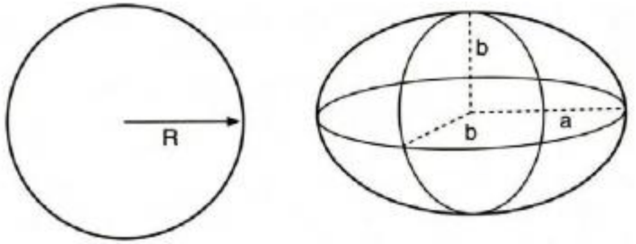
$X = R/r = E / V(R)$ ➔ $G \propto Z/E^{1/2}$ ➔ $\lambda \propto v_o/2R\,\exp(-2G)$
$\tau \approx$ from ns to 10^{17} years!

Nuclear fission

Potential during Spontaneous Fission



Deformed Sphere into ellipsoid



$$\left.\begin{aligned} a &= R\,(1+\varepsilon) \\ b &= R\,(1-\varepsilon/2) \end{aligned}\right\}\; ab^2 \approx R^3$$

$$E_s = a_s\, A^{2/3} \left[1 + \frac{2}{5}\varepsilon^2 + \cdots\right]$$
$$E_c = a_c \frac{Z^2}{A^{1/3}} \left[1 - \frac{1}{5}\varepsilon^2 + \cdots\right]$$

▷ small deformation ε changes E by :

$$\Delta E \approx \frac{\varepsilon^2}{5}\left[2a_s\, A^{2/3} - a_c\, Z^2 A^{-1/3}\right]$$

▷ fission barrier disappears for :

$$\frac{Z^2}{A} \gtrsim \frac{2a_s}{a_c} \approx 48$$

$\rightsquigarrow$ about $Z > 114$ and $A > 270$ …

Induced Fission:

Z ≈ 92: barrier ~ 6 MeV

N capture by odd N Nuclei ➔ δ-term +δ

^{235}U (not ^{238}U) , ^{233}Th, ^{239}Pu….

Beta-decay

- Introduction
- Formalism
- Beta-decay and fundamental interactions
- Beta decay and the structure of the nucleus

definition

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

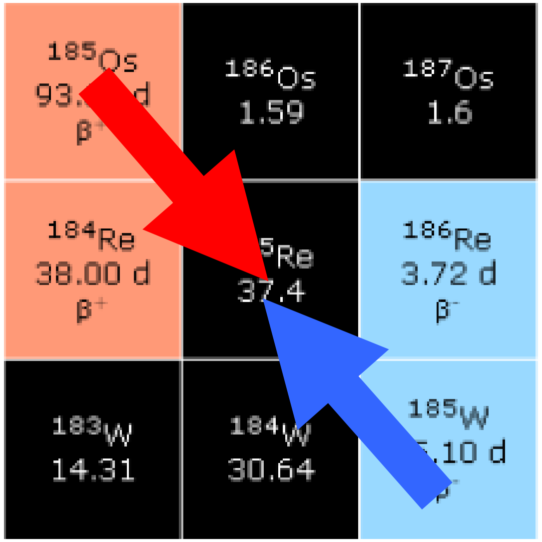
Takes place is 3 different forms
β^-, β^+ & EC (capture of an atomic electron)

β^+: p → n + e$^+$ + ν

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

EC: p + e$^-$ → n + ν

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



β^-: n → p + e$^-$ + $\tilde{\nu}$

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

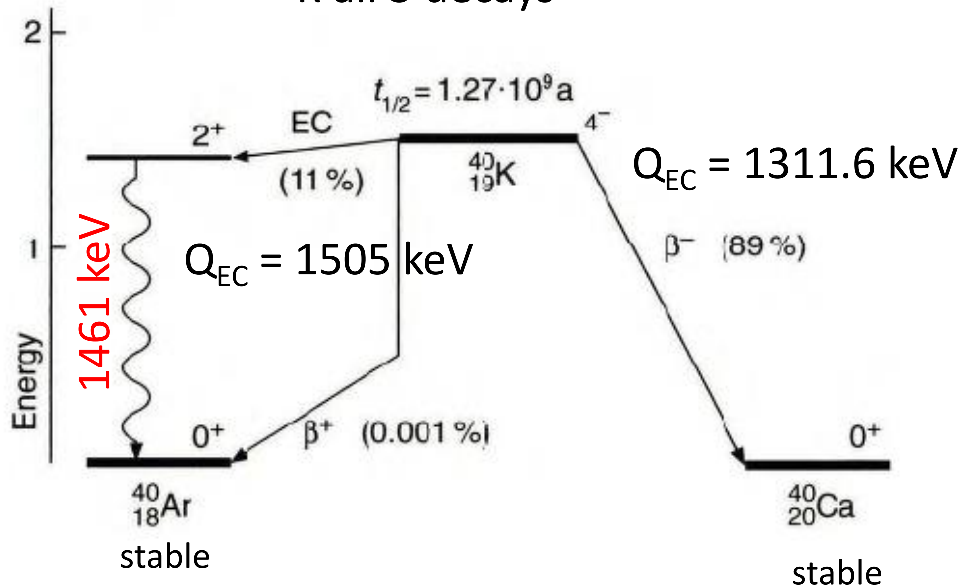
a nucleon inside the nucleus is transformed into another

The decay of ^{40}K

- Radioactive decay :
  - probability per unit time λ
  - lifetime τ, half-life $t_{1/2}$
  - activity A (decays per unit time)

$$\tau = 1/\lambda$$
$$t_{1/2} = \ln 2/\lambda$$
$$A(t) = \lambda N(t) = \lambda N_0 e^{-\lambda t}$$
$$1 \text{ Bq} = 1 \text{ decay/s}$$

^{40}K all 3 decays



- ^{40}K is 0.01% of natural $^{39-41}$K :
  - K^+ signal transmitter in nervous system
  - 16% of human radiation exposure !
  - 70 kg human = 4,400 decays/s !
  - K-Ar dating method for rocks

Introduction

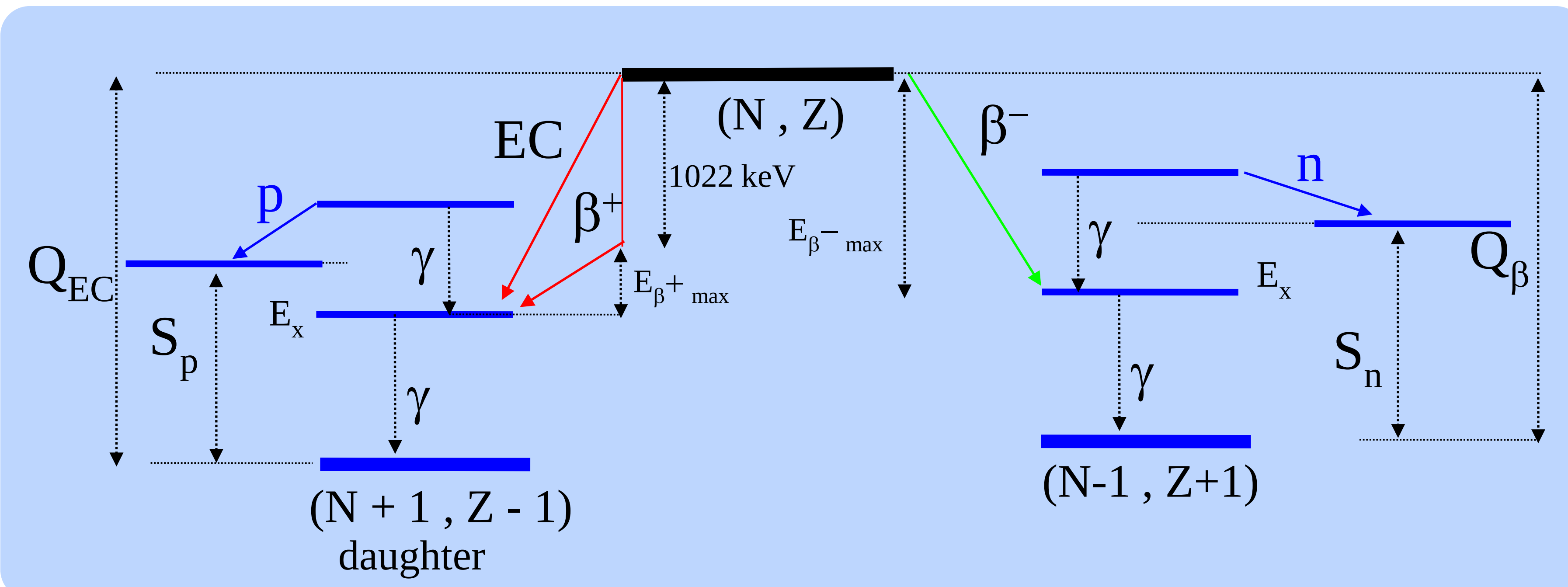
Process mediated by the weak interaction between two isobars

β^-

$(N , Z) \; \text{--->} \; (N-1, Z+1) + e^- + \nu$ $\qquad$ $M(Z) - M(Z+1) = E_\beta + E_\nu + Ex$

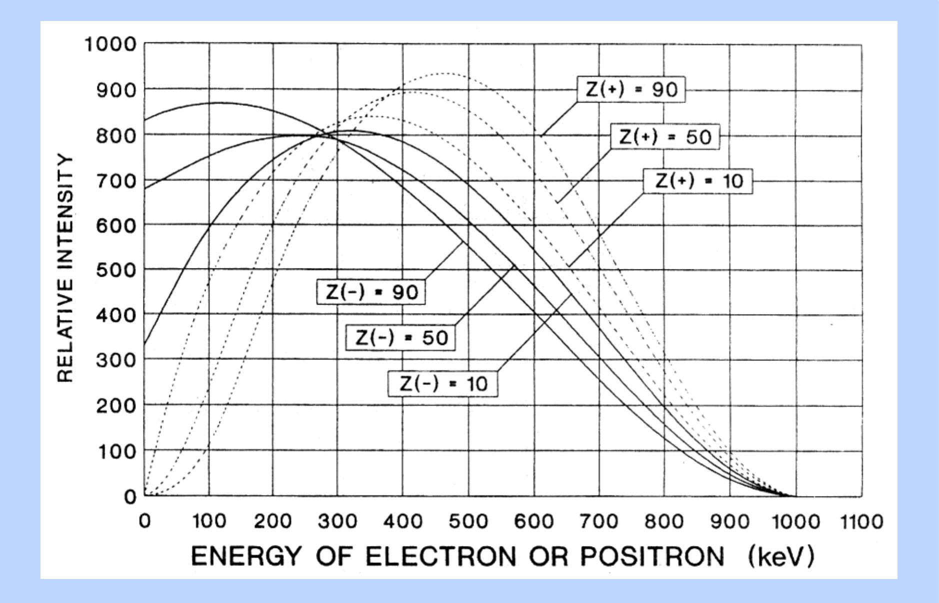
$\beta^+ + EC$

$(N , Z) \; \text{--->} \; (N+1, Z-1) + e^+ + \nu$ $\qquad$ $M(Z) - M(Z-1) = E_{\beta+} + E_\nu + 1022 + Ex$



Introduction (II)

Spectra $\beta^{\pm}$



Expand in a large E-scale

$E_{\beta-}$= 18,6 keV (^{3}H, β^{-})

$E_{\beta-}$= 22800 keV (^{22}N, β^{-})

Half-life

$T_{1/2}$: ms --> 10^{15} years

^{35}Na, $T_{1/2}$ = 1,5 ms

^{148}Sm, $T_{1/2}$ = 7 10^{15} years

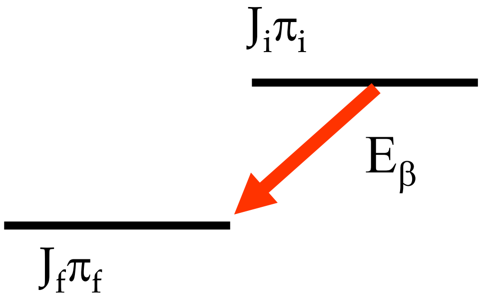
Emission of delayed particles

β p, β2p, β3p, ...βn, β2n ...

P_p = 6 10^{-6} (^{151}Lu) to 100 % (^{31}Ar)

P_n = 5,5 10^{-4} (^{79}Ge) to 99 % (^{11}Li)

Classification of β-decay transitions



$$J_i = J_f + L_\beta + S_\beta \qquad \pi_i \pi_f = (-1)^{L_\beta}$$

$$L_\beta = l_{\beta-(\beta+)} + l_{\tilde{\nu}(\nu)} = 0,1,2$$

$$S_\beta = s_{\beta-(\beta+)} + s_{\tilde{\nu}(\nu)} = \begin{cases} 0 & \uparrow\downarrow \\ 1 & \downarrow\downarrow \text{ or } \uparrow\uparrow \end{cases}$$

L_β = defines the degree of forbiddenness

allowed

when L_β=0 and $\pi_i\pi_f$=+1

$$\Delta I = \left| I_i - I_f \right| \equiv 0,1$$

forbidden

when the angular momentum conservation requires that

L_β>0 and/or $\pi_i\pi_f$=-1

Allowed transitions

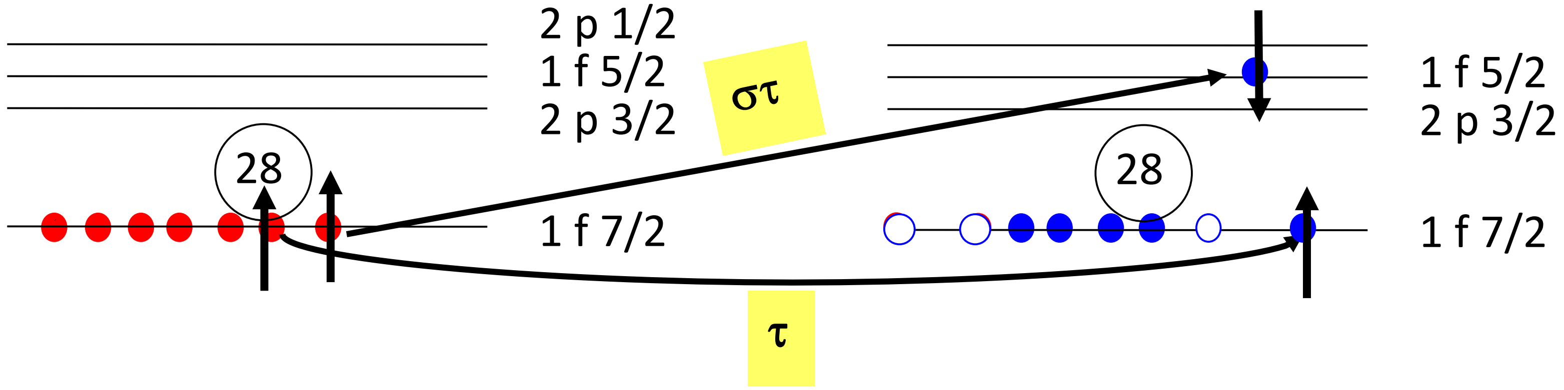
$J_i = J_f + L_{e\nu} + S_{e\nu}$ $\qquad L_{e\nu} = 0$ $\qquad \pi^i = \pi^f (-1)^{L e\nu}$

spins ν & electron ↑↑ $S_{e\nu} \neq 0$ → **transition type Gamow Teller (GT)**

access to the structure of the nucleus

spins ν & electron ↑↓ $S_{e\nu} = 0$ → **transition du type Fermi (F)**

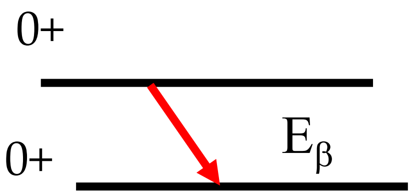
access to the weak interaction



Classification of allowed β-transitions

$$(\pi_i \pi_f = +1)$$

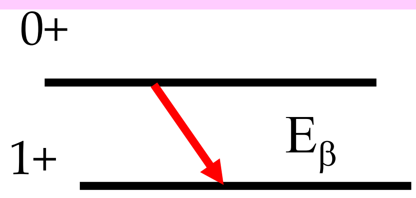
Fermi



$$\Delta I = \left| I_i - I_f \right| \equiv 0$$

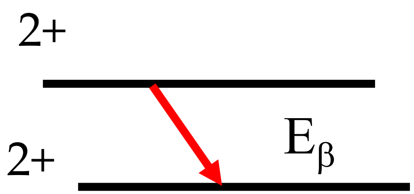
$$L_\beta = 0 \qquad S_\beta = 0 \downarrow\uparrow$$

Gamow-Teller



$$\Delta I = \left| I_i - I_f \right| \equiv 1$$

$$L_\beta = 0 \quad S_\beta = 1 \uparrow\uparrow or \downarrow\downarrow$$



mixed Fermi & Gamow-Teller

$$\Delta I = \left| I_i - I_f \right| \equiv 0 \qquad I_i \neq 0$$

Beta-decay Formalism

Fermi gold rule

| i > ---> | f >

Transition probability

$p = 2\pi/h \, |M_{if}|^2 \, dn/dE$

Density of final states

$M_{if} = \int \phi_f \, H \, \phi_i \, dv$; where H?

$\phi_f = \varphi_e \, \varphi_n \, \varphi_{daughter}$

$$\varphi_e(r) = \frac{1}{\sqrt{V}} e^{ip.r/h} = \frac{1}{\sqrt{V}}\left[1 + \frac{ip.r}{h} + \ldots\right] \cong \frac{1}{\sqrt{V}}$$

Energy conservation

$dn = dn_e \, . \, dn_\nu = \frac{(4\pi)^2 V^2 p^2 dp q^2 dq}{h^6}$

Radioactive decay constant: $\lambda = {}_0\int^{Po} p \, dp$

$$d\lambda = \frac{2\pi}{h} g^2 |M_{if}|^2 (4\pi)^2 \frac{p^2 dp q^2}{h^6} \frac{dq}{dE_f}$$

For a certain β transition $\lambda \, t = \text{Log}2 = \text{Cte} \, |M_{if}|^2 \, f(Z, E_\beta) \, t$

Fermi function

- ~ 1 for Z <10
- ↘ for Z ↗, > 1 β^+
- ↗ for Z ↗, < 1 β^-

Radioactive constant

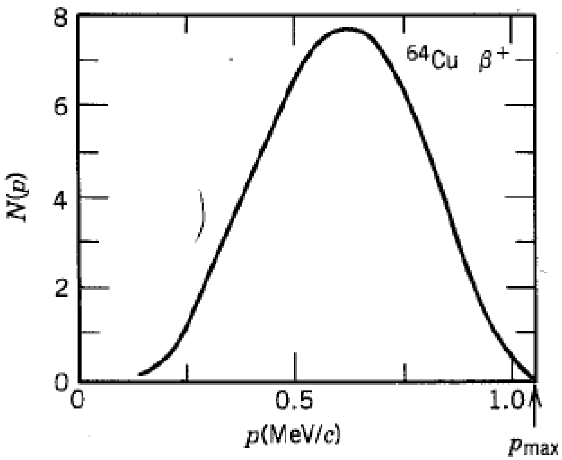
t partial half-life

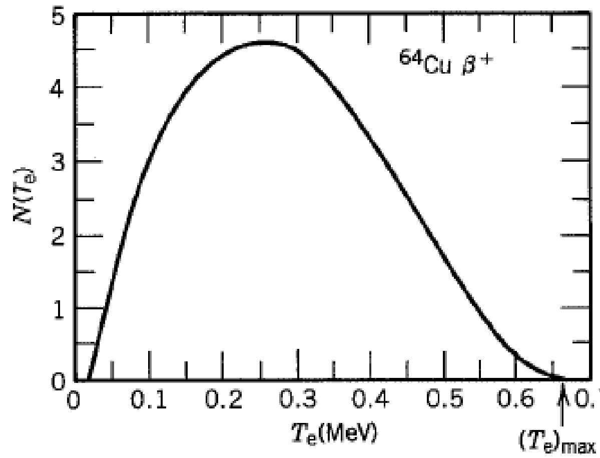
$$t = \frac{T_{1/2}}{\%\beta}$$

% β feeding

→ $f(Z, E_\beta) \, t = \text{Cte} / |M_{if}|^2$

The shape of the β-spectrum



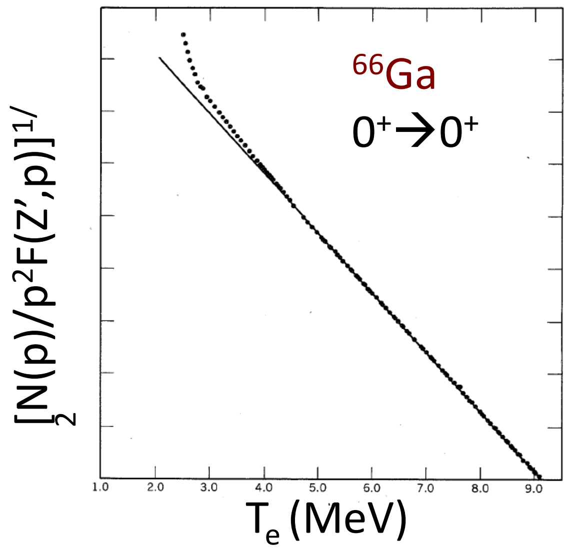


^{64}Cu $\beta^{\pm}$ decay

$$N(p)dp = cp^2q^2dp = \frac{C}{c^2}p^2(Q-T_e)^2 = \frac{C}{c^2}p^2\left[Q-\sqrt{p^2c^2+m_e^2c^4}+m_ec^2\right]^2 dp$$

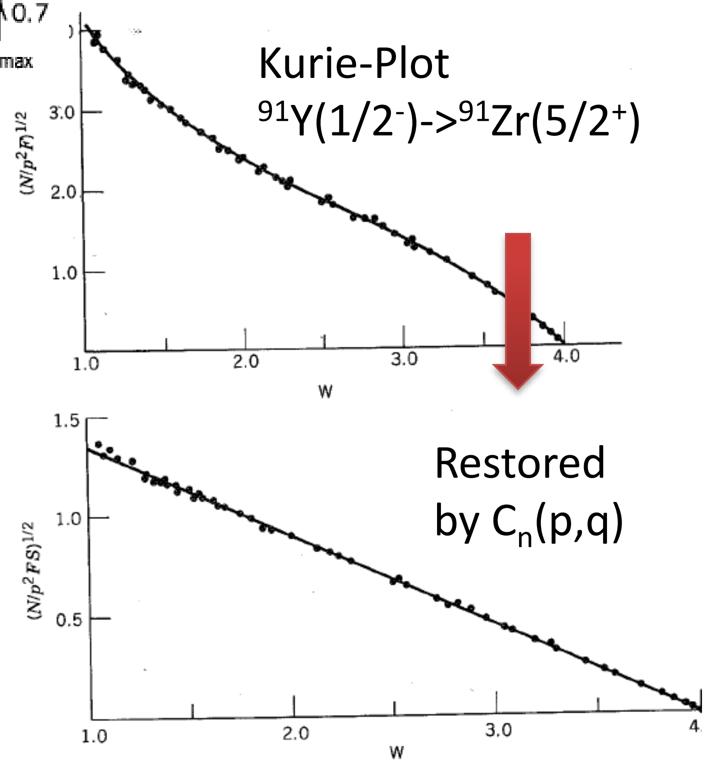
Kurie-Plot

$$(Q-T_e) \propto \sqrt{n(p)/p^2F(Z',p)}$$



Kurie-Plot

$^{91}Y(1/2^-) \rightarrow {}^{91}Zr(5/2^+)$



Restored by $C_n(p,q)$

Beta-decay lifetime

$t \equiv T_{1/2}^{\beta_i} = \frac{T_{1/2}^{\exp}}{P_{\beta_i}}$ partial half-life of a given β⁻ (β⁺,EC) decay branch (*i*)

$$\frac{\ln 2}{T_{1/2}^{n}} = \frac{g^2}{2\pi^3}\int_1^W p_e W_e (W_0 - W_e)^2 F(Z,W_e) C_n dW_e$$

Assuming
F (Z,W)= 1 & Q >>$m_e c^2$
$f = W_o^5/30$ (β^+)
$f = (W_o+1)^5/30$ (β^-)

g – weak interaction coupling constant

p_e – momentum of the β particle

W_e – total energy of the β particle

W_0 – maximum energy of the β particle

$F(Z,W_e)$ – Fermi function – distortion of the β particle wave function by the nuclear charge

C_n – shape factor ≠ 1 for forbidden transitions = C(p,q)

Z – atomic number

Classification of β-transitions

Type of transition	Order of forbiddenness	ΔJ	$\pi_i \pi_f$
Allowed		0,+1	+1
Forbidden unique	1	∓ 2	-1
	2	∓ 3	+1
	3	∓ 4	-1
	4	∓ 5	+1
	.	.	.
Forbidden	1	0, ∓ 1	-1
	2	∓ 2	+1
	3	∓ 3	-1
	4	∓ 4	+1
	.	.	.

The order of forbideness is given by the angular momentum carried by the electron and neutrino.

Classification of the transitions

log f t

Independent of Energy range and Z

B. Singh, et al. N.D.S 84, 487 (1998)

log f t	*Transition type*	$\Delta\pi$	ΔJ
< 3,8	super allowed	Non	0
< 5,9	Allowed	Non ($\Delta L = 0$)	0, 1
> 6	"special allowed" $\Delta L = 2$	Non ($\Delta L = 2$)	0, 1
7 (1)	first forbidden	Yes	0, 1
8,5 (5)	first forbidden	Yes	2
~ 13	second forbidden	Non	2, 3
~ 18	Third forbidden	Yes	3, 4

transitions between analogue :

log f t = 3,5 (^{14}O, ^{34}Cl, ^{42}V ...)

$^{12}B \rightarrow {}^{12}C$

- I_β (gs) = 97,1 %
- $T_{1/2}$ = 20,4 ms
- Q_{β^-} = 13,37 MeV

→ log f = 5,77 → log f t = 4,09

$F = (13.37/0.51 + 1)^5/30$ → log ft = 4,02

experimental determination de $T_{1/2}$, % β, E_β → $|M_{if}|^2$

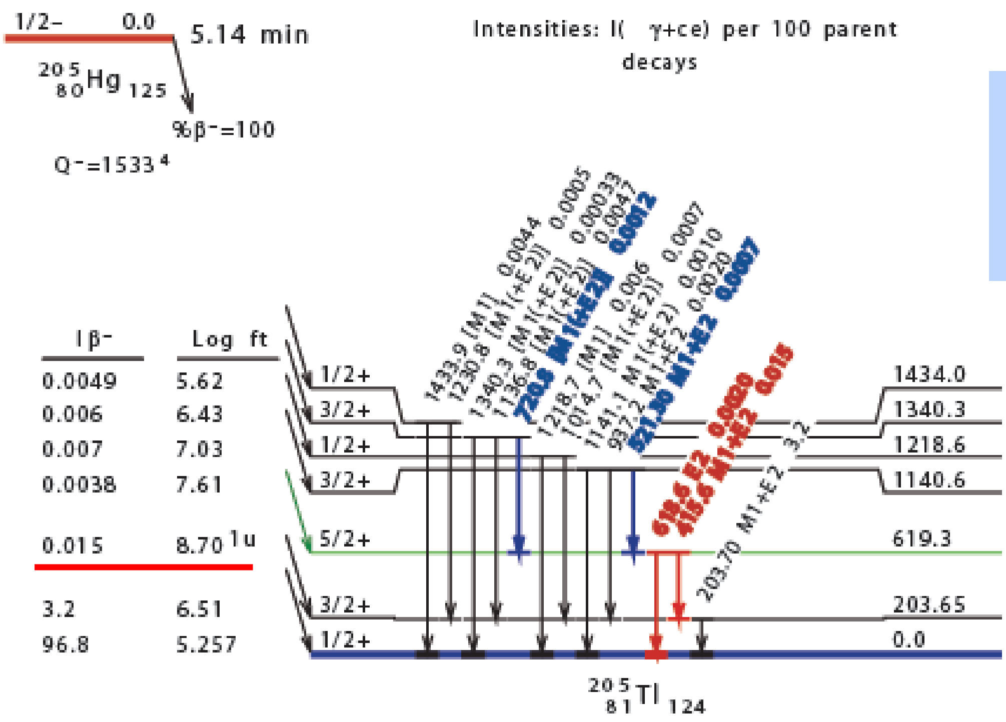
Practical example

$$t \equiv T_{1/2}^{\beta_i} = \frac{T_{1/2}^{\exp}}{P_{\beta_i}}$$

$$P_{\beta_i} = \eta[I^{tot}(out) - I^{tot}(in)]$$

$$I^{tot}(out/in) = \sum_i I_{\gamma_i}(1+\alpha_{T i})$$

$$\alpha_T(M1+E2) = \frac{\alpha_T(M1) + \delta^2 \alpha_T(E2)}{1+\delta^2}$$



- What we want to know accurately
  - ✓ $T_{1/2}$, I_γ, α_T & δ

In

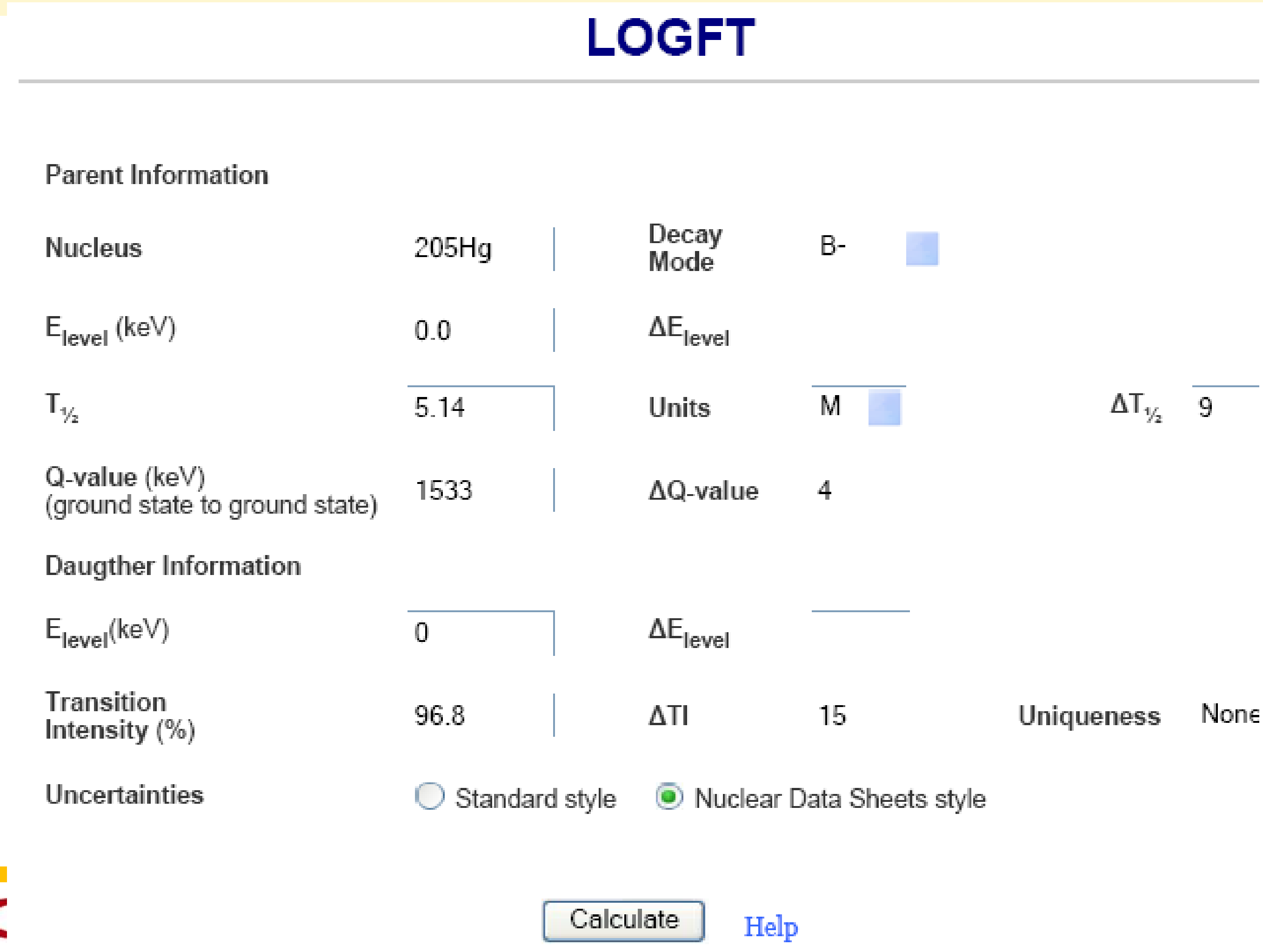
$$\frac{I^{tot}(521+721) = 0.086(16)}{I^{tot}(416+619) = 0.78(10)} = 0.69(10) \text{ (net)}$$

Out

$$\eta = 0.0022 \rightarrow t = 2.056\times10^6[s] \rightarrow \log t = 6.31 \rightarrow \log f = 2.386 \rightarrow \log ft = 8.7$$

Logf for dummy's

- ENSDF analysis program LOGFT – both Windows & Linux distribution
  http://www.nndc.bnl.gov/nndcscr/ensdf_pgm/analysis/logft/
- LOGFT Web interface at NNDC http://www.nndc.bnl.gov/logft/



LOGFT

Parent Information

Nucleus	205Hg	Decay Mode	B-		
E_{level} (keV)	0.0	ΔE_{level}			
$T_{½}$	5.14	Units	M	$\Delta T_{½}$	9
Q-value (keV) (ground state to ground state)	1533	ΔQ-value	4		

Daugther Information

E_{level}(keV)	0	ΔE_{level}			
Transition Intensity (%)	96.8	ΔTI	15	Uniqueness	None
Uncertainties	○ Standard style	● Nuclear Data Sheets style			

Calculate Help

CSIC IEM

The isospin formalism

p and n are the same kind of particles with a different isospin state (T)

The third component T_z is very clear:

$$T_Z = \frac{N-Z}{2}$$

τ Fermi

It can only change the third component of isospin:
Only one state called Isobaric Analog State (IAS)

$$B_F = \left|\left\langle \psi_f \,|\, \sum \tau^{\pm} \,|\psi_i \right\rangle\right|^2$$

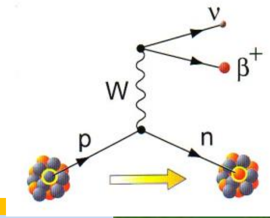
B(F) = T (T + 1) - Tz_i Tz_f

στ Gamow-Teller

Can change the spin and the isospin:
Many possible final states

$$B_{GT} = \left|\left\langle \psi_f \,|\, \sum \sigma\tau^{\pm} \,|\psi_i \right\rangle\right|^2$$

$$f\,(Z, E_\beta)\; t = K \,/\, |\, M_{if}\,|^2 = C \,/\, (\, B(F) + B(\,GT\,)\,)$$



Fermi & Gamow Teller transitions

$$T_Z = \frac{N - Z}{2}$$

$^{74}_{36}Kr_{38}$ $\quad T = 1, \quad T_Z = 1$

β⁺

$^{74}_{35}Br_{39}$ $\quad T \neq 1, T = 2, \quad T_Z = 2$

$^{88}_{37}Rb_{51}$ $\quad T=8, \quad T_Z=7$

β⁻

$^{88}_{36}Kr_{52}$ $\quad T=8, \quad T_Z=8$

In β^+ Fermi, forbidden for N>Z

In β^- allowed but energetically difficult

In β^+ Gamow Teller "allowed"

In β^- Gamow Teller "allowed"

Beta-decay and Nuclear Structure: Observables

Mass Originally determine by the Q_{β}-endpoint

→ Measurement of Q_{β} { Direct measure of E_{β} / coincidences β.γ, β.n, βp } Precision ~ 400 keV

Use of Local Ma… …00 keV

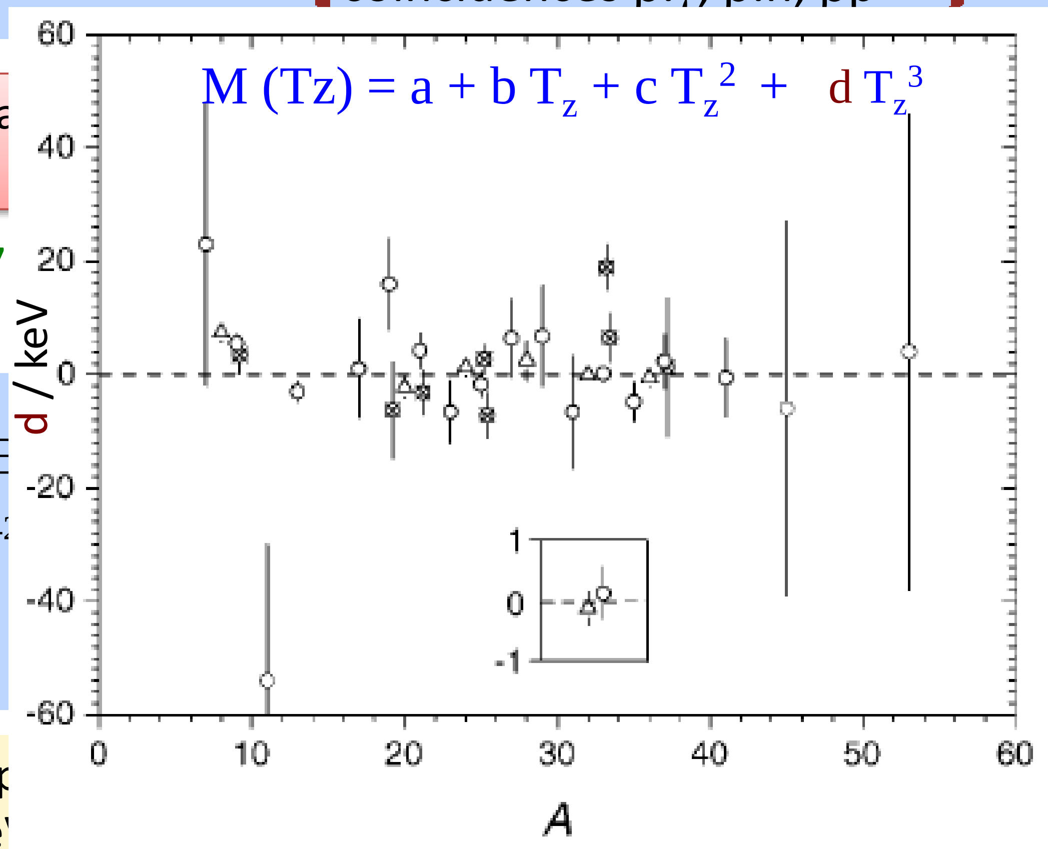
Wigner in 1957 … that the
members of an …

→ IMME…

33, 34, 4… …25 (1998)

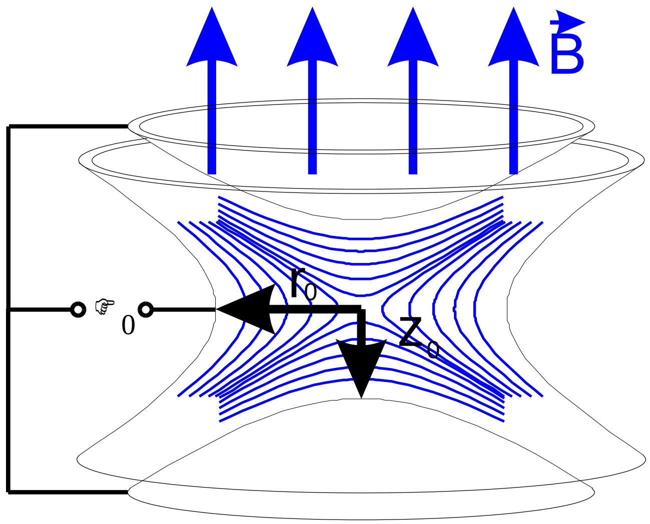
…1 (2001)

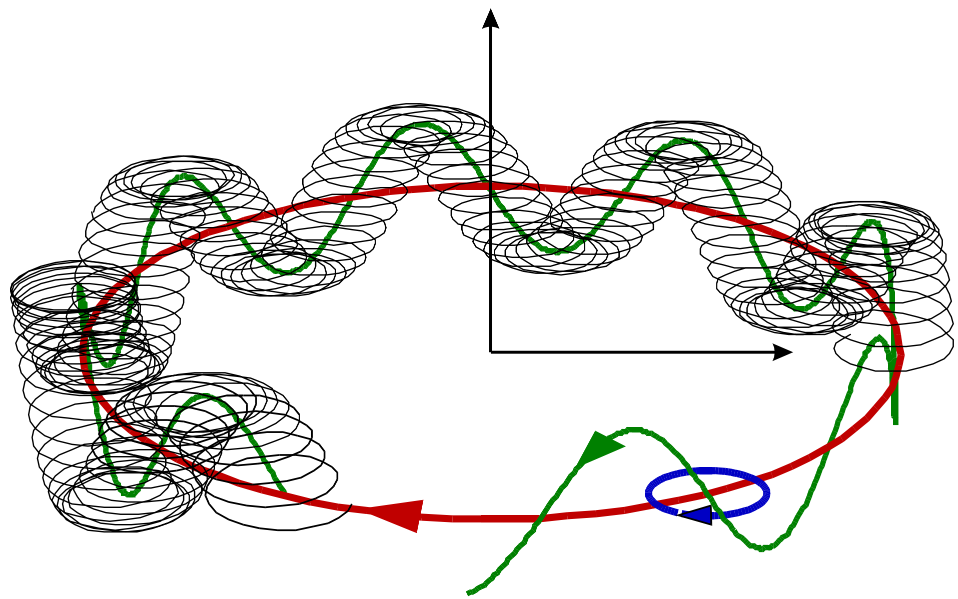
Penning trap…
level of 2 ke…



K. Blaum et al. PRL 91, 260801 (2003)

Principles of the Penning trap





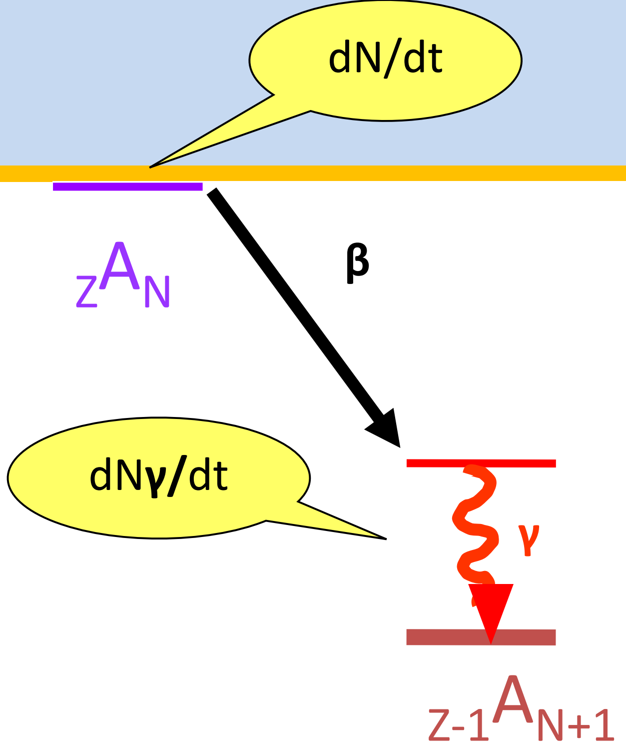
A Penning trap can be defined as the superposition of a homogeneous magnetic field and an electrostatic quadrupole field.

$$\omega_c = \frac{Q}{m} B$$

Mass measurements at storage rings

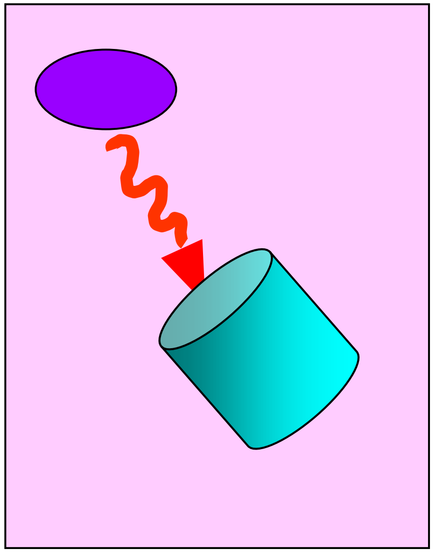
"Recent trends in the determination of nuclear masses" *Review: D. Lunney et al, Rev. Mod. Phys. 75, 1021 (2003)*

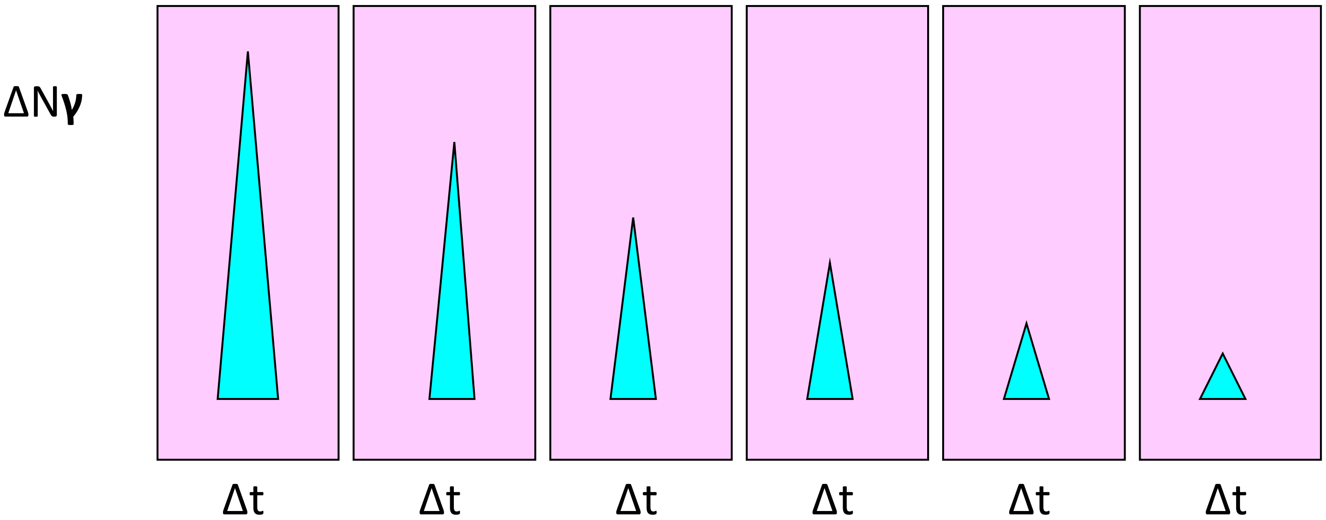
Half-life measurement

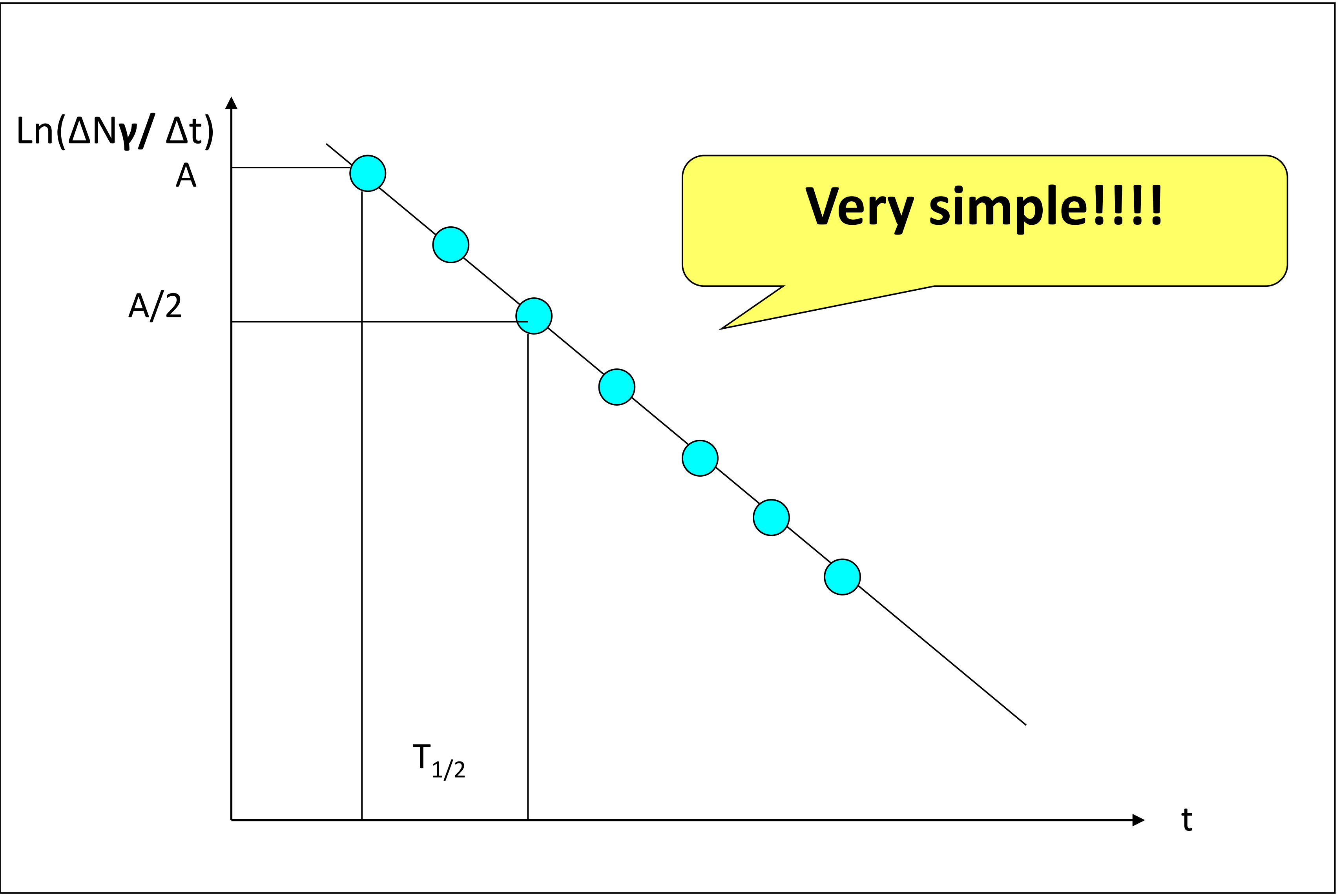


$$\frac{dN}{dt} = \frac{dN_0}{dt} e^{-\lambda t}$$

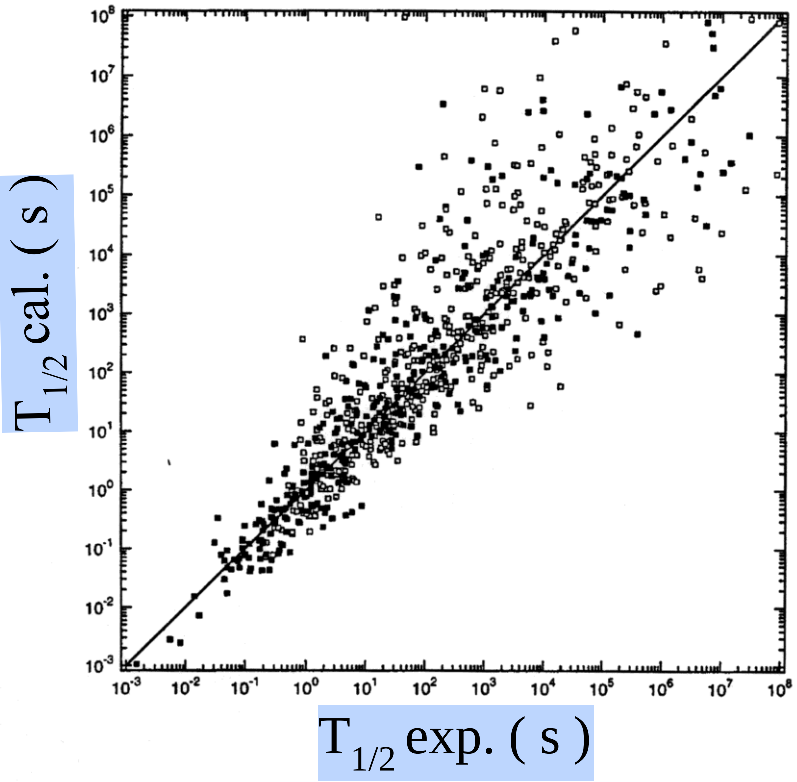
$$\lambda = \frac{1}{\tau} = \frac{Ln2}{T_{1/2}}$$

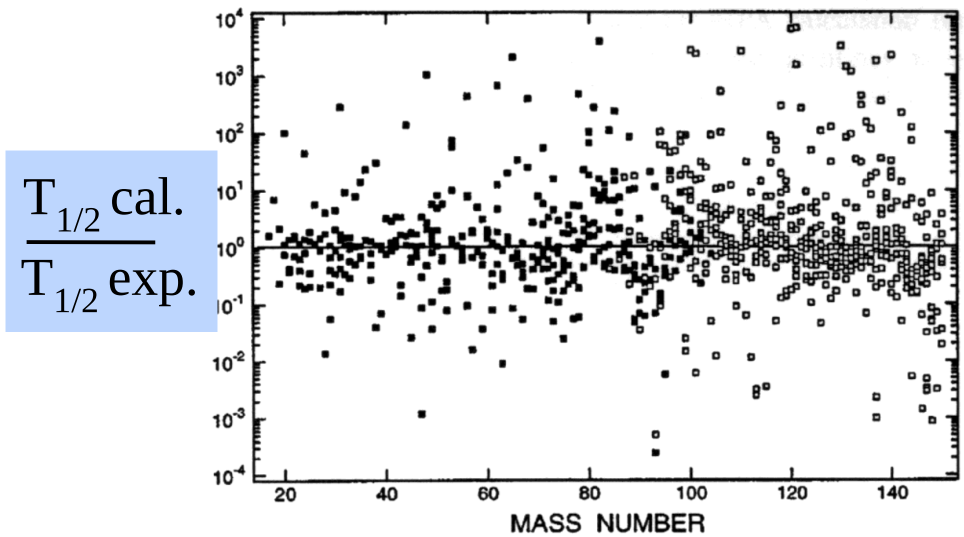





Ln(ΔNγ/ Δt)
A
A/2
T1/2
t
Very simple!!!!

Half-live: First Glance into Nuclear Structure

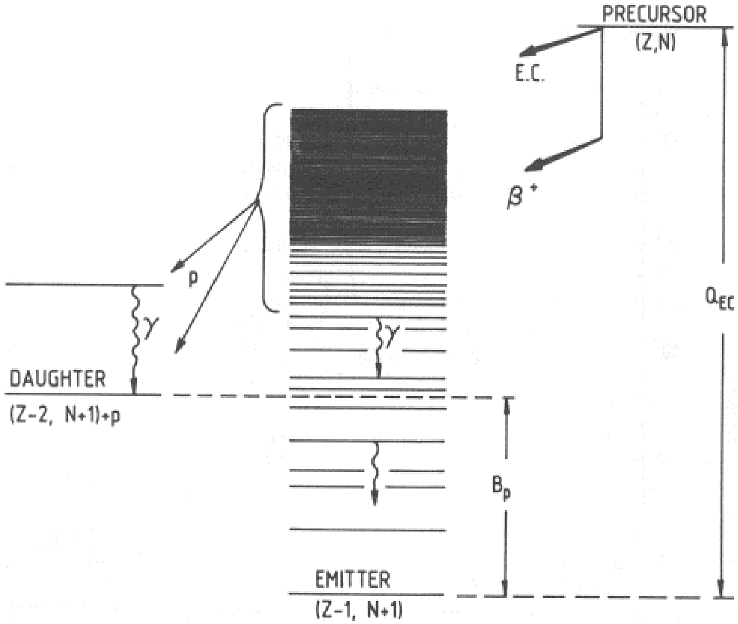




Beta Delayed Proton Emission

- **1963** **Barton &Bell** in McGill identify ^{25}Si as first proton precursor thanks to the used of Si-surface barrier detectors

Decay Scheme of β-delayed proton precursor

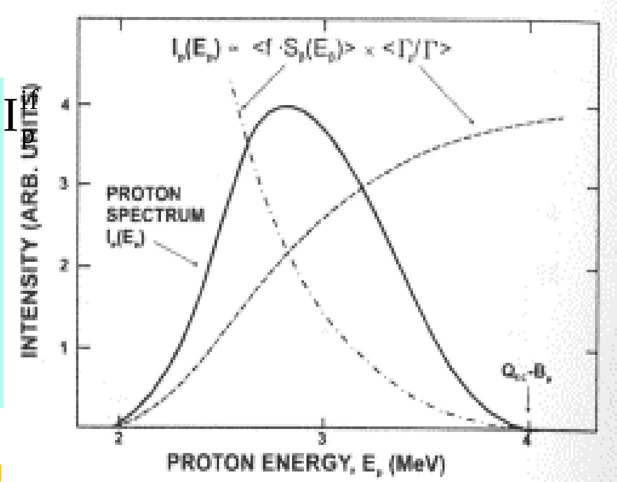


- Particle energy spectrum determined by 2 factors
  1-intensity of β-decay branches from precursor to the emitter
  2-probability of emission by proton rather gamma

$$I_p^{if} = I_\beta^{i} \frac{\Gamma_p^{if}}{\Gamma^{if}}$$

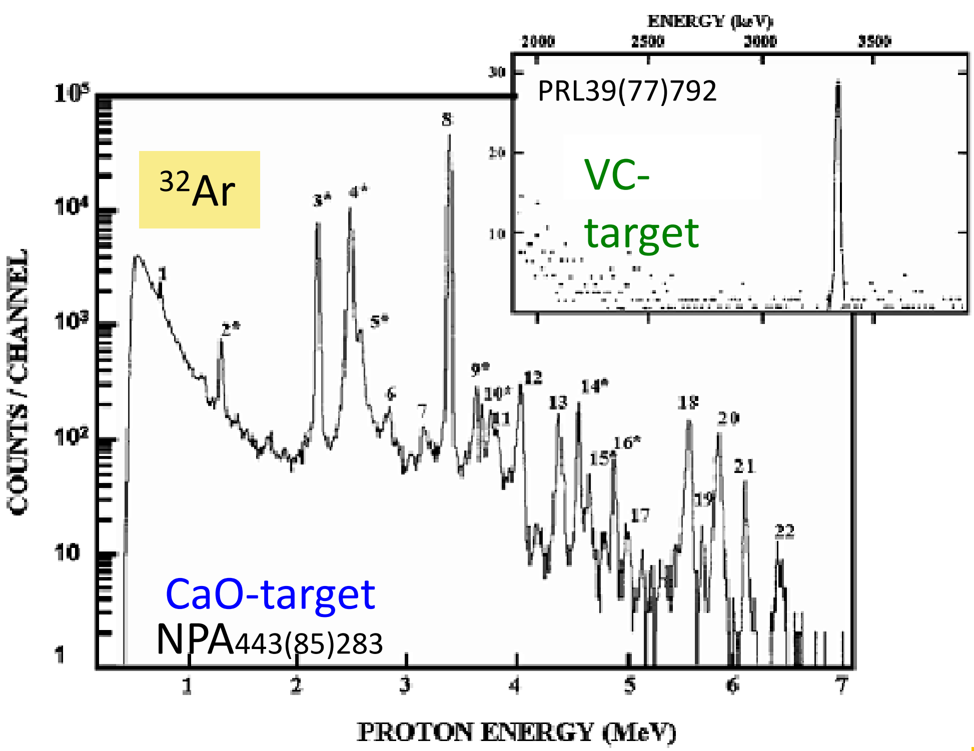
Formula valid for light precursor when individual transitition are resolved

- For heavier precursors, I_p^{if} is statistically averaged over an energy range with Bell shape (neglecting nuclear structure)



Beta-proton emitters

- ✓ More than 160 precursors identified
- ✓ For every element up to Z = 73 at least one proton precursor
- ✓ The βp spectrum depends on the Z and A of the precursor and differs in the different mass region due to diferences in level density in the Q-Sp window
- ✓ Properties of βp well understood → large variety of spectroscopic information



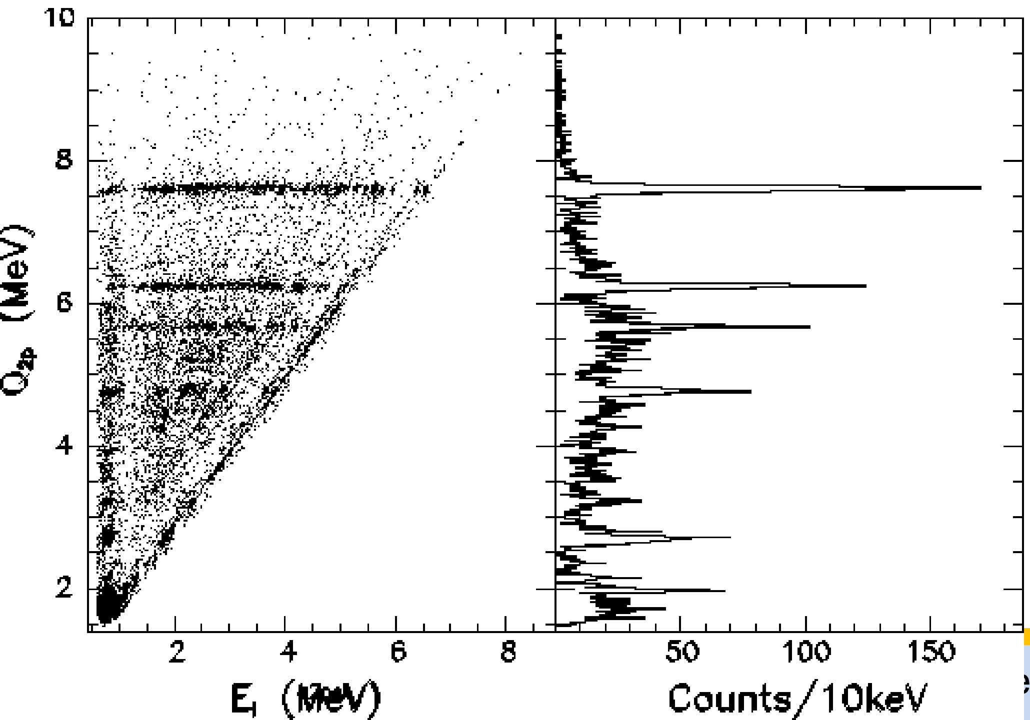
✓For light nuclei with $Z \geq 8$, the IAS within the Qec window.
✓ From βp energy of IAS ➔Q_{EC}-Sp deduced.
✓Test Isobaric Multiplet Mass eq. $M(A,T,T_z) = a + bT_z + cT_z^2 + \delta(dT_z^3+eT_z^4)$
✓ If strength to IAS $\neq B_F$ ⇔ Isospin Mixing
✓If IAS in the middle of the Q_{EC} large part of the GTGR available => quenching factor deduced
✓Test of Mirror Symmtry

2p emission from ^{31}Ar IAS

a) Energy Conservation $$\frac{\vec{P}_1^{\,2}}{2m_P}+\frac{\vec{P}_2^{\,2}}{2m_P}+\frac{\vec{P}_r^{\,2}}{2m_r}=Q_{2p}$$

b) Momentum Conservation $$\vec{P}_1^{\,2}+\vec{P}_2^{\,2}+\vec{P}_r^{\,2}=0$$

$$Q_{2p}=E_1+E_2+\frac{m_p}{m_r}\left(E_1+E_2+2\sqrt{E_1E_2}\cos\theta_{2p}\right)$$



2p emission from ^{31}Ar IAS

a) Energy Conservation

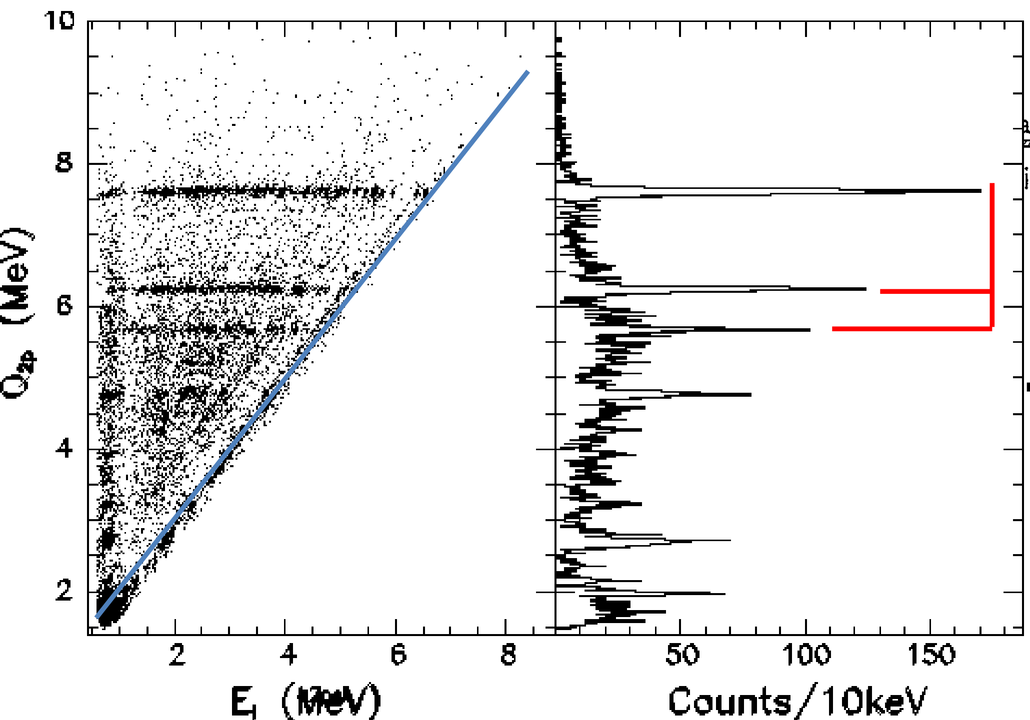
$$\frac{\vec{P}_1^{\,2}}{2m_P}+\frac{\vec{P}_2^{\,2}}{2m_P}+\frac{\vec{P}_r^{\,2}}{2m_r}=Q_{2p}$$

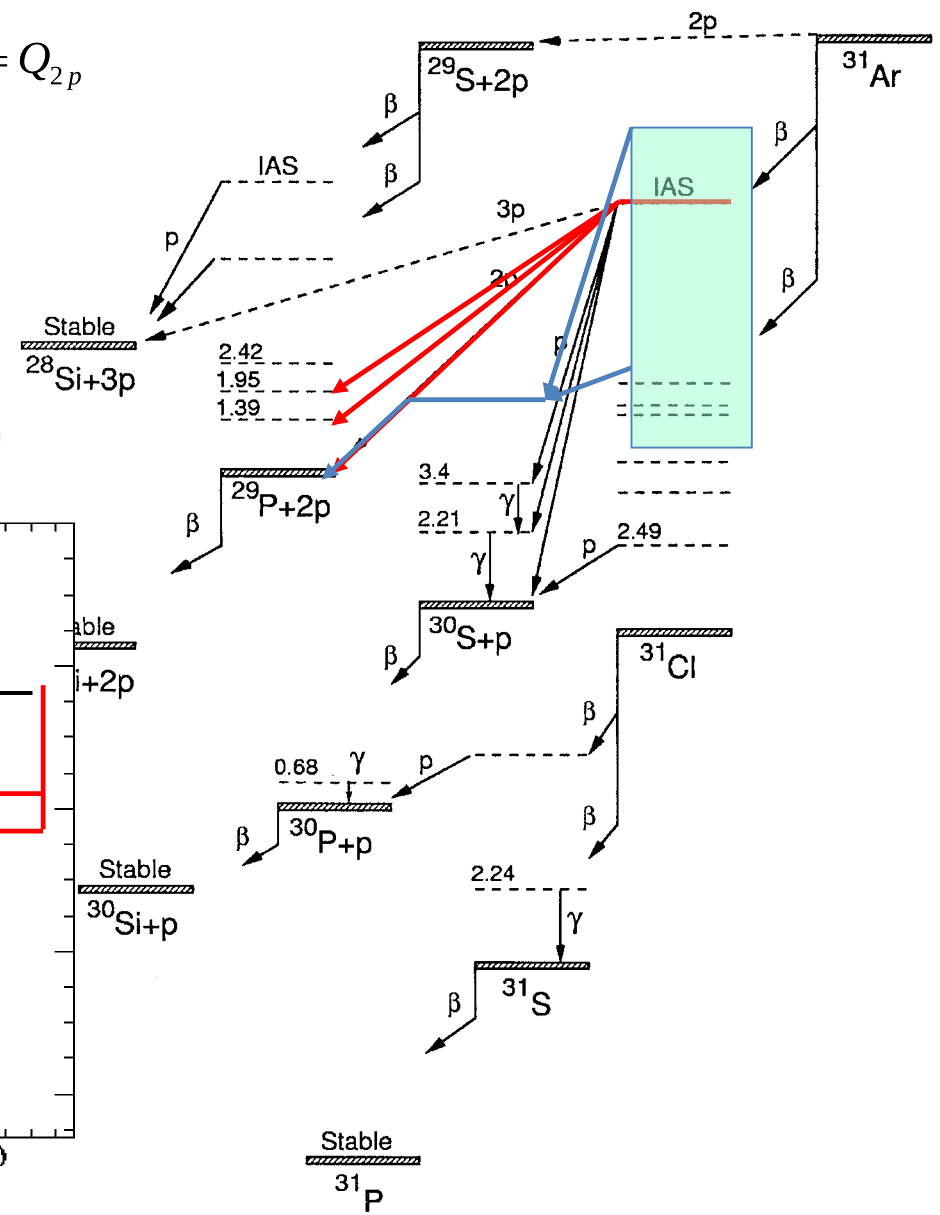
b) Momentum Conservation

$$\vec{P}_1^{\,2}+\vec{P}_2^{\,2}+\vec{P}_r^{\,2}=0$$

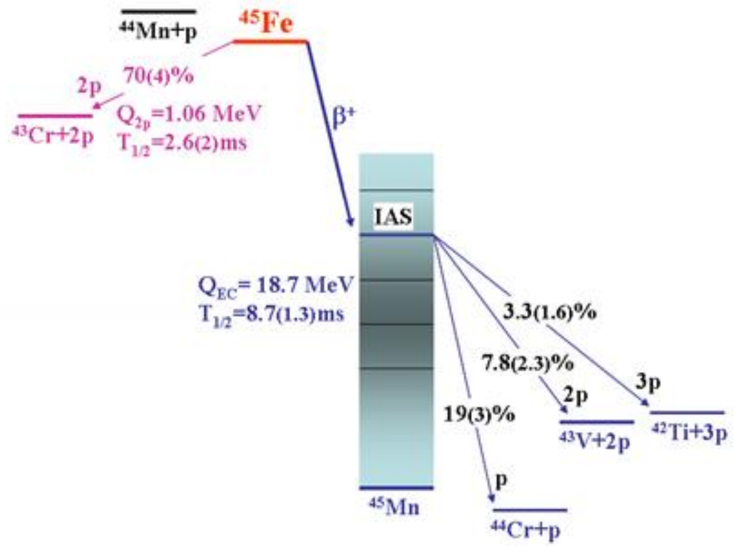
$$E_1=\frac{M_{D1}}{M_{D1}+m_p}Q_1$$

$$Q_{2p}=E_1+E_2+\frac{m_p}{m_r}\left(E_1+E_2+2\sqrt{E_1E_2}\cos\theta_{2p}\right)$$



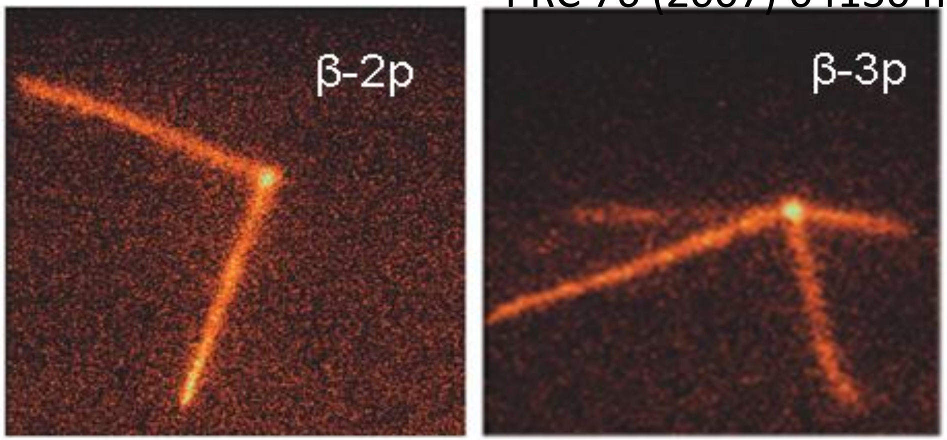


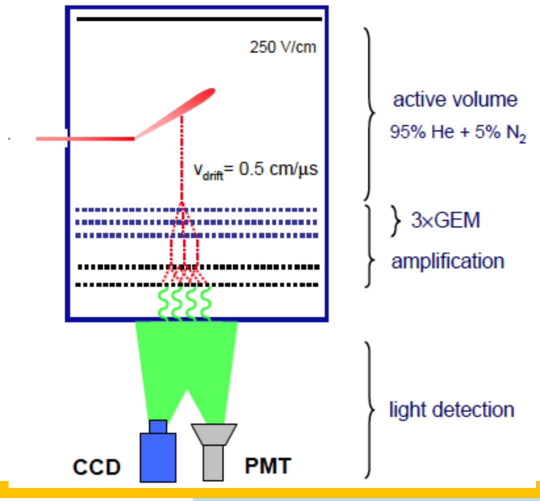
β-delayed 3p-emitters



Decay mode search for in ^{31}Ar where the Q3p is around 4.8 MeV

PRC 76 (2007) 041304R

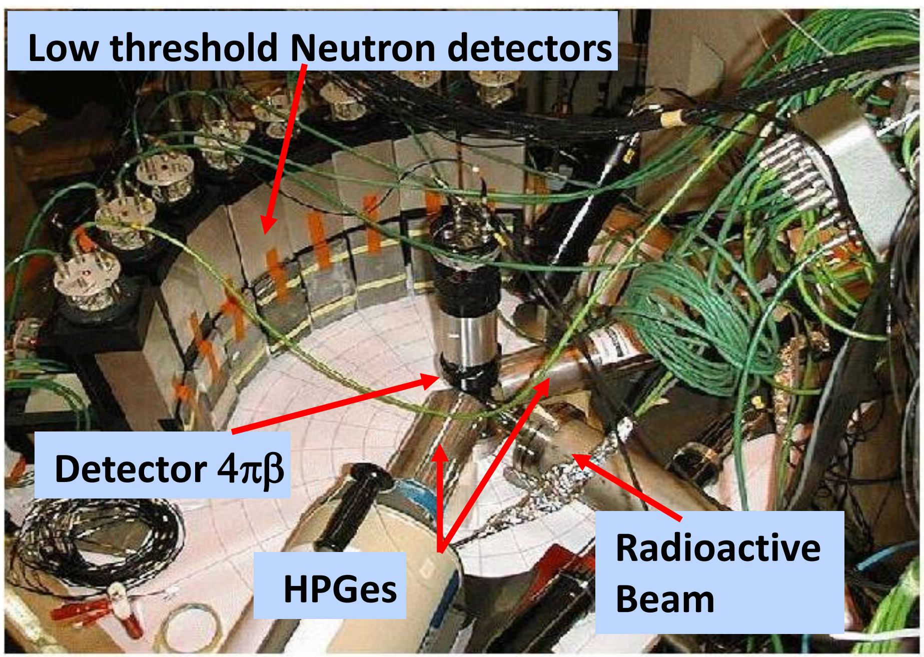




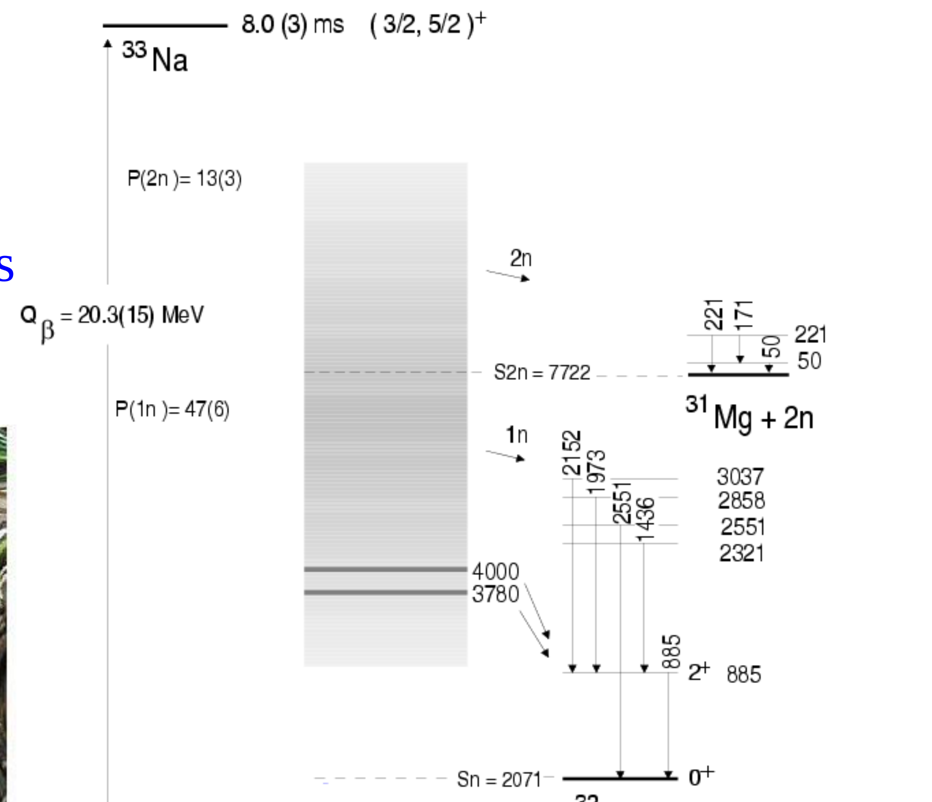
Decay Scheme ➔ Structure Information (N= 20)

^{33}Na

ISOLDE
fragmentation U (46g/cm^2) 2000º
1,4 GeV protons 3 10^{13} / pulse (1,2s) ^{33}Na 2 at / s



exp. : coinc. β neutrons β.γ.n

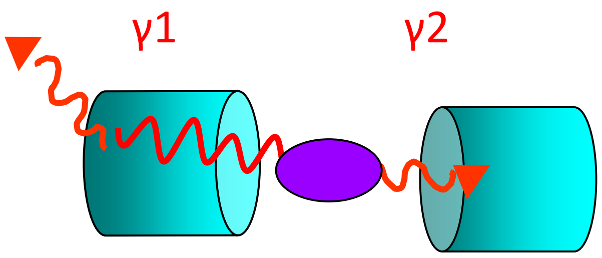


^{33}Na $T_{1/2}$ = 8.0 (3) ms
Detailed Level Scheme
inversion of $3/2^+$ $7/2^-$ orbits in ^{33}Mg

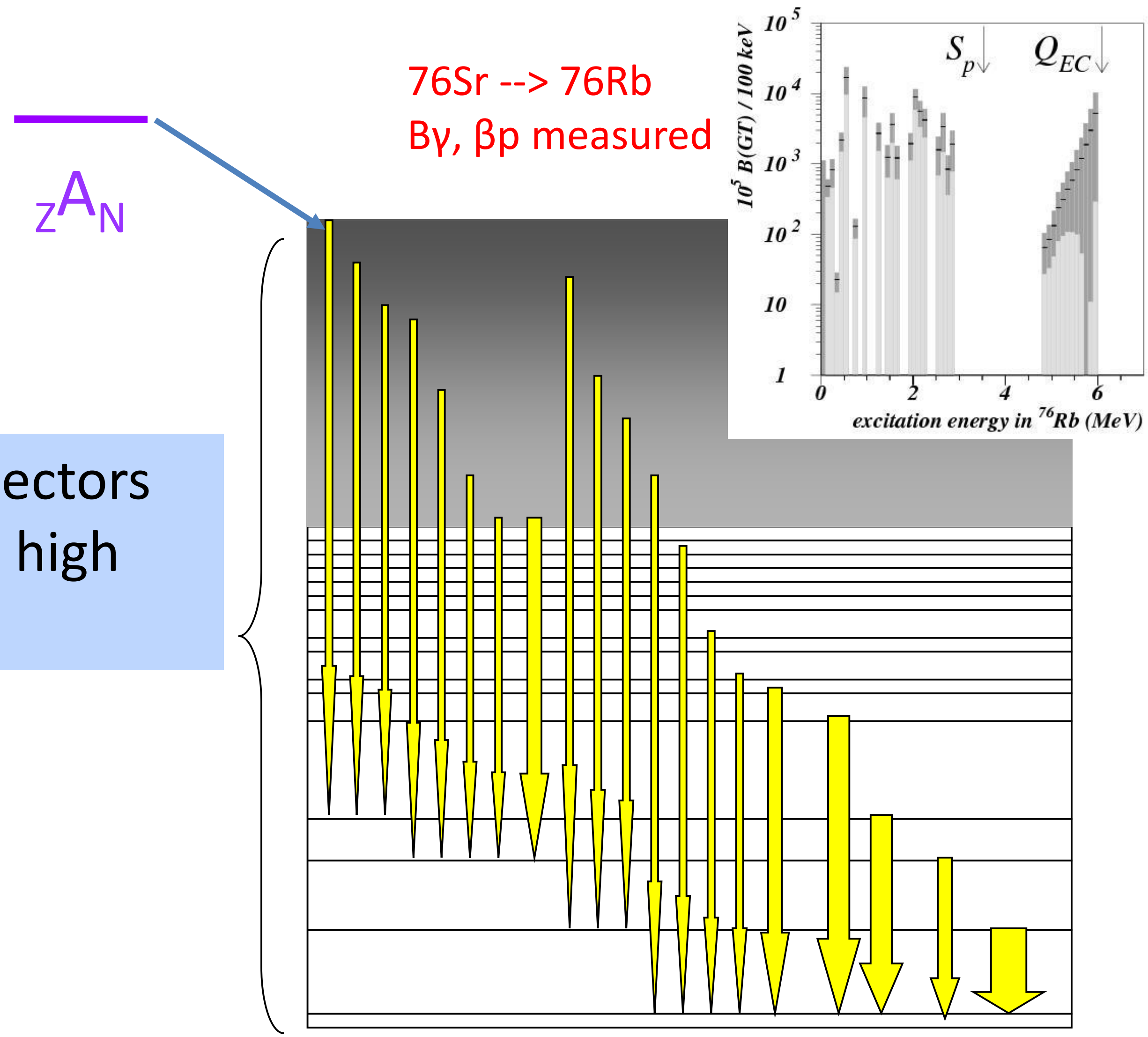
M. Langevin et al NP A414 151 (1984)
S. Nummela et al PRC64 054313 (2001)

Beta-decay : Limitations: beta feeding

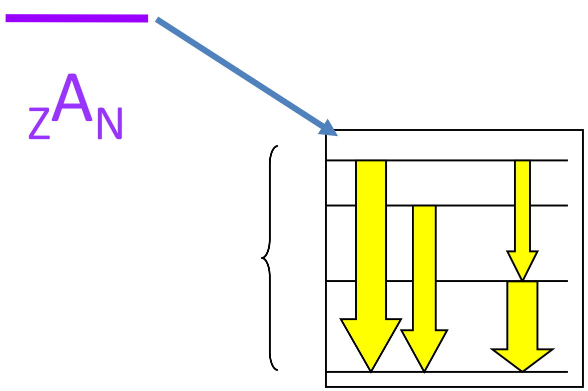
Traditionally



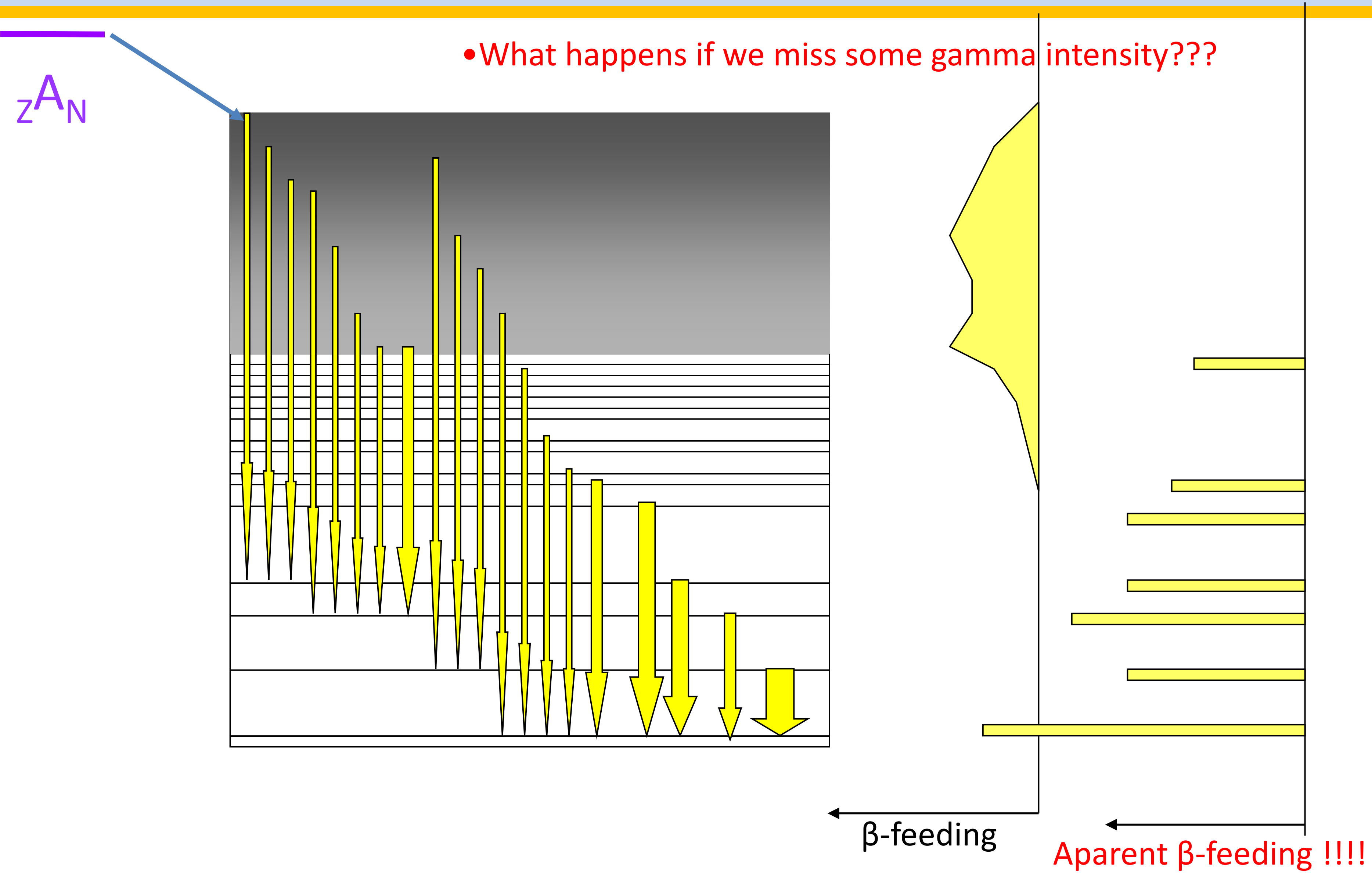
76Sr --> 76Rb
Bγ, βp measured



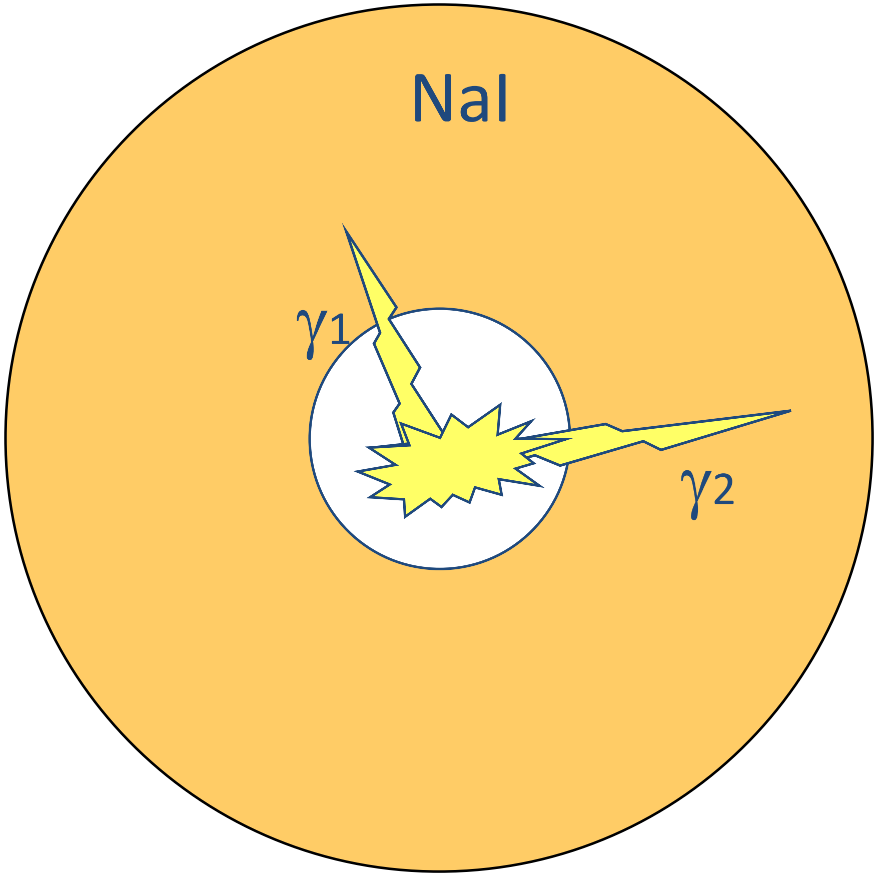
For high Q-values, Ge detectors fail to detect β-feeding at high excitation energy!!!

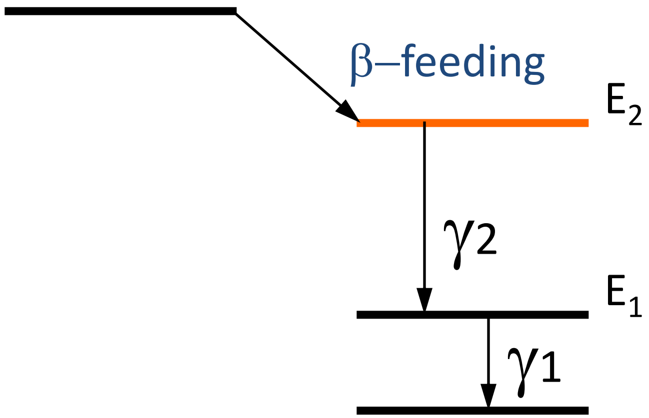


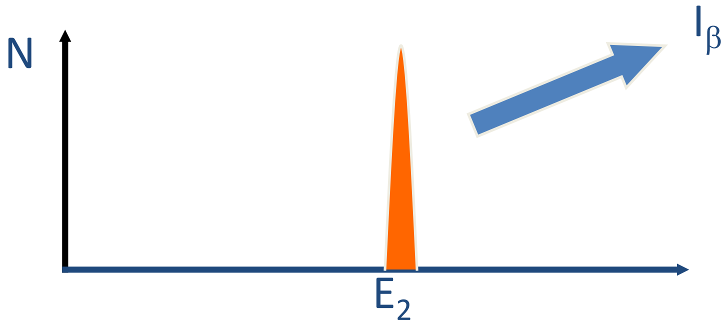
- We use Ge detectors to construct the decay scheme
- From the γ-balance we extract the β –feeding



Total Absorption spectroscopy





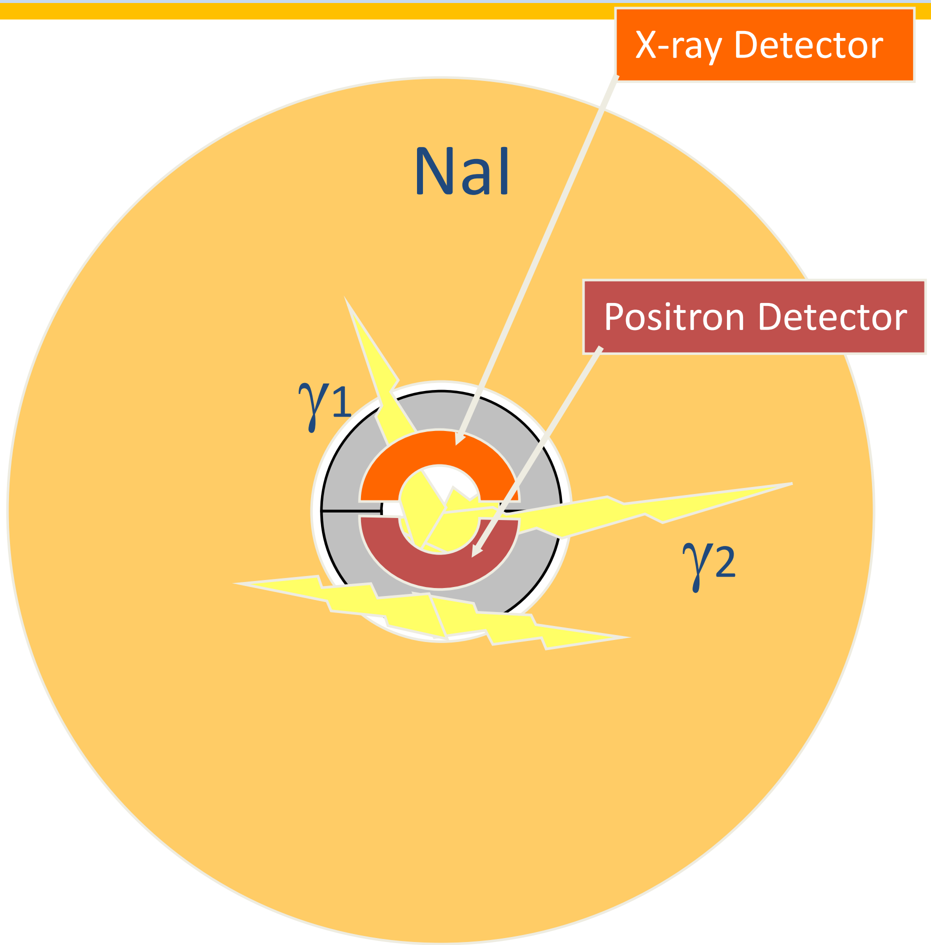


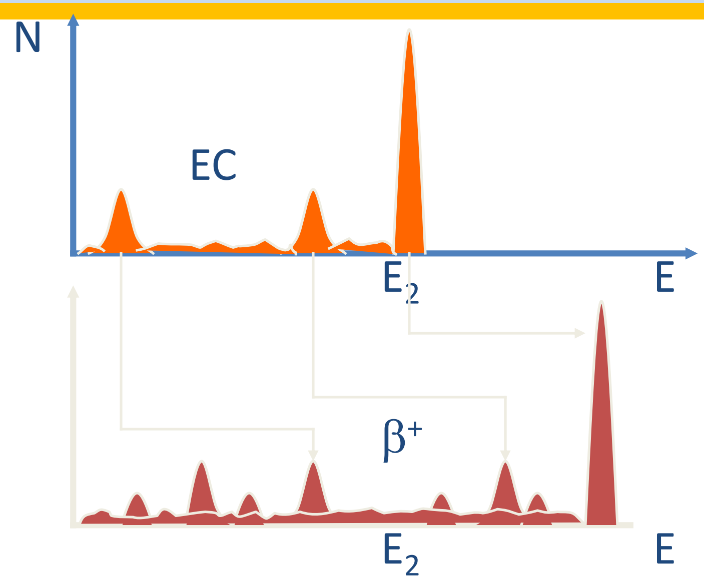
Ex in the daughter

Ideal case

By B. Rubio

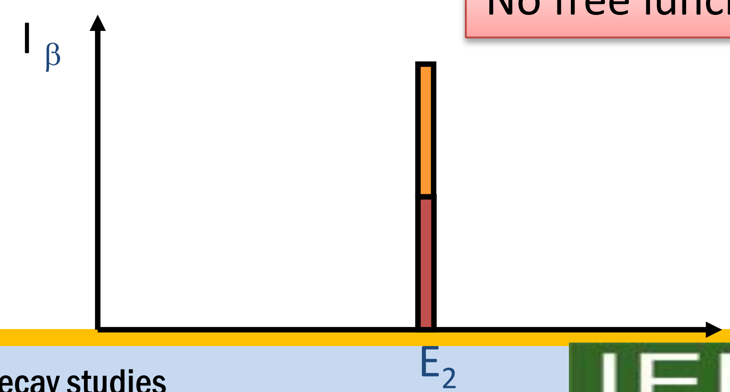
Total absorption spectroscopy





After Deconvolution and sum

No free lunch!!



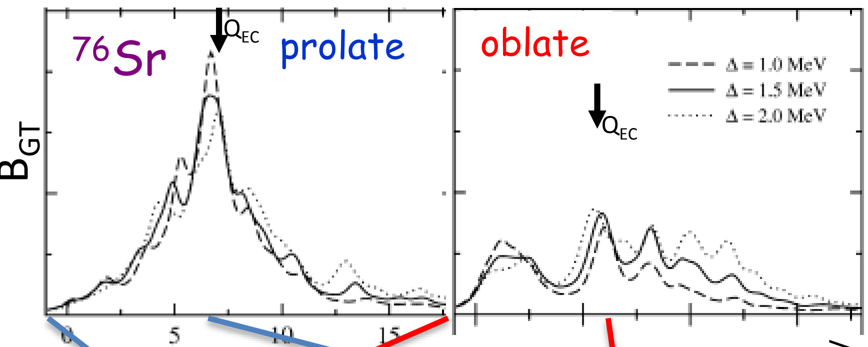
Real case

By B. Rubio

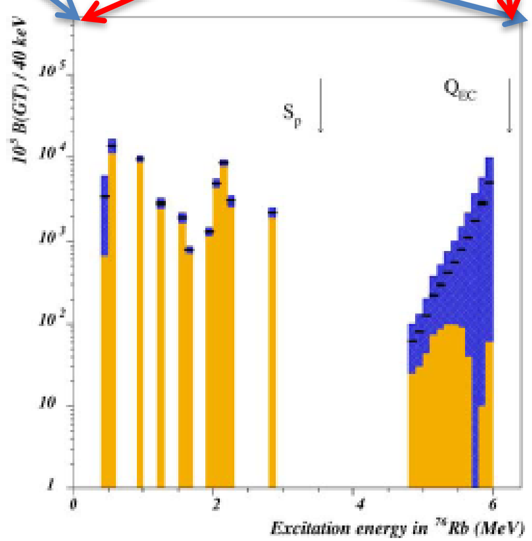
Deformation in the region N ~Z with 70 < A < 80

High resolution measurements: β,βγ,βp

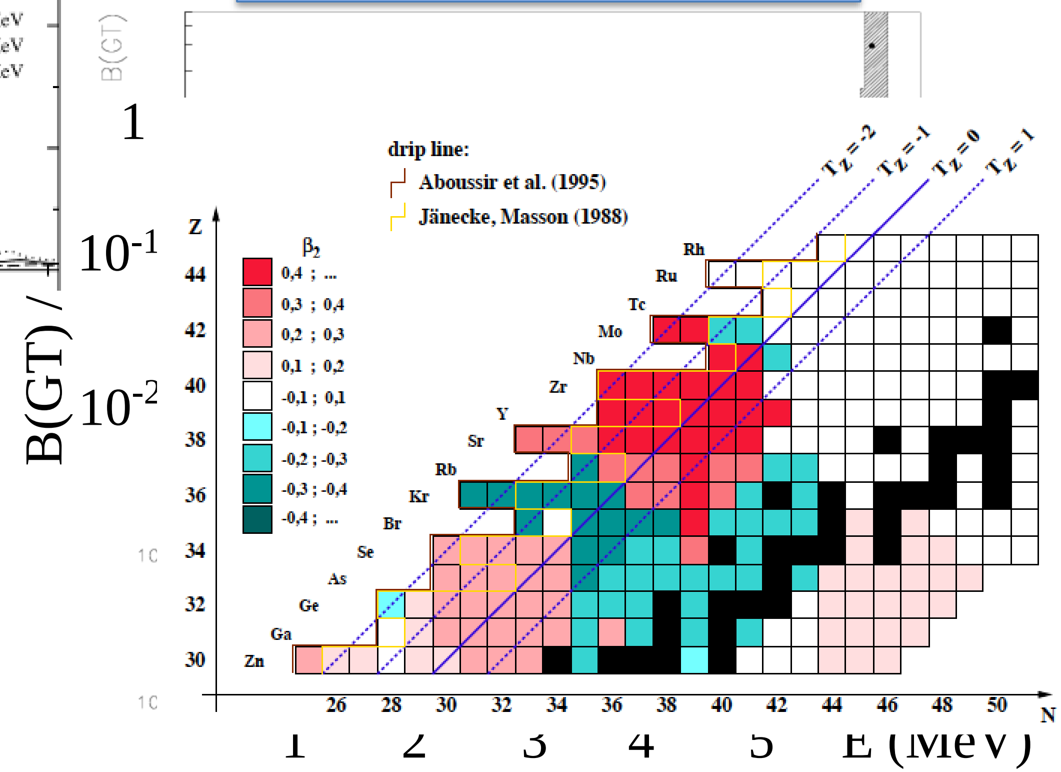
$^{76}Sr \xrightarrow{\beta^+ EC} {}^{76}Rb$



Sarriguren NPA 691(2001)631

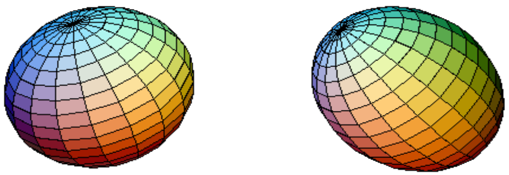


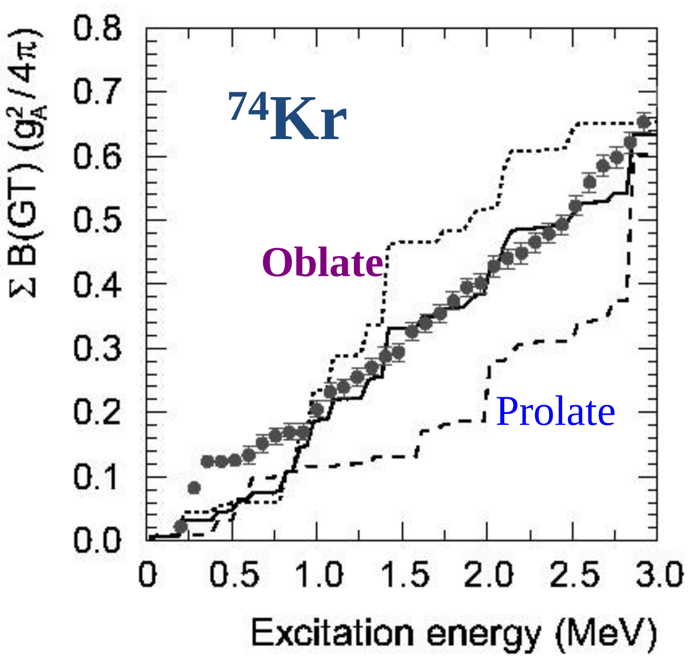
After the TAgS measurements



Mass ~70 : Strong Deformation & Shape Coexistence

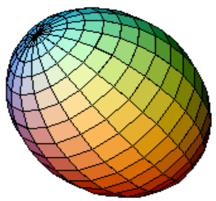
^{74}Kr, shape admixture

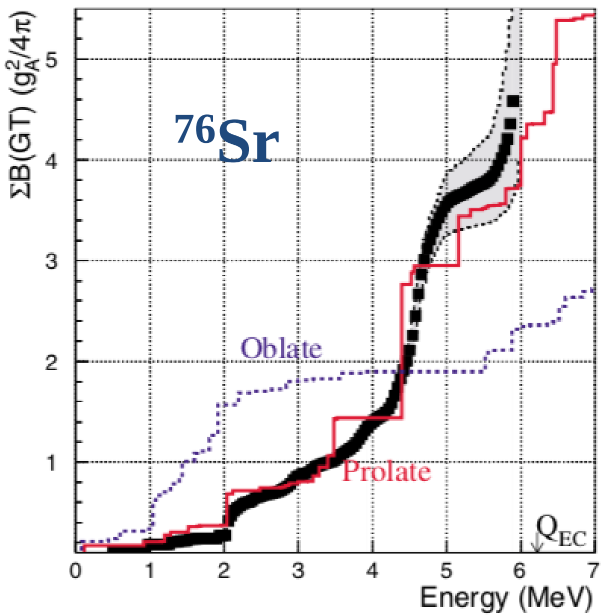




Poirier et al., PRC 69 (2004) 034307

^{76}Sr clearly prolate

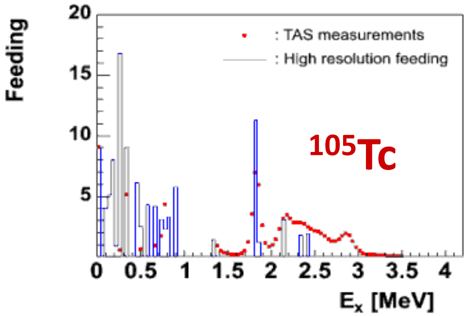




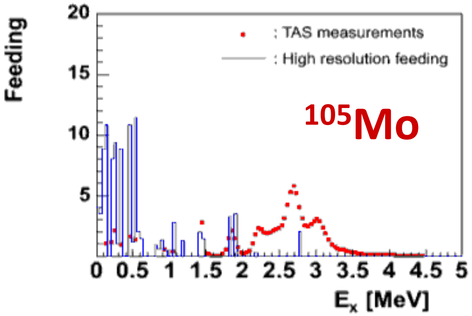
Nácher et al., PRL 92 (2004) 232501

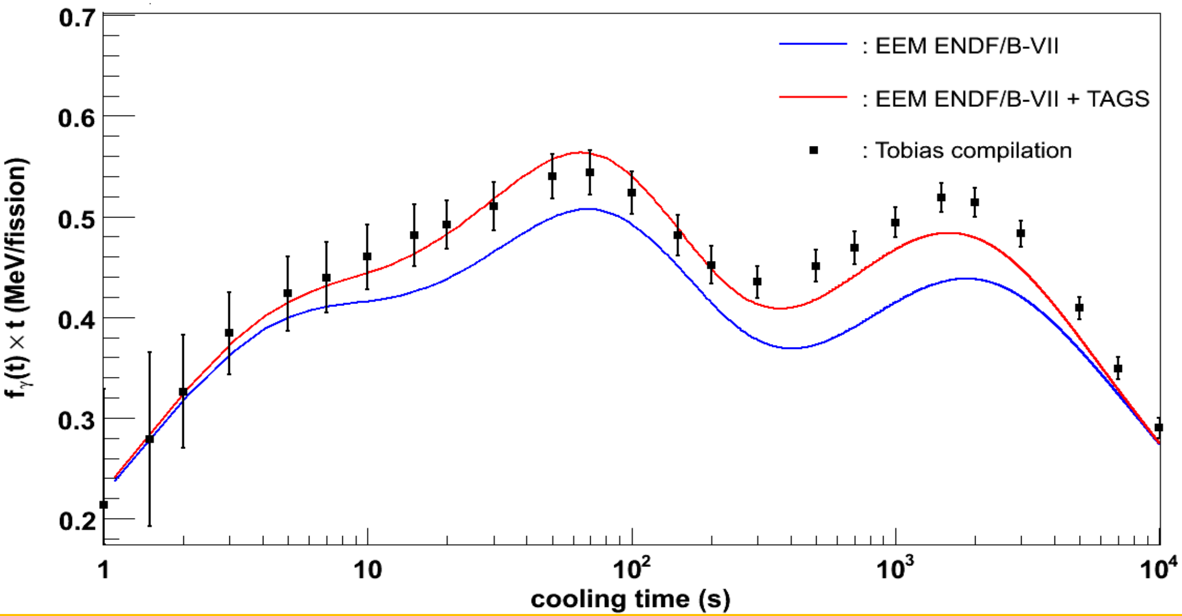
New results on Reactor Decay Heat discrepancies

- Experiment at IGISOL-JYFL (Jyvaskyla), A. Algora et al. Phys. Rev. Lett
- Total Absorption Gamma-ray Spectroscopy (TAGS) technique: IFIC & CIEMAT
- First use of a Penning Trap with TAGS to purify samples



- The new data on the decay of Mo, Tc and Nb isotopes helps to solve a large fraction of the discrepancy between calculated and measured decay heat



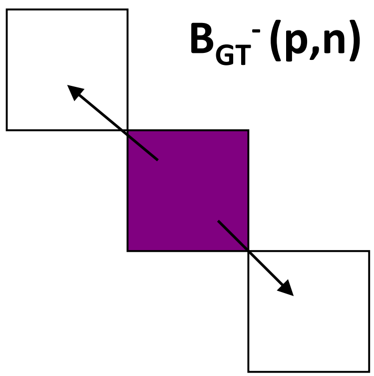


Charge exchange reactions ⟷ Beta decay process

Beta decay and Charge Exchange are two processes governed by the same **στ (τ)** operator

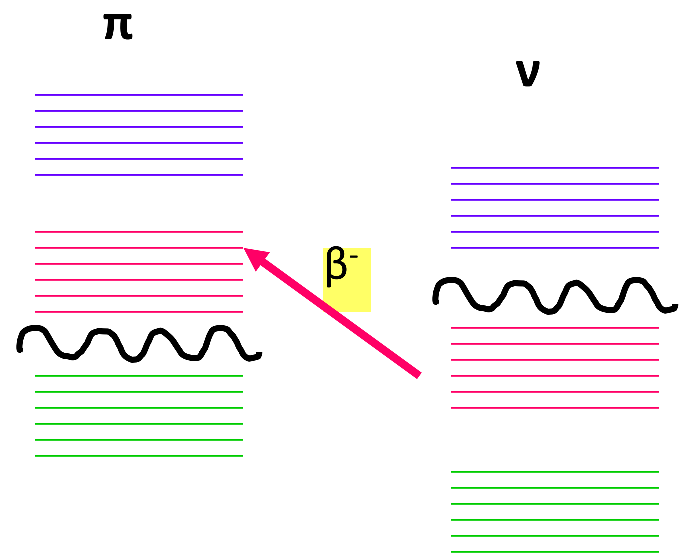
The Ikeda sum rule: Independent

$$S^{-}-S^{+}=B_{GT}^{-}-B_{GT}^{+}=3(N-Z)$$



B_{GT}^{-} (p,n)

B_{GT}^{+}(n,p)



In principle β^- decay is more interesting because most of the nuclei have more neutrons than protons, and then most of the Ikeda sum rule is in the β^- side.

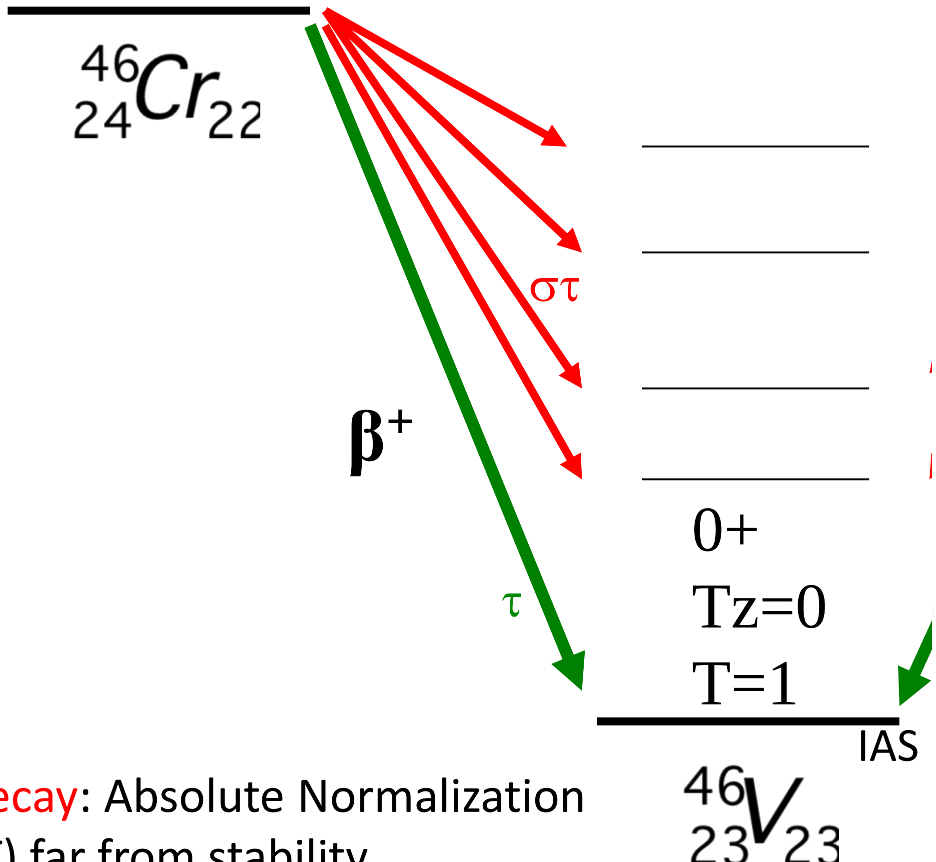
The "experimental B_{GT}" is obtained from the reaction cross section, with all the problems and ambiguities associated (back ground, L transfer, target, current normalisation, detector efficiency....)

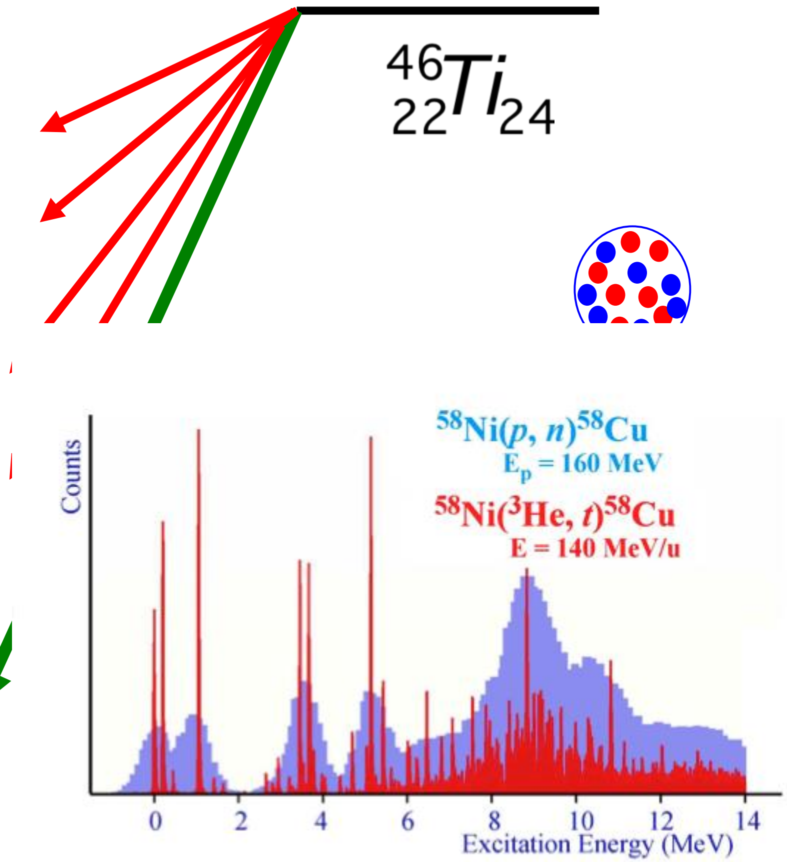
Beta decay versus Charge exchange reactions

Advantages & disadvantages

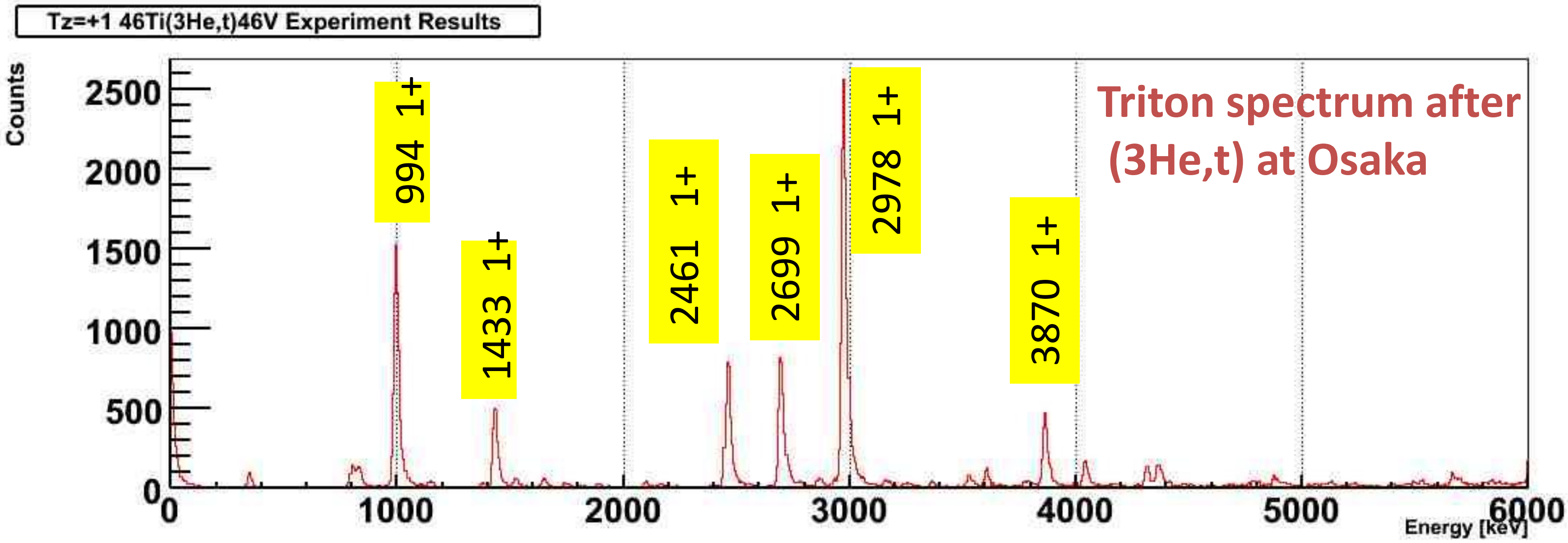
- Mechanism under control
- No background ambiguities
- No normalisation ambiguities
- β^+ or β^- given by nature, β^- almost always bigger than β^+
- Q_β given by nature
- The further from stability the bigger the Q_β window
- At some moment β delayed protons and β delayed neutrons set in

If isospin symmetry holds, mirror nuclei should populate the same states with the same probability, in the daughter nucleus, in the two mirror processes

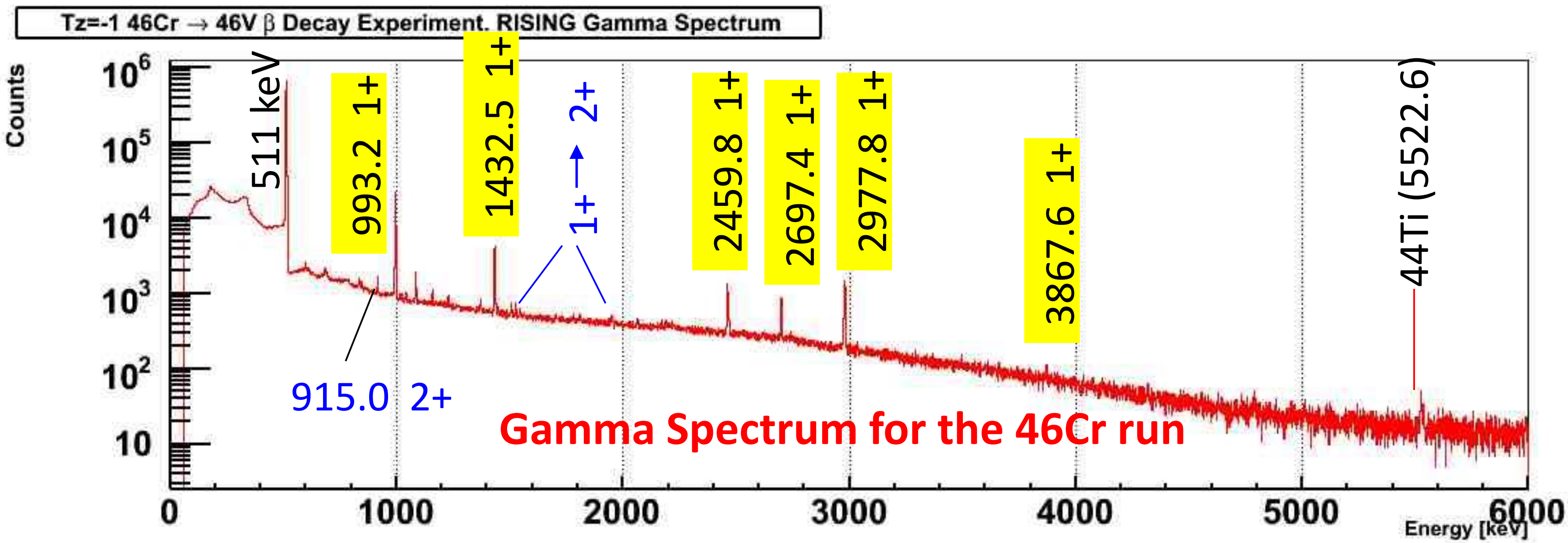




Beta Decay: Absolute Normalization of B(GT) far from stability.



Tz=+1 46Ti(3He,t)46V Experiment Results
Counts
Energy [keV]
994 1+
1433 1+
2461 1+
2699 1+
2978 1+
3870 1+
Triton spectrum after (3He,t) at Osaka



Tz=-1 46Cr → 46V β Decay Experiment. RISING Gamma Spectrum
Counts
Energy [keV]
511 keV
993.2 1+
1432.5 1+
1+ → 2+
2459.8 1+
2697.4 1+
2977.8 1+
3867.6 1+
44Ti (5522.6)
915.0 2+
Gamma Spectrum for the 46Cr run

Double- β Decay

Of interest: *Particle Physics*
Nuclear Physics

ββ2ν : Predicted by the Standard Model

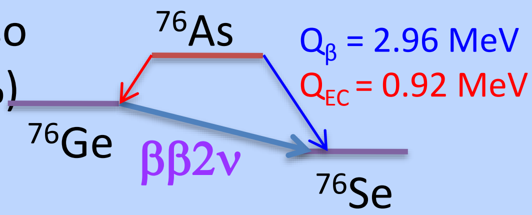
$$(Z, A) \dashrightarrow (Z+2, A) + 2\, e^- + 2\bar{\nu}$$

S.M. (*E. Caurier et al. PRL 77, 1954 1996*) $T_{1/2\ \text{calc.}}$ ~ 0.3 - 1

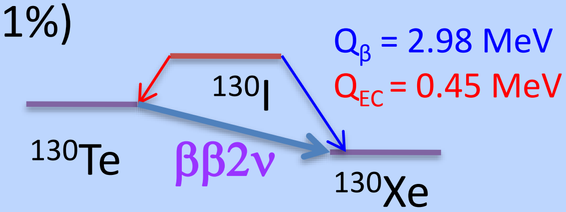
QRPA (J.Engel et al. PRC 37, 731 1988)

Future in Gran Sasso

GERDA (^{76}Ge, 7.6 %)

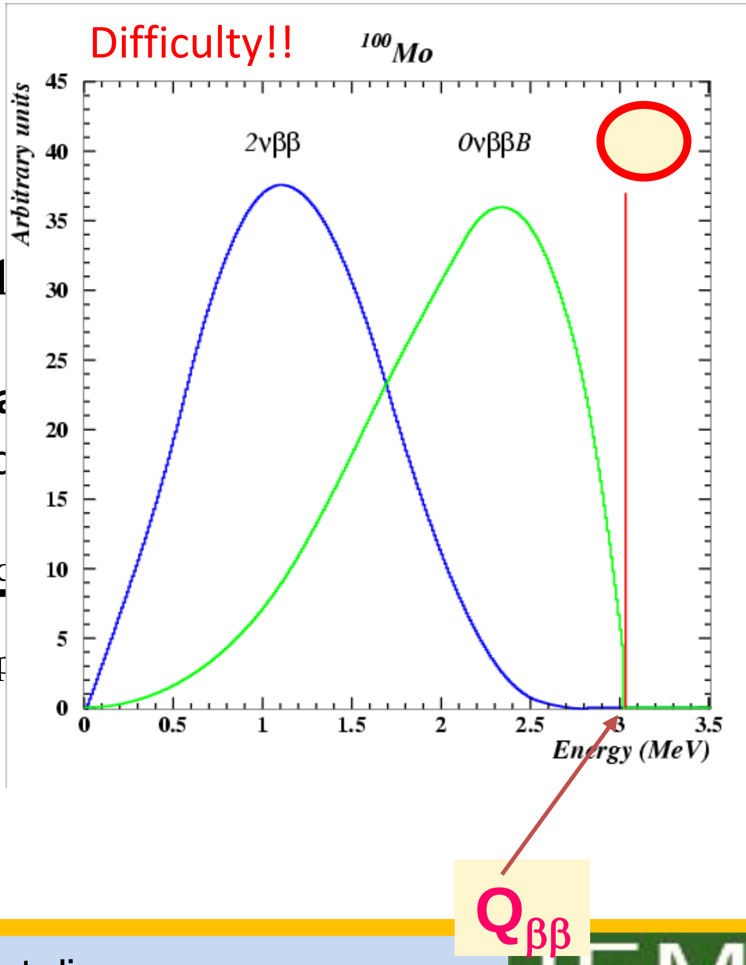


CUORE (^{130}Te, 34.1%)



Super Nemo

NEXT(^{134,136}Xe(20%) TPC, ββ2ν not yet measured)

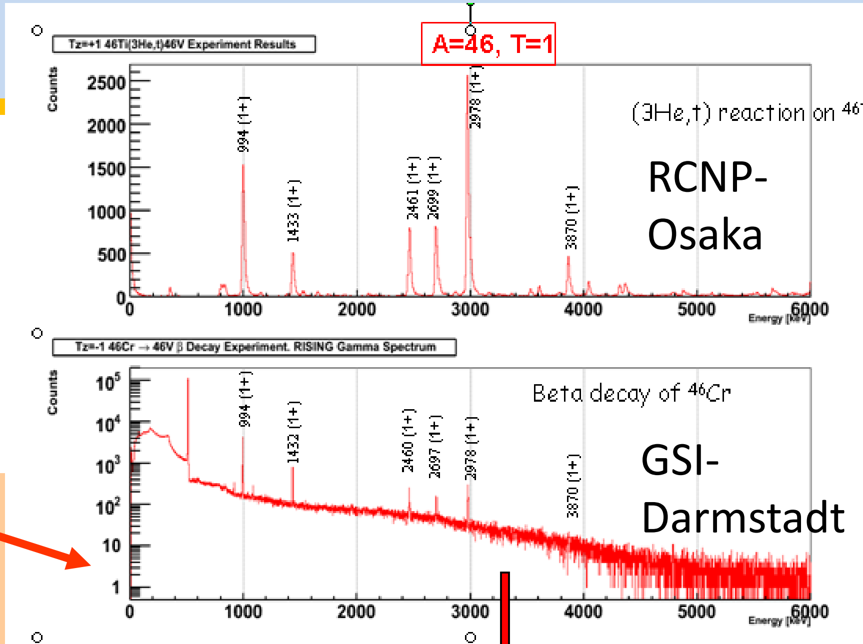


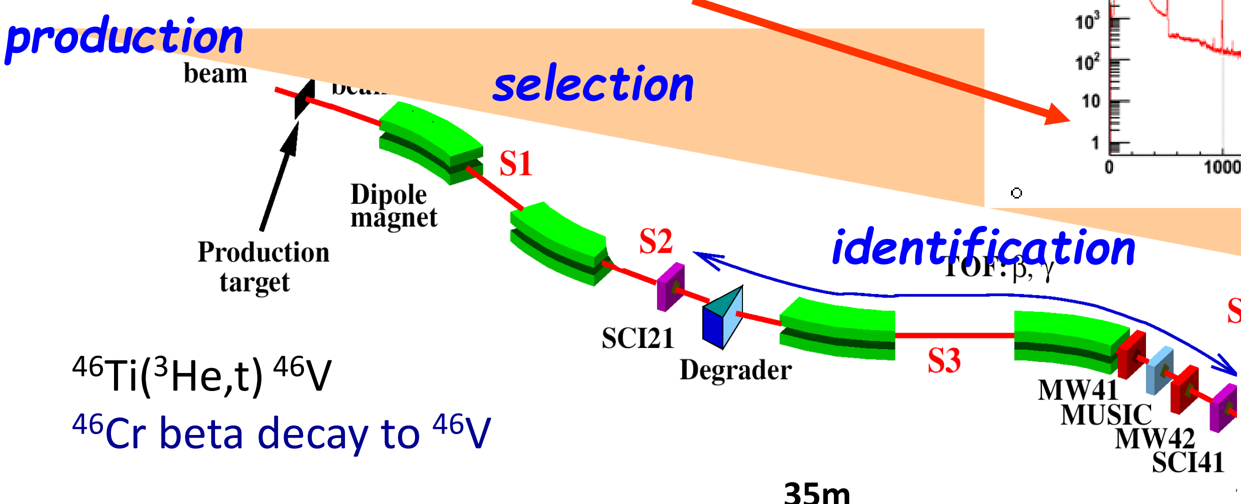
Conclusion

- Beta decay studies is a wonderful tool to peer into the structure of the nucleus

Nuclear Isospin Symmetry Studies using the Weak and Strong Interactions

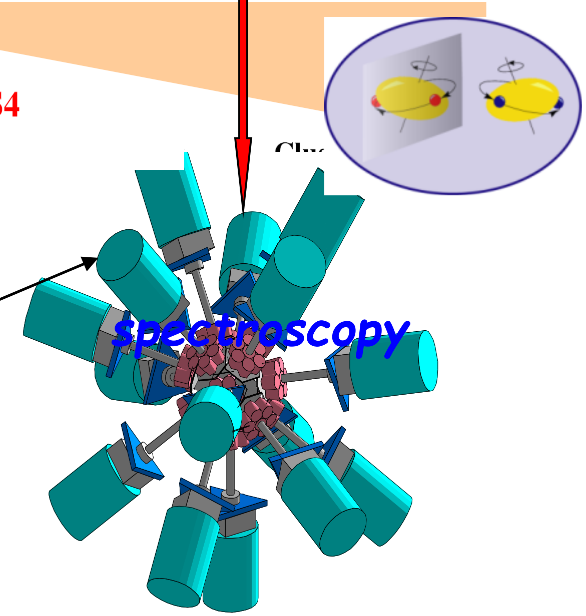
- GSI experiments (towards DESPEC-FAIR),
Co-Spokesperson: B. Rubio
- Fragment Separator (FRS) + Ge- Array RISING





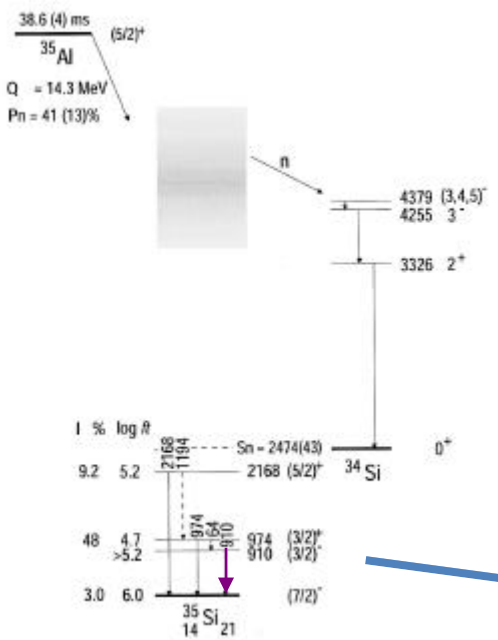
$^{46}Ti(^{3}He,t)\,^{46}V$

^{46}Cr beta decay to ^{46}V

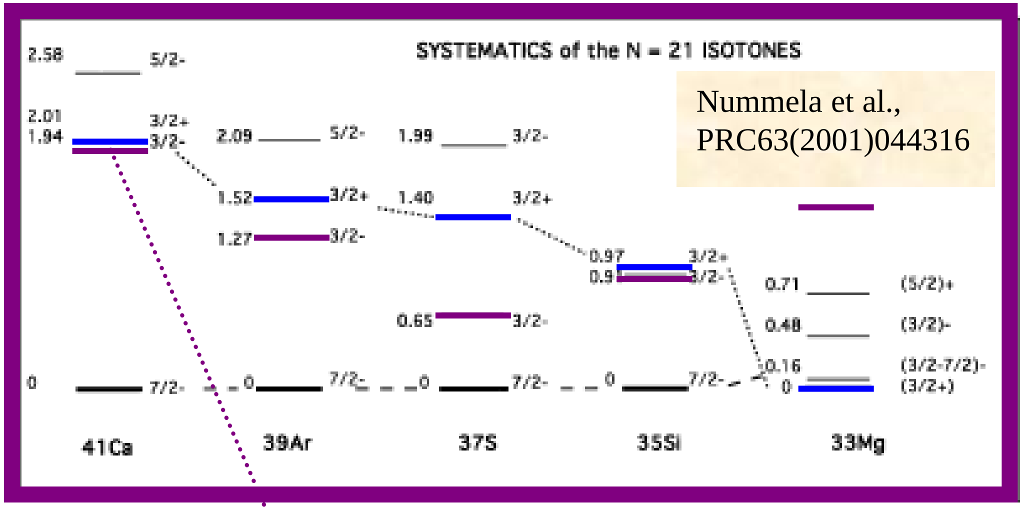


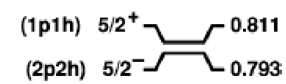
- The states observed in the charge exchange reaction have been also seen
for the first time in the beta decay process
(mirror transitions)

Intruder states & shape coexistence



Nummela et al., PRC63(2001)044316





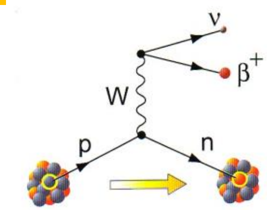
Position of 3/2$^-$ state in N = 21

Fix the single particle energy the effective interaction

- Shell Model describe well by intruder states the Island of Inversion and the deformed region around ^{32}Mg.
- Predicts vulnerability of N= 28 closure for ^{44}S, ^{42}Si and ^{40}Mg $\Rightarrow$ confirmed for ^{44}S (Sohler, PRC66 (2002) 054302)).

0.418
0.352
0.000
Z
^{33}Mg

Superallowed Fermi transitions



For pure Fermi Transition 0+ ➔ 0+

$$f\,(Z, E_b)\, t = K \,/\, |\, M_{if}\, |^2 = \frac{K}{G_v^{\;2}\, |\, M_F\, |^2}$$

$B(F) = \mathrm{I}\, M_F\, \mathrm{I}^2 = T\,(T+1) - Tz_i\, Tz_f$

Hypothesis of the « Conserved Vector Current »

$$f\,(Z, E_b)\,(1 + \delta_R)\, t\;(1 - \delta_C) = \frac{K}{G_v^{\;2}\,(1 + \Delta_R)\, |\, M_F\, |^2}$$

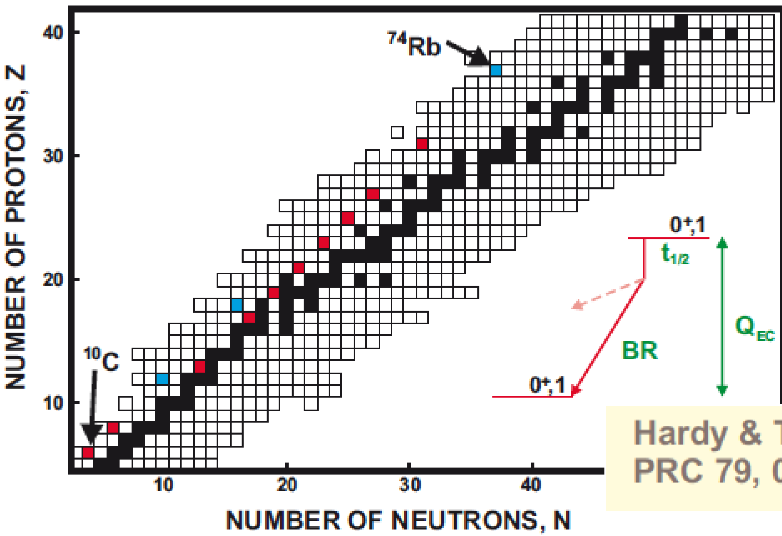
Identical for all transitions estimation of G_V

corrections

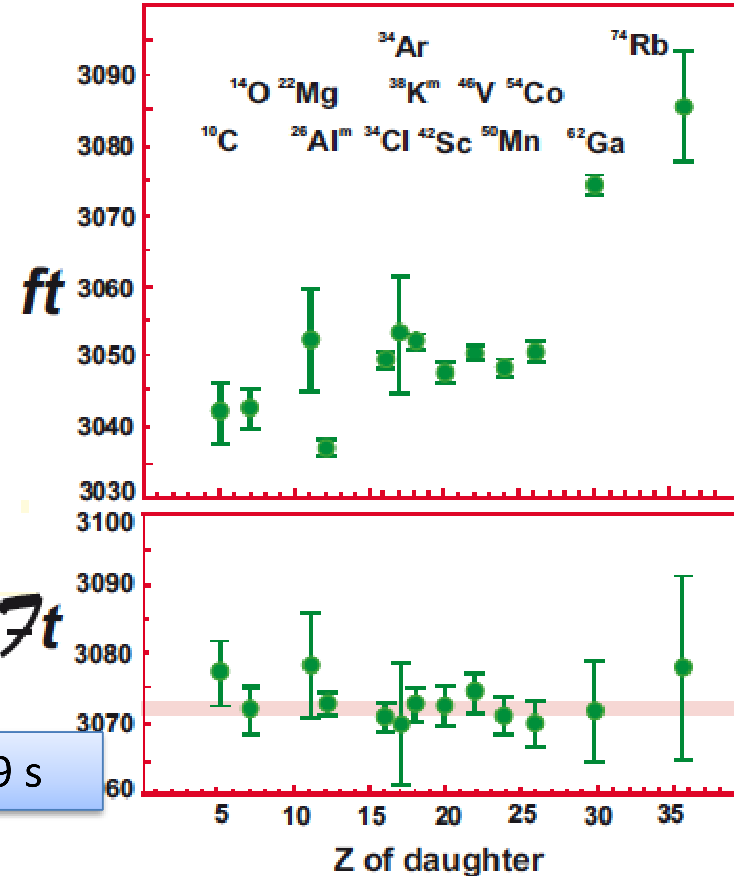
radiatives	Δ_R (2,5 %)	**Independent of nucleus function of model**
	δ_R (1,5 %)	**Exchange of photons between e^+ and nucleus Depend of the nucleus**
Isospin impurities	δ_C (0, 2 – 4 %)	**For states with isospin mixing**

A. Sirlin et al., NP B71, 29 (1974)
D.H. Wilkinson et al., NIM A 335, 172 (1993)
W.E. Ormand et al., PRC 52 2455 (1995)

World data for $0^+ \rightarrow 0^+$ transitions, 2009



Hardy & Towner
PRC 79, 055502 (2009)



- 10 cases with *ft*-values measured to ~0.1% precision; 3 more cases with <0.3% precision.
- ~150 individual measurements with compatible precision

Ft = 3072.08 ± 0.79 s

1) G_V constant ✔ verified to ± 0.013%

2) $|V_{ud}| = G_V/G_\mu$ = 0.97425 ± 0.00022

$$\mathcal{F}t = ft\,(1+\delta_R')[1-(\delta_C-\delta_{NS})] = \frac{K}{2G_V^2\,(1+\Delta_R)}$$

J. Hardy's Talk @ ARIS 2011

3) CKM unitarity established ✔

$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99990 \pm 0.00060$$