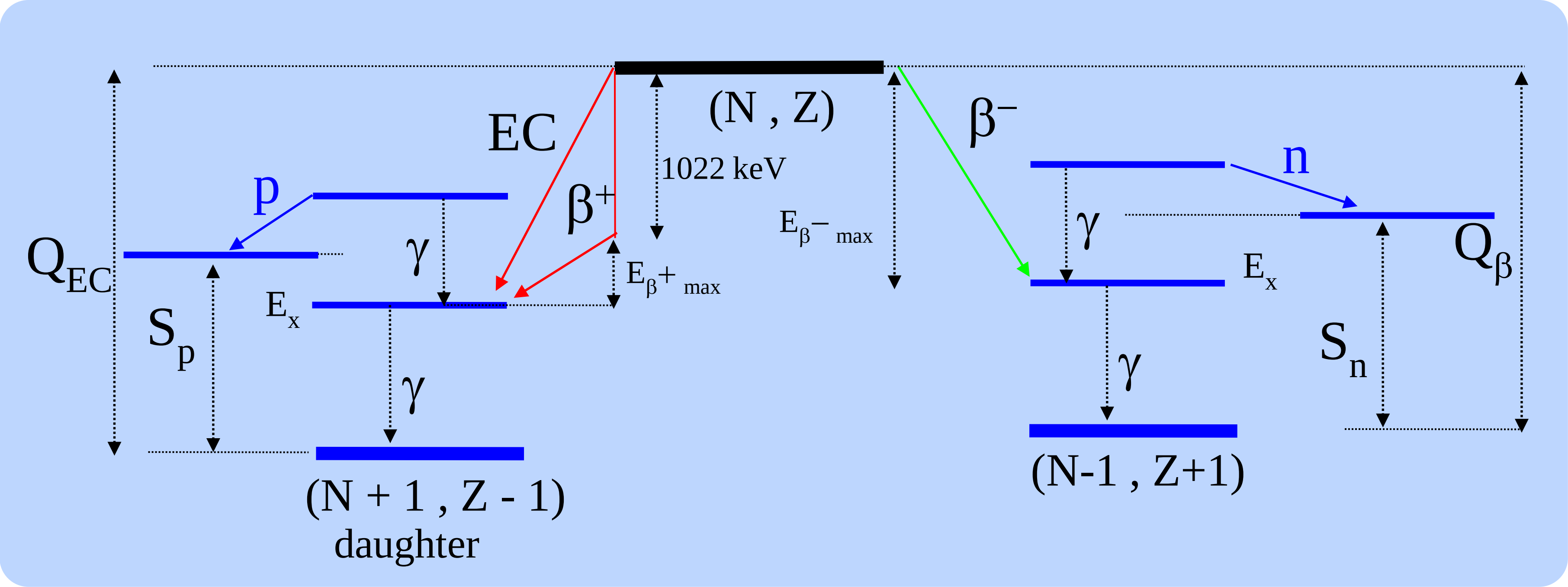
Introduction

Process mediated by the weak interaction between two isobars

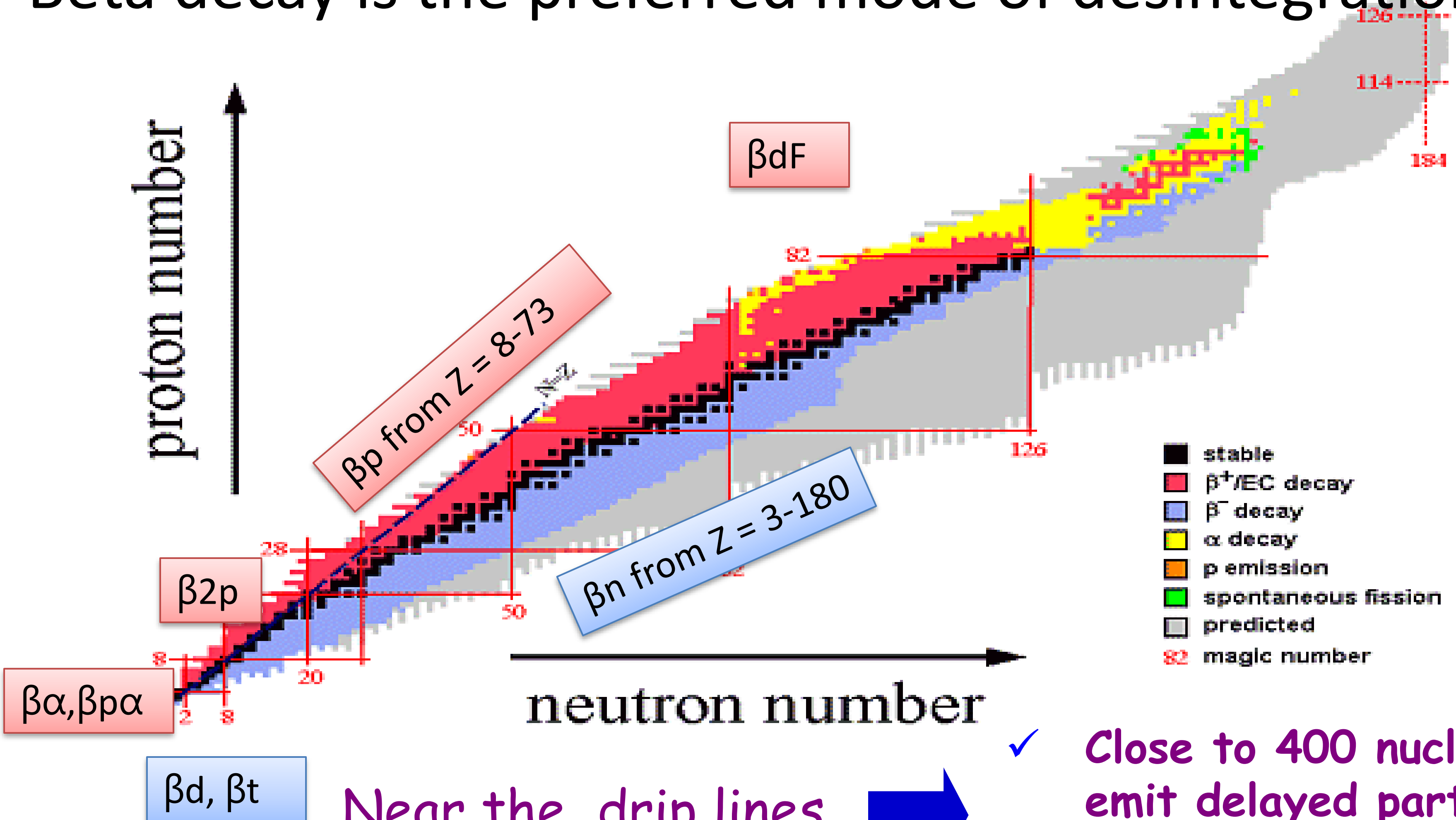
$(N , Z) \xrightarrow{\beta^-} (N\text{-}1, Z\text{+}1) + e^- + \bar{\nu}$ M(Z) - M(Z+1)= $E_\beta + E_\nu$ + Ex

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



Beta Delayed Particle Emission

Beta decay is the preferred mode of desintegration



Near the drip lines

- ✓ Close to 400 nuclei emit delayed particles
- ✓ Exotic decays

Planning and References

- Beta delayed Particle emission
  - Mechanisms of Breakup
  - Analysis technique

References:

✓"Particle Emission from Nuclei" Ed. D.N. Poenaru & M.S. Ivaçcu CRD 1989 Vol I, II, III

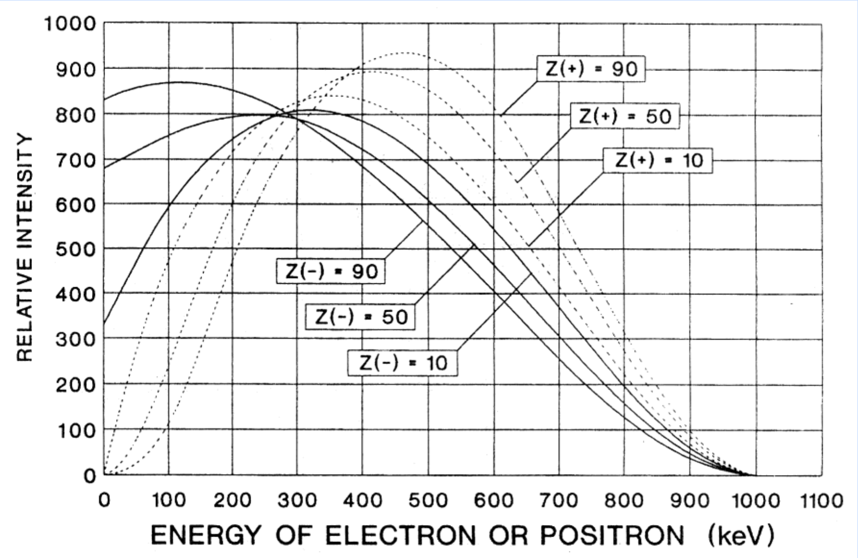
✓B. Blank and M.J.G. Borge, Prog Part and Nuc. Phys 60 (2008) 403

✓M. Pfützner, L.V. Grigorenco, M. Karny & K. Riisager, Rev. Mod. Phys,ArXiV:1111.0482

✓Euroschool on Exotic Beams, Lectures Notes: "Decay Studies of N~Z Nuclei", E. Roeckl, École Joliot-Curie de Physique Nucleaire, **2002**

Reminder

Spectra $\beta^{\pm}$



Expand in a large E-scale

E_{β^-} = 2,6 keV (^{187}Re, β^-)

E_{β^-} = 22800 keV (^{22}N, β^-)

$Q = M(Z,N) - M'(Z+1,N-1) - m_e c^2 = T_{M'} + Te + T\nu$

$N(p) \propto p^2(Q\text{-}Te\text{-}T\nu)$

Half-life

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

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

^{50}V, $T_{1/2}$ = 10^{17} y; (^{115}In, 10^{14} y ; ^{113}Cd, 10^{15} y)

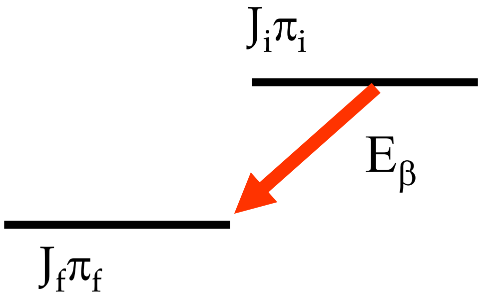
Emission of delayed particles

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

Practical example

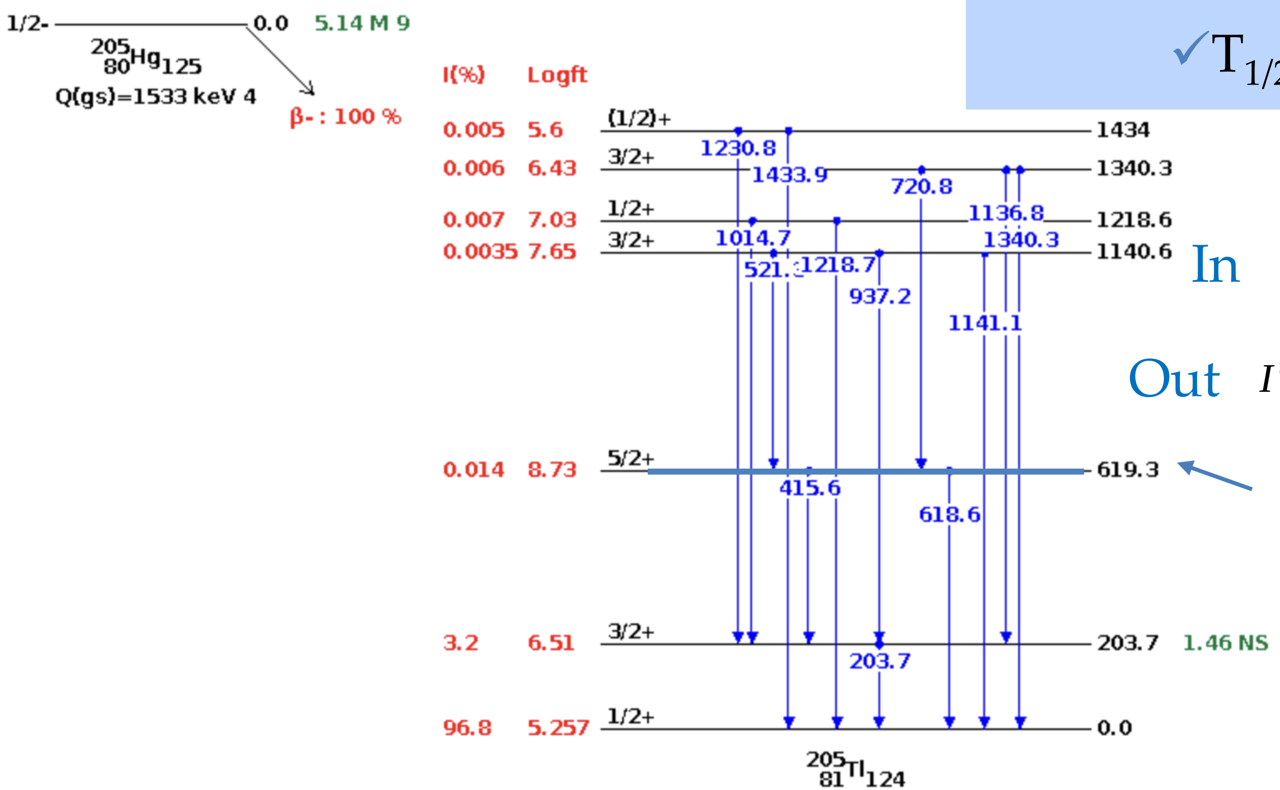
$$t \equiv T_{1/2}^{\beta_i} = \frac{T_{1/2}^{\exp}}{P_{\beta_i}}$$

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

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

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

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



In $I^{tot}(521+721) = 0.086(16)$

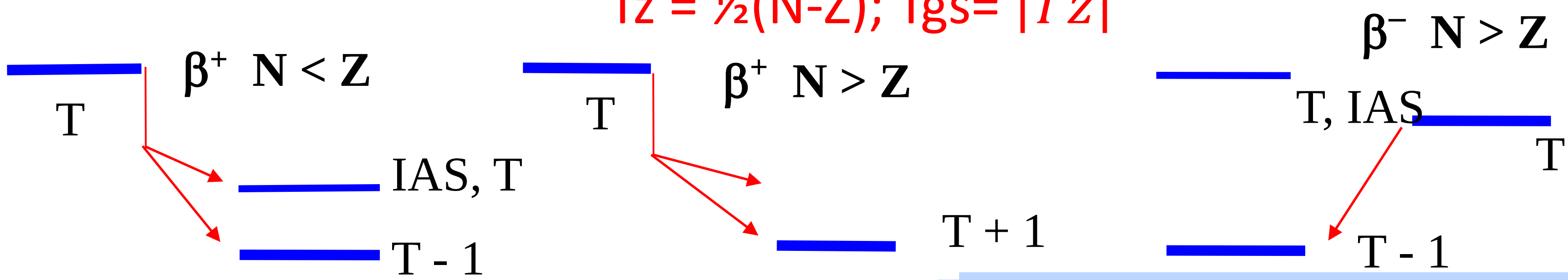
Out $I^{tot}(416+619) = 0.78(10)$

I(in) –I(out) [619,3 keV]= 0.69(10)

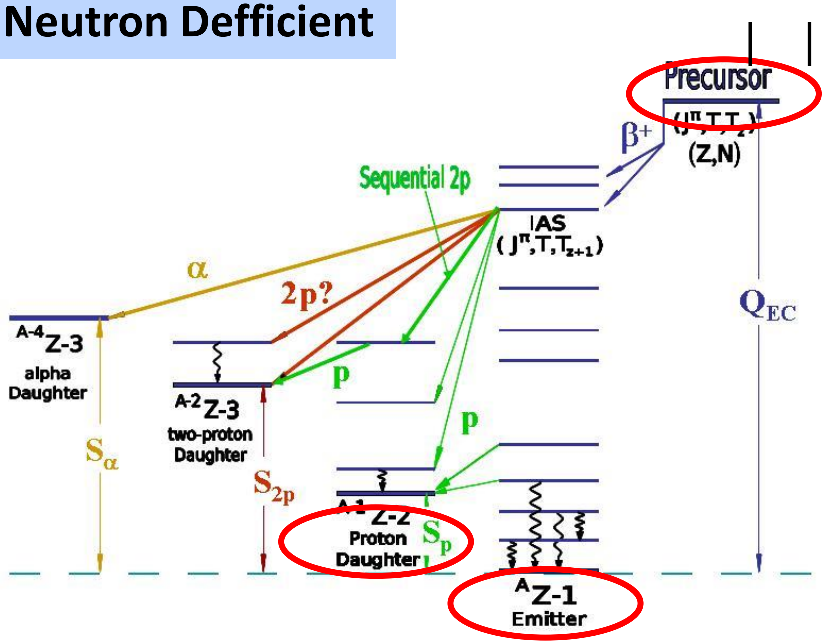
$$\eta = 0.0022 \rightarrow t = 2.056\times10^6[s] \rightarrow \log t = 6.31 \rightarrow \log f = 2.386 \rightarrow \log ft = 8.7$$

Beta Transitions

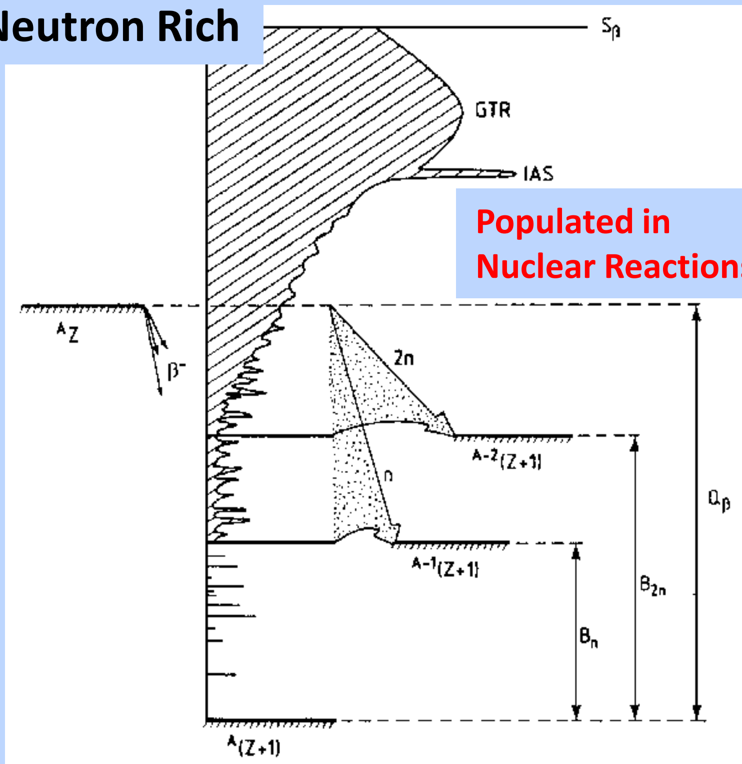
Tz = ½(N-Z); Tgs= $|Tz|$



Neutron Defficient



Neutron Rich



Populated in Nuclear Reactions

Decay properties of exotic nuclei

- 1916 **Rutherford & Wood** βα [*Philos. Mag.* ***31*** *(1916) 379*]
- 1963 **Barton & Bell** identified ^{25}Si as βp

➢ Global properties

- ***Short half-lives (~ms)***
- ***High Q_β values***
- ***Low $S_{p/n}$ values***

→ β-delayed particle emission

- ***Reduced transition probability:***

$$ft = f * \frac{T_{1/2}}{B.R.} = \frac{K}{G_V^2 |\tau|^2 + G_A^2 |\sigma\tau|^2} = \frac{C}{B(F) + B(GT)}$$

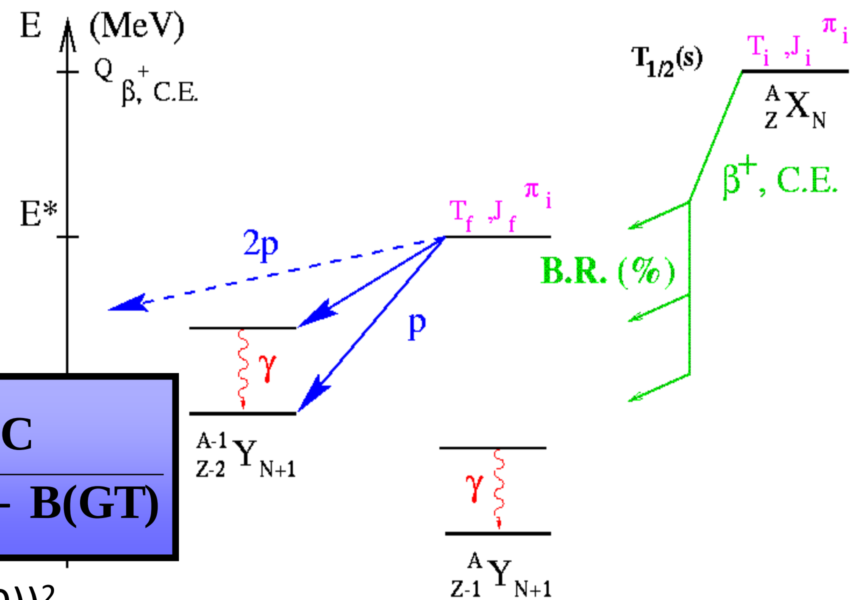
$K/G_V^2 = 6144(1)$ s = C and $(G_A/G_V)^2 = (-1{,}2695(29))^2$

Fermi Strength independent of Nuclear Structure

$$B_F^+ - B_F^- = Z - N \qquad B_F = T(T+1) - T_{zi}T_{zf}$$

Gamow-Teller strength obeys the Ikeda sum Rule

$$\Sigma B_{GT}^- - \Sigma B_{GT}^+ = 3\,(N-Z)$$

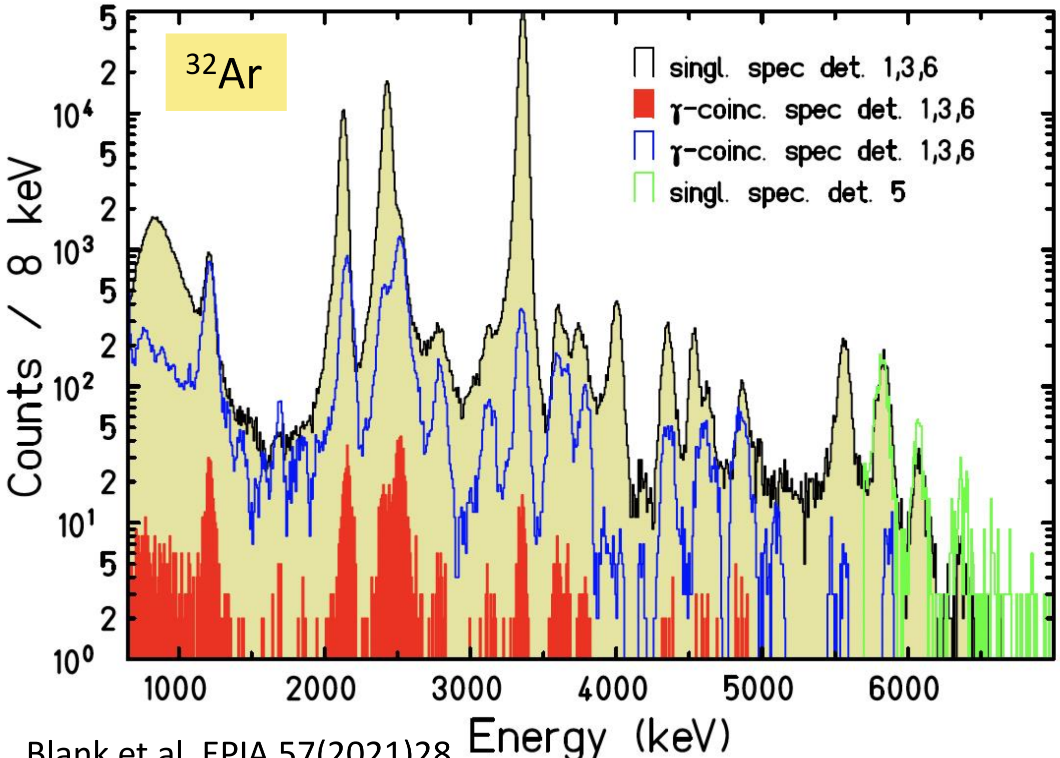


$$I_p^{if} = f(B_F^i + B_{GT}^i)\frac{\Gamma_p^{if}}{\Gamma_p^i + \Gamma_\gamma^i}$$

E, Γ
Level density
Spin, Isospin
β-decay properties

Beta-proton emitters

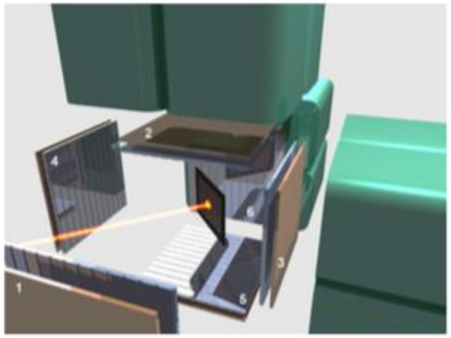
- ✓ More than 160 precursors identified
- ✓ For every element up to Z = 73 at least one proton precursor
- ✓ The βp spectrum depends on the Z and A of the precursor and differs in the different mass region due to diferences in level density in the Q-Sp window
- ✓ Properties of βp well understood → large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

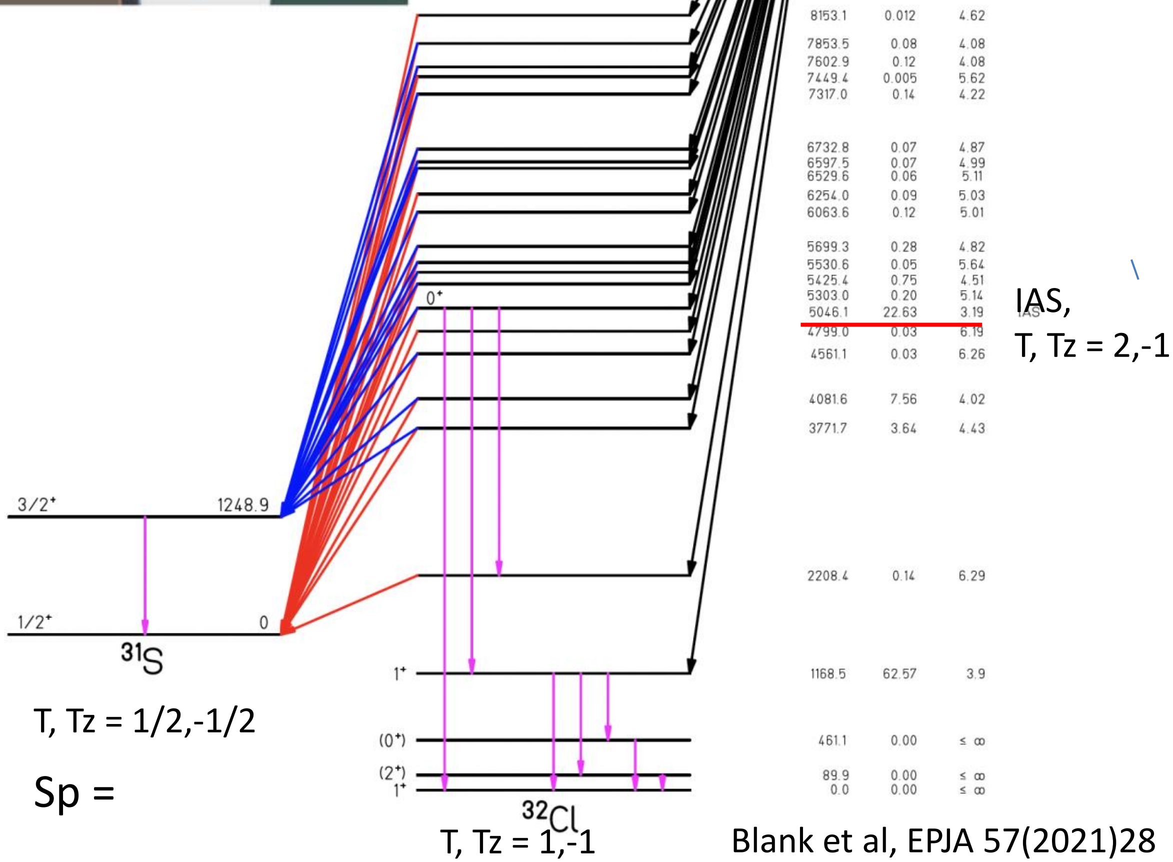


Blank et al, EPJA 57(2021)28

- ✓For light nuclei with Z ≥ 8, the IAS within the Q_{EC} 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 ≠ 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 Symmetry

$^{32}Ar(Z=18, N=14) \rightarrow {}^{32}Cl\ (Z=17, N=15)$





Blank et al, EPJA 57(2021)28

- By $\beta p \rightarrow$ study up to 8153 keV $\rightarrow$73% of energy window
- 22.6% feeding IAS$\rightarrow$ logft = 3.19

Γ_p / Γ_γ(IAS) = 11.2(11)

$\Gamma = \Gamma_p + \Gamma_\gamma = 20(5)$ eV

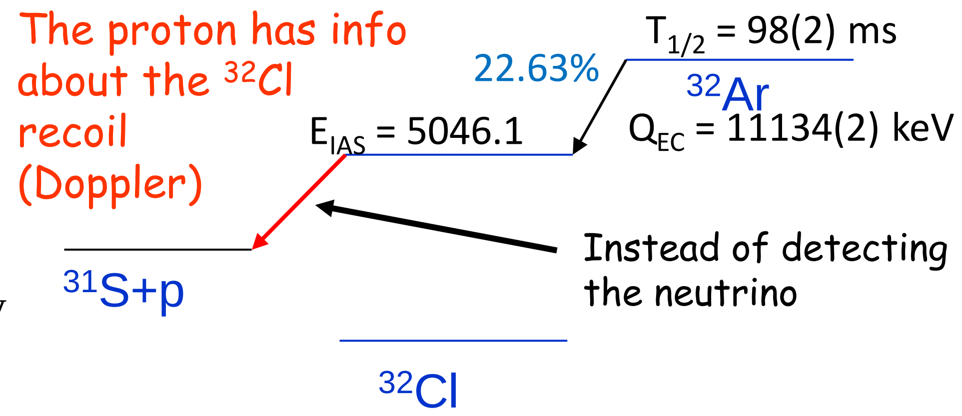
The width of the IAS is very narrow as the proton emisión is isospín forbidden, facilitating the emisión of M1 transition of the 5.046 MeV IAS

$B(F) = T(T+1)-T_{zi}T_{zf} = 2x3-(-2)(-1) = 6-2 = 4$

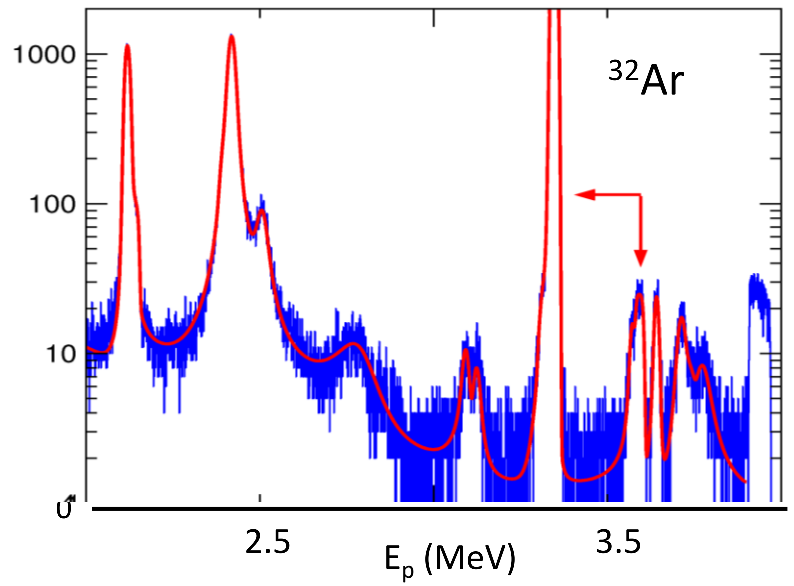
Predicted mixing with 0^+ T= 1 states $\rightarrow$No strong feeding observed to states nearby. Closest E = 5425 keV (ΔE = 379 keV)

Electron-Neutrino Correlations (βp emitters)

- ✓ βν correlation depends of the type of the transition
- ✓ Important probe of the nature of weak interaction

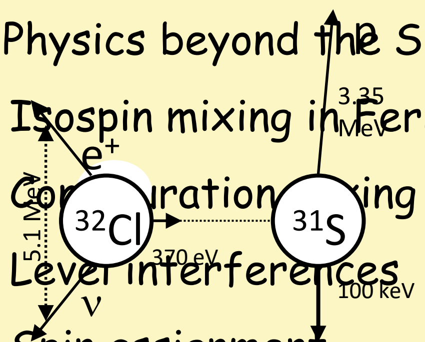


The V-A character of β-decay was determined by measuring the recoil energy spectrum of ^{6}He [Johnson et al, PR132(63)1149]



Study of the proton line shape

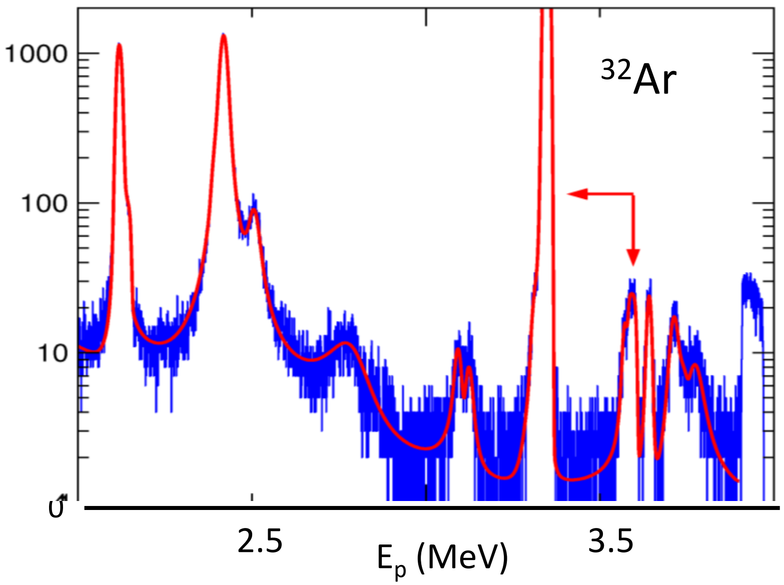
- Physics beyond the SM
- Isospin mixing in Fermi decays
- Configuration mixing
- Level interferences
- Spin assignment
- Excitation energies



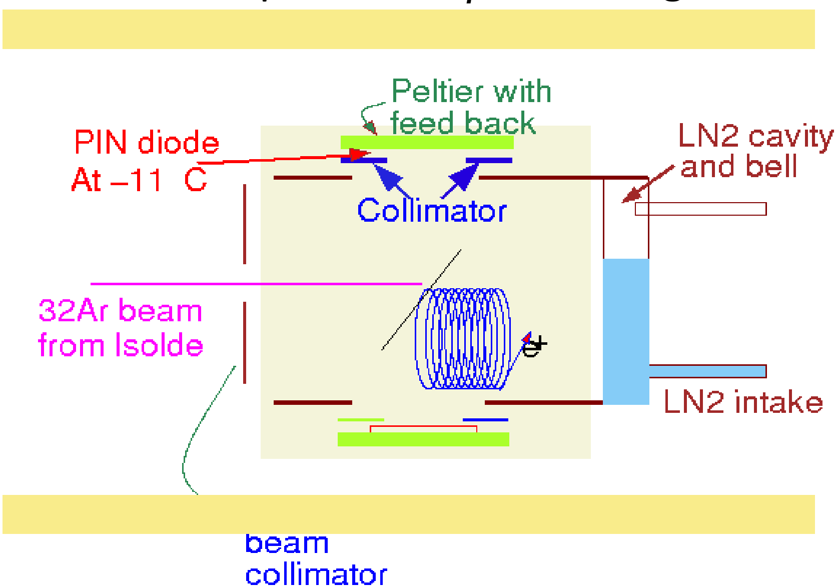
Schardt & Riisager, Z. Phys. A 345 (1993) 265

Adelberger & Garcia, Hyp. Int 129 (2000) 237

$\beta\nu$ correlation studies: Search for New Physics



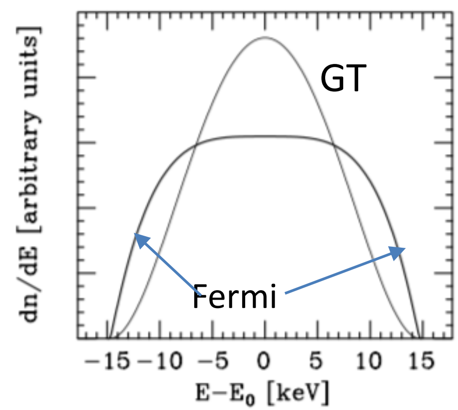
- Set-up to avoid β-summing @ ISOLDE



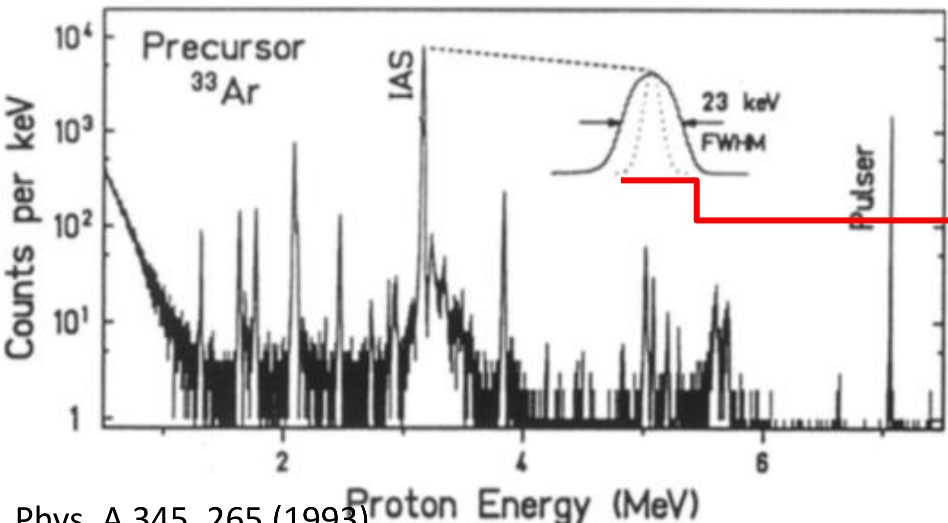
- If βp emitter ⇒ measurement of e-ν correlation ⇒ F/GT nature of transition **from the broadening of proton peak.**
- Limit for scalar component in beta decays

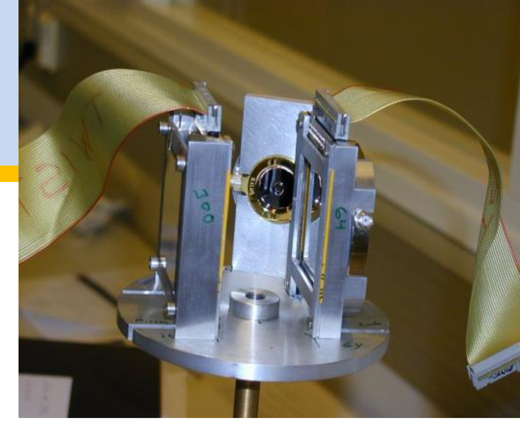
  $M_S \geq 4.1\ M_W$

Adelberguer et al., PRL (1999)



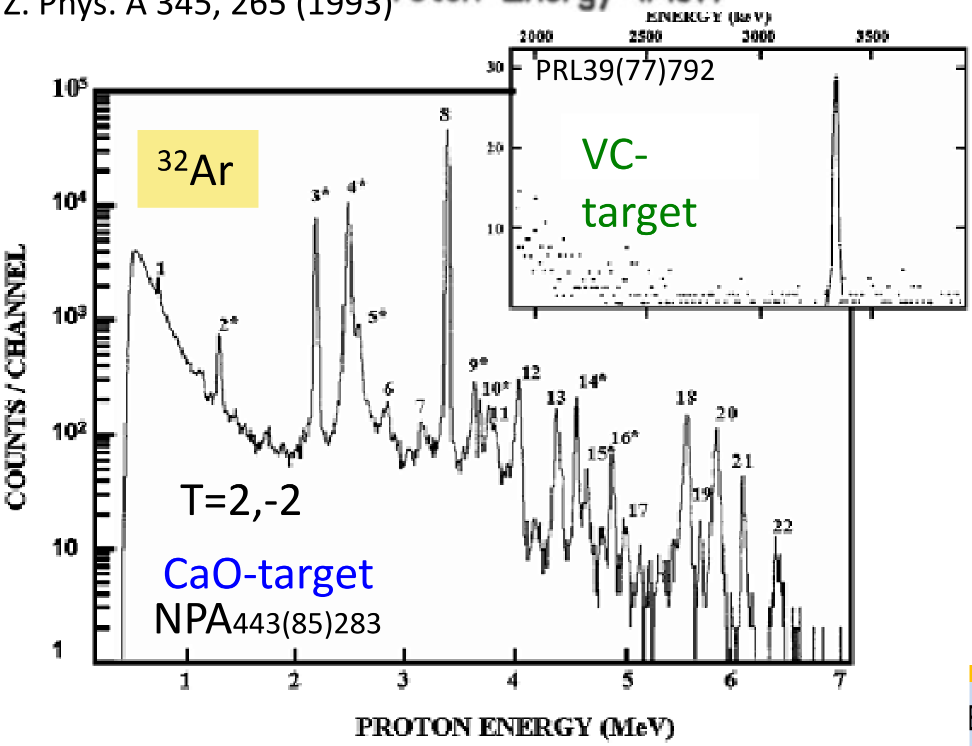
$^{32,33}Ar$ – β decay





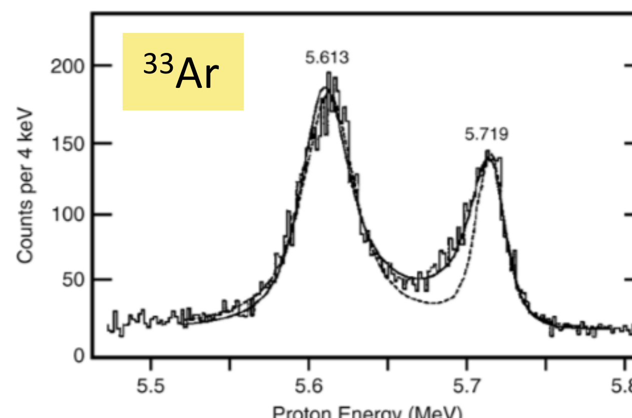
E-resolution = 8 keV

Z. Phys. A 345, 265 (1993)

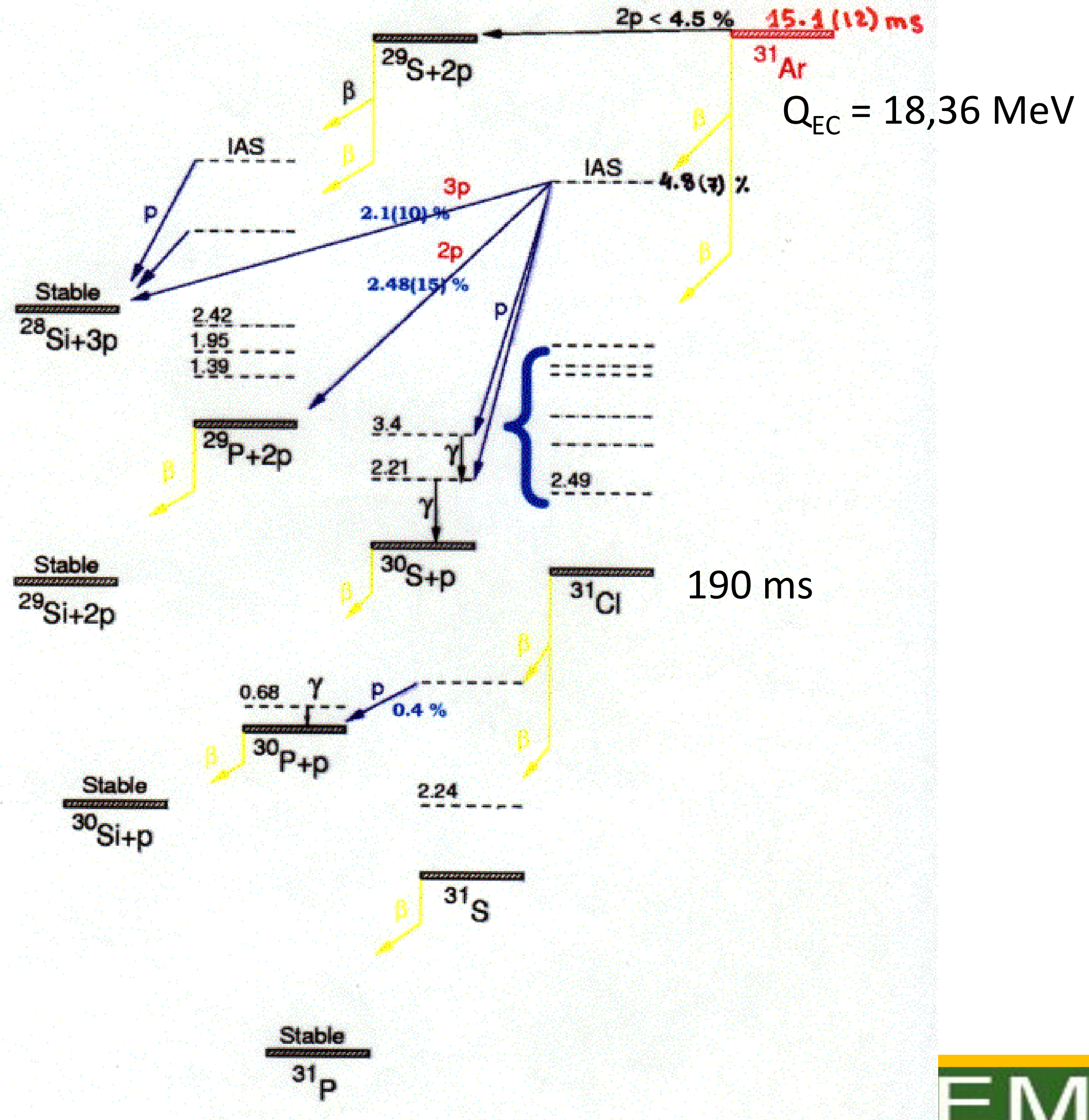


Angular correlations between e+ and ν in the Fermi and GT transitions → the Doppler effect larger recoil broadening of the proton lines for Fermi than for GT decay (Emission before the recoil daughter comes to rest)

$$E^* = Ep(CM) + Sp(33Cl) = Ep\frac{\Delta M(32S)+\Delta M(p)}{\Delta M(32S)} + Sp(33Cl)$$

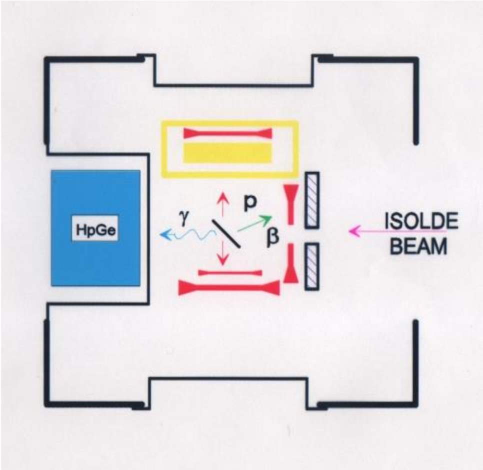


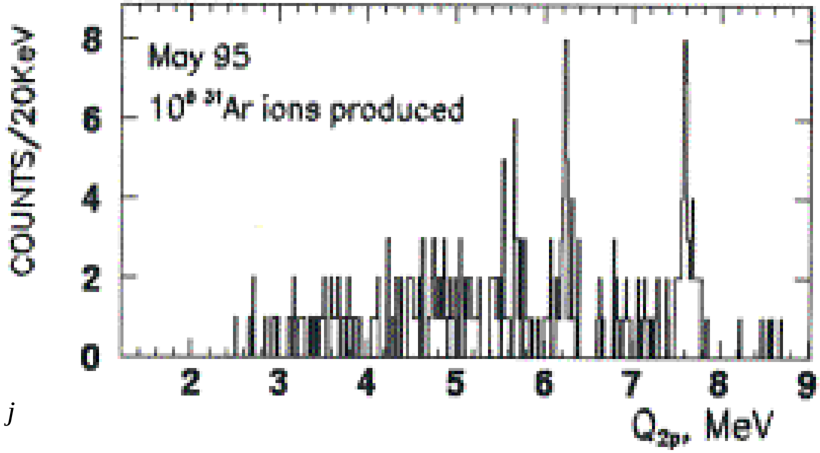
The decay of ^{31}Ar



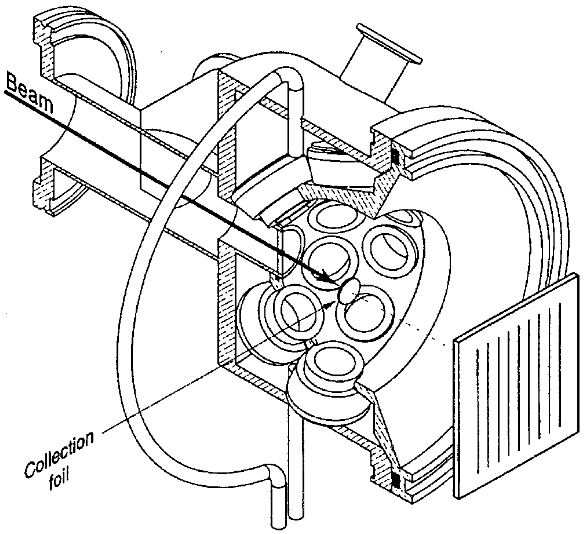
CSIC

β-delayed 2p emission from ^{31}Ar

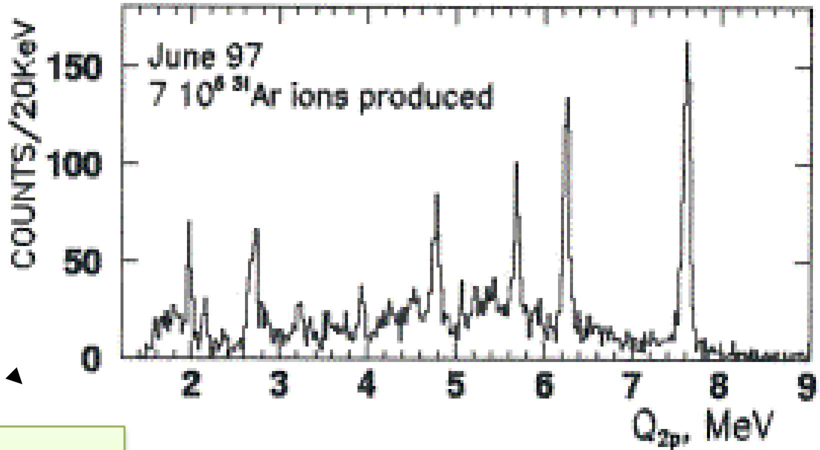




$$\varepsilon_{2p} = \left(\sum_{I=1}^{N}\Omega_i\right)^2 = \sum_{i=1}^{N}\Omega_i^2 + 2\sum\Omega_i\Omega_j$$



Yield	**2 atom/s**
Solid angle 14 + 11 %	
ε_{1p}	**23.7 %**
ε_{2p}	**5.2 %**
ε_{3p}	**1.3 %**

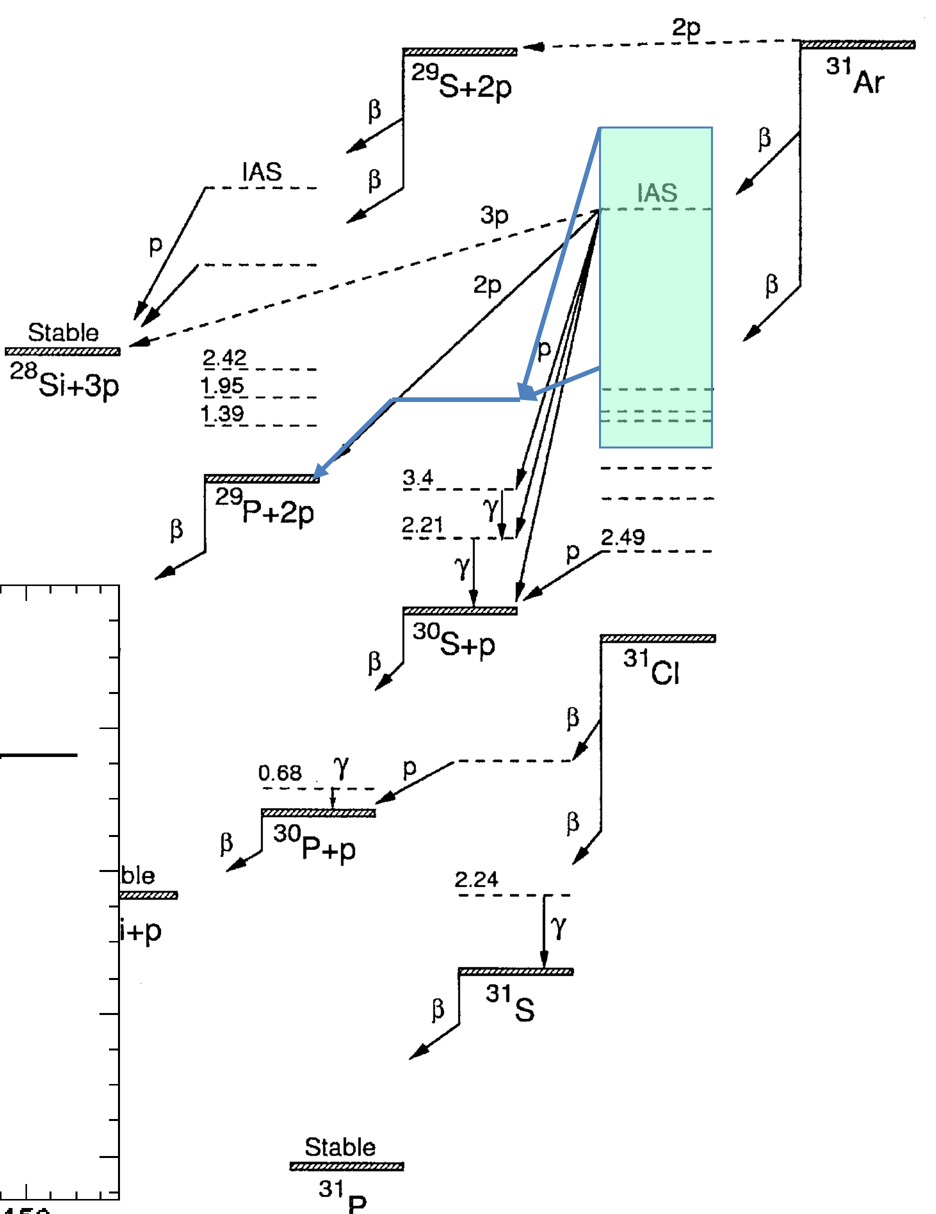


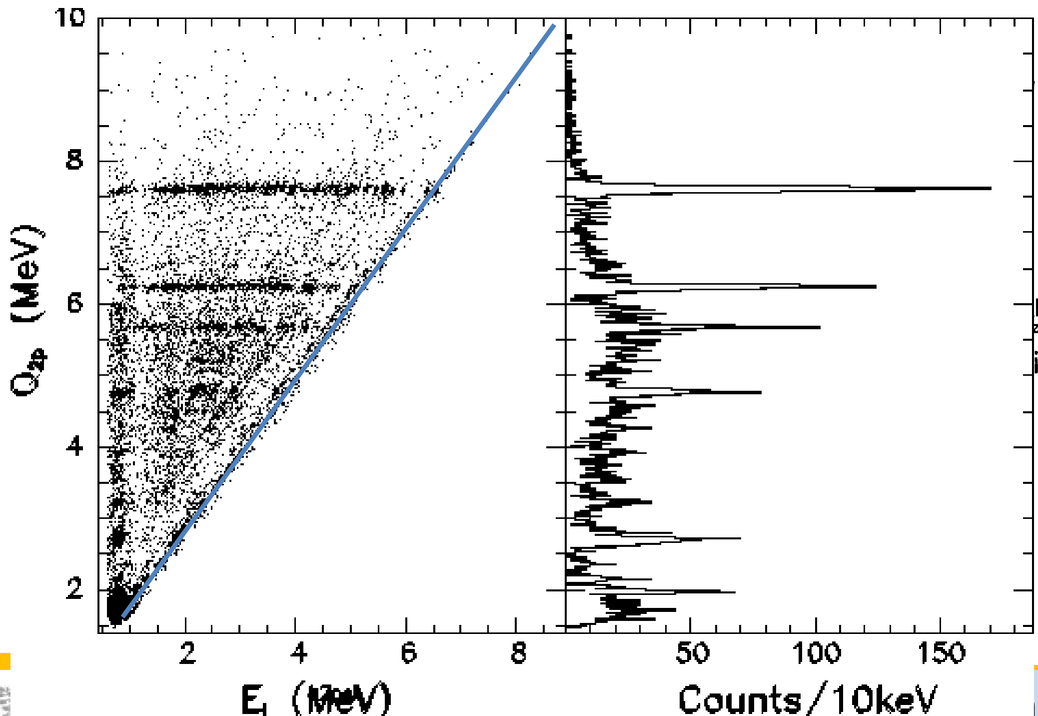
Granularity Increases
Multiparticle Efficiency

Diagonal from decays via single intermediate state from many initial states fed in beta-decay

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

$M_{D1} = M(^{30}S)$



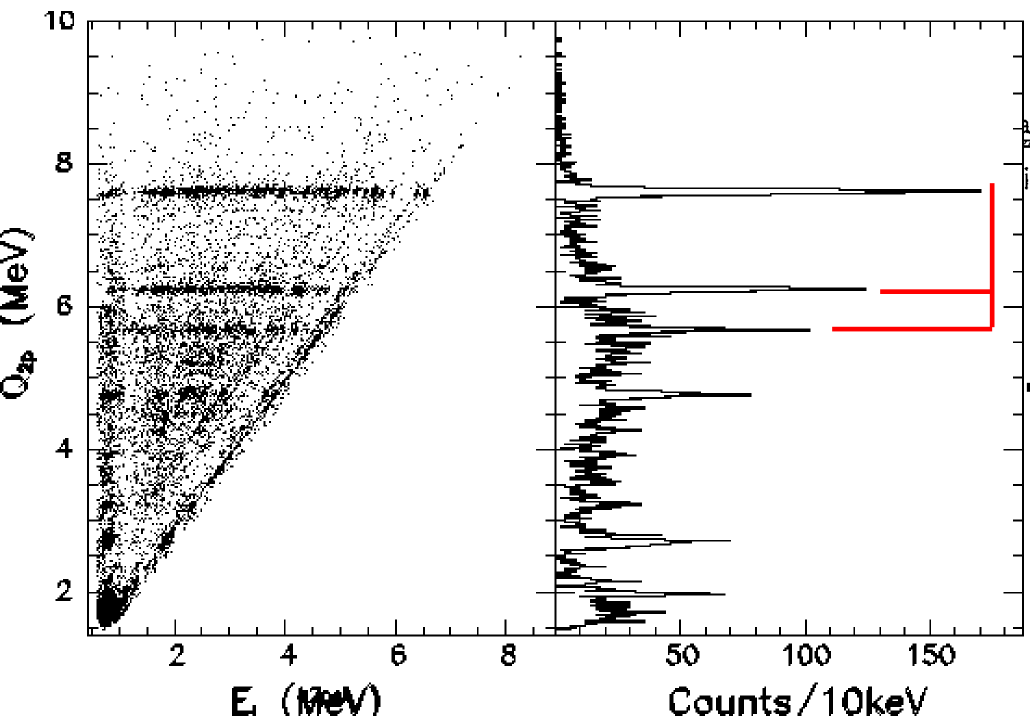


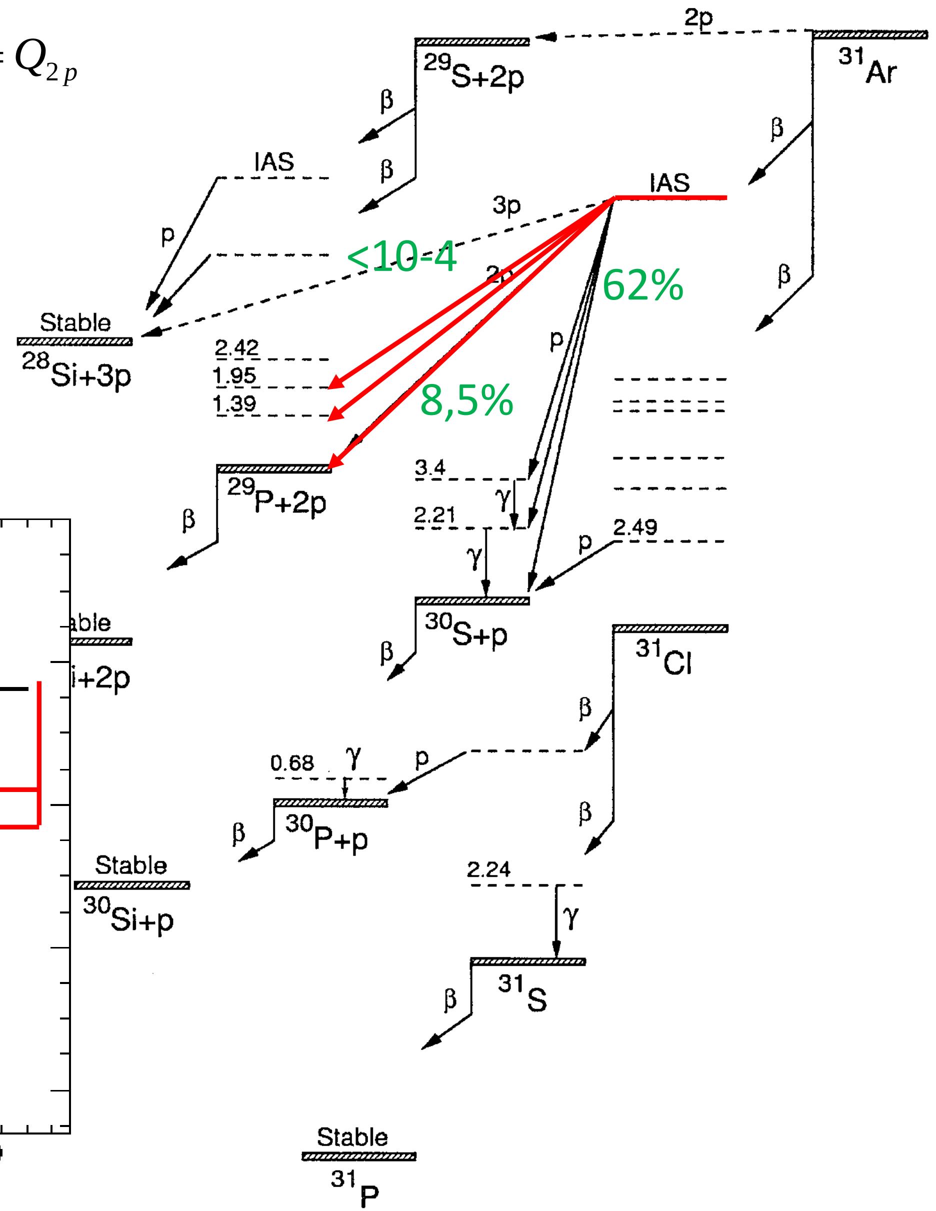
2p emission from ^{31}Ar IAS

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

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





Individual proton projections from β2p in ^{31}Ar

In sequential two-proton emission the energy of the first proton is

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

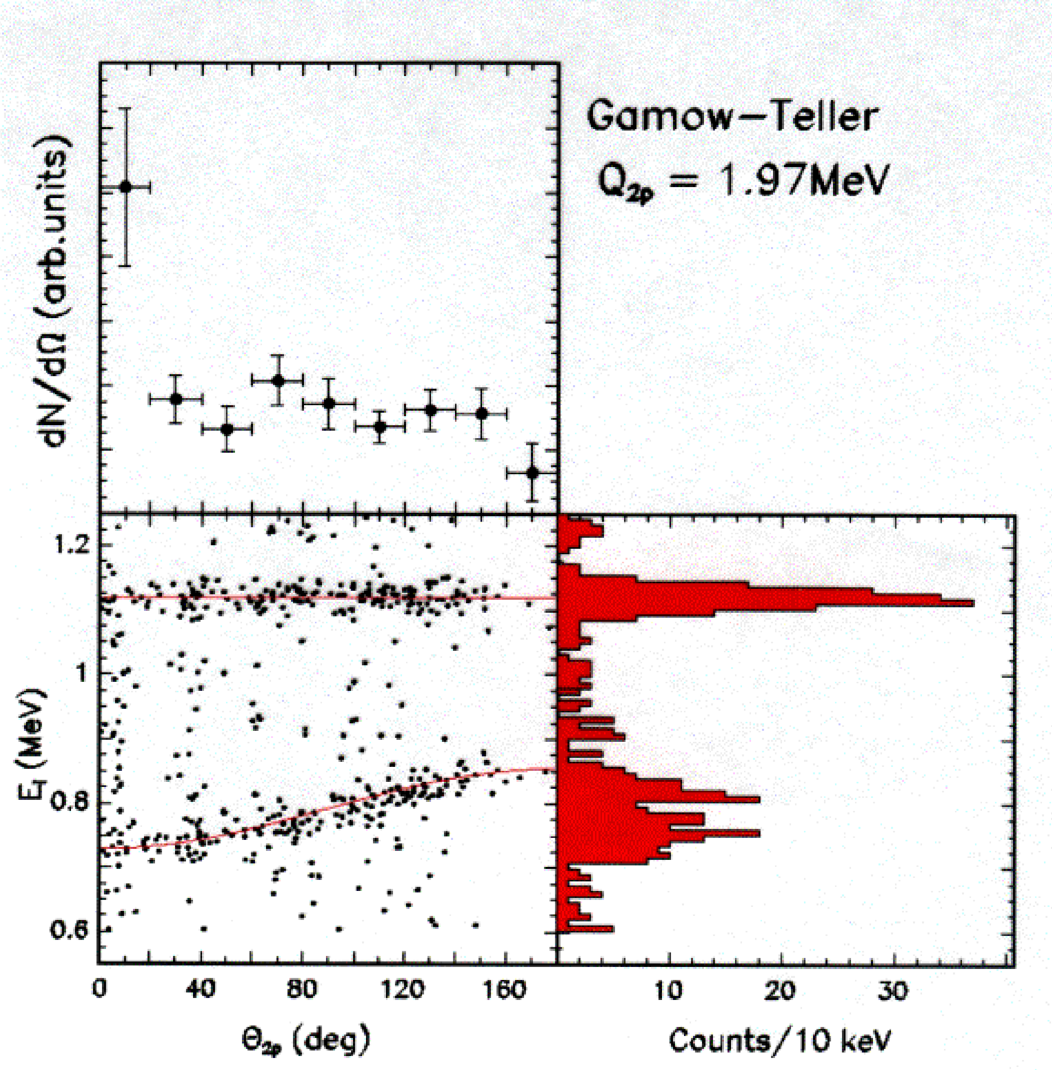
$M_{D1} = M(^{30}S)$

$$Q_1 = E(^{31}Cl) - E(^{30}S) - S_{pl}$$

$$E_2^{'} = \frac{M_{D2}}{M_{D2} + m_p} Q_2$$

$$Q_2 = E(^{30}S) - E(^{29}P) - S_{p2}$$

$$E_2 = E_2^{'} + \left(\frac{m_p}{M_{D1}}\right)^2 E_1 - \frac{m_p}{M_{D1}} \sqrt{E_1 E_2^{'}} \cos\theta_{2p}$$



Decay of the *IAS* of ^{31}Ar (Z =18,N=13)

E_{IAS} = 12322(2)(50) keV from Q2p

$Q_{EC} = E_{IAS} + \Delta Ec - \Delta np$

✓ $\Delta Ec = 1448.8\ [ZA^{-1/3}] - 1026.3$ keV

Antony & Pape [ADNDT 34 (86) 279]

✓ ΔEc =7045 keV

Leaving the coef. free and using exp. Coulomb energy shifts

between ^{32,33,34}Cl and ^{32,33,34}Ar

ΔEc =6950(90) keV ⇒

Q_{EC} = 18,49(11) MeV

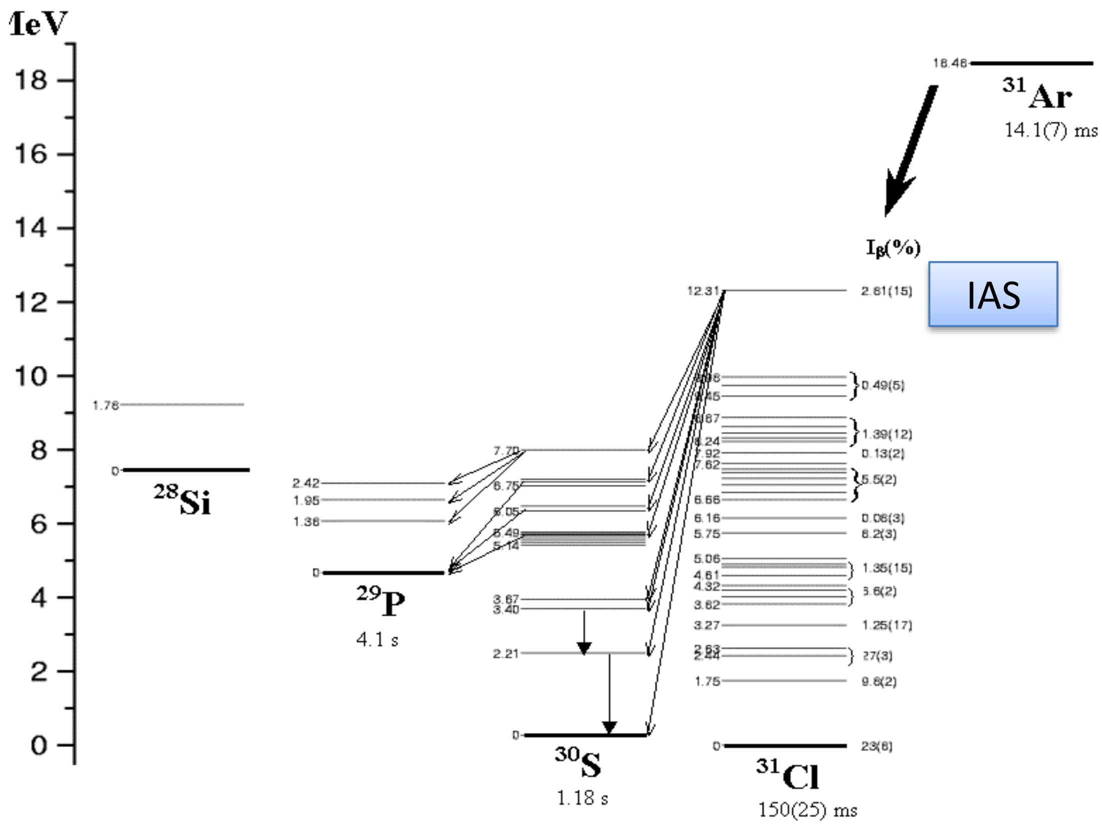
$f(E_{\beta IAS})t_{IAS}$ = 6145(4) s / [B(F) + B(GT)]

b.r.(IAS) = $T_{1/2} / t_{IAS}$

$B(F) = [T(T+1)-T_{zi}T_{zf}]\delta_{if} = 5$

Expected b.r. (IAS) = 4.35(31)%

Experimentally: b.r. (IAS) = 4.25(30) %



β2p/β1p (IAS) ~ 9

Fynbo et.al. NP A677(2000)38

Mapping of Neutron Deficient nuclei 22 < Z < 28

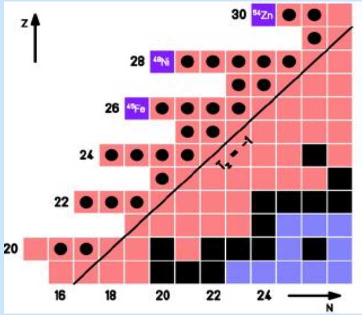
Spectroscopy studies with β-p-γ, β-γ

✓23 isotopes Studied

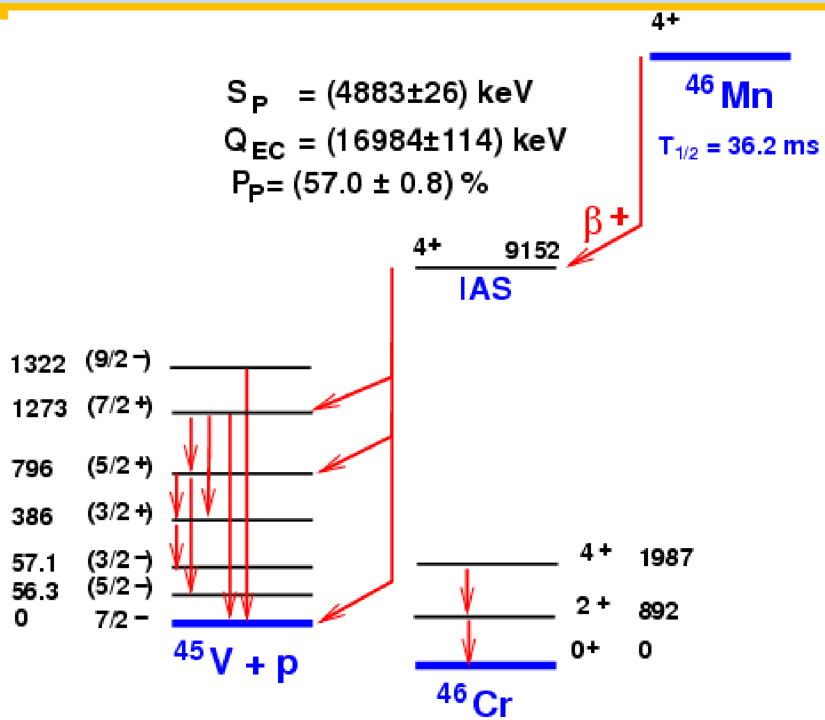
✓Macroscopy Properties : $T_{1/2}$, P_p

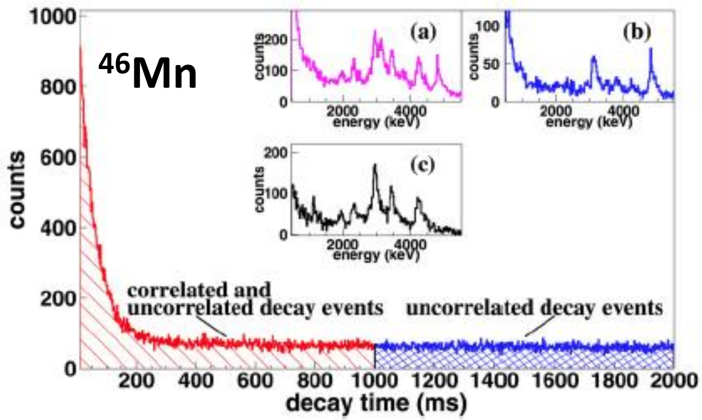
✓ Spectroscopy:

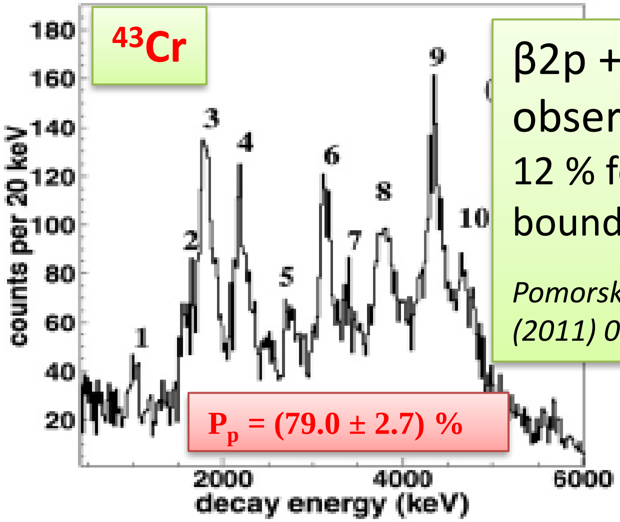
- Partial Decay scheme
- IAS Identification
- IMME



Dossat et al., NPA702 (2007) 18







β2p + β3p observed.

12 % feeding to bound states.

Pomorski PRC 83 (2011) 061303

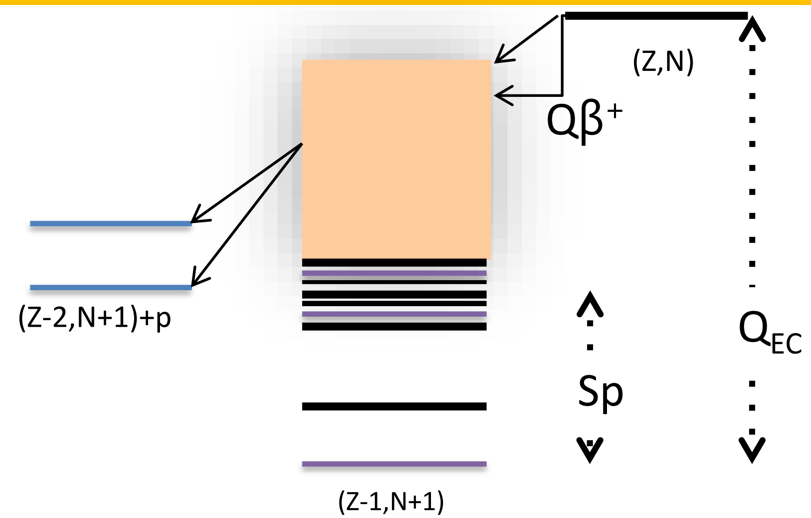
P_p = (79.0 ± 2.7) %

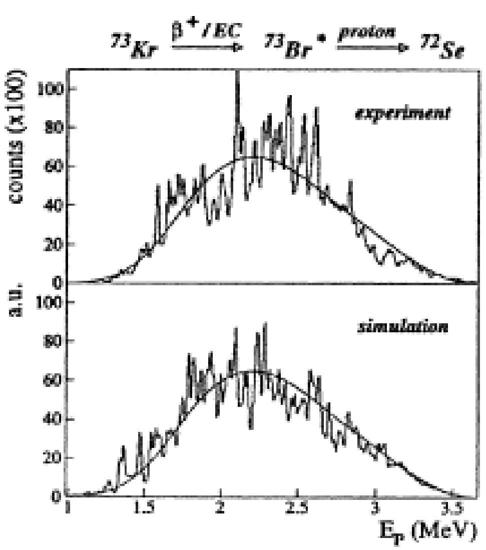
From peaks to continua (Hardy, Cargese, 1976)

βp explored high excitation energy in the daughter => individual transition are not longer resolved

$$I(Ep) = \sum_{i,f} f(Z,Q-E^{i})S_{\beta}(E^{i})\ \frac{\Gamma_{p}^{ij}}{\Gamma_{p}^{i}+\Gamma_{\gamma}^{i}}$$

To fit the proton spectrum average of the above quantities are considered.



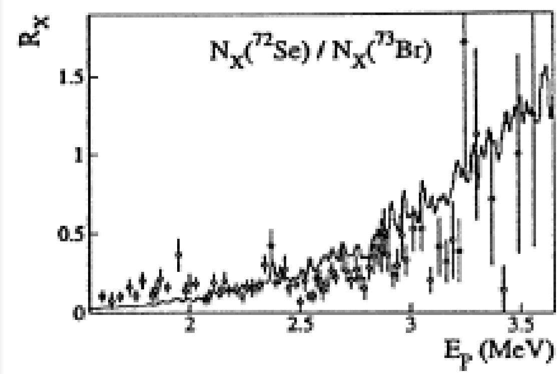


Giovinazzo et al, NPA674 (2000) 394

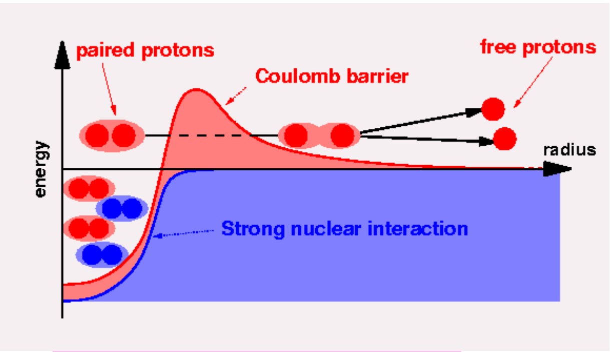
βp + X-Ray ratio strongly constraint the level density distribution

Good estimate of proton and gamma widths for exotic nuclei of interest for nucleosynthesis

The Porter Thomas distribution accounts of the fluctuations observed in the spectrum



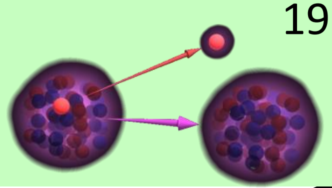
Exotic Radioactivities



1p-radioactivity

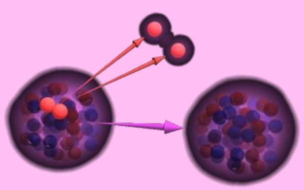
(Z,N) → p + (Z-1,N)

1981

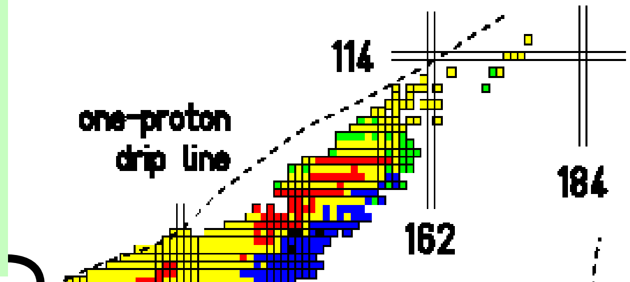


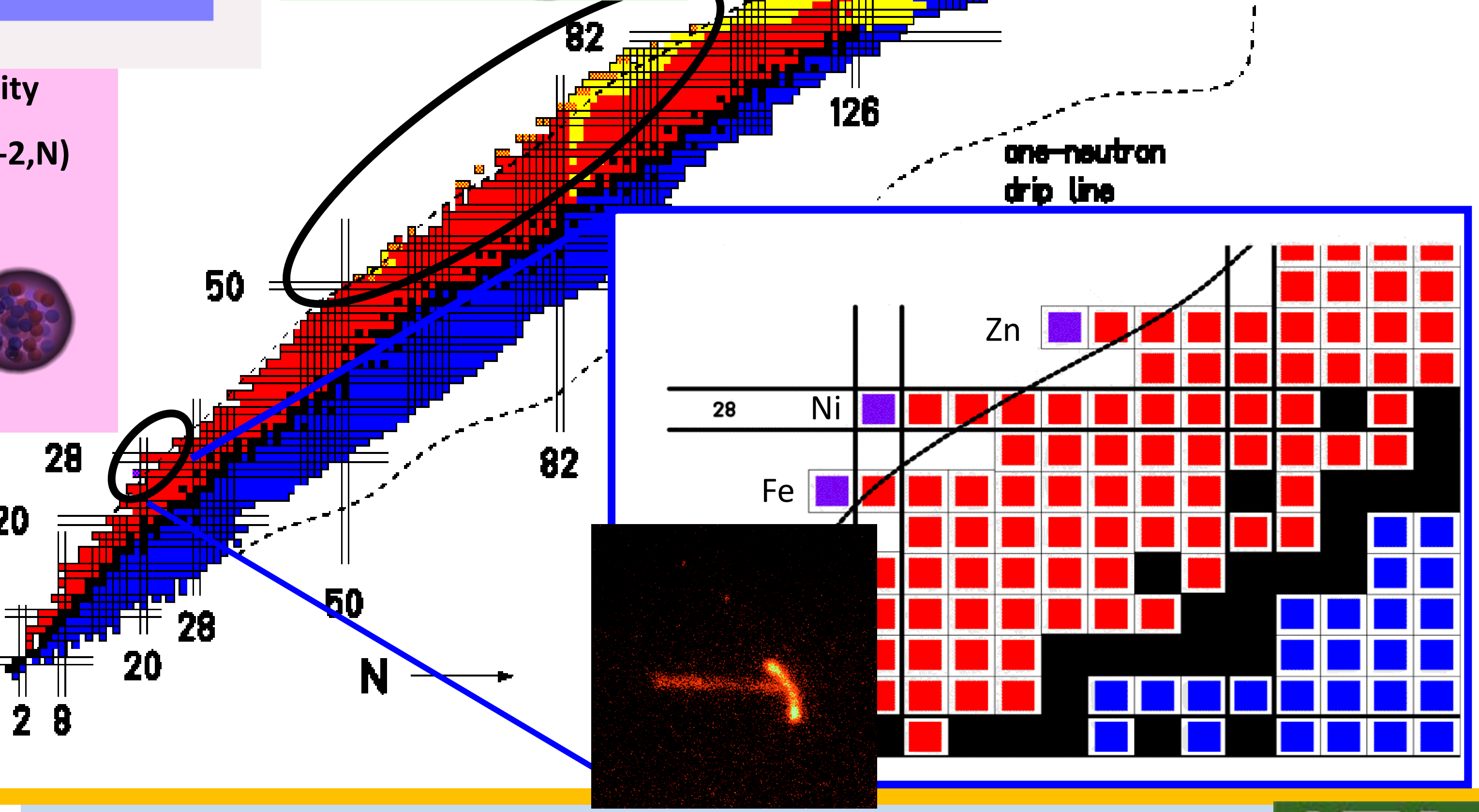
2p-radioactivity

(Z,N) → 2p + (Z-2,N)

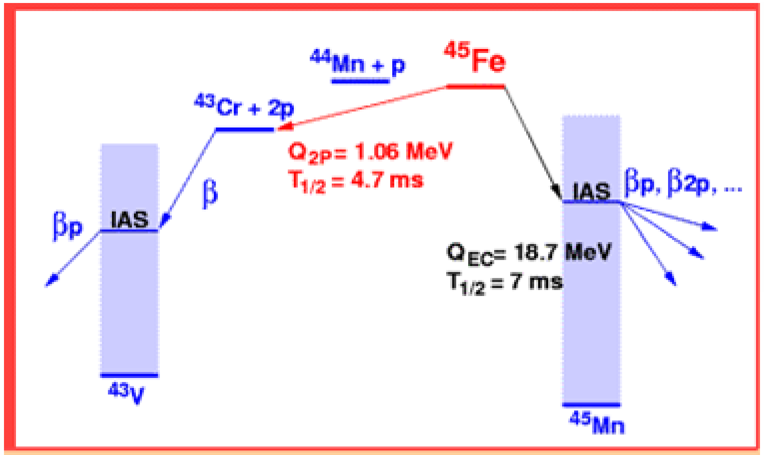


2002

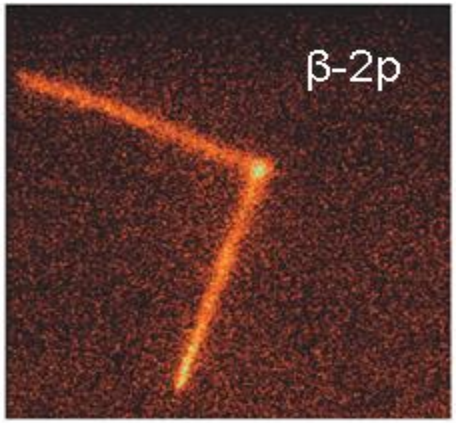


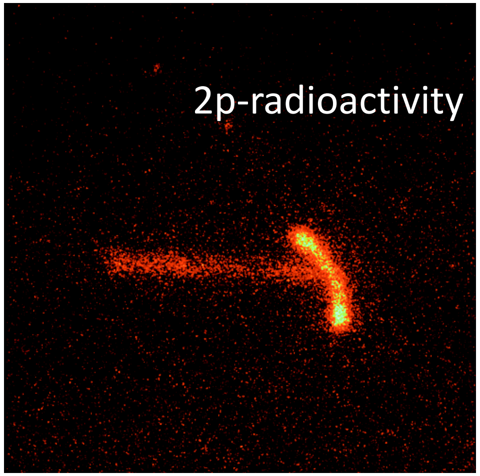


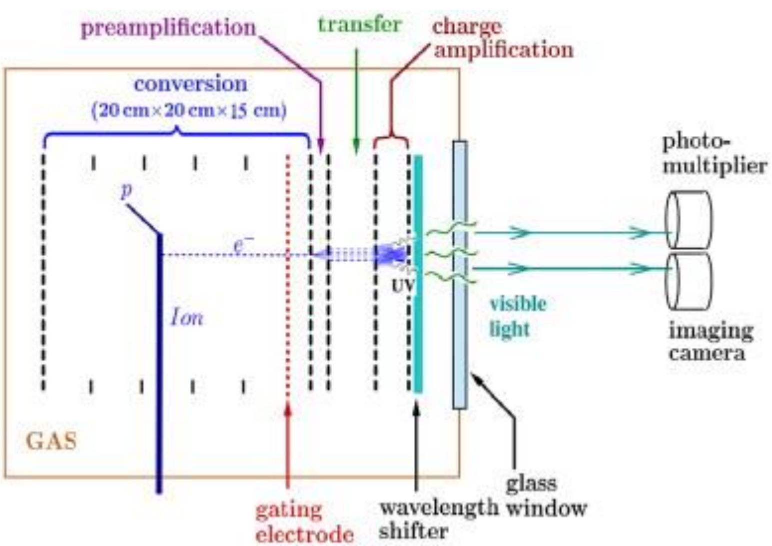
2p-correlation measured for first time in ^{45}Fe

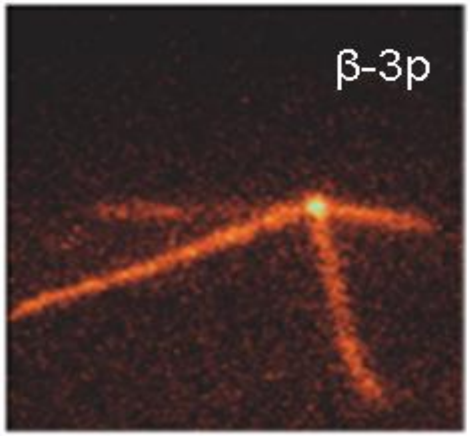


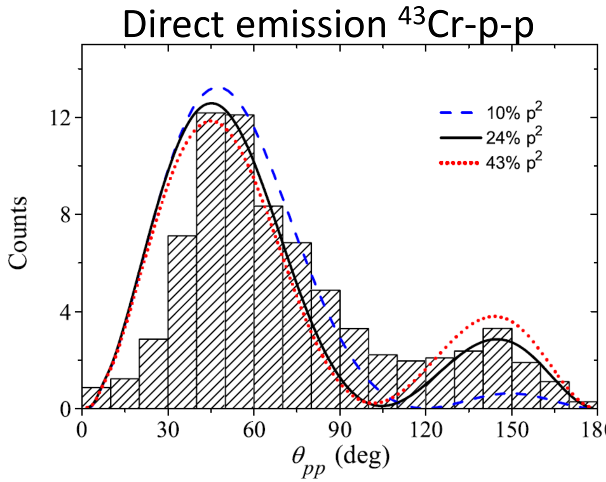
Miernik et al,
NIM A 581 (2007) 194
PRL 99 (2007) 192501
PRC 76 (2007) 041304R





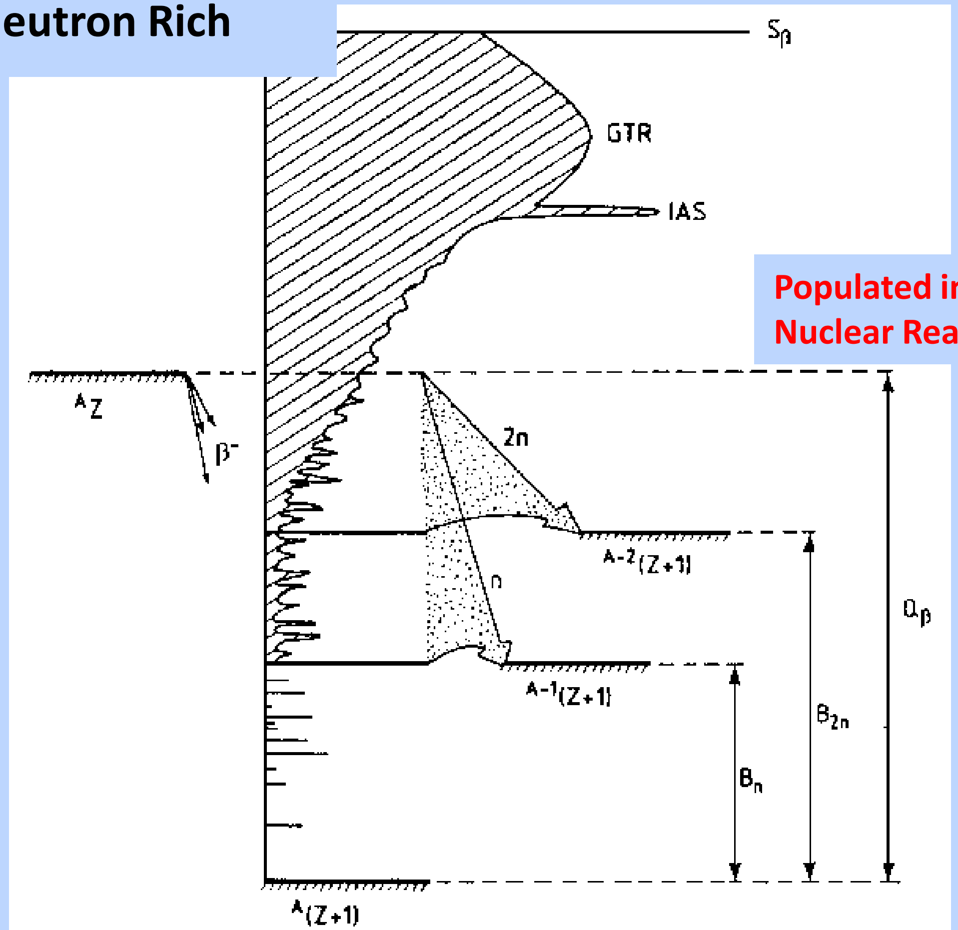






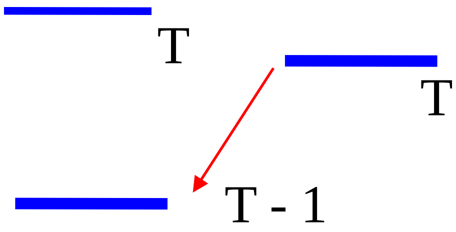
Beta-delayed Neutron Emission

Neutron Rich



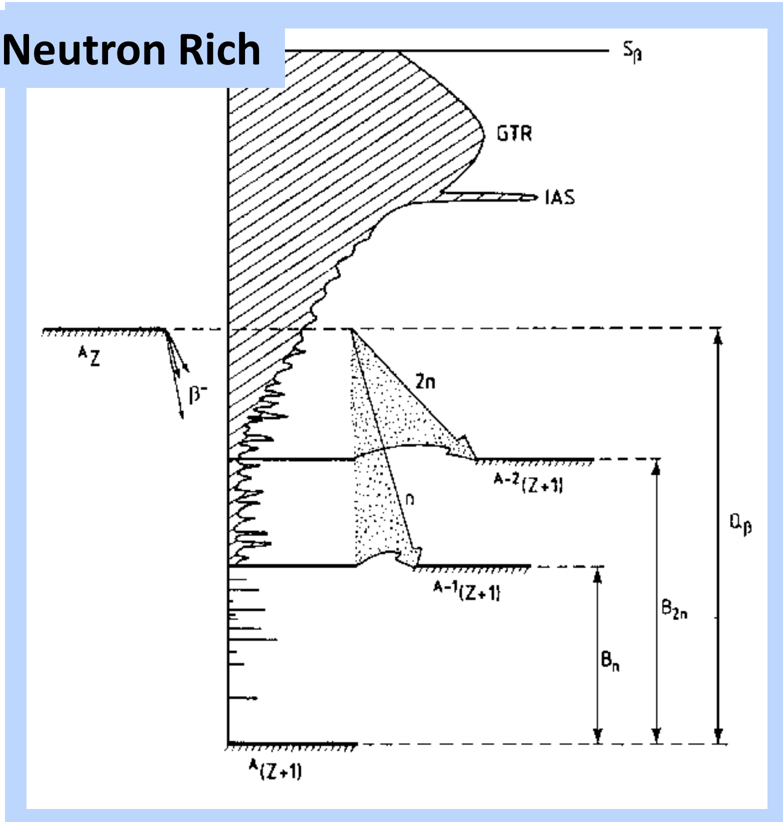
Populated in Nuclear Reactions

β^- N > Z



Beta-delayed Neutron emitters

Neutron Rich



About 220 cases measured,
Mainly $T_{1/2}$ and P_n-values
Spectroscopy hampered by
Detection system.

Compilation for fission products 26 < Z < 58,
Pfeiffer, Kratz, Möller, Prog. Nucl. Energy 41(2002)39

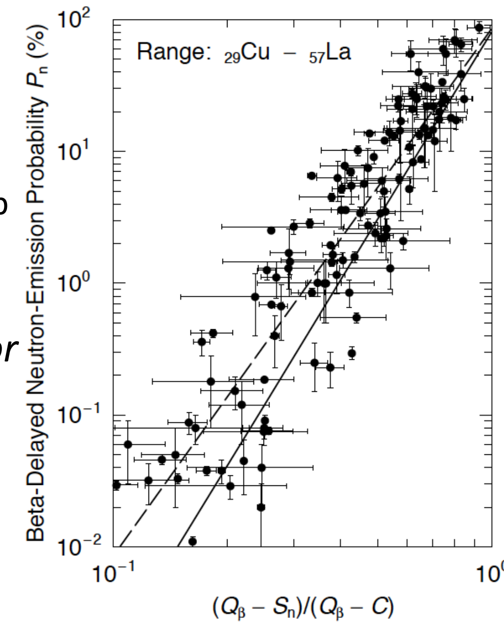
$$1/T_{1/2} = \sum_{E_i \geq 0}^{E_i \leq Q_\beta} S_\beta(E_i) \times f(Z, Q_\beta - E_i)$$

$$P_n = \frac{\sum_{B_n}^{Q_\beta} S_\beta(E_i)\, f(Z, Q_\beta - E_i)}{\sum_{0}^{Q_\beta} S_\beta(E_i)\, f(Z, Q_\beta - E_i)}$$

Kratz-Hermann formula

$$P_n \approx a[(Q_\beta - S_n)/(Q_\beta - C)]^b$$

Where C is the parameter of pairing, depending of even or odd character of daughter nucleus



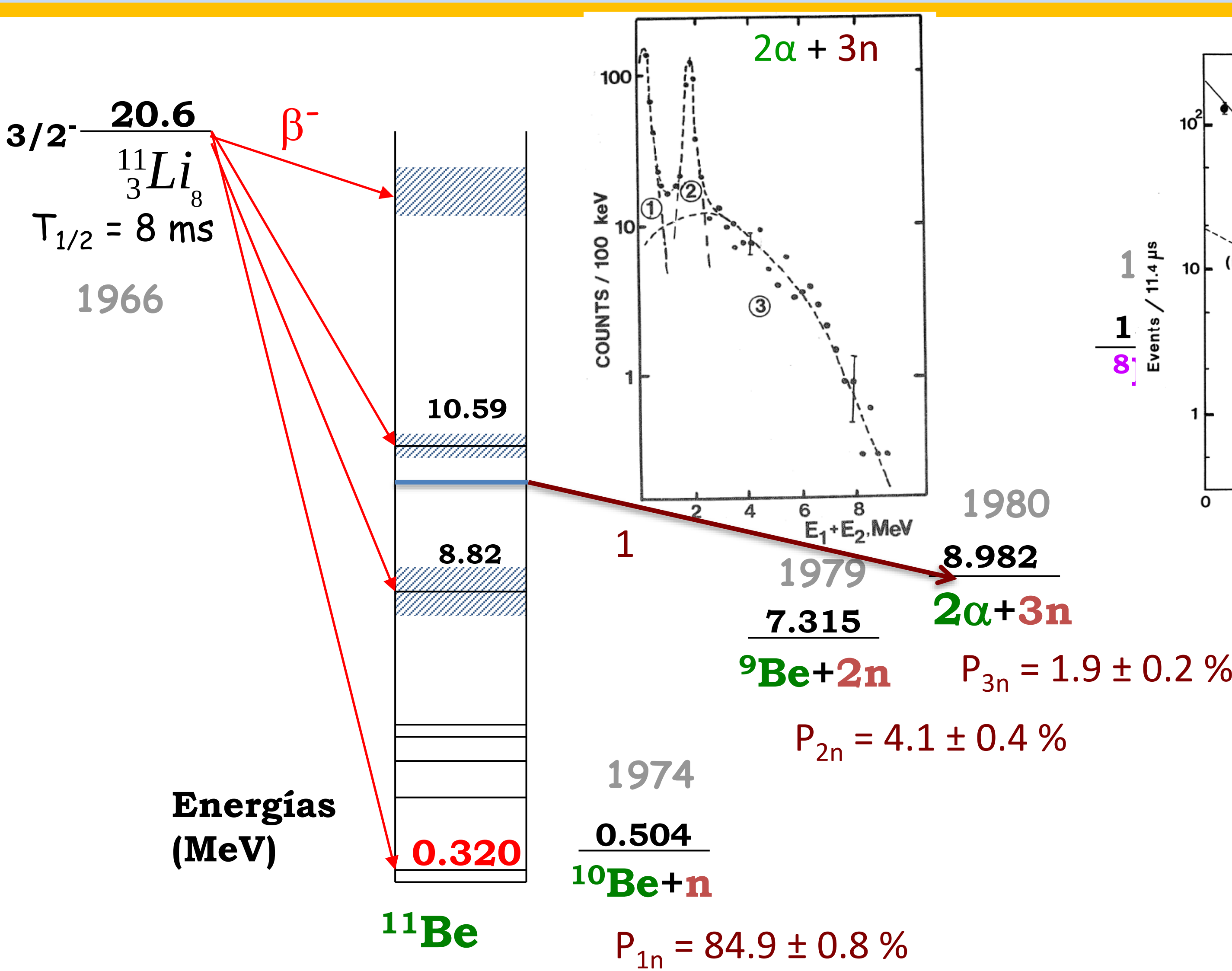
	a	b	regr	a	b	χ2
$29 \leq Z \leq 57$	85.16	3.99	0.83	80.58 ±20.72	4.72 ±0.34	78.23

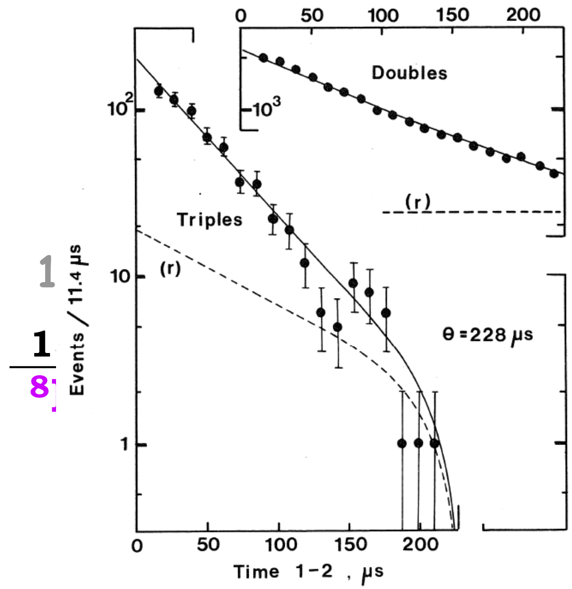
Measurement of Neutrons & βn

- Long Counter: reduced energy to termal values by scattering in parafine.
- Time-of-Flight, giving signals in plastic scintillator. Energy of neutron deduced.
- βn can be deduce by obsevation of γ-ray transition in the beta-delayed neutron daughter.

Talk on Neutron deteccion by JL Tain

Beta decay of an exotic n-rich nuclei





Identification of 2n & 3n by time correlations
Azuma et al., PLB 96 (1980) 31

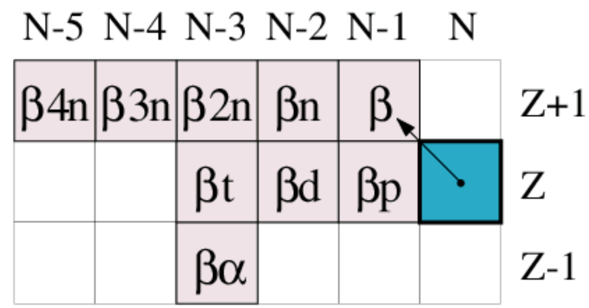
Beta delayed particle emitters

For β⁻-delayed x-neutron emission of ^{A}Z

$BE(A,Z) = ZM_pc^2 + NM_nc^2 – M'(AZXN)c^2$

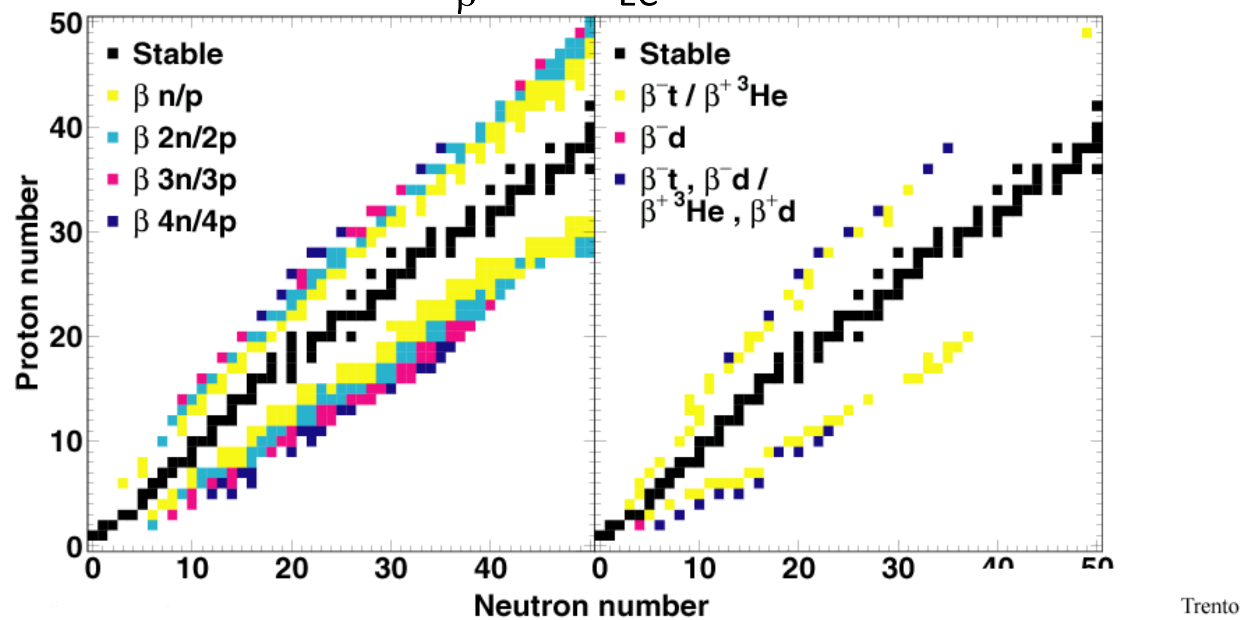
Using the Bethe-Weizsäcker mass equation for BE(A,Z)

$M'(AZXN)c^2 = (ZM_p + NM_n)c^2 - a_vA + a_sA^{2/3} + a_cZ(Z-1)A^{-1/3} + a_A(A-2Z)^2/A - a_pA^{-1/2}$



$Q_{\beta nx} = Q_\beta – S_{xn}(^{A}(Z+1)) = Q_\beta(^{A-x}Z) - S_{xn}$

For β⁺-delayed x-proton emission of ^{A}Z $Q_{\beta^-} \rightarrow Q_{EC}$



B.Jonson & K. Riisager, NPA693 (2001) 77

Exotic decays

							^{17}Ne B, βp,βα							
								^{17}F β	^{18}F β	^{19}F stable				
			Z=8	^{12}O 2p	^{13}O β, βp	^{14}O β	^{15}O β	^{16}O stable	^{17}O stable	^{18}O stable				
			^{10}N P?	^{11}N p	^{12}N β,βα	^{13}N B, noγ	^{14}N stable	^{15}N stable	^{16}N β, βα	^{17}N B, βn,βα	^{18}N β,βn,βα	^{19}N β, βn	^{20}N β, βn	
		^{8}C 2p	^{9}C B,βp,βα	^{10}C β	^{11}C B,noγ	^{12}C	^{13}C	^{14}C B, noγ	^{15}C β, βn	^{16}C β, βn	^{17}C β, βn	^{18}C β, βn	^{19}C β, βn	
		^{7}B p	^{8}B B,β2α	^{9}B p	^{10}B	^{11}B	^{12}B B, βα	^{13}B B, βn	^{14}B β, βn	^{15}B β, βn	^{16}B unbound	^{17}B β, βn,β4n	^{18}B unbound	^{19}B β, βn,β2n
		^{6}Be 2p	^{7}Be β	^{8}Be α	^{9}Be	^{10}Be β, noγ	^{11}Be B, βα	^{12}Be β, βn	^{13}Be unbound	^{14}Be 4.35 ms				
	^{4}Li p	^{5}Li p	^{6}Li	^{7}Li	^{8}Li β,β2α	^{9}Li β, βn, βα	^{10}Li unbound	^{11}Li β,β3n,βd,βt						
Z=2	^{3}He	^{4}He	^{5}He unbound	^{6}He β, βd	^{7}He unbound	^{8}He β, βn, βt	^{9}He unbound	N=8						
^{1}H	^{2}H	^{3}H β												
	n 10.25 m	N=2												

$Q_{\beta d}$ = 3 – S_{2n} (MeV): ^{6}He,^{11}Li, ^{14}Be, ^{17}B, ^{19}B, ^{22}C

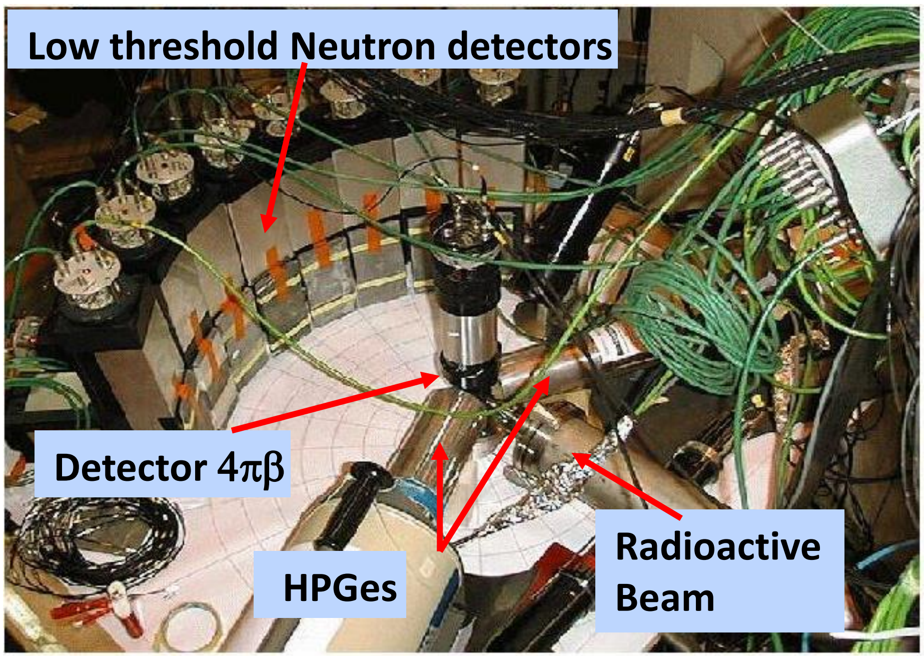
$Q_{\beta t}$ = 9264-S_{3n} (MeV): ^{8}He,^{11}Li, ^{14}Be, ^{16}B, ^{17}B, ^{19}C, ^{20}C

Qpα ó Qαp : ^{9}C, ^{13}0, ^{17}Ne, ^{21}Mg, ^{23}Si

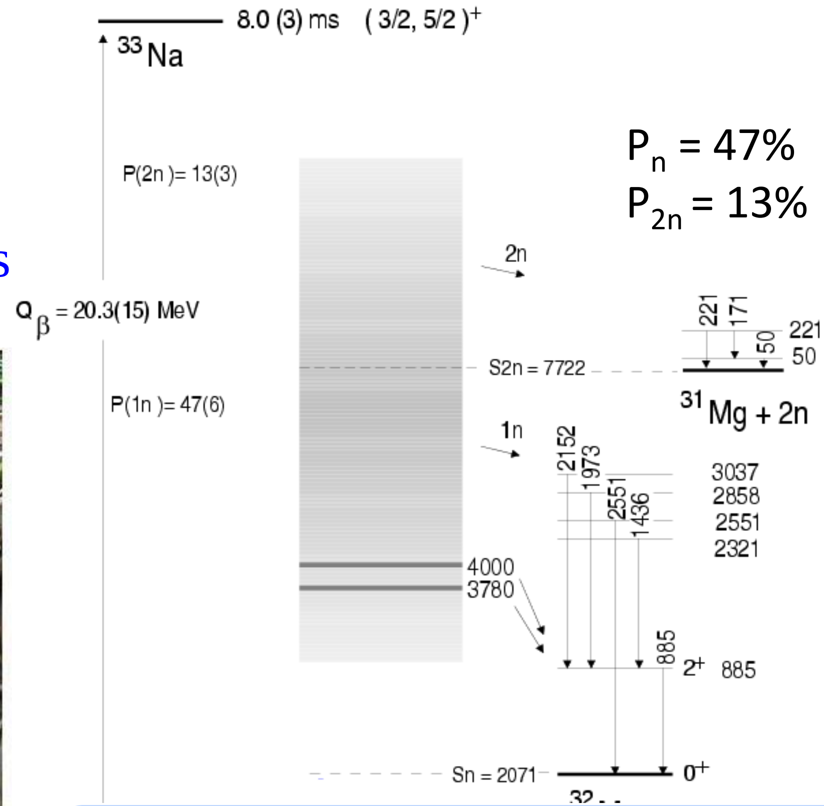
Decay Scheme ➔ Structure Information (N= 20)

^{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

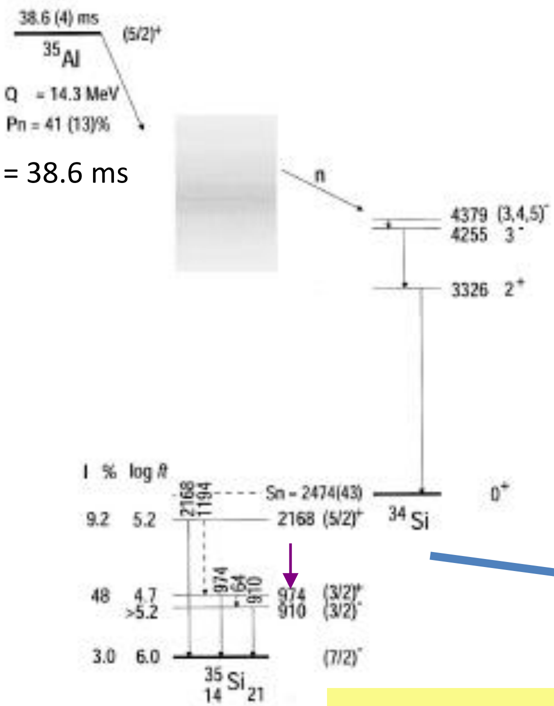


P_n = 47%
P_{2n} = 13%

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

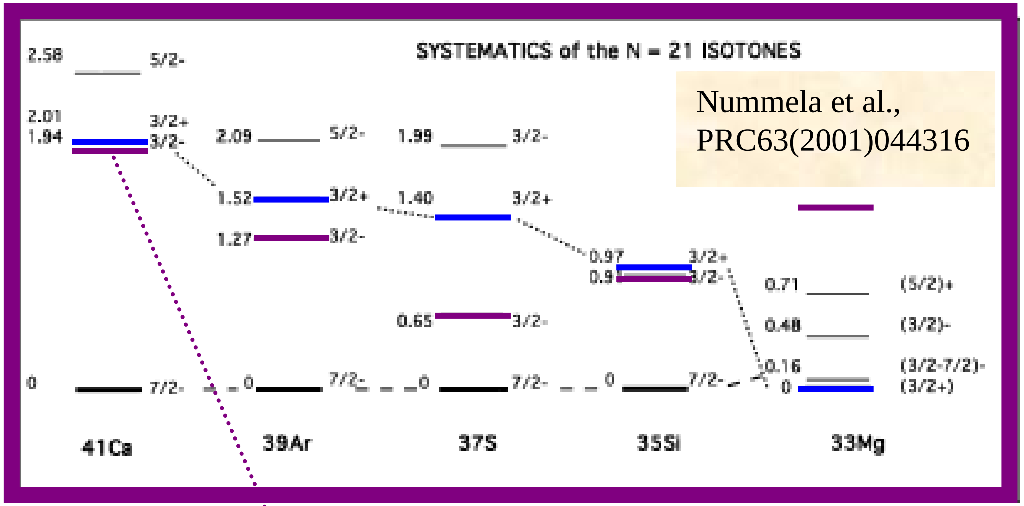
M. Langevin et al NP A414 151 (1984)
S. Nummela et al PRC64 054313 (2001)

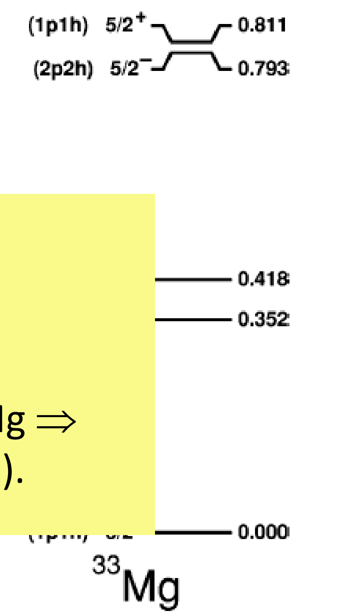
Intruder states & Effective interaction in sd-pf shell



$T_{1/2}$ = 38.6 ms

Nummela et al., PRC63(2001





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 ⇒ confirmed for ^{44}S (Sohler, PRC66 (2002) 054302)).

βn from ^{133g}In($9/2^+$) and ^{133m}In($1/2^-$) → ^{133}Sn study

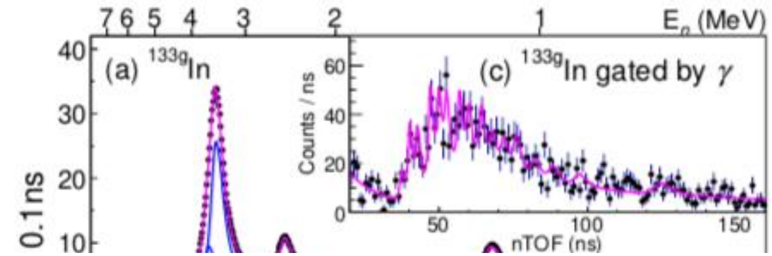
^{133}In is a key nucleus for

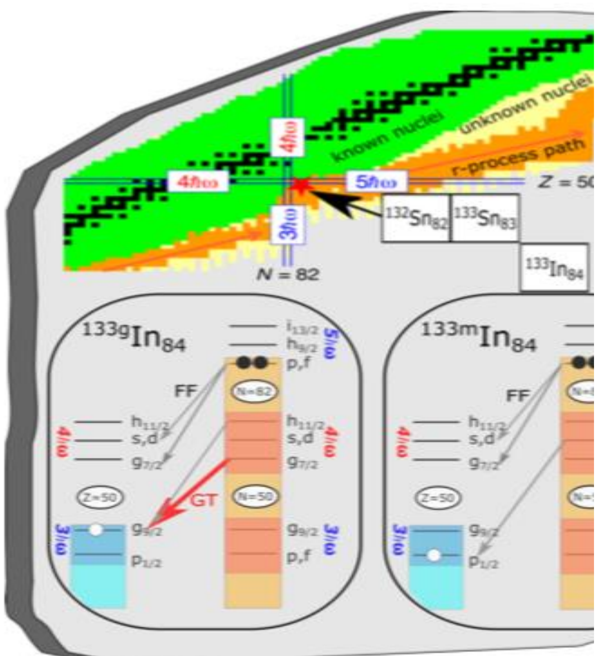
- Astrophysics due to its placement on the r-process bottleneck regions in most scenarios.
- its proximity to the doubly magic ^{132}Sn (50 protons and 82 neutrons) offers a uniquely simple β-decay system to validate nuclear theories.
- β,γ,n,βn,βnγ measured

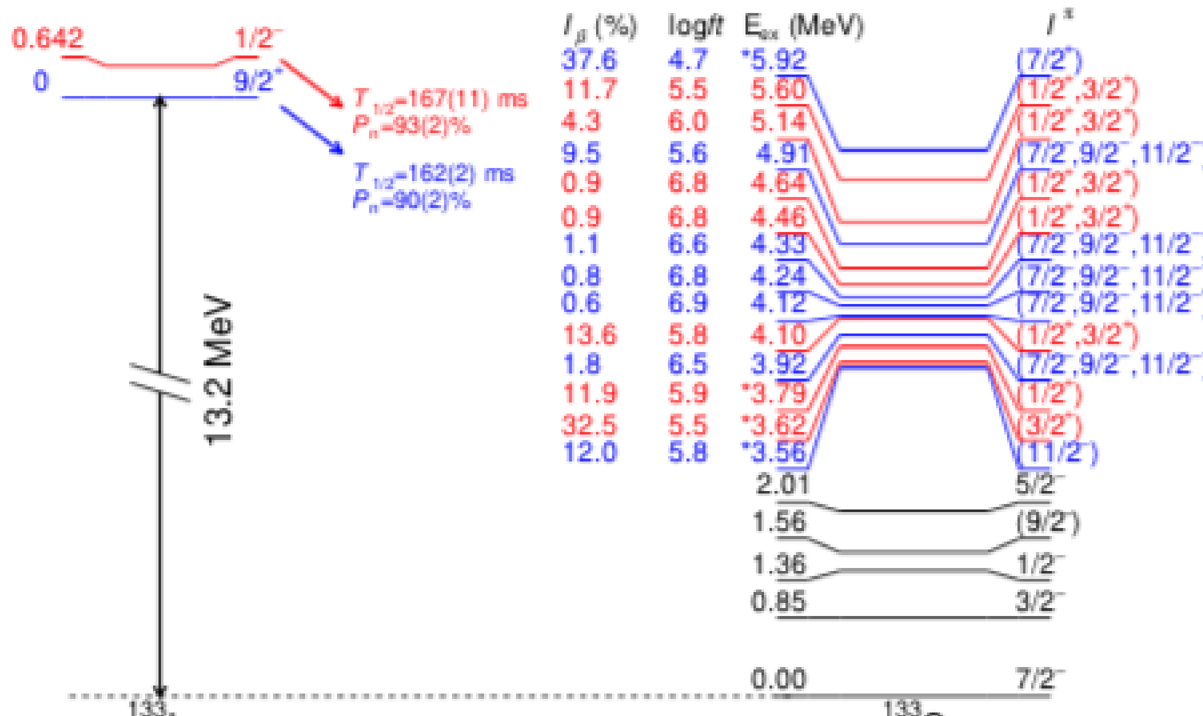
High resolution laser tuning allowed

Separate the contribution from gs and isomer ^{133}In

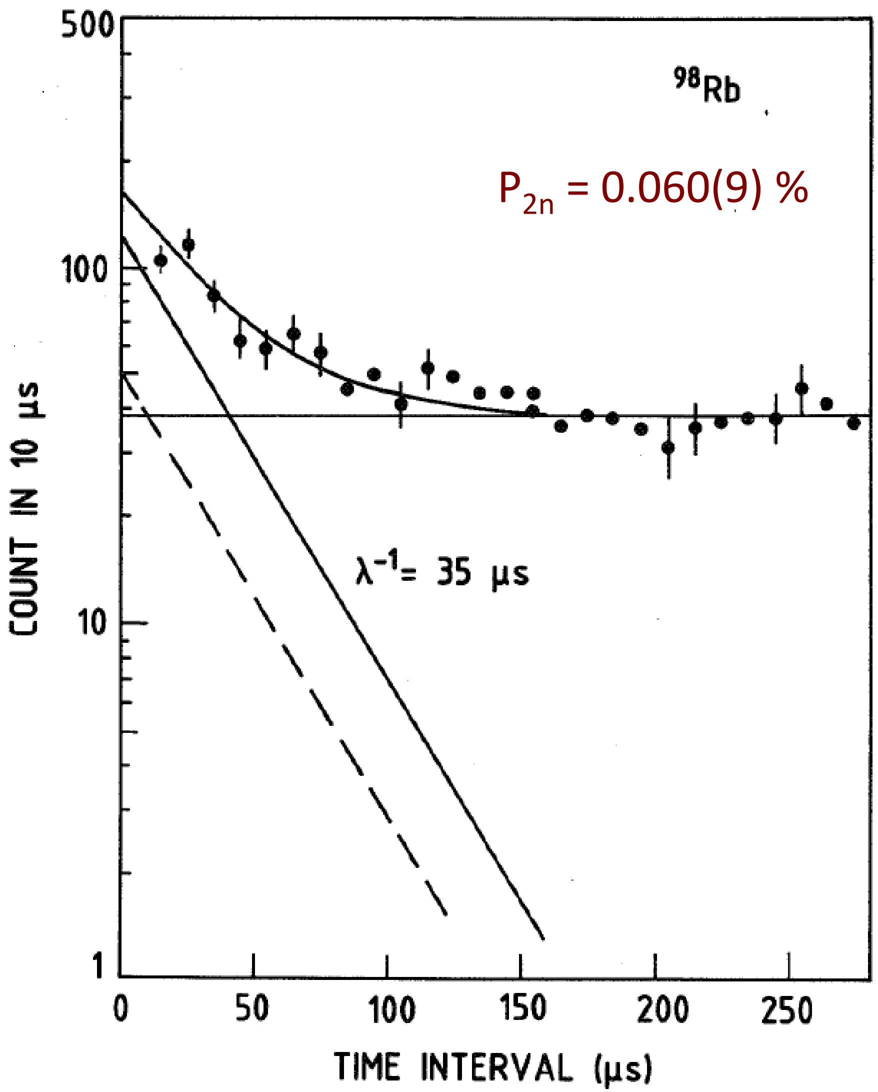
Neutron ToF Spectrum from VANDLE





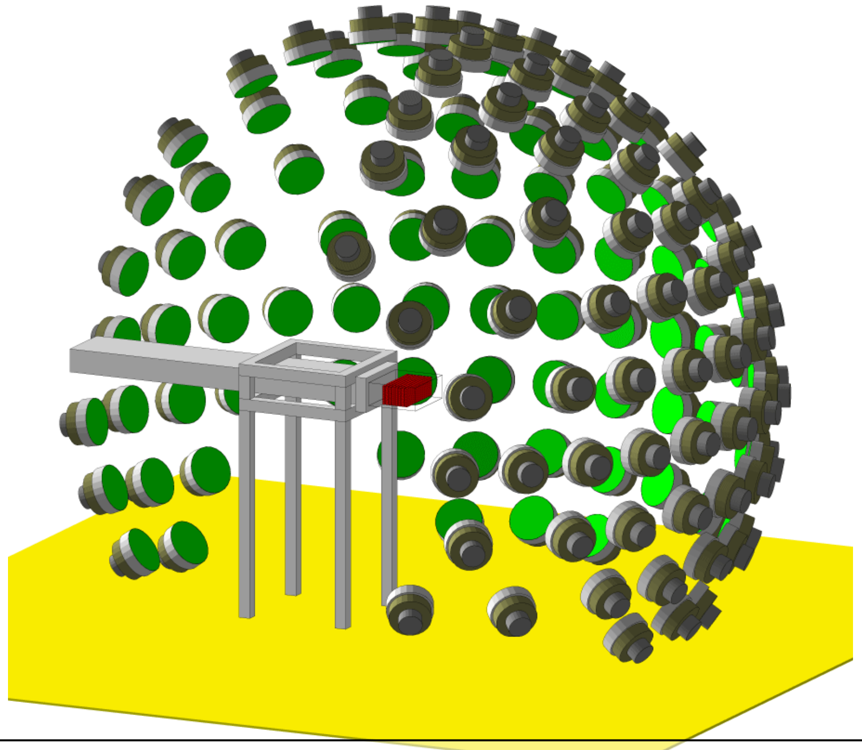


Neutron Detection systems



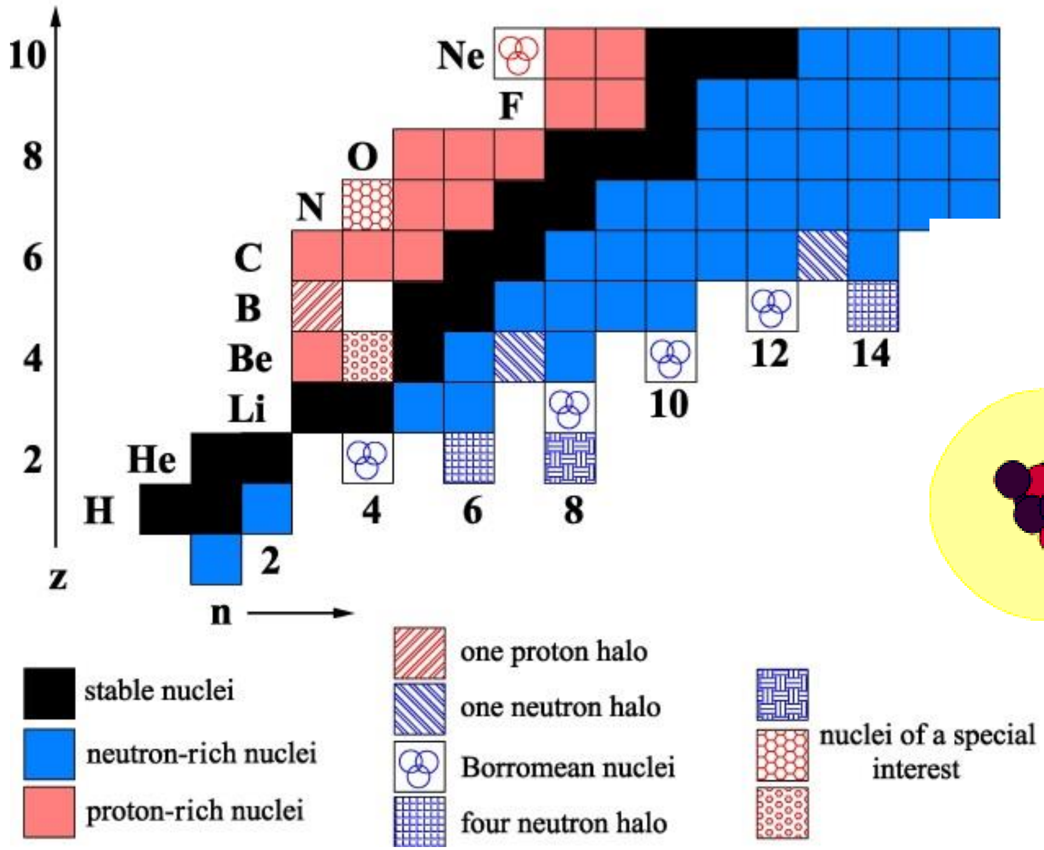
Measured

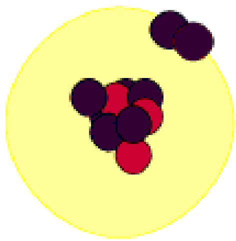
4π Counter
With 40 ^{3}He tubes embedded in parafine with 59 % efficiency.

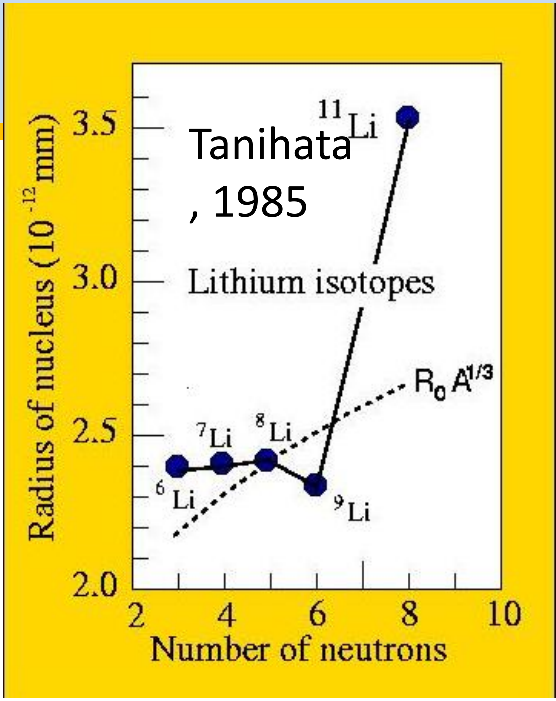


TOF spectrometer: array of liquid scintillators (BC501A)

Halo nuclei

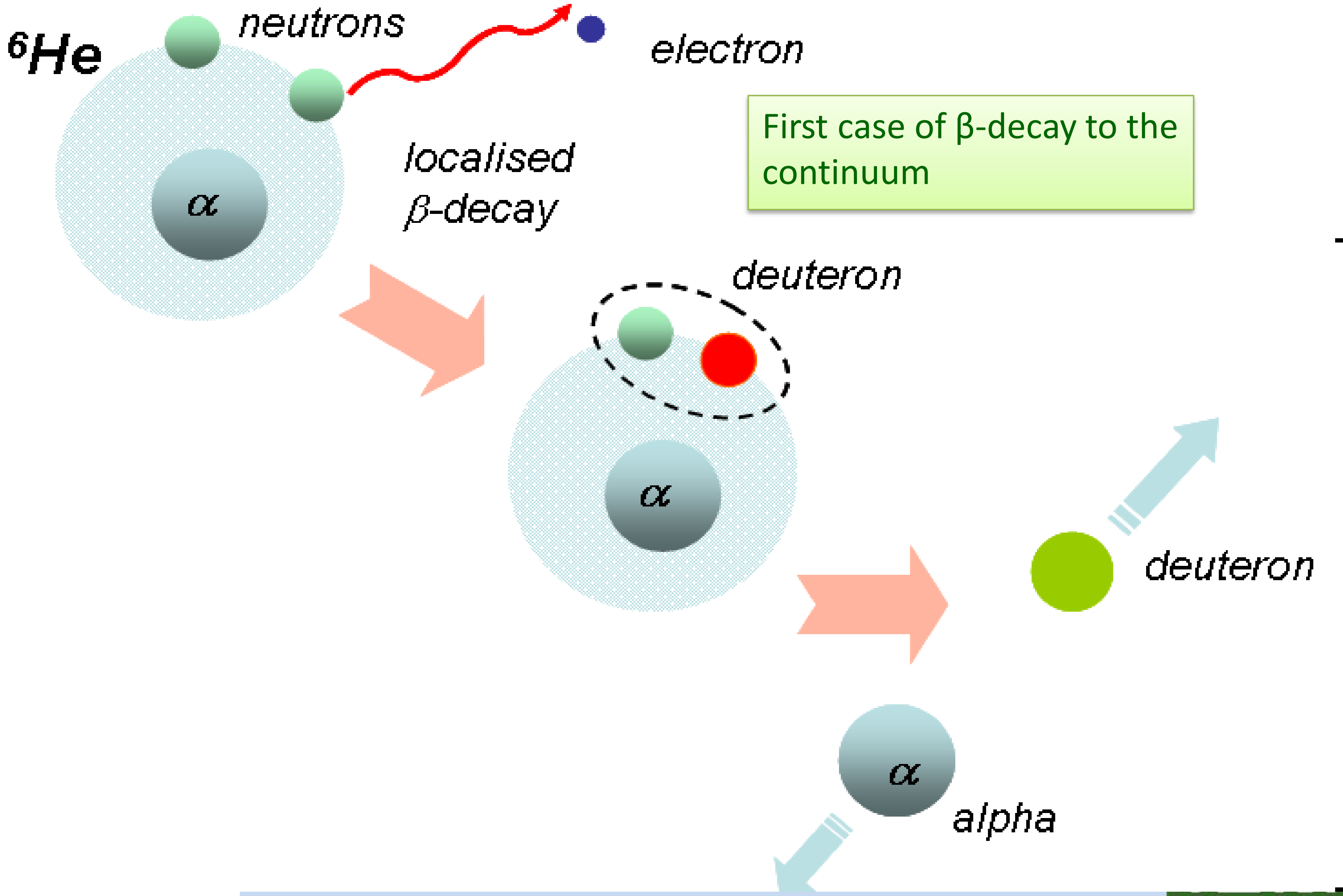






- ✓Energy threshold effect
- ✓Highlight by nuclear reactions
- ✓Effects in beta decay

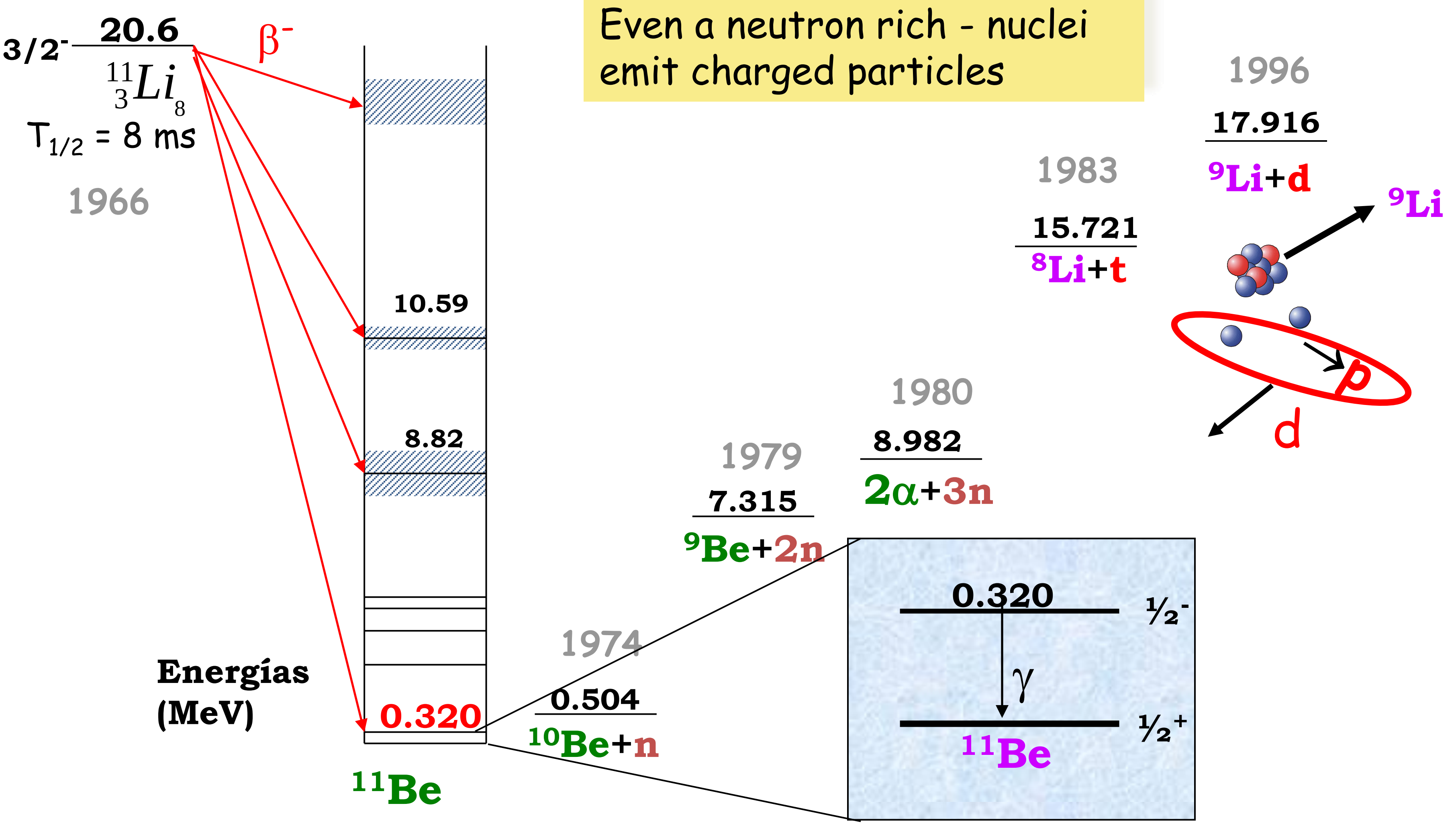
Beta-delayed deuterons



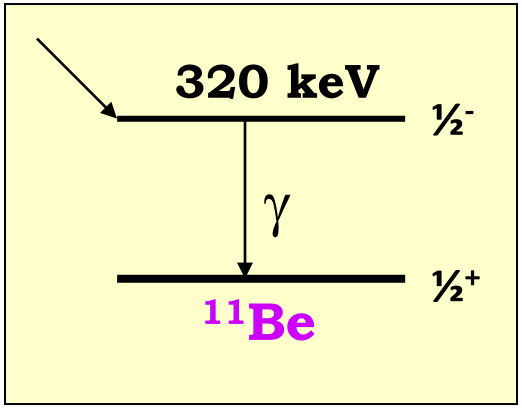
First case of β-decay to the continuum

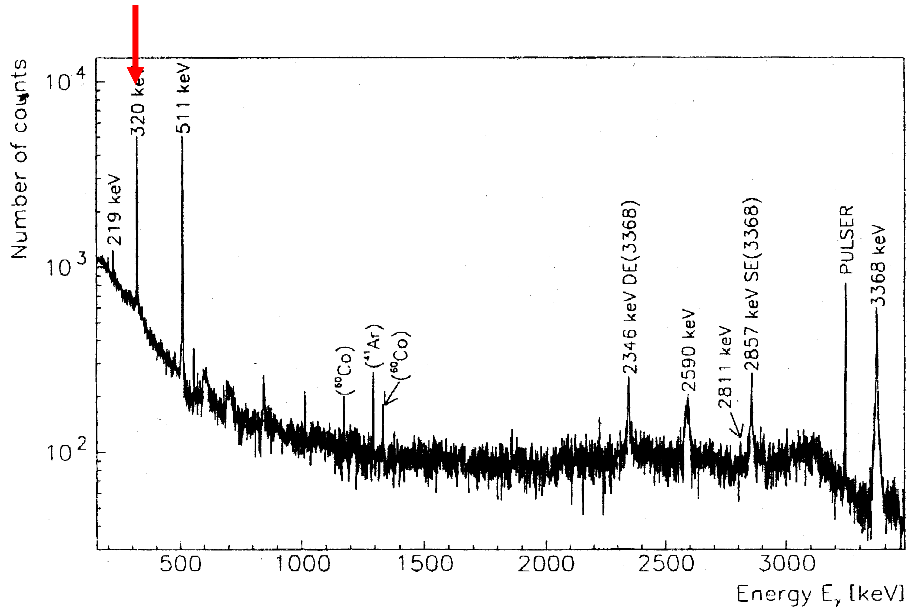
Beta decay of an exotic nuclei

Even a neutron rich - nuclei emit charged particles



^{11}Li, gamma rays





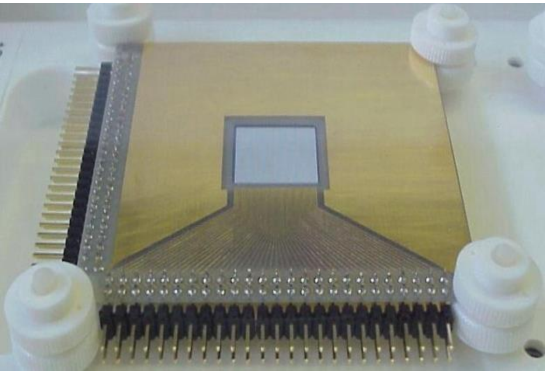
M.J.G. Borge et al., PRC55 (97) R8
N. Aoi et al., NPA616 (97) 181c
D. Morrisey et al., NPA627 (97) 222

Q = 20.62 MeV, $T_{1/2}$ = 8.2 ms
b(320) = 6.3(6) %
log *ft* = 5.73

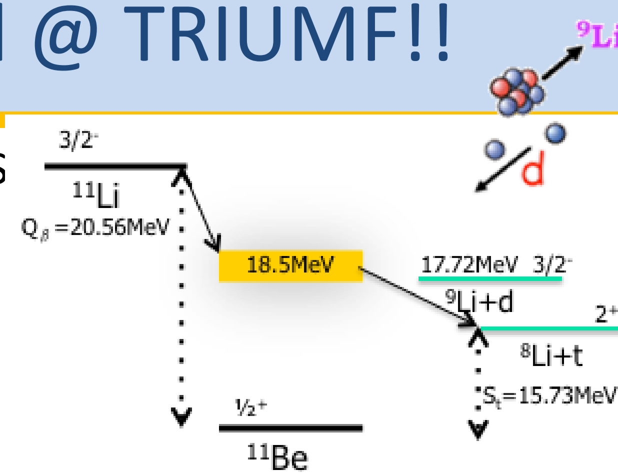
$(1s_{1/2})^2/(0p_{1/2})^2 \sim 1$

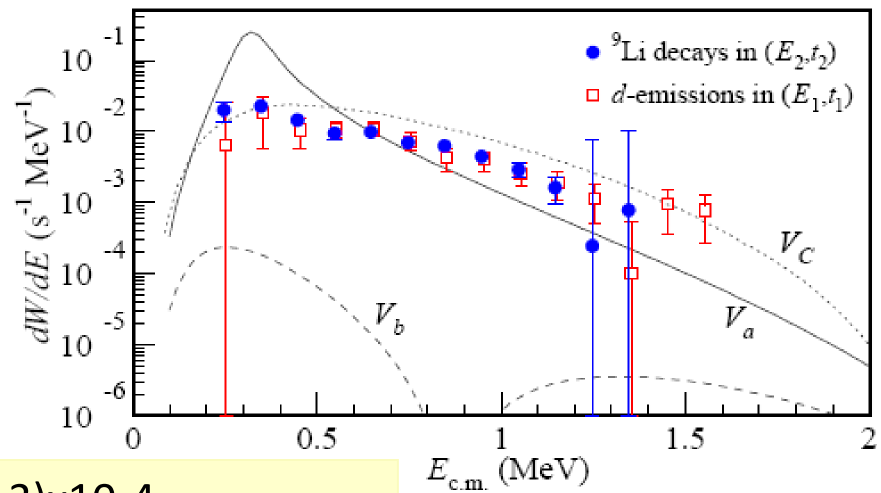
^{11}Li βd spectrum finally measured @ TRIUMF!!

- Implantation of ^{11}Li beam on DSSS Detector
- Very precise B.R.
- Low detection threshold
- Low beta background
- History of each decay

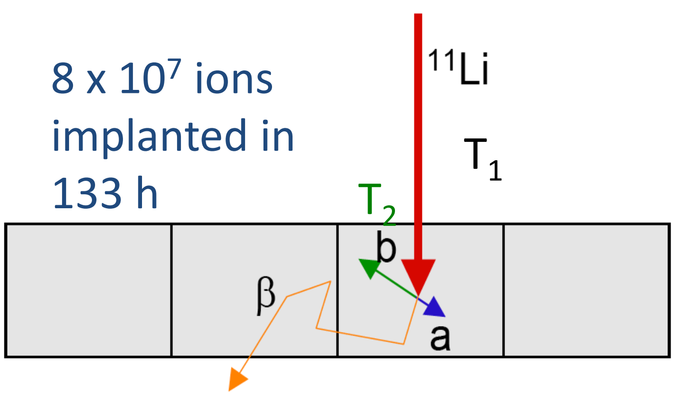


DSSSD 16x16 mm², 70μm thick
48x48 strips, 300 μm, 2304 pixels
J. Büscher et al., NIM B 266 (2008) 19





8 x 10^{7} ions implanted in 133 h



B.R = 1.30(13)x10-4
E_{cm} > 200 keV
Deuteron Spectrum
Decay to the continuum confirmed !
Raabe et al, PRL 101 (2008) 212501

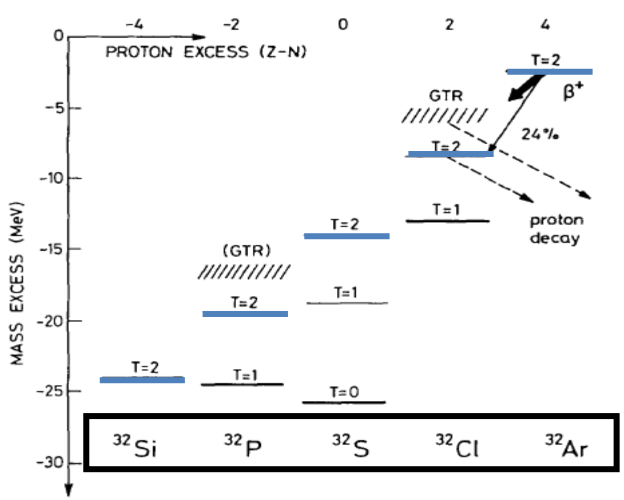
Stringent test of Nuclear Models

✓Test Isobaric Multiplet Mass eq.
$M(A,T,T_z) = a + bT_z + cT_z^2 + \delta(dT_z^3 + eT_z^4)$

✓ If 2-body forces responsible of charge dependence in nuclei IMME to T_Z^2

✓ $B_F = T(T+1) - T_{Zi}T_{Zf}$

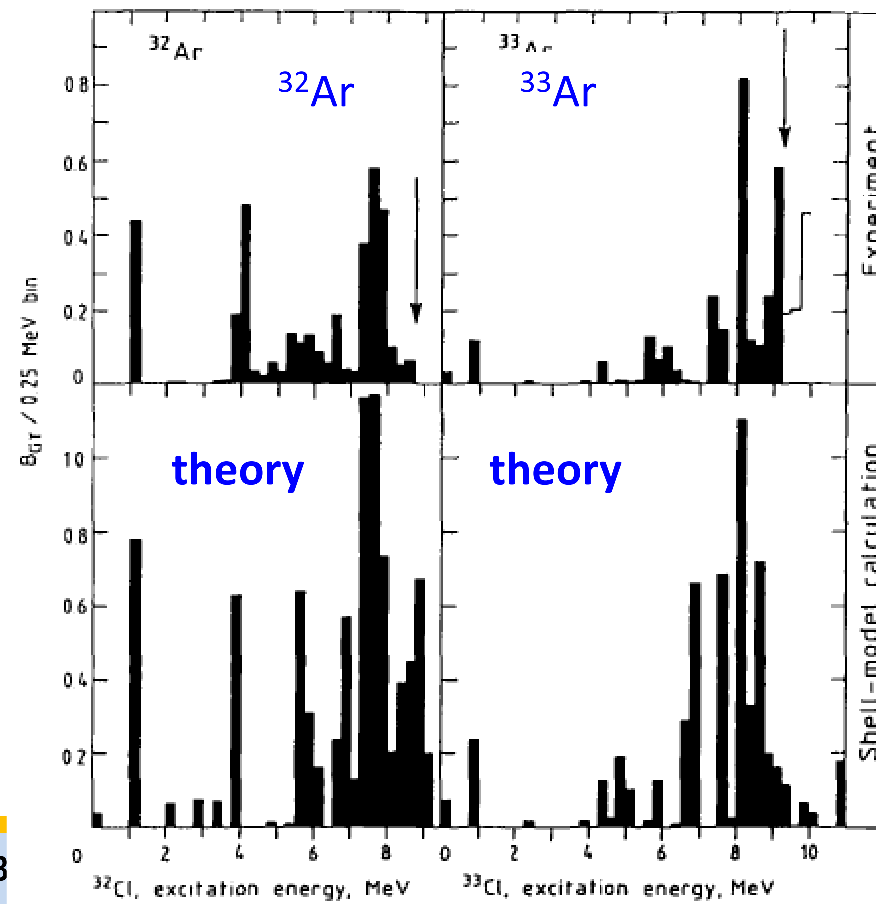
✓ If strength to IAS $\neq B_F \Leftrightarrow$ Mixing



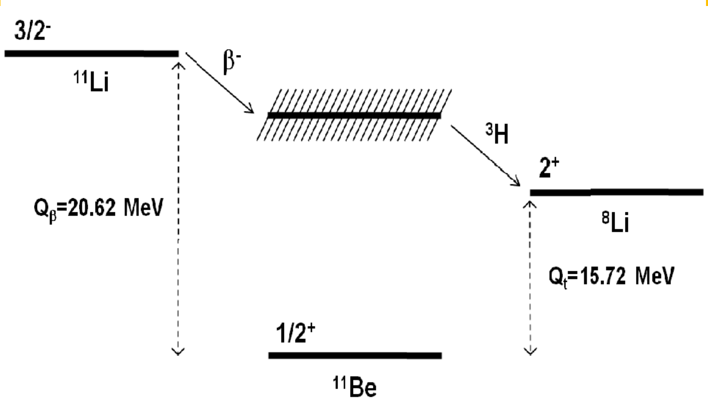
Quintet test→ d = 0.89(11) keV

✓ Impressive reproduction of the B_{GT} distribution by Shell Model calculation

✓ Quenching factor close to one, sensitive to the placement of the GTGR

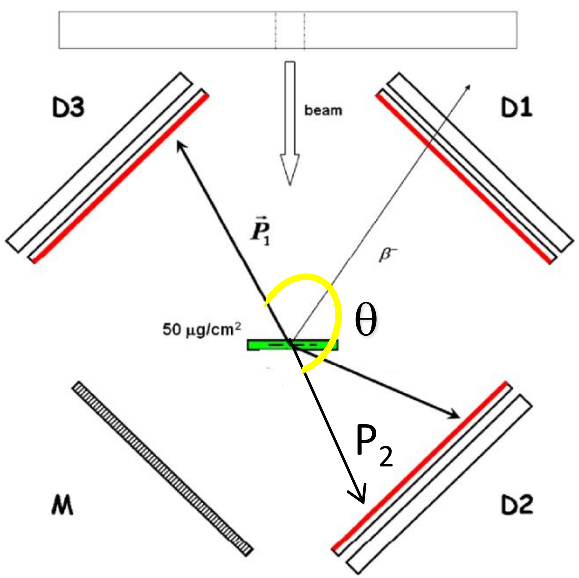


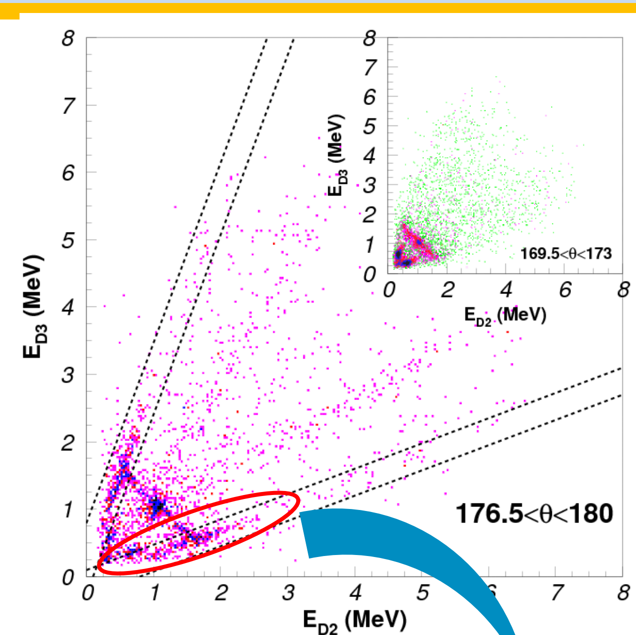
Kinematic identification of βt emission in ^{11}Li

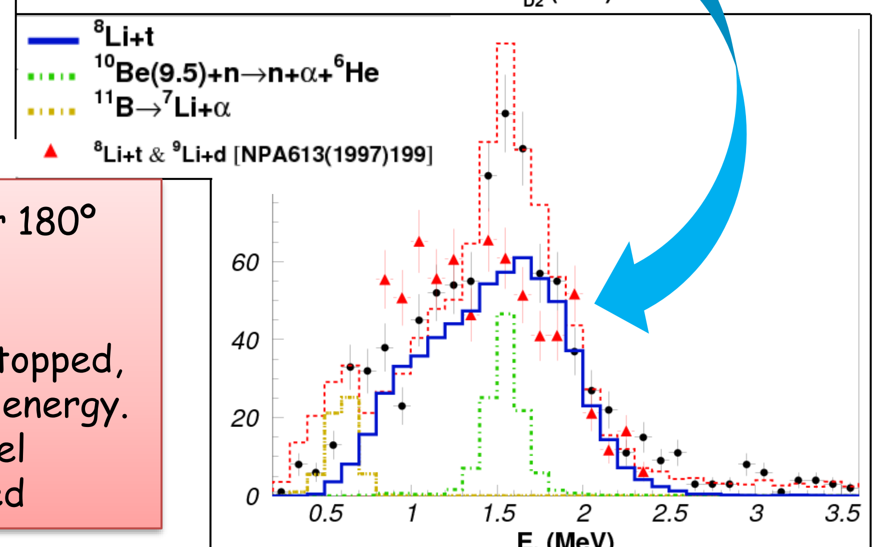


$$Q_{\beta t} = \Delta M(^{11}Li) - \Delta M(^{8}Li) - \Delta M(t) = 4822(5)\ keV$$

Madurga et al., Eur. Phys. J A42 (2009)415

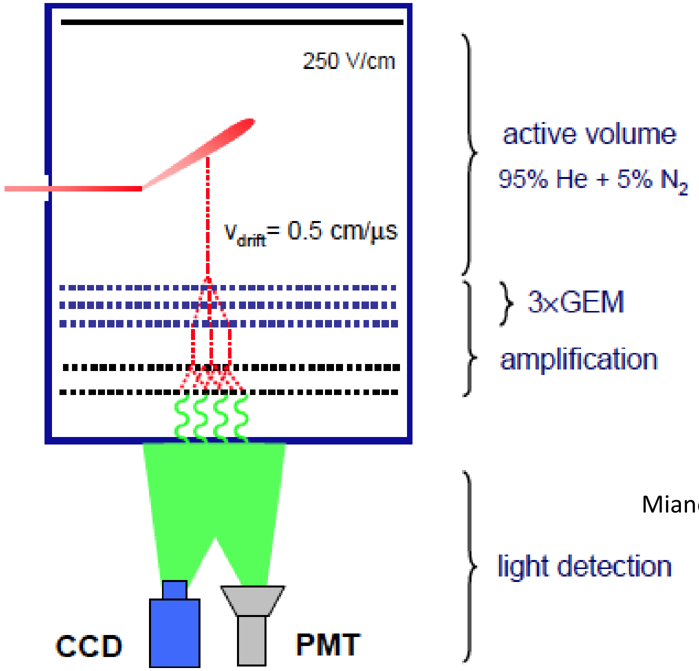






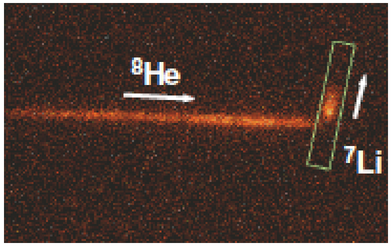
- Kinematics near 180° between charged particles.
- ^{9}Li+d channel stopped, ^{9}Li too low recoil energy.
- The ^{8}Li+t channel uniquely separated

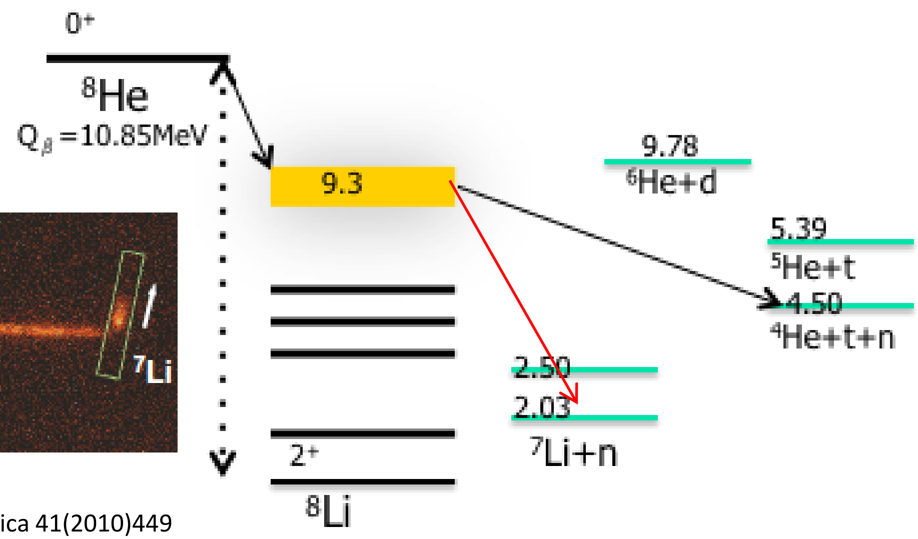
Viewing β-delayed triton emission



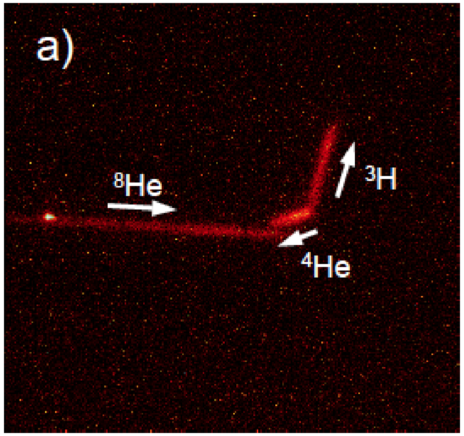
Optical Time Projection Chamber

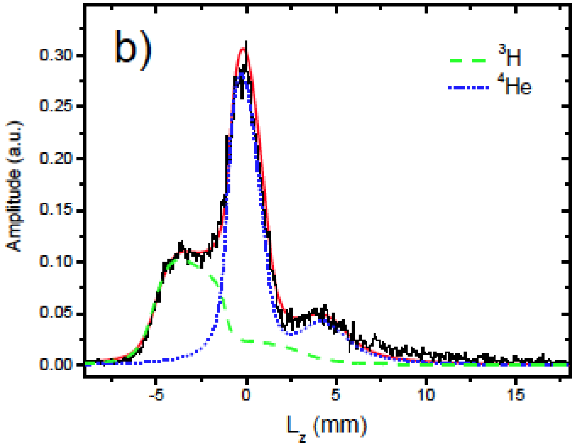
The strong βt branch allowed to identified feeding to a highly excited state in ^{8}Li.
New branch βn from this state confirming the character of super-allowed transition





Mianowski et al, Acta Polonica 41(2010)449

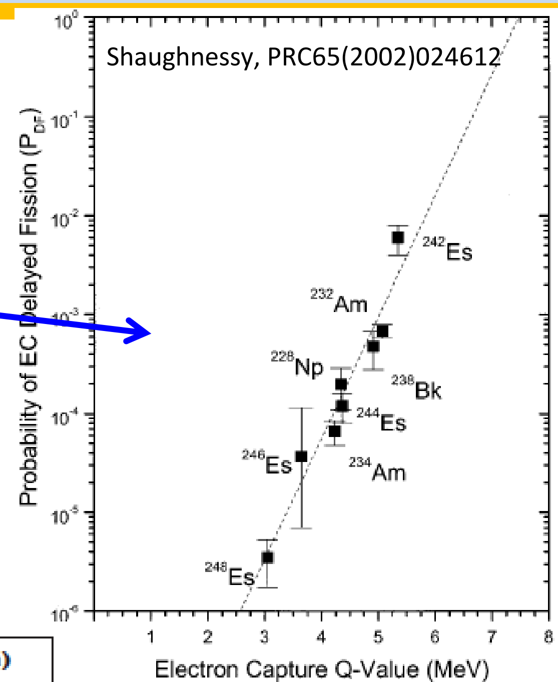


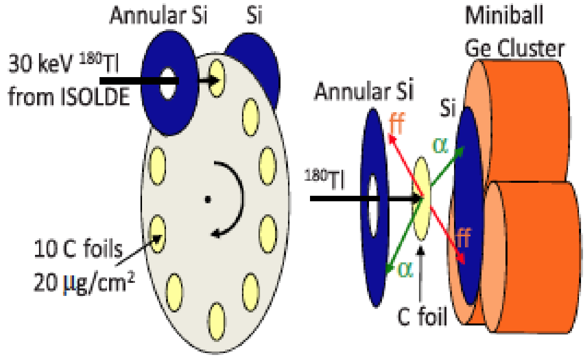


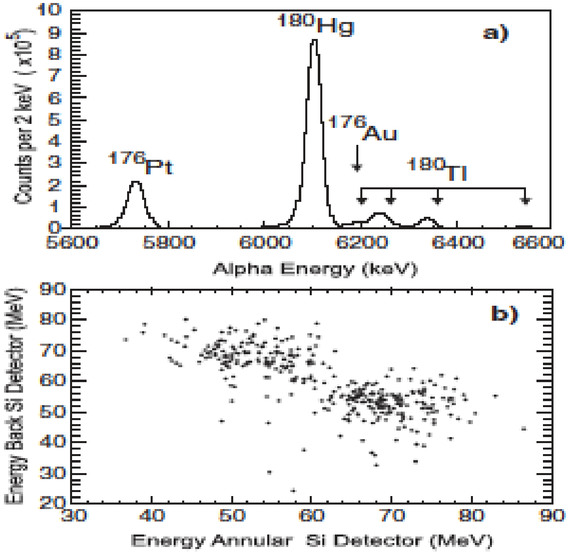
Beta-delayed Fission in the Pb-region

Discover in Dubna in ^{232,234}Am in 1966
Allows to study low energy fission properties at unusual N/Z ratios
Max energy of fissioning nucleus < Q_{EC} of precursor

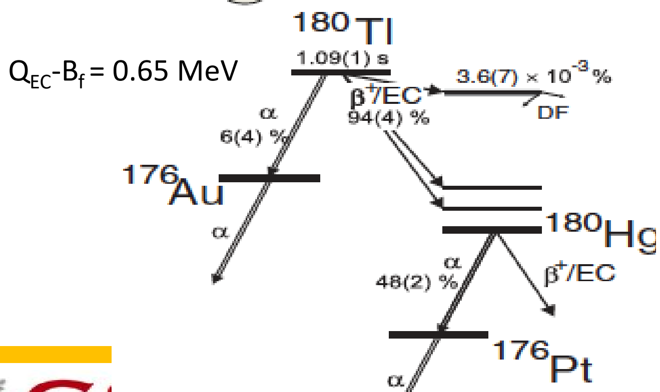
Two region : 12 cases identified in the U-region
neutron defficient Pb-region

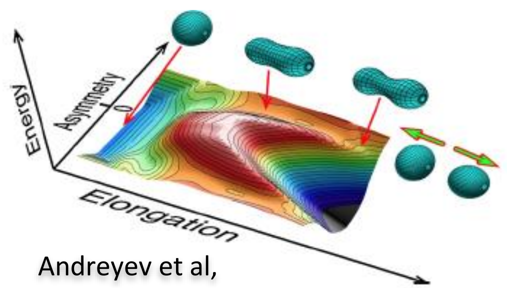






Unexpected Asymetric Fission Fragments !



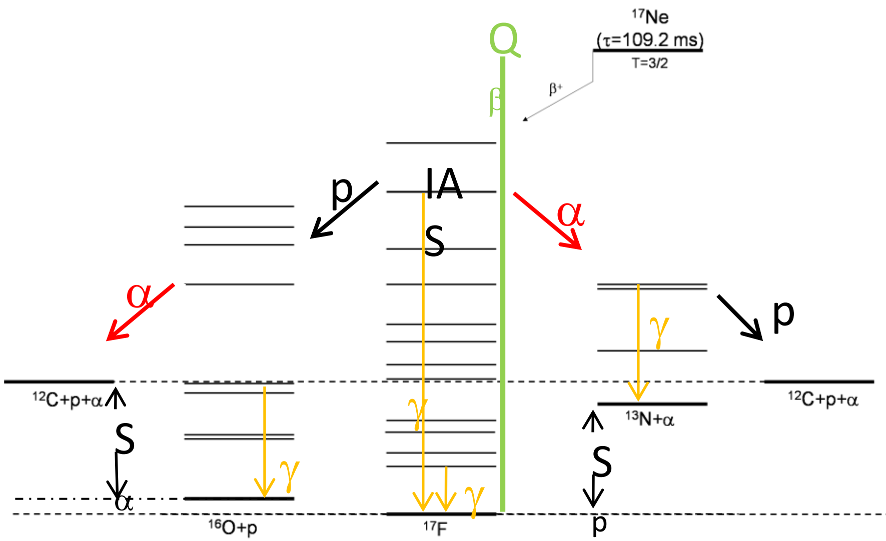


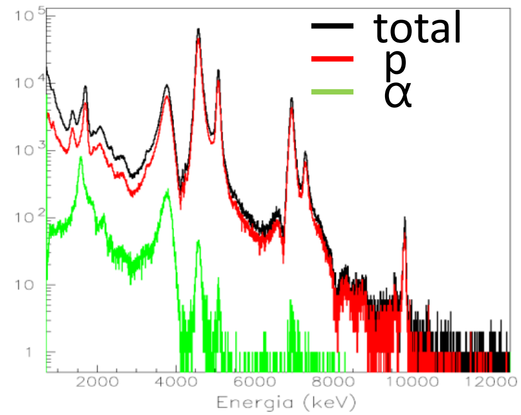
Andreyev et al, PRL105(2010)252502

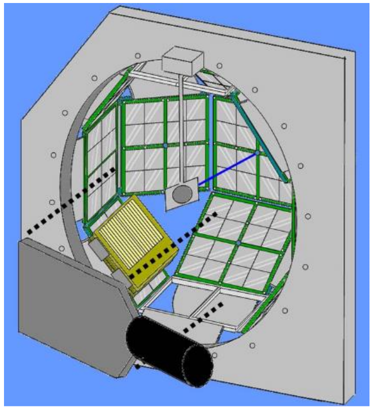
Beta-alpha emission

- βα-Identified first in Natural radiactivity
- βα favoured in light nuclei with Tz = -1: ^{8}B, ^{12}N, ^{20}Na…
- In cases were both βα and βp are allowed =>βp dominates due to barrier penetrabilities
- Branches of βα > 1% are only observed in nuclei A < 20 and ^{118}I
- Some of these states are of astrophysical relevance
  - For instance the ^{16}N(βα) helped to elucidate the $^{12}C(\alpha,\gamma)^{16}O$
- βpα or βαp is a decay mode open for ^{9}C, ^{13}O, ^{17}Ne, ^{21}Mg and ^{23}Si
  - Only identified ^{9}C and ^{17}Ne
    - ^{9}C special as the daughter is unbound to p-emission. Expectacular asymmetry in some of the mirror transitions with ^{9}Li
    - ^{17}Ne astrophysical relevance to learn about the E2 capture rate in stellar $^{12}C(\alpha,\gamma)^{16}O$ reaction

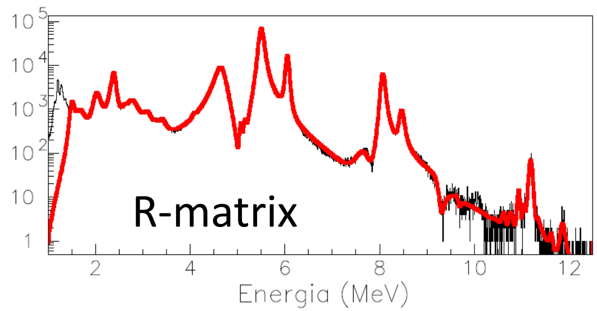
Beta-decay of ^{17}Ne

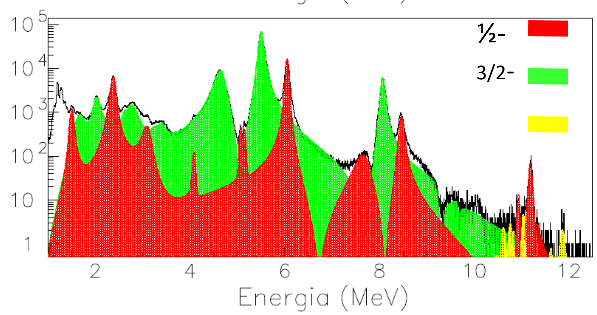






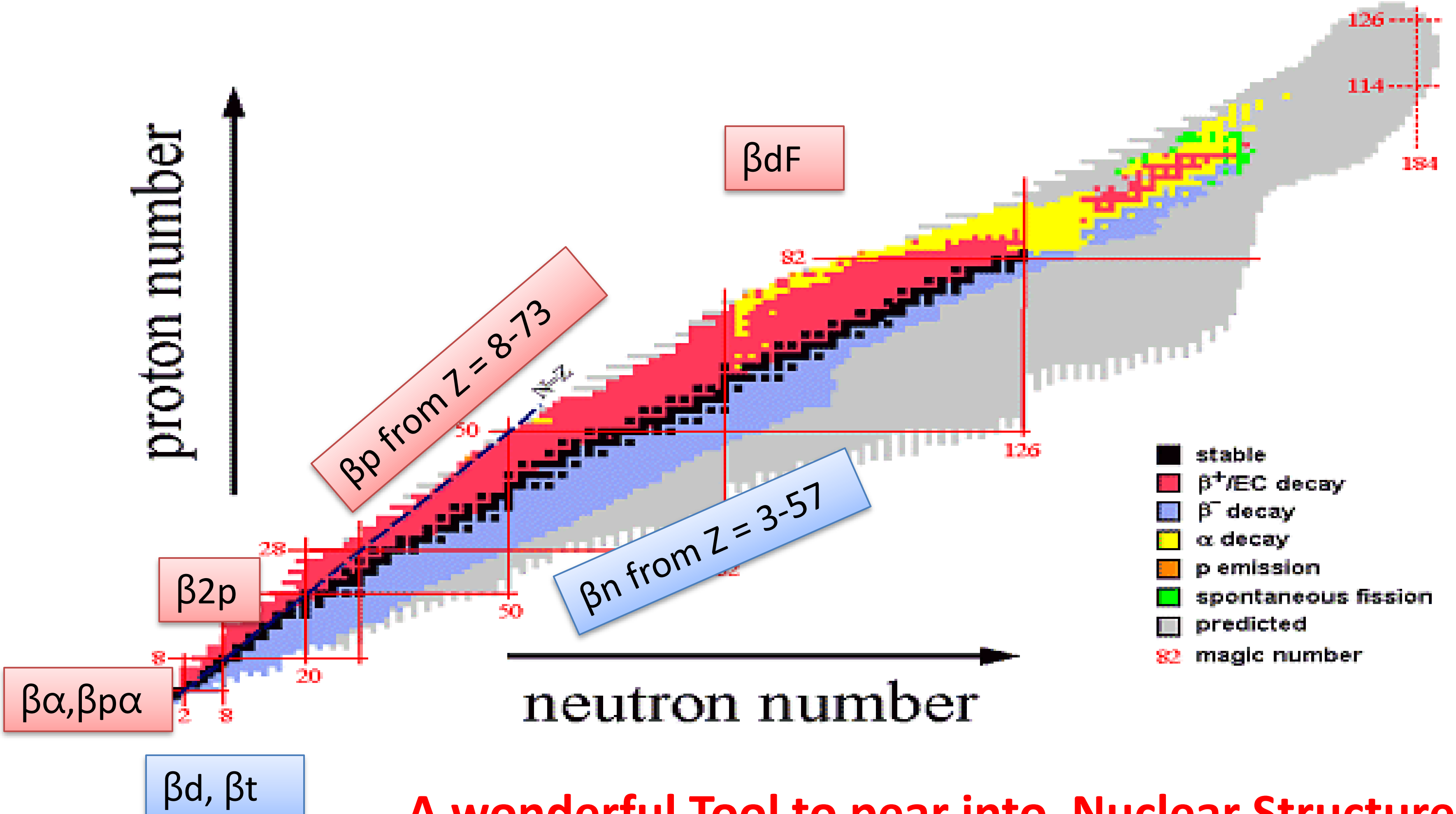
Characterization of the α-width of the subthreshold states of ^{16}0 at 6.9 and 7.1 MeV of interest for the ^{12}C(α,γ)^{16}0 capture rate.





- Separation of βp, βα channels with ΔE-E and ToF techniques, allowing independent analysis of the two spectra.
- Bp and Bα branches confimed previous values with higher precision.
- Treatment of the full proton spectrum using R-Matrix.
- Feeding to subthreshold ^{16}0 states, study of their partial α-widths on progress.

Beta Delayed Particle Emission



A wonderful Tool to pear into Nuclear Structure!!

βν correlation studies: peering into Nuclear Structure

$$W(\theta) = 1 + a\frac{p_\beta}{E_\beta}cos(\theta_{\beta\nu}), \qquad with \quad a = \frac{g_V^2 B_F - \frac{1}{3}g_A^2 B_{GT}}{g_V^2 B_F + g_A^2 B_{GT}}.$$

If the decay is followed by particle emission, the recoil of the daughter shifts the energy of the delayed particle by about 10 keV that it is easy to measure.

✓First used to deduced the nature of the decay of ^{8}Li β2α

$$W = 1 + \frac{1}{2}(3a - A)\frac{p_\beta}{E_\beta}cos\theta_{\beta\nu} + \frac{3}{2}(A - a)\frac{p_\beta}{E_\beta}cos\theta_{p\beta}cos\theta_{p\nu}$$

$$A = \frac{g_V^2 B_F - (\frac{1}{3} + \frac{2}{30}\tau\Theta)g_A^2 B_{GT}}{g_V^2 B_F + g_A^2 B_{GT}}$$

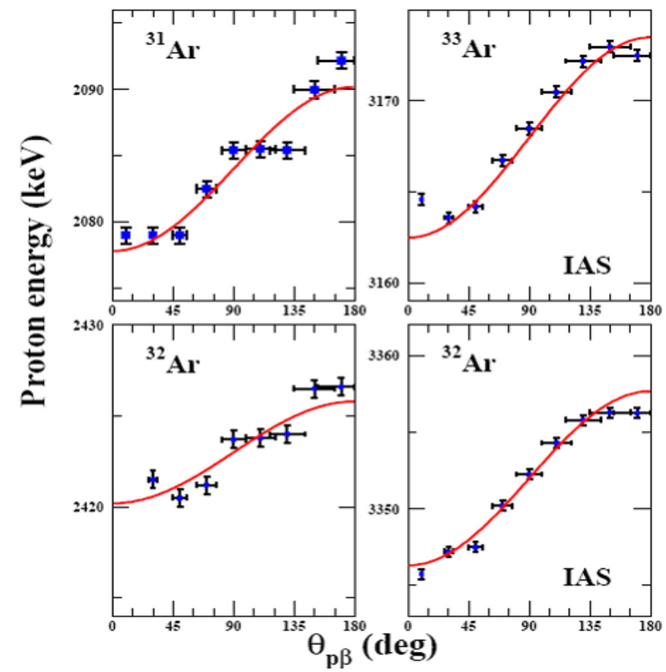
Θτ ≠0 { GT, Ip ≠0

β – ν correlations allow to extract:

- Spins: ^{31}Ar
- Fermi / GT character
- Intrinsic widths of levels
- Final state (gs/excited) of delayed particle

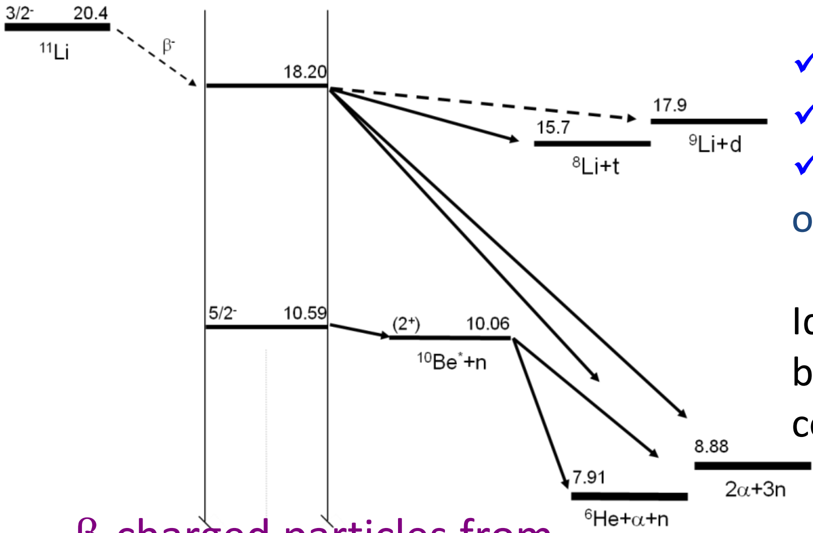
The energy shift in the delayed particle averaged over the neutrino angles

$$< t >_\nu = -kcos\theta_{p\beta}\left(1 + \frac{1}{3}A\frac{p_\nu c}{E_\beta}\right)p_\beta c$$



Thaysen et al, Phys. Lett B 467 (1999) 194

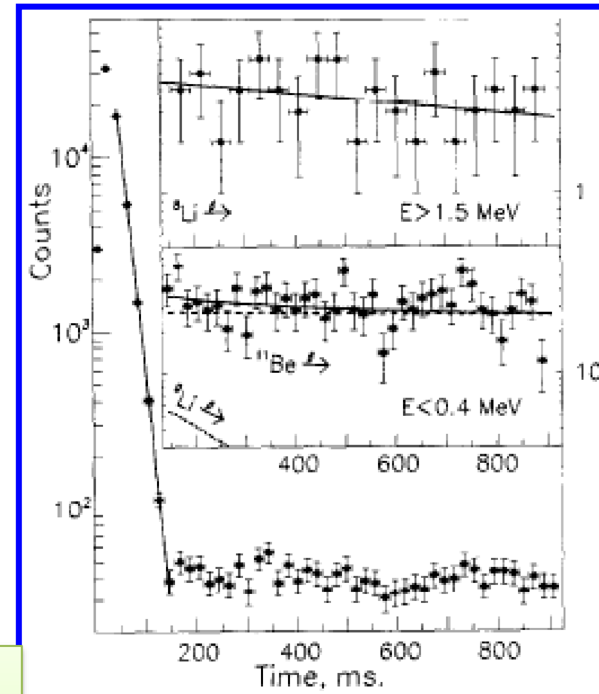
^{11}Li (βd) @ ISOLDE



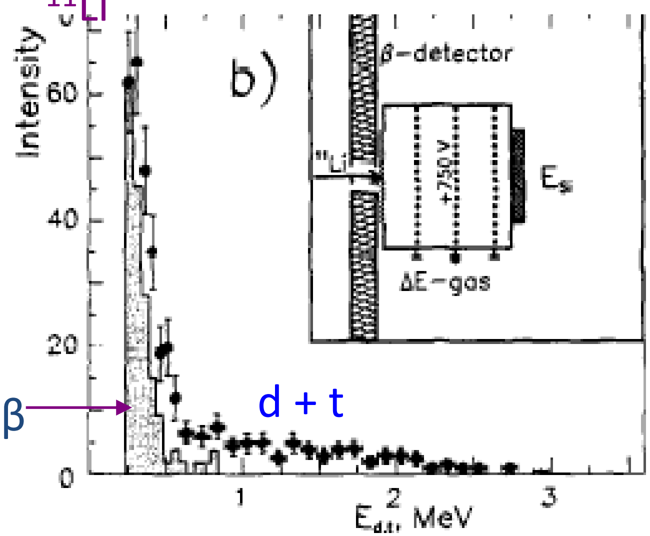
- ✓ Complicated decay
- ✓ B.R. of βd ~ βt ~ 10^{-4}
- ✓ Used of pulsed structure of ISOLDE beam

Identification of the βd branch by energy and time correlation

Time correlation



β-charged particles from ^{11}Li



Study of correlation between the Z = 1 particles (T < 0.06 ms) and delayed alphas between 0.15 < T < 0.9 s

B.R.(βd) ~ 1×10^{-4}
Mukha et al., PLB367 (96) 65