Proton emission in radioactive decay

experimental studies

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Foreword

Radioactivity

an old science (~120 years…)
initially related to chemistry, then to physics (nuclear & particle)

first experimental probe to study atomic nucleus
still a way to address many questions of the sub-atomic world

Objectives of the lecture

focus on decay modes involving one or several protons emission
give a flavor of the physics topics that can be addressed with these processes

questions considered from the experimental side

Summary

- **General considerations about radioactivity**
  present the context of the decay modes involving proton emission
  basic and qualitative aspects

- **Production of radioactive ions**
  present the main techniques used to produce the nuclei of interest
  and study their radioactive decay

- **Beta-delayed proton(s) emission**
  illustrate with selected subjects the additional (sometimes unique)
  information that beta-delayed proton emission brings for our
  understanding of the atomic nucleus

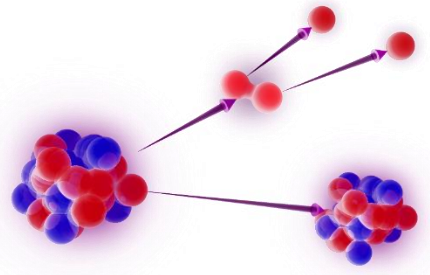
- **Proton(s) radioactivity**
  experimental studies of these very exotic decay modes

- **…**
  if there's a bit of time left…

Proton emission in radioactive decay

experimental studies

first session



General consideration about radioactivity

- **Introduction**
  - Brief overview of radioactive decay modes
  - Instability of atomic nucleus
- **Decay of proton-rich nuclei**
  - Beta plus and the isospin formalism
  - Towards the proton drip-line

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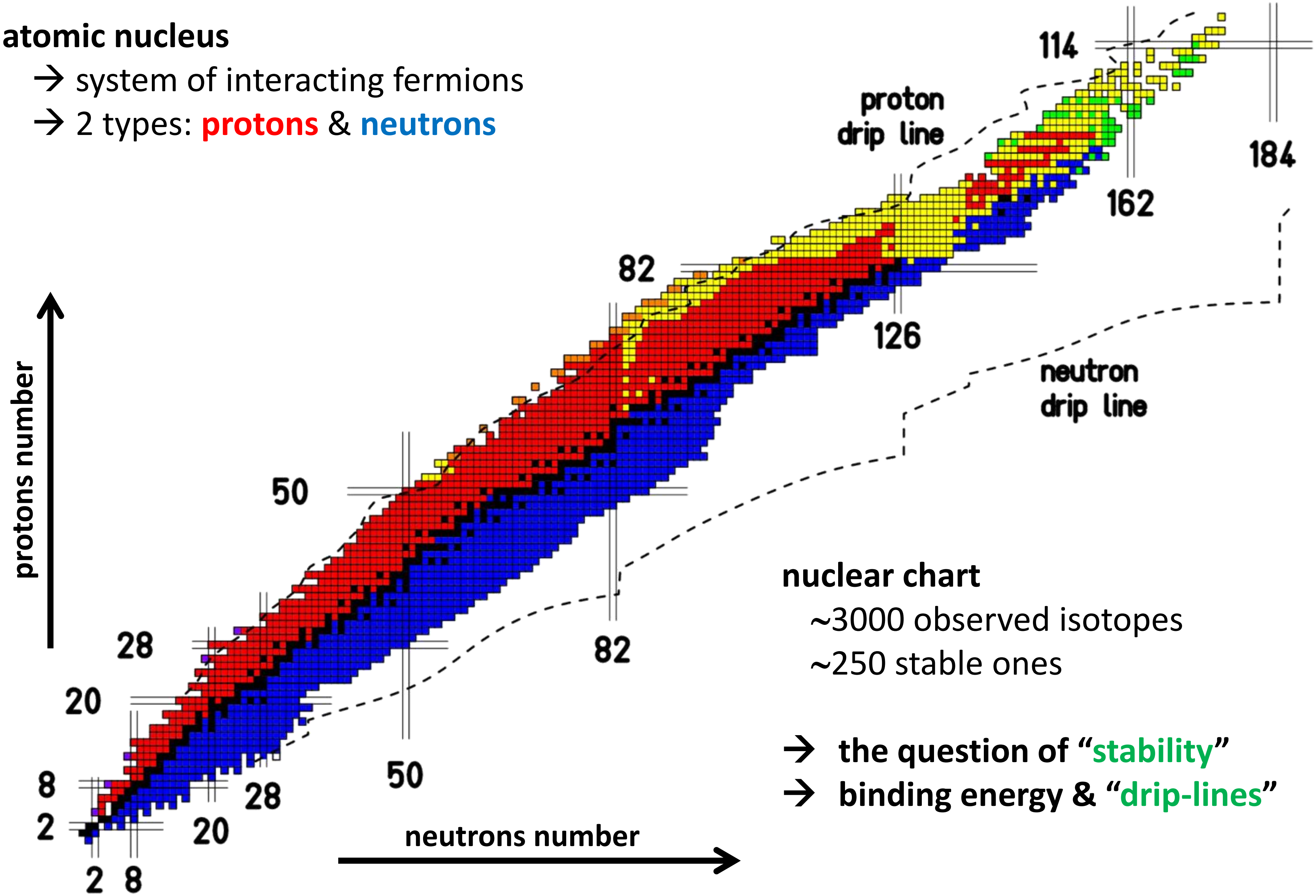
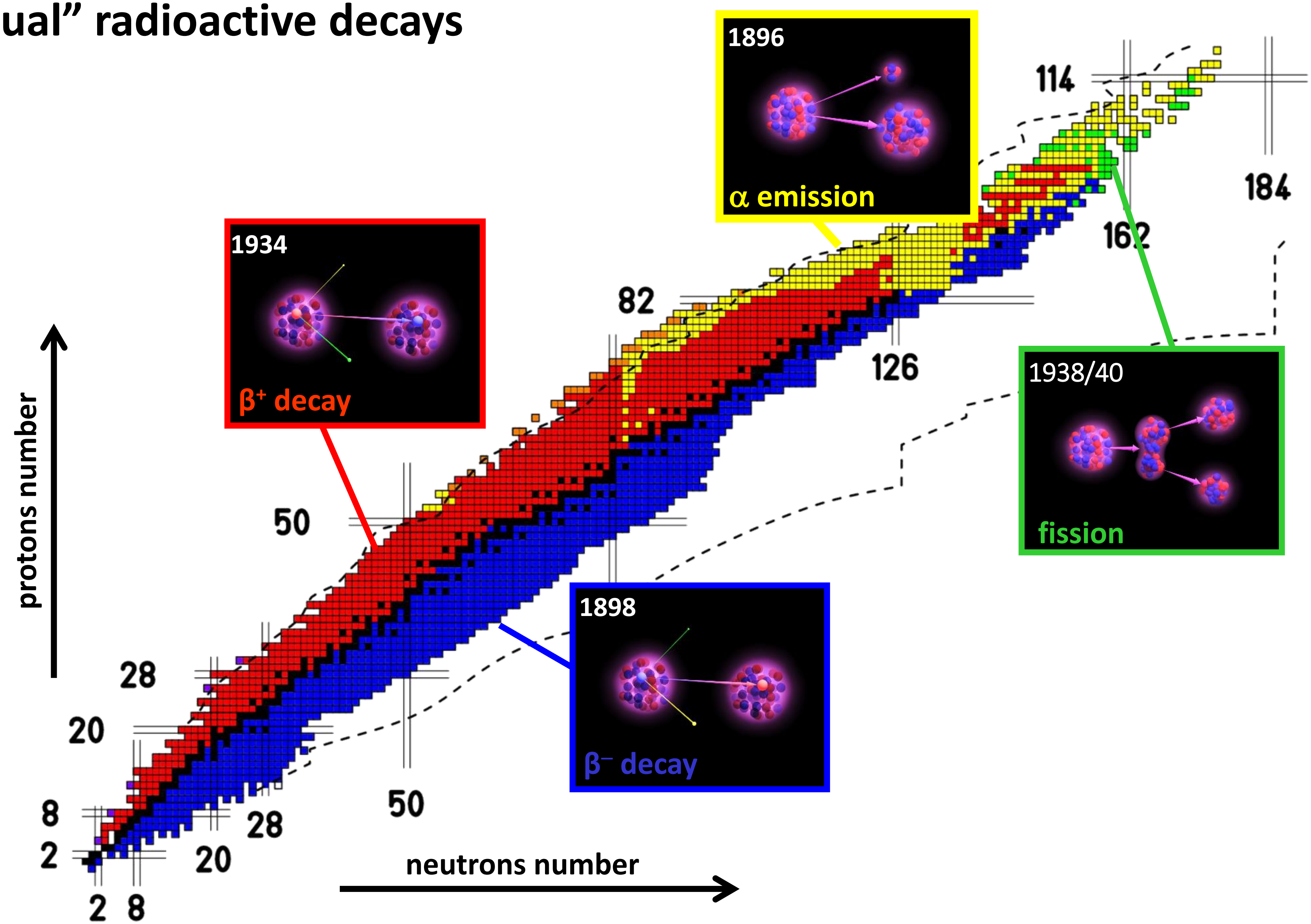
atomic nucleus
- → system of interacting fermions
- → 2 types: protons & neutrons



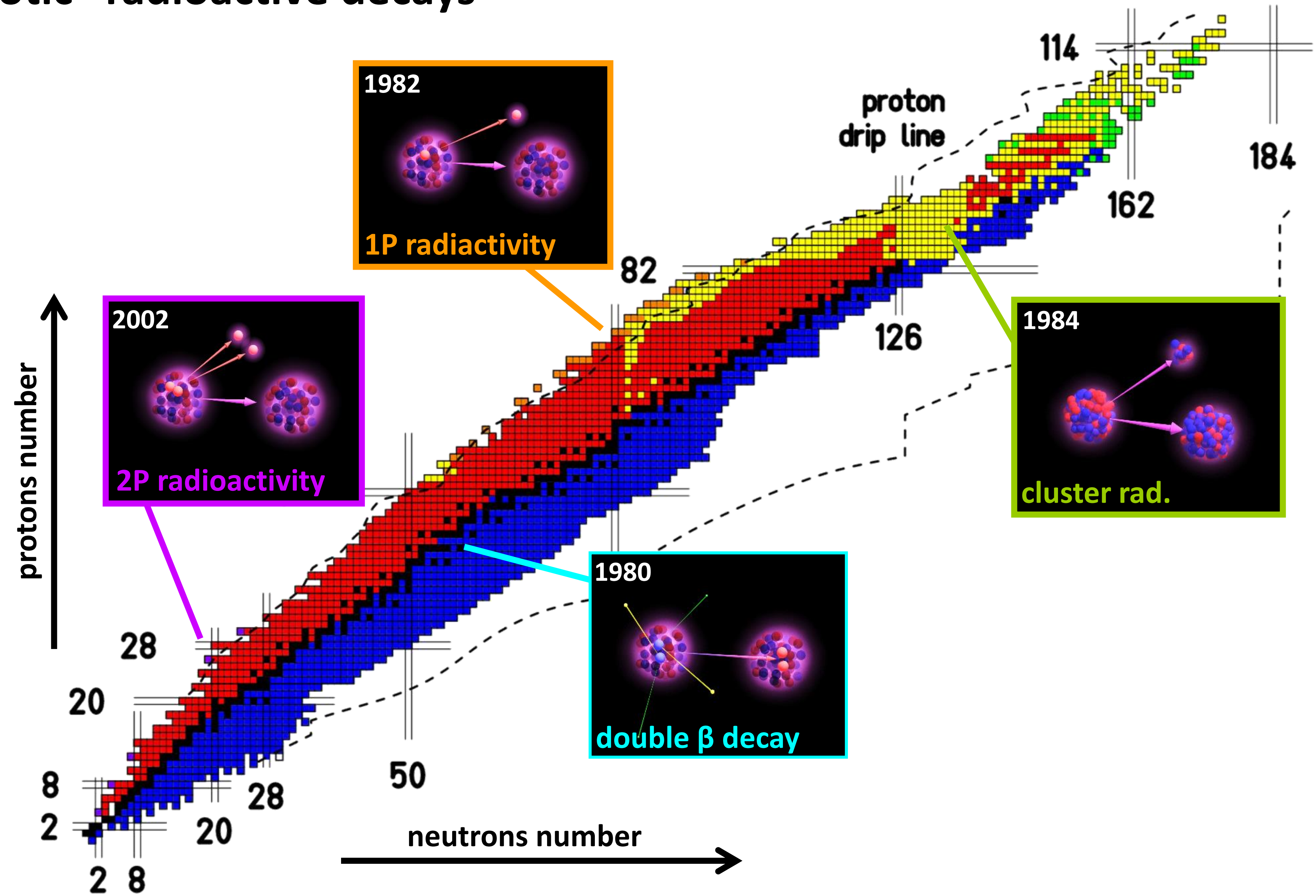
nuclear chart
- ~3000 observed isotopes
- ~250 stable ones

→ **the question of "stability"**
→ **binding energy & "drip-lines"**

“usual” radioactive decays



“exotic” radioactive decays



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any system tends to minimize its energy

radioactivity:

spontaneous (no external perturbation) **transformation of the nucleus to release energy**

energy ⇔ mass ($\times c^2$)

$$\mathbf{A} \Leftrightarrow \mathbf{B} + \mathbf{C_1} + \mathbf{C_2} + \ldots + \mathbf{Q}$$

⇔ conservation laws
(quantum numbers: baryonic, leptonic, charge…)

$$Q = M(\mathrm{A}) - [M(\mathrm{B}) + M(\mathrm{C_1}) + M(\mathrm{C_2}) + \ldots]$$

if **Q > 0** the system (nucleus) **A is instable** (radioactive)
it decays to **B**, with emission of **C_1, C_2**… particles

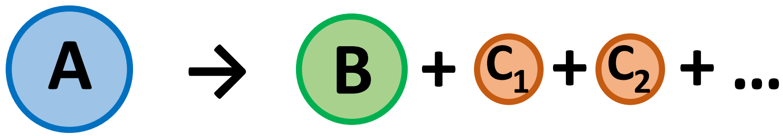
any system tends to minimize its energy

radioactivity:
spontaneous (no external perturbation) **transformation of the nucleus to release energy**

energy ⇔ mass ($\times c^2$)

$$A \rightarrow B + C_1 + C_2 + \ldots + Q$$

radioactivity (more official and etymological definition):
focuses on the consequence, not the cause
emission of particles / radiation (caused by this energy release)



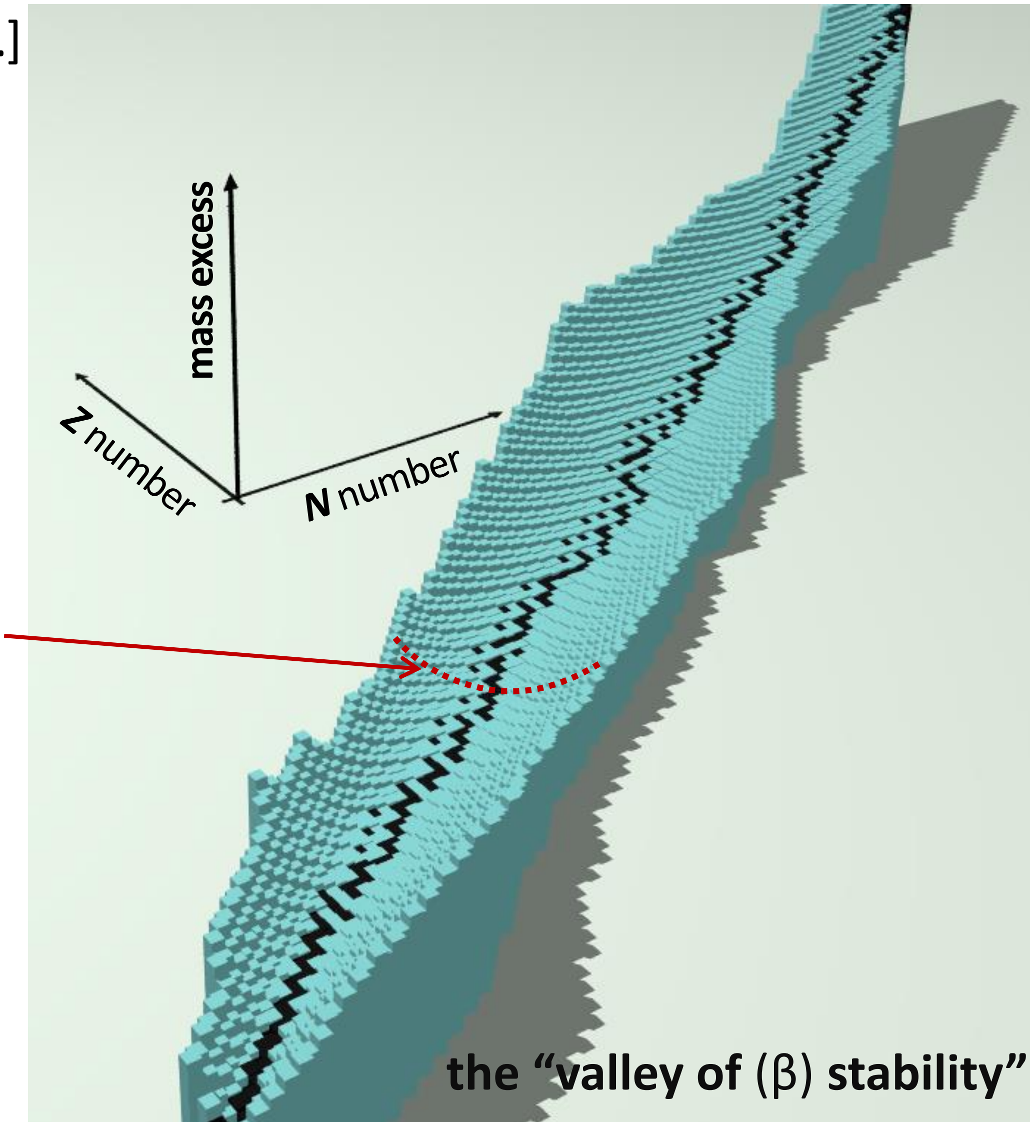
$$Q = M(\mathrm{A}) - [M(\mathrm{B}) + M(\mathrm{C}_1) + M(\mathrm{C}_2) + \ldots]$$

nuclear stability is directly related to masses

we use **mass excess**:

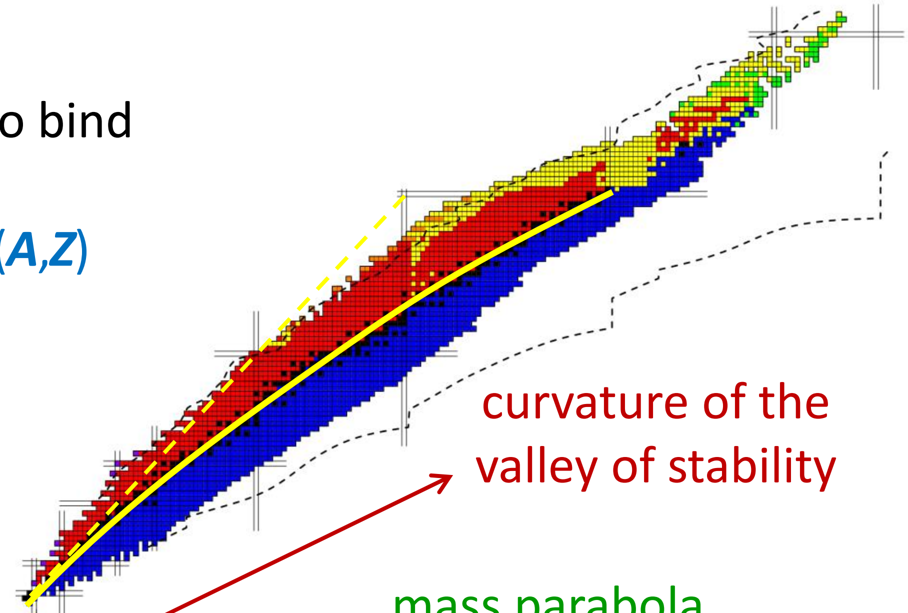
$$\Delta m = M - (N + Z) \times u$$

mass parabola
(same $A = N + Z$ → β decay)



⚠ mass compilations usually give the **atomic masses**, with electrons rest mass & binding energy

drip-lines and binding energy



binding energy

the part of the "mass energy" used to bind the system components

$$B(A,Z) = [\, Z \times m_p + N \times m_n \,] - M_{nuc}(A,Z)$$

(similar to $-\Delta m$)

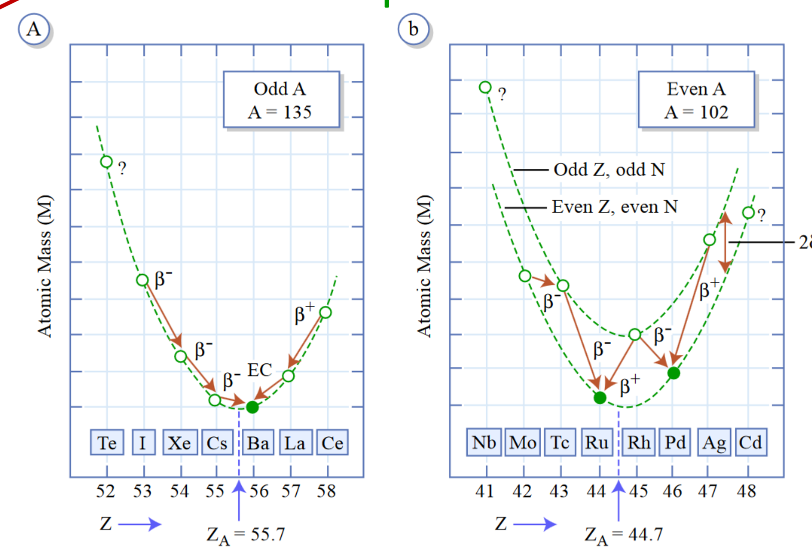
curvature of the valley of stability

Bethe-Weizsäcker (liquid drop model)

$$B(A,Z) = a_v \cdot A \qquad \text{volume}$$
$$- a_s \cdot A^{\frac{2}{3}} \qquad \text{surface}$$
$$- a_c \cdot \frac{Z(Z-1)}{A^{1/3}} \qquad \textbf{Coulomb}$$
$$- a_a \cdot \frac{(N-Z)^2}{A^{1/3}} \qquad \textbf{symmetry}$$
$$\pm a_p \cdot A^{-1/2} \qquad \text{pairing}$$

+ shell effects (magic numbers)…

mass parabola



drip-lines and binding energy

binding energy

the part of the "mass energy" used to bind the system components

$$B(A,Z) = [\, Z \times m_p + N \times m_n \,] - M_{nuc}(A,Z)$$

separation energy (for protons)

$$S_p(A,Z) = [\, M_{nuc}(A-1,Z-1) + m_p \,] - M_{nuc}(A,Z) = B(A,Z) - B(A-1,Z-1)$$

$$S_{2P}(A,Z) = [\, M_{nuc}(A-2,Z-2) + 2 \times m_p \,] - M_{nuc}(A,Z) = B(A,Z) - B(A-2,Z-2)$$

(proton) drip-line

if ($S_P < 0$) or ($S_{2P} < 0$) → last proton(s) not bound to the nucleus wrt the nuclear interaction

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beta decay & isospin

details for theory of beta decay and isospin formalism
not presented here → textbooks

lecture from E. Liénard

Fermi & Gamow-Teller transitions

considering...

- isospin as a good quantum number
- only allowed transitions (most common case)

$(T_i, T_{Zi} \,;\, J_i^{\pi}) \rightarrow (T_f, T_{Zf} \,;\, J_f^{\pi})$ for β^+ : $T_{Zi} \rightarrow T_{Zf} = T_{Zi} + 1$

Fermi (F) $|J_i - J_f| = 0 \;;\; \pi_i \pi_f = +1 \;;\; |T_i - T_f| = 0$

(coupling of e^+ and v to $L = 0$)

Gamow-Teller (GT) $|J_i - J_f| \leq 1 \;;\; \pi_i \pi_f = +1 \;;\; |T_i - T_f| \leq 1$

(coupling of e^+ and v to $L = 1$) ($\Delta J = 0$ forbidden for a $0^+ \rightarrow 0^+$ transition)

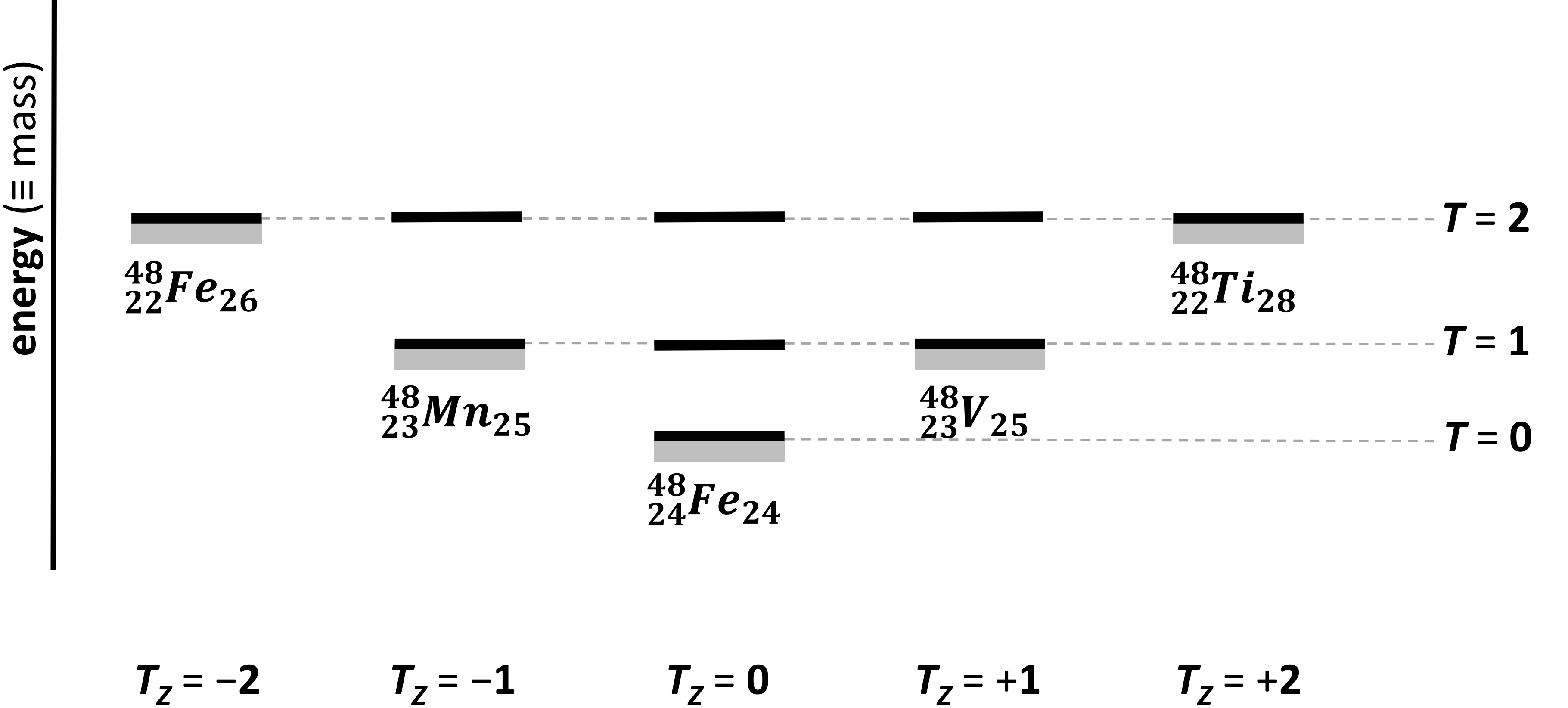
isospin multiplet

isospin as good quantum number & no Coulomb

⇩

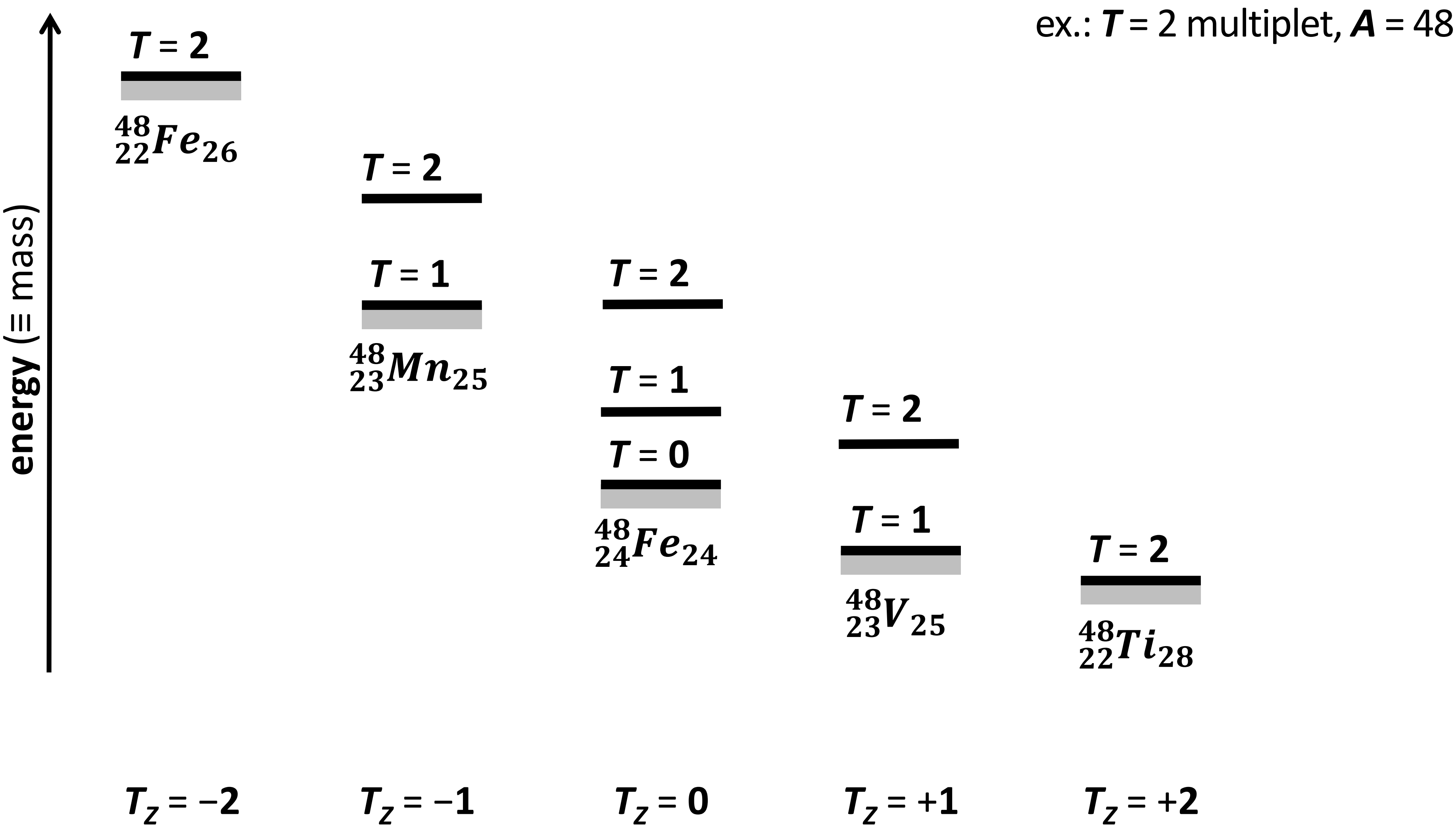
ex.: ***T*** = 2 multiplet, ***A*** = 48

perfect N - Z symmetry



isospin multiplet

in real life (with Coulomb → curvature of the stability)

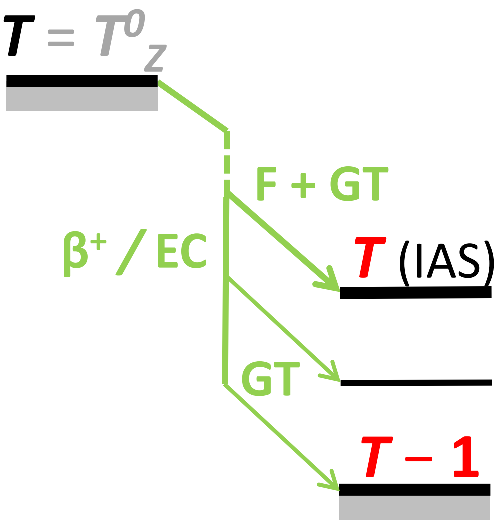


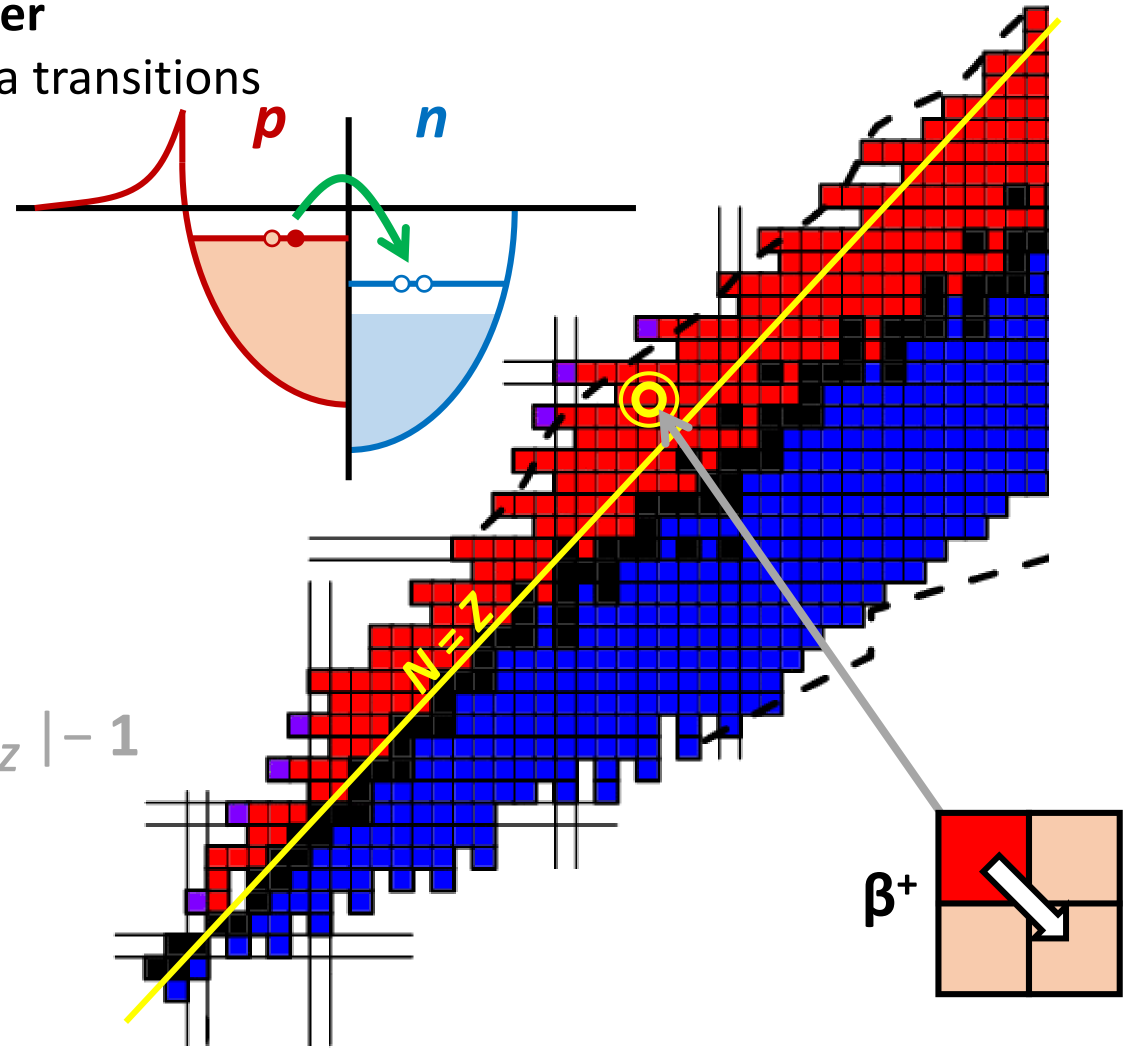
beta plus & isospin

for ***N*** < ***Z*** nuclei

⇒ **Gamow-Teller**

& **Fermi** beta transitions





$T^0_Z < 0$ $\quad |T^1_Z| = |T^0_Z| - 1$

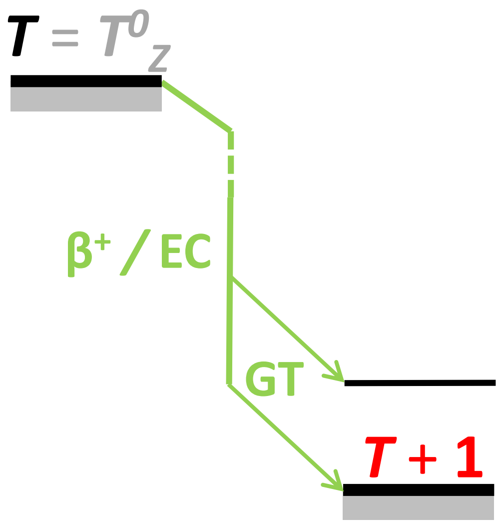
$(N < Z)$

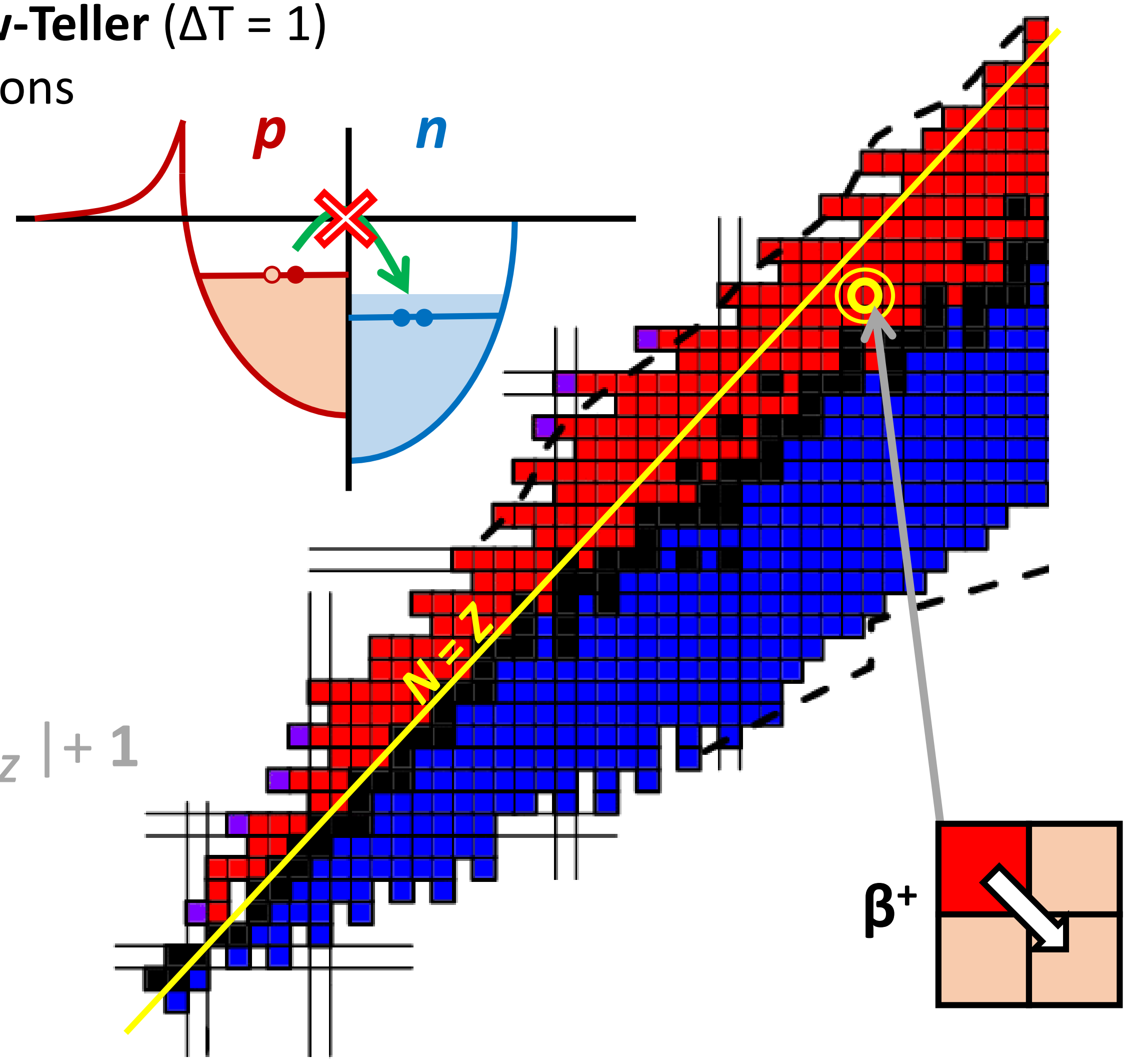
(*) for a $J^\pi = 0^+ \rightarrow 0^+$ transitions, $\Delta J = 0$ is forbidden because $S_{e\nu} = 1$

beta plus & isospin

for ***N*** < ***Z*** nuclei

⇒ only **Gamow-Teller** (ΔT = 1) beta transitions





$T^0_Z > 0$ $\quad |T^1_Z| = |T^0_Z| + 1$

$(N > Z)$

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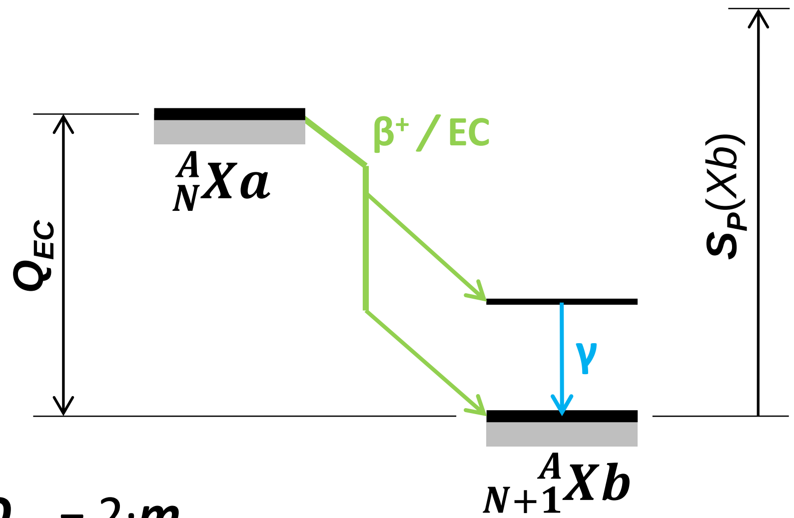
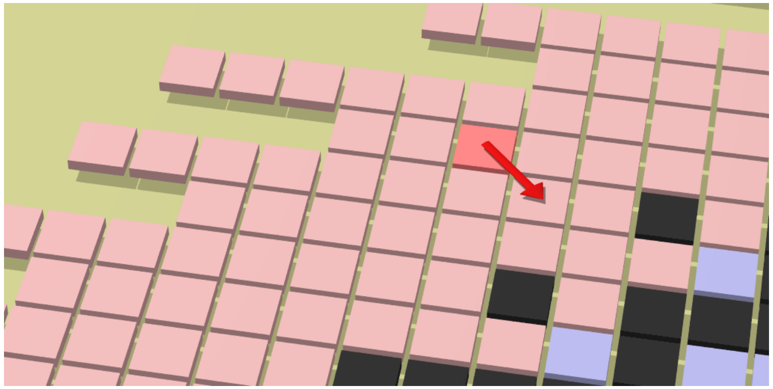




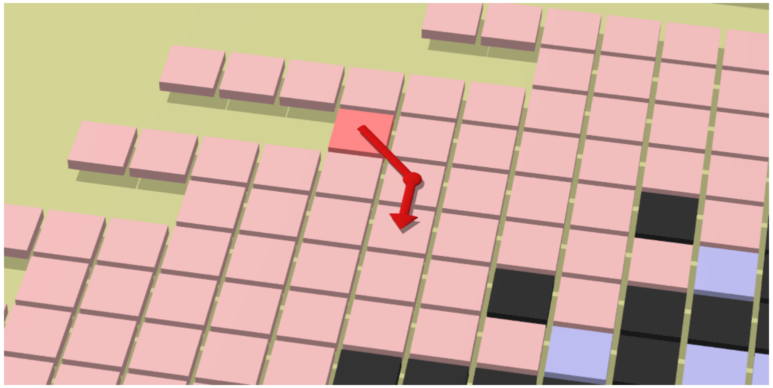
$Q_{\beta+} = Q_{EC} - 2 \cdot m_e$

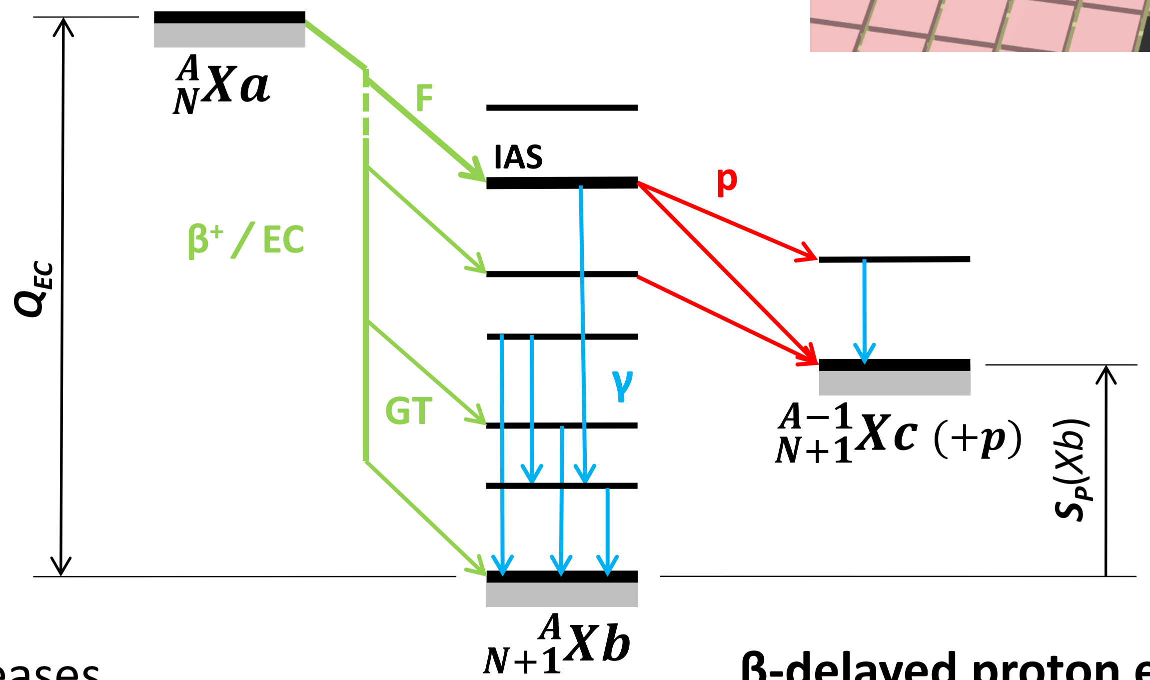
β and β-γ decays:

- spectroscopy and nuclear structure
- precision tests of weak interaction

β⁺/EC decay energy: Q_{EC} ~ few *MeV*

proton separation: $S_p(Xb) > Q_{EC}$ (*B/A* ~8 *MeV*)

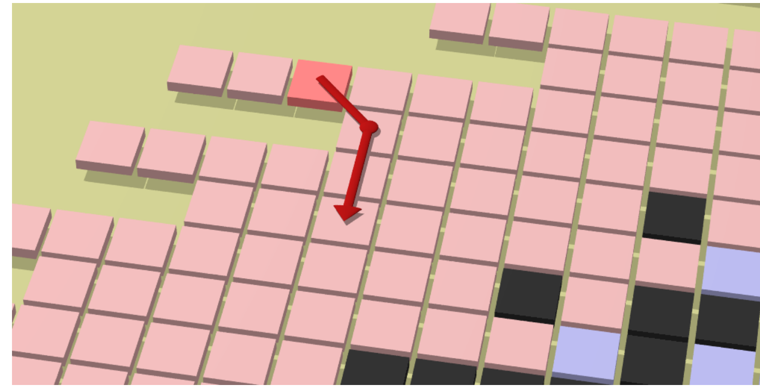




Q_{EC} increases
$S_p(Xb)$ decreases

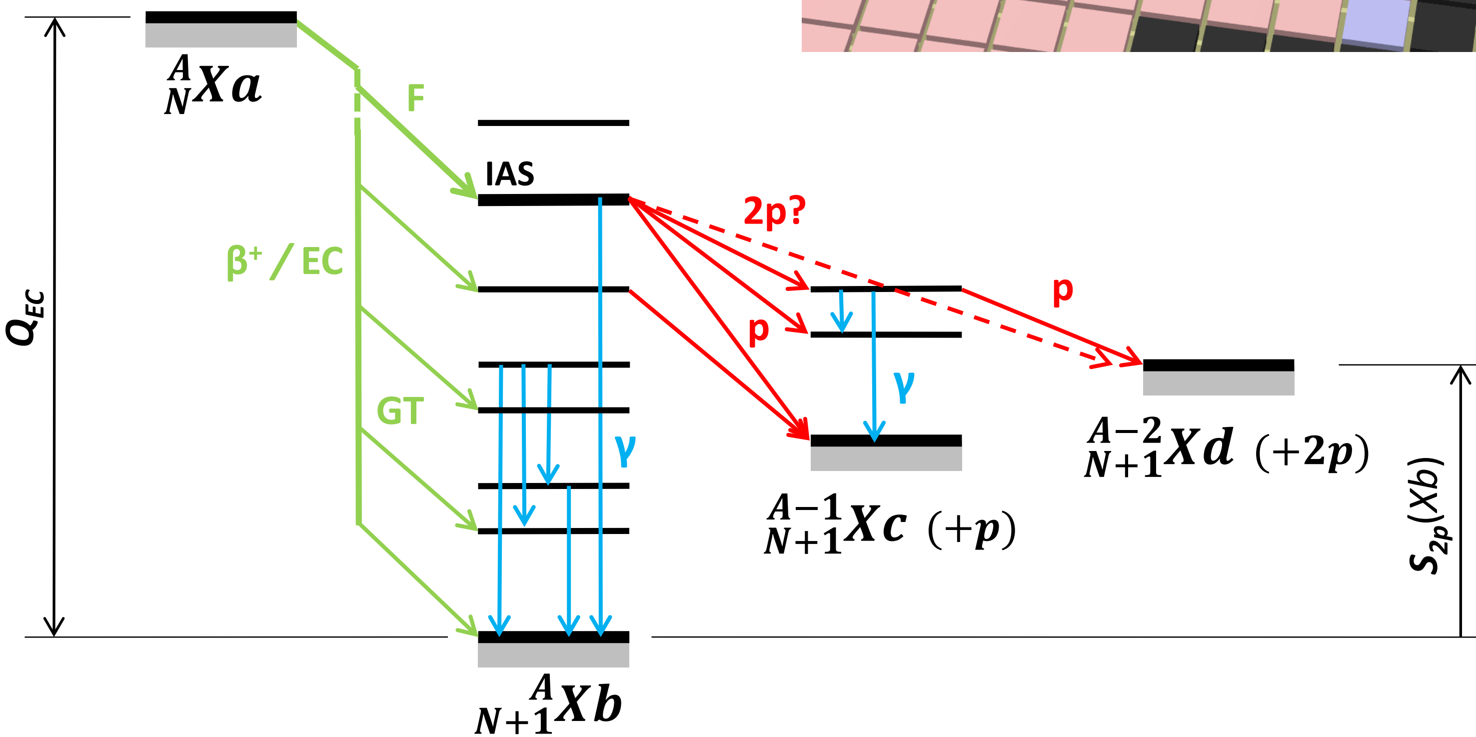
β-delayed proton emission:
- nuclear astrophysics
- gamma / proton competition

proton transitions: precise probe

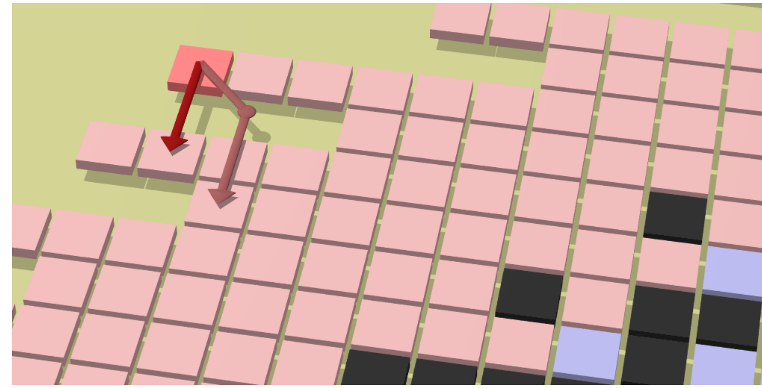


β-delayed multi- proton emission:

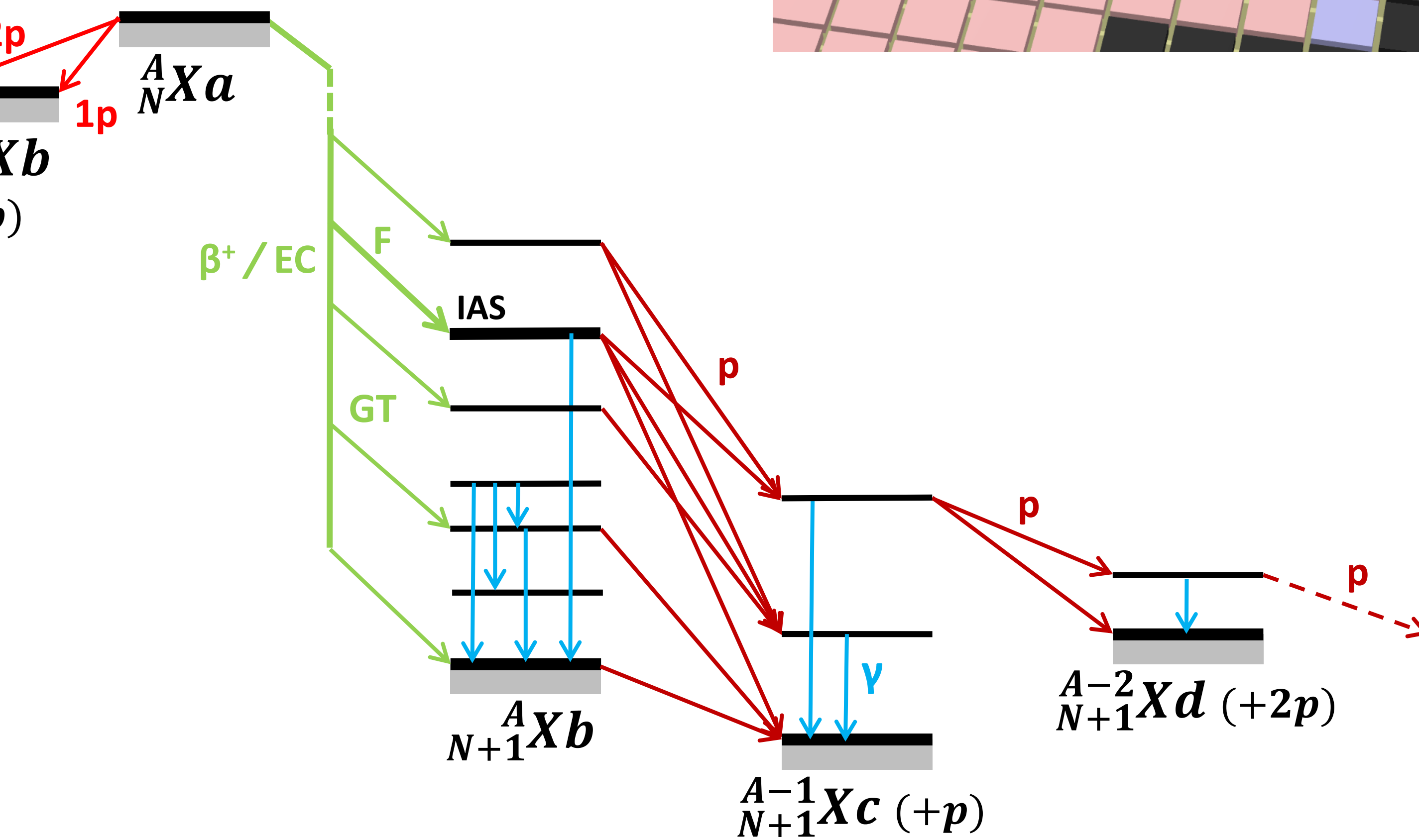
- *rp*-process waiting points
- search for direct 2P emission



- often the only access to very exotic isotopes
- complex proton emission patterns: level densities & statistical aspects



unbound with respect to proton(s) emission



$S_p(Xa) < 0$

and/or

$S_{2p}(Xa) < 0$

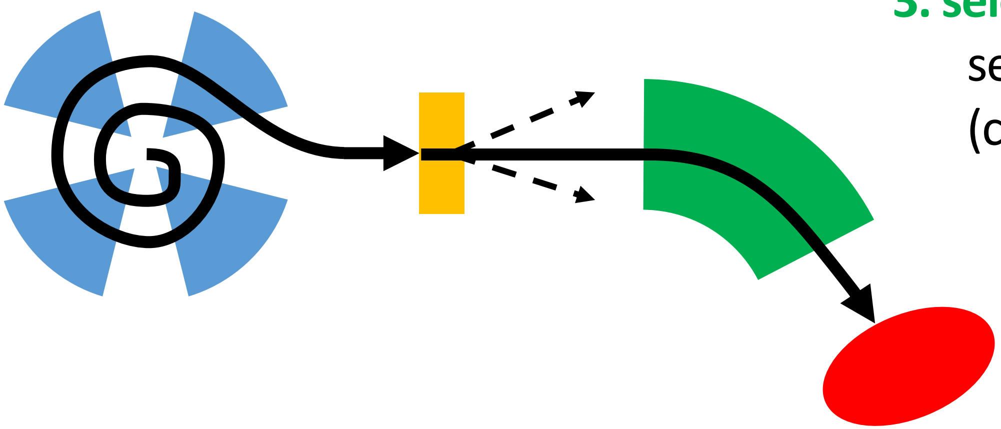
Experimental techniques for proton emission decay studies

- Production of radioactive ions
  - Production reactions
  - Separation techniques
- Experimental & detection techniques
  - For ISOL-type experiments
  - For fragmentation-type experiments

General experiment scheme

2. reaction in target
selectivity of the reaction
thickness / extraction of products

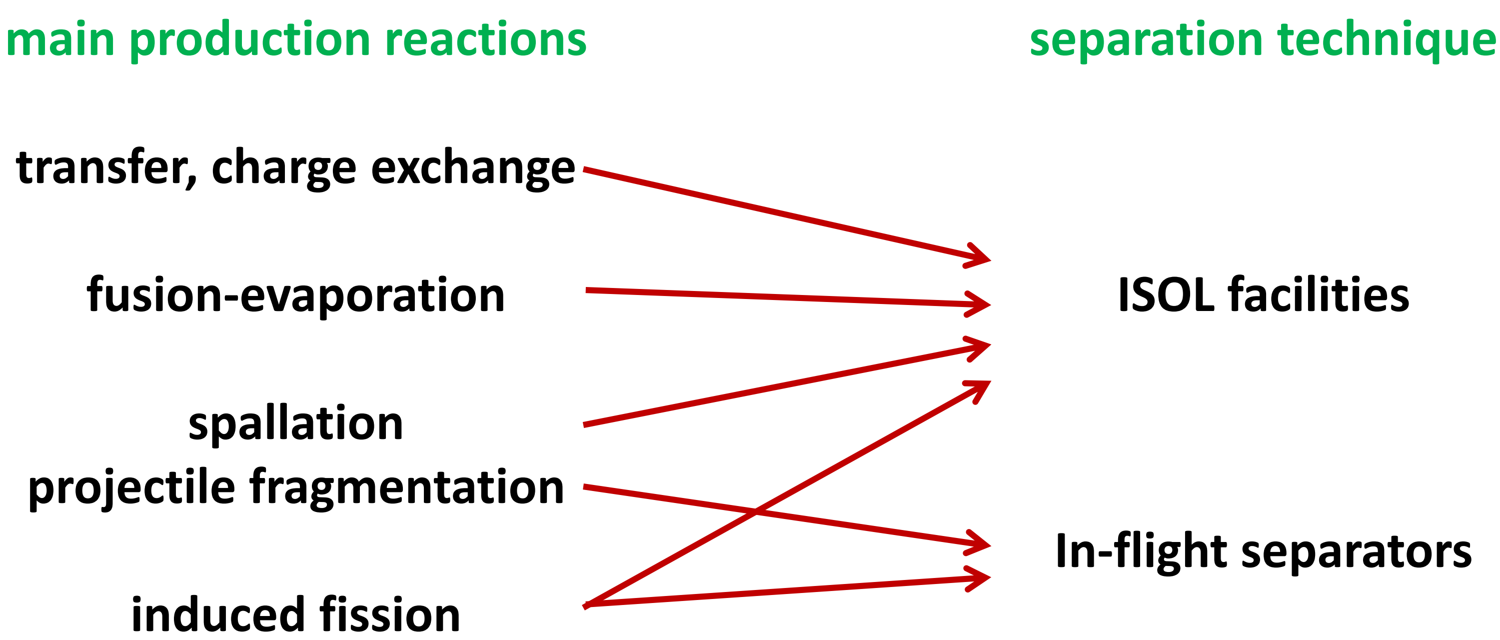
1. primary (stable) beam
ion, intensity & energy



3. selection / separation
separation capabilities
(contamination)

4. collection & decay
depends on the
separation technique

General experiment scheme



various possibilities, different limitations

Experimental techniques for proton emission decay studies

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main production reactions

transfer, charge exchange

fusion-evaporation

spallation

projectile fragmentation

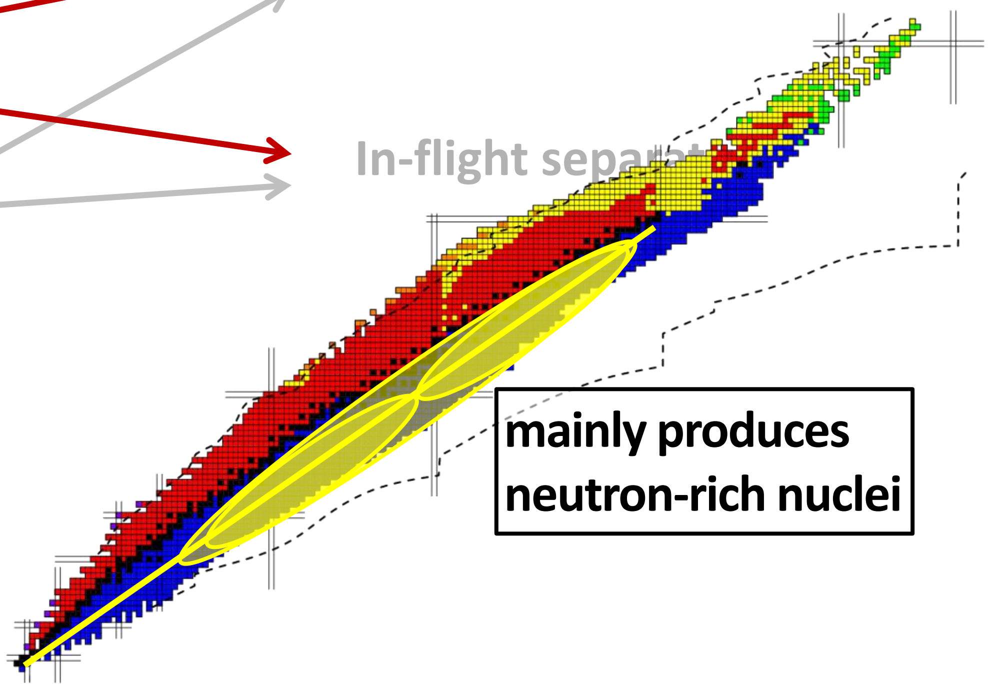
induced fission

separation technique

transfer of few nucleons (1 or 2)
→ not far from stability

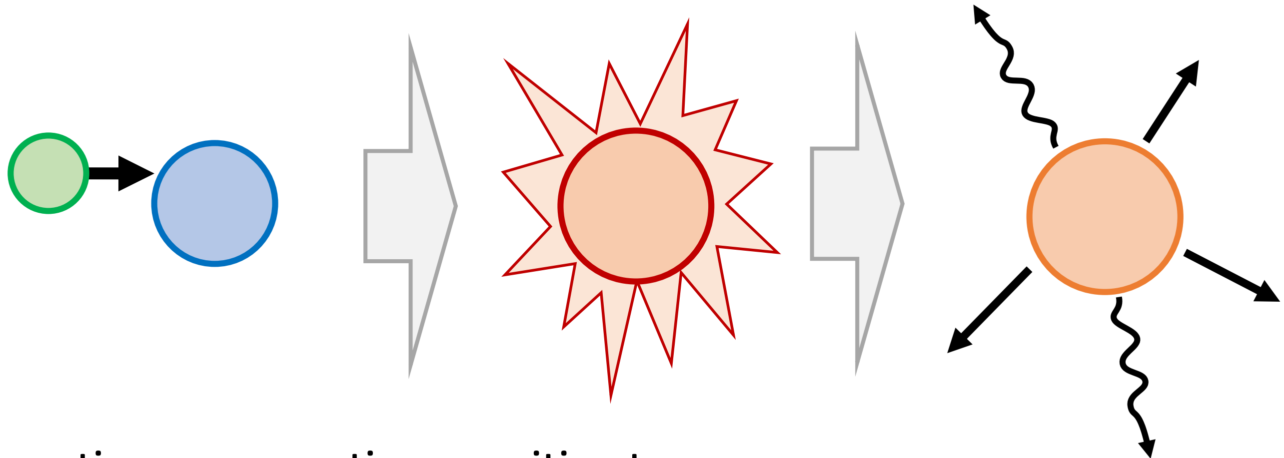
ISOL facilities

In-flight separation



mainly produces neutron-rich nuclei

Fusion-evaporation

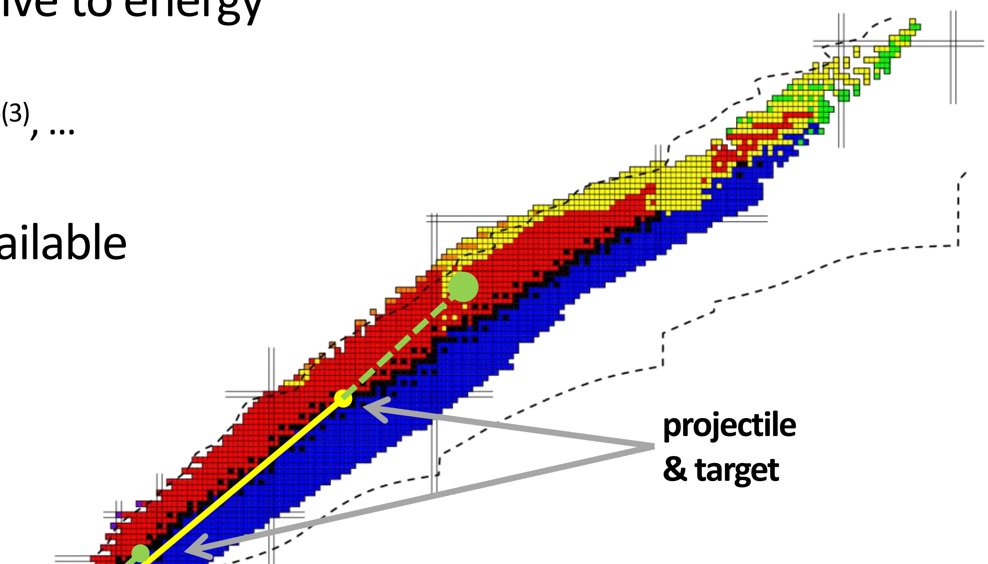


residue formation cross section sensitive to energy
(E_{inc} ≥ Coulomb barrier)
→ calculation codes: CASCADE[1], PACE[2], HIVAP[3], ...

selectivity due to excitation energy available for evaporation

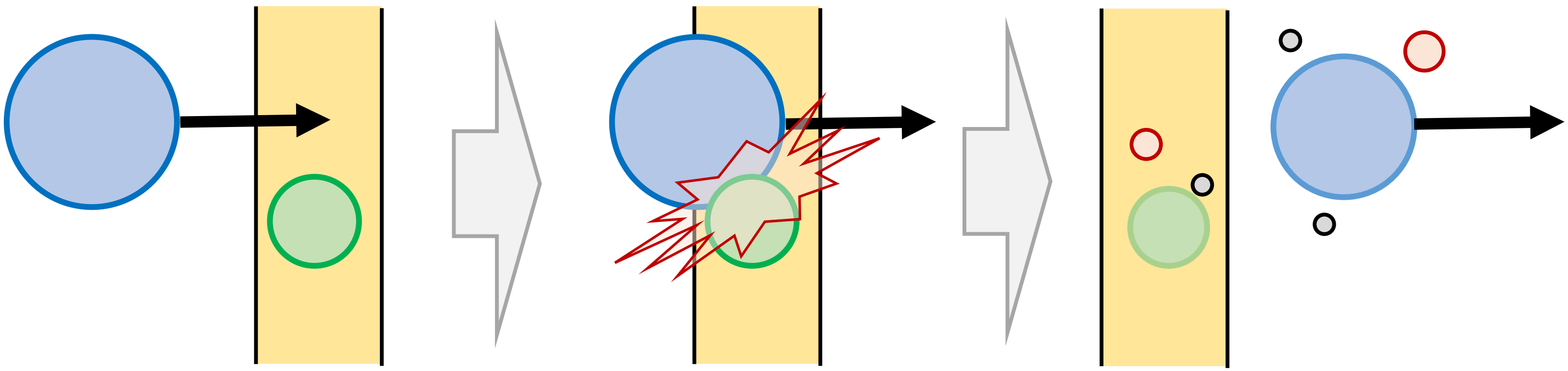
produces **proton-rich** residues

more suitable for ISOL technique



(1) Intra-nuclear cascade (Monte-Carlo)
(2) Projection-Angular momentum Coupling Evaporation
(3) Heavy Ions Vaporization (statistical de-excitation)

Projectile fragmentation

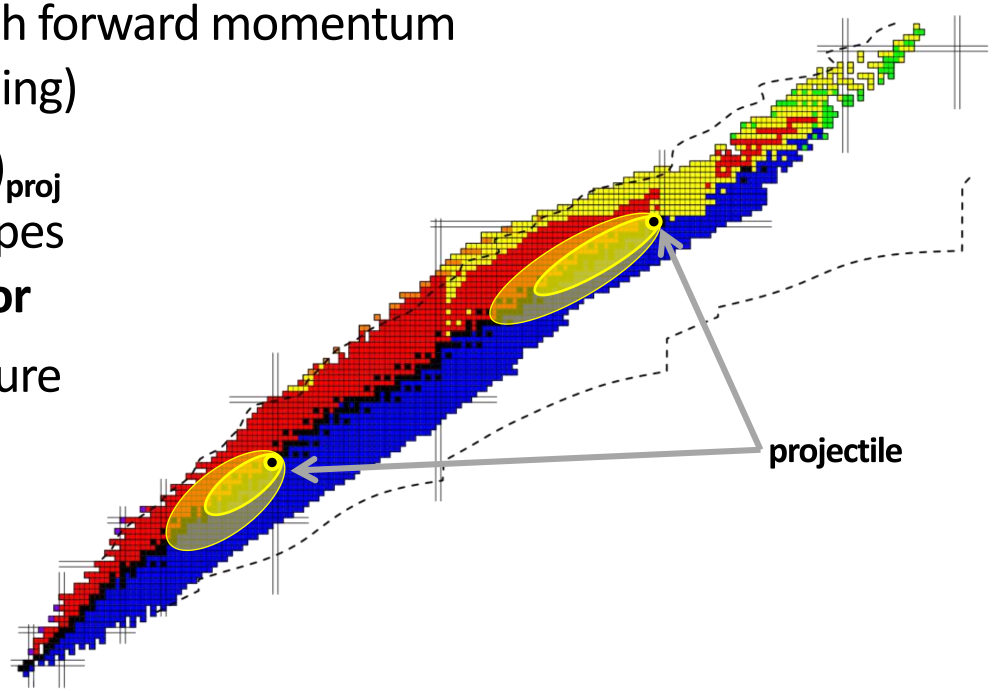


high energy heavy ion projectile on target

thin target: quasi-projectile with high forward momentum
(higher beam energy → more focusing)

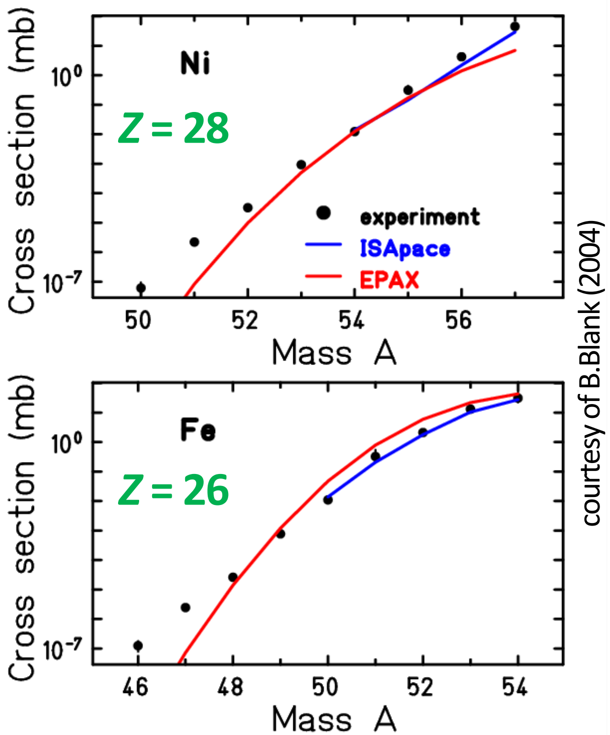
produce any fragments below $(A,Z)_{proj}$
both neutron-rich or deficient isotopes
→ requires a **fragment separator**

1st order: not sensitive to target nature
(Be → high melting temp.)
obs. in A~50 region: contrib. of proton pick-up from a Ni target



perfectly adapted to in-flight technique

Projectile fragmentation

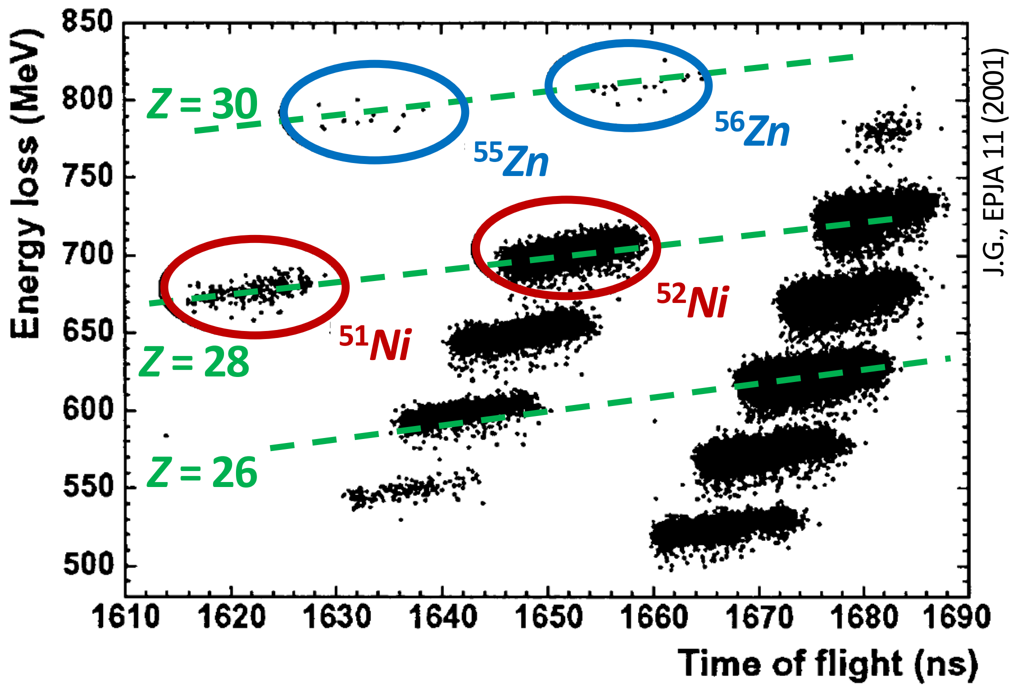


Cross-section evaluation

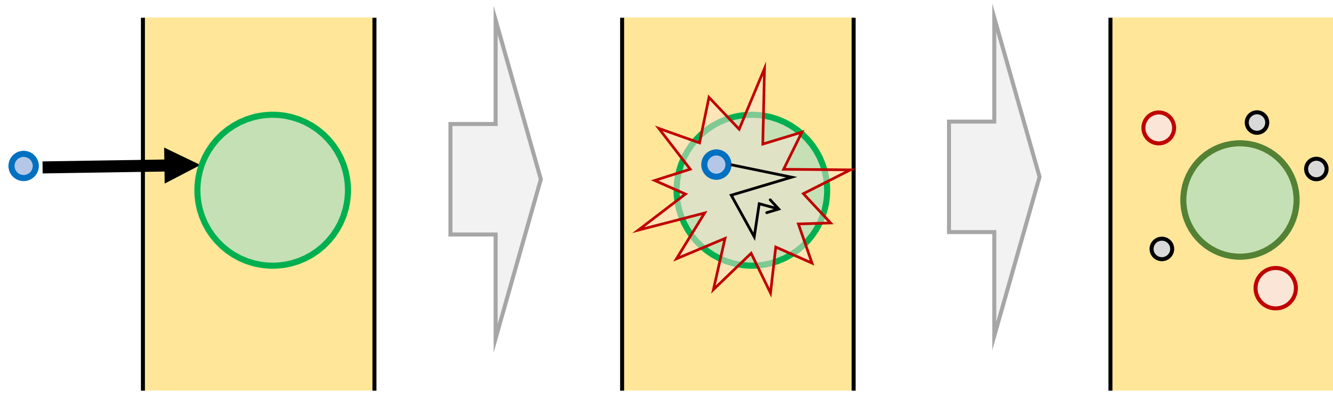
codes: EPAX (empirical, several updates)

experimental points: **loss of a factor 20~40 per neutron removal** !

^{56}***Ni*** beam (Z=28 !) on a ***Ni*** target → ***Zn*** (Z = 30)



Target spallation



high energy light projectile on heavy target

(similar to fragmentation)

light projectile (proton, deuton, …) and **thick target**

→ products need to be extracted from target

intra-nuclear collisions / excitation

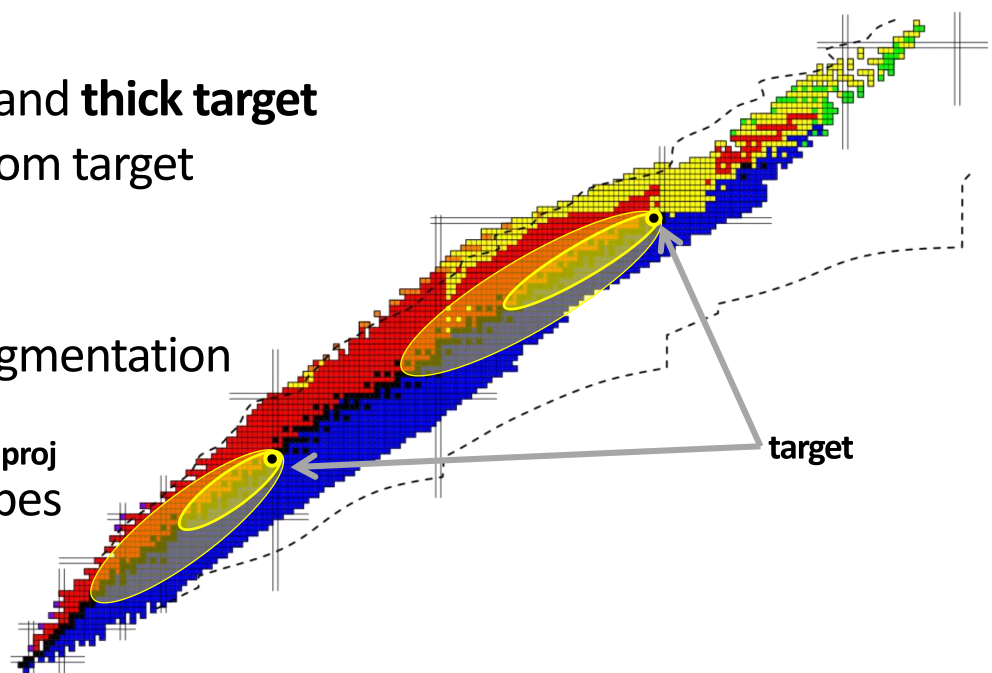
→ highly excited target

+ evaporation or (multi) fragmentation

can produce any nuclei below $(A,Z)_{proj}$

both neutron-rich of deficient isotopes

largely used with ISOL technique



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Isotopic Separation Online (ISOL) – principles

target-source ensemble

reaction products **stopped** in a thick target (or in gas)

source extraction: chemical selectivity (not all elements)
(surface ionization, ECR/plasma, LASER excitation)

limited efficiency, **long release time**
low energy beams (few tens of *keV*)
→ excellent beam properties / manipulation

high resolution spectrometer

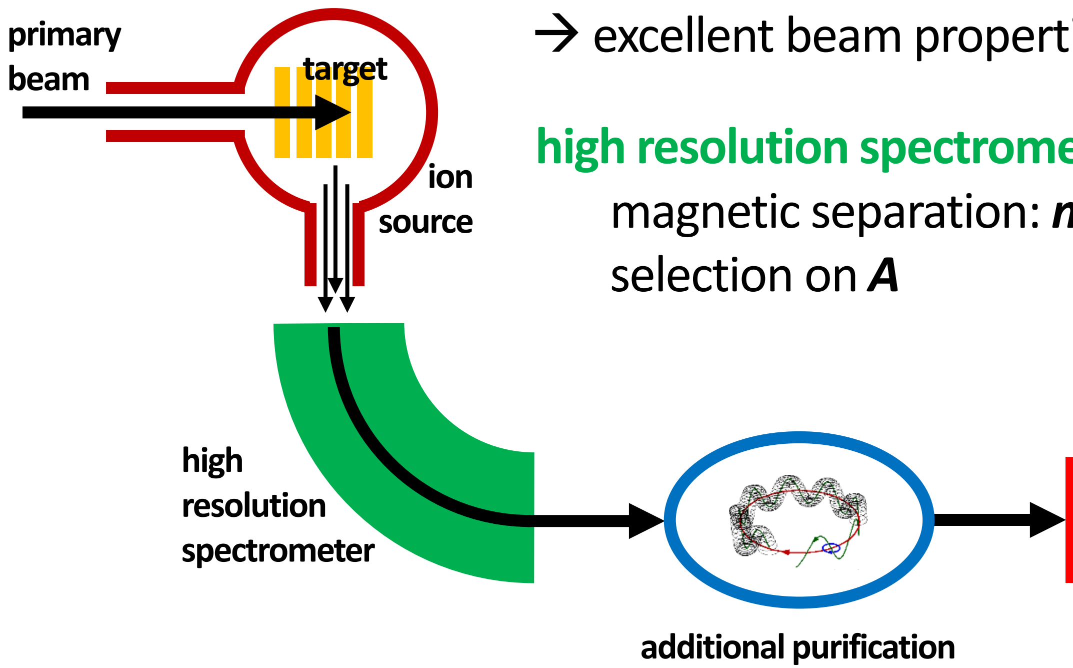
magnetic separation: $\boldsymbol{m} / \Delta \boldsymbol{m} = 5000\sim20000$
selection on $\boldsymbol{A}$

additional beam purification

Penning trap / MR-ToF-MS
→ precision measurements
→ isomeric states separations

nuclei deposit on thin catchers

→ adapted to decay studies



ISOLDE @ CERN, IGISOL @ JYFL, ISAC @ TRIUMF…

In-flight (fragments) separators – principles

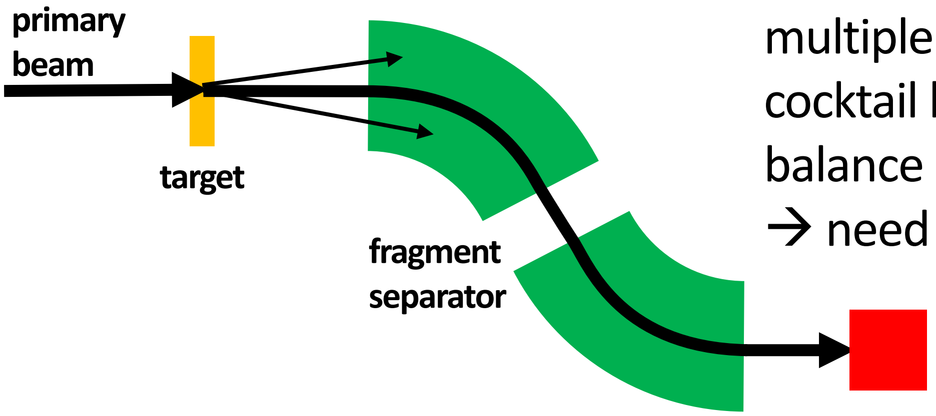
implantation-decay experiments

half-lives from **1 μs ~ 1 *ms*** → few seconds (flight time through the separator)

projectile fragmentation of a high energy beam in a thin target

fragments (quasi-projectile) with close to beam velocity

no chemical selectivity / limitation – **momentum dispersion**



fragment separator

multiple stage separation (A & Z)

cocktail beams or limited purity

balance between contamination & **transmission**

→ need for fragments identification

implantation in thick stoppers (detectors)

→ particles from radioactive decay may not escape (protons)

→ degraded energy resolution

→ 100-1000 energy deposit factor between ions impl. and decay part.

LISE @ GANIL (95 MeV/A)

A1900 @ NSCL (160 MeV/A)

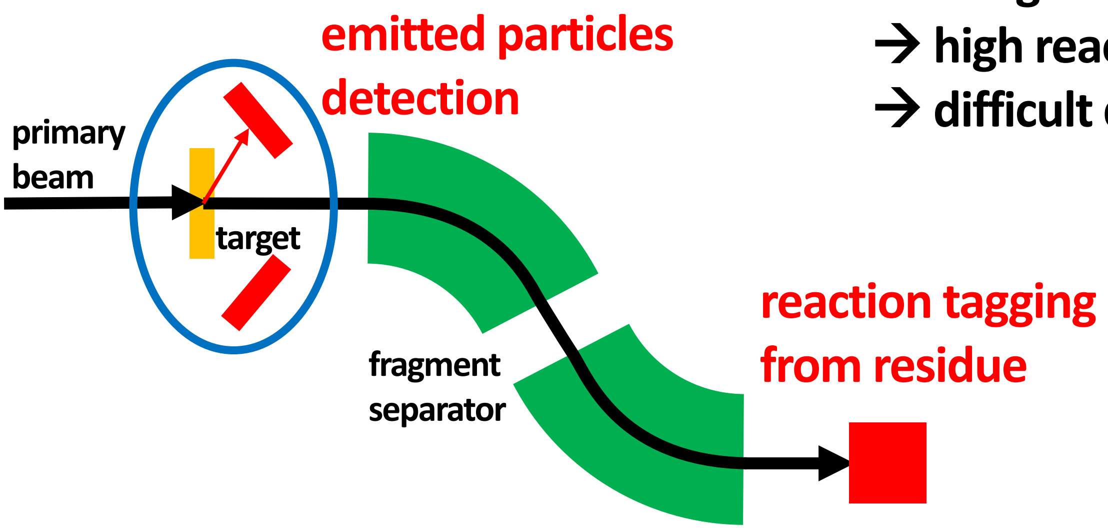
BigRIPS @ RIKEN (350 MeV/A)

FRS @ GSI (600-1000 MeV/A)

In-flight (fragments) separators – principles

decay of very short lived nuclei (< 10 *ns*) → **decay at target location**

with high intensity beams
→ high reactions rate
→ difficult detection environment



In-flight (fragments) separators – principles

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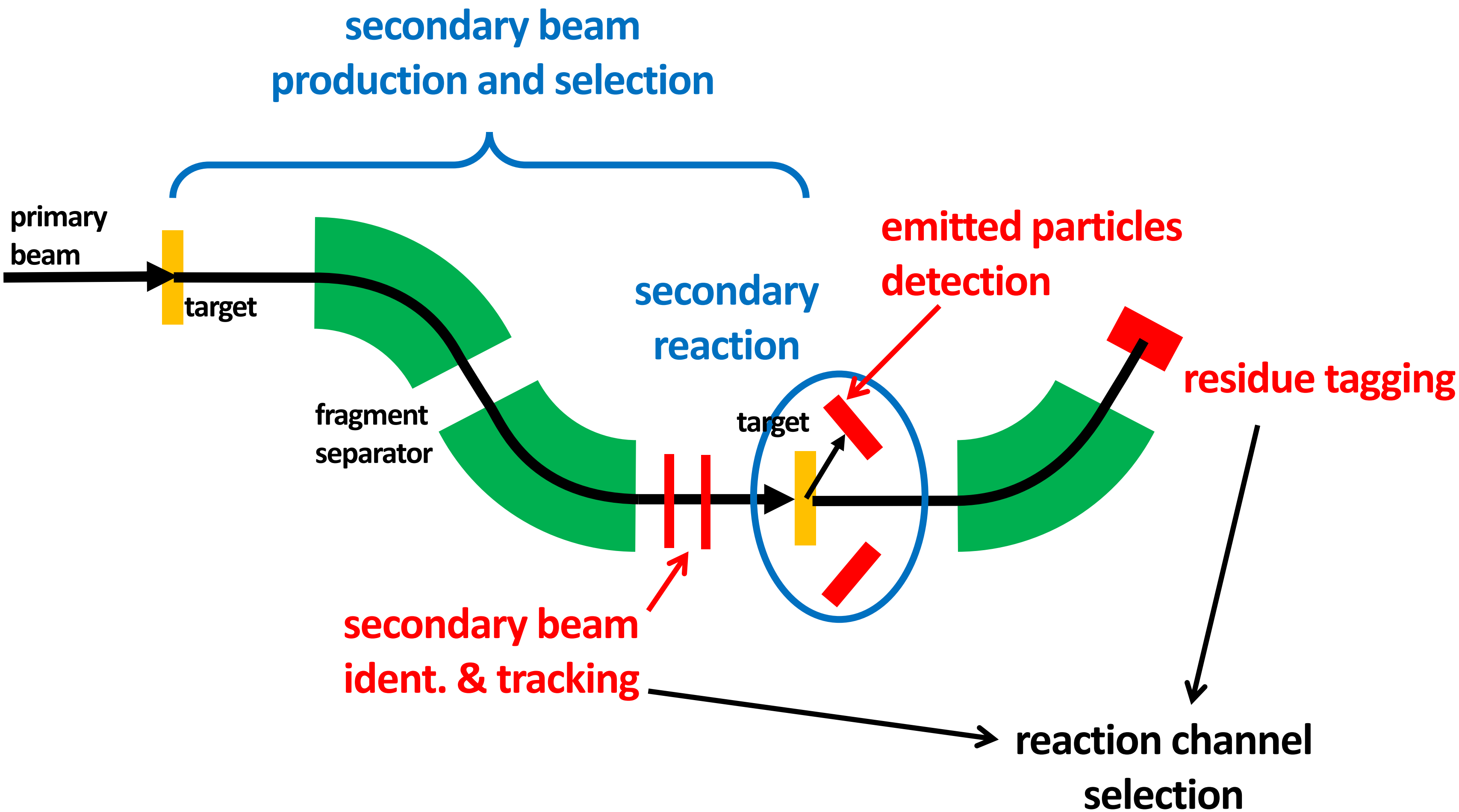

Separation techniques comparison

ISOL	In-flight
very high purity	limited purity / mixed decay contributions
point source on thin catcher	thick catcher, large spot size
chemical selectivity	no element limitation
$T_{1/2}$ > few 100 milliseconds	$T_{1/2}$ down to microseconds (or less)
possibly very high statistics (less exotic) minimum count rate (0.1~1 evt/s)	only access to most exotic nuclei down to < 1 evt/day
⇓	⇓
precision / high resolution experiments	**discovery / pioneering experiments**

!!! highly complementary methods !!!

(+ combining possibilities)

Experimental techniques
for proton emission decay studies

- Production of radioactive ions
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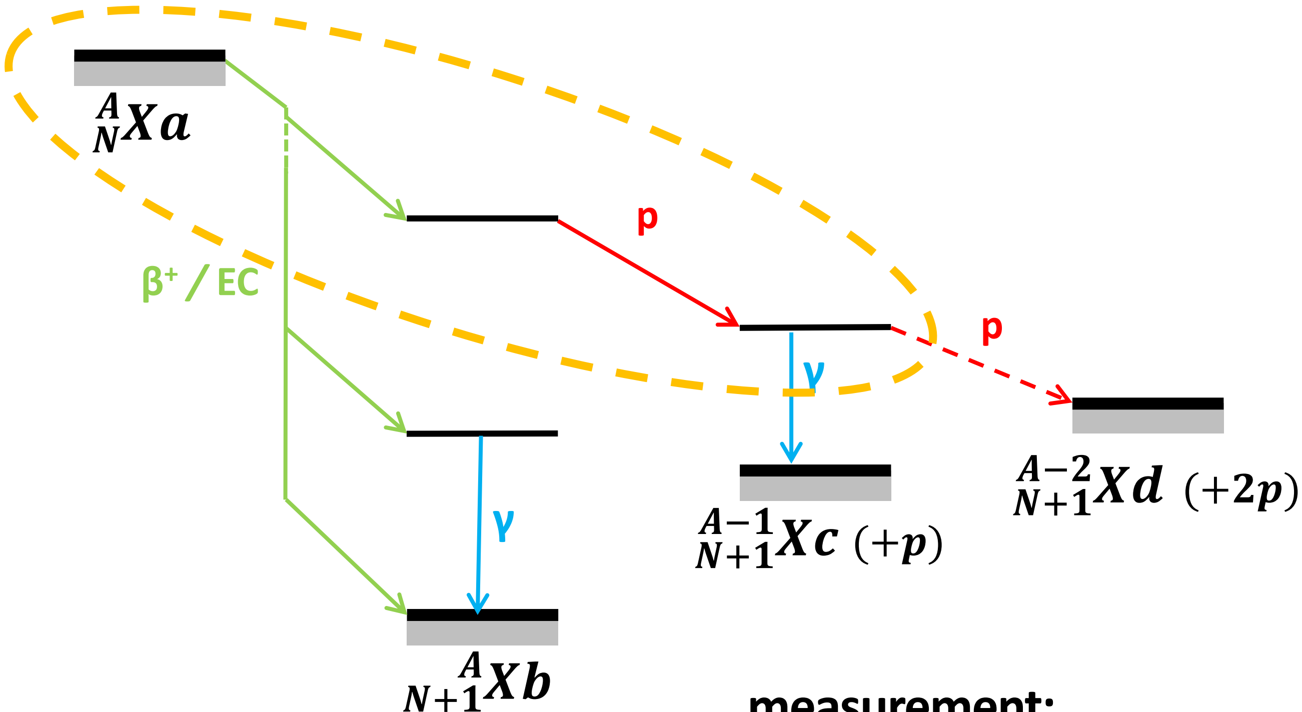
  - Production reactions
- Experimental & detection techniques
  - For ISOL-type experiments
  - For fragmentation-type experiments

Detection techniques

case of a **β-p**(**-γ**) or **β-2p** decay: **ISOL** vs **in-flight** experiment



measurement:

- **beta** decay half-life
- **proton** transitions (***E*** & intens.)
- **gamma** transitions (***E*** & intens.)

Experimental techniques for proton emission decay studies

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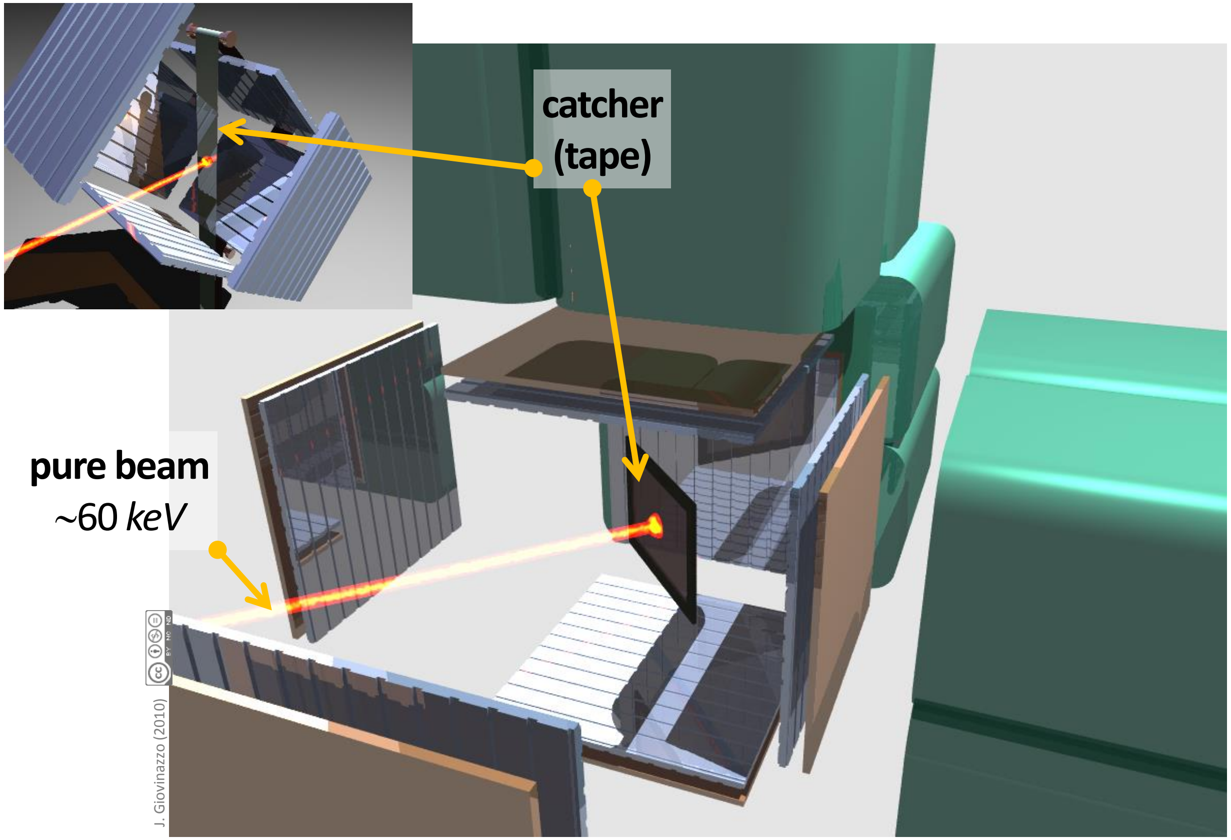
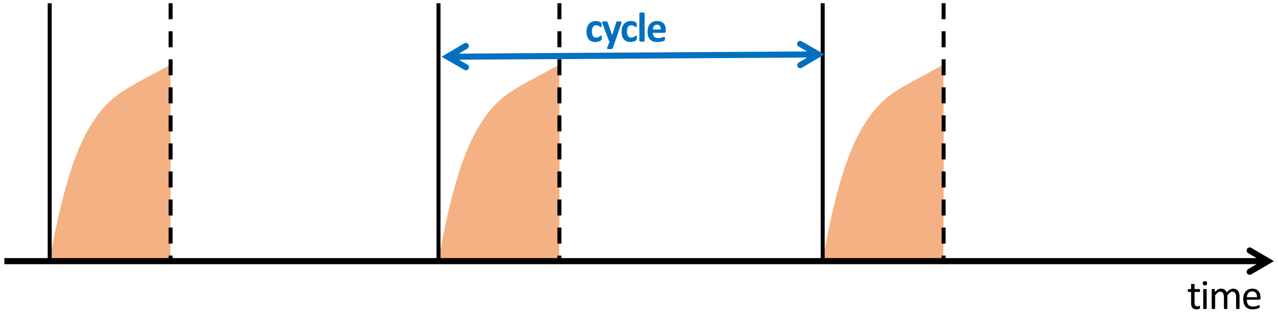
Isotopic Separation Online (ISOL) – typical experiment

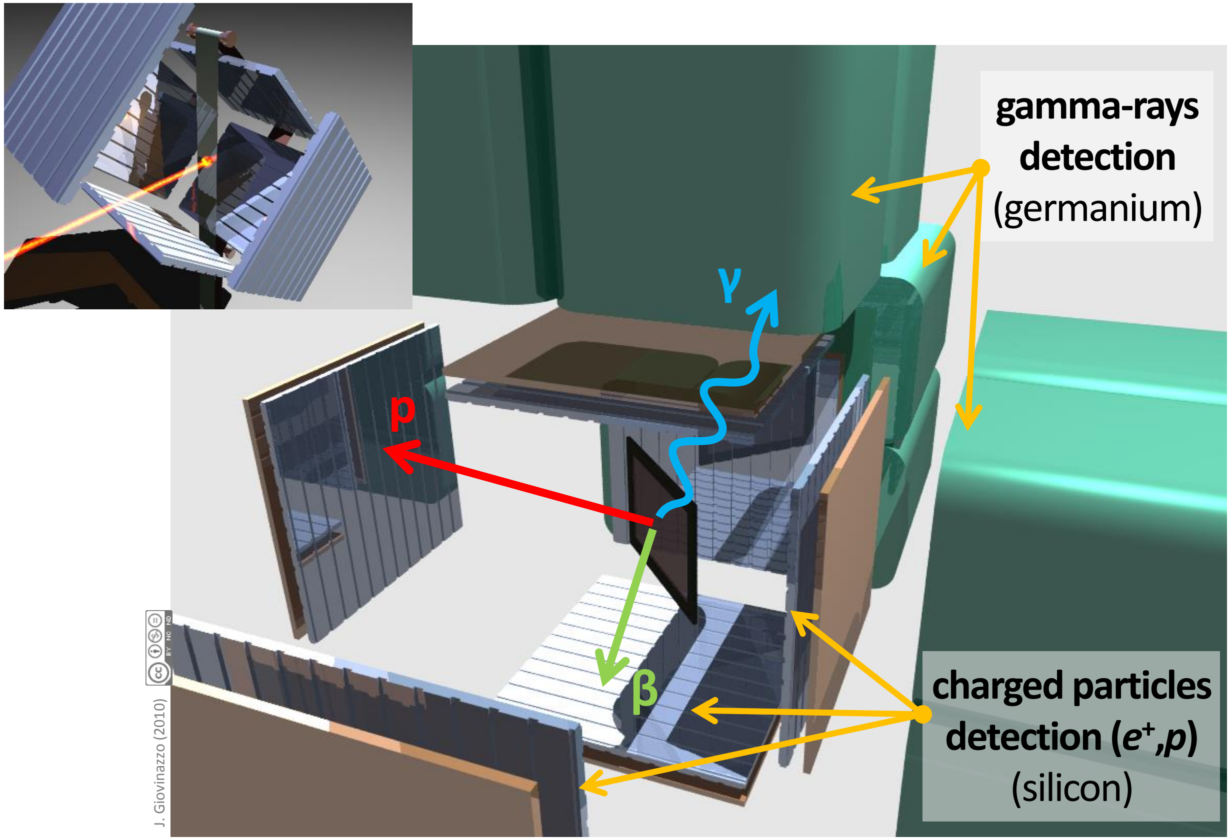


cycles measurements

- radioactive source collection
- ...

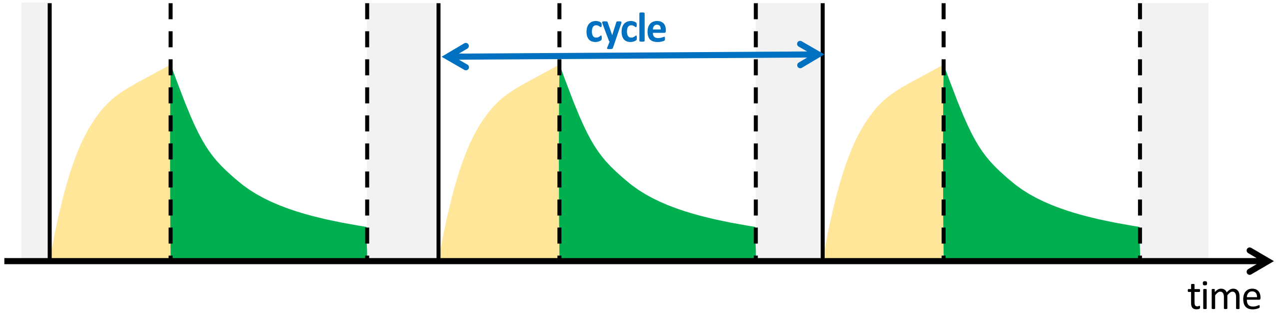


Isotopic Separation Online (ISOL) – typical experiment

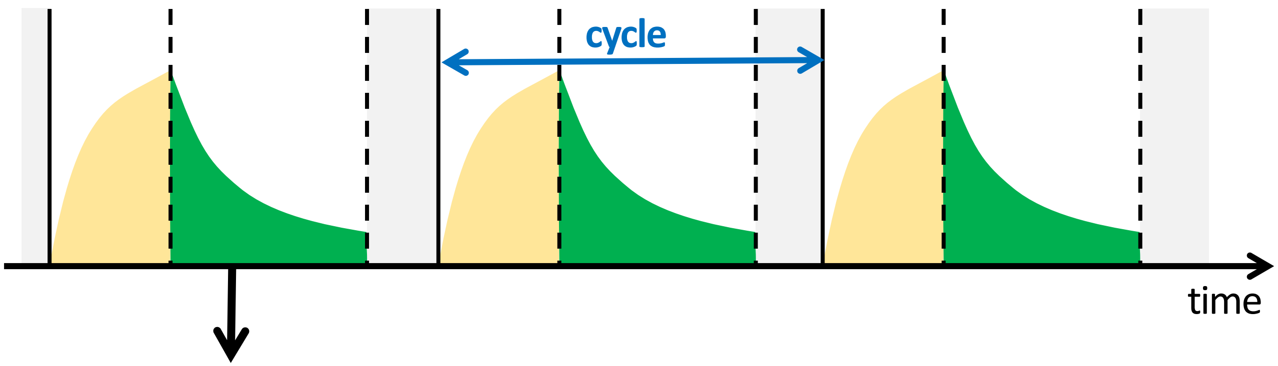


cycles measurements

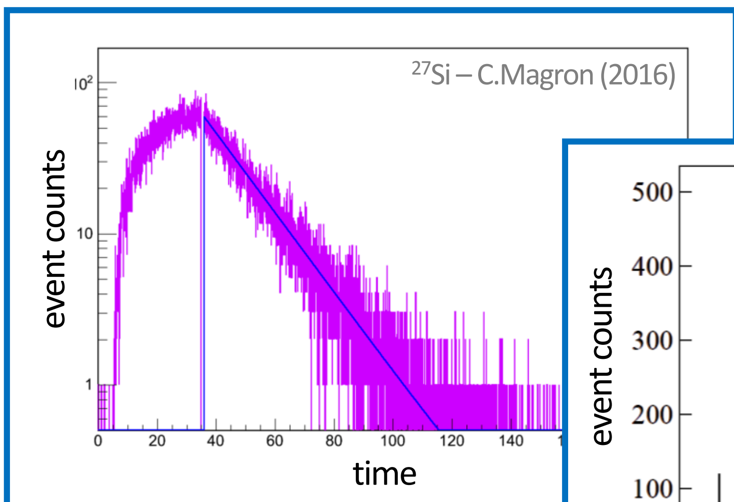
- radioactive source collection
- **decay measurement**
- ...

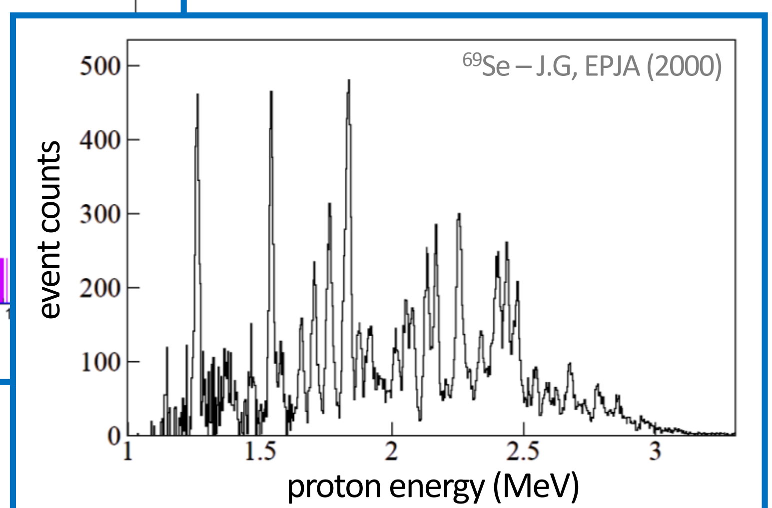


Isotopic Separation Online (ISOL) – typical experiment



beta events time distribution → $T_{1/2}$
(+ instrumental corrections)





cycles measurements

- **radioactive source collection**
- **decay measurement**
- **residual activity evacuation** (tape transport system)

Isotopic Separation Online (ISOL) – typical experiment

gamma detection

spectroscopy (high resolution / low efficiency): Ge ~2.5 *keV* @ 1 MeV

new types of detectors: LaBr3, …

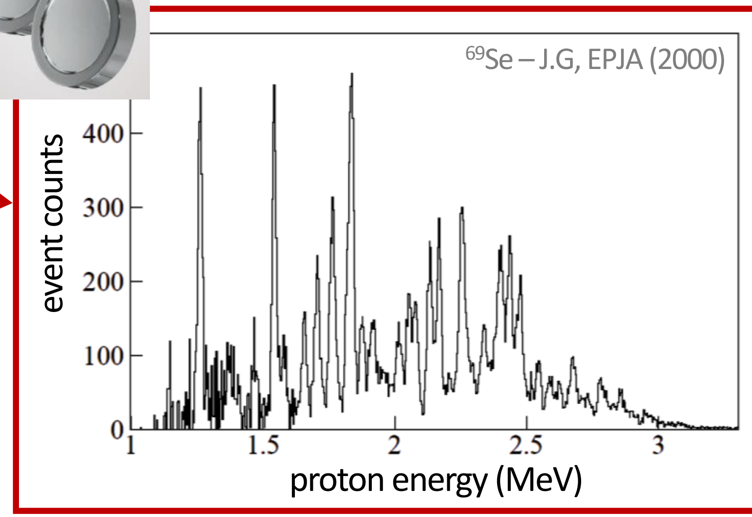
not discussed here

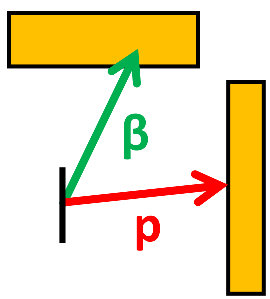
Isotopic Separation Online (ISOL) – typical experiment

charged particles (protons) detection

silicon diodes (~1960): high resolution
typical FWHM 25~30 *keV*
cooled (alcohol) ≤ 10~15 *keV*

ISOL exp.: ***p*** & **β** in diff. detectors
- clean proton peaks
- **surface barrier Si**: small correction
- recoil energy: $E_{mes} \sim E_p \times (1 - 1/A)$





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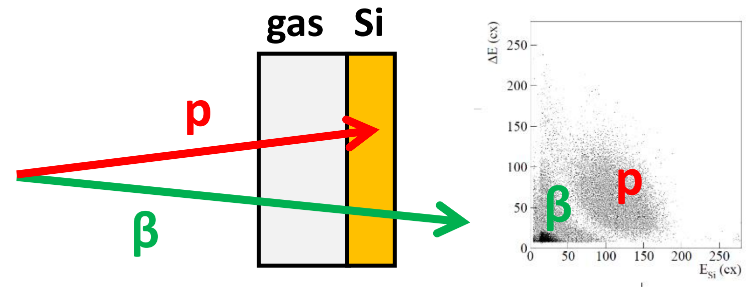
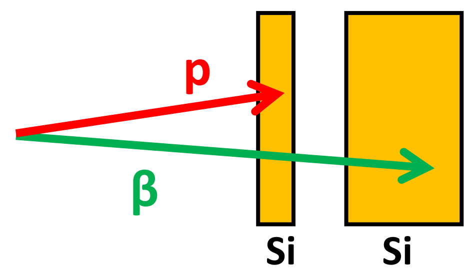
use of **telescopes** for ***p*****/β** pile-up
- gas-Si → ***p*****/β** discrimination
- Si-Si → **β** rejection

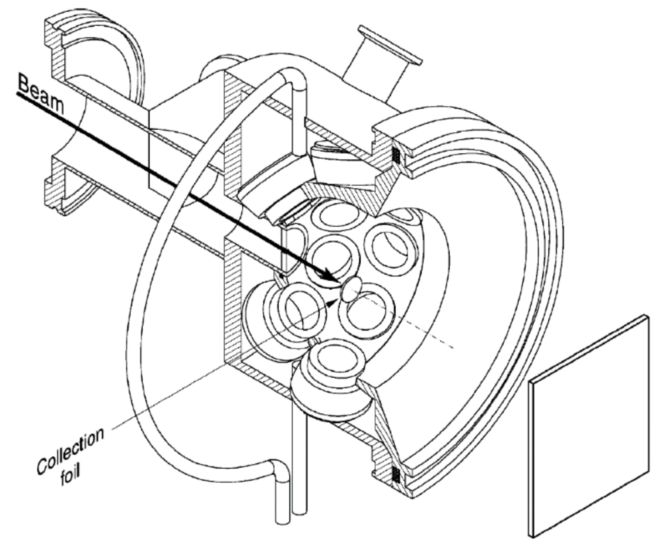




Isotopic Separation Online (ISOL) – typical experiment

charged particles (protons) detection

H.O.U.Fynbo, Nucl. Phys. A 677 (2000)



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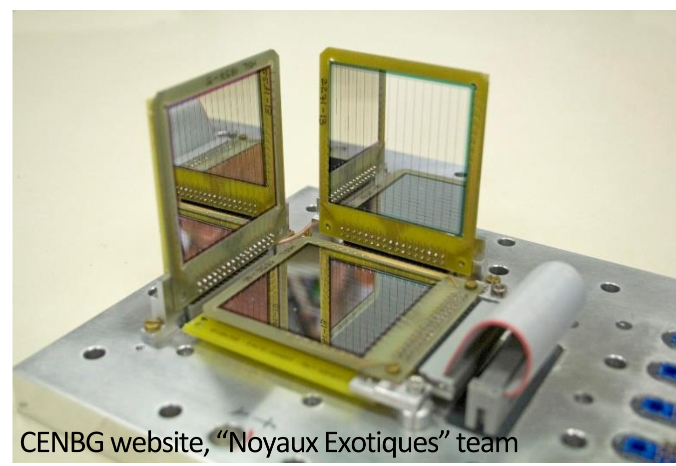
high granularity detectors:
FUTIS (1998): gas-Si telescopes
Si-cube (2009,CENBG) / Si-ball (2003, ISOLDE)

→ **for multi-particle emission (β-2p, β-3p, …)**



CENBG website, "Noyaux Exotiques" team

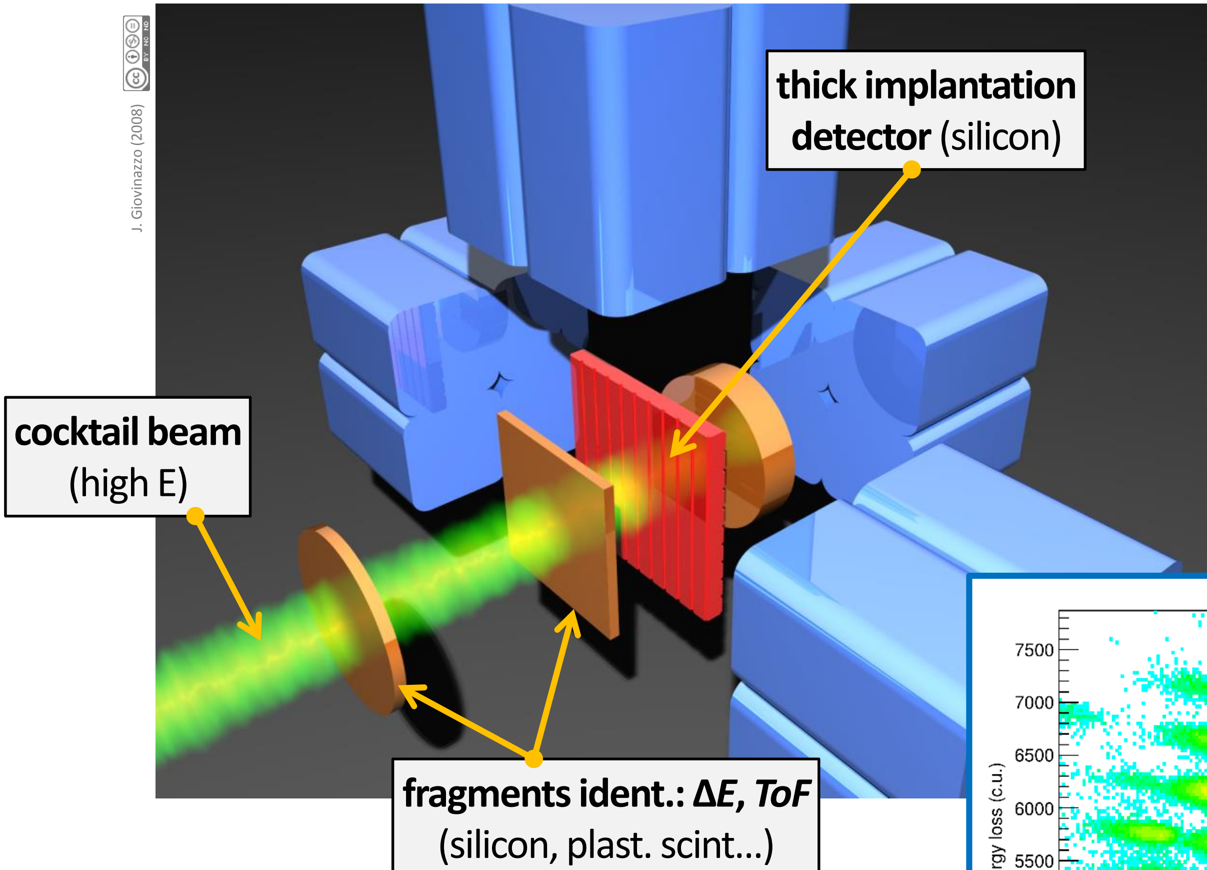
Experimental techniques for proton emission decay studies

- Production of radioactive ions
  - Separation techniques
  - Production reactions
- Experimental & detection techniques
  - For ISOL-type experiments
  - For fragmentation-type experiments

Implantation-decay experiments

for half-lives from **0.1 ~ 1 *ms*** → few seconds

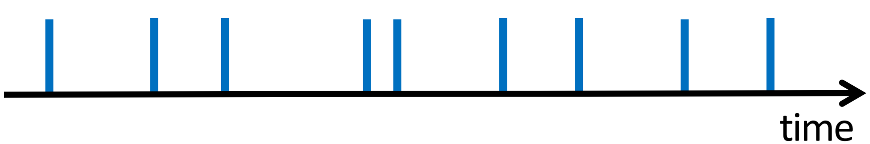
In-flight (fragments) separators – typical experiment

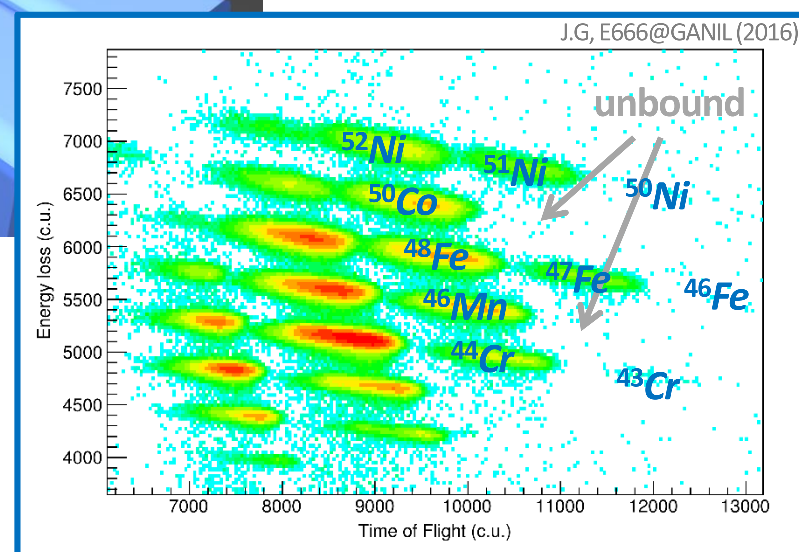


implantation events

- **identification of fragments**

continuous (random) **implantation**





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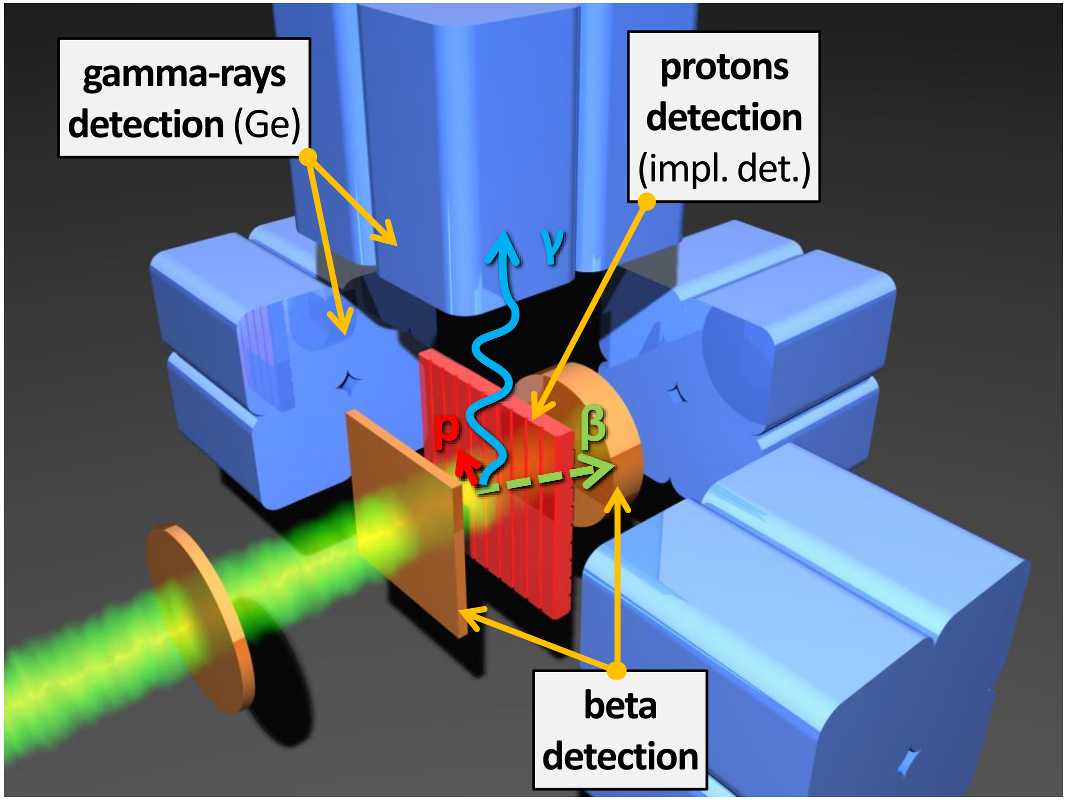
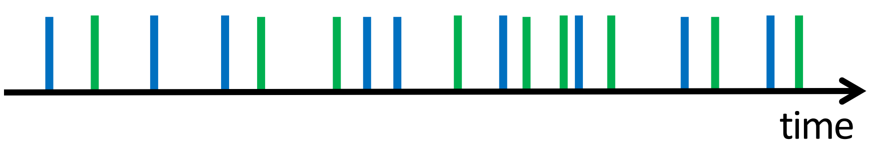


decay events

- **proton** emitted & stopped in implantation detector
- **beta** escaping:
  - partial energy deposit
  - neighbor detectors

decay events mixed with implantations



no direct assignment of a decay event to an identified implantation !!!

→ specific correlation procedure

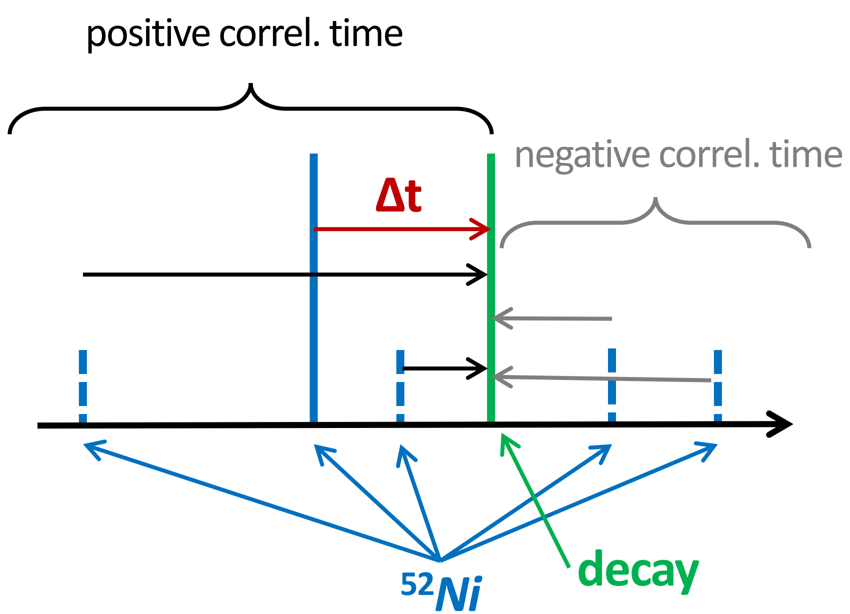
In-flight (fragments) separators – typical experiment

implantation-decay correlations

correlate **all** **decay** events (unknown emitting nucleus)
with **all** **implantations** of studied nucleus (ex. ^{52}Ni) – in a finite time window

→ **only 1 correlation is "good"** (impl. occurs ***before*** corresponding decay)

→ other (wrong) correlations



impl. event [k] ≡ $id[k]$; $t_{imp}[k]$

decay event [j] ≡ $t_{dec}[j]$; $E_{dec}[j]$

correlation [j,k] ≡ { $id[k]$; $E_{dec}[j]$;

$\Delta t\ [j,k] = t_{dec}[j] - t_{imp}[k]$ }

In-flight (fragments) separators – typical experiment

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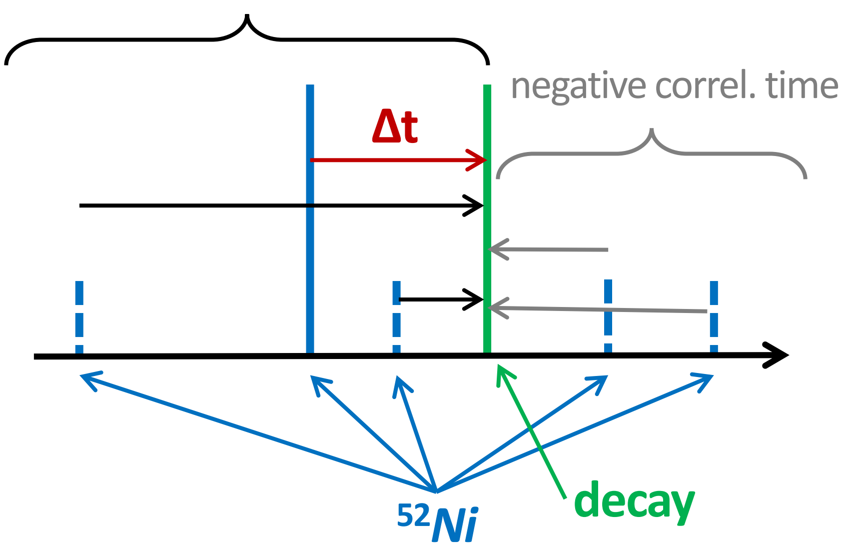
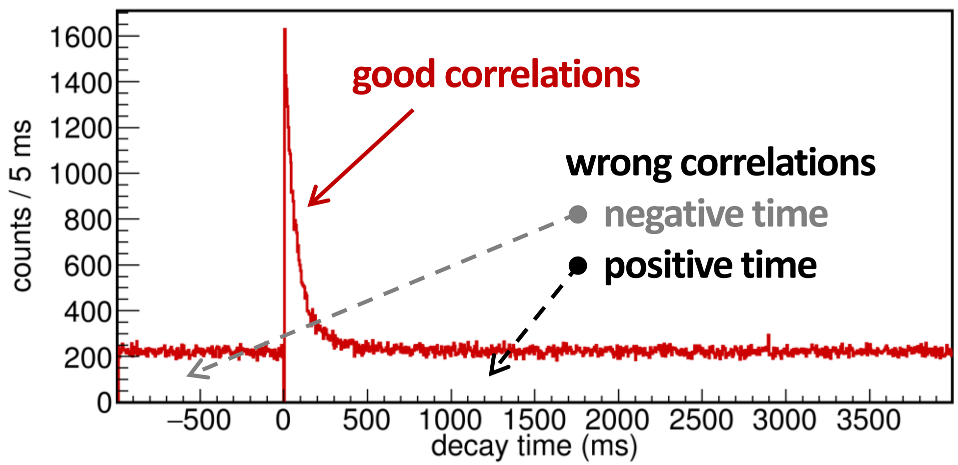
→ **only 1 correlation is "good"** (impl. occurs ***before*** corresponding decay)
decay time: exponential probability → $T_{1/2}$
→ other (wrong) correlations: **flat random** background



decay time distribution
(all possible correlation)



In-flight (fragments) separators – typical experiment

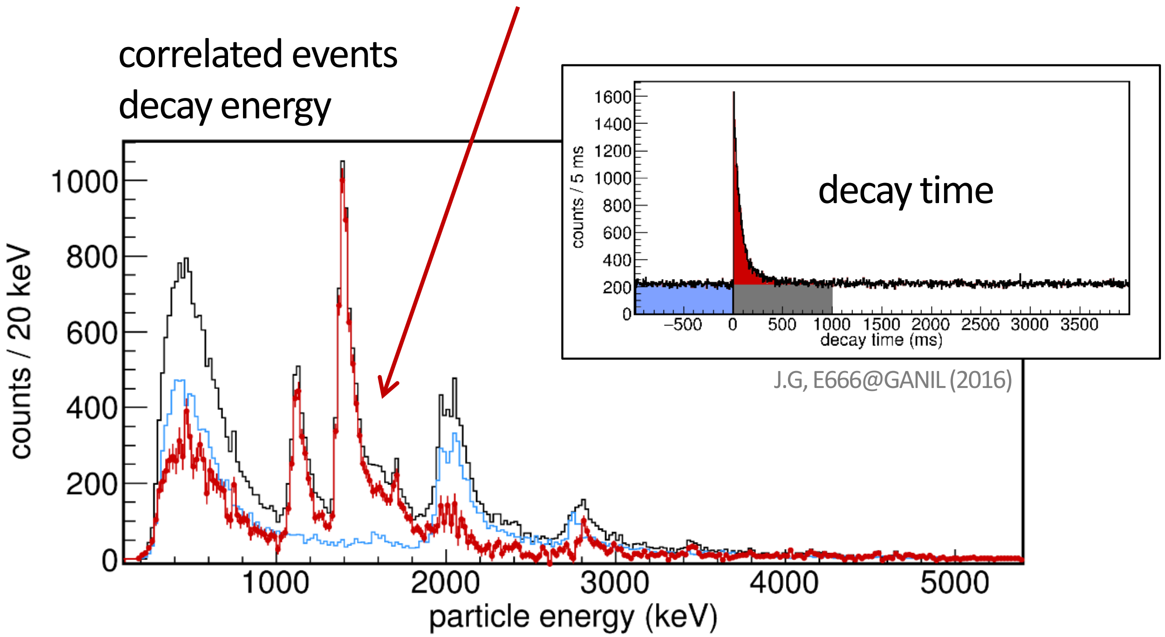
implantation-decay correlations

correlate **all** **decay** events (unknown emitting nucleus)
with **all** **implantations** of studied nucleus (ex. ^{52}Ni)

→ 1 decay event may be correlated to **several** implantations
→ multiple counts in energy distributions

$$S(E) = S_{\Delta t>0}(E) - S_{\Delta t<0}(E)$$

on a statistical basis !!!



J.G, E666@GANIL (2016)

remove contamination from decay of other nuclei

remove self-contamination (for correct intensities)

increased statistical fluctuations

In-flight (fragments) separators – typical experiment

implantation-decay correlations

event rates considerations

impl.: n_{imp} / s

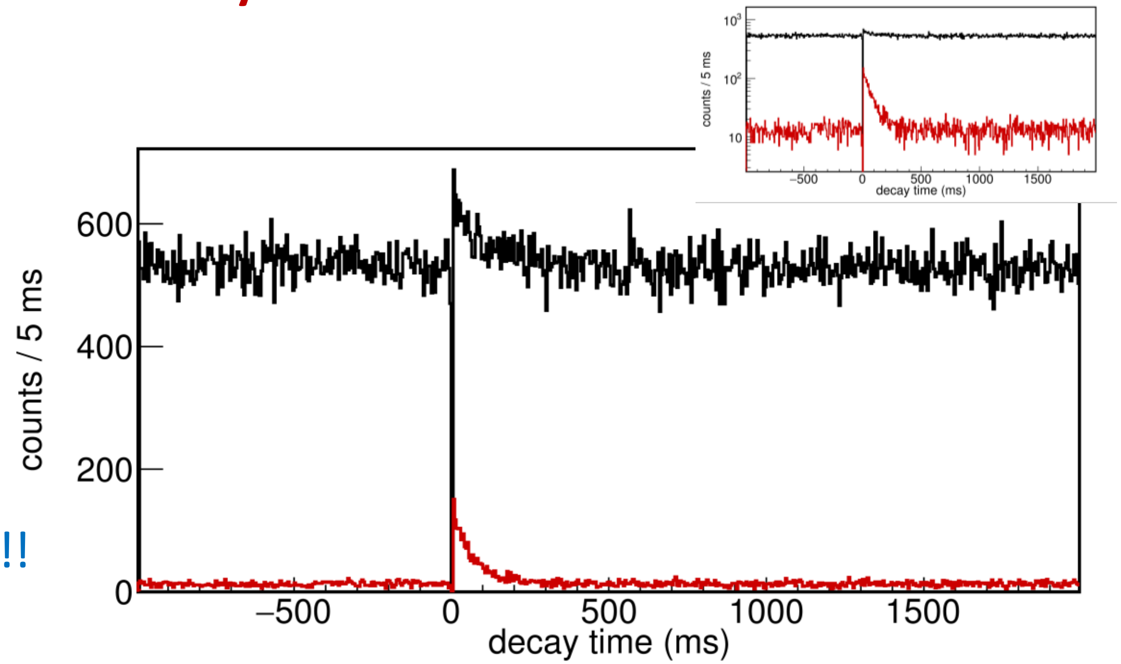
decay: n_{dec} / s

correl.: $n_{cor} = n_{dec} \times n_{imp}$ / s

$n_{imp} \sim n_{dec} \sim$ 200/s

$\Rightarrow n_{cor} \sim$ 40 000/s

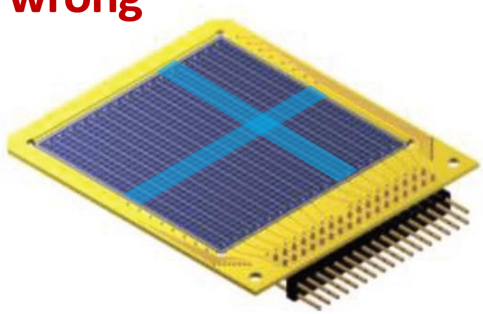
only ~**1/200** being good (**0.5%**) !!!



use of stripped silicon detectors (DSSSD)

only **impl. and decays in same pixel**

→ **reduction of wrong correlations**



ex.: (N_X=10 ; N_Y=10) DSSSD

& uniform implantation in DSSSD

$\Rightarrow n_{imp} \sim n_{dec} \sim$ 2/pixel/s

$\Rightarrow n_{cor} \sim$ 4/pixel/s $\Rightarrow$ ~**1/4** good corr. (**25%**)

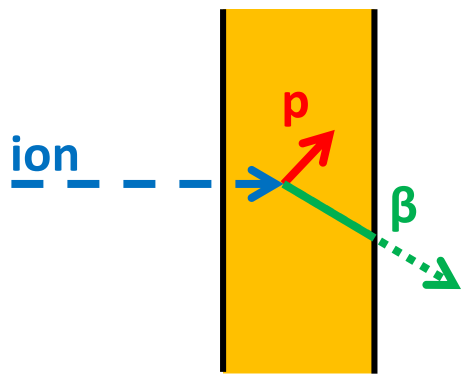
In-flight (fragments) separators – typical experiment

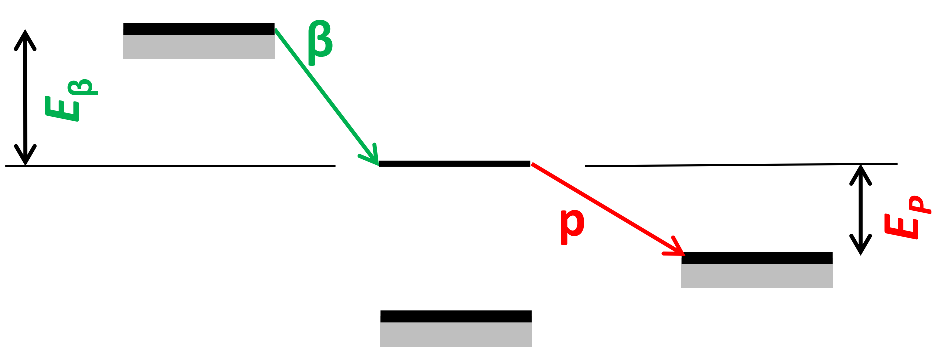
implantation-decay correlations

emitted protons detection

implantation inside a thick detector
(Si: 300 ~1000 μm)
decay from implantation location

→ beta & proton emitted simultaneously at electronics scale
→ protons stopped inside (5 *MeV* proton range ~150 μm)
→ β escapes the detector





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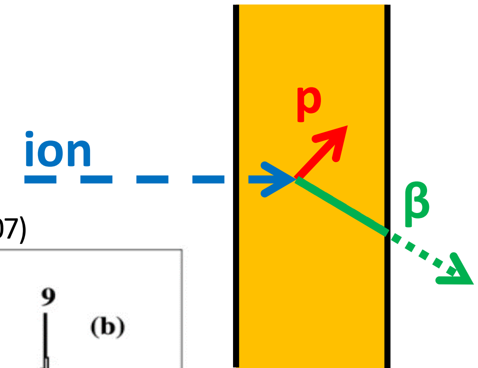
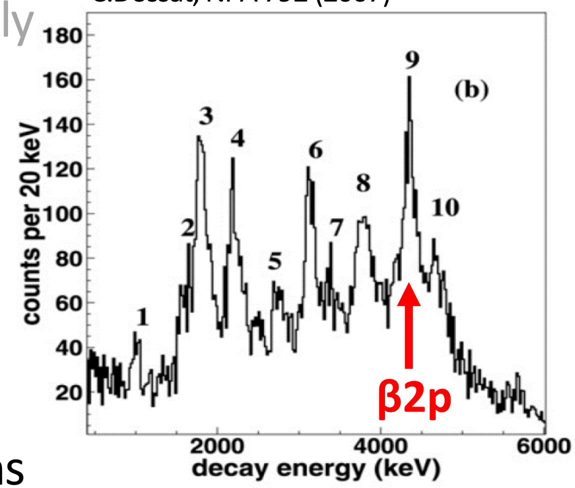
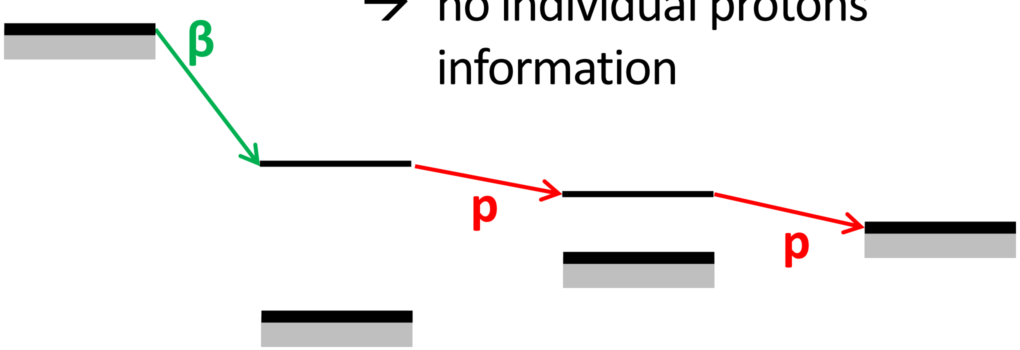


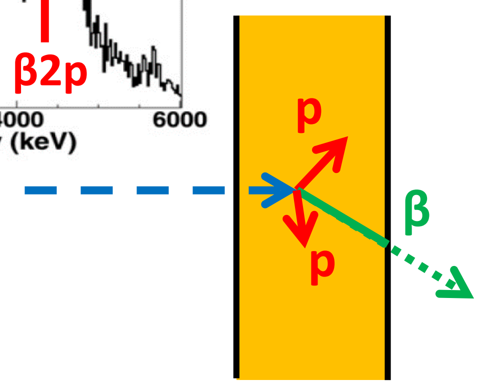
C.Dossat, NPA 792 (2007)



multiple proton emission

→ no individual protons information





In-flight (fragments) separators – typical experiment

implantation-decay correlations

emitted protons detection

implantation inside a thick detector

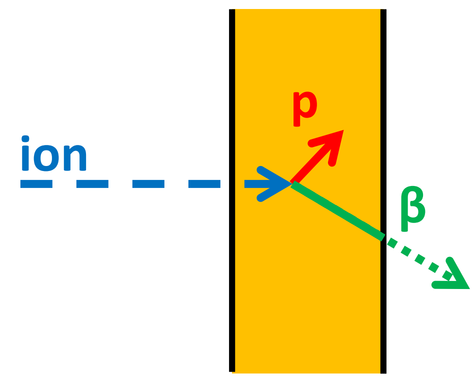
(Si: 300 ~1000 μm)

decay from implantation location

→ beta & proton emitted simultaneously at electronics scale

→ protons stopped inside: full E_P deposit (5 *MeV* proton range ~150 μm)

→ β escapes the detector: partial ΔE_β deposit



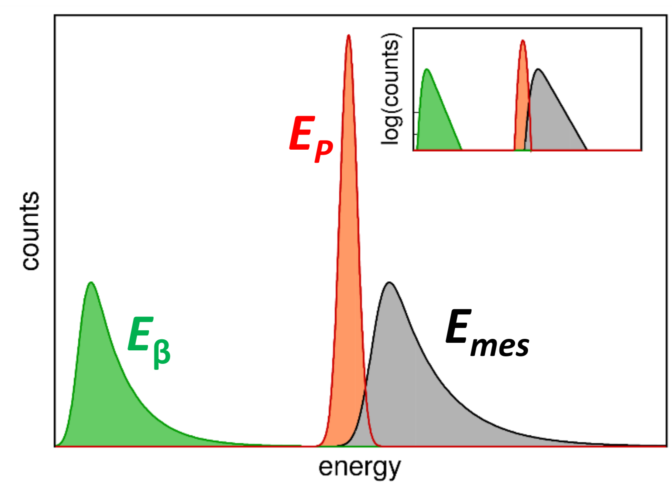
measured energy

$E_{mes} = E_P + \Delta E_\beta$

⚠ → shifted transition energy

→ degraded resolution

but ~100% efficiency !



In-flight (fragments) separators – typical experiment

implantation-decay correlations

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(Si: 300 ~1000 µm)
decay from implantation location

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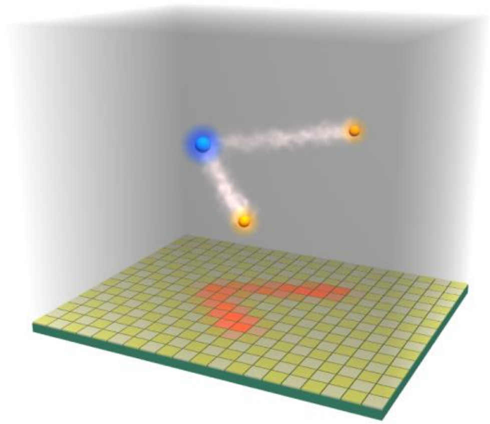
implantation in a TPC
(particles tracking)



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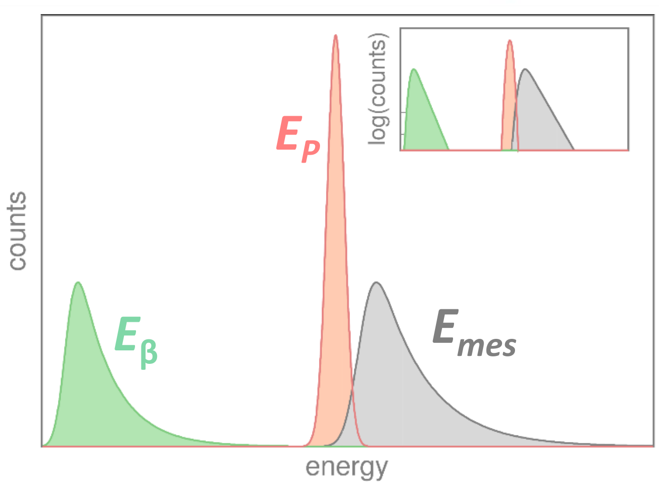
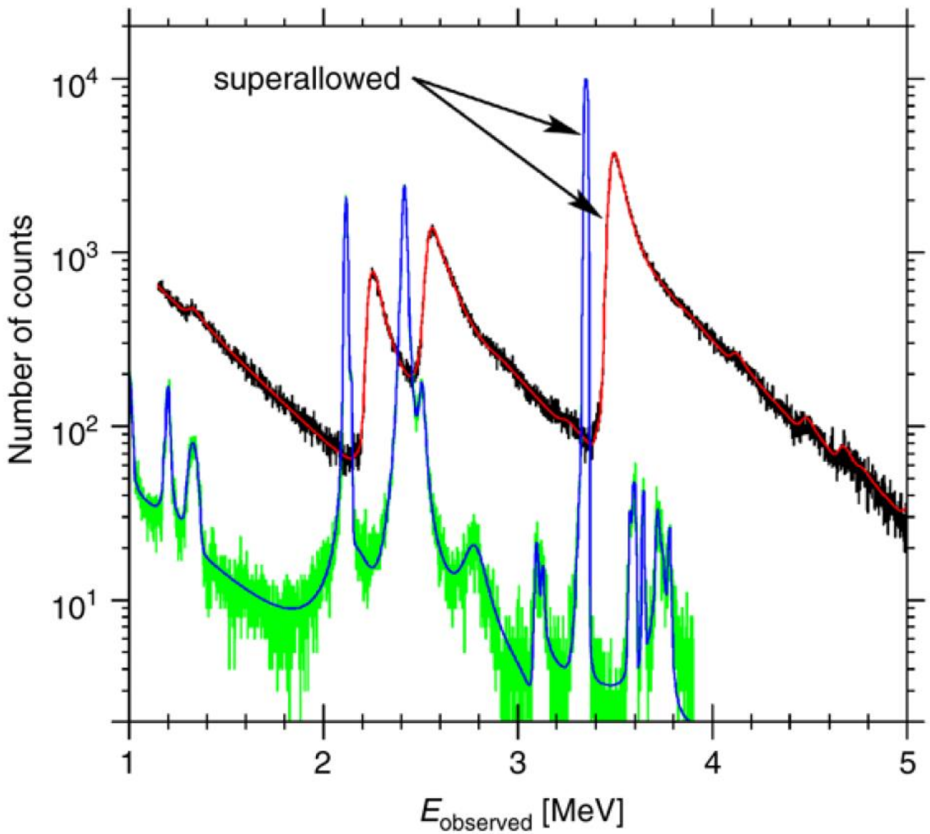


ISOL / In-flight experiments comparison

^{32}*Ar* β-*p* decay @ ISOLDE & MSU
(used for complementary analysis)



D. Melconian, adapted from B.Blank & M.J.G.Borge , PPNP (2008)

Corrections to experimental data

measurement of proton transitions

- time (or time diff.) ⇨ **half-life**
- energy peak: position ⇨ transition **energy**
  integral ⇨ **intensity**

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measurement of proton transitions

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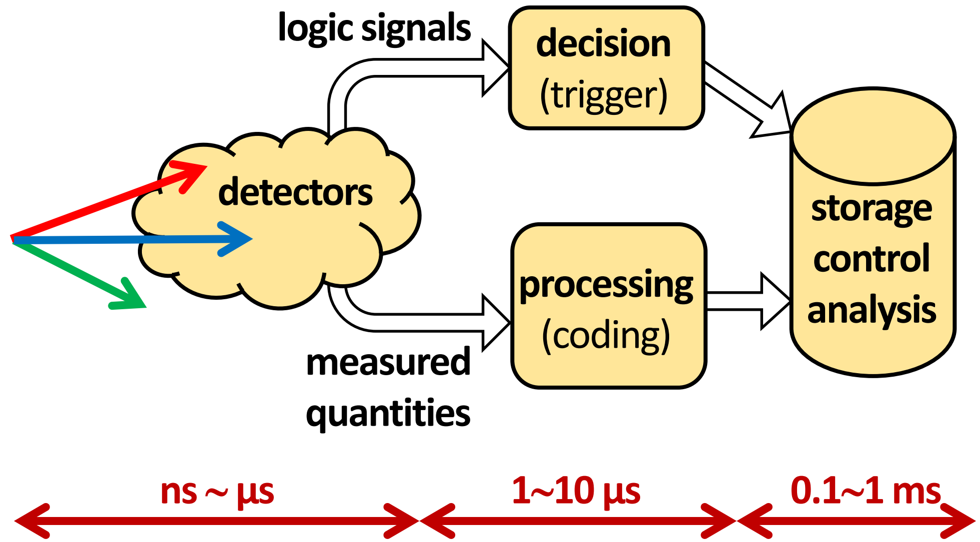
Energy corrections

ISOL: recoil of nucleus

in-flight: ΔE_β pile-up

already mentioned



Intensity corrections

- detection efficiency: I_{mes} / ε_{det}
- acquisition system dead-time
  - **missed events** because acq. busy (processing previous event)
  - typical DT: 100~1000 μs
    increasing number of channels (DSSSD,…)
    new technologies (standard for comm. protocols)

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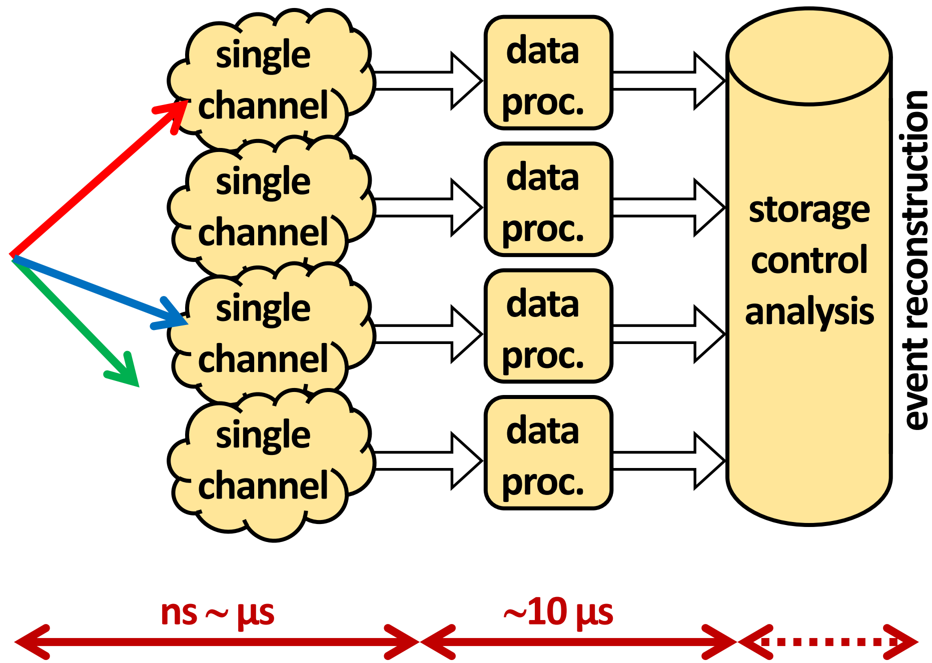

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    increasing number of channels (DSSSD,…) → “triggerless” DAQ

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Corrections to experimental data

measurement of proton transitions

- time (or time diff.) ⇨ **half-life**
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Energy corrections

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Intensity corrections

- detection efficiency: $I_{mes} / \varepsilon_{det}$
- **acquisition system dead-time**
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  - typical DT: 100~1000 μs

    increasing number of …els (DSSSD,…) → "**triggerless**" DAQ

    new technologies (standard for comm. protocols)

corrections due to DT → zero at low count rates

Decay intensity correction

ISOL decay (cycles) **experiment**

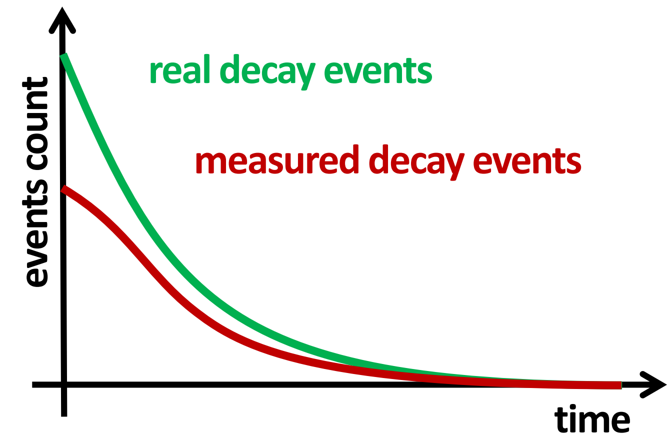
→ collection-decay phases

→ non uniform DT fraction:

distorted decay rate curve

$$N \approx \int n_{mes}(t) \cdot \frac{1}{1-\langle DT\rangle_{evt} \cdot n_{mes}(t)} \cdot dt$$

uncorrected fit induces an **error on $T_{1/2}$**



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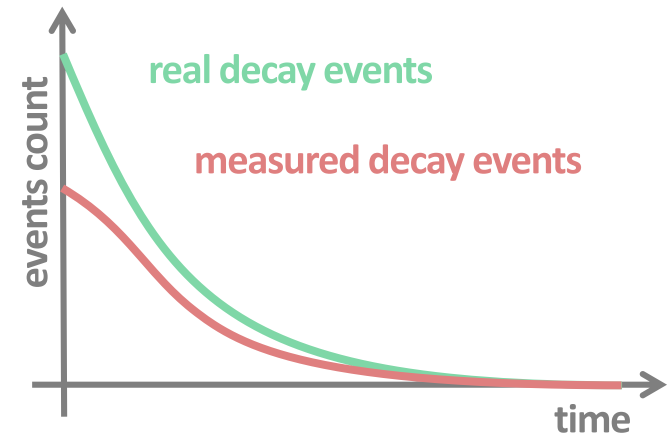


in-flight implantation-decay experiment

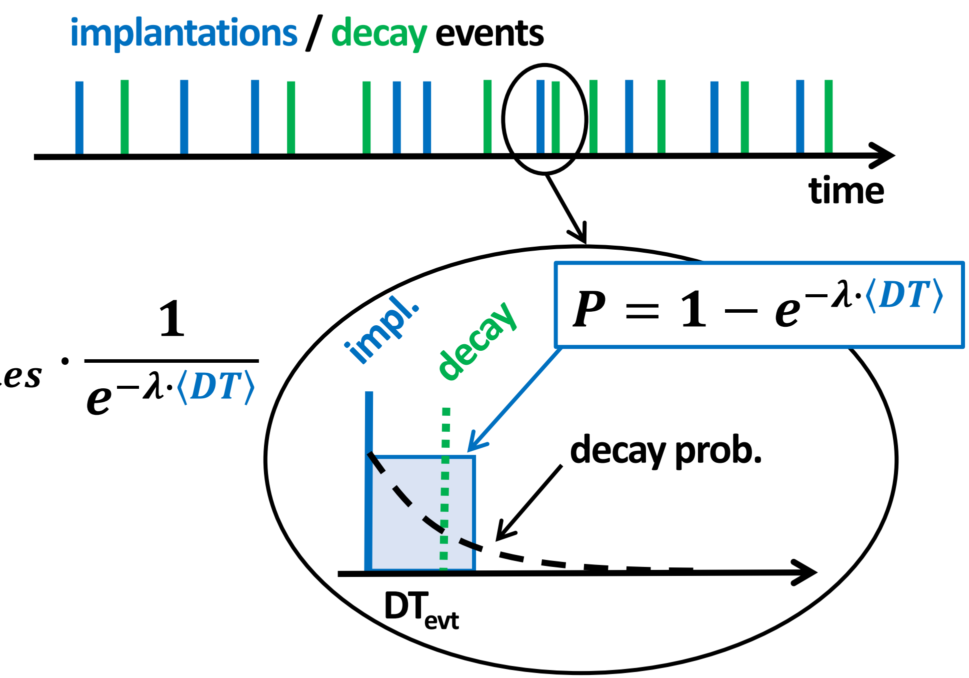
→ continuous implantation and decay
uniform dead-time fraction

$$N^{(dec)} \approx \frac{N_{mes}^{(dec)}}{1 - \langle \rho_{DT} \rangle}$$

$$\langle \rho_{DT} \rangle \sim \frac{N_{mes}^{(all)} \cdot \langle DT \rangle_{evt}}{T_{exp}}$$

→ systematic loss after implantation: depends on $T_{1/2}$

$$N \approx N_{mes} \cdot \frac{1}{e^{-\lambda \cdot \langle DT \rangle}}$$



Decay intensity correction

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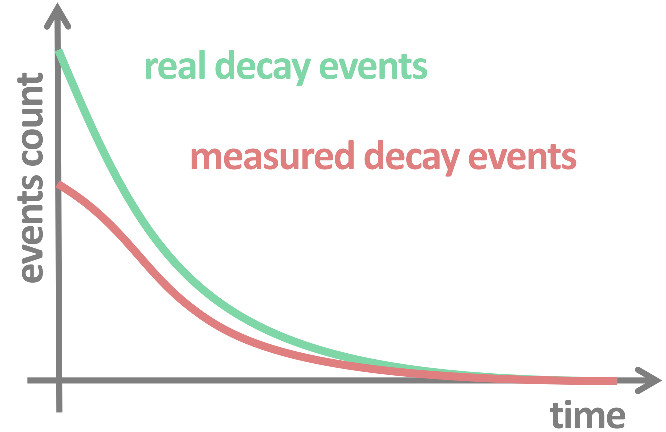

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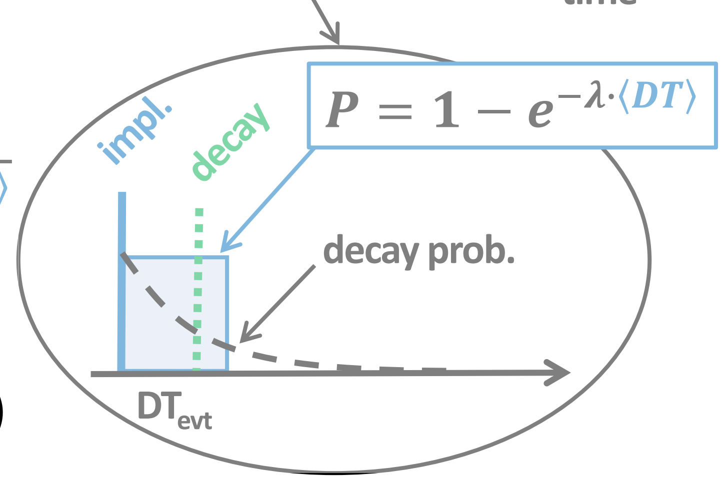


+ pile-up corrections (coinc. or random)

→ 2nd order corrections (precision measurements)

Beta-delayed proton(s) emission

- **Beta-delayed 1 proton emission**
  - Fermi transition & isospin symmetry
  - β-p and Gamow-Teller strength distribution
  - Proton emission and nuclear levels half-life
- **Beta-delayed multi-proton**
  - Sequential vs direct emission
  - First experiment
  - β-2p and search for the *“^{2}He”* emission
  - Delayed multi-proton emission

Historical milestones

beta delayed proton emission

1963	**first observation:**	Karnaukhov et al., conf. proc. 1963
		^{20}Ne → (Ni,Ta) target, precursor was not identified
	first precursor:	***^{25}Si,*** R. Barton, et al., Can. J. Phys. 41 (1963) 2007
1966	**ten precursors:**	V.I. Goldanskii, Ann. Rev. Nuclear Sci. (1966)
1977	**~40 known**	J. Cerny, J.C. Hardy, Ann. Rev. Nuclear Sci. (1977)

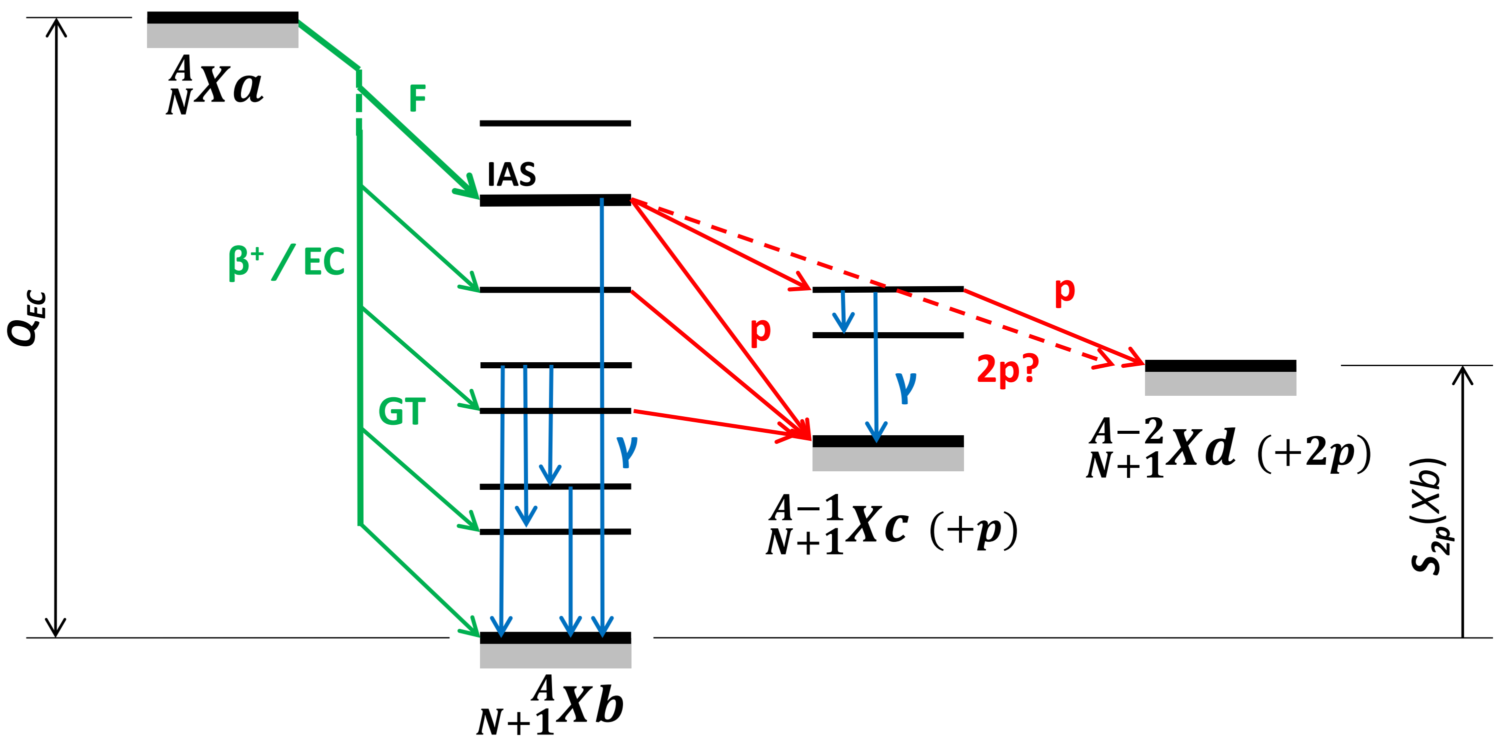
...

today ~160 known

beta delayed multi-proton emission

β-2p	first case: ***^{22}Al*** (Cable et. al, 1983), today ~15 identified cases
β-3p	few cases, not much to learn

Delayed-proton(s) emission: a rich physics case !



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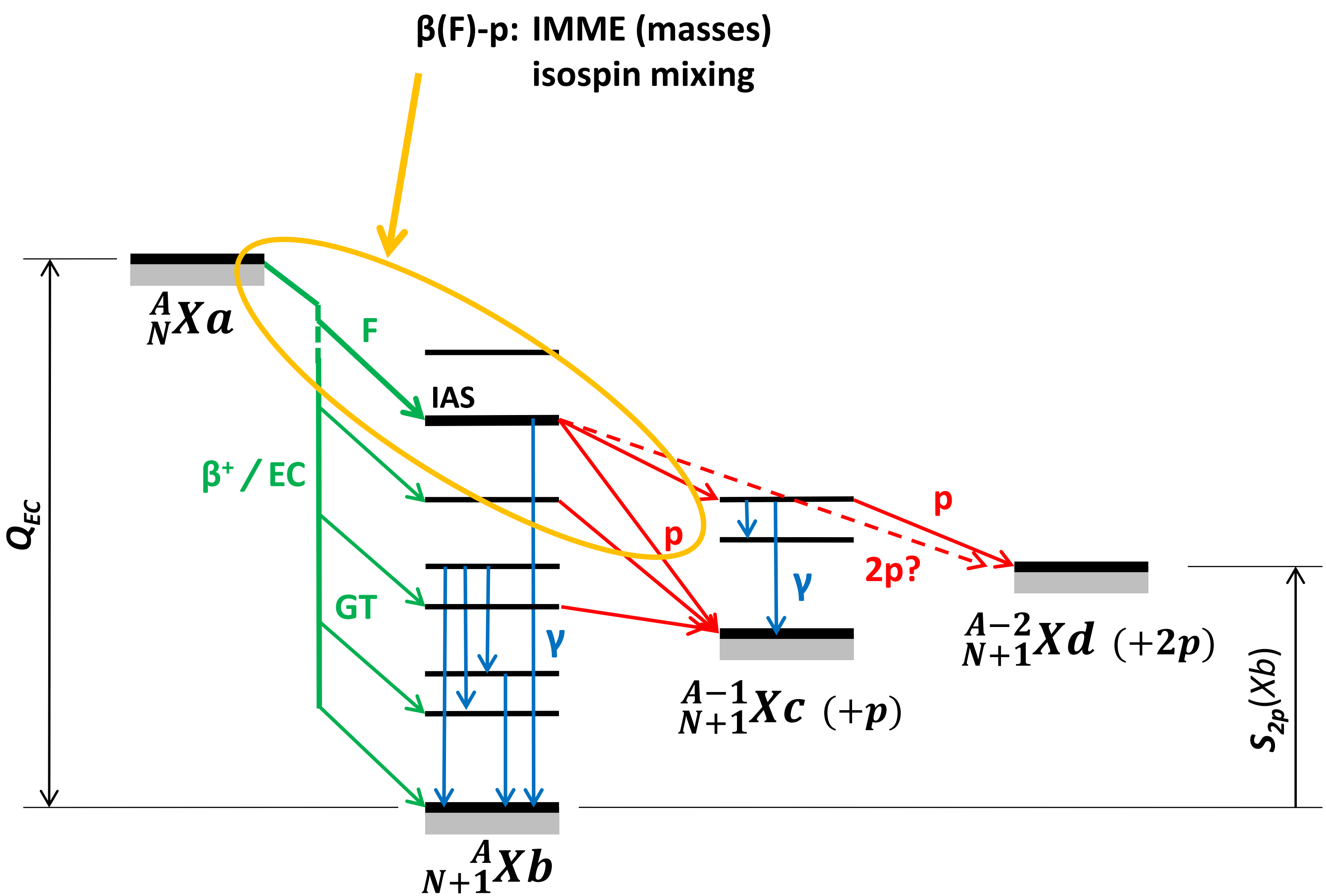
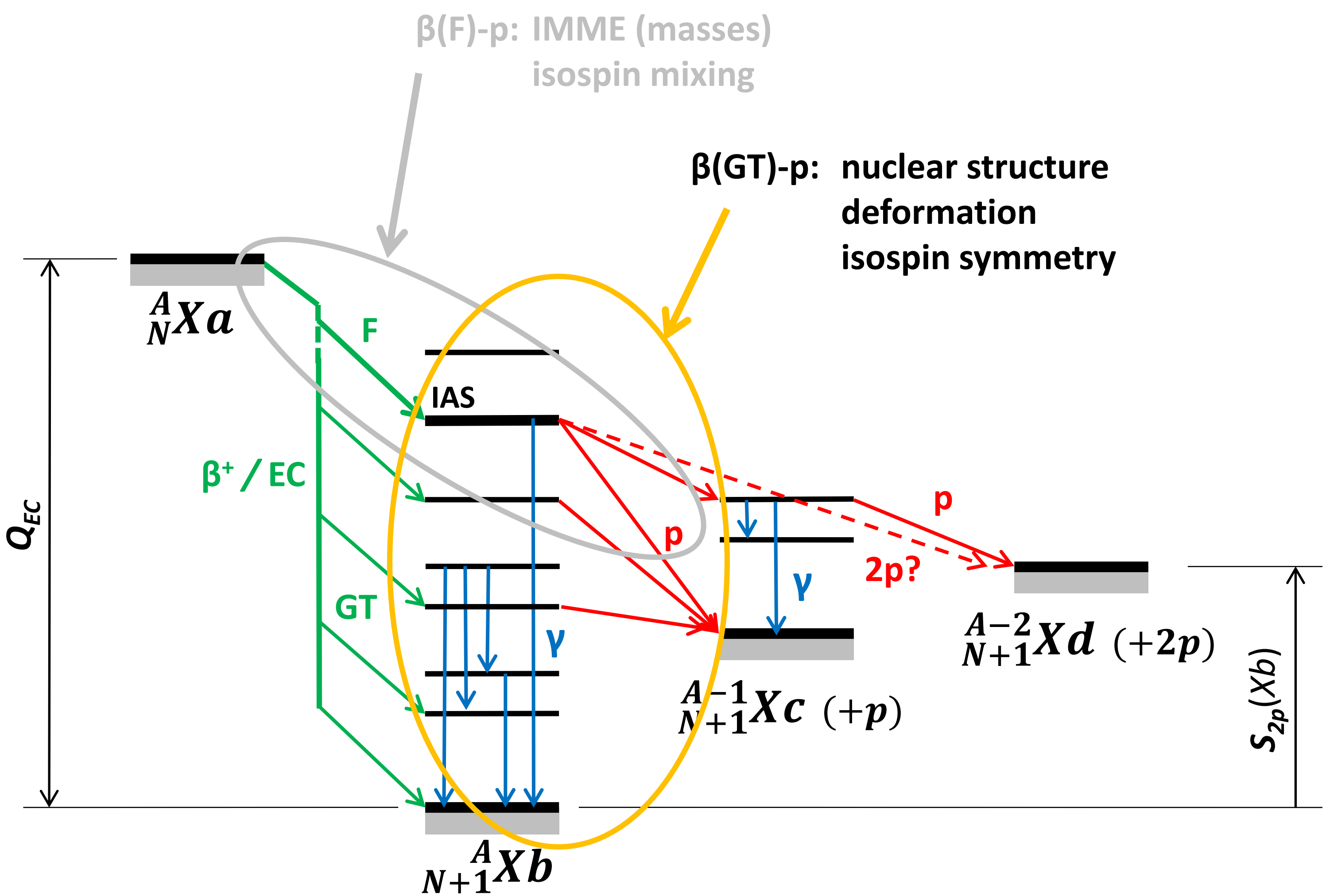
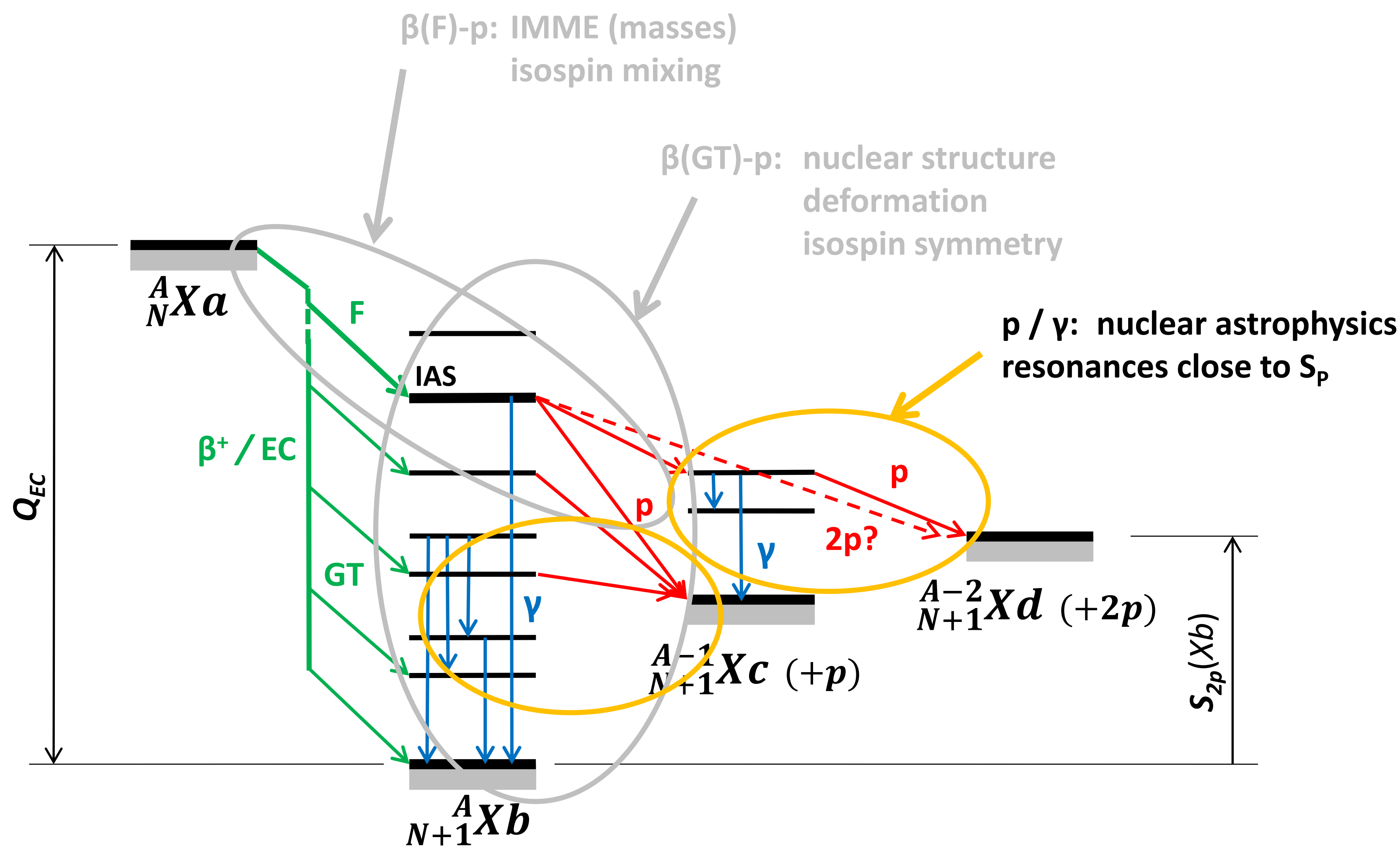


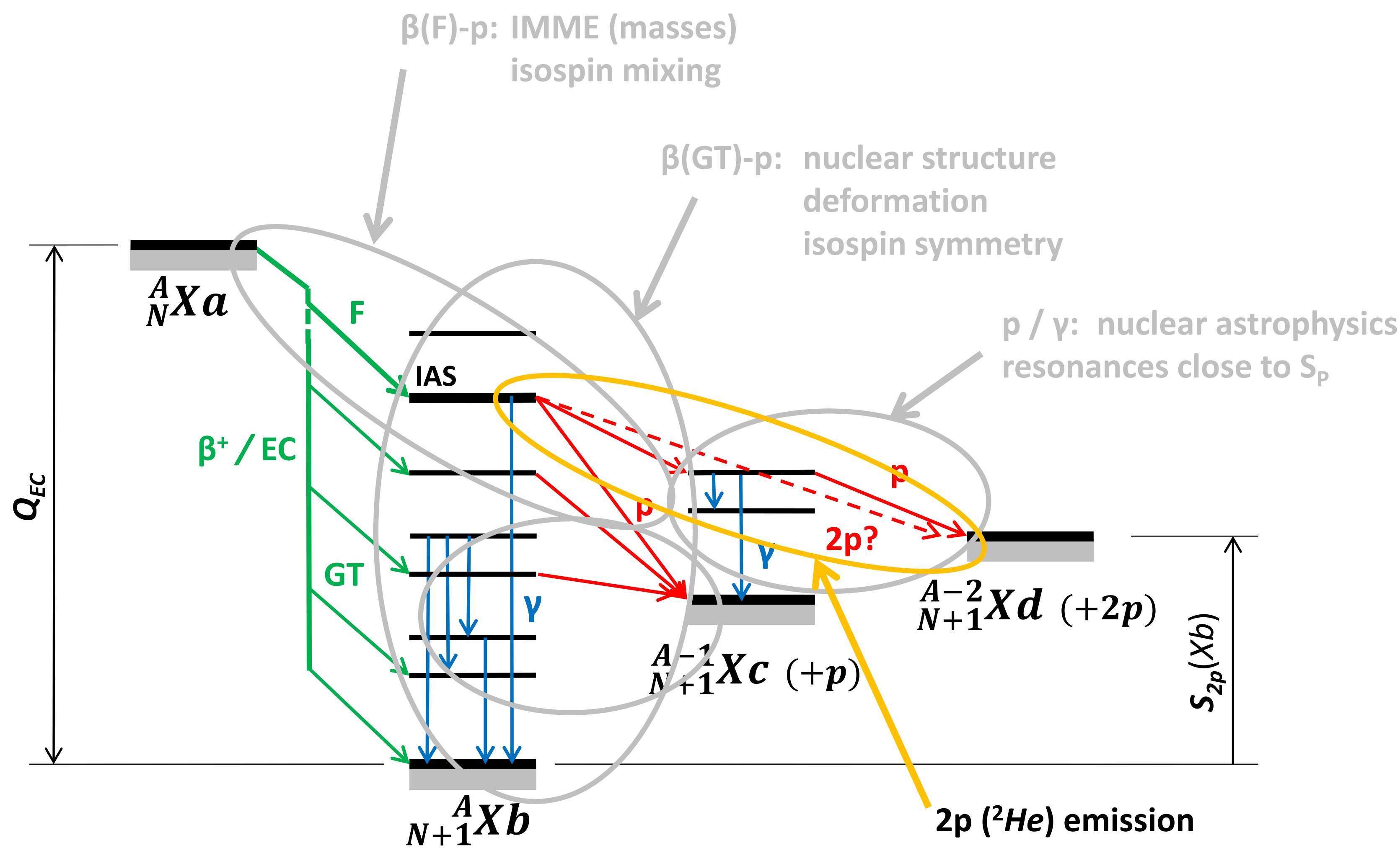
Delayed-proton(s) emission: a rich physics case !



Delayed-proton(s) emission: a rich physics case !



Delayed-proton(s) emission: a rich physics case !



Beta-delayed proton(s) emission

- Beta-delayed 1 proton emission
  - **Fermi transition & isospin symmetry**
  - β-p and Gamow-Teller strength distribution
  - Proton emission and nuclear levels half-life
- Beta-delayed multi-proton
  - Sequential vs direct emission
  - First experiment
  - β-2p and search for the "^{2}*He*" emission
  - Delayed multi-proton emission

A first access to the mass of exotic nuclei

Isobaric Multiplet Mass Equation (IMME, Wigner, 1957)

charge independent strong nuclear interaction + Coulomb

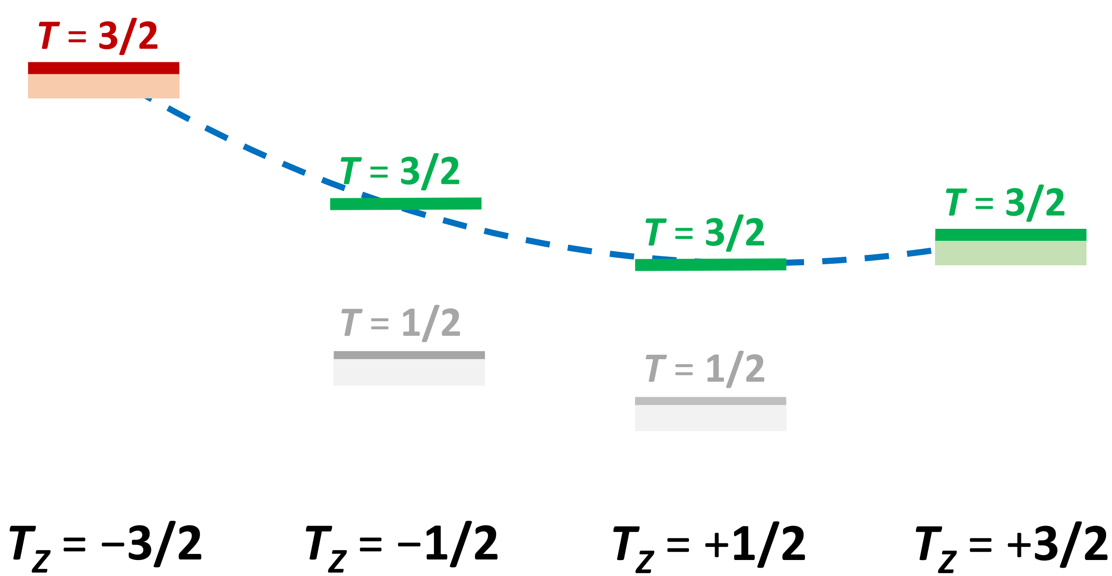
$$M(T_z) = a + b \times T_z + c \times T_z^2$$ (+ possible higher order correction)

T ⇨ $(2T+1)$ projections T_z

if ($T \geq 3/2$) ⇨ at least 4 values of T_z

⇨ if 3 masses are known, determination of (a,b,c) coefficients

⇨ **mass estimate of other multiplet members**



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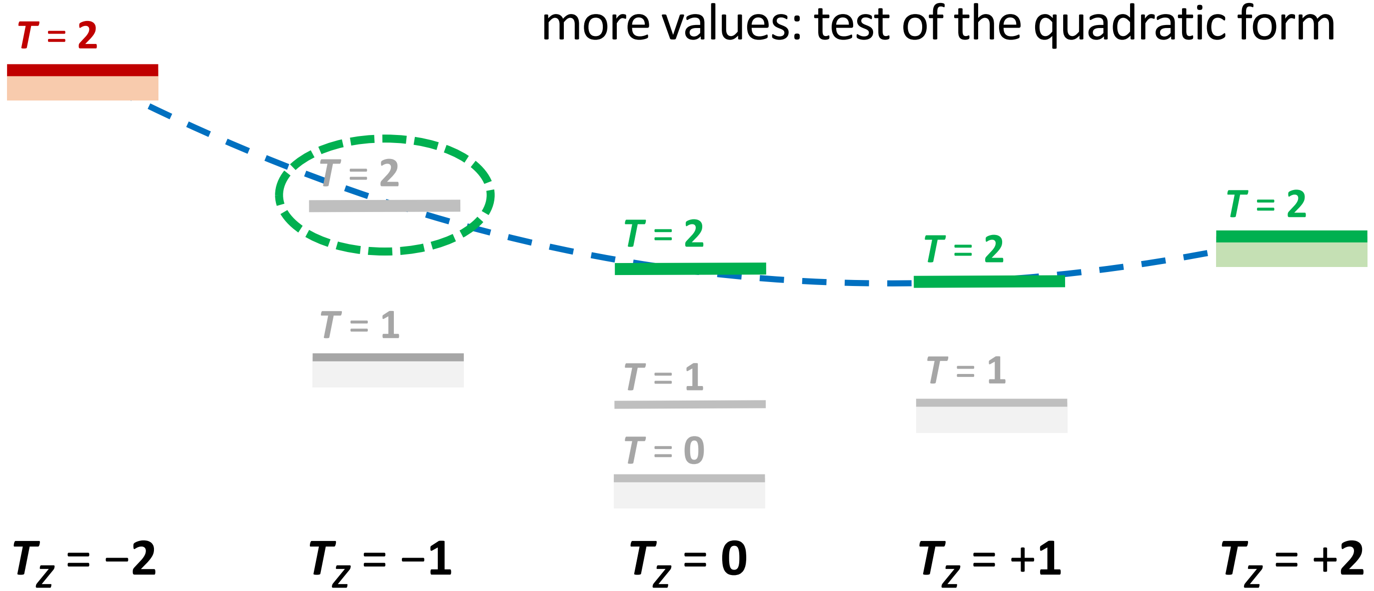
⇨ **mass estimate of other multiplet members**

more values: test of the quadratic form



A first access to the mass of exotic nuclei

for nuclei far from stability (with $Z > N$)

Fermi transition to IAS + proton emission

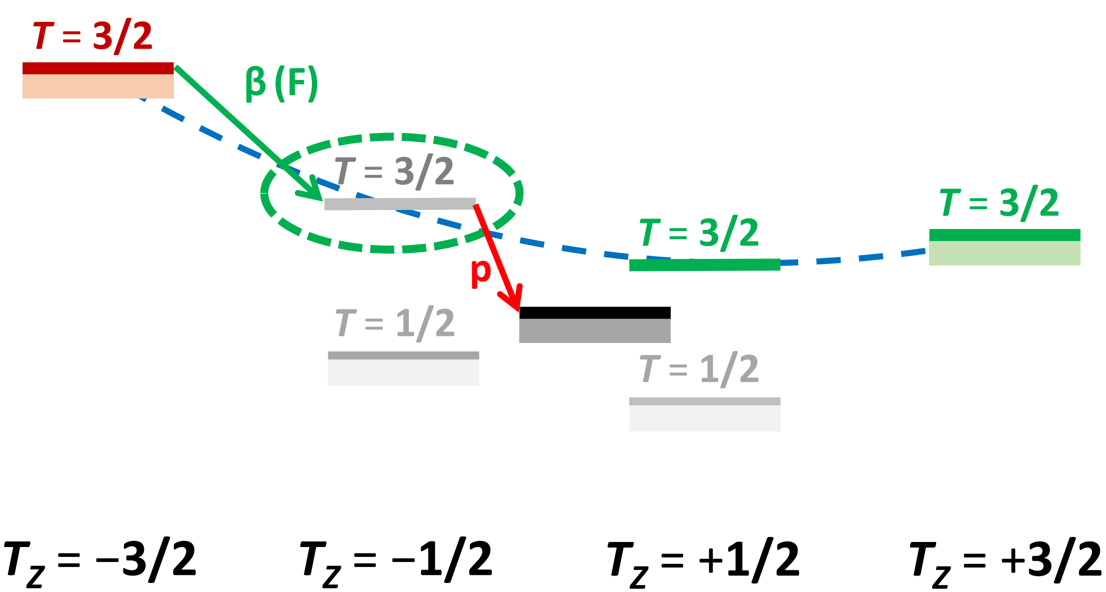
precise proton transition energy

less exotic **daughter** (usually better known → mass)

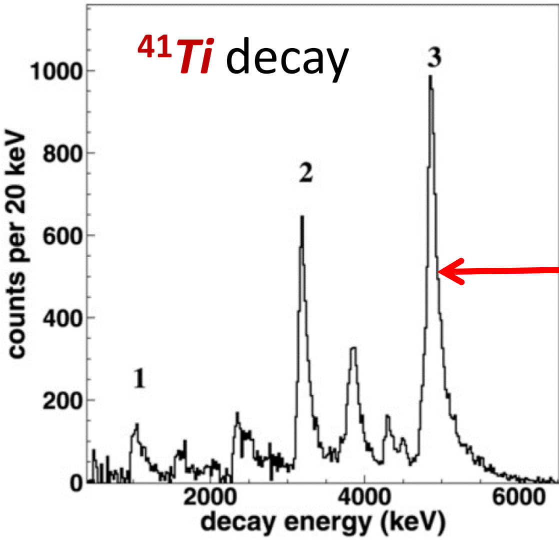
→ estimate of **IAS mass** (excess)

other multiplet members less exotic

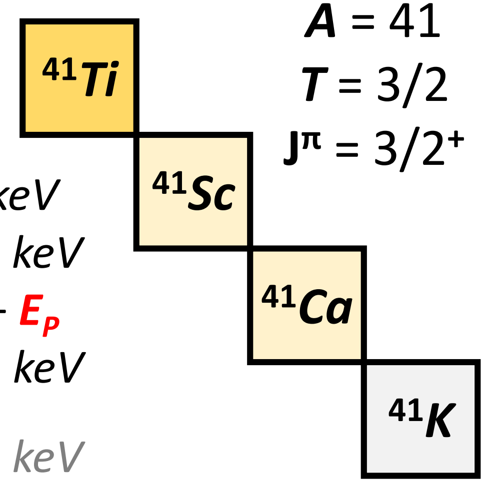
→ use IMME for precursor ground state mass



A first access to the mass of exotic nuclei



C.Dossat, NP A792 (2007)

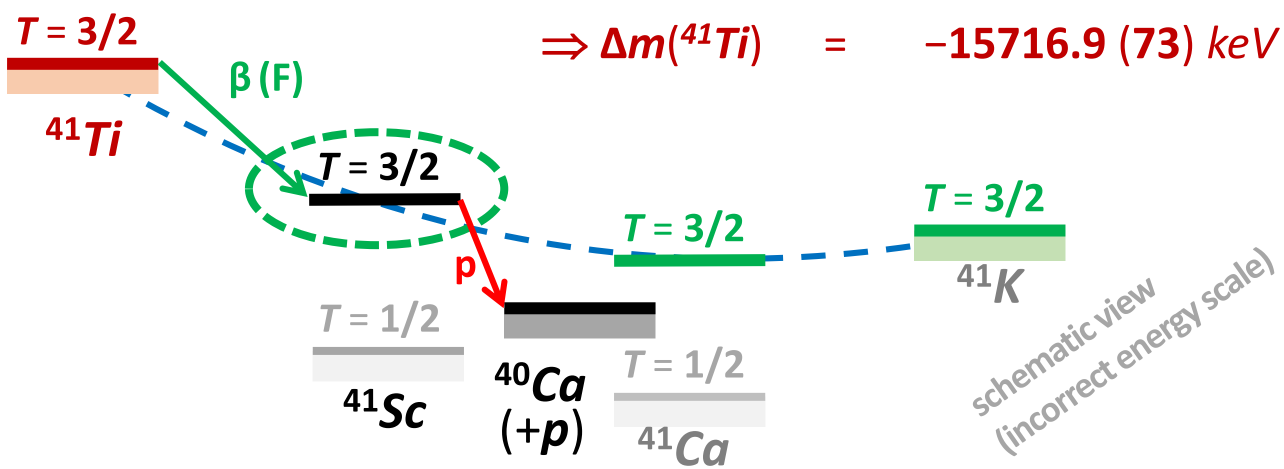


A = 41
T = 3/2
$J^\pi = 3/2^+$

$\Delta m(^{40}Ca)$ = −34846.3 (2) keV
$Ep(\text{IAS} \rightarrow {}^{40}Ca)$ = 4852.8 (26) keV
$\Delta m(^{41}Sc\ \text{IAS}) = \Delta m(^{40}Ca) + \Delta m_p + E_p$
= **−22704.6 (26)** keV

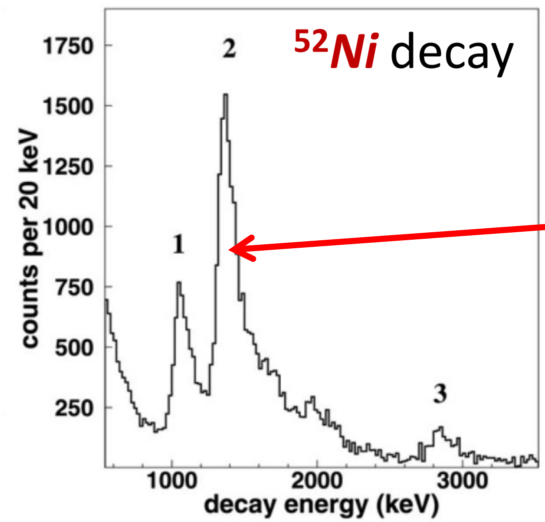
$\Delta m(^{41}Ca)$ = −29318.8 (20) keV
$\Delta m(^{41}K)$ = −22704.7 (24) keV

$\Rightarrow \Delta m(^{41}Ti)$ = **−15716.9 (73)** keV



$T_z = -3/2$ $T_z = -1/2$ $T_z = +1/2$ $T_z = +3/2$

A first access to the mass of exotic nuclei



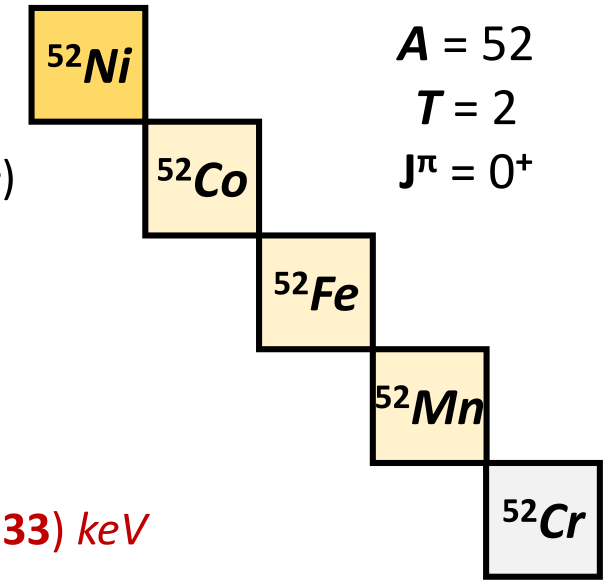
C.Dossat, NP A792 (2007)

$\Delta m(^{52}Co\ \text{IAS}) = \Delta m(^{51}Fe) + \Delta m_p + E_p(\text{IAS} \rightarrow {}^{51}Fe)$

$+\ \Delta m(^{52}Fe\ T{=}2)$

$+\ \Delta m(^{52}Mn\ T{=}2)$

$+\ \Delta m(^{52}Cr\ T{=}2)$



$A = 52$

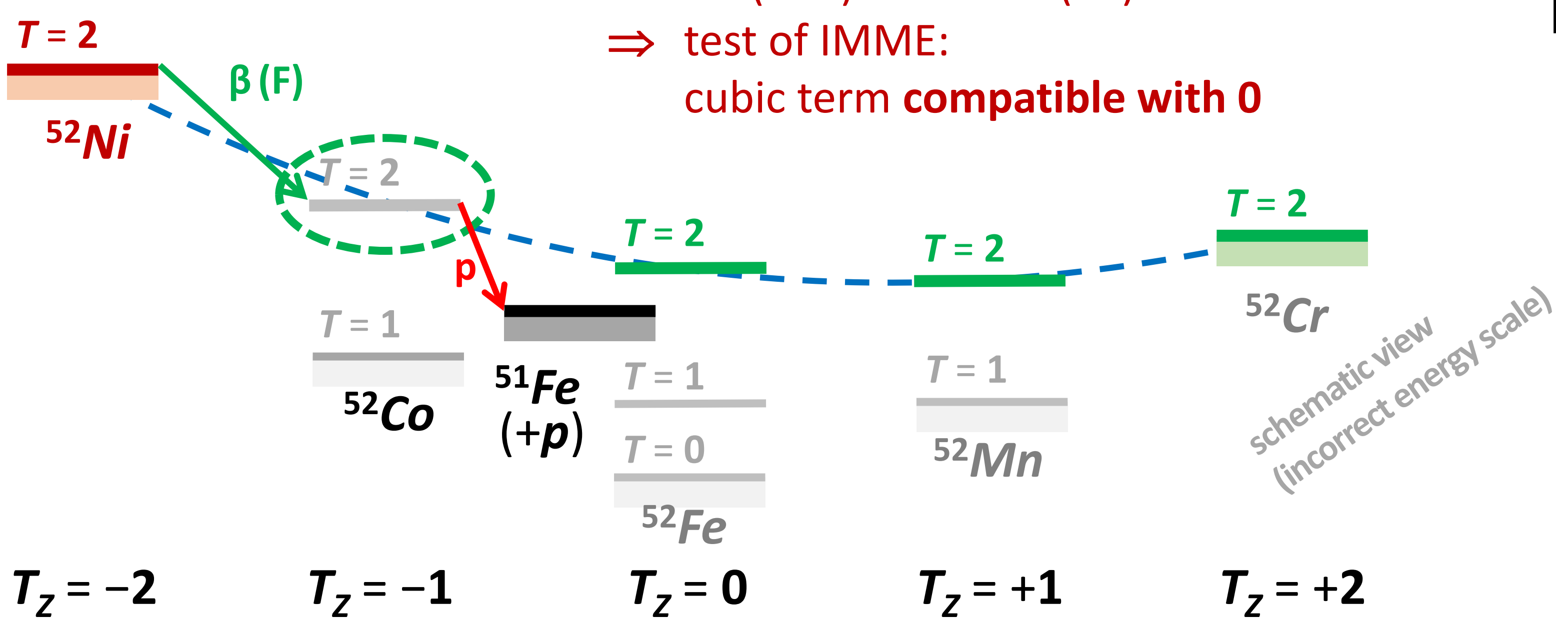
$T = 2$

$J^{\pi} = 0^{+}$

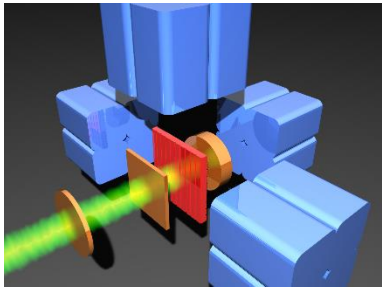
⇒ 4 multiplet members

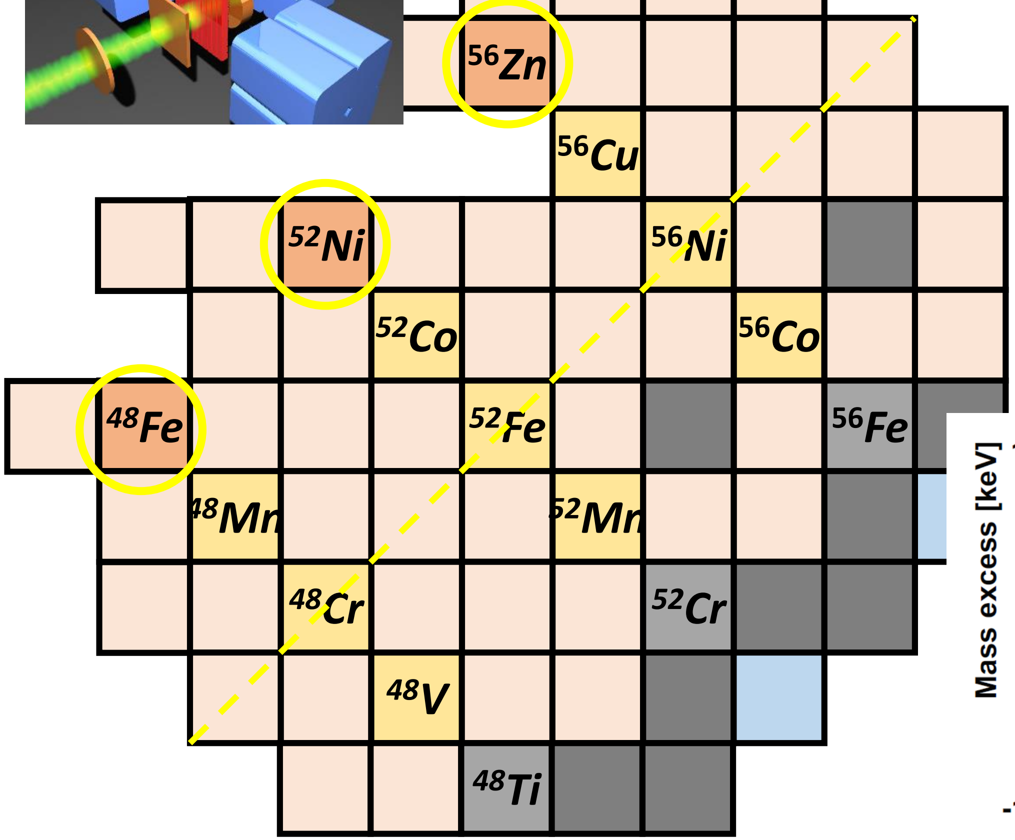
⇒ **$\Delta m(^{52}Ni)$ = −22639 (33)** *keV*

⇒ test of IMME:
cubic term **compatible with 0**



A first access to the mass of exotic nuclei

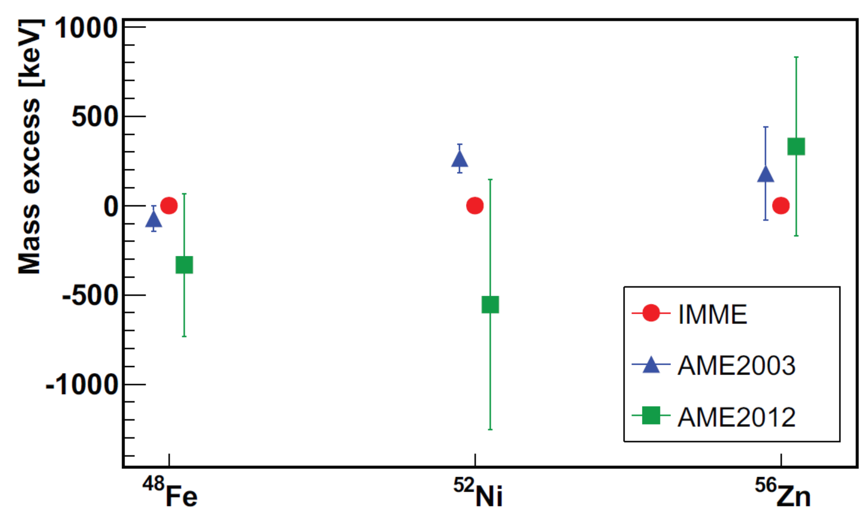




experiment @ GANIL / LISE3

comparison of masses
from IMME (exp.)
with A.M.E.

S.E.A. Orrigo *et al.*, PRC 93 (2016)



A first access to the mass of exotic nuclei

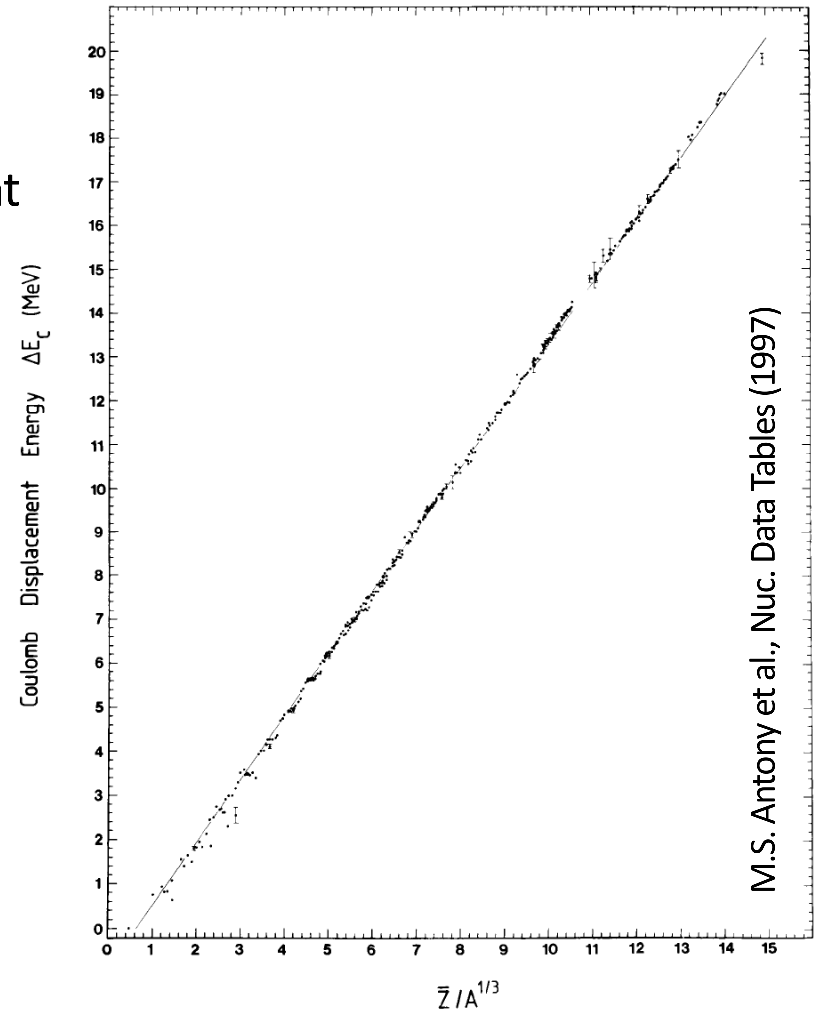
Coulomb displacement energy

if less than 3 masses are known

→ parametrization of Coulomb displacement between analog states

M.S. Antony et al., Nuc. Data Tables (1997)

$$\Delta E_C = a(T) \cdot \bar{Z} \cdot A^{-\frac{1}{3}} + b(T)$$



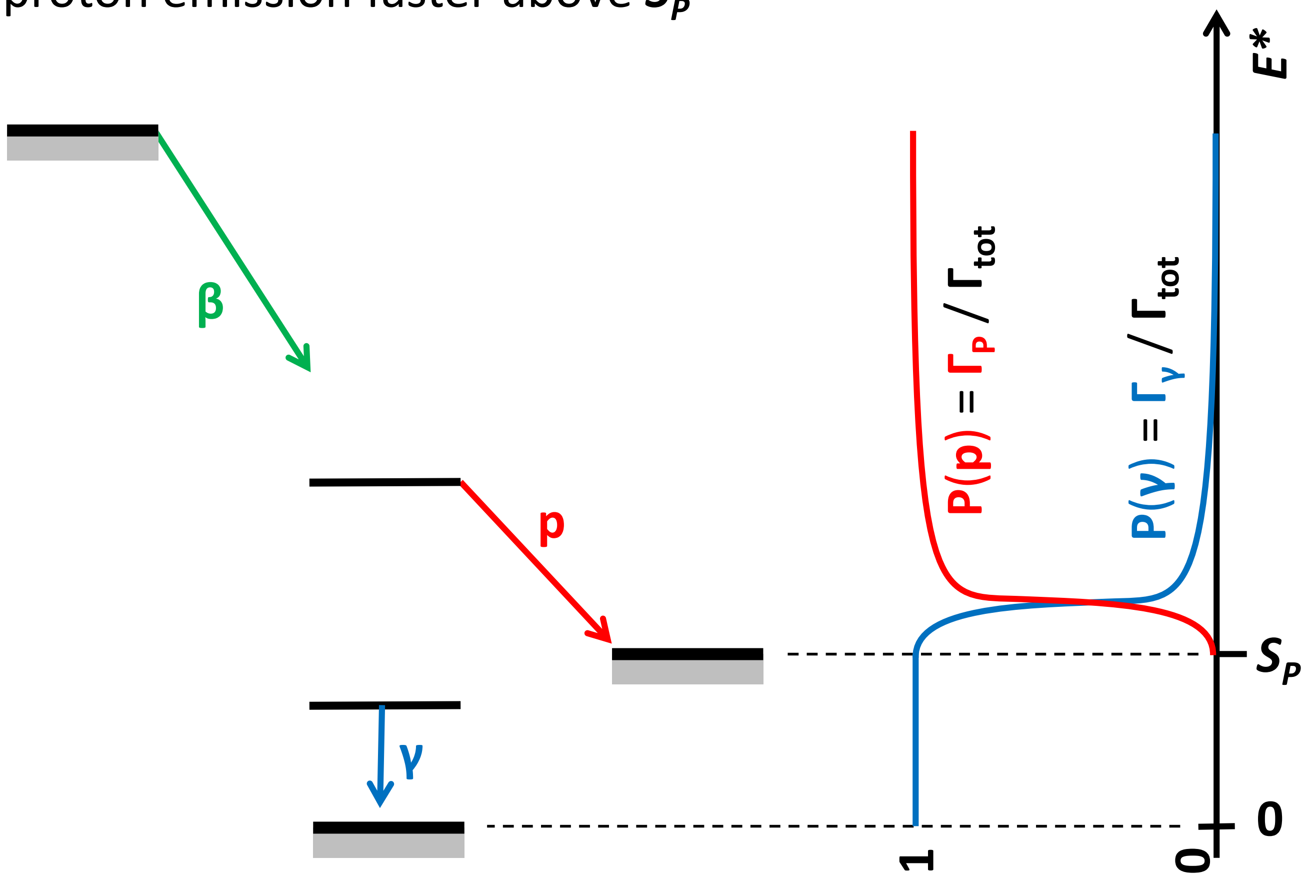
M.S. Antony et al., Nuc. Data Tables (1997)

IMME precision does not compete with current mass measurement techniques (only measurement for very exotic)

$\Delta m / m$ =	(IMME)	~10^{-5}-10^{-6}
	(cyclo+ToF)	~10^{-5}-10^{-6}
	(storage ring)	~10^{-6}
	(Penning trap)	**~10^{-7}-10^{-8}**

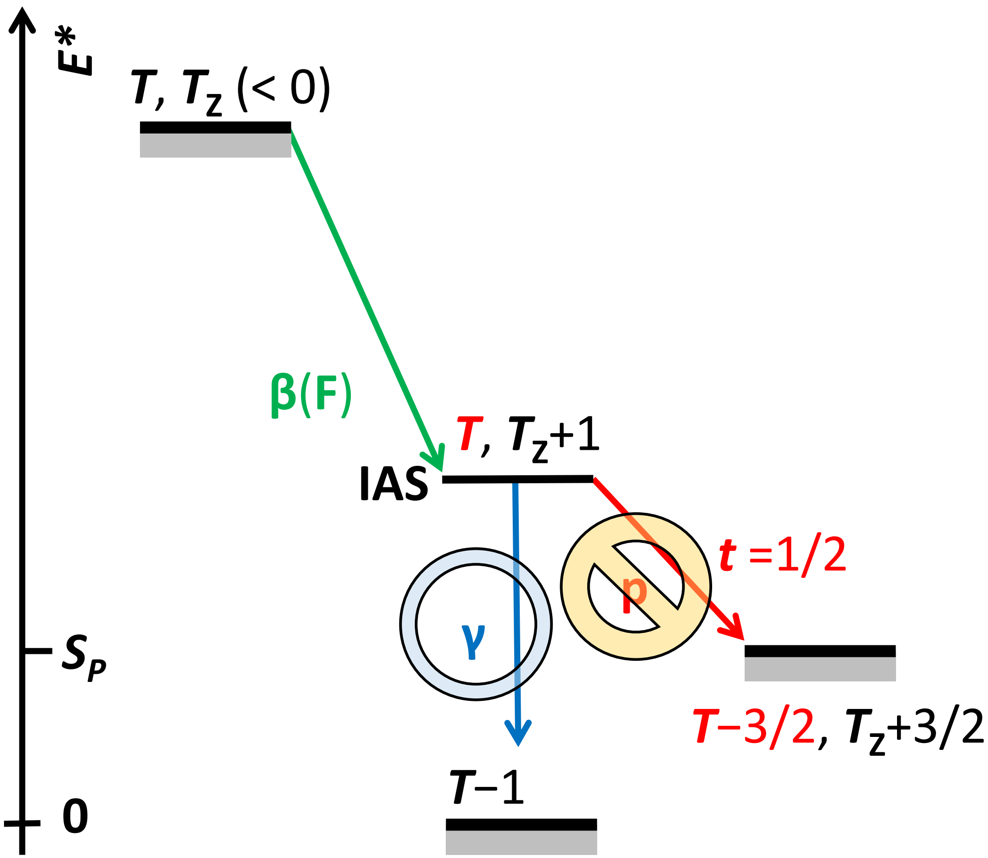
Proton emission from IAS and isospin mixing

gamma de-excitation: **electromagnetic** process
proton emission: **strong nuclear** interaction process
→ proton emission faster above S_P



Proton emission from IAS and isospin mixing

Fermi transition + proton emission (from IAS): **isospin forbidden**



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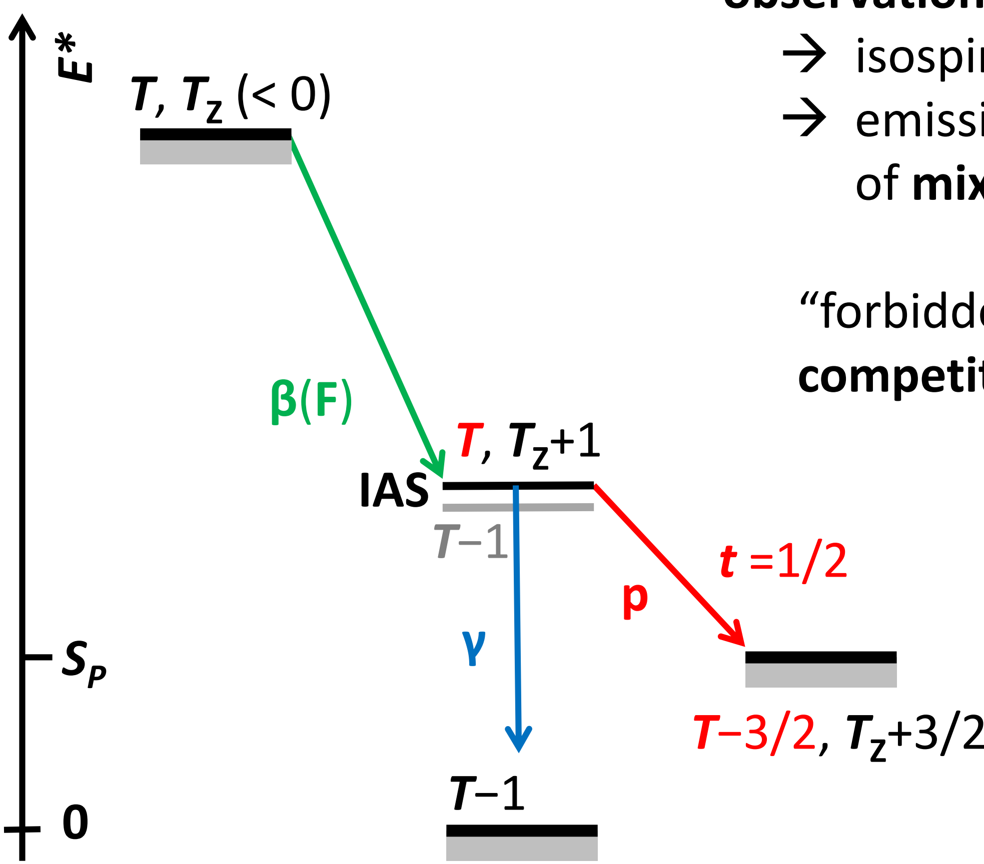


observation of protons from IAS

→ isospin symmetry breaking

→ emission possible due to a fraction of **mixing with T−1** states of the IAS

"forbidden" proton transition (slower)

competition with gamma de-excitation

experimental information to test isospin impurity

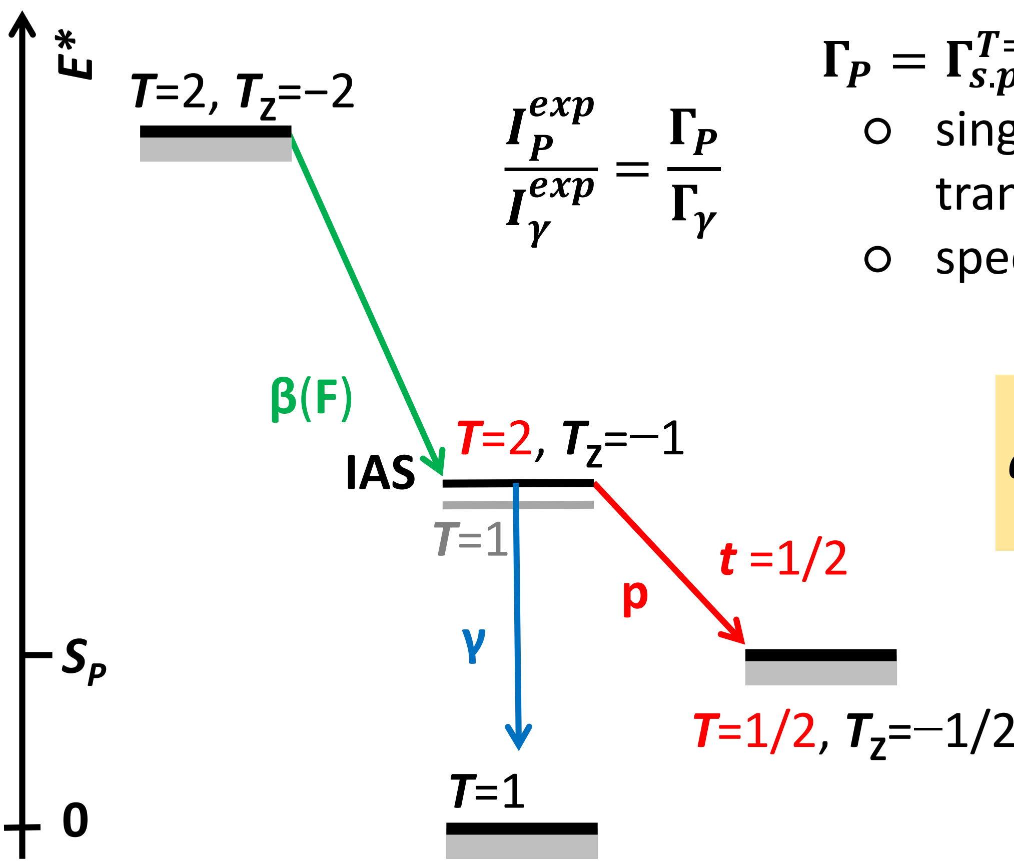
→ test INC terms in nuclear interaction (not well known)

→ …

Proton emission from IAS and isospin mixing

simple 2-state mixing picture

$$|\,IAS\,\rangle = \sqrt[2]{1-\alpha^2}\cdot|\,T=2\,\rangle + \alpha\cdot|\,T=1\,\rangle$$



$$\frac{I_P^{exp}}{I_\gamma^{exp}} = \frac{\Gamma_P}{\Gamma_\gamma}$$

$$\Gamma_P = \Gamma_{s.p.}^{T=1}\cdot\alpha^2\cdot S_{T=1}$$

- single particle width for isospin allowed transition
- spectroscopic factor for allowed trans.

$$\alpha^2_{estim} = \frac{I_P^{exp}}{I_\gamma^{exp}} \times \frac{\Gamma_\gamma}{\Gamma_{s.p.}^{T=1}\cdot S_{T=1}}$$

experimental measurements

theoretical calculations

Γ_γ shell model

S shell model

$\Gamma_{s.p.}$ barrier penetration

Proton emission from IAS and isospin mixing

experiment by-product in ***A***~50 mass region with ***T***=2 (Dossat et al., NP A792, 2007)

→ trigged an experimental / theoretical program
(B. Blank *et al*., E666 exp. 2016; N. Smirnova *et al*., PRC95 2017)

try to understand the estimated isospin mixing

→ put experiment constraints on theoretical calculations

Pre-cursor	J_i^π	J_f^π	$E_{\mathrm{IAS}}^{\mathrm{exp}}$ (MeV)	$E_{\mathrm{IAS}}^{\mathrm{th}}$ (MeV)	E_p (keV)	I_p	I_γ	Γ_p (eV)	Γ_γ (eV)	α^2 (%)
^{44}Cr	0^+	$7/2^-$	3.410	3.251	910(11)	1.7(3)	26.3(3)	0.032(5)	1.08	220(50)
		$3/2^-$	3.410	3.251	910(11)	1.7(3)	26.3(3)	10.06(14)	1.08	0.69(15)
^{45}Cr	$7/2^-$	0^+	4.790	4.456	2087(9)	19.6(15)	12.4(15)	134.8(49)	1.76	2.06(30)
^{48}Fe	0^+	$3/2^-$	[illegible].04		1006(12)	1.9(3)	43.1(3)	8.1(11)	0.60	0.33(7)
^{49}Fe	$7/2^-$	2^+	4.[illegible]1		1975(13)	34.5(2)	[illegible].5(2)	5835(3[illegible]5)	0.76	0.033(2)
^{50}Co	6^+	$13/2^-$	8.4[illegible]		1874(16)	1.0(2)	4.0(2[illegible])	2486(1[illegible]1)	0.45	0.009(2)
^{52}Ni	0^+	$5/2^-$	2.93		1349(10)	10.3(8)	55.7(8)	0.385(3[illegible]5)	0.19	9.1(11)
^{53}Ni	$7/2^-$	2^+	4.38		1929(17)	5.4([illegible])	[illegible]	[illegible]8)	0.76	0.0033(3)
^{56}Zn	0^+	$7/2^-$	3.51	3.817	2929(31)	20([illegible])	[illegible]	479(44)	0.11	0.02(1)

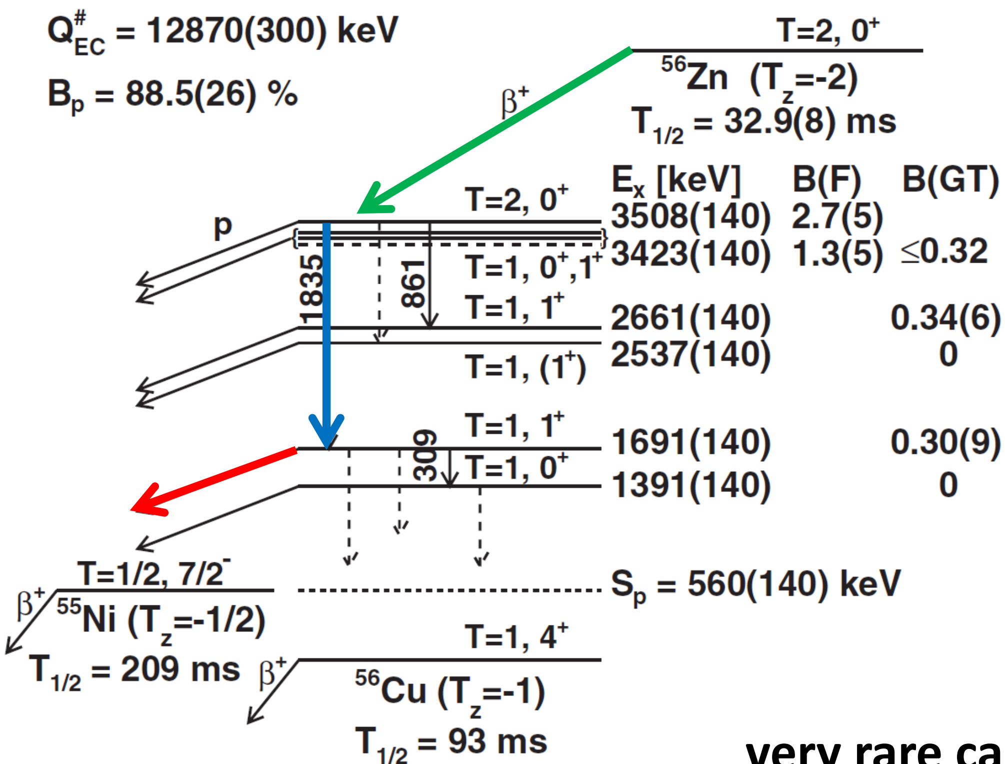
28 % in mirror
⇓
dev. of shell model
→ **33 %**

B.Blank *et al.*, GANIL/E666 proposal (2015)

require improved β-p(γ) (final state) and **β-γ** (for Γ_γ calc.) **data**

Proton emission from IAS and isospin mixing

S.E.A. Orrigo *et al.*, PRL 112 (2014)



α^2 = 33 ± 10 %

(28 ± 1 % in mirror ^{56}*Fe*)

very rare case of

beta-gamma-proton decay

- proton emission isospin-forbidden
- gamma de-excitation to an unbound state

Beta-delayed proton(s) emission

- Beta-delayed 1 proton emission
  - Fermi transition & isospin symmetry
  - β-p and Gamow-Teller strength distribution
  - Proton emission and nuclear levels half-life
- Beta-delayed multi-proton
  - Sequential vs direct emission
  - First experiment
  - β-2p and search for the “^{2}*He*” emission
  - Delayed multi-proton emission

Gamow-Teller strength distribution

$$B(GT) \propto |\langle f|\sigma\tau|i\rangle|^2$$

→ **probe the nuclear structure far from stability**

high selectivity of populated states (selection rules)

test of nuclear models

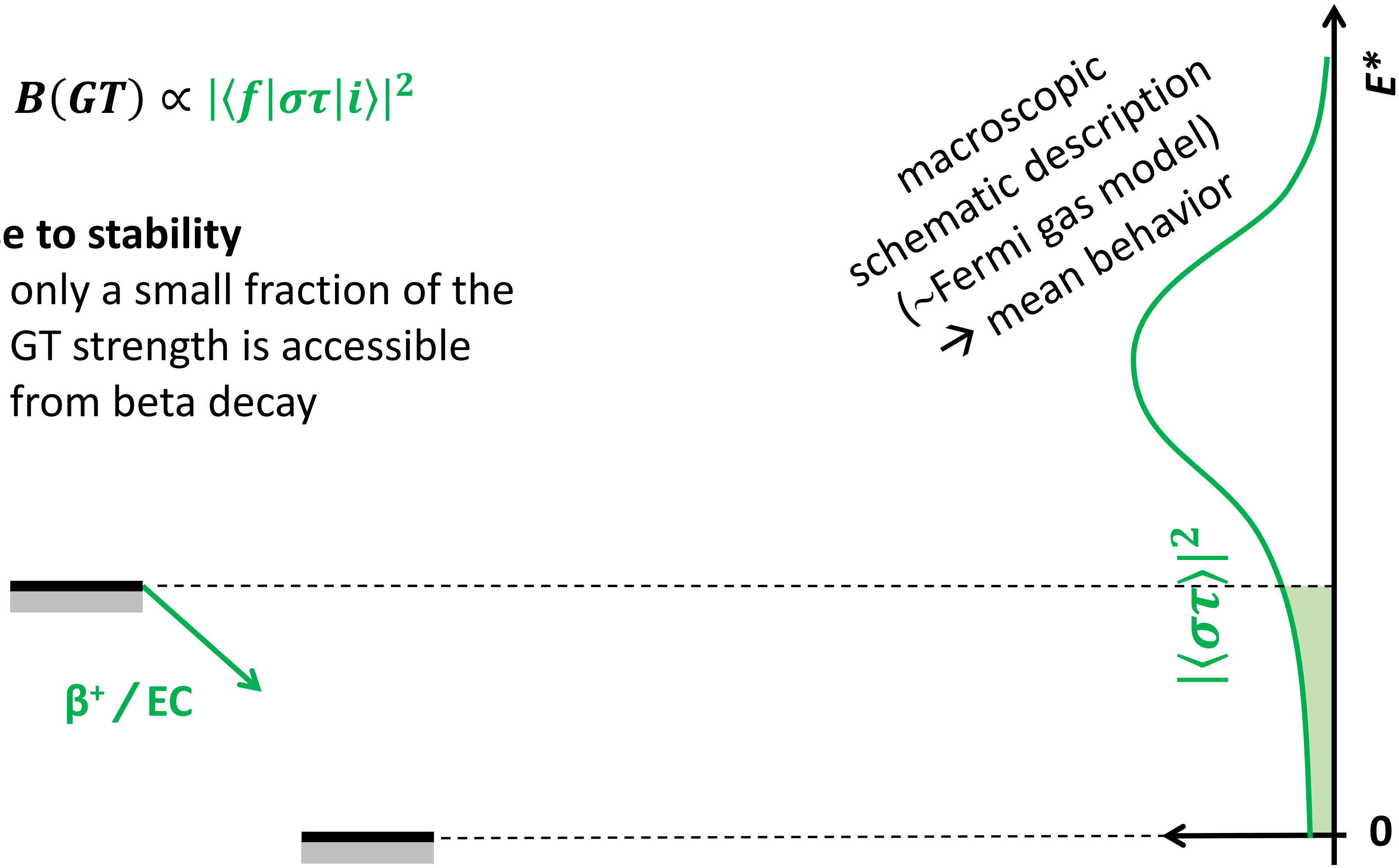
- predicted half-lives
- sum rule & quenching factor ($q^2 = B(\mathrm{GT})_{exp} / B(\mathrm{GT})_{th} \sim 0.7^2$)
- deformation
- proton-neutron pairing (along $N = Z$)
- …

Gamow-Teller strength distribution

$$B(GT) \propto |\langle f|\sigma\tau|i\rangle|^2$$

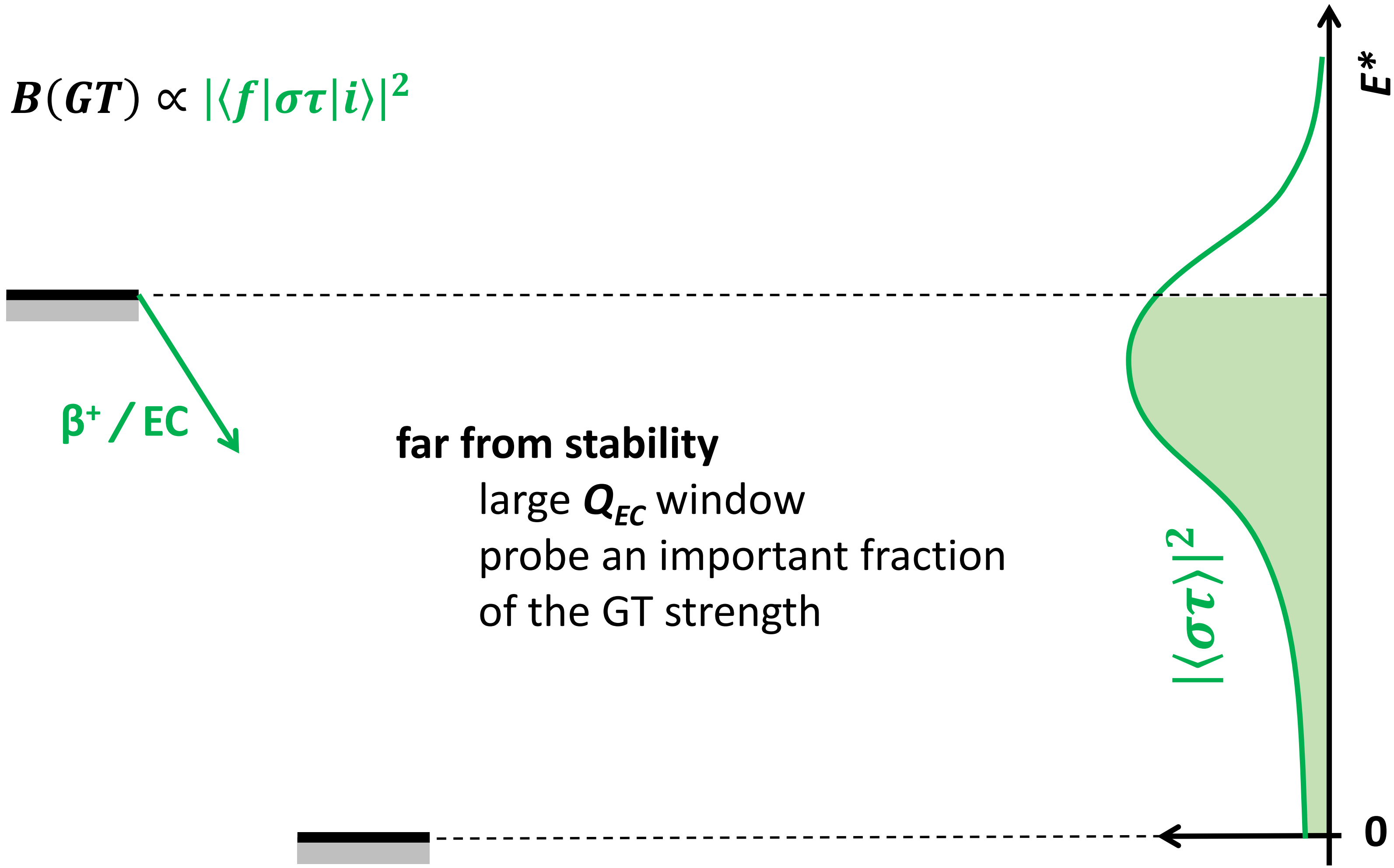
close to stability

only a small fraction of the GT strength is accessible from beta decay



Gamow-Teller strength distribution

$$\boldsymbol{B(GT)} \propto |\langle \boldsymbol{f} | \boldsymbol{\sigma\tau} | \boldsymbol{i} \rangle|^2$$

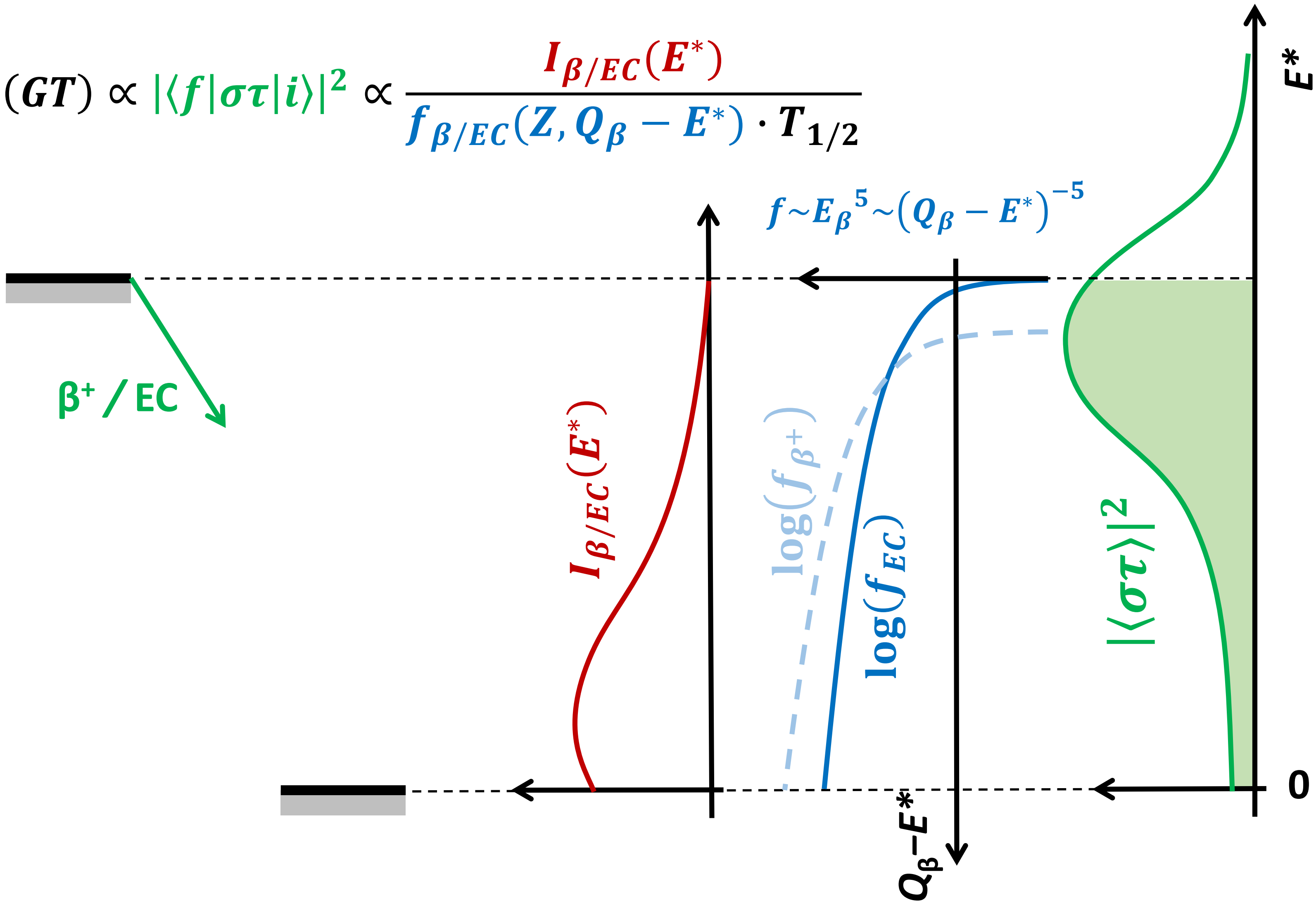


far from stability

- large $\boldsymbol{Q_{EC}}$ window
- probe an important fraction of the GT strength

Gamow-Teller strength distribution

$$B(GT) \propto |\langle f|\sigma\tau|i\rangle|^2 \propto \frac{I_{\beta/EC}(E^*)}{f_{\beta/EC}(Z, Q_\beta - E^*) \cdot T_{1/2}}$$



Gamow-Teller strength distribution

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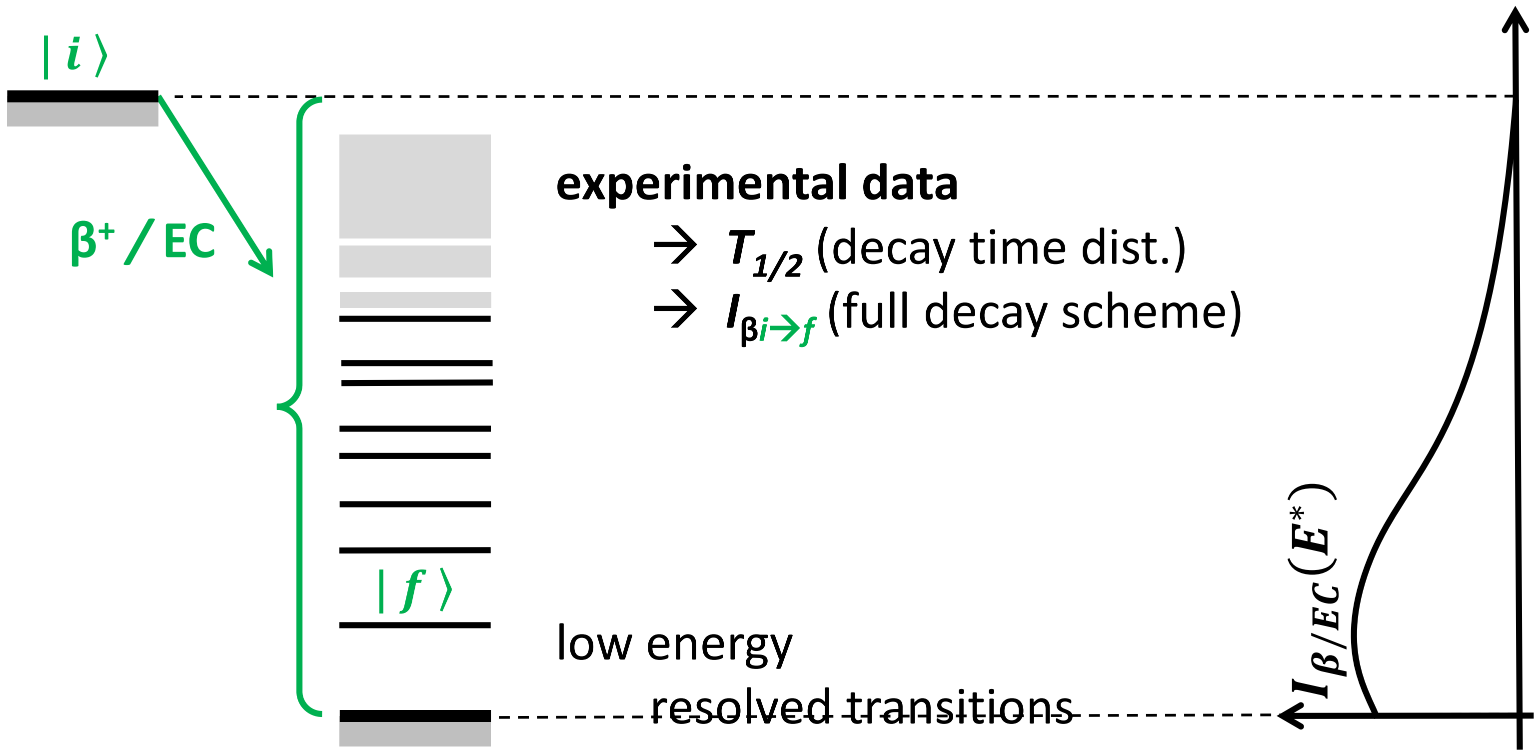


experimental data

→ $T_{1/2}$ (decay time dist.)

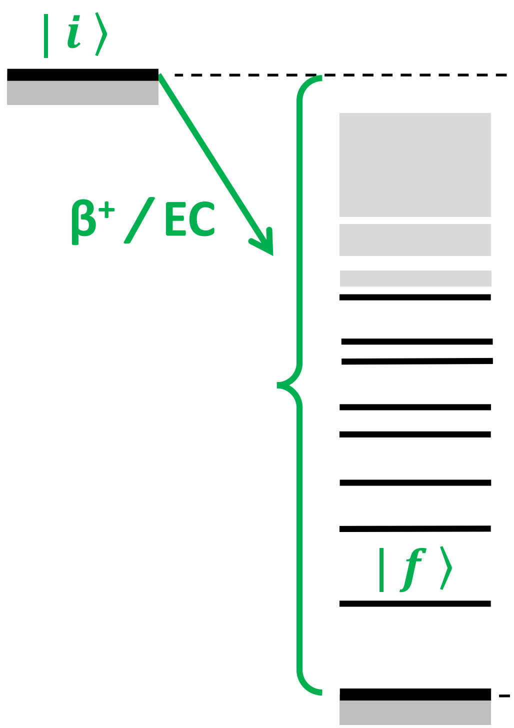
→ $I_{\beta_{i \to f}}$ (full decay scheme)

low energy

resolved transitions

Gamow-Teller strength distribution

$$B(GT) \propto |\langle f|\sigma\tau|i\rangle|^2 \propto \frac{I_{\beta/EC}(E^*)}{f_{\beta/EC}(Z, Q_\beta - E^*)\ T_{1/2}}$$



experimental data

→ $T_{1/2}$ (decay time dist.)

→ $I_{\beta i \to f}$ (full decay scheme)

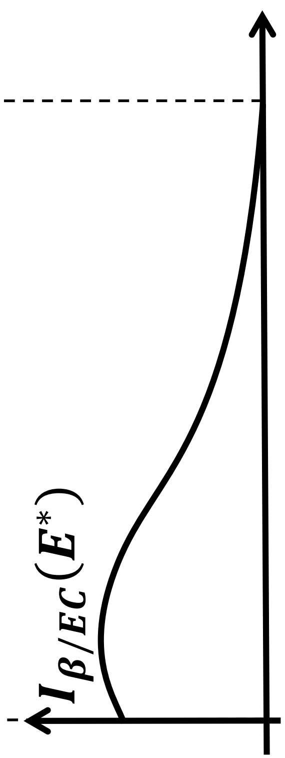
high energy

very high density of states

$\rho(E^*) \propto e^{-\sqrt{a \cdot E^*}}$

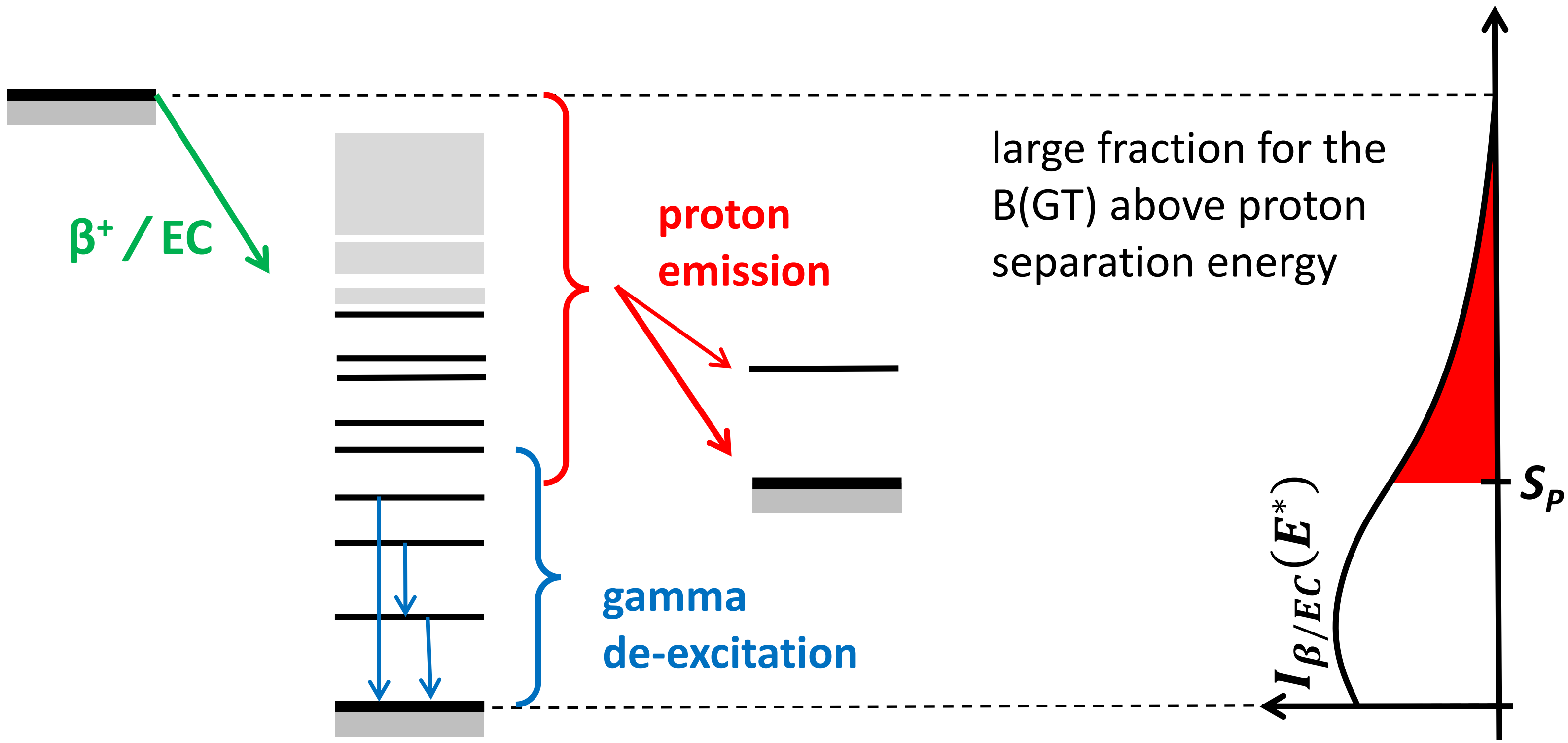
low energy

resolved transitions



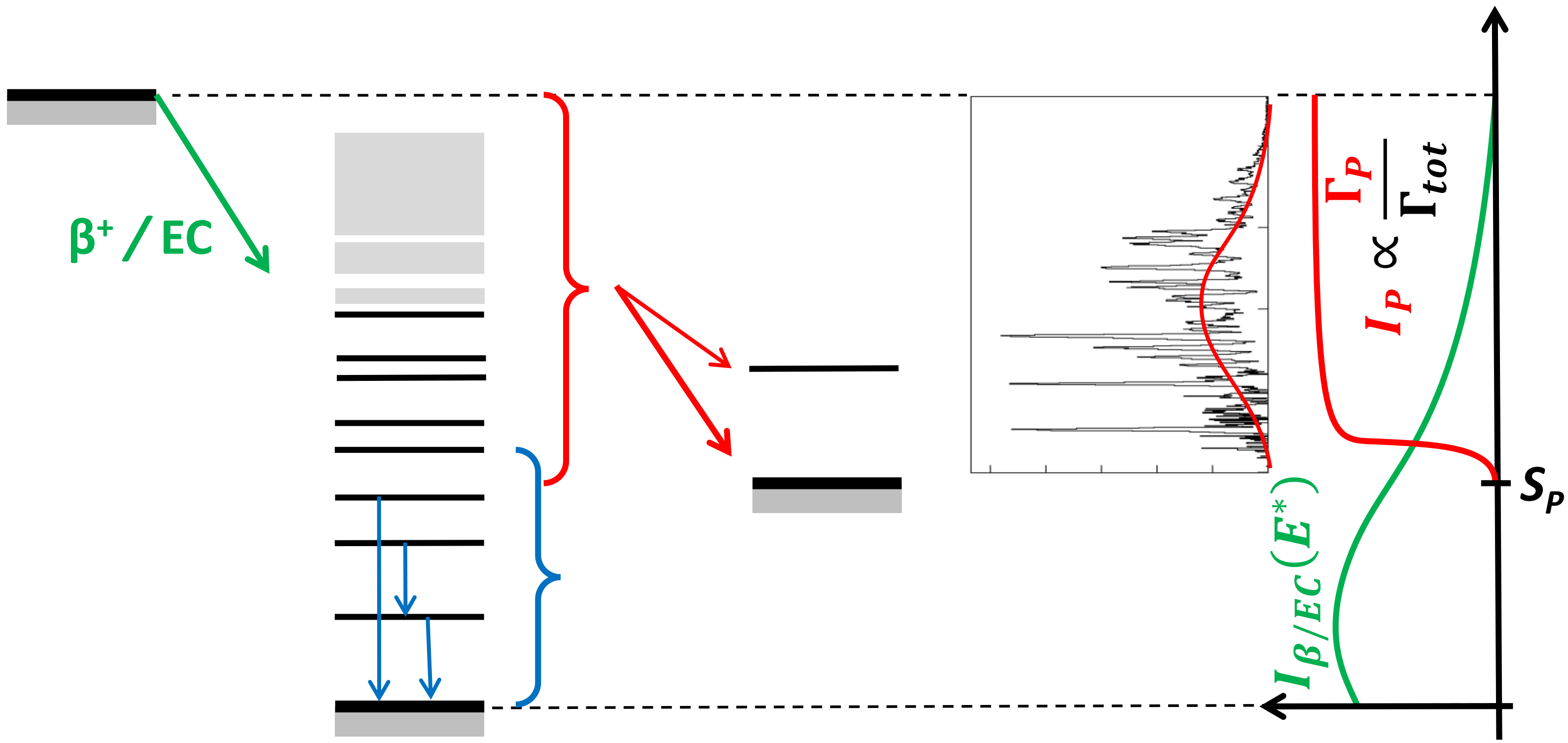
Gamow-Teller strength distribution

$$B(GT) \propto |\langle f|\sigma\tau|i\rangle|^2 \propto \frac{I_{\beta/EC}(E^*)}{f_{\beta/EC}(Z, Q_\beta - E^*) \cdot T_{1/2}}$$

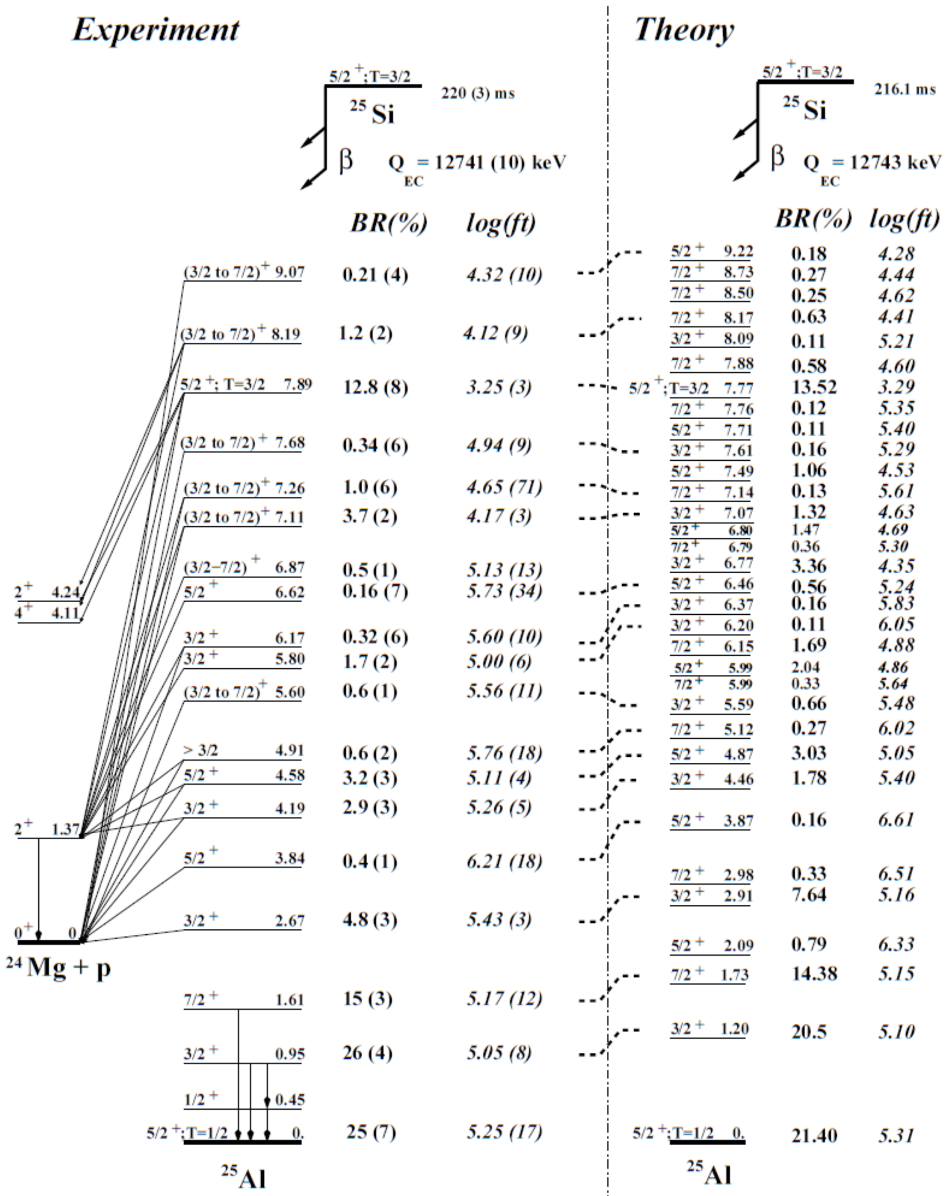


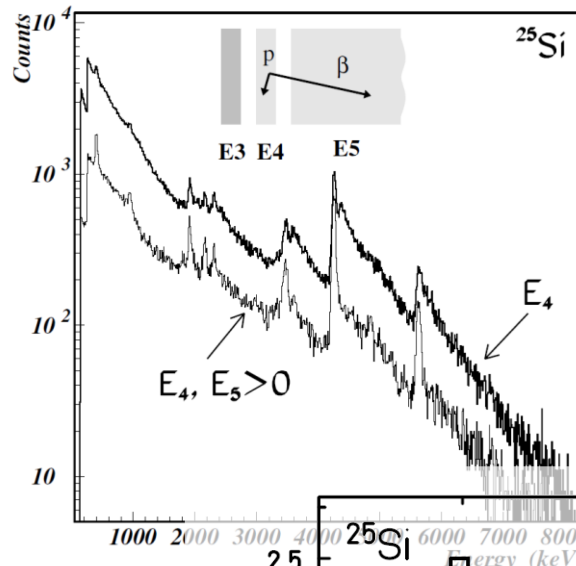
Gamow-Teller strength distribution

proton detection: only access to high E^* states
efficient and precise probe → even for low proton branching



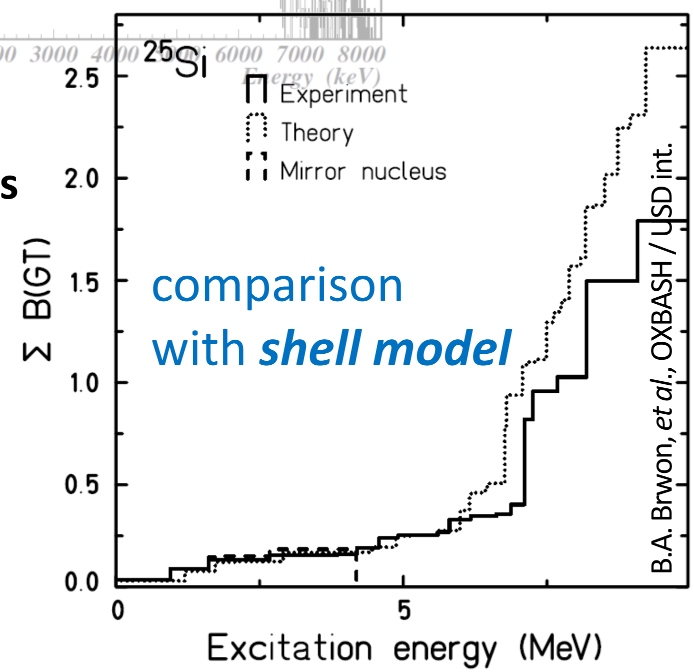
B(GT) in light nuclei: decay of ^{25}Si @ GANIL (in-flight)





J.-C. Thomas *et al.*, EPJA (2004)

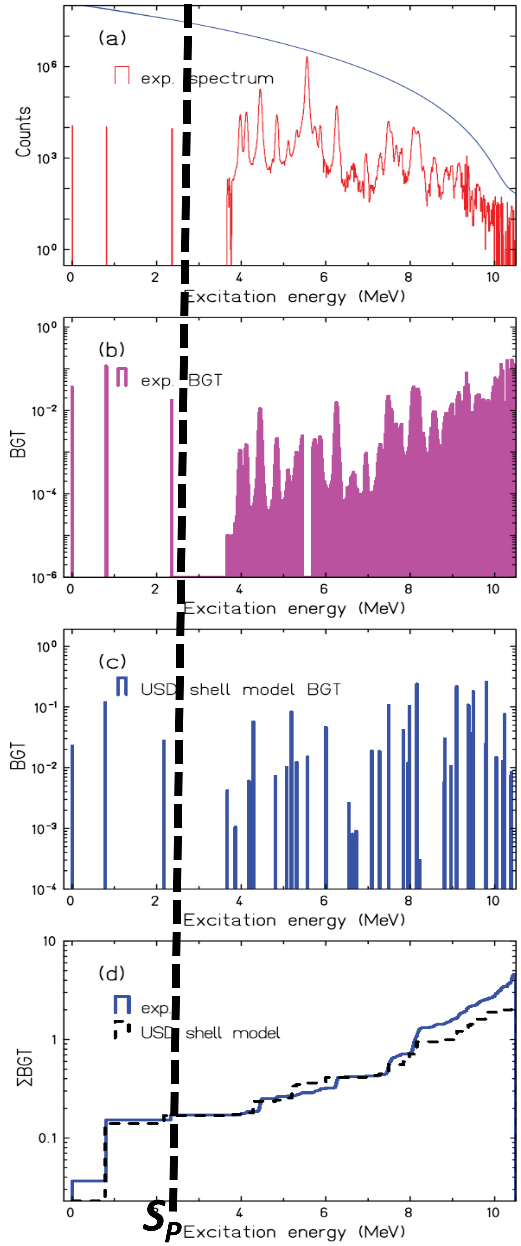
resolved transitions



comparison
with ***shell model***

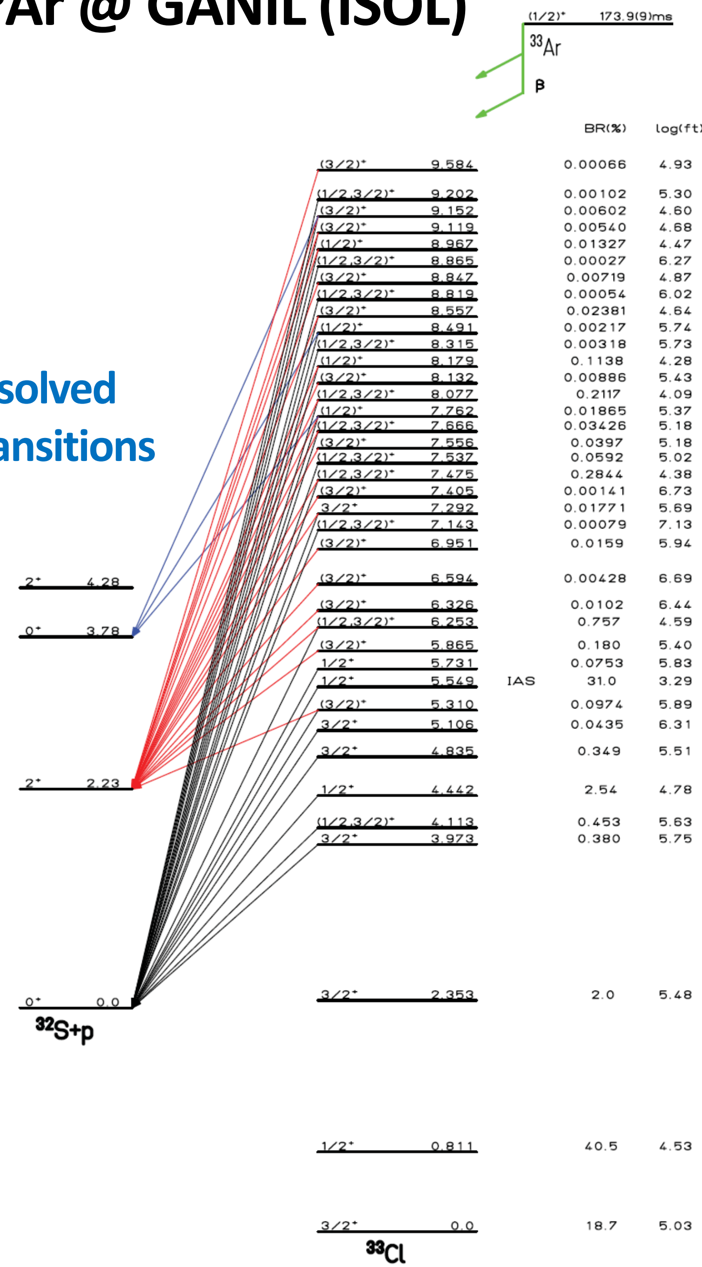
B.A. Brwon, *et al.*, OXBASH / USD int.

B(GT) in light nuclei: decay of ^{33}Ar @ GANIL (ISOL)



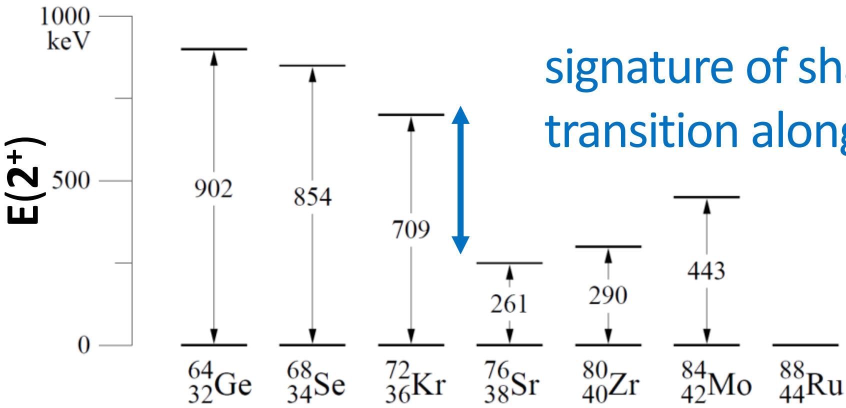
N. Adimi *et al.*, PRC (2010)

resolved transitions



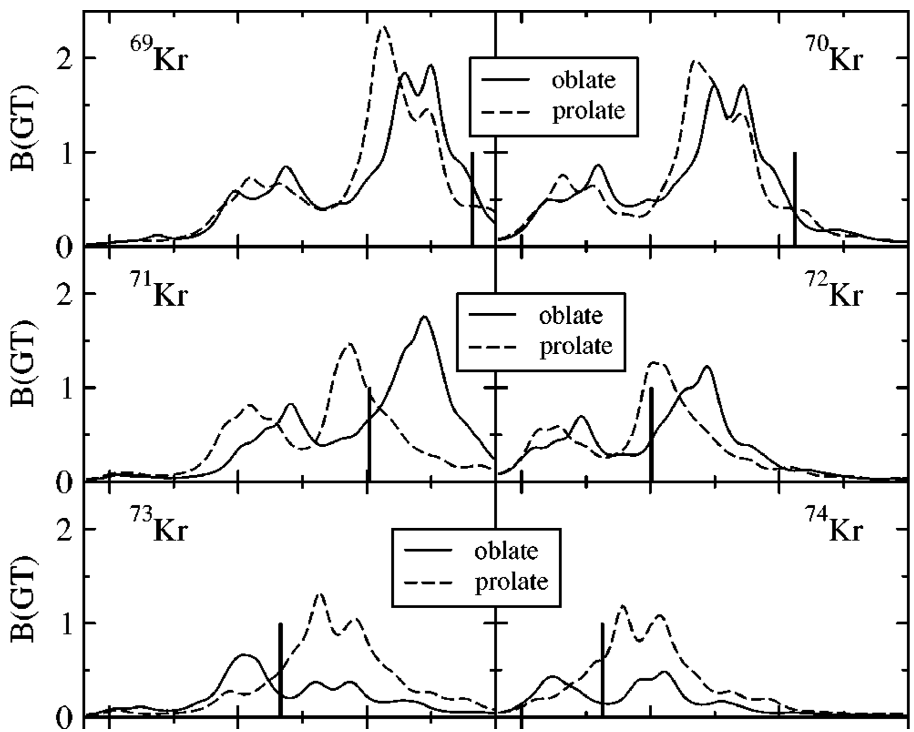
B(GT) and nuclear deformation

W.Gelletly *et al.*, Phys. Lett. B253 (1991)

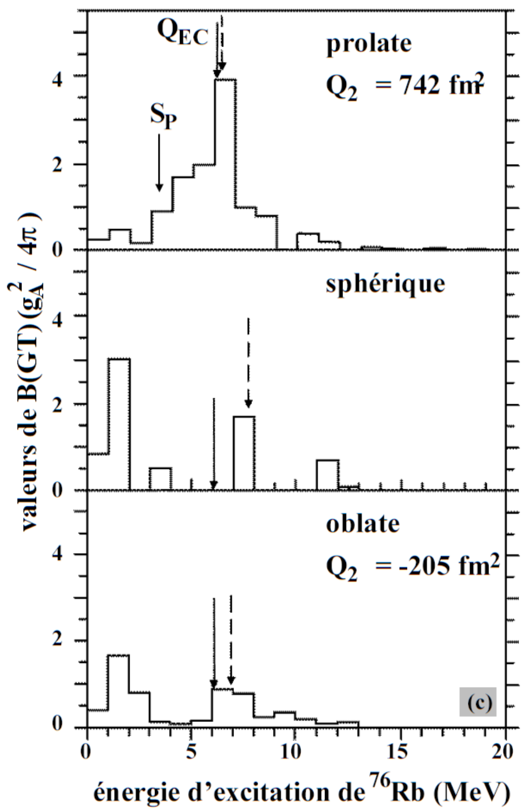


signature of shape transition along ***N*** = ***Z***

influence of deformation on ***B***(**GT**) distribution (HF+BCS+QRPA)

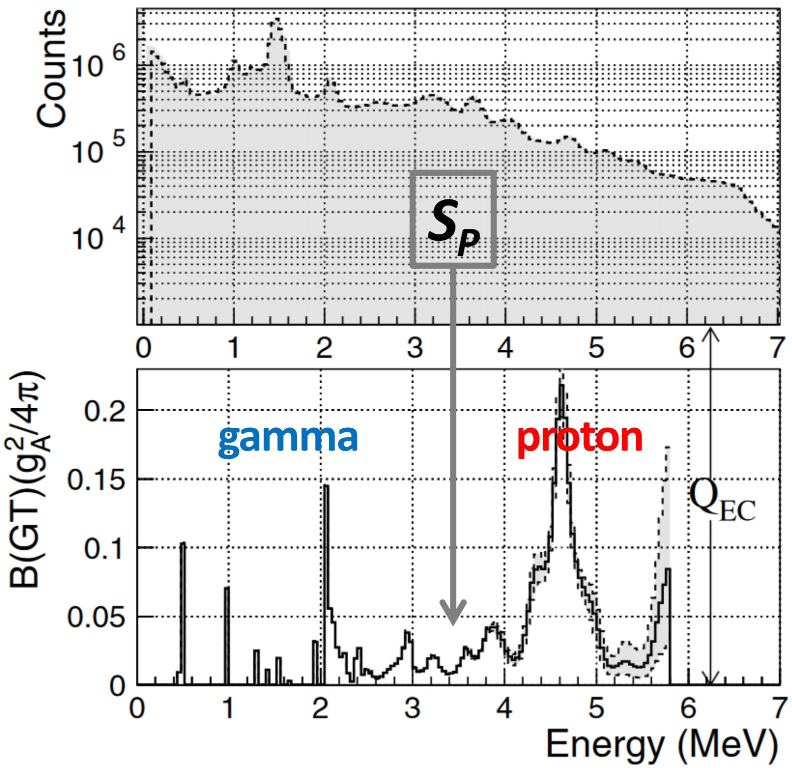


P.Sarriguren *et al.*, Phys. Rev. C64 (2001)

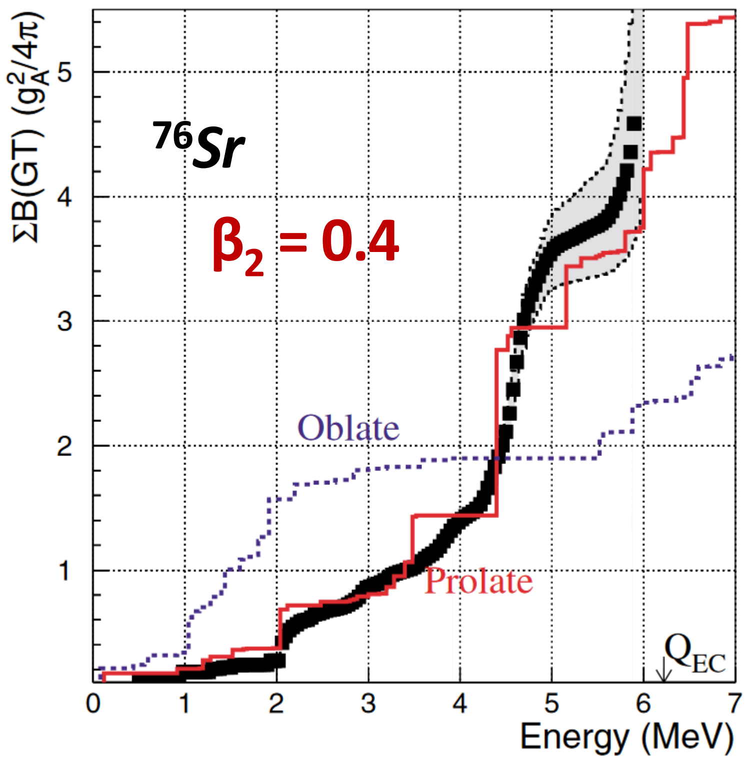


I. Hamamoto *et al.*, Z. Phys. A353 (1995)

B(GT): decay of ^{72}Kr and ^{76}Sr @ ISOLDE



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



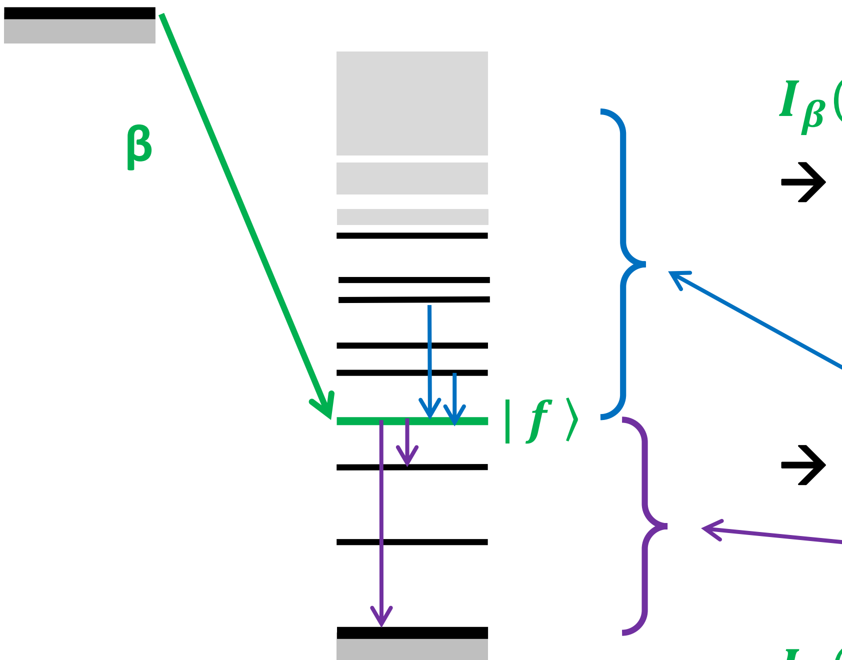
few percent only as proton emission in these cases

→ becomes more important for more exotic nuclei (A. Algora exp. @ RIKEN: $^{70,71}Kr$)

B(GT) distribution: experimental difficulties

the "pandemonium" effect (beta-gamma spectroscopy)

J.Hardy *et al.*, Phys. Lett. B71 (1977)



$I_\beta(f)$ determination

→ **transitions populating *f*:**

- direct beta feeding $I_\beta(f)$
- gamma from states fed by β at higher energy: $\sum_i I_\gamma(i \to f)$

→ **transitions depopulating *f*:**

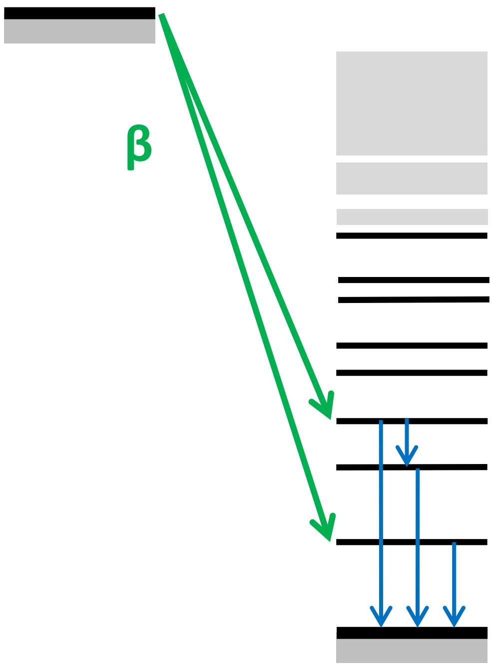
- gamma to low energy states: $\sum_j I_\gamma(f \to j)$

$$I_\beta(f) = \sum_j I_\gamma(f \to j) - \sum_i I_\gamma(i \to f)$$

B(GT) distribution: experimental difficulties

the "pandemonium" effect (beta-gamma spectroscopy)

J.Hardy *et al.*, Phys. Lett. B71 (1977)



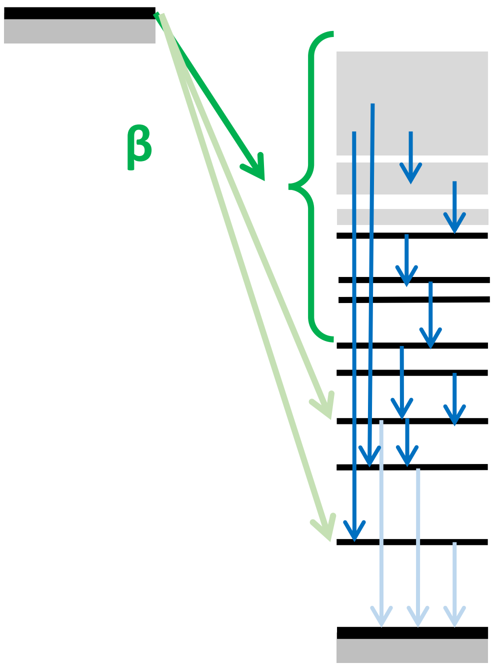
high resolution gamma spectroscopy

→ **low energy states**
- significant β feeding
- low nuclear states density
- "easily" observed

B(GT) distribution: experimental difficulties

the "pandemonium" effect (beta-gamma spectroscopy)

J.Hardy *et al.*, Phys. Lett. B71 (1977)



high resolution gamma spectroscopy

→ **low energy states**
- significant β feeding
- low nuclear states density
- "easily" observed

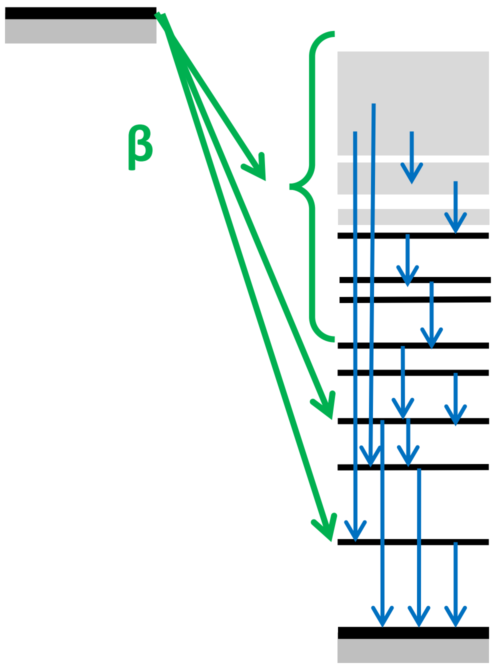
→ **high energy states**
- weak β feeding
- high level density
- gamma de-excitation:
  - few high energy gamma-rays
    → **no detection efficiency**
  - many low energy gamma-rays
    → **fragmented strength: too low intensity**

missed *B*(GT) strength at high excitation energy !!!

B(GT) distribution: experimental difficulties

the “pandemonium” effect (beta-gamma spectroscopy)

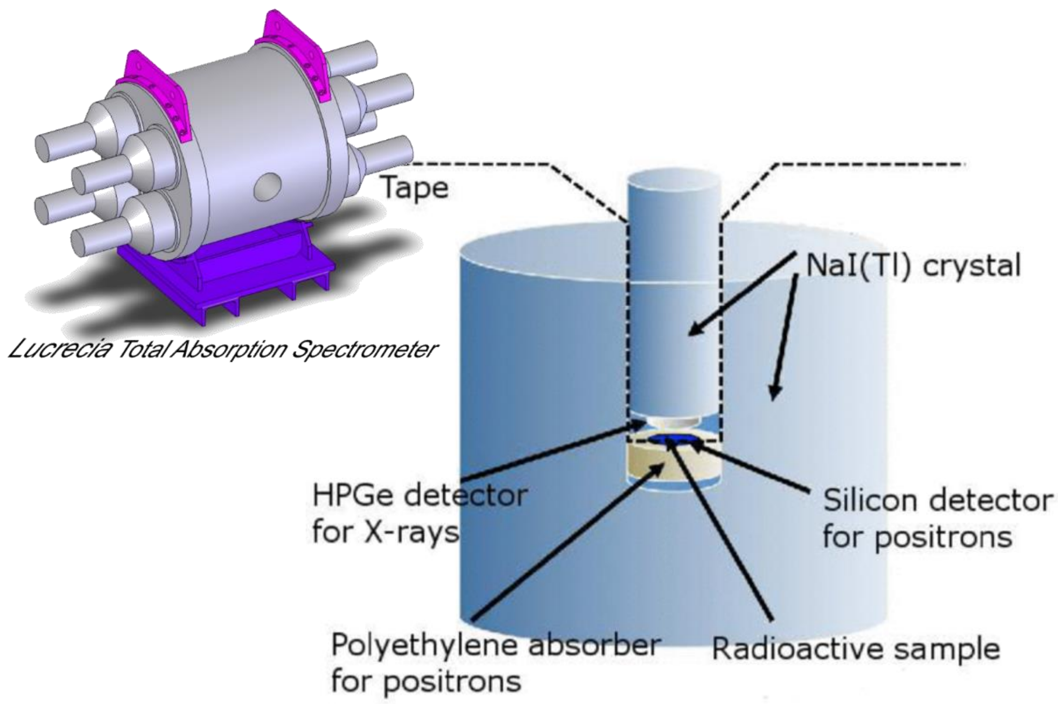
J.Hardy *et al.*, Phys. Lett. B71 (1977)



use of a total absorption spectrometer (TAS)

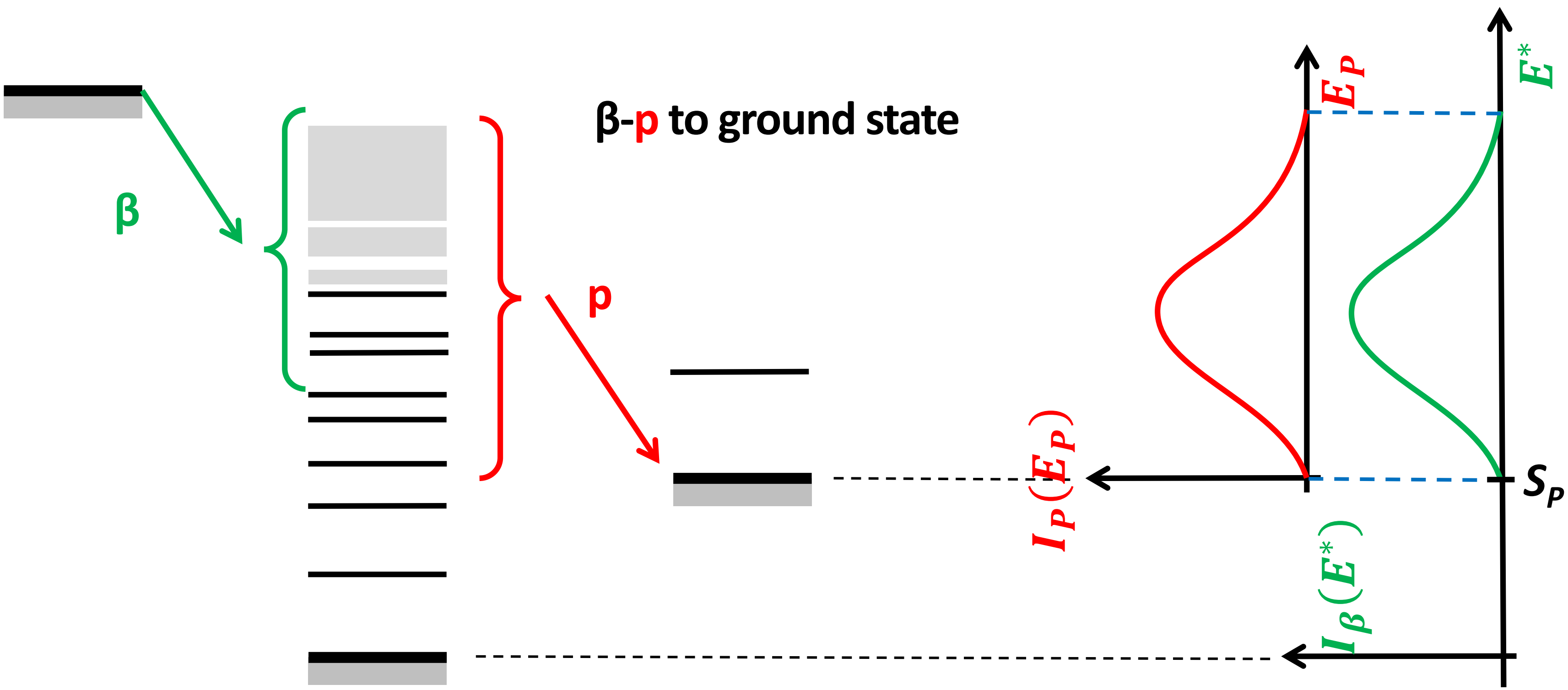
→ gamma “**calorimeter**”

→ need for additional β-*p* discrimination (telescope)

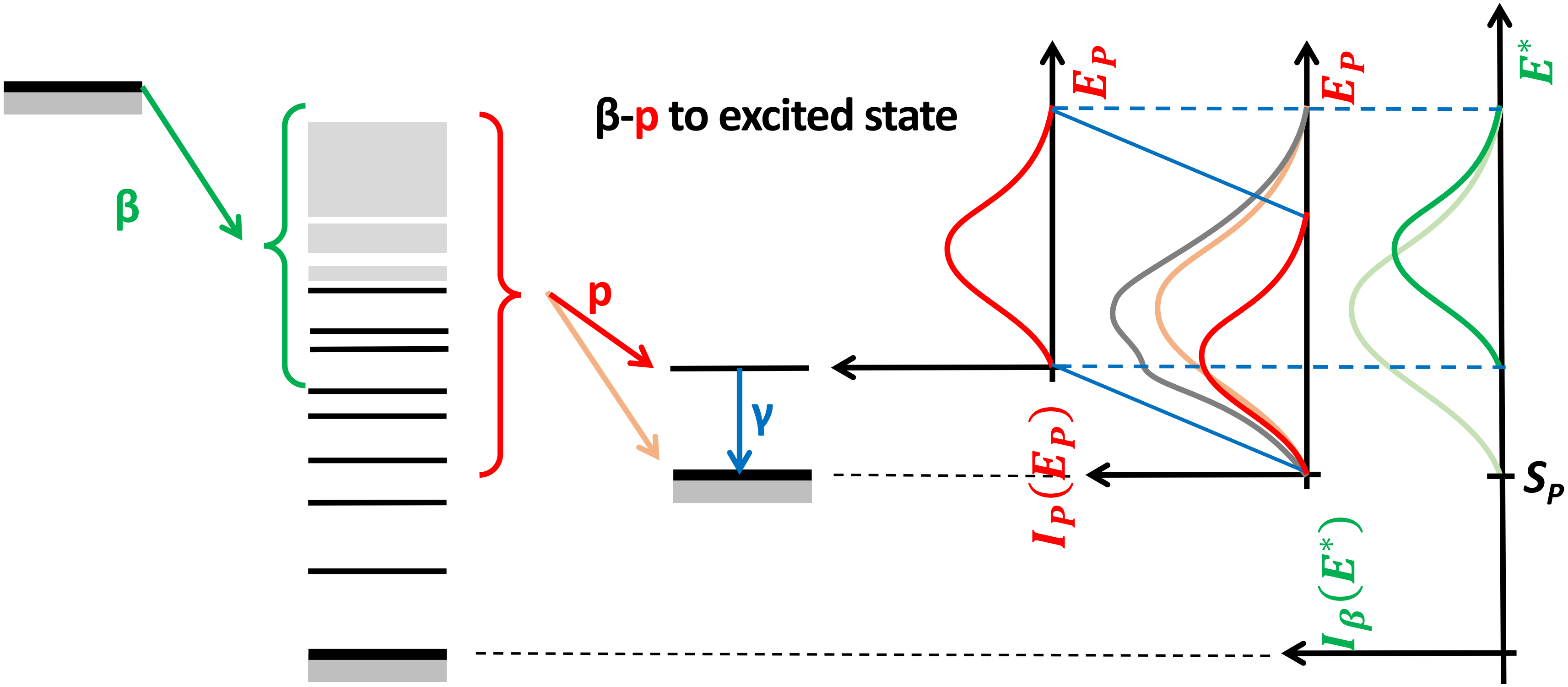


B.Rubio *et al.*, J. Phys. G: Nucl. Part. Phys. 44 (2017)

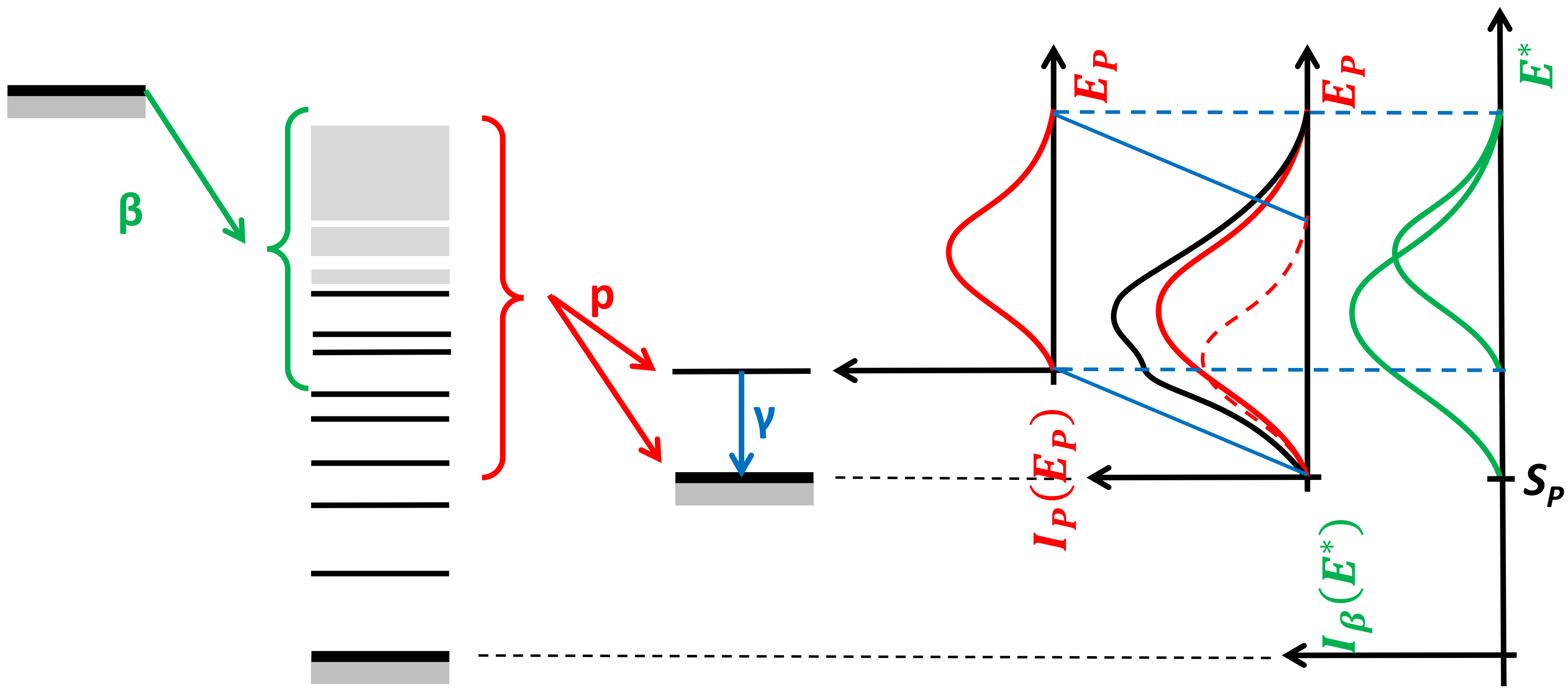
B(GT) distribution: experimental difficulties
proton emission to excited states



B(GT) distribution: experimental difficulties
proton emission to excited states



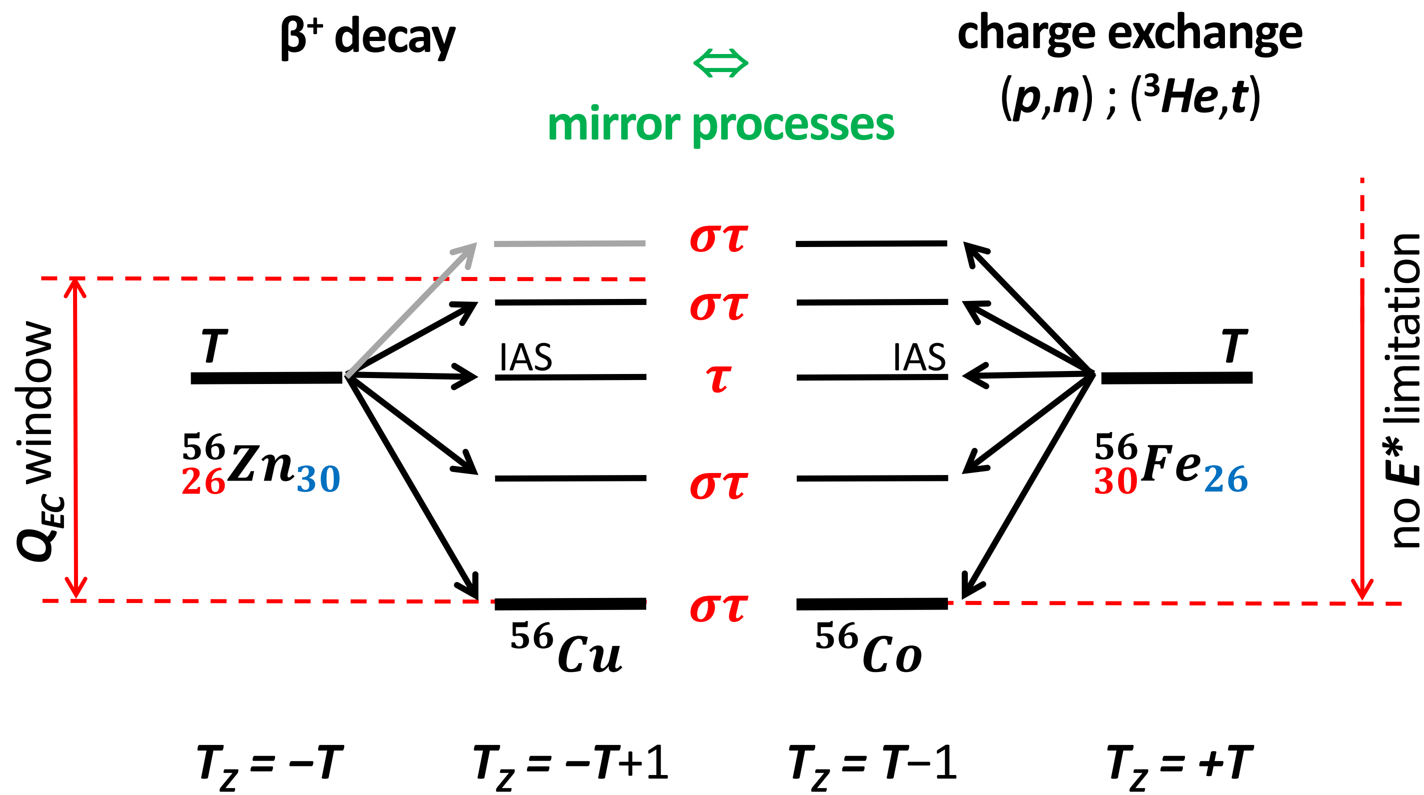
B(GT) distribution: experimental difficulties
proton emission to excited states



resolved transitions: **(β-)p-γ coincidences → OK**

high exc. energy: **need for (very) high statistics for p-γ coincidences to disentangle contributions**
(or statistical analysis → no detailed spectroscopy)

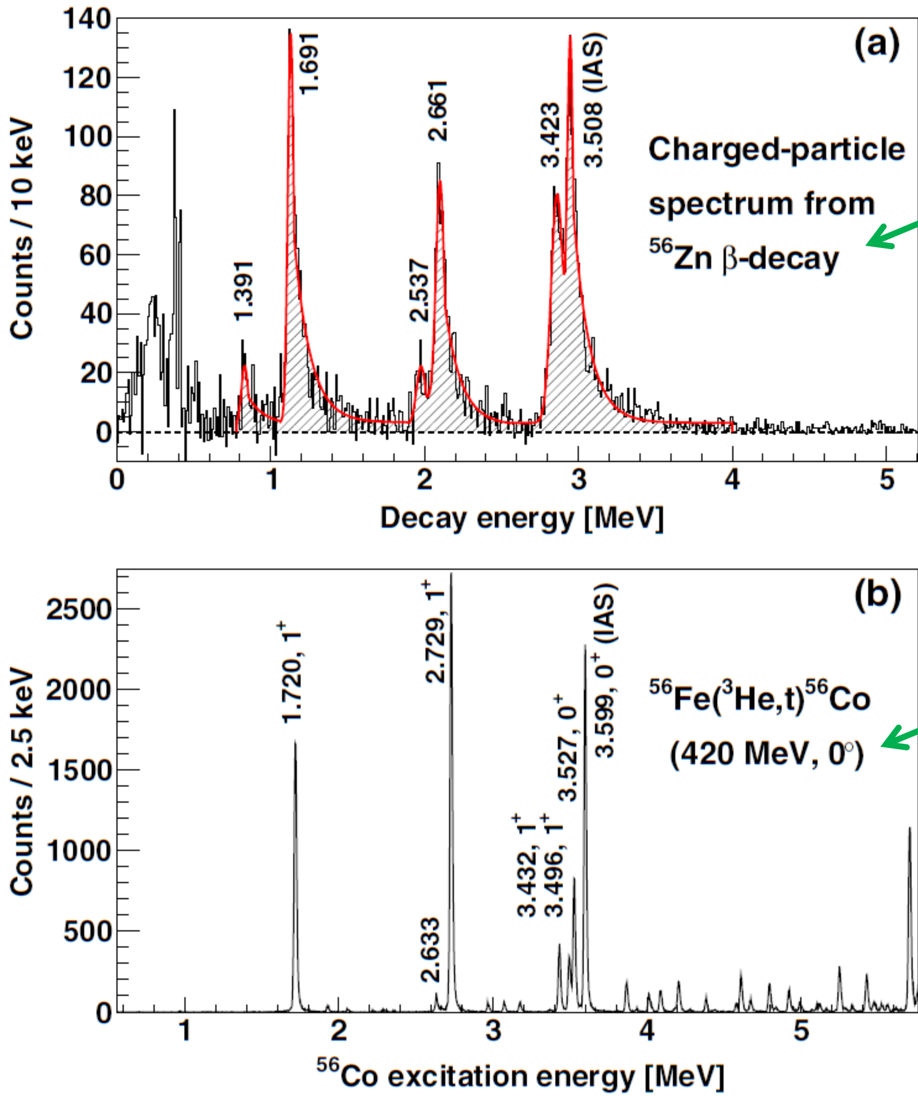
B(GT): test of isospin symmetry far from stability



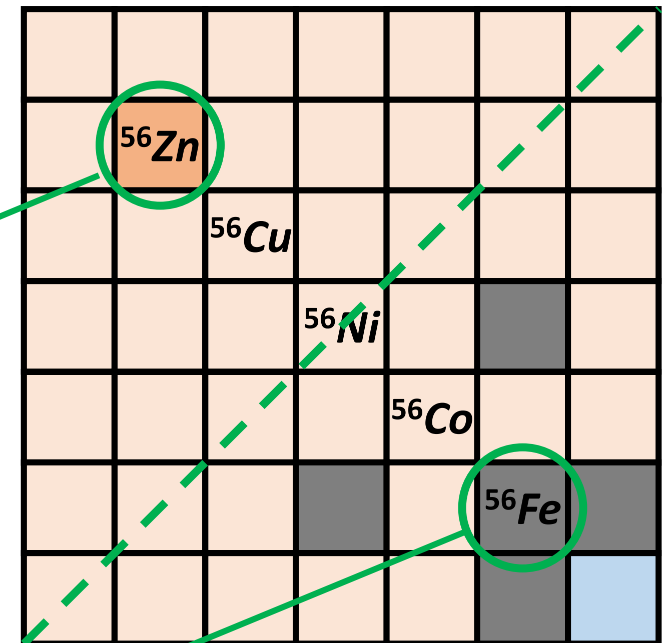
$$B(GT) \propto \frac{I_\beta(E^*)}{f(Z, Q_\beta - E^*) \cdot T_{1/2}}$$

$$B(GT) \propto \frac{\delta\sigma}{\delta\Omega}(0^\circ)$$

B(GT): test of isospin symmetry far from stability



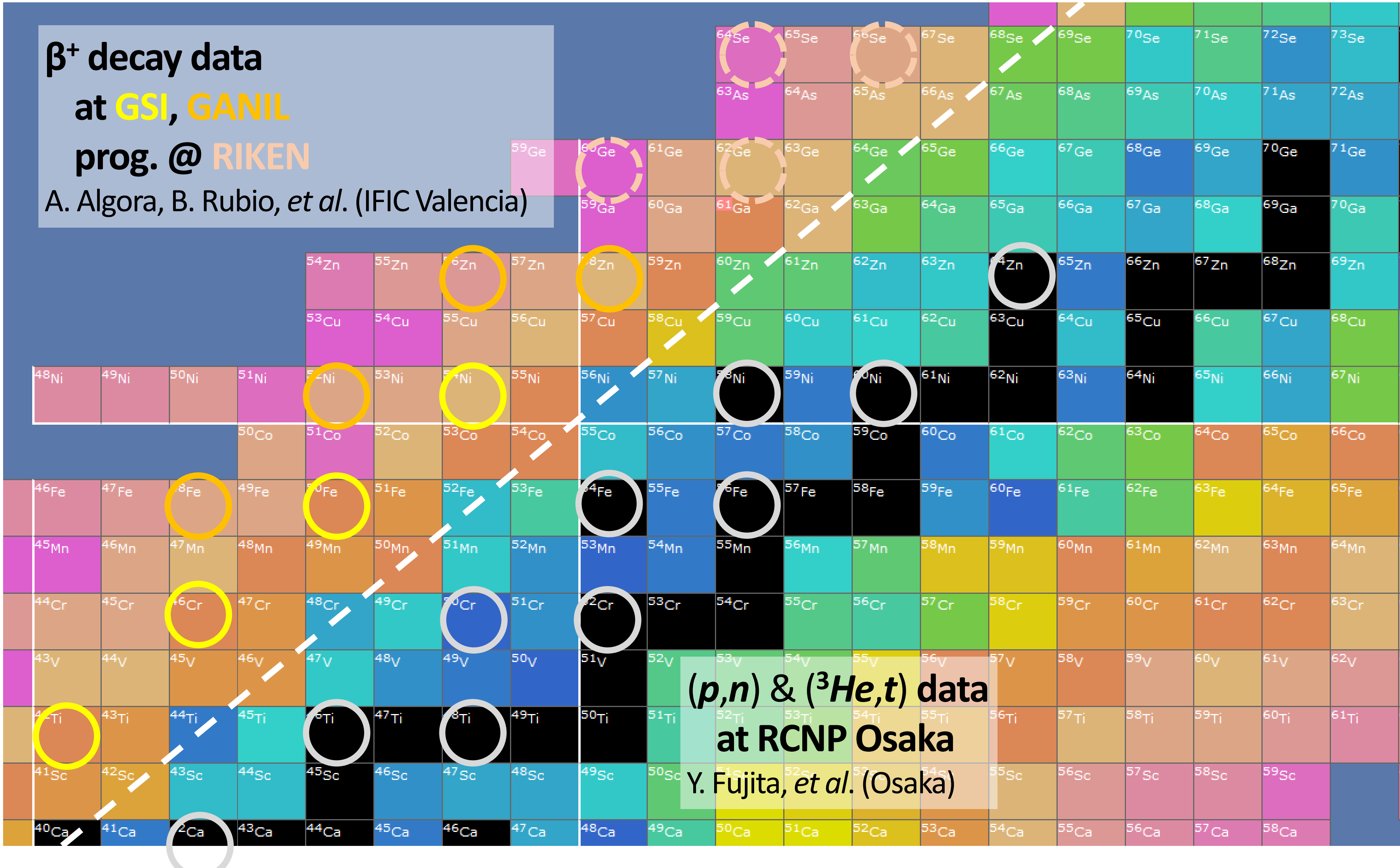
S.E.A.Orrigo *et al.*, Phys. Rev. Lett. 112 (2014)



good agreement with mirror symmetry

indication of non resolved proton transitions (close to IAS)

B(GT): test of isospin symmetry far from stability



Beta-delayed proton(s) emission

- Beta-delayed 1 proton emission
  - Fermi transition & isospin symmetry
  - β-p and Gamow-Teller strength distribution
  - **Proton emission and nuclear levels half-life**
- Beta-delayed multi-proton
  - Sequential vs direct emission
  - First experiment
  - β-2p and search for the "^{2}*He*" emission
  - Delayed multi-proton emission

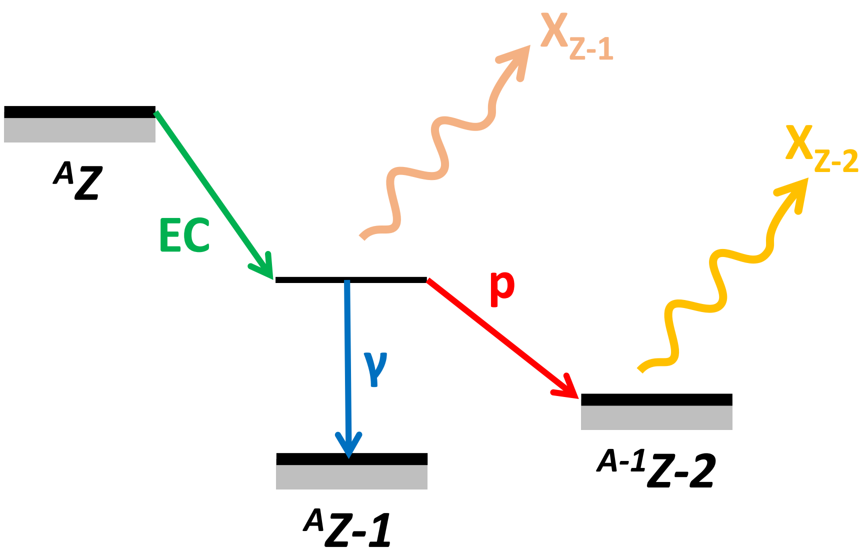
to β-2p
to WISArD

Particle – X-ray coincidence technique (PXCT)

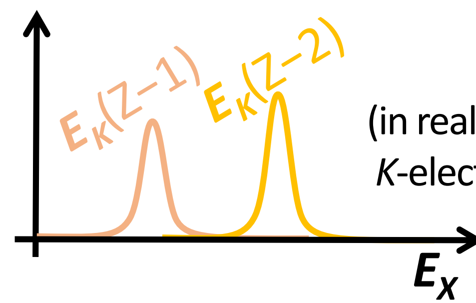
proposed by J.C. Hardy (PRL 37, 1976)

very elegant technique, despite not much used

→ ***X***-ray emission from atomic rearrangement after electron capture



X-ray energy depends on the element (***Z***)



(in reality, not only *K*-electrons)

Particle – X-ray coincidence technique (PXCT)

proposed by J.C. Hardy (PRL 37, 1976)

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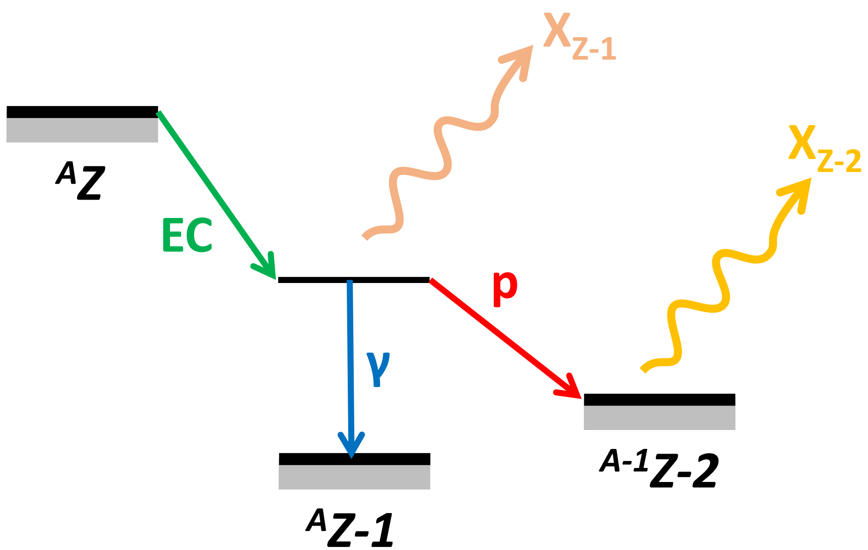
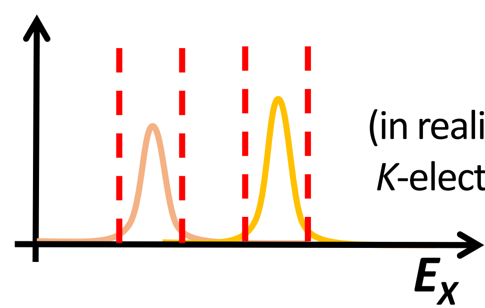
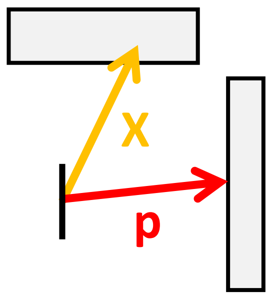
→ ***X***-ray emission from atomic rearrangement after electron capture



X-ray energy depends on the element (***Z***)



proton - ***X***-rays coincidence measurement



with E_X gates on E_P distribution:

$$R_X(E_P) = \frac{N(E_P)_{Z-2}}{N(E_P)_{Z-1}}$$

Particle – X-ray coincidence technique (PXCT)

$$R_X(E_P) = \frac{N(E_P)_{Z-2}}{N(E_P)_{Z-1}}$$

→ depends if proton emission is faster than atomic rearrangement

→ known atomic process (atomic data tables) in the range **~2^−15** *s* (carbon) to **~6^−18** *s* (uranium)

comparable with (some) **proton emission from nuclear states**
(depends on energy, angular momentum…)

probability analysis of processes order

(1) ***EC*** – **γ** → ***X***(***Z***–1) ; no proton detected
(2) ***EC*** (– ***X***) – **p** → ***X***(***Z***–1) with proton
(3) ***EC*** – **p** (– ***X***) → ***X***(***Z***–2) with proton

$$N(E_P)_{Z-1} = N(E_P)_0 \cdot \frac{\Gamma_X}{\Gamma_P+\Gamma_\gamma+\Gamma_X} \cdot \frac{\Gamma_P}{\Gamma_P+\Gamma_\gamma}$$

$$N(E_P)_{Z-2} = N(E_P)_0 \cdot \frac{\Gamma_P}{\Gamma_P+\Gamma_\gamma+\Gamma_X}$$

$$R_X(E_P) = \frac{\Gamma_P + \Gamma_\gamma}{\Gamma_X} = \frac{\tau_X}{\tau_{nuc}}$$

Particle – X-ray coincidence technique (PXCT)

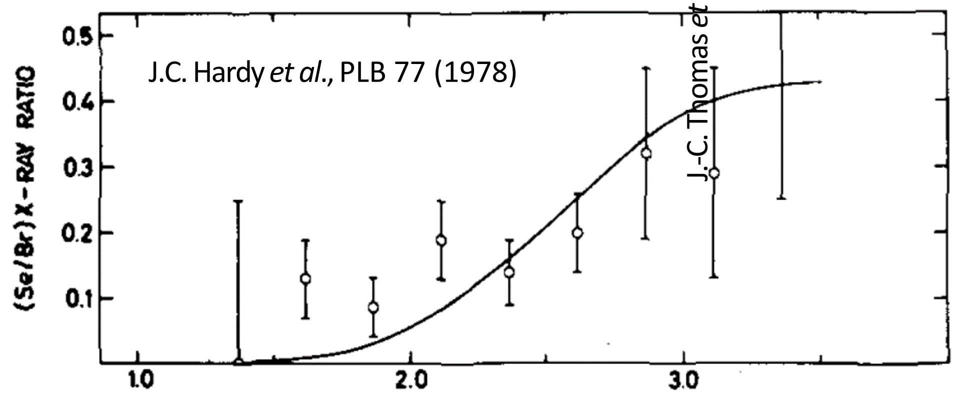
for resolved states → direct measurement of the nuclear lifetime

for unresolved states → average behavior

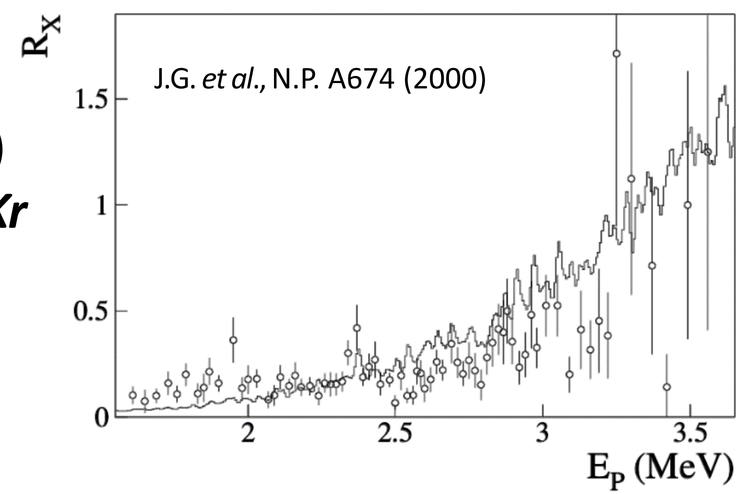
statistical model analysis, sensitive to
- level density parameter
- proton / gamma width models

applied in A ~ 70 mass region
(for $T_Z = 1/2$ → only GT)

J.-C. Thomas *et al.*, EPJA (2004)



***N_X*(⁷²*Se*) / *N_X*(⁷³*Br*)** → $N_X(^{72}Se) / N_X(^{73}Br)$
in β-p decay of ^{73}Kr

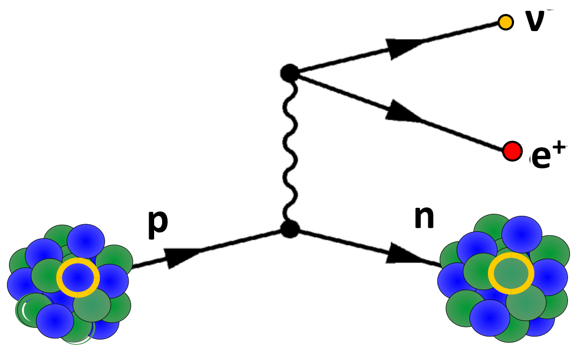


to WISArD

Additional selected topics

- **Delayed proton emission to test weak interaction**
- ACTAR TPC

Weak interaction currents



general form of the β⁺ hamiltonien

$$H_{\beta^+} \sim \sum C_i(\bar{u}_p O_i u_n)\left(\bar{u}_e O_i \left[1 - \frac{C'_i}{C_i}\gamma_5\right] u_\nu\right)$$

5 types of operators to satisfy Lorentz invariance

S	scalar	1	
V	**vector**	γ_i	γ_i the Dirac matrices
T	tensor	σ_{ij}	$\sigma_{ij} = \frac{1}{2}(\gamma_i\gamma_j - \gamma_j\gamma_i)$
A	**axial-vector**	$\gamma_5\gamma_i$	
P	pseudo-scalar	γ_5	→ 0 in non relat. limit

only V & A in standard model
→ explains observations

see lecture from E. Liénard

existence of weak currents (S, T) ?
(beyond standard model)

beta-neutrino angular distribution

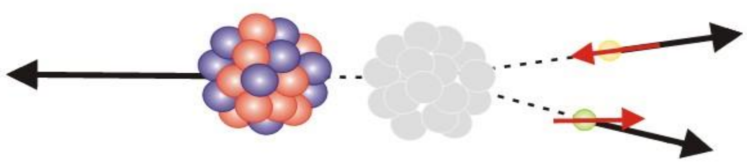
pure Fermi transition: Vector (standard model) / Scalar (beyond SM)

different beta-neutrino angular distributions

vector

favors small β-ν angle

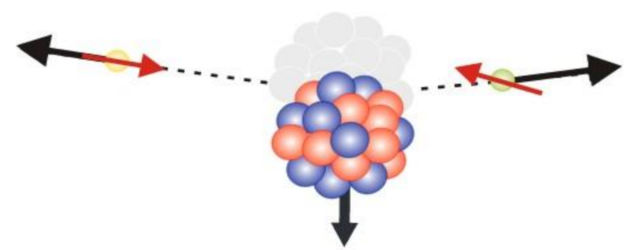
large nucleus recoil



scalar

favors large β-ν angle

small nucleus recoil

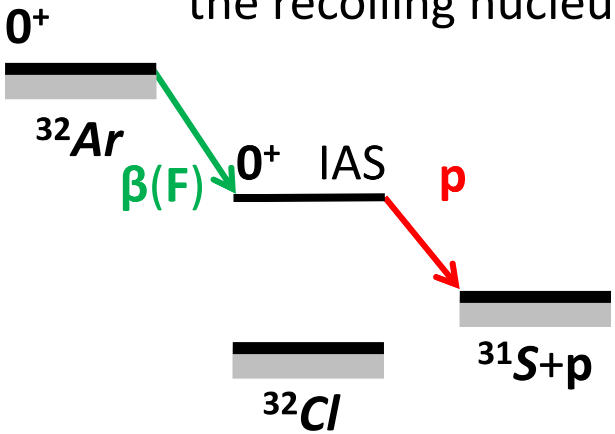


measure β-ν angle → difficult !!!

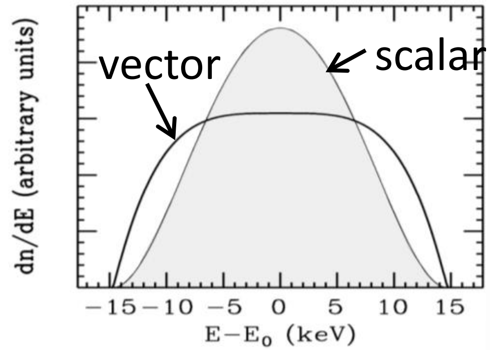
- beta-recoil angular distribution (in traps)
- alternative: beta-delayed proton

beta-delayed protons to test weak interaction

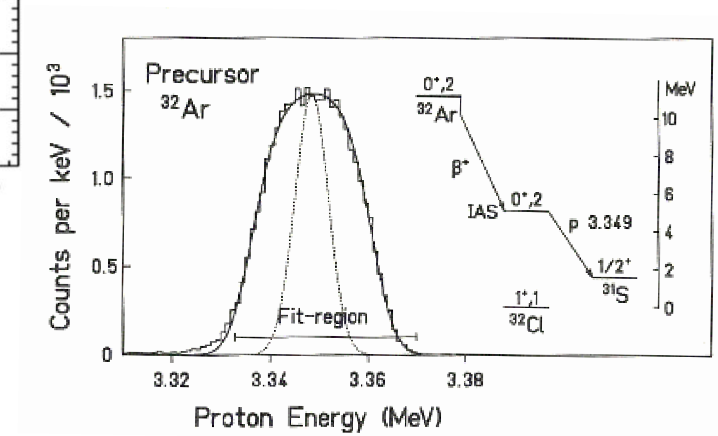
proton emitted from
the recoiling nucleus → **affects the proton peak shape**



Adelberger *et al.*, PRL 83 (1999)

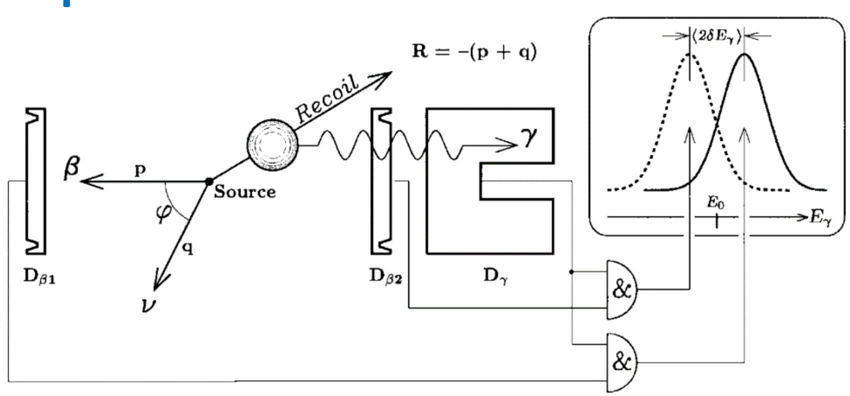


search for a **scalar fraction** contribution in dominating vector contribution



D. Schardt, K. Riisager, Z. Physik A (1993)

→ **peak shift**



shift measurement: higher sensitivity

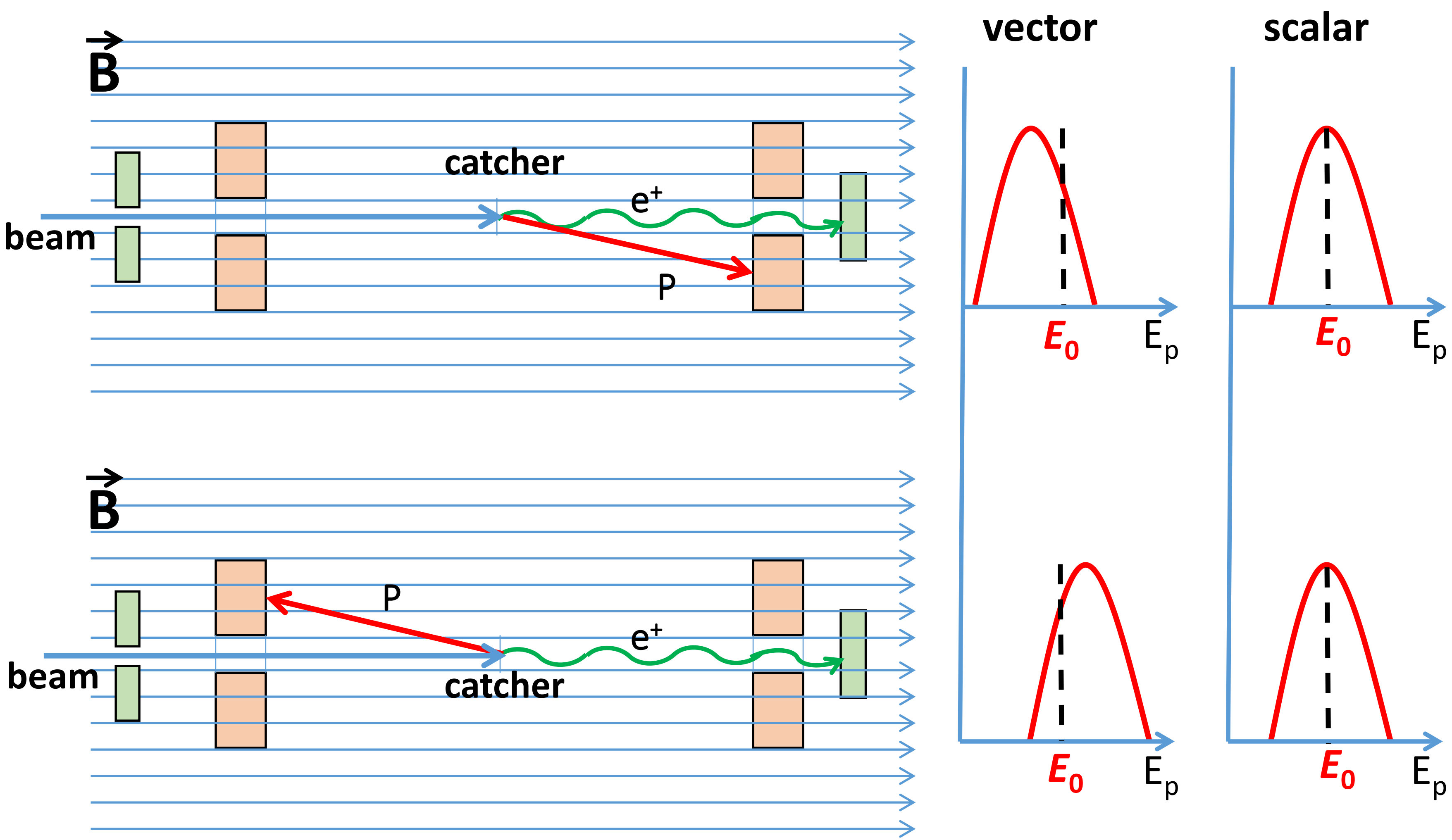
prev. studies: Doppler shift in β-γ

^{18}*Ne* (V. Egorov et al., NP A621, 1997

^{14}*O* (V. Vorobel, Eur. Phys. J A 16, 2003)

⇨ **upper limit for scalar current**

Proton energy shift measurement: WISArD project



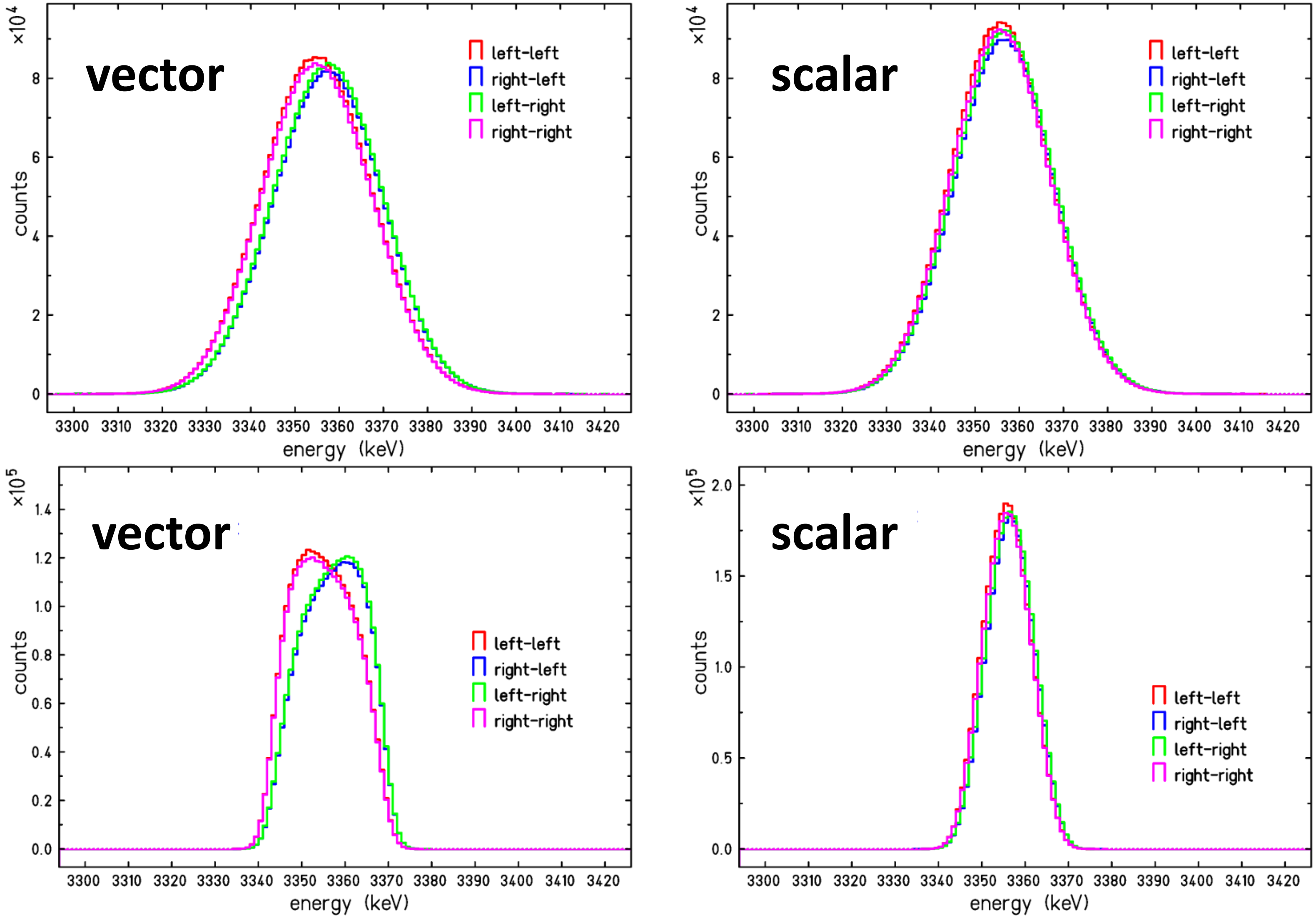
coll. Bordeaux, Leuven, Caen, Prague - ISOLDE proposal

Challenge: energy resolution

simulation

FWHM = 10 *keV*

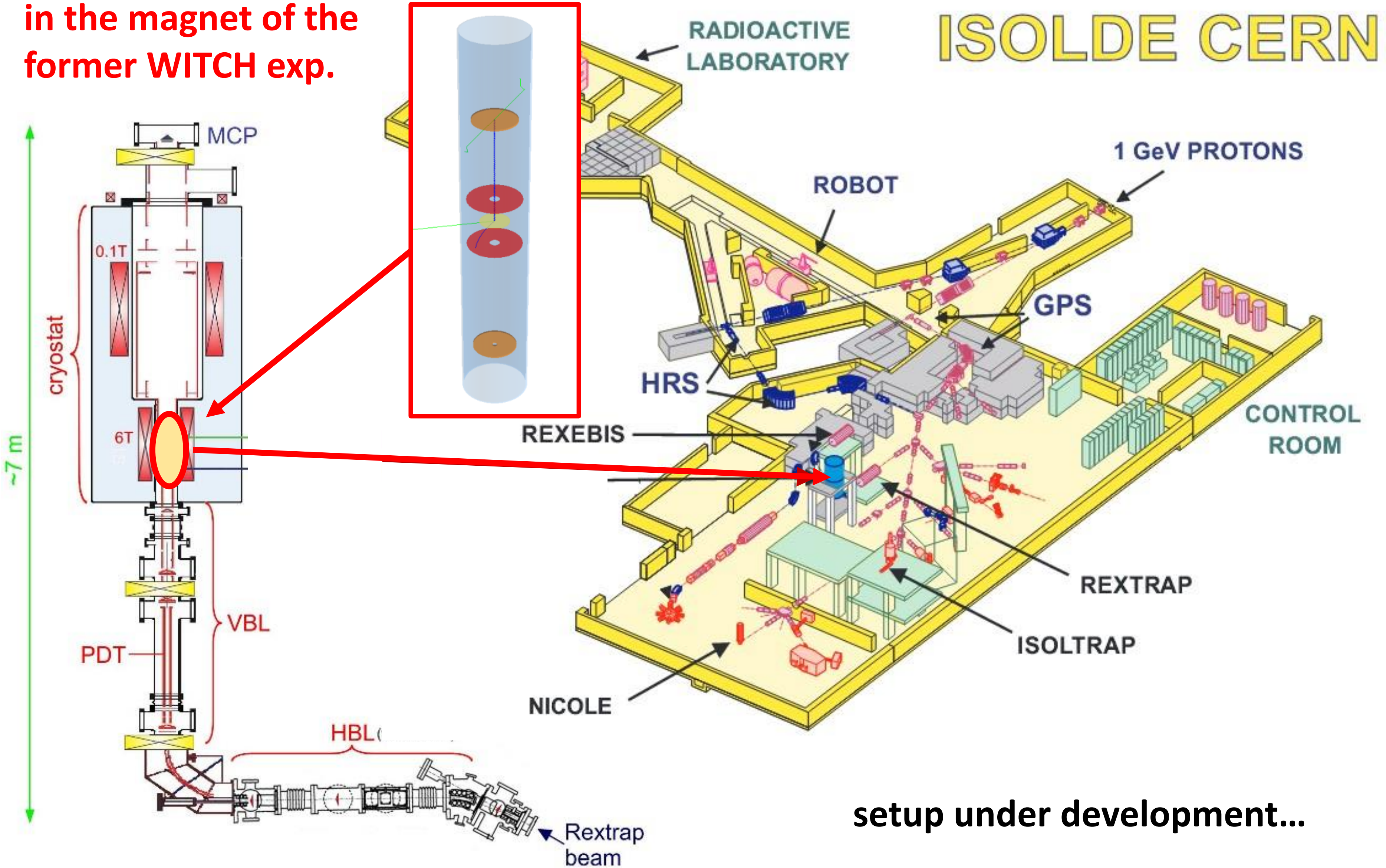
FWHM = 2 *keV*



B. Blank, J.G..

WISArD at ISOLDE

in the magnet of the former WITCH exp.

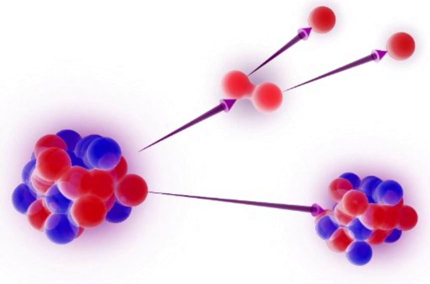


setup under development…

Proton emission in radioactive decay

experimental studies

second session



Beta-delayed proton(s) emission

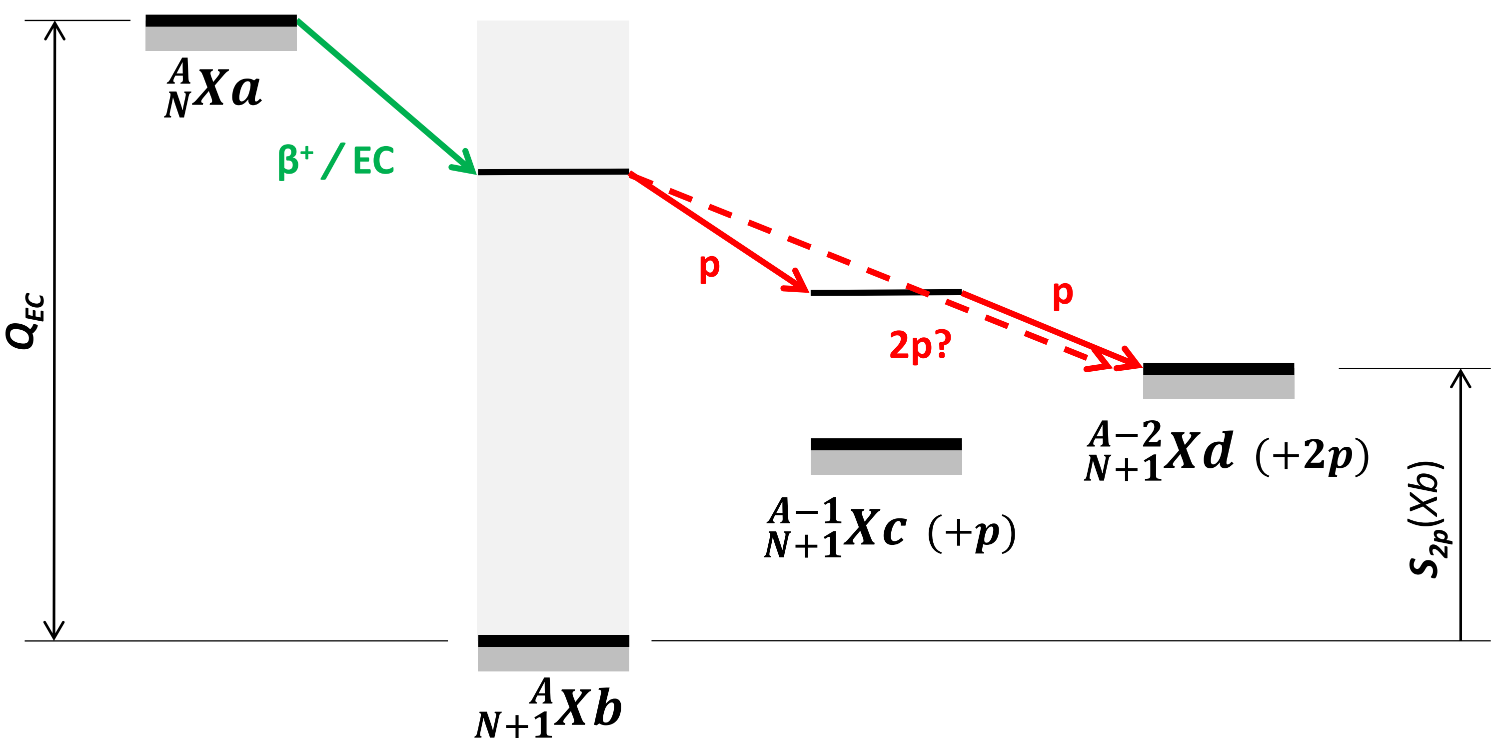
- Beta-delayed 1 proton emission
  - Fermi transition & isospin symmetry
  - β-p and Gamow-Teller strength distribution
  - Proton emission and nuclear levels half-life
- **Beta-delayed multi-proton**
  - Delayed 2-proton emission scheme
  - Experimental search for the delayed *"^{2}He"* emission
  - Delayed multi-proton emission

Beta-delayed 2-proton emission

nuclear structure: similar to β-1p…
(fewer cases, less statistics)

large Q_{EC} to populate states at high enough E^*
→ very neutron deficient nuclei (low S_p & S_{2p})

→ focus on sequential versus direct 2p (or "²He") emission

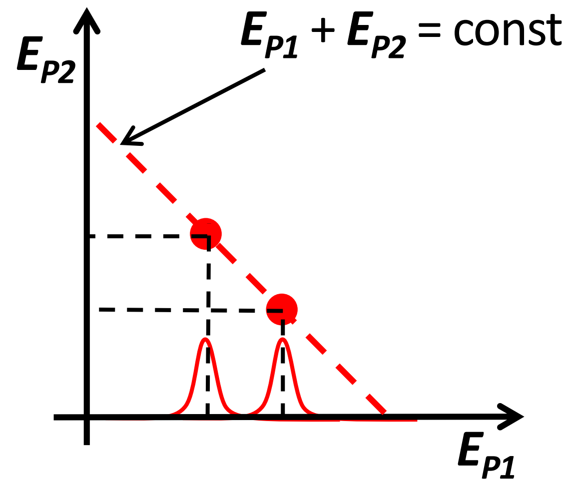


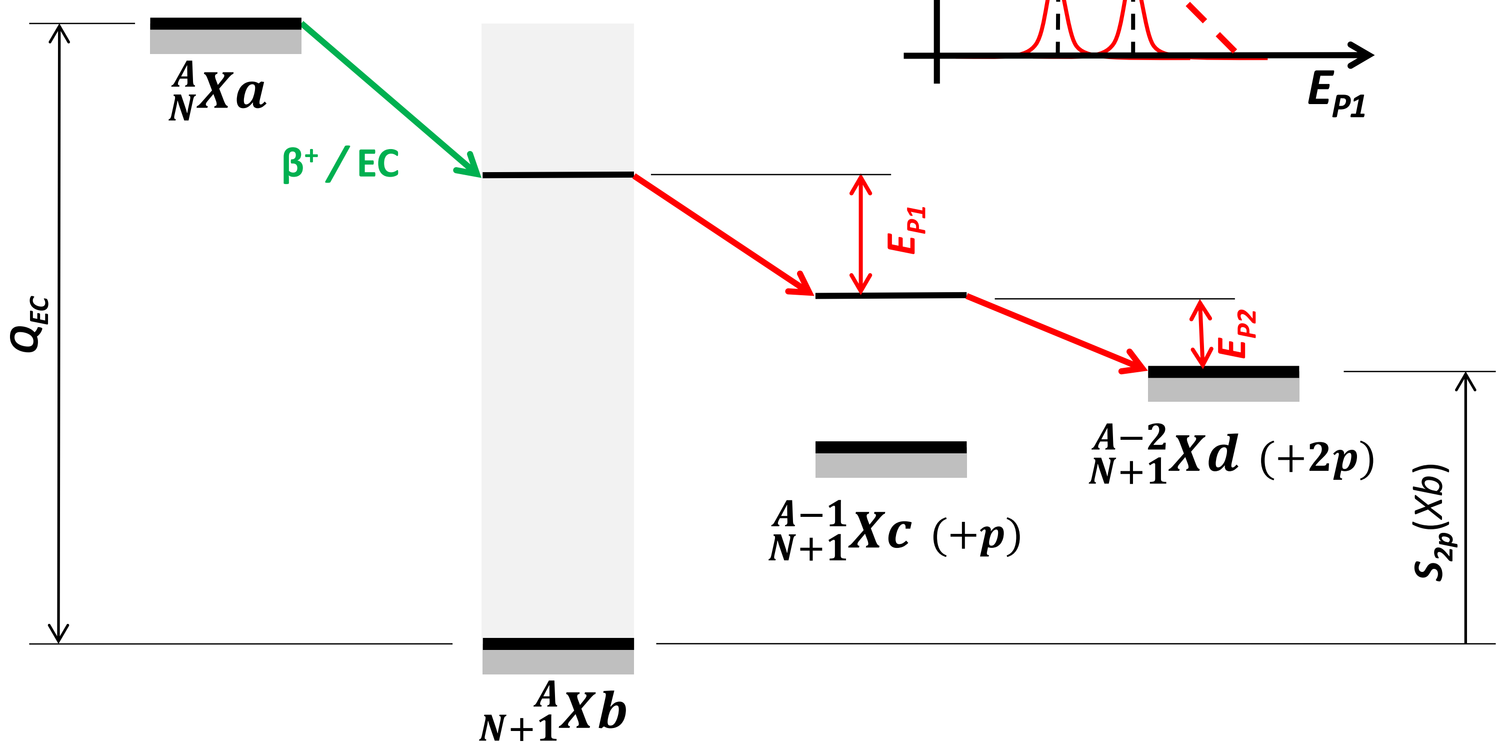
Sequential vs. direct 2P emission

sequential emission

- intermediate state
- well defined transition energies: E_{P1} & E_{P2}

  (+ kinematic shift: 2nd proton emitted from recoiling nucleus)



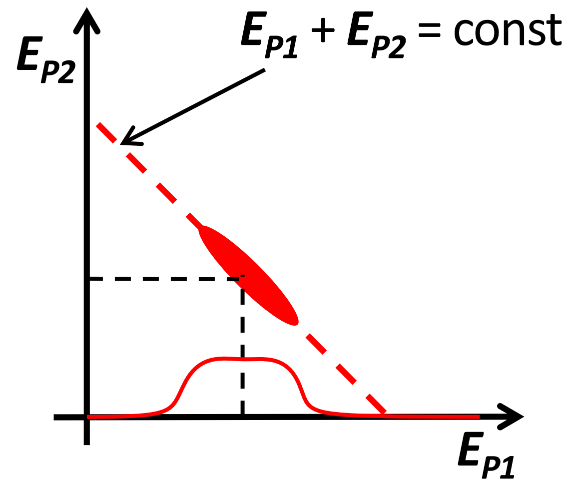


Sequential vs. direct 2P emission

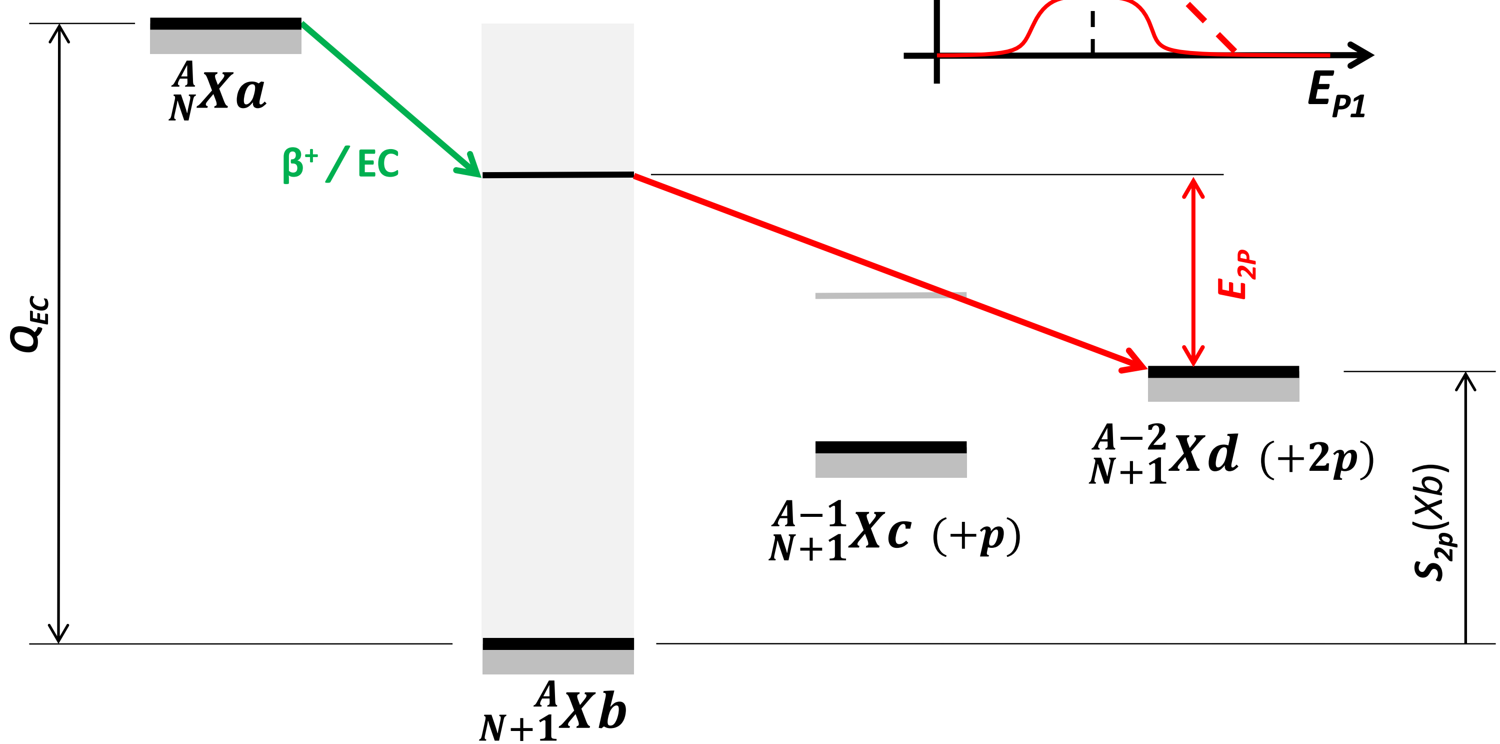
direct 2p emission ("^{2}He")

- not via intermediate state
- total energy (E_{2P}) sharing: $E_{P1} \sim E_{P2}$

angular and energy correlations ?



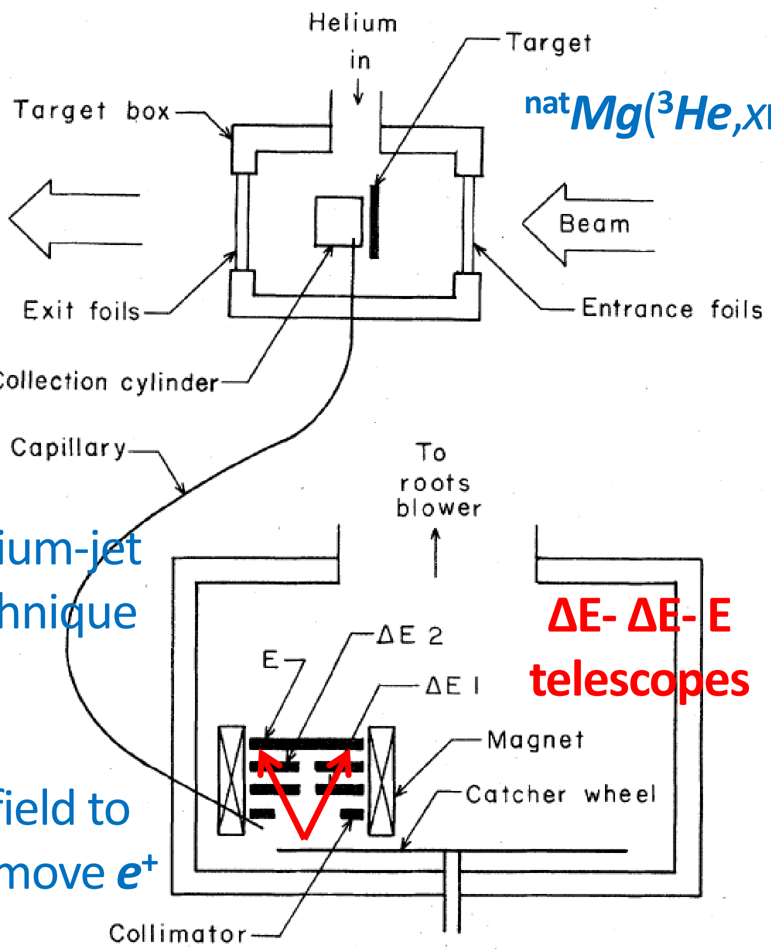
see discussion on 2P radioactivity



^{22}Al experiment

Cable *et al.*, PRL 50 (1983), PRC 30 (1984)

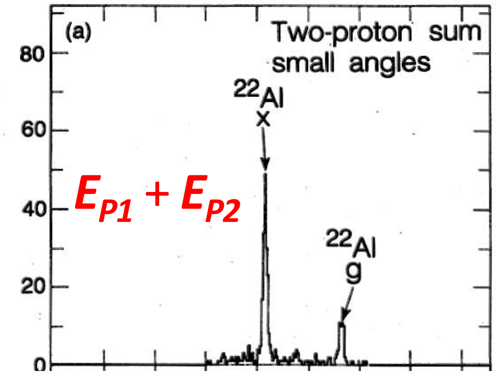
$^{nat}Mg(^{3}He,xn)^{22}Al$



helium-jet technique

B field to remove e^+

ΔE- ΔE- E telescopes



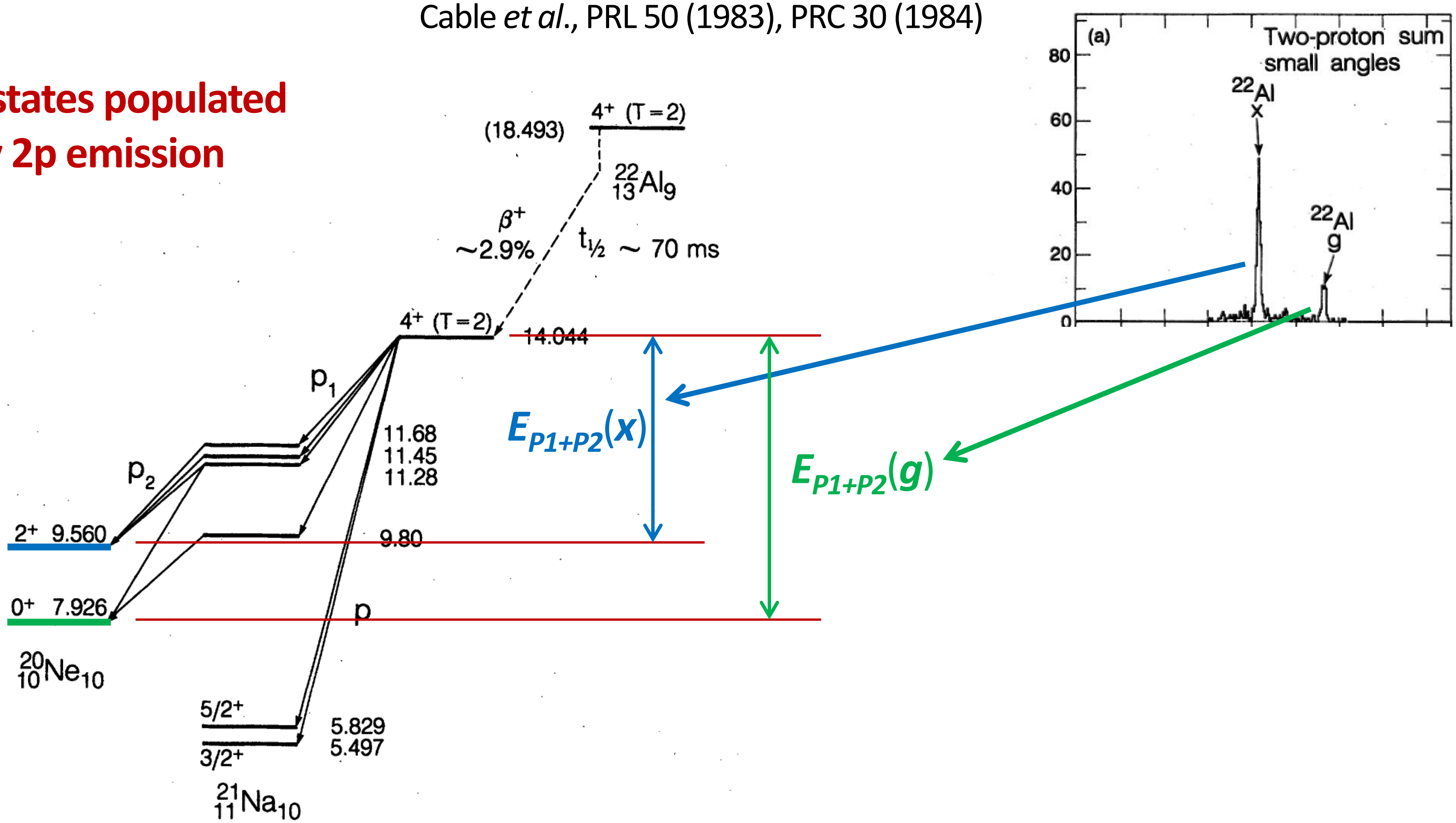
$E_{P1} + E_{P2}$

events with 2 protons

^{22}*Al* experiment

Cable *et al.*, PRL 50 (1983), PRC 30 (1984)

2 states populated by 2p emission

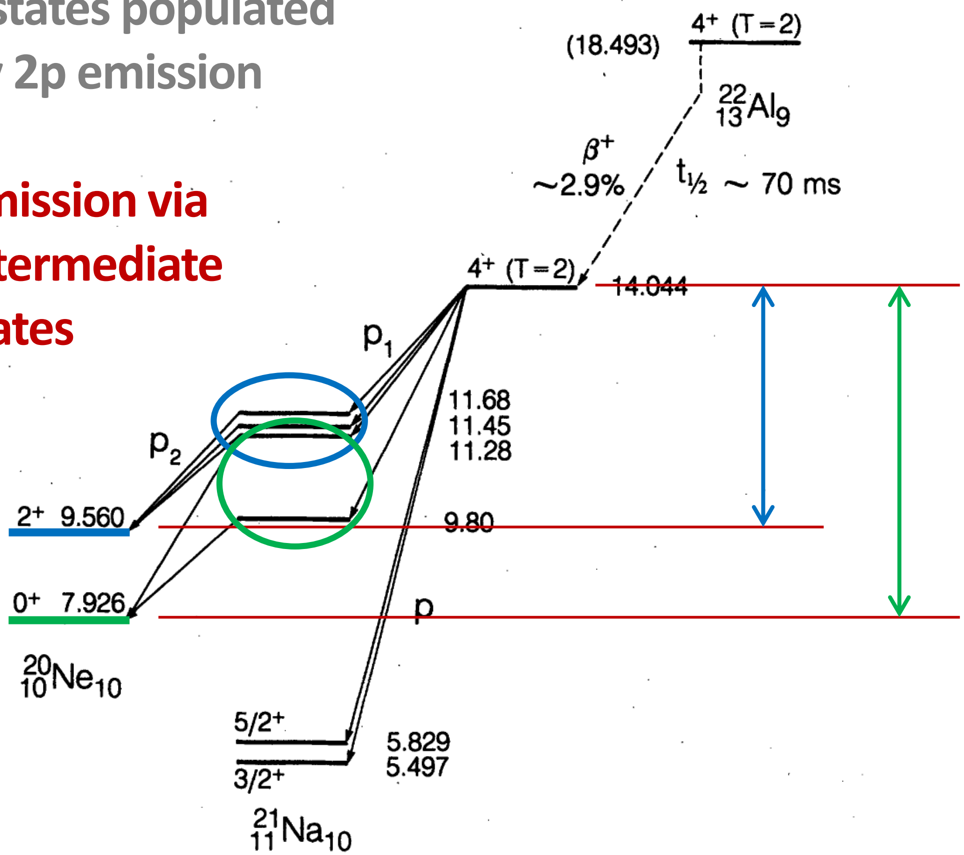


^{22}*Al* experiment

Cable *et al.*, PRL 50 (1983), PRC 30 (1984)

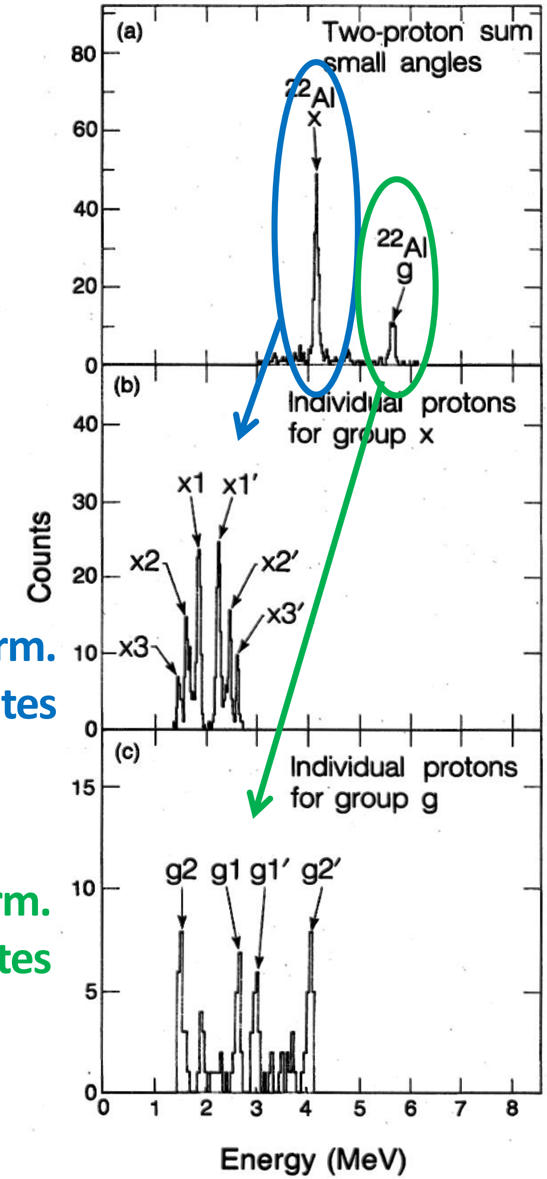
2 states populated by 2p emission

emission via intermediate states



3 interm. states

2 interm. states



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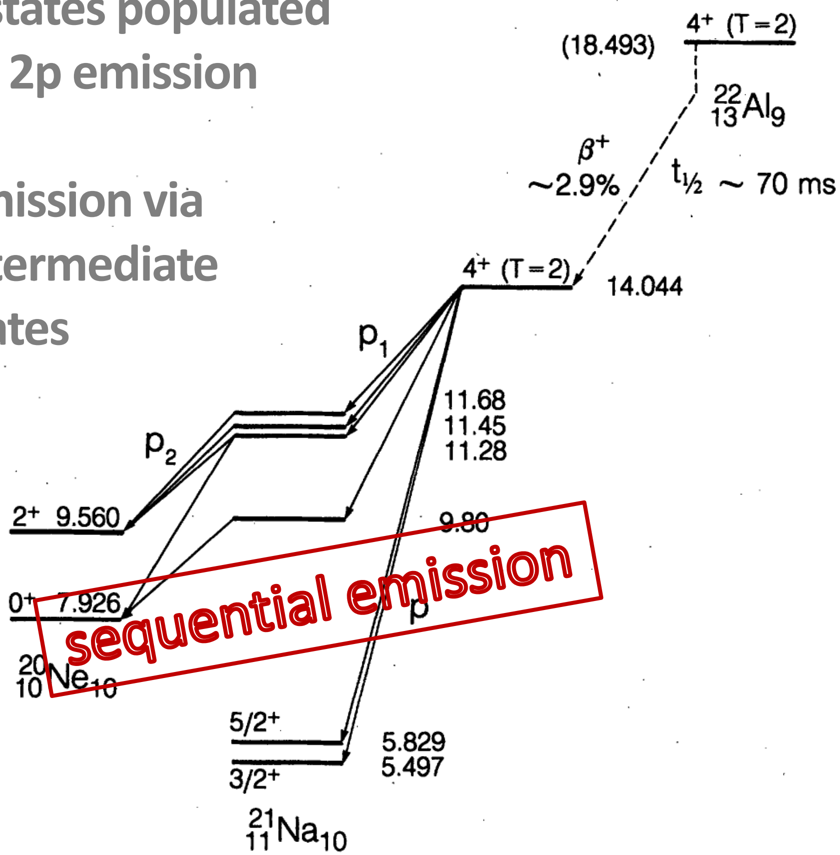
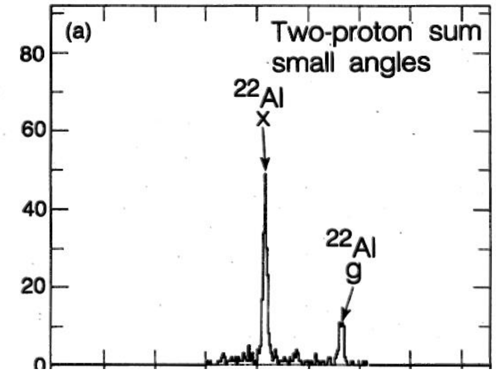
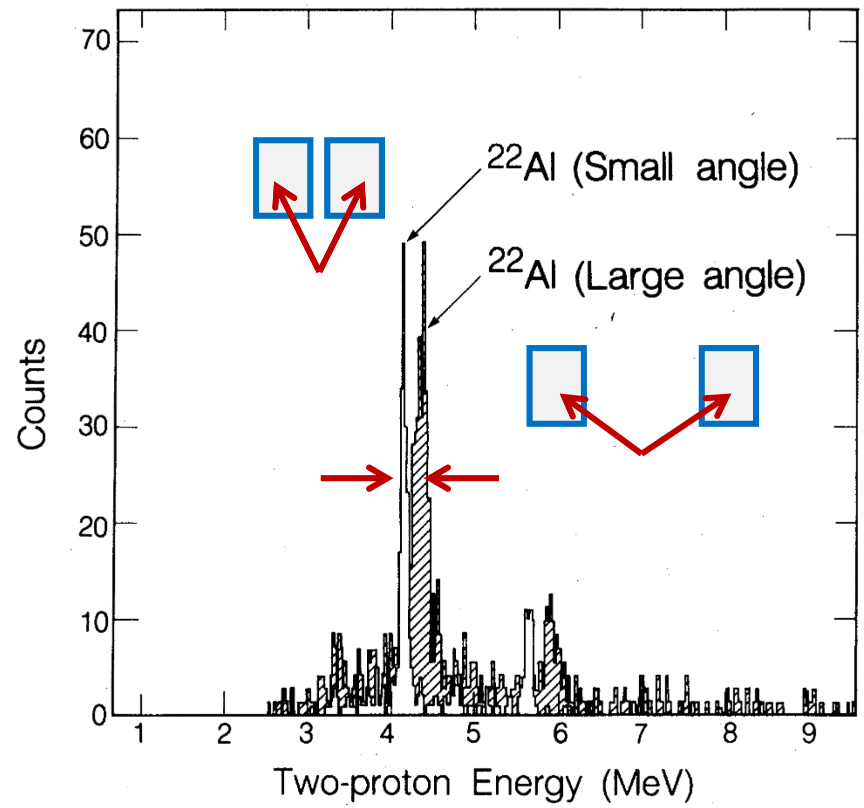


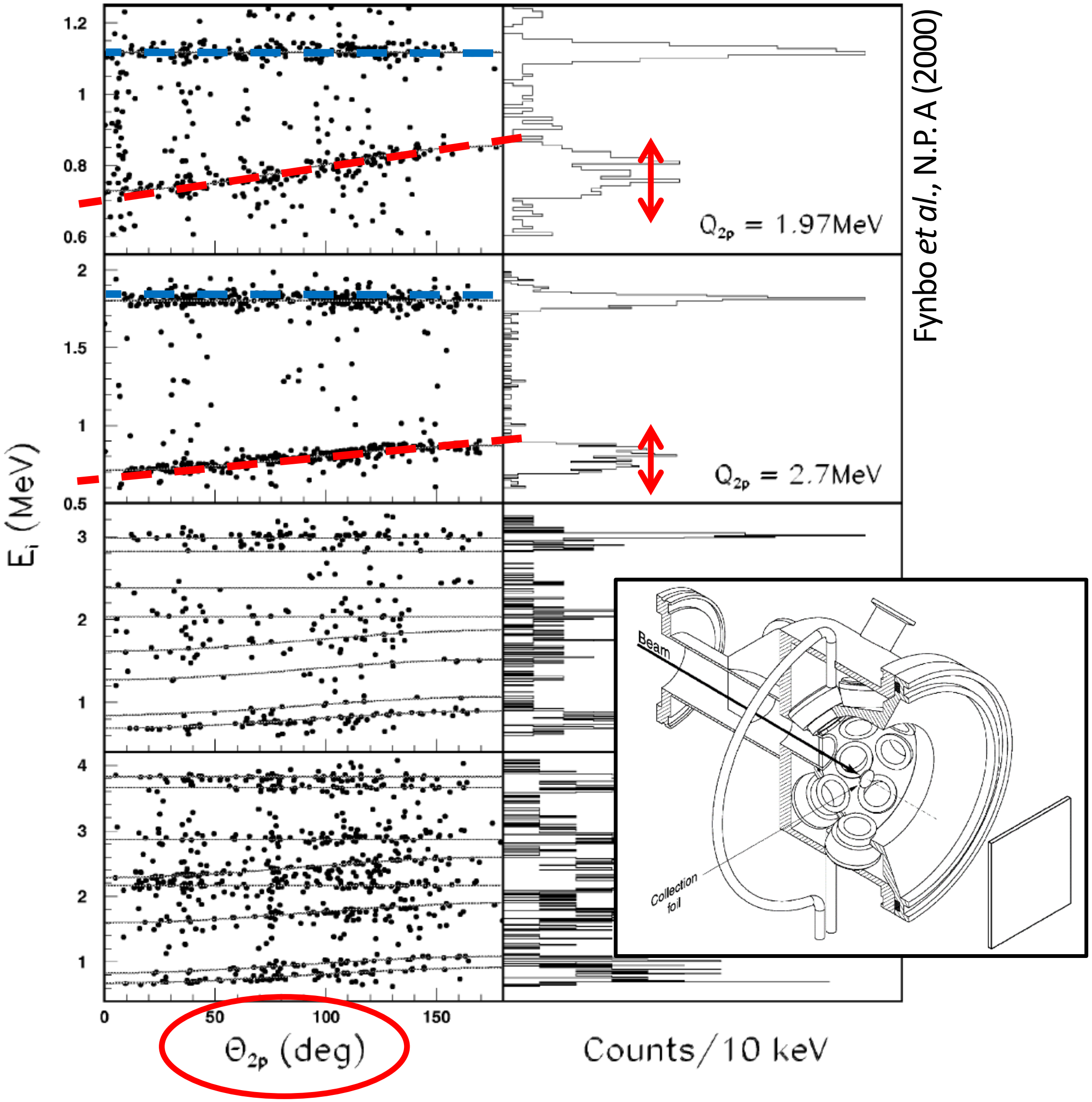




2 detection config.: small & large angles

→ kinematic shift

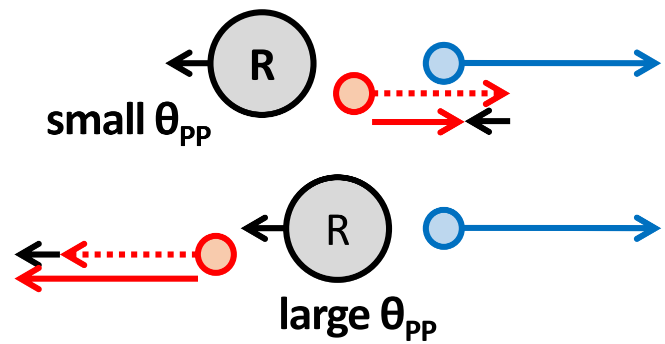
^{31}*Ar* beta-2p decay



^{31}*Ar*, the most studied case

exp. at ISOLDE:

variation of 2nd P energy with θ_{PP} due to recoil



→ broadening of peak

sequential emission

beta-^{2}He emission

direct 2p emission has never been observed experimentally

- several cases: ^{22}Al, ^{26}P, ^{31}Ar, ^{35}Ca, ^{39}Ti, ^{43}Cr, ^{45}Fe, ...
  sequential emission or too low statistics
- few % of the 2P branching expected (B.A. Brown, PRL 65,1990)
  (for ^{22}Al, 1~1.5 % expected)

search for best cases

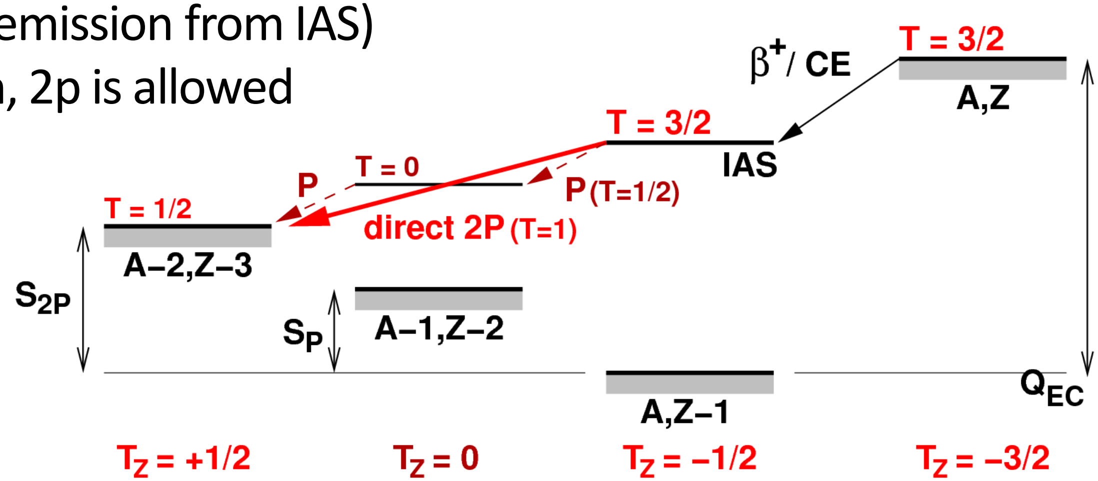
→ **no intermediate state available**

2P as only decay channel: no 1P (sequential) competition
ideal, but very unlikely for candidate nuclei...

→ **β-2p** of $T_z = -3/2$ nuclei (emission from IAS)

1p is isospin forbidden, 2p is allowed

light nuclei
not exotic enough
heavier (^{61}Ge...)
$S_{2P} > E_{IAS}$



beta-^{2}*He* emission: further studies

search for "^{2}He" emission

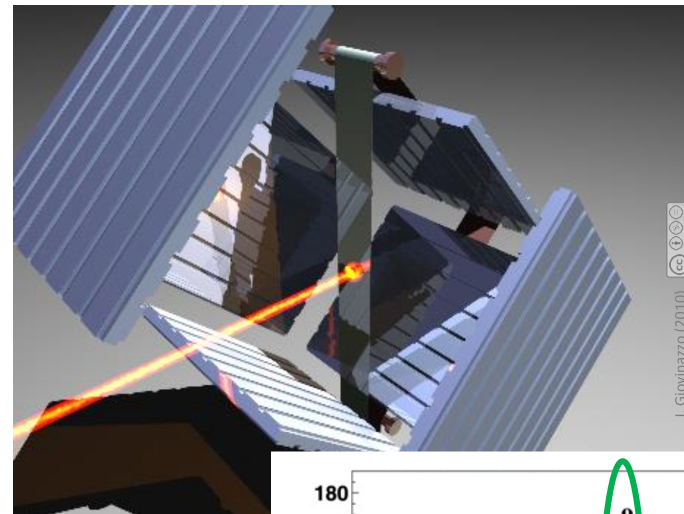
signature of the emission: possible with a simple experimental set-up

angular correlations: dedicated set-up

I_{2P} ~few % ; I_{2He} / I_{2P} ~1 % ; ε_{2P}

⇨ ≥ **10^5** nuclei for signature

⇨ ≥ **10^6** nuclei for angular distribution



at ISOL facilities

high granularity: direct multiplicity

efficiency: ε_{1P}~60 % ; ε_{2P}~35 %

(not uniform with θ_{PP} → simulations)

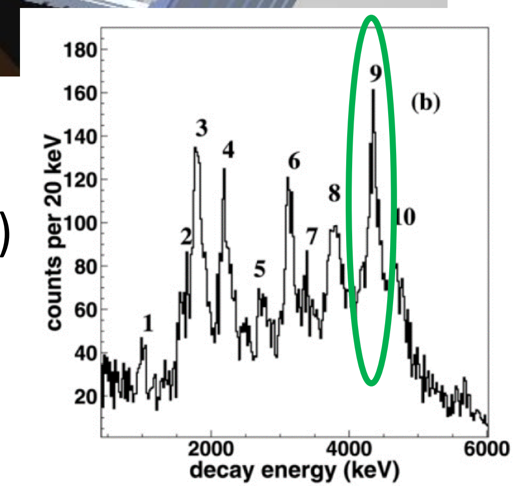
at in-flight separators

standard decay spectro. (impl. in silicon)

→ no individual protons information

^{43}*Cr*

($T_{1/2}$ = 21 *ms*)



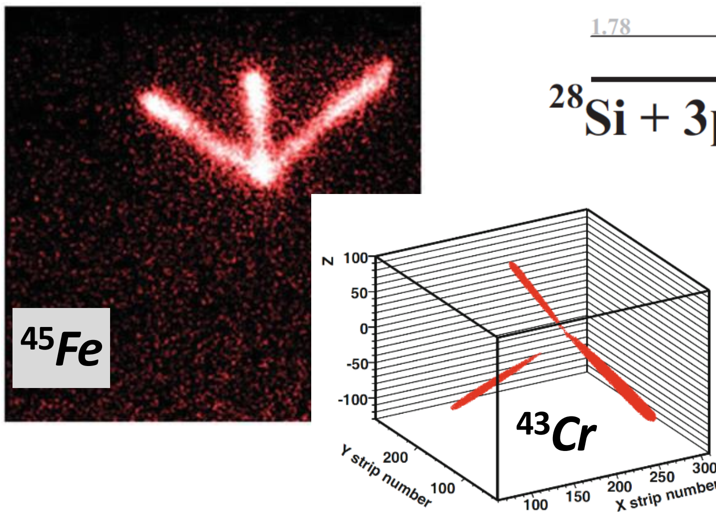
→ need for a TPC (energy resolution ? count rates ?)

beta-delayed 3-proton emission

delayed emission of 3 or more particles is possible

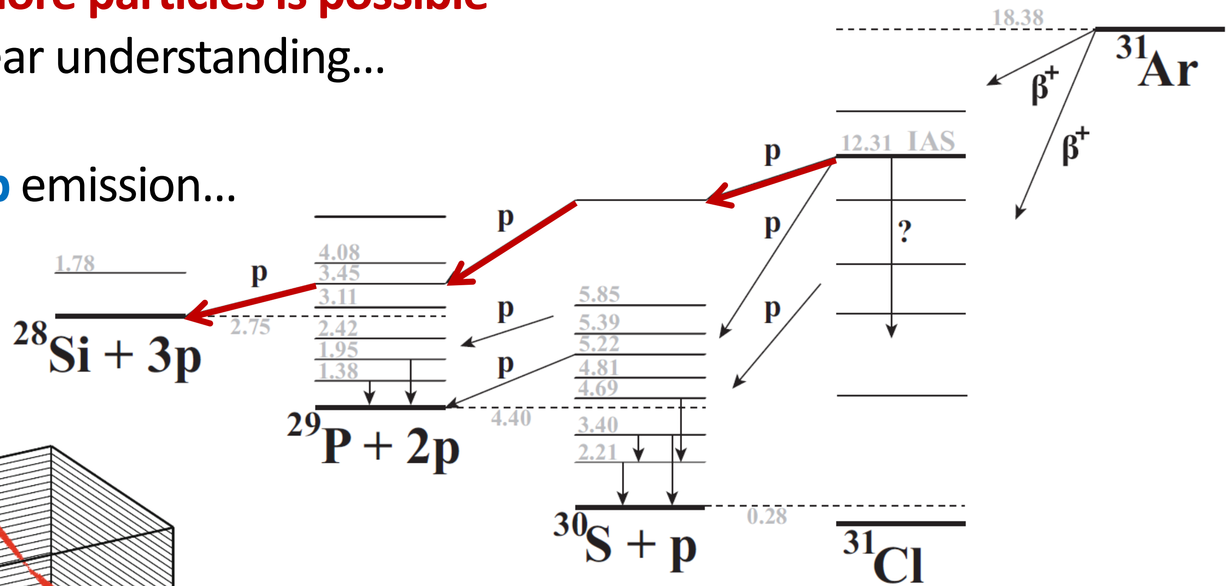
limited interest for nuclear understanding…

few observations of **β-3p** emission…



proj. fragmentation & TPC

- OTPC (Warsaw collab.)
  - in ^{45}*Fe* (Miernik *et al.*, EPJA **2009**)
  - in ^{43}*Cr* (Pomorski *et al.*, PRC **2011**)
- TPC-CENBG
  - in ^{43}*Cr* (Audirac *et al.*, EPJA **2012**)



ISOLDE & Si-Cube

in ^{31}*Ar* (Koldste *et al.*, PRC **2014**)

previously claimed (D. Bazin, 1992) but more likely β-2p

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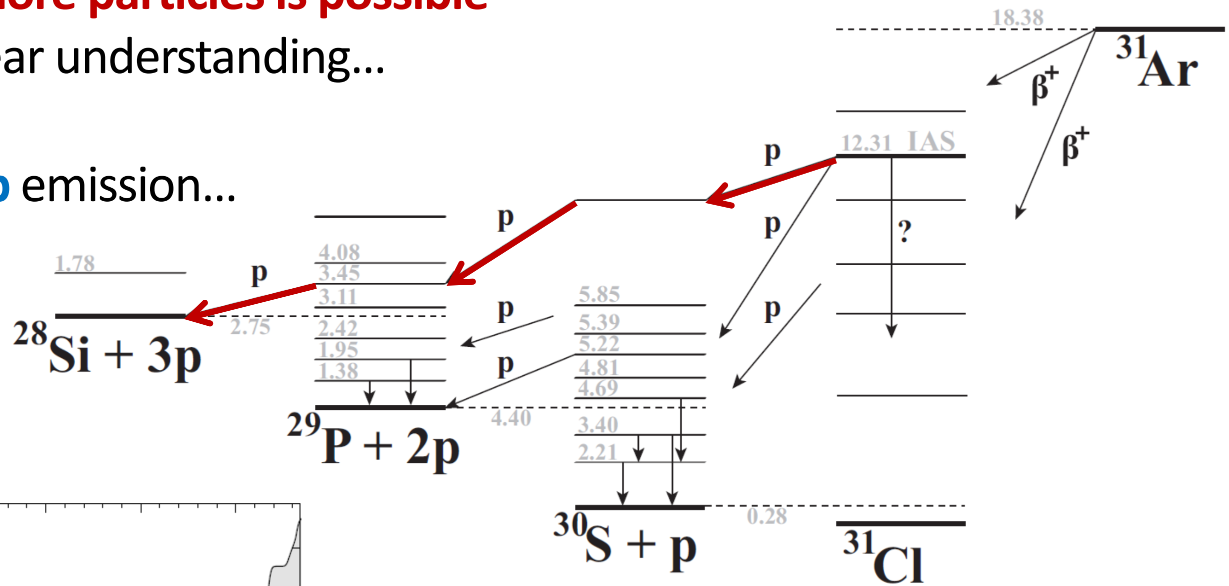

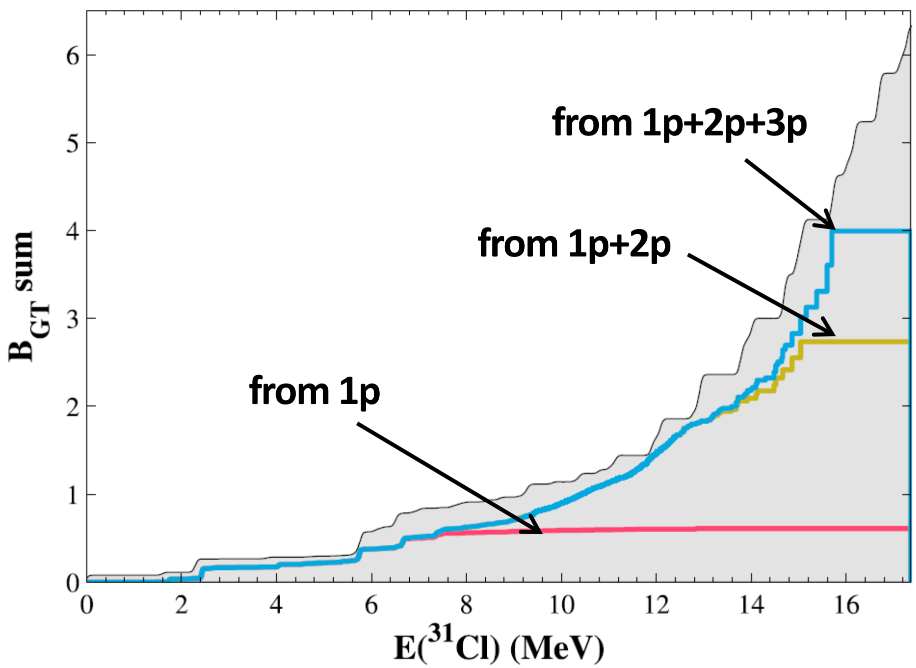

Koldste *et al.*, Phys. Lett. B (2014)

ISOLDE & Si-Cube

in ^{31}***Ar*** (Koldste *et al.*, PRC **2014**)

previously claimed (D. Bazin, 1992) but more likely β-2p

Proton(s) radioactivity

- **Particle emission at the proton drip-line**
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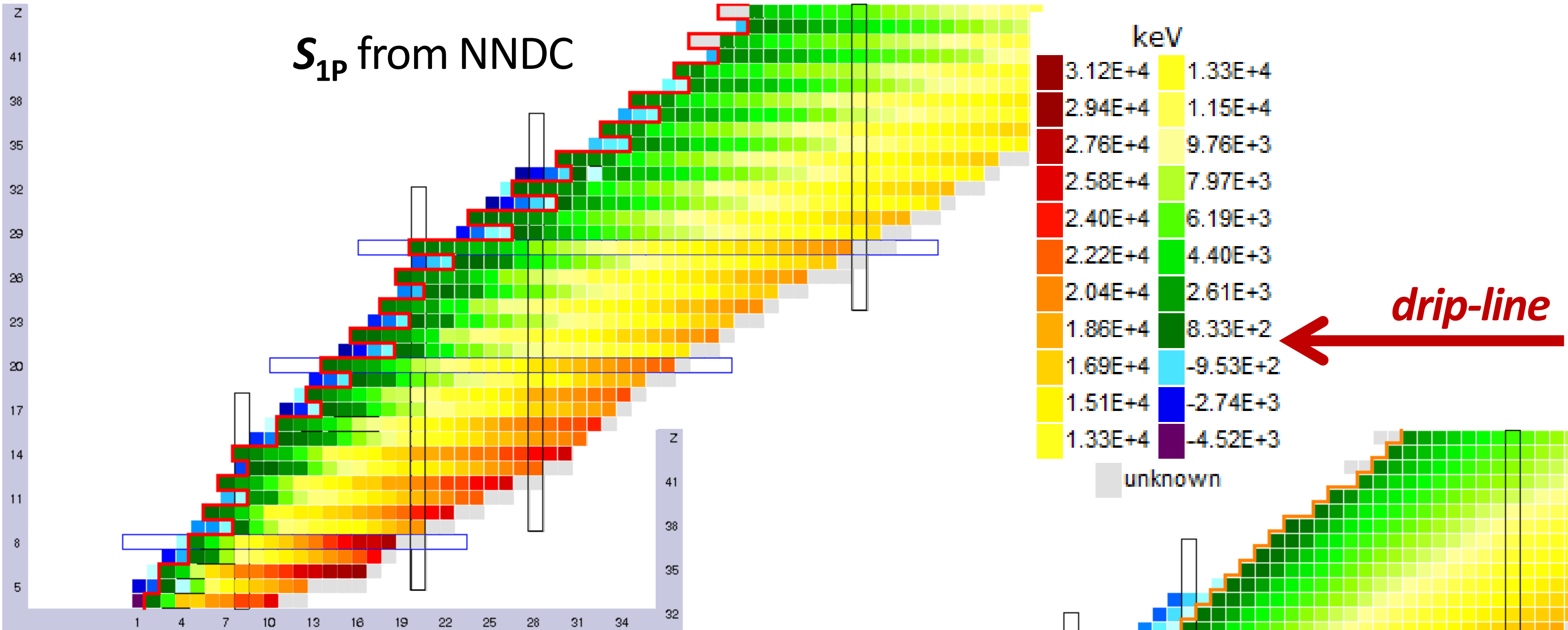
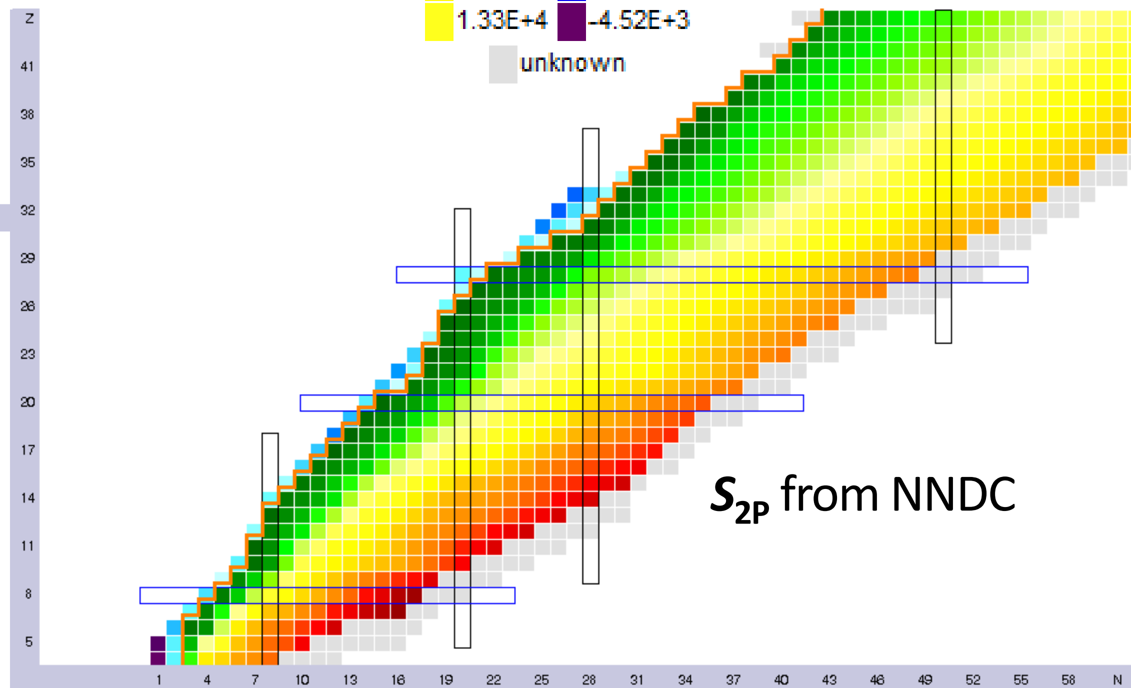
The proton drip-line



$S_{1P} < 0$ or $S_{2P} < 0$

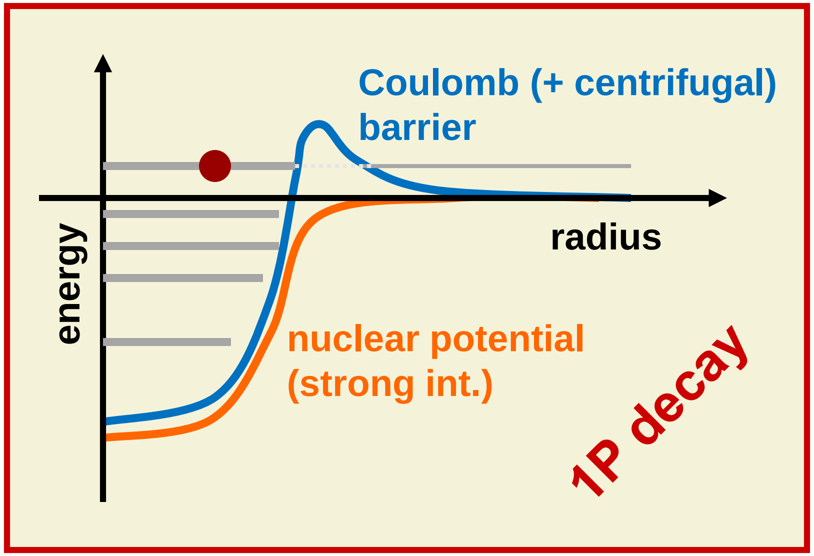
⇓

unbound / nuclear interaction

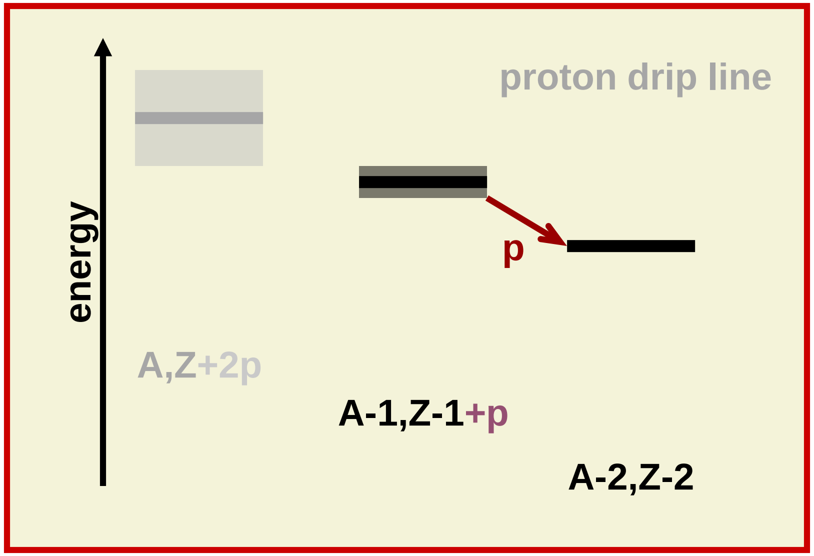


http://www.nndc.bnl.gov/chart

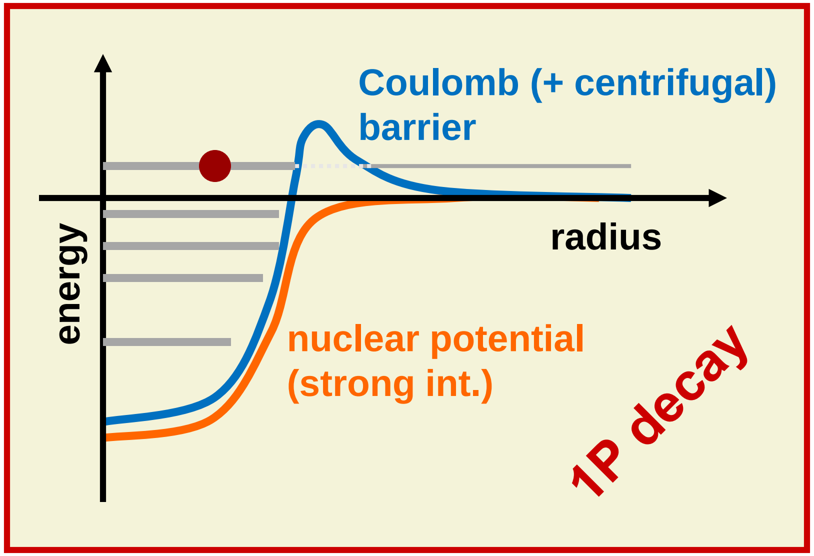
Quasi-(un)bound ground state



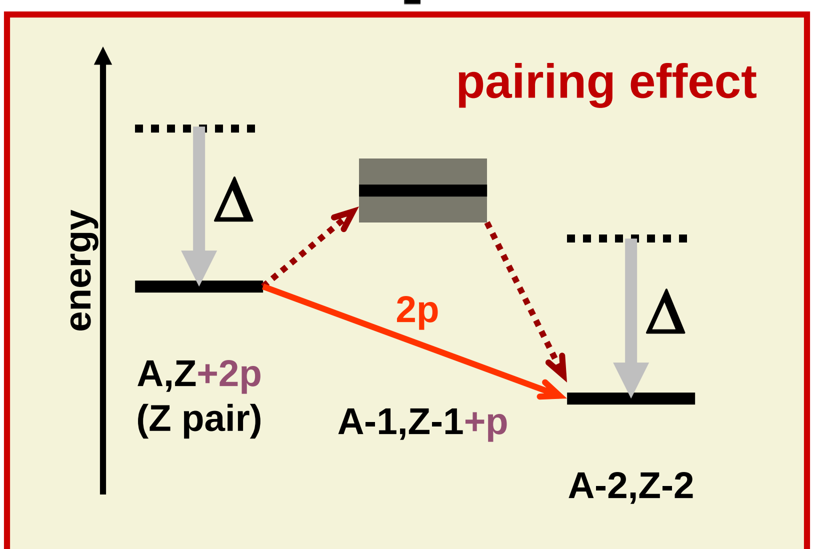
odd-Z isotope

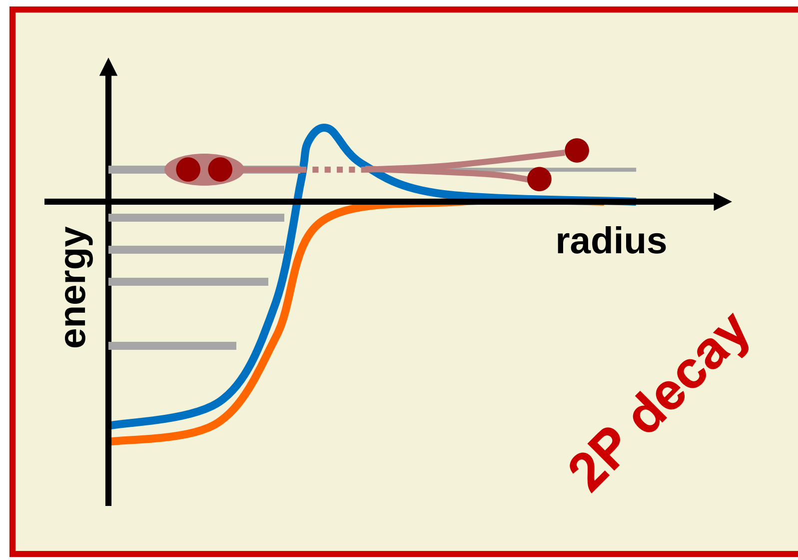


Quasi-(un)bound ground state



odd-Z isotope





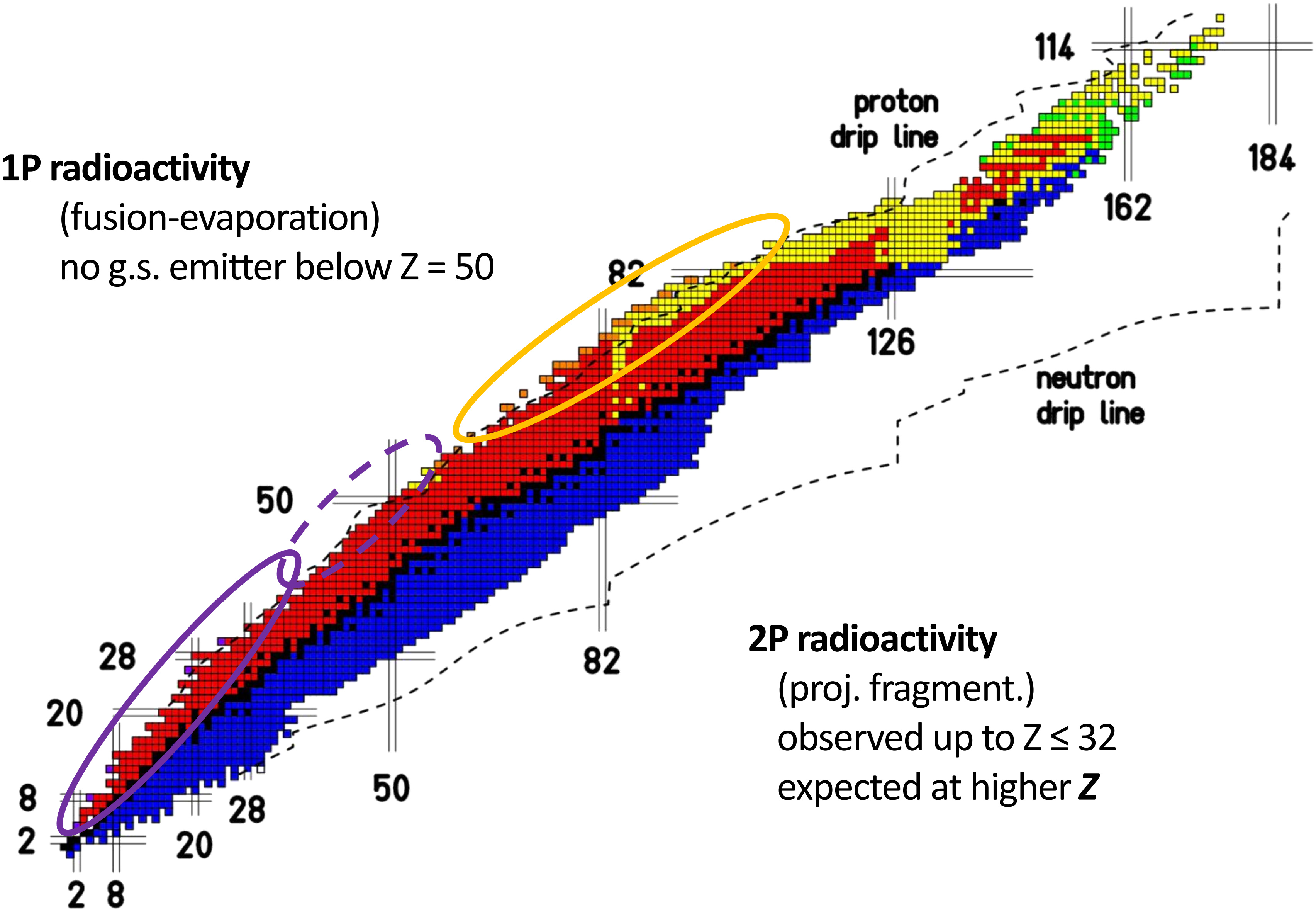
even-Z isotope

1 proton emission forbidden

(so called "***true***" 2P radioactivity)

1P and 2P ground-state emitters

1P radioactivity
(fusion-evaporation)
no g.s. emitter below Z = 50



2P radioactivity
(proj. fragment.)
observed up to Z ≤ 32
expected at higher ***Z***

1P and 2P radioactivity

proton emission → discussed in beta-delayed emissions

short nuclear lifetimes: $\mathbf{10^{-17}} \sim \mathbf{10^{-20}}$ s.

→ strong interaction process time scale

→ not considered as radioactivity

1p & 2p radioactivity

Goldanskii considered a lower $T_{1/2}$ limit of $\sim\mathbf{10^{-12}}$ *s*.

limit to consider the nucleus as “thermalized” ? ($\mathbf{10^{-18}}\sim\mathbf{10^{-19}}$ *s* ?)

(lifetime >> nucleon motion time in nucleus)

upper limit defined by **competition with beta decay**

half-life for proton emission

→ Coulomb + centrifugal barrier (ground state 1p & 2p emitters)

→ spin isomers (1p)

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Experimental discovery of proton radioactivity

→ 1970 (V.A. Karnaukhov et. al, conf. proc.)
results in contradiction with more recent work

→ **1970: first observation from** ^{53m}*Co* (spin isomer: 245 *ms*, J^{π}=19/2^{-}, *l*=9)
(Jackson *et al.*, Phys. Lett. B33)
reaction: $^{40}Ca(^{16}O,3n)^{53m}Co$ proton detection in silicon Δ*E*-*E* telescope
(Cerny *et al.*, Phys. Lett. B33)
confirmation with $^{54}Fe(p,2n)^{53m}Co$

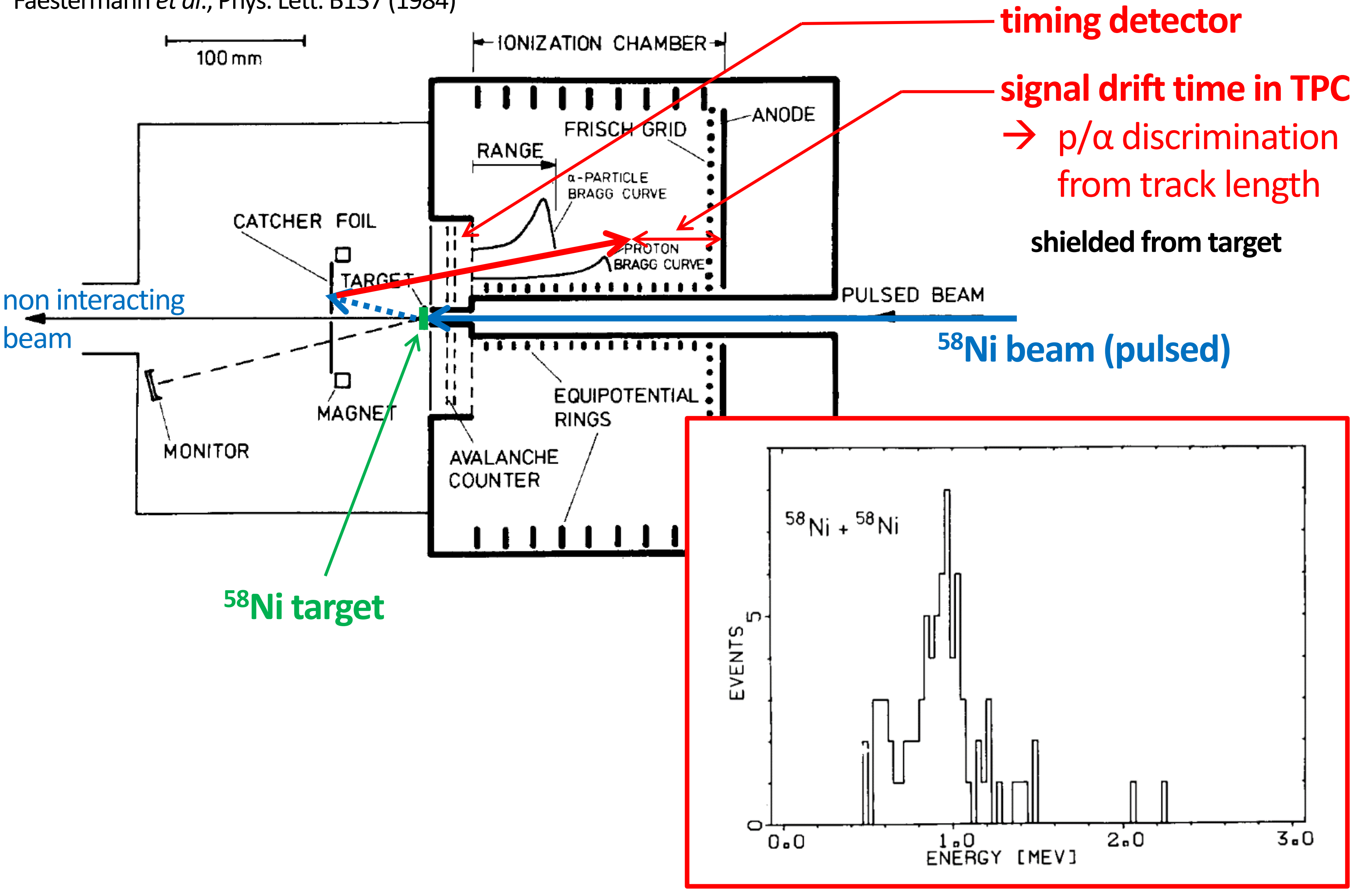
→ **1982: ground state radioactivity of** ^{155}*Lu* (80.6 *ms*) & ^{147}*Yb* (420 *ms*)
(Hofmann *et al.*, Zeit. Phys. A305)
reaction: $^{92}Mo + ^{63}Cu \rightarrow ^{155}Lu$
SHIP (@GSI) velocity filter (separator) + Si telescope
(Klepper et al., Zeit. Phys. A305)
reaction: $^{92}Mo(^{58}Ni,3n)^{147}Yb$
catcher + ion source; GSI online separator (ISOL) + Si telescope

→ 1984: short-lived emitters: ^{113}*Cs* (~1 *μs*) & ^{109}*I* (> 25 *μs*)
(Faestermann *et al.*, Phys. Lett. B137)

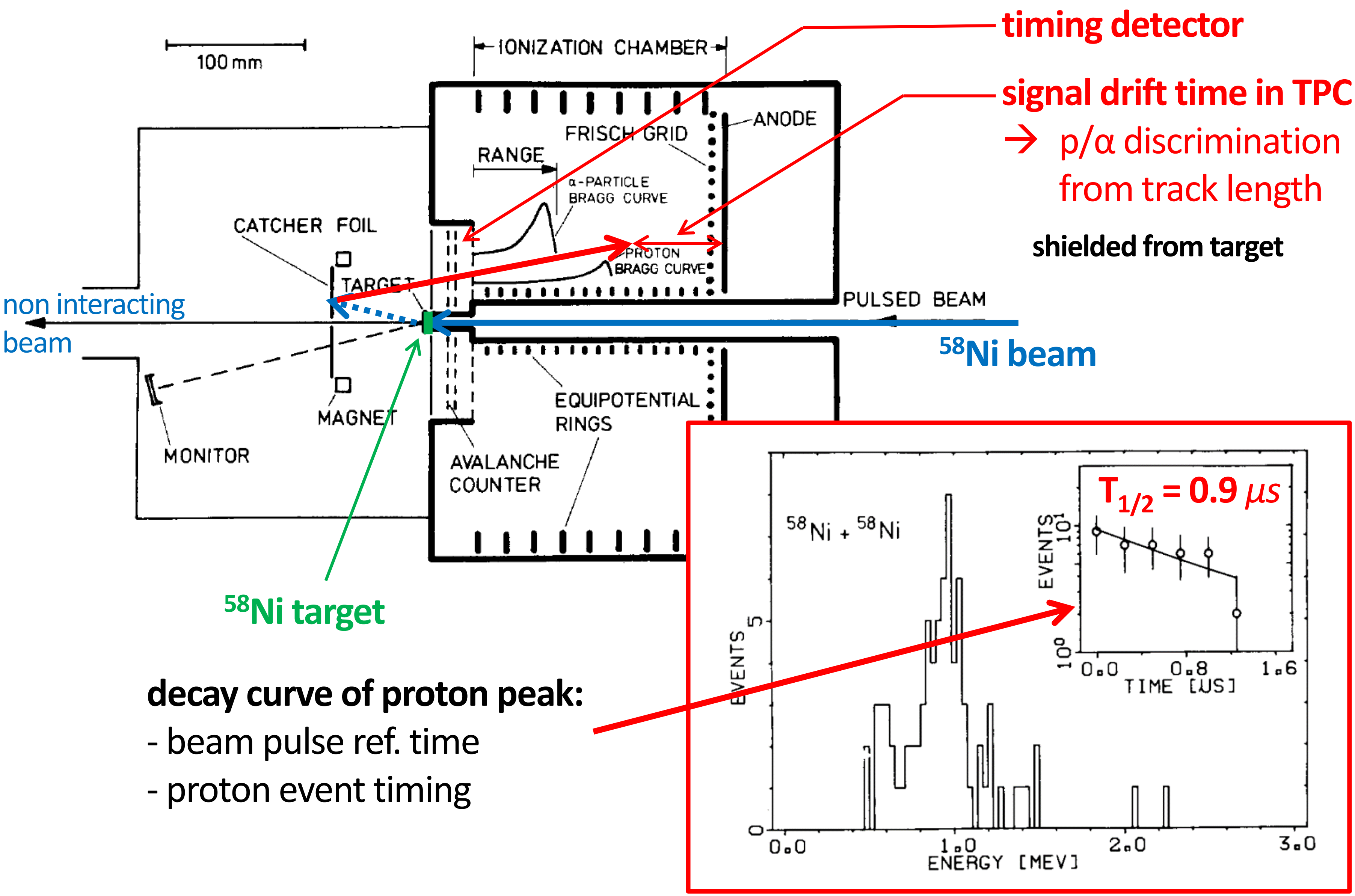
about 50 known emitters today (ground- or isomeric state)

Experiment @ Munich MP tamdem

Faestermann *et al.*, Phys. Lett. B137 (1984)



Experiment @ Munich MP tamdem



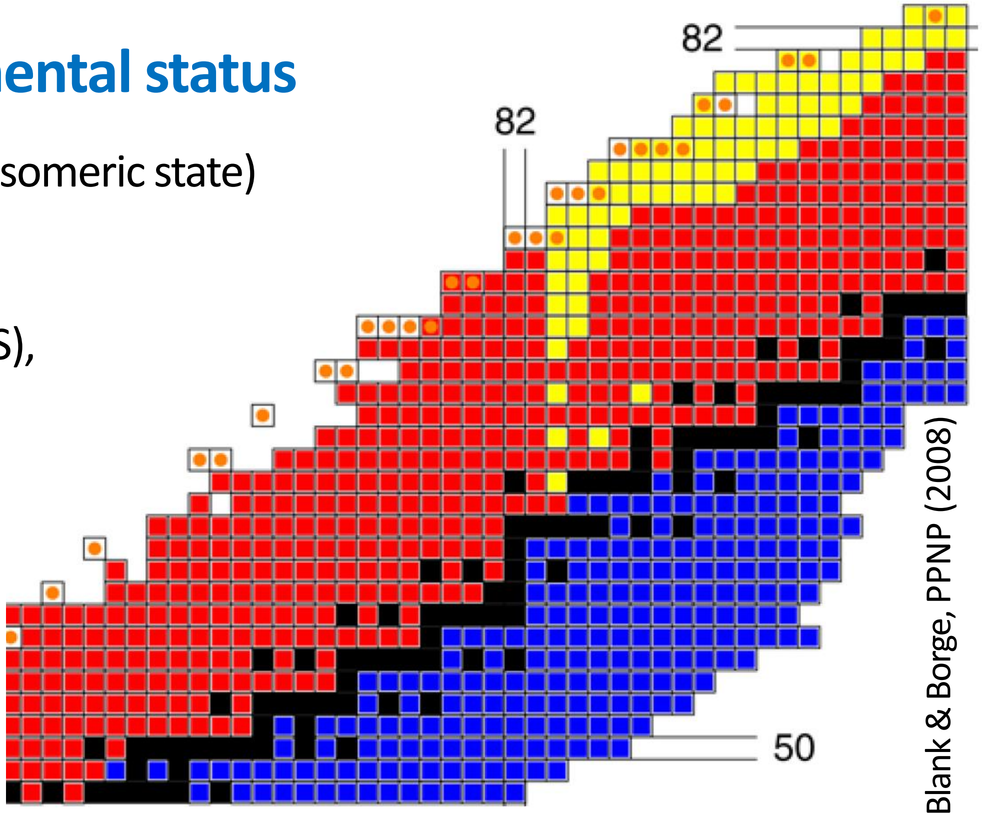
decay curve of proton peak:

- beam pulse ref. time
- proton event timing

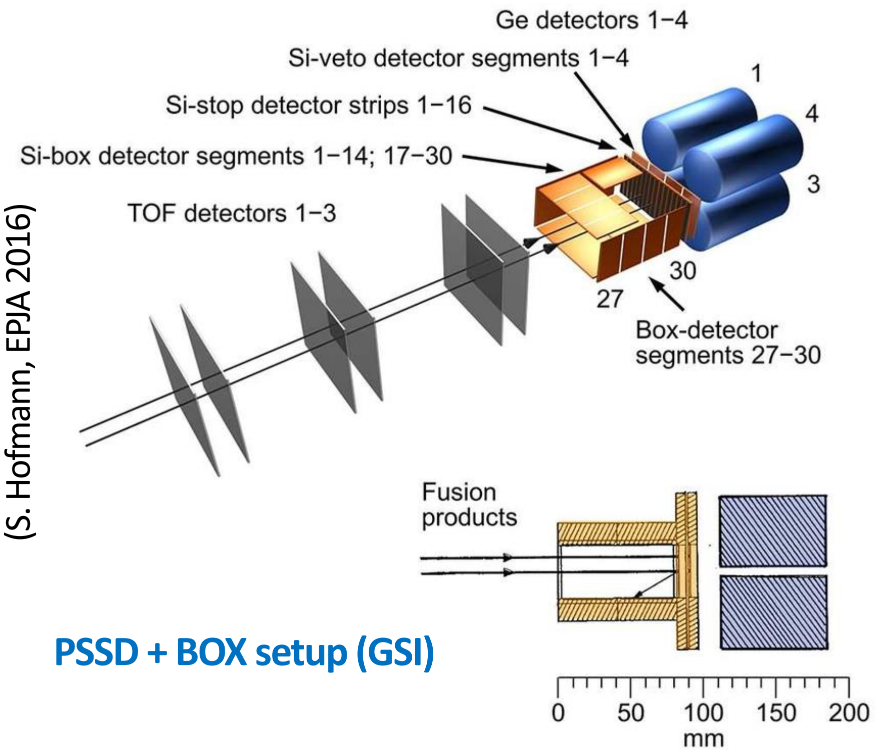
Experimental status

about 50 known emitters today (ground- or isomeric state)

in the 1990's → Daresbury (UK)
then ANL (Argonne, US), ORNL (Oak Ridge, US),
Legnaro (Italy) and JYFL (Finland)
and (still…) GSI



Blank & Borge, PPNP (2008)



(S. Hofmann, EPJA 2016)

PSSD + BOX setup (GSI)

development of experimental set-up

sensitive improvements due to the use of highly segmented silicon strip detectors and the use of fast acquisition systems

proton-gamma coincidences
(decay to excited states: "fine structure")

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Direct probe of nuclear structure beyond the drip-line

1P radioactivity: a "simple" emission process

no preformation required (as for alpha emission)

nuclear models

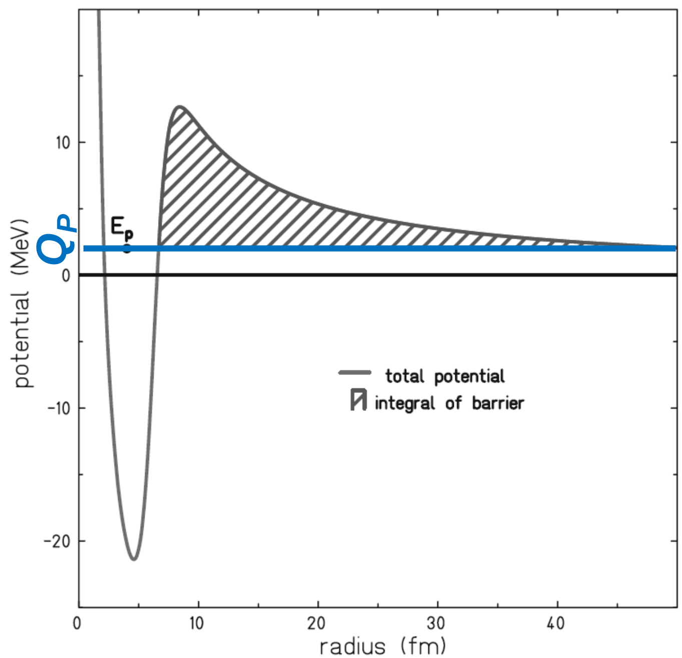
- masses at the drip-line
- at first order, **single particles** in a mean potential
  → (almost) direct test of the s.p. orbitals & nuclear configuration

Proton emission half-life

tunneling process: $T_{1/2} = f\,(\,{}^{A}Z,\, Q_P,\, L\,)$

simple models (core + p):
- "frequency of assault"
- WKB approximation...

see lecture from L.V. Grigorenko



Direct probe of nuclear structure beyond the drip-line

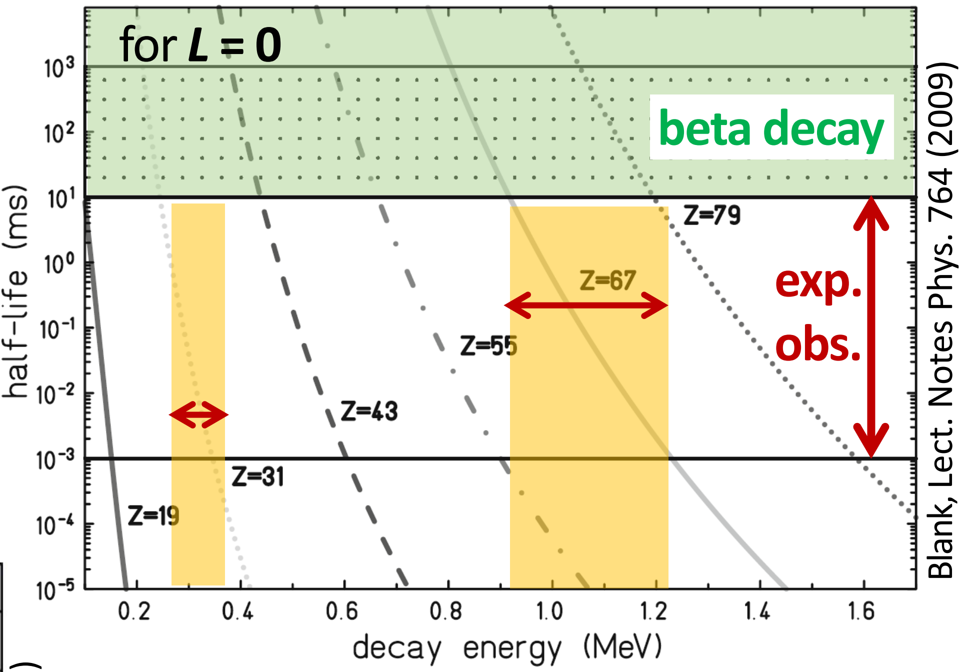
exp. information vs. **model calculation**

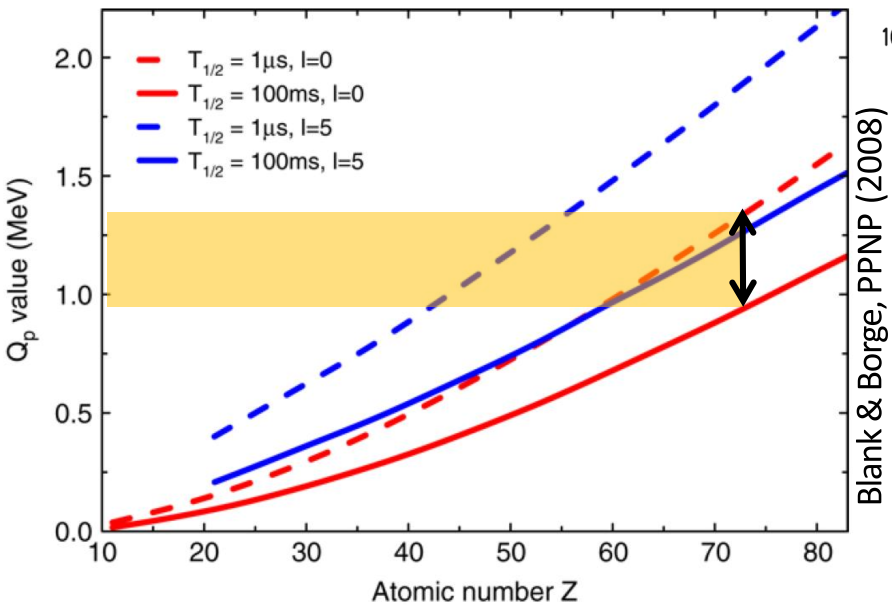
$$T^{P}_{1/2} = \frac{T_{1/2}}{I_P} \leftrightarrow T^{th}_{1/2}(Q_P\, l)$$

observation condition

→ *Z* dependence (Coulomb barrier)

→ ang. momentum dep.





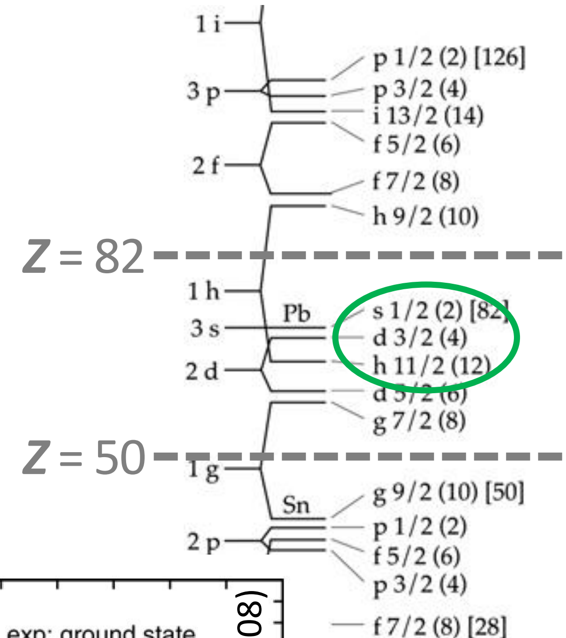
favorable energy range larger at higher Z

→ no observation of ground-state emitters at low ***Z***...

Direct probe of nuclear structure beyond the drip-line

exp. information vs. **model calculation**

$$T^{P}_{1/2} = \frac{T_{1/2}}{I_P} \leftrightarrow T^{th}_{1/2}(Q_P, l)$$

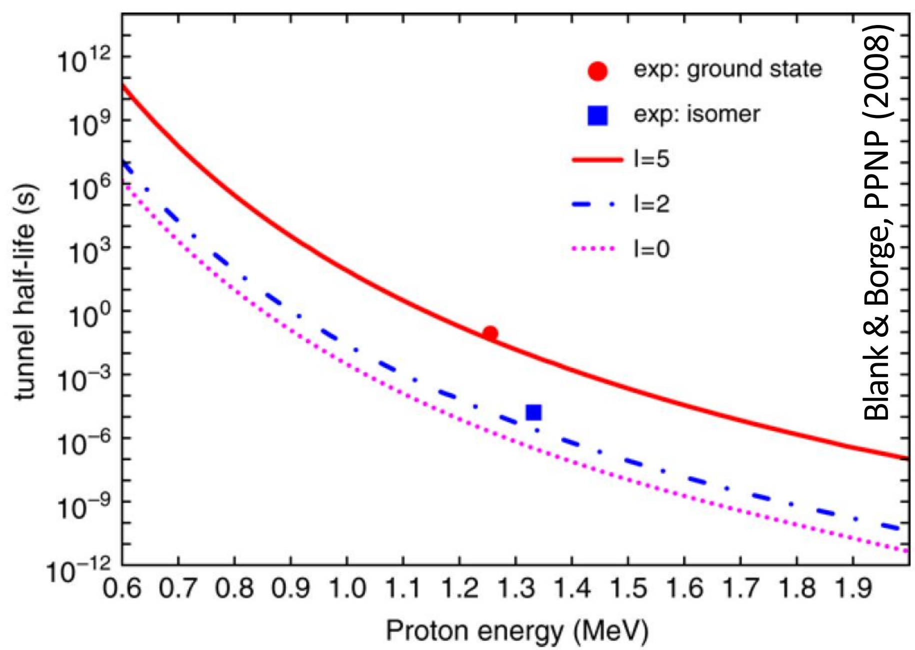


^{151}Lu decay

g.s. emission: $l = 5$
→ proton in $h_{11/2}$

isomer: $l = 2$
→ proton in $d_{3/2}$

simple picture...



Direct probe of nuclear structure beyond the drip-line

Spectroscopic factor

purity of the single particle state

→ structure (wave functions) effects that slow the process

S_{th} calculated in more realistic approaches

$$S_{exp} = \frac{T_{1/2}^{th}}{T_{1/2}^{exp}}$$

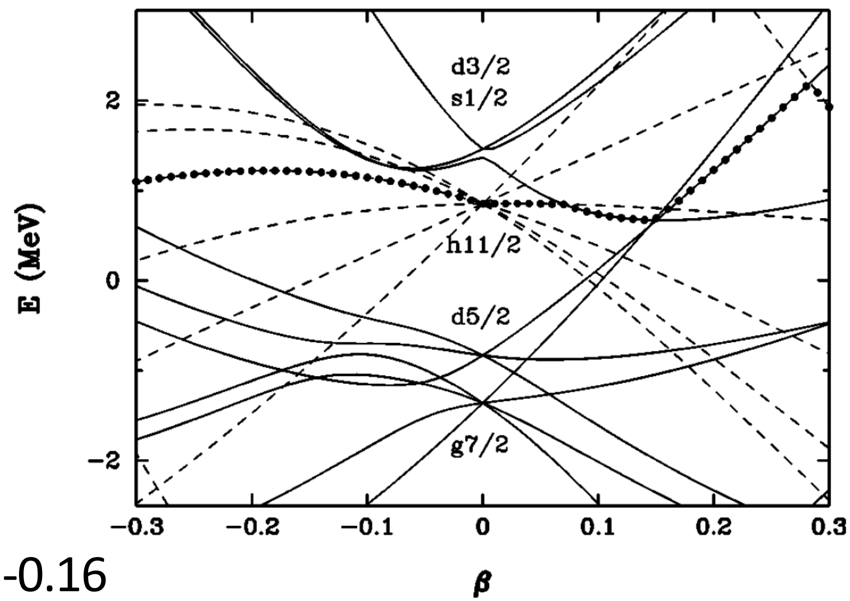
⇩

comparison to probe model hypothesis

→ orbitals occupancy

→ deformation

^{151}Lu



Ferreira & Maglione, PRC61 (2000)

^{151}Lu: β_2 = -0.16

(expected from Möller & Nix predictions)

Many studies…

experimental measurements and nuclear structure interpretations

(see refs. in B. Blank & M.J.G. Borge, Prog. Part. Nucl. Phys. 60, 2008)

Direct probe of nuclear structure beyond the drip-line

emission for odd-Z even-N nuclei

simplest case: emission of the unpaired proton: ***core+p*** description

daughter $J^{\pi} = 0^{+}$ (even-even)

⇨ emitter $J = L \pm ½$ and $\pi = (-1)^{L}$

emission for odd-Z odd-N nuclei

interaction of the unpaired proton & neutron

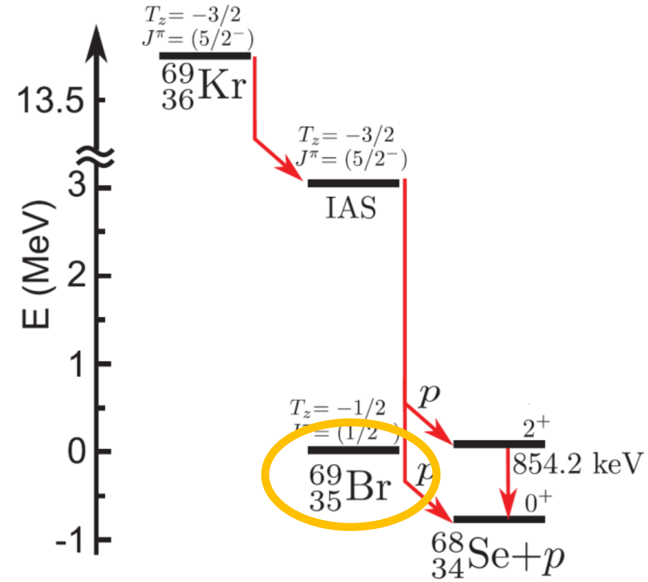
→ changes in states configurations

more than 1 unpaired proton

for high spin / high exc. energy isomers: ^{53m}***Co***, ^{54m}***Fe***, ^{94m}***Ag***

require a more detailed structure description

Further studies



in the region 50 < Z < 82

other proton emitters could / should exist

no observed case at $Z = 61$ (Pm) ?

no emitters in the region Z < 50

small Q_p window for observation

→ no emitters or exp. limitation (short $T_{1/2}$) ?

mass region accessible at fragmentation facilities

→ difficult with implantation-decay technique

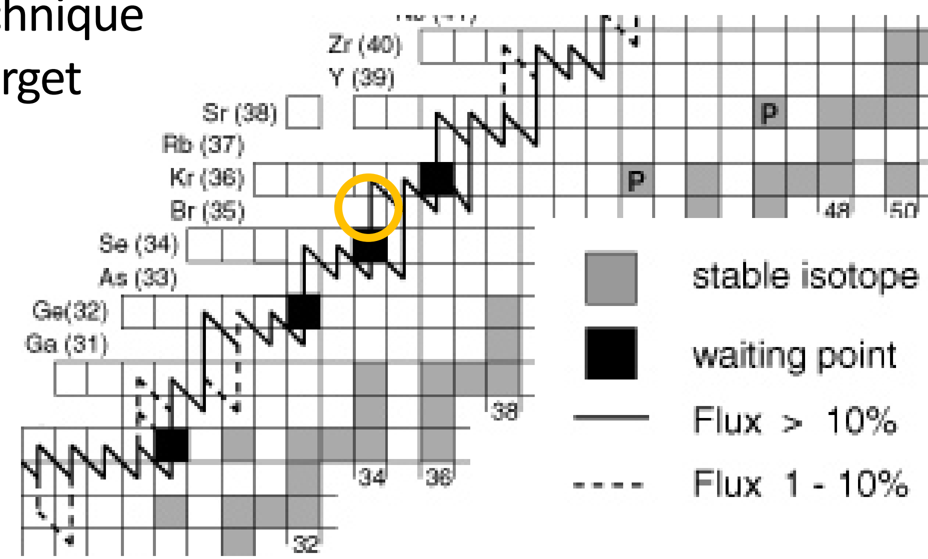
secondary reaction + detection at target

(+ fast electronics)

nuclear astrophysics:

rp **process waiting points + p**

(observed in β-p decay in proj. frag.)



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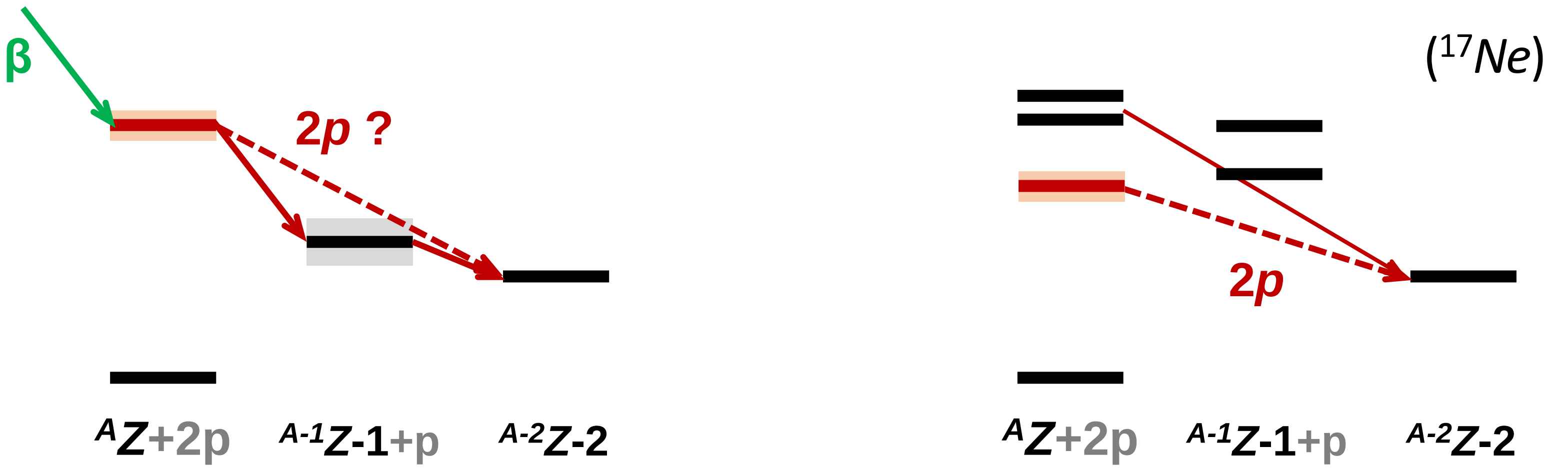
Two-proton emission from a nuclear state

from an excited state



after beta decay

(discussed previously)

→ only sequential decay observed

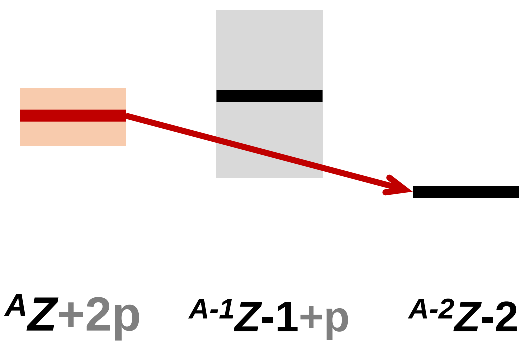
populated in reactions

cases with no intermediate state

^{14}***O***, ^{16,17}***Ne***… no clear evidence

Two-proton emission from a nuclear state

ground-state 2P emission



short-lived emitters

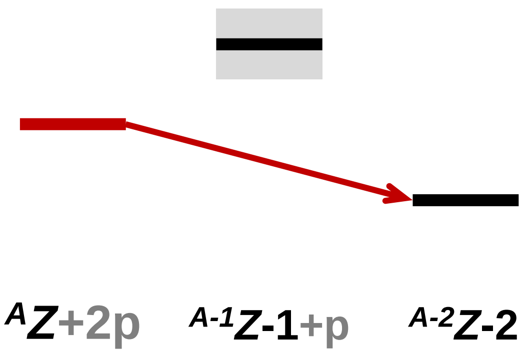
first obs. "simultaneous" emission

light emitters: ^{6}***Be***, ^{12}***O***, ^{16}***Ne***…

→ $T_{1/2} \sim 10^{-20}\ s$

"democratic" decay

3-body break-up (reaction)



long-lived emitters

→ **1P emission forbidden**

^{45}***Fe***, ^{48}***Ni***, ^{54}***Zn*** and ^{67}***Kr***, $T_{1/2} \sim ms$

^{19}***Mg***, $T_{1/2} \sim ps$ (discussed later)

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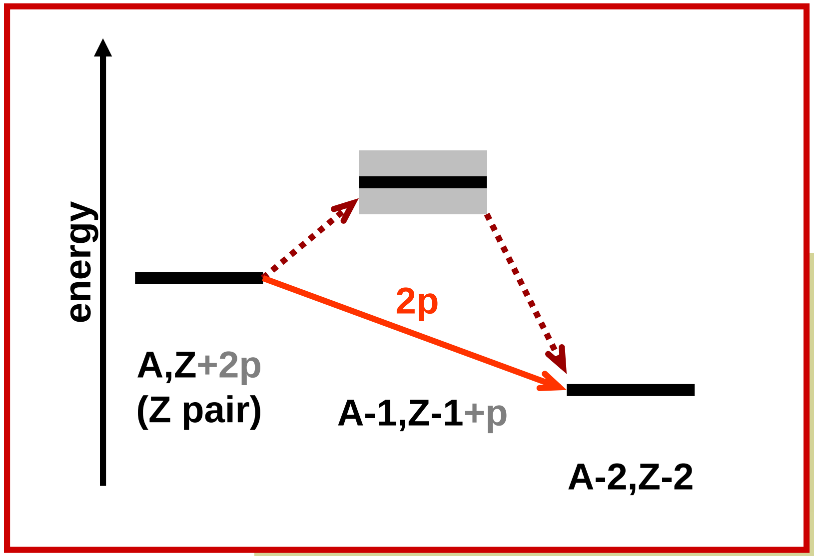
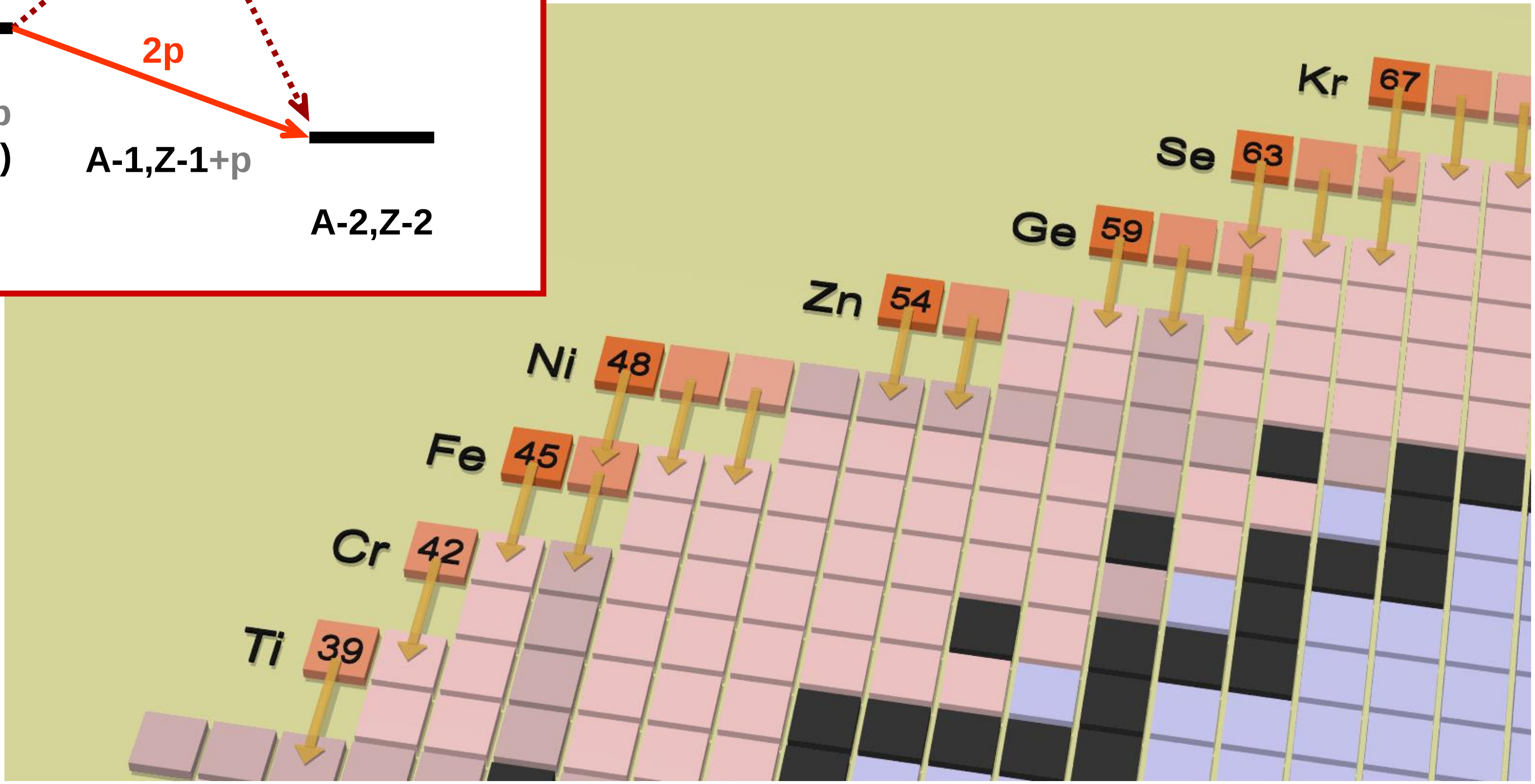
Search for candidates

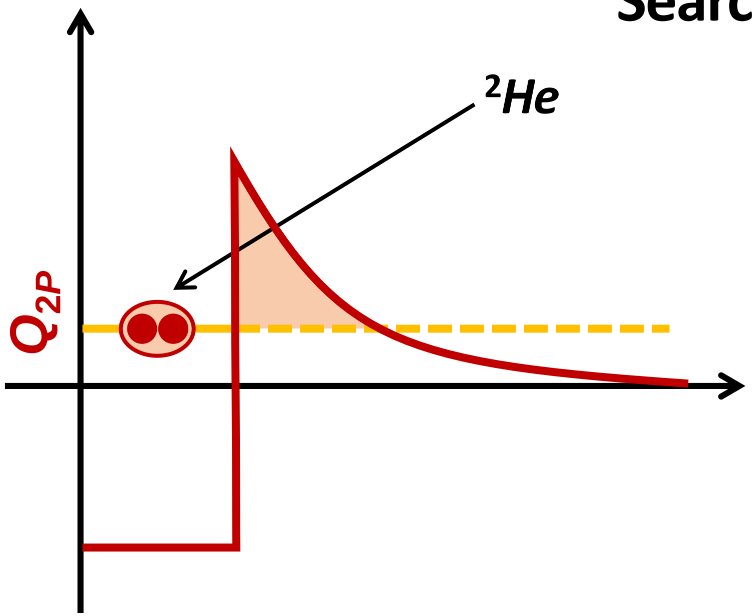


pairing: longer isotope chains for even-***Z***

all **even-*Z*** nuclei at the proton **drip-line** are *potential* 2P emitters



Search for candidates



first predictions (V.I. Glodanskii, 1960)

simple potential

barrier penetration of a ^{2}He particle

vs. simultaneous emission of 2 protons

Q_{2P} from mass predictions

A ~ 50 mass region (already) more favorable

confirmed by (more) **recent mass predictions**

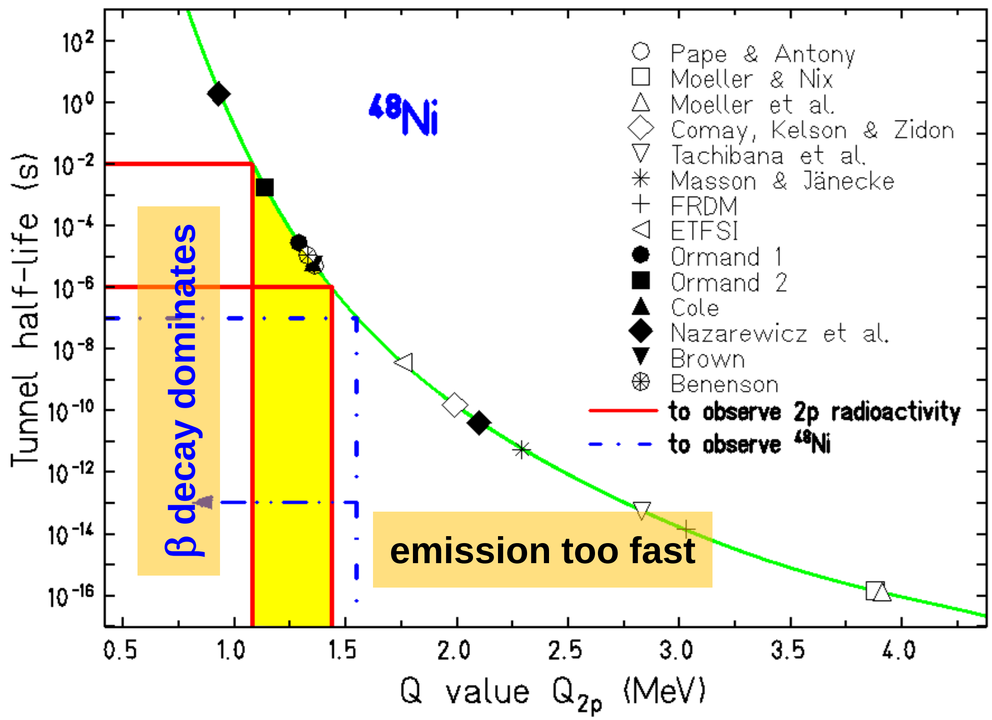
& local mass models

(Garvey-Kelson, IMME…)

$T_{1/2} = f(Q_{2P})$ → narrow window

Q_{2P} too high ⇨ **too short $T_{1/2}$**

Q_{2P} too small ⇨ too slow, **β⁺ dominates**



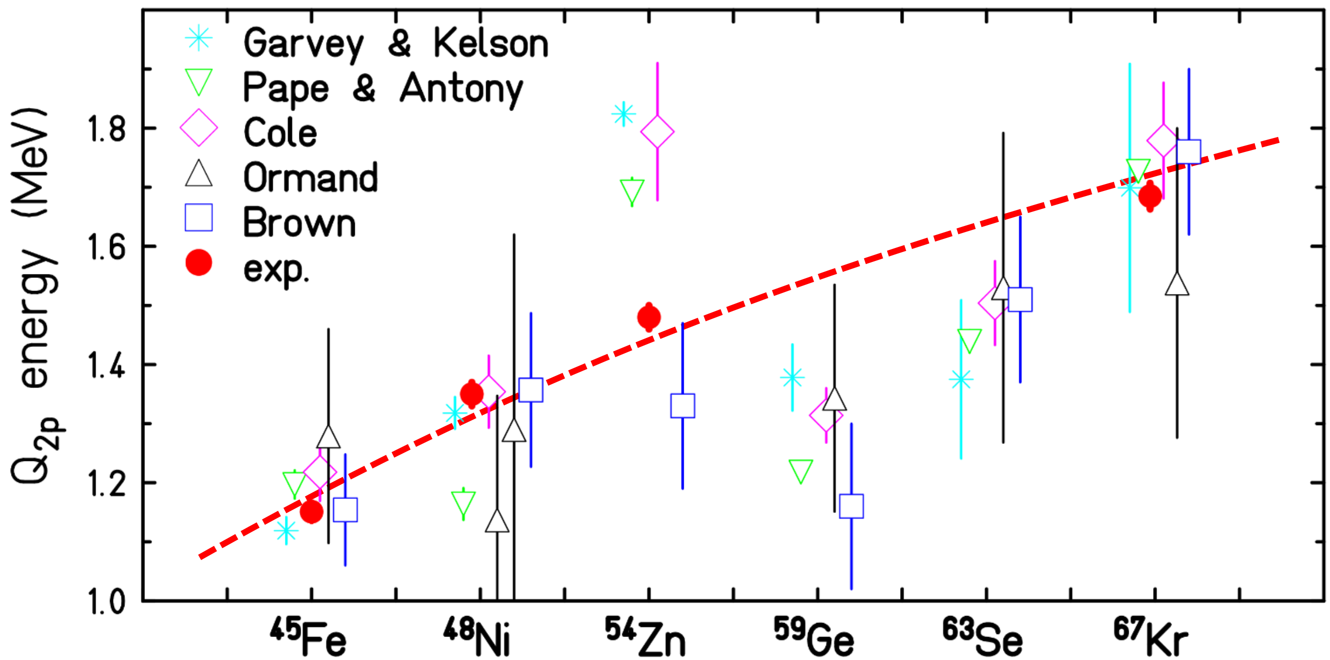
B. Blank, PRL (1999)

Search for candidates

1P-bound: $Q_{1P} < 0$ and 2P-unbound: $Q_{2P} > 0$

favorable case: dependence with Z due to Coulomb barrier

known *ms* 2P ground-state emitters



T. Goigoux *et al.*, PRL (2016)

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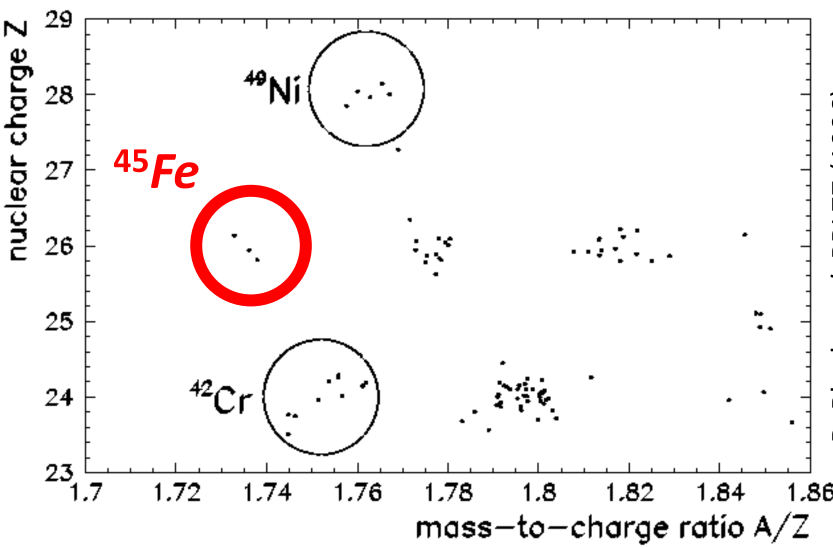
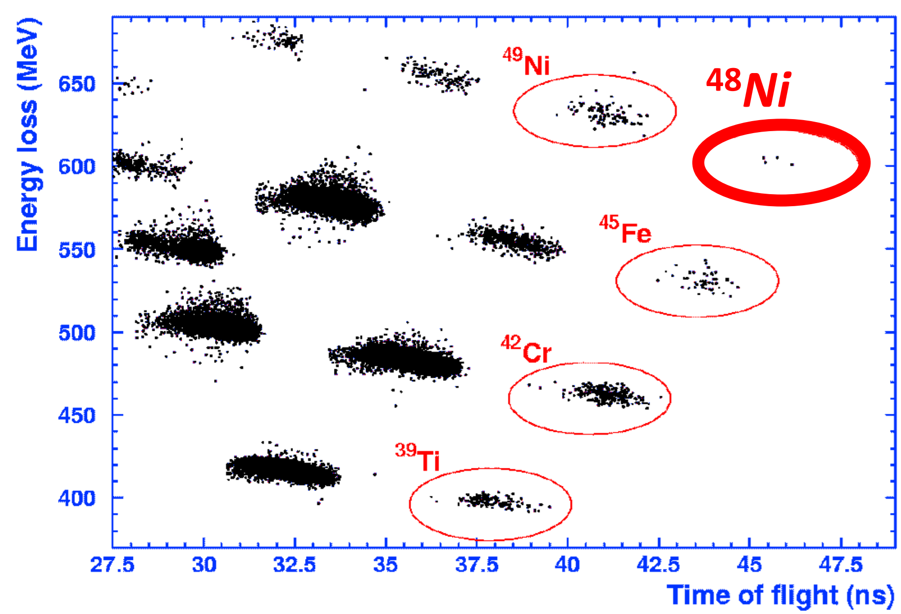
first attempts in the A ~ 50 region

^{58}Ni beam fragmentation at GSI & GANIL



B. Blank *et al.* PRL77 (1996)



B. Blank *et al.* PRL84 (2000)

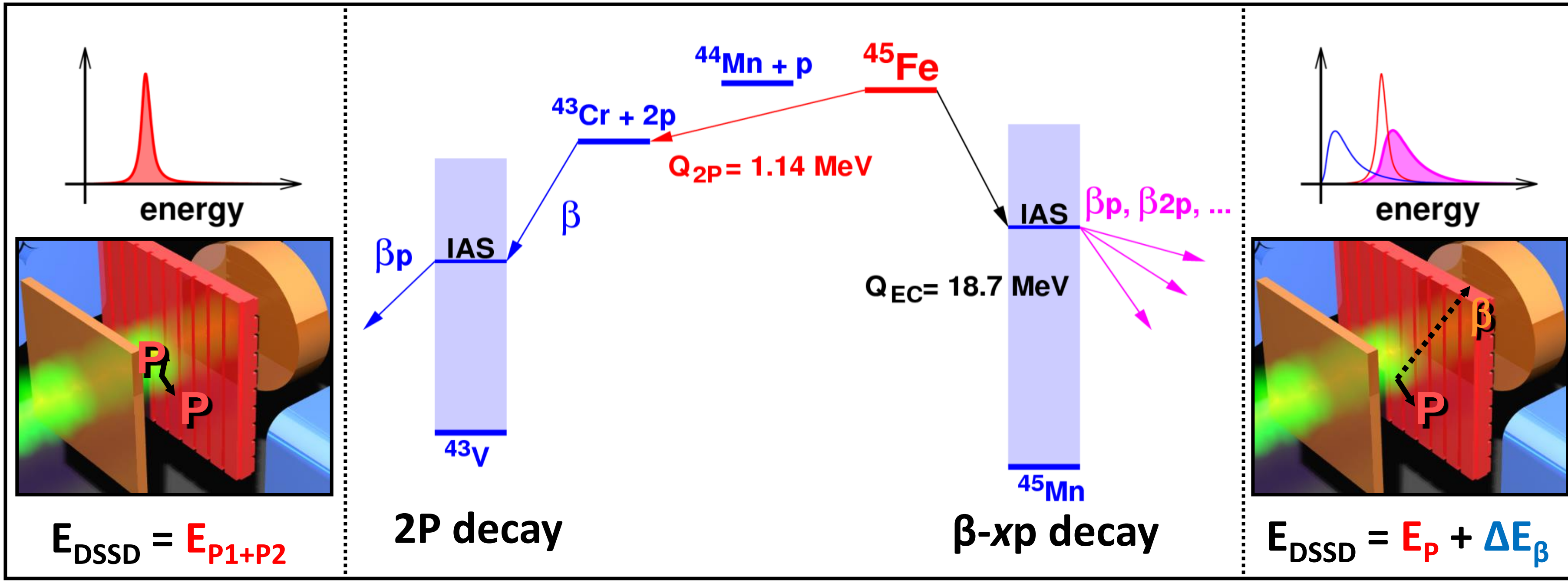
first observation of ^{45}Fe
GSI experiment (1996)
3 events

first observation of ^{48}Ni
GANIL experiment (1999)
4 events

no measurement of the decay modes…

β-(*x*)p versus 2P decay discrimination

(GANIL exp.) proj. fragmentation; implantation in a 300 μm DSSSD



no β coincidence
narrow peak

+ subsequent decay
of 2P **daughter**

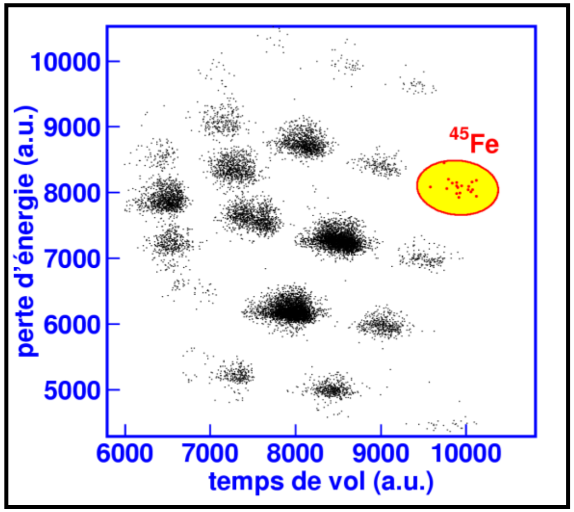
detection
$\varepsilon_p \sim 99$ % (– dead-time)
$\varepsilon_\beta \sim 40$ % (coinc.)

coincident β particle
degraded peak energy

^{45}*Fe* decay @ GANIL / LISE

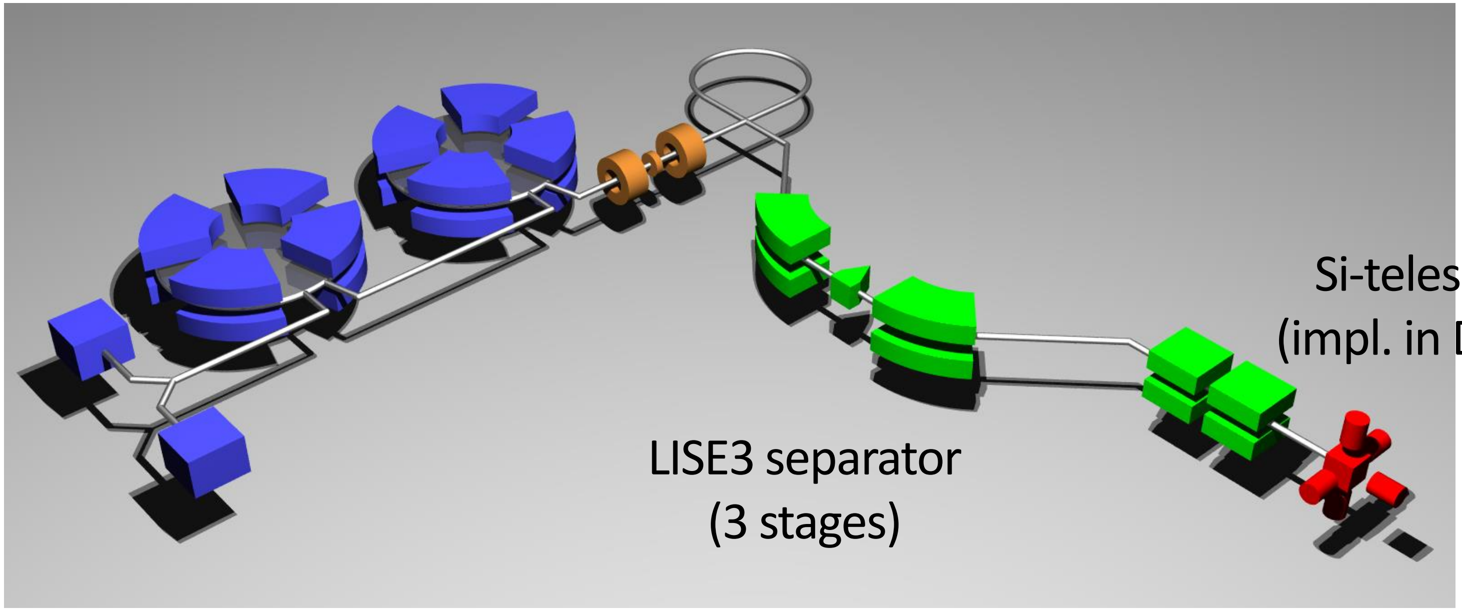
identification matrix

→ 22 events for ^{45}Fe



^{58}*Ni* beam @ 75 MeV/A
(~10^{13} pps)

^{nat}*Ni* target
(240 μm)



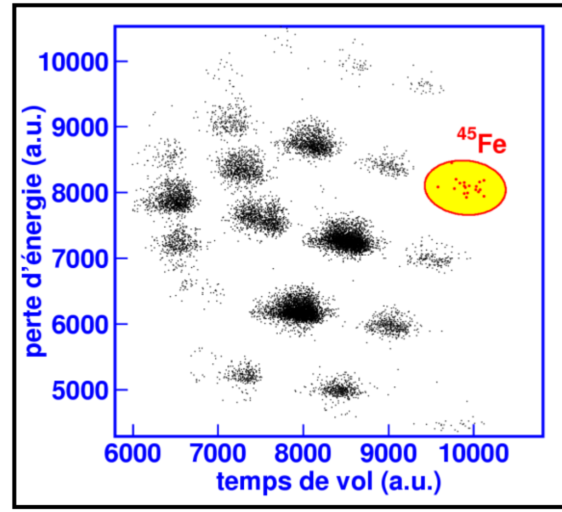
LISE3 separator
(3 stages)

Si-telescope
(impl. in DSSSD)

^{45}*Fe* decay @ GANIL / LISE

identification matrix

→ 22 events for ^{45}Fe



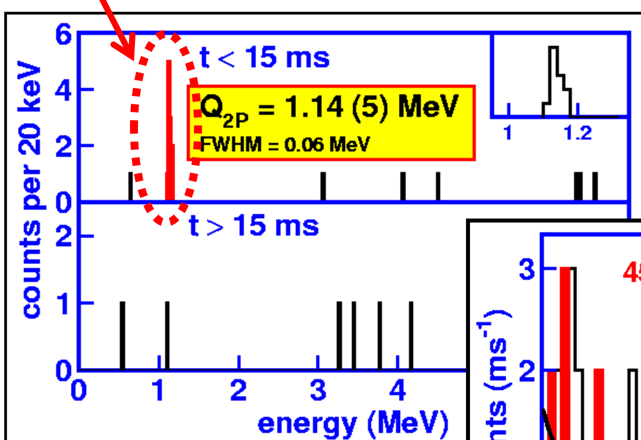
2-proton transition

experimental information: Q_{2P}, $T_{1/2}$

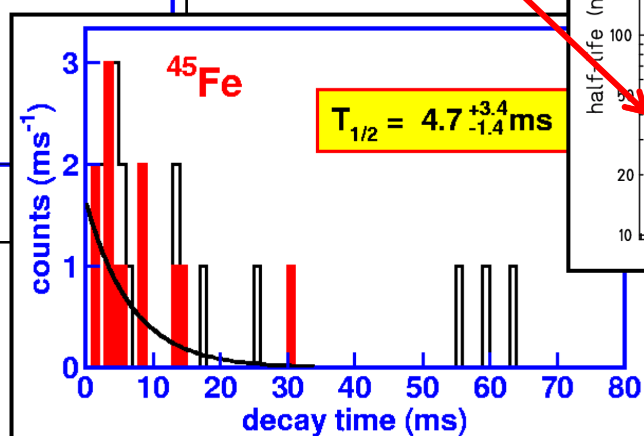
→ **no β coincidence** (>99% C.L.)

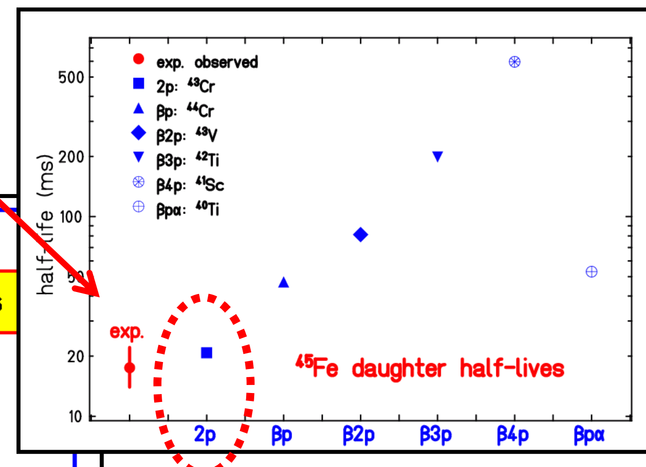
→ **no ΔE_β pile-up** (peak 30% narrower than β- p)

→ **daughter decay half-life :** ^{43}Cr

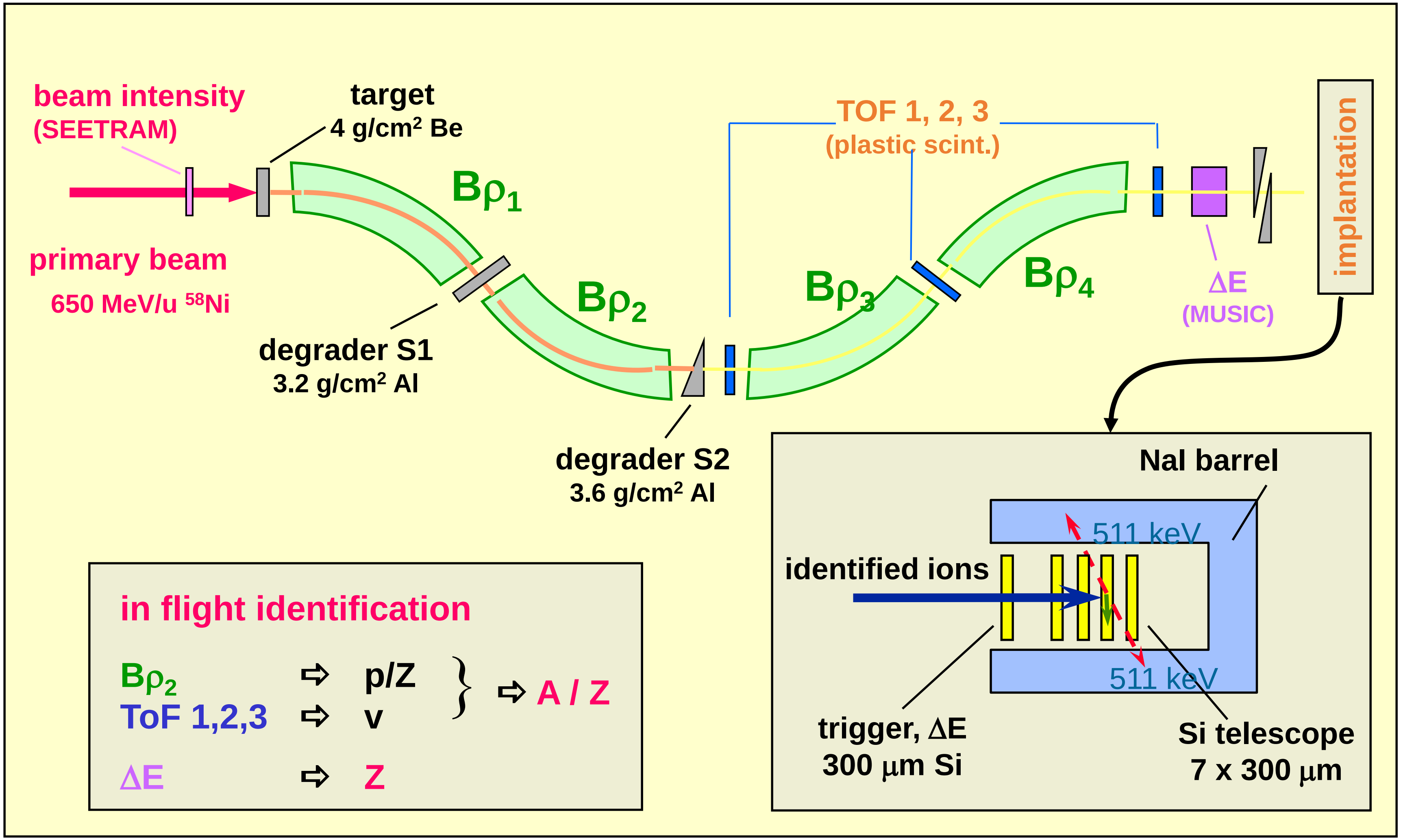


J.G. *et al.*, PRL (2002)





^{45}*Fe* decay @ GSI / FRS

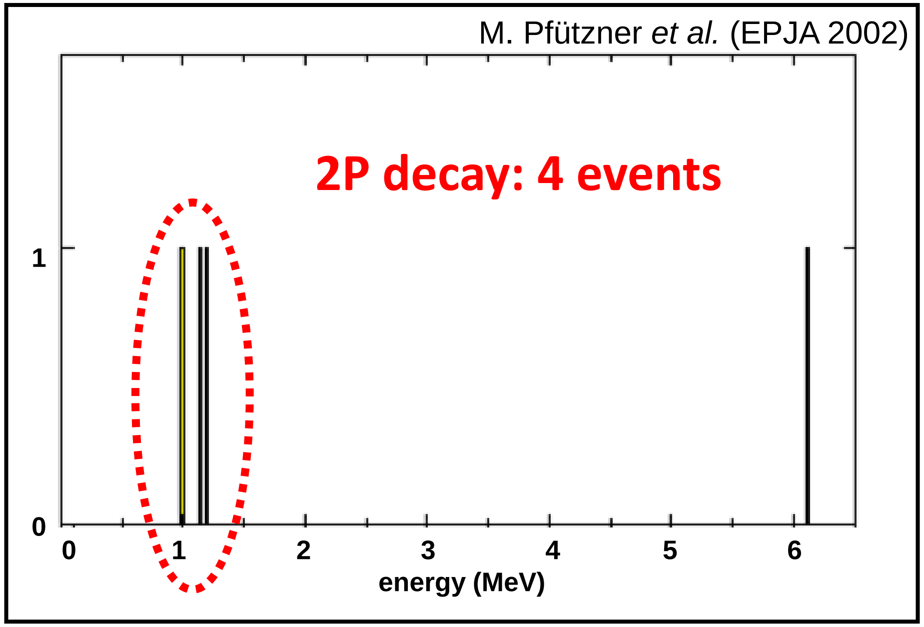


^{45}Fe decay @ GSI / FRS

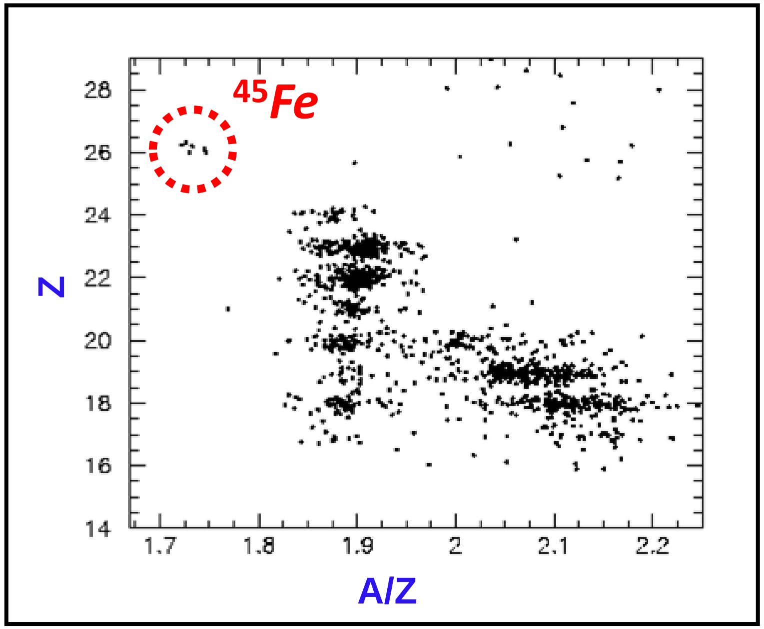
Decay analysis

$\beta^+ \rightarrow$ positron: 2×511 *keV* annihilation γ

2P → γ anti-coincidence



Identification plot (6 events)



$$T_{1/2} = 3.4^{+3.4}_{-1.1}\ ms$$

$$Q_{2P} = 1.1 \pm 0.1\ MeV$$

Good agreement with GANIL experiment for Q_{2P} and $T_{1/2}$

similar experiments

^{54}Zn

peak:

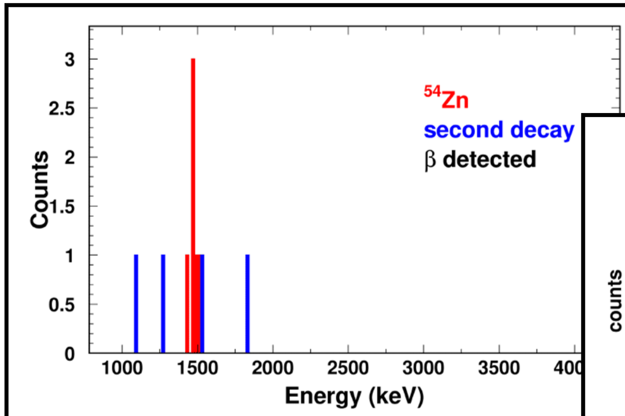
$$T_{1/2} = 3.2^{+1.8}_{-0.8}\ ms$$

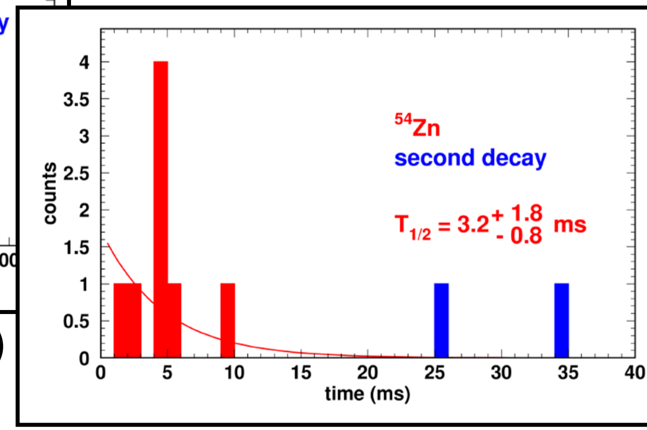
daughter (^{52}Ni):

$$T_{1/2} = 30 \pm 20\ ms$$

(C. Dossat, PhD: 39.9 ± 0.7 ms)

→ 2-proton emitter !





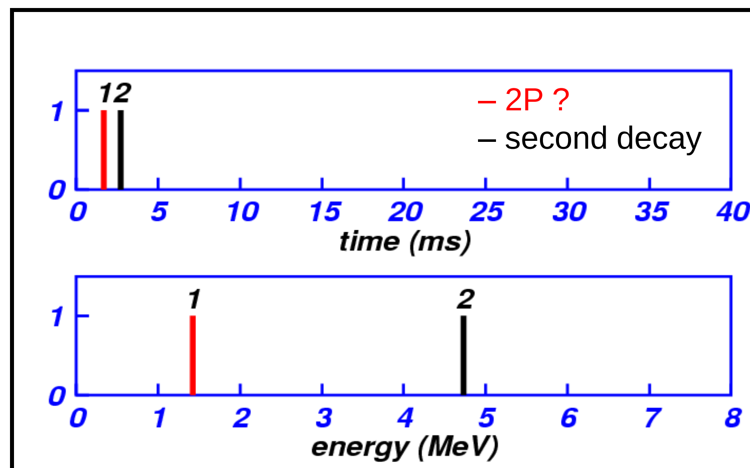
Blank *et al.* (PRL 2005)

^{48}Ni

3 decay events: **$T_{1/2}$ ~ 1-2 ms**

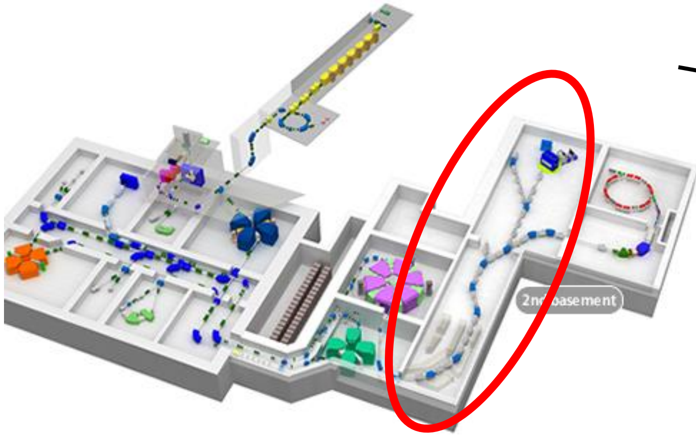
- 2 are compatible with β-delayed particle emission (β coinc. and high part. energy)
- 1 is compatible with **2-proton decay**

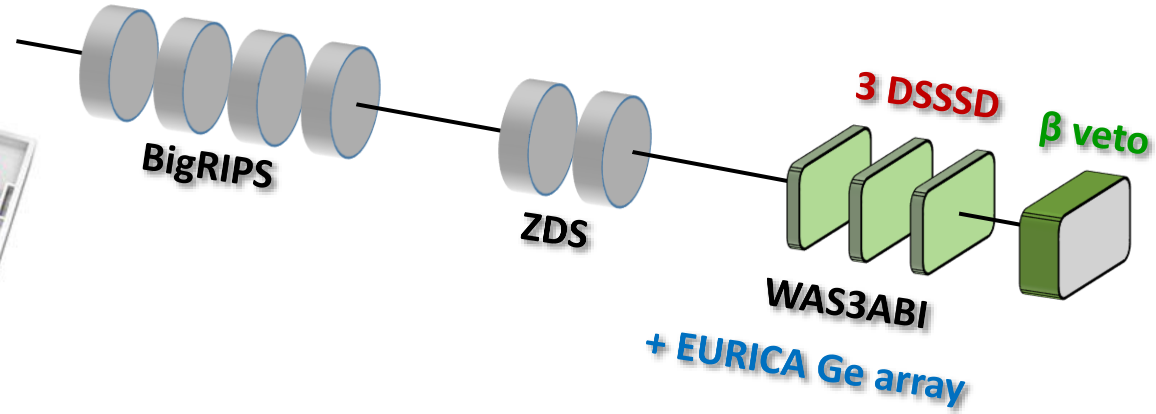
→ not enough to conclude…



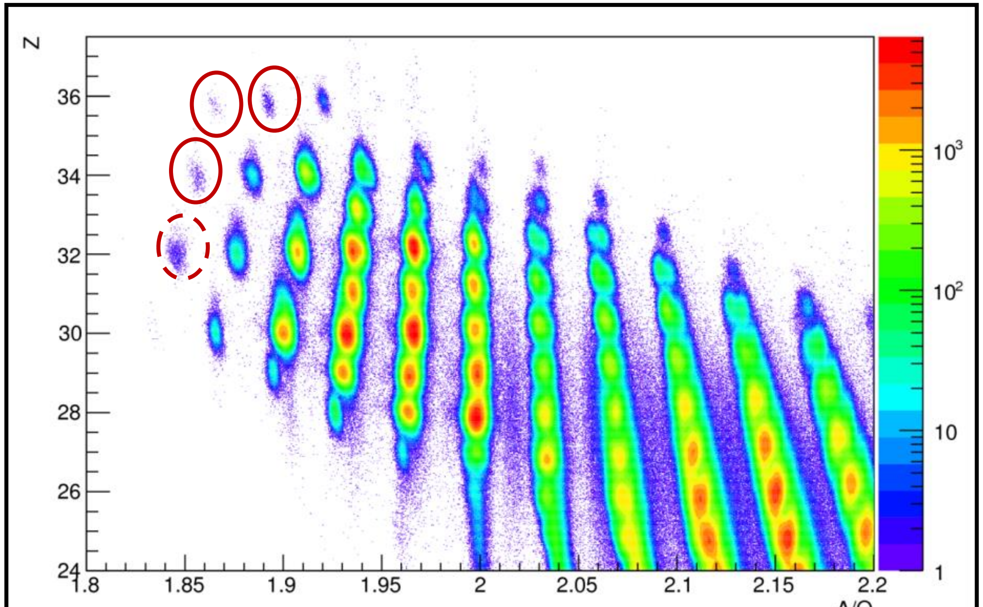
Dossat *et al.* (PRC 2005)

last identified emitter: ^{67}Kr





BigRIPS (+ZDS) ^{78}Kr beam campaign (2015): 350 MeV/A – 250 pnA
setting on ^{65}Br (between ^{63}Se & ^{67}Kr): about 5 days



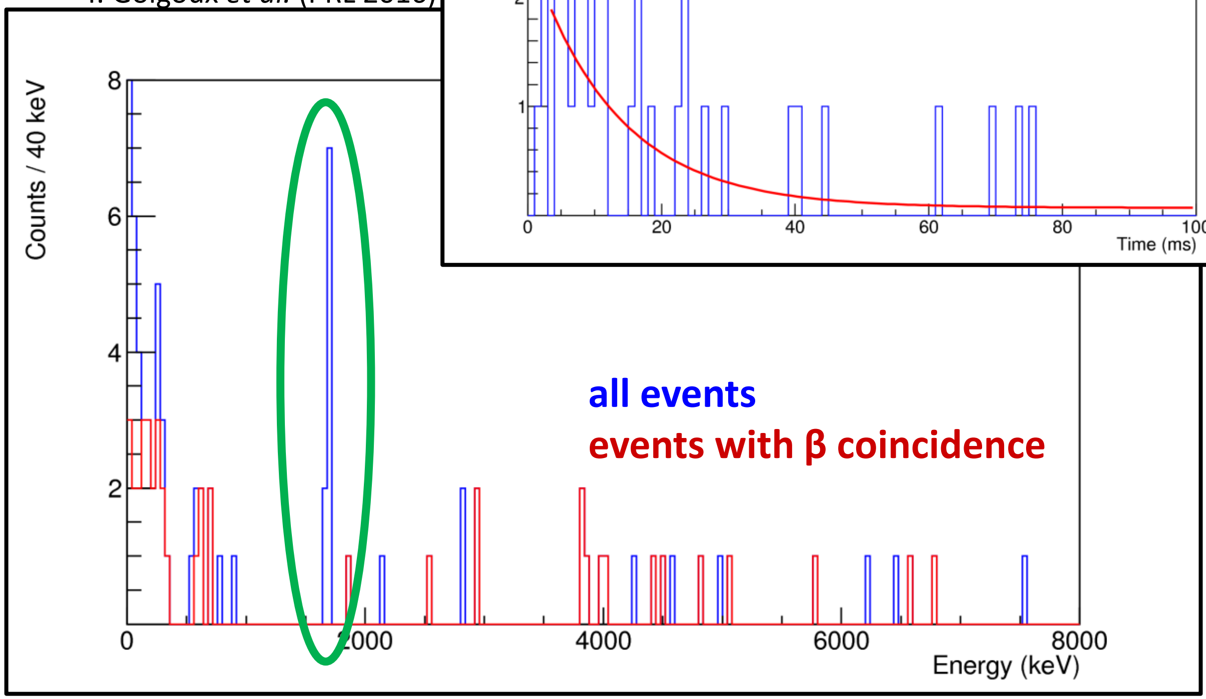
B. Blank *et al.* (PRC 2016)

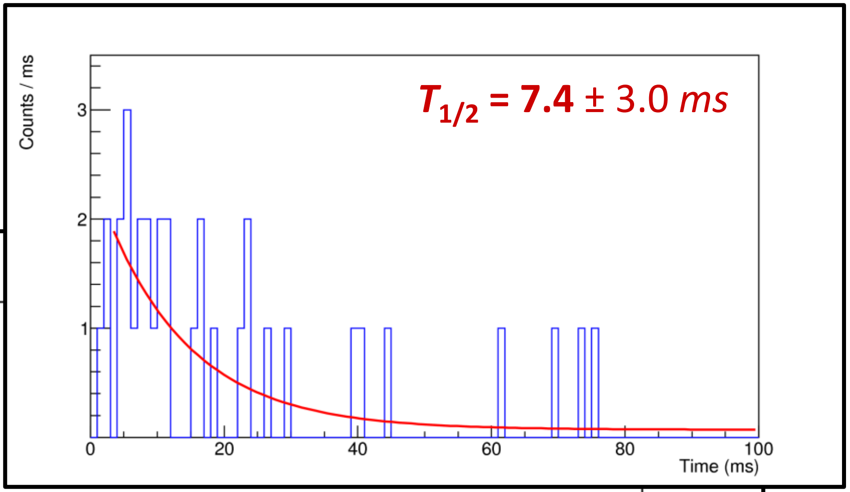
observed production

	BigRIPS (F7)	ZDS (F11)	WAS3ABI
^{59}Ge	1170	**979**	563
^{63}Se	336	**258**	193
^{67}Kr	80	**79**	49

last identified emitter: ^{67}Kr

T. Goigoux *et al.* (PRL 2016)





observed peak: 9 events

Q_{2P} = **1.69** ± 0.02 *MeV*

no beta coincidence

ε_β = **67** %

prob. to miss all ≈ $\mathbf{5\times10^{-6}}$

no annihilation 511 *keV*

ε_γ ≈ **8** %

prob. to miss all ≈ **45 %**

Q_{2P} = **1.69** ± 0.02 *MeV*

$T_{1/2}$ = **7.4** ± 3.0 *ms*

BR_{2P} = **37** ± 14 **%**

Indirect measurements

(long lived emitters)

in the 60's first predictions by Goldanskii

late 90's candidates can be produced at fragmentation facilities (discovery of ^{45}**Fe**, ^{48}**Ni**)

Discovery experiments

indirect measurements: global quantities only

2002 2-proton radioactivity of ^{45}**Fe** at GANIL & GSI

2004 2-proton radioactivity of ^{54}**Zn** (GANIL)
indication of a possible 2P-decay for ^{48}**Ni** (1 event)

2016 2-proton radioactivity of ^{67}**Kr** (RIKEN)

indirect evidence

→ **no individual observation of the emitted particles**

experimental information:

→ only **global quantities**: Q_{2P} , $T_{1/2}$ and **B.R.**

→ limited theoretical interpretation
(1 information, since Q_{2P} is an **input** for calculations)

Indirect measurements

L.V. Grigorenko: emission dynamics
half-lives:
$T_{1/2}$ for pure (s^2,) p^2 and f^2 config.

B.A. Brown: nuclear structure
2-proton amplitudes:
for pure (s^2,) p^2 and f^2 config

"Shell model corrected half-lives"

$A = A(f^2) + A(p^2) \Longrightarrow T_{1/2}(2P)$

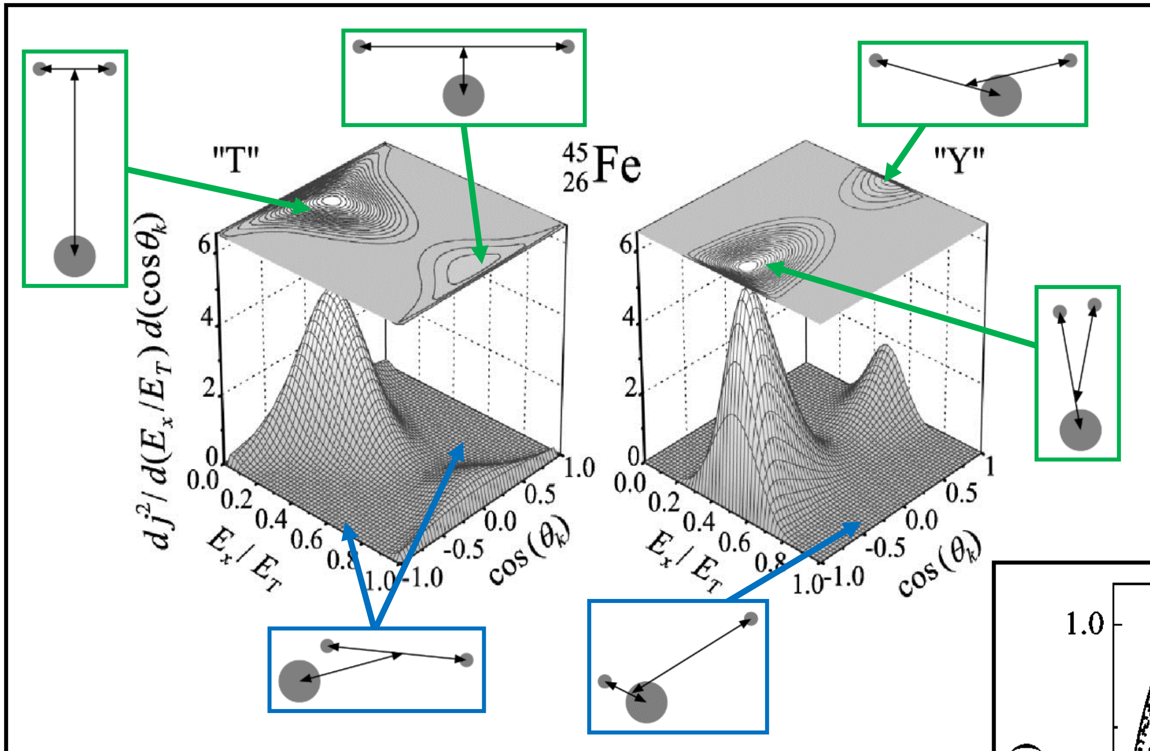
	calculation	experiment(s)	
^{45}Fe	2.7 *ms*	$3,76 \pm 0,26$ *ms*	OK
^{54}Zn	1.6 *ms*	$1.98^{+0.73}_{-0.41}$ *ms*	OK
^{67}Kr	660 *ms*	21 ± 12 *ms*	**!?**

Lower life-time for 3-body model: 240 ms (pure p^2 configuration)

Proton(s) radioactivity

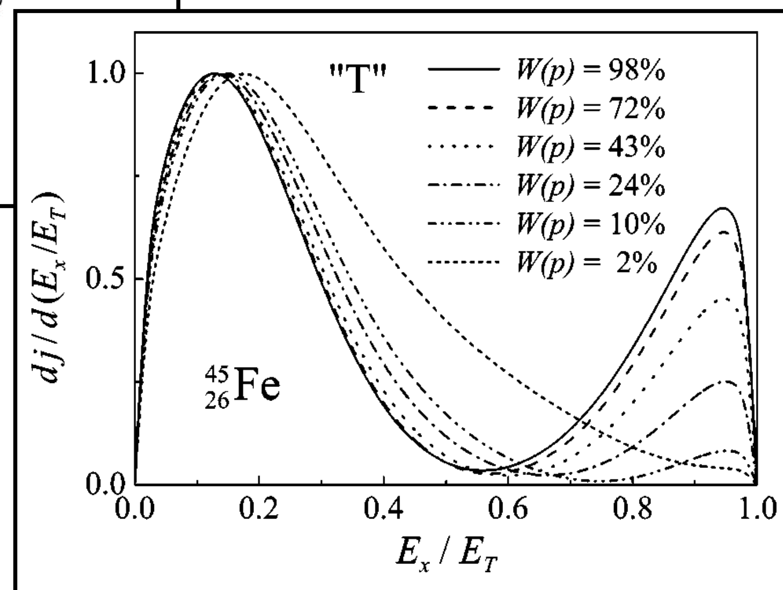
- Particle emission at the proton drip-line
- 1-proton radioactivity
  - Experimental studies
  - Probing nuclear structure
- **2-proton radioactivity**
  - Search for candidates
  - Discovery experiments
  - **Tracking experiments**

Proton-proton correlations: 3-body model



L.V. Grigorenko, Phys. Rev. C (2003)

see lecture from L.V. Grigorenko



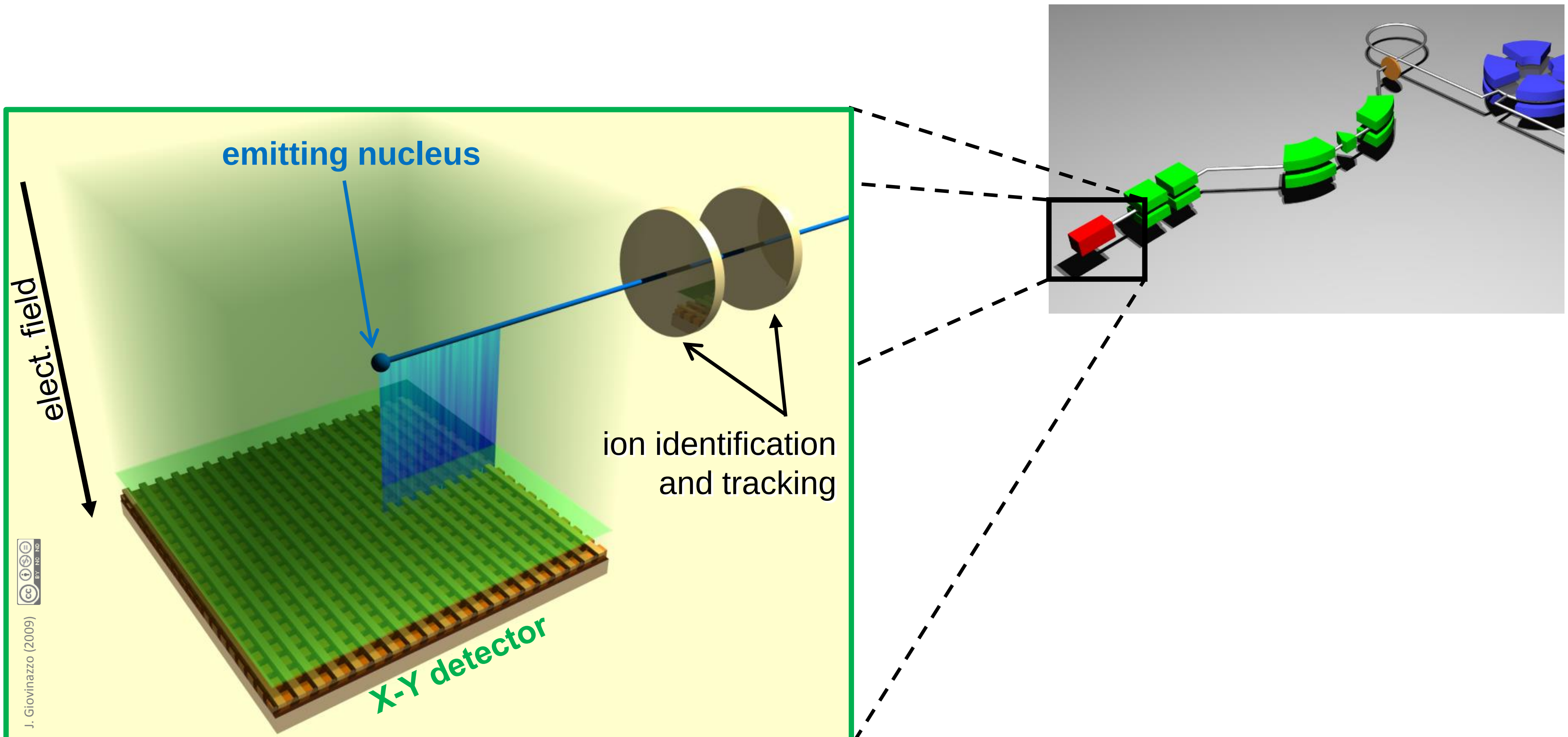
prediction of distributions for
- **energy sharing between protons**
- **proton-proton angular correlations**

emission kinematics
sensitive to the emitter structure

Proton-proton correlations measurement

nuclei produced only at fragmentation facilities
→ implanted in a thick stopper
→ need to “see” the protons in the stopper

} use of an active gas stopper: **TPC**



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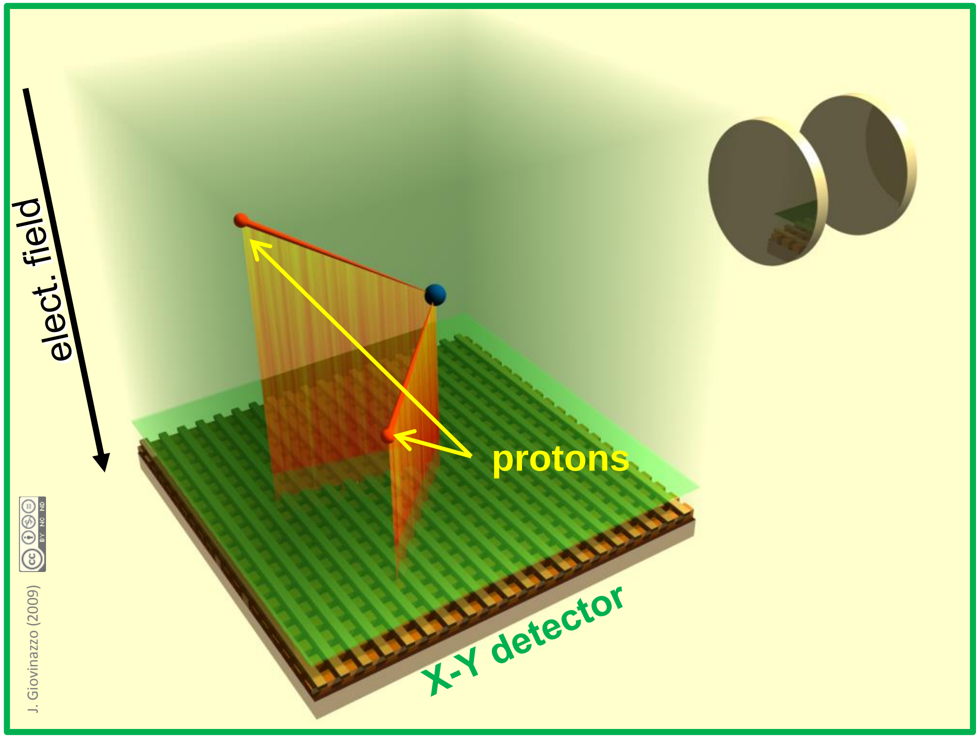


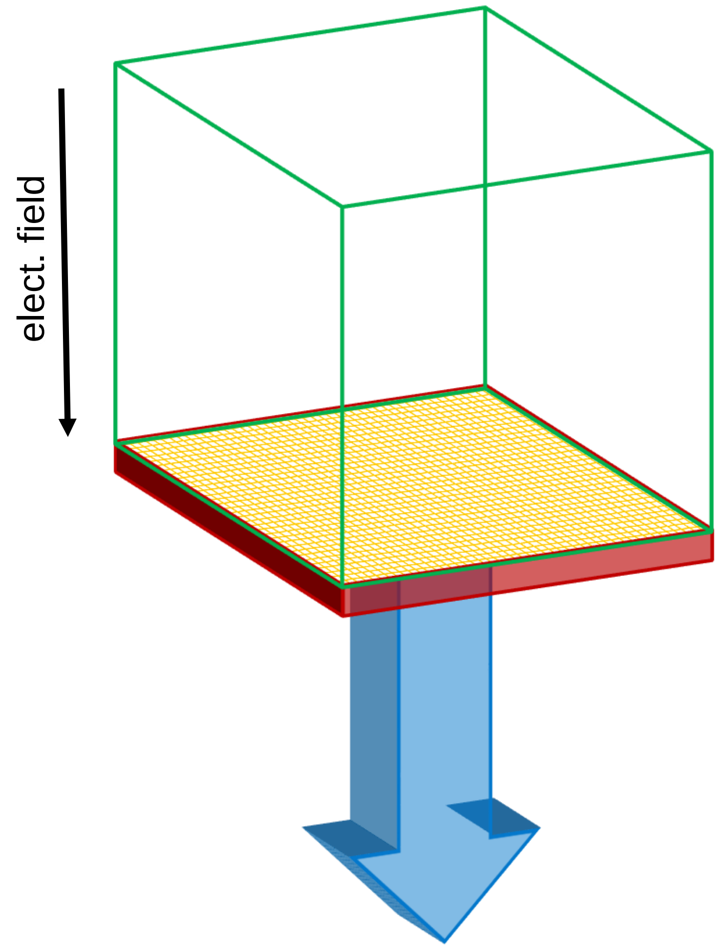
charged particles slow down in the **gas volume**

ionisation electrons drift to a 2D detector

the **2D detector** registers the **tracks projection**

the **drift time** measures the **3rd dimension**

TPCs for 2-proton radioactivity studies

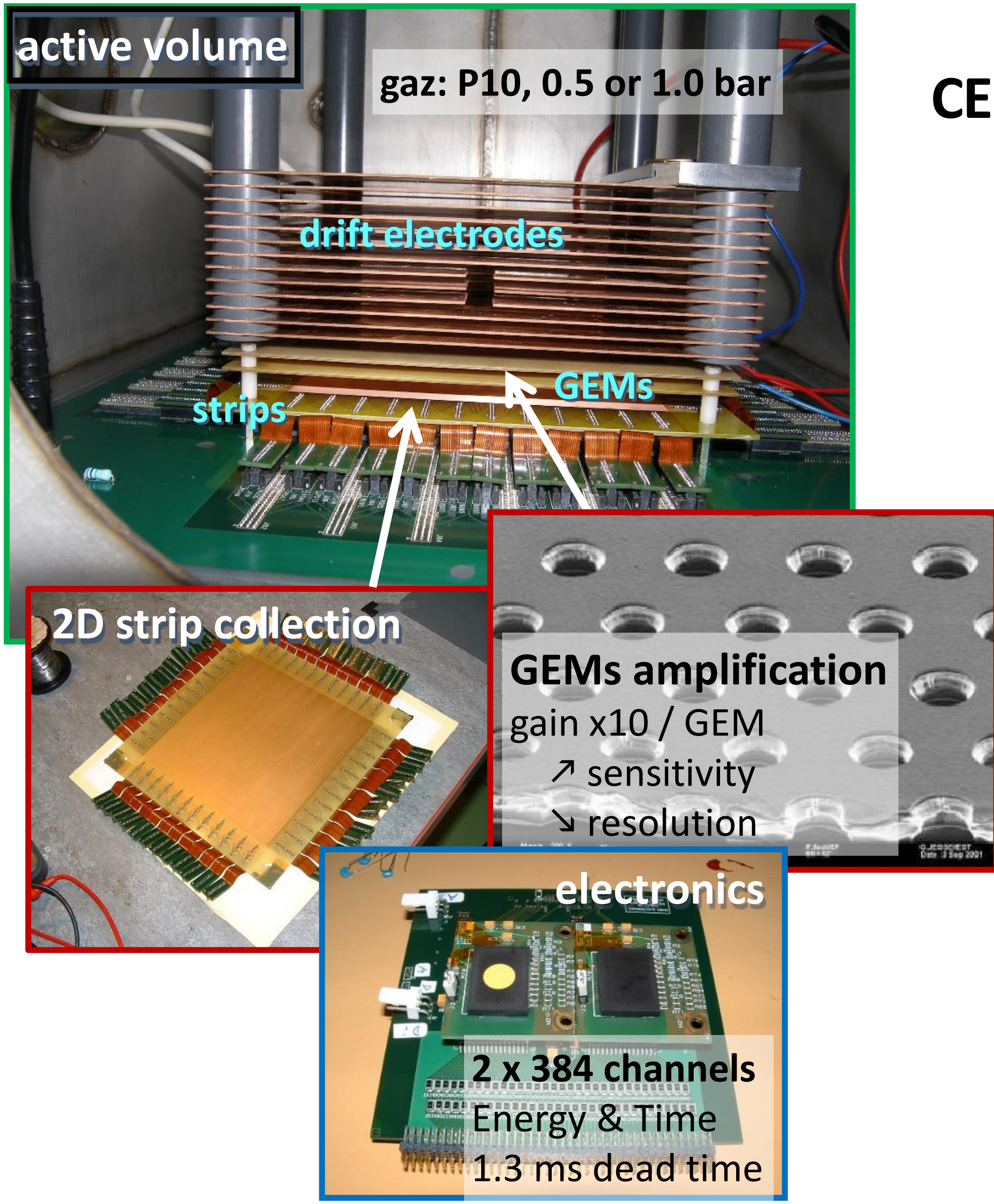


drift volume (gas)
(uniform electric field)

collection plane
(charge collection)

signal readout
(amplitude and time)

TPCs for 2-proton radioactivity studies



CENBG TPC

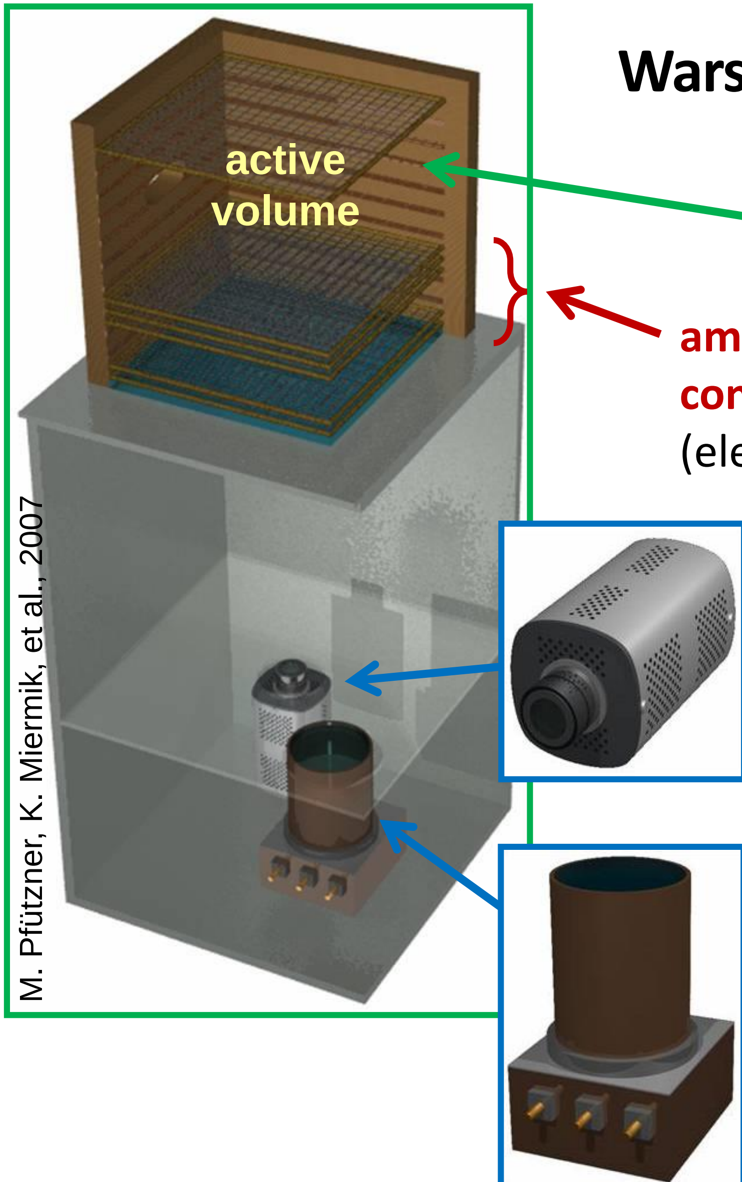
drift volume (gas)
(uniform electric field)

collection plane
(charge collection)

signal readout
(amplitude and time)

TPCs for 2-proton radioactivity studies

Warsaw Optical-TPC



drift volume (gas)
(uniform electric field)

amplification and conversion
(electrons to light)

collection plane
(charge collection)

CCD camera
cumulated light
full 2D projection

signal readout
(amplitude and time)

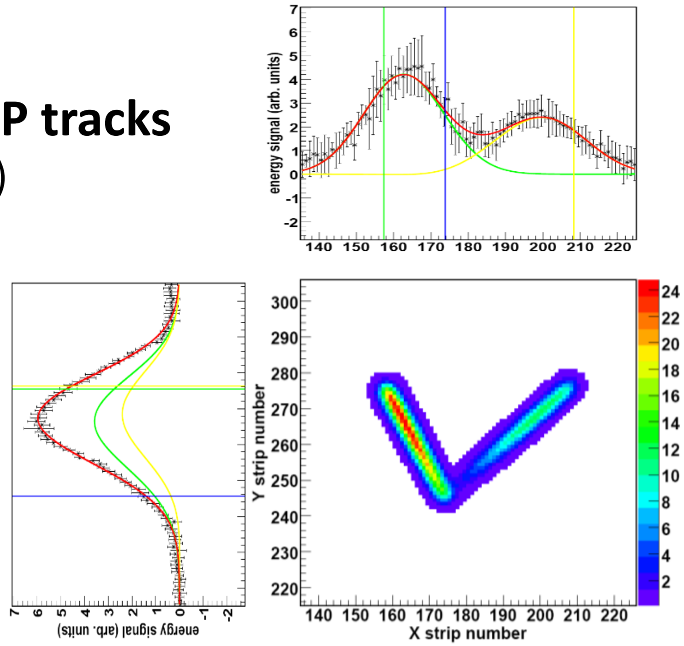
Photomultiplier
with sampling ADC
→ **time** distribution of total signal

Direct observation of 2-proton radioactivity

^{45}Fe

first 2P tracks

(GANIL)

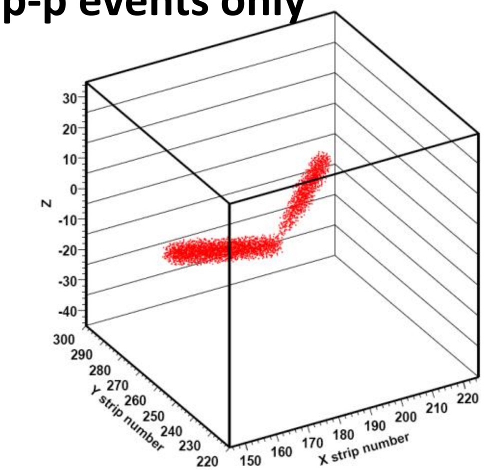


J.G. *et al.*, PRL 2007

^{54}Zn

(GANIL)

7 p-p events only



P. Ascher *et al.*, PRL 2011

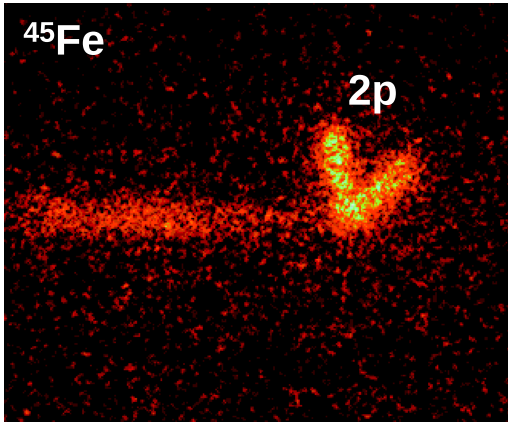
^{48}Ni

established as 2P emitter

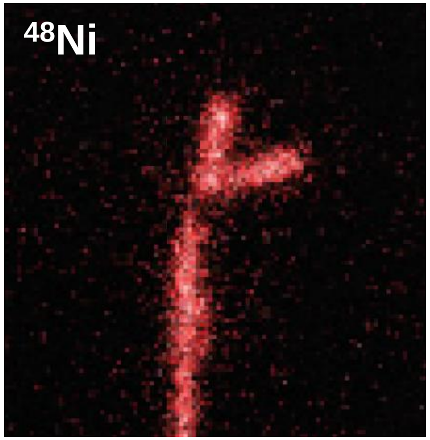
4 p-p events

experiment @ NSCL

→ 75 counts of p-p correlations



K. Miernik *et al.*, PRL 2007

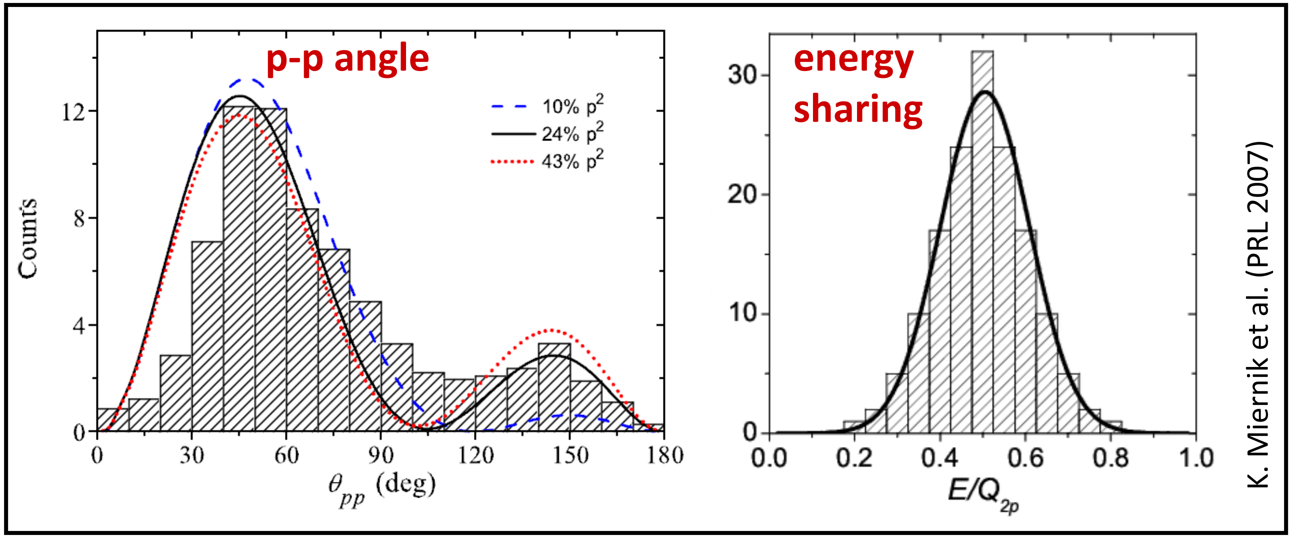


M. Pomorski *et al.*, PRL 2011

Probing nuclear structure

first angular distribution: good agreement with **predictions** from the 3-body model

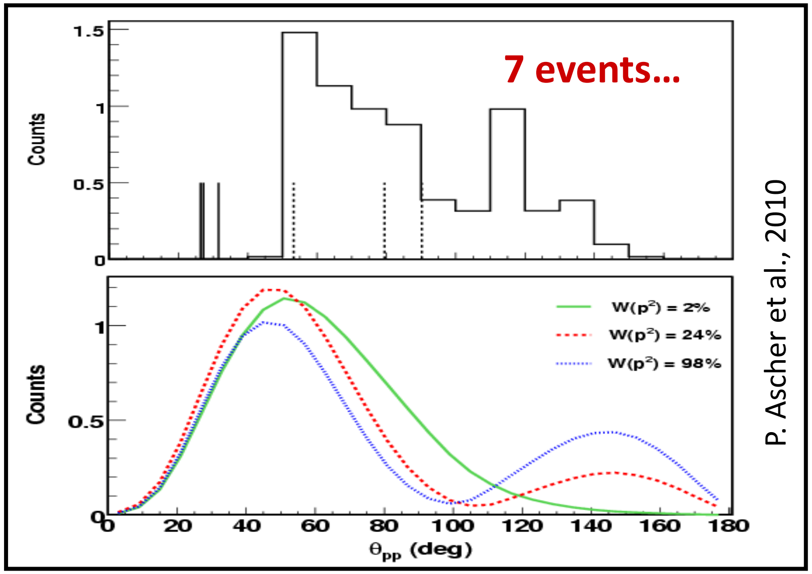
^{45}Fe (MSU)



pioneering experiments

→ **opening structure studies** at the drip-line
→ angular distribution probes the **wave function** content (single particle states)

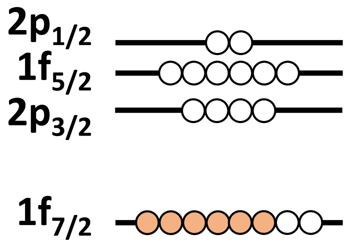
requires more statistics
other cases to test the models descriptions



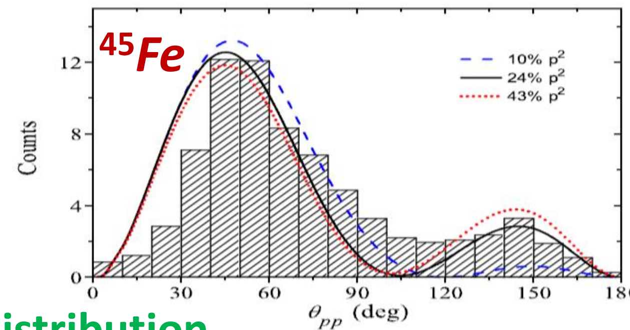
^{54}Zn (GANIL)

Probing nuclear structure

^{45}Fe : Z = 26

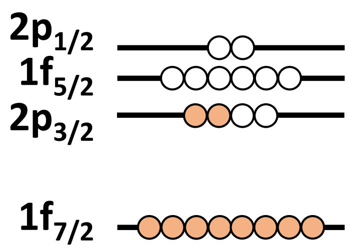


$W(p^2) = 24\%$



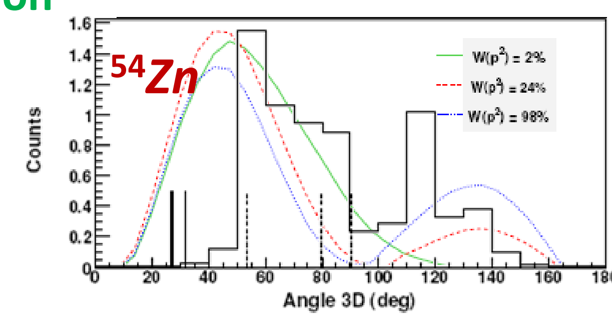
K. Miernik *et al.*, EPJA (2009)

^{54}Zn : Z = 30



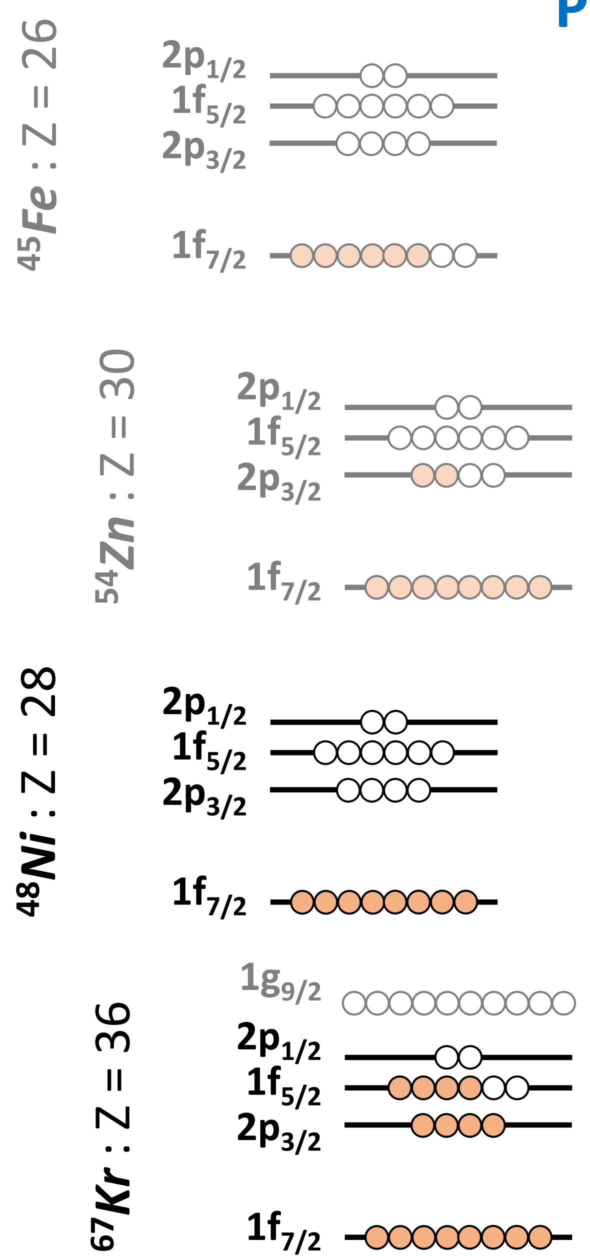
proton-proton angular distribution
→ orbitals configuration

$W(p^2) = 30^{+33}_{-21}\%$



P. Ascher *et al.*, PRL (2011)

Probing nuclear structure



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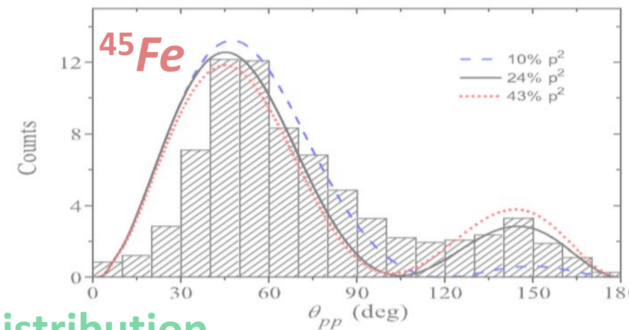

K. Miernik *et al.*, EPJA (2009)

proton-proton angular distribution
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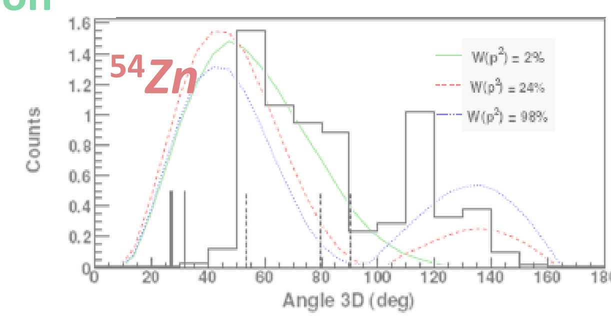


P. Ascher *et al.*, PRL (2011)

^{48}Ni ??

doubly magic → pure configuration ?

^{67}Kr ??

calculation: $(p_{3/2})^2$ configuration ?
→ deformation ?
→ mixed direct / sequential emission ?

lecture from L. Grigorenko

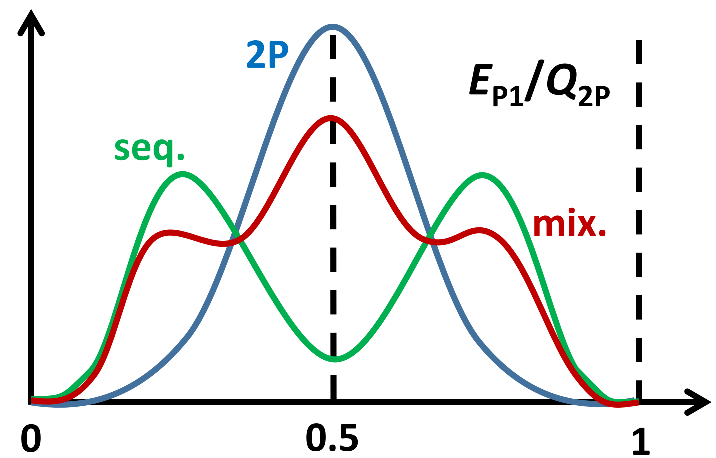
Further studies for 2P radioactivity

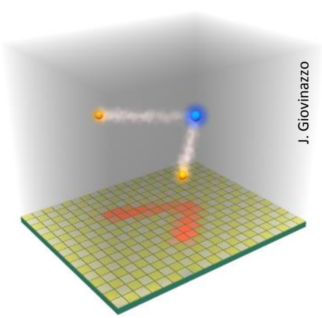
(1) improve experimental information of known emitters

→ ^{54}***Zn***: experiment accepted at RIKEN with O-TPC (M. Pfützner *et al.*)

→ ^{48}***Ni***: (doubly magic) exp. at GANIL (J.G. *et al.*)
limited statistics expected (~20 counts)
require improvements of identification to increase separator acceptance

→ ^{67}***Kr***: exp. at RIKEN (J.G. *et al.*):
different decay pattern (sequential) ?
energy sharing distribution…





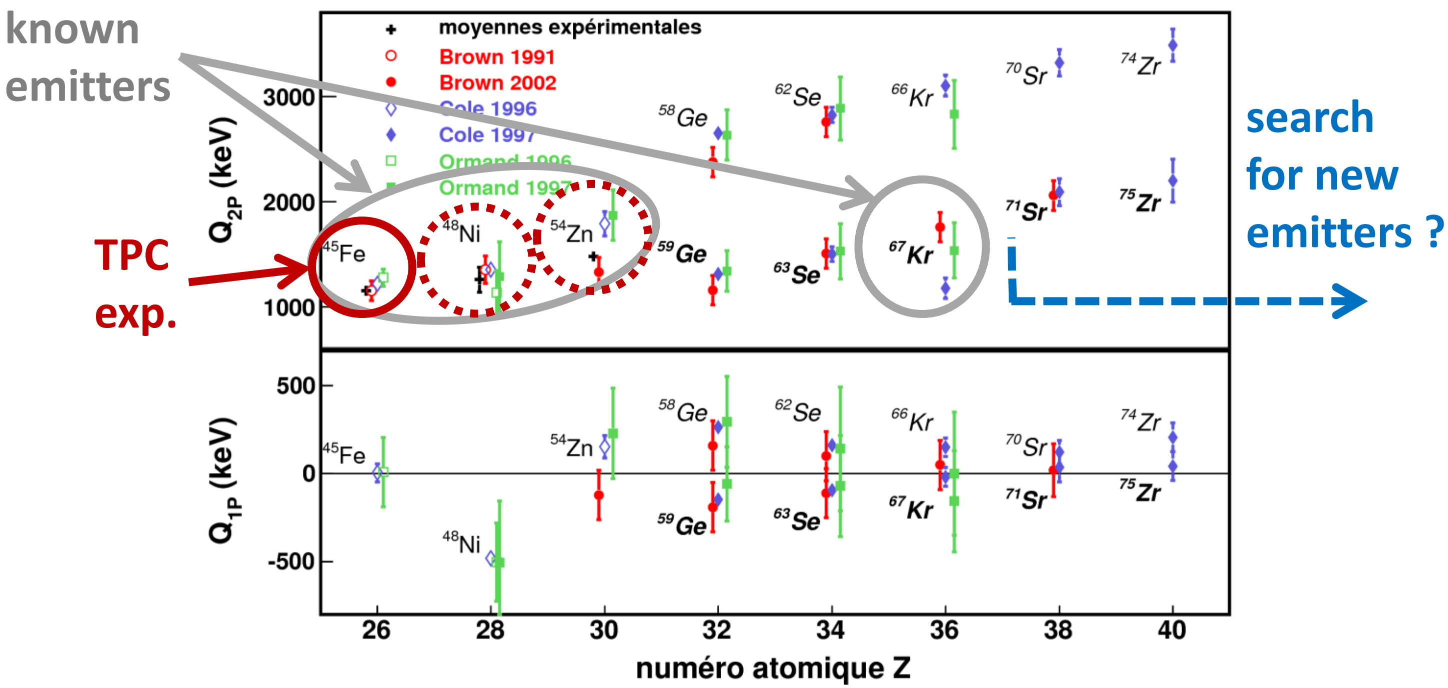
tech. dev.: ACTAR TPC
(for ^{48}***Ni*** & ^{67}***Kr*** exp.)

Further studies for 2P radioactivity

(1) improve experimental information of known emitters

(2) search for new candidates up to $Z \sim 50$ (Tin)

production at FAIR / SuperFRS



Further studies for 2P radioactivity

(1) improve experimental information of known emitters

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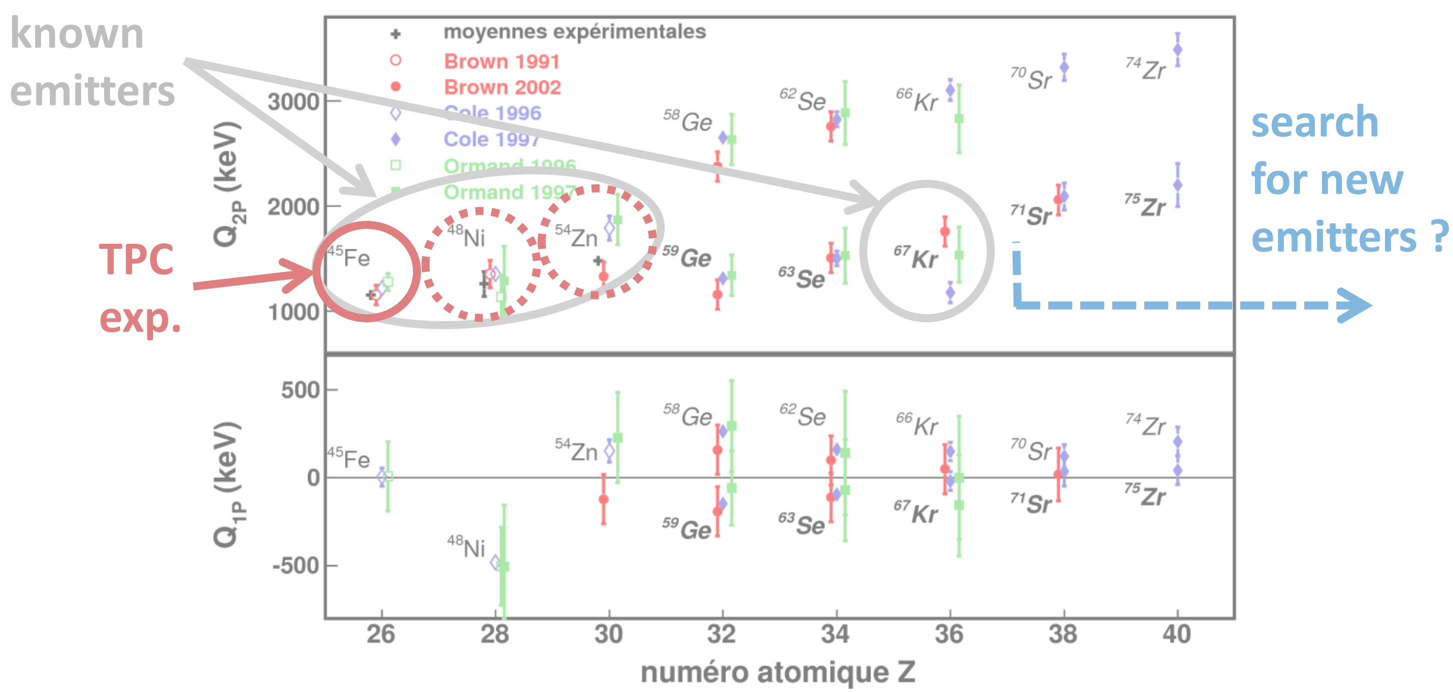
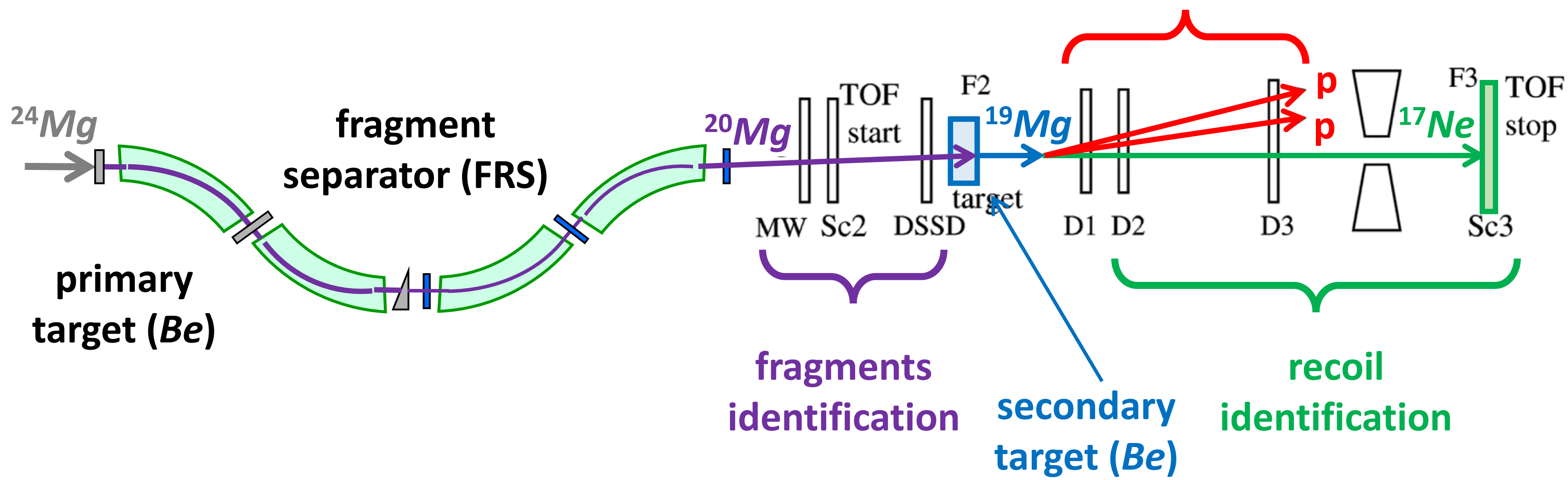


(3) consolidate and improve theoretical interpretations

for a combined nuclear structure and emission dynamics

^{19}*Mg*: a short-lived 2P emitter

secondary reaction production (GSI/FRS)



I. Mukha *et al.*, PRL 2007

^{19}*Mg*: a short-lived 2P emitter

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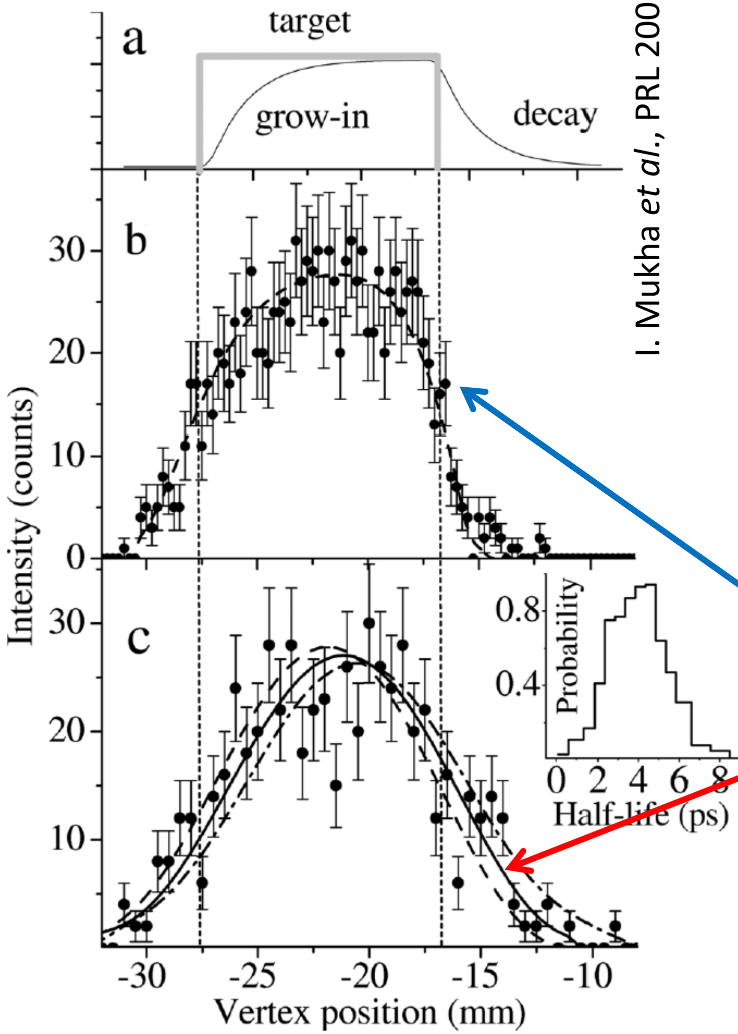
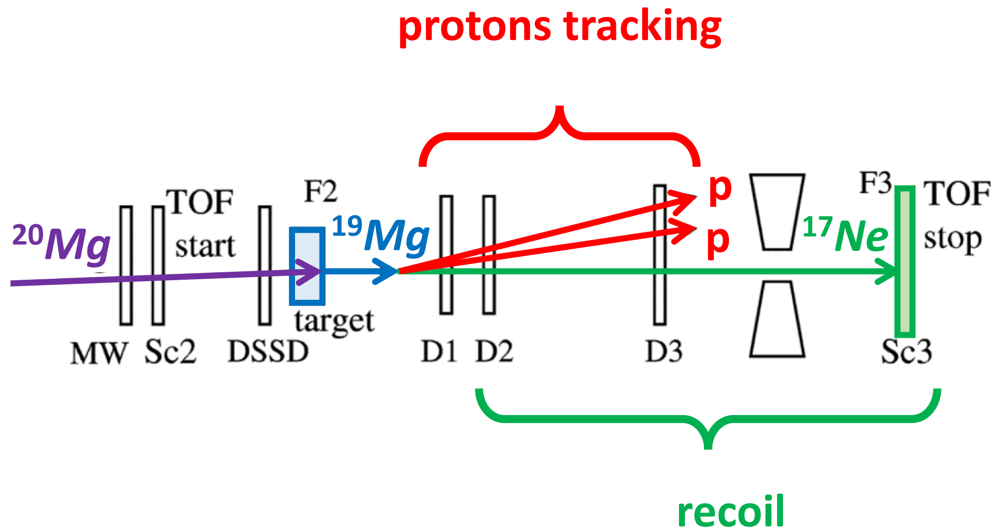


I. Mukha *et al.*, PRL 2007



^{17}*Ne*+p+p events kinematics reconstruction

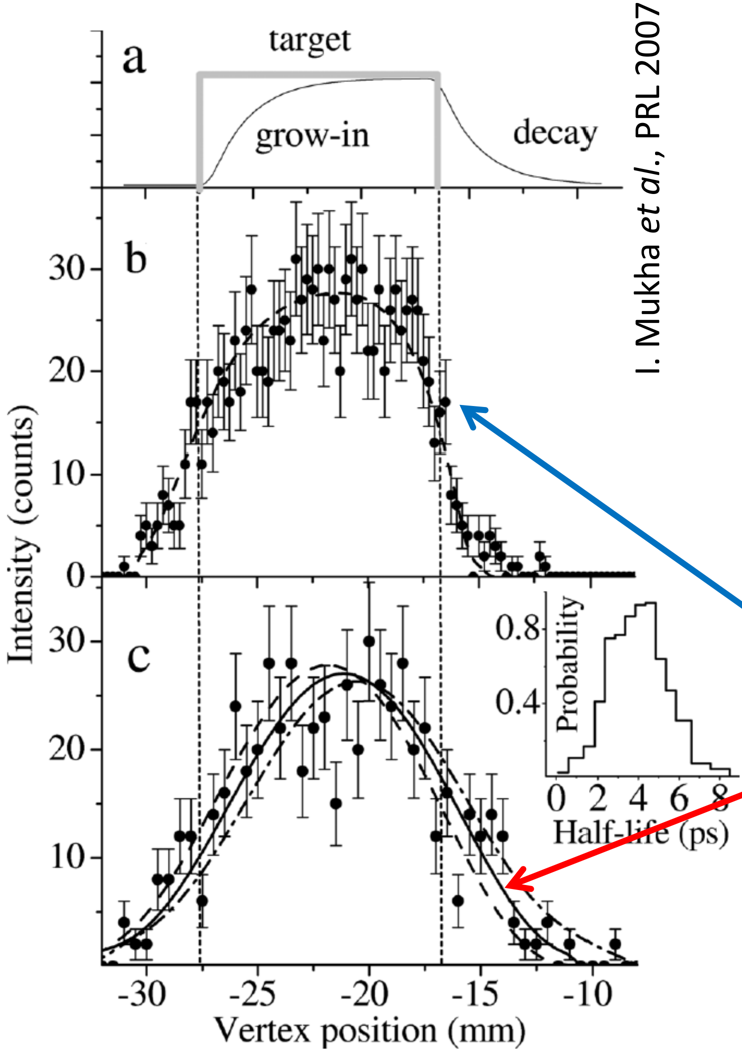
→ from vertex position:

- **fast emission of excited states**
- **delayed decay of ground state:**

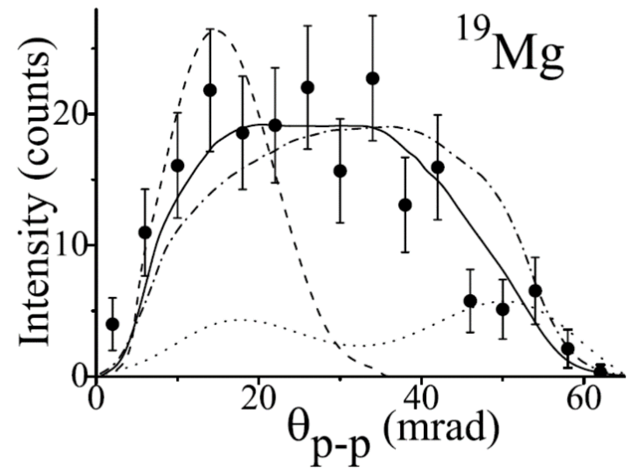
  $T_{1/2}$ = 4.0 ± 1.5 *ps*

^{19}*Mg*: a short-lived 2P emitter

secondary reaction production (GSI/FRS)



I. Mukha *et al.*, PRL 2007



I. Mukha *et al.*, PRC 2008

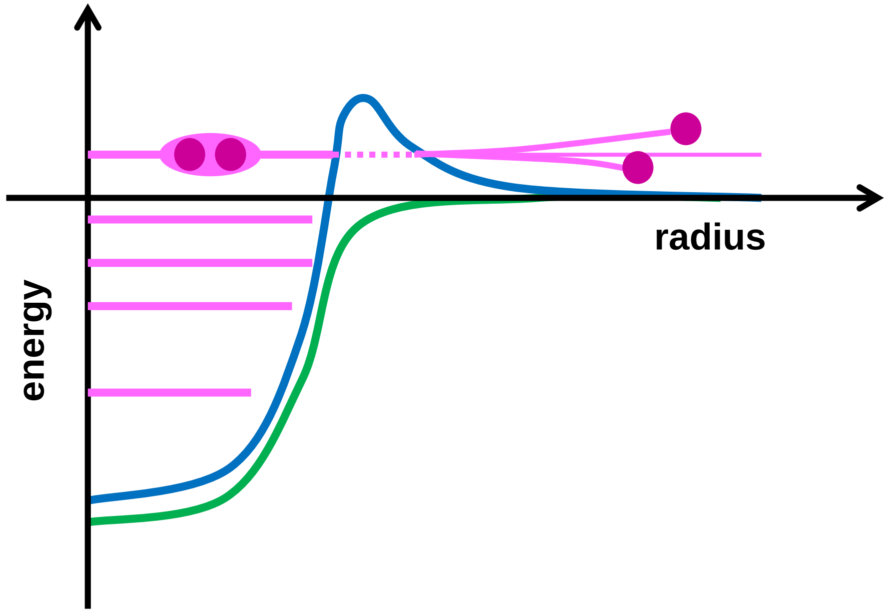
^{17}*Ne*+*p*+*p* events kinematics reconstruction

→ from vertex position:

- **fast emission of excited states**
- **delayed decay of ground state:**
  $T_{1/2}$ = 4.0 ± 1.5 *ps*

→ *p-p* angles reconstruction
good agreement with 3-body model

Physics of two-proton radioactivity



ground-state 2-proton radioactivity

→ **drip-line and masses**
(beyond the « drip-line »)
transition Q-values

→ **nuclear structure**
energies, half-life,
levels configuration

→ **pairing**
correlations in energy and angle
of emitted protons

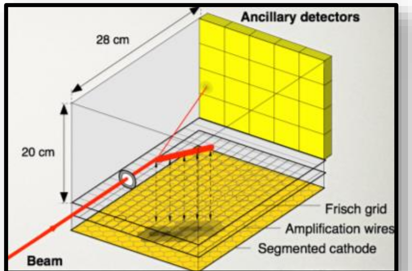
→ **tunnel effect**
theoretical descriptions

the emitted protons carry information on what's going on inside the nucleus
the 2-proton radioactivity mixes the **structure** (wave functions) and the (decay) **dynamics**

Additional selected topics

- Delayed proton emission to test weak interaction
- ACTAR TPC

time projection chambers for (fundamental) nuclear physics

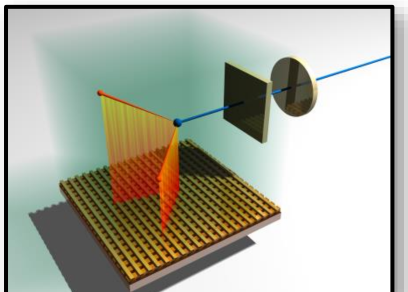


MAYA

(GANIL and coll.)

nuclear reactions

pads (hex): 2D proj.
wires: drift time



CENBG TPC

ions stopping and decay

X-Y strips
energy & time:
2x 1D proj.

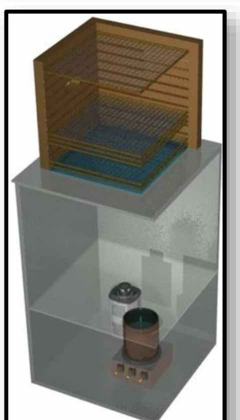


image Warsaw coll.

Optical TPC
(Warsaw)

ions stopping and decay

CCD cam.: 2D proj.
PM + sampling:
global time dist.

development of a new TPC
for a large (nuclear) physics case

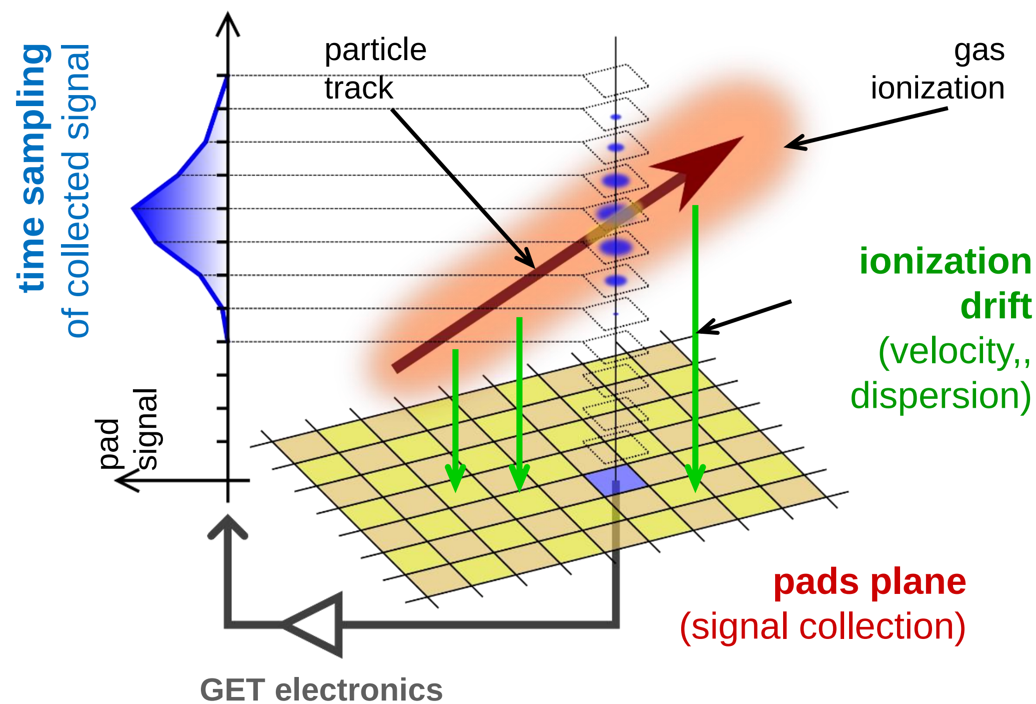
actar TPC

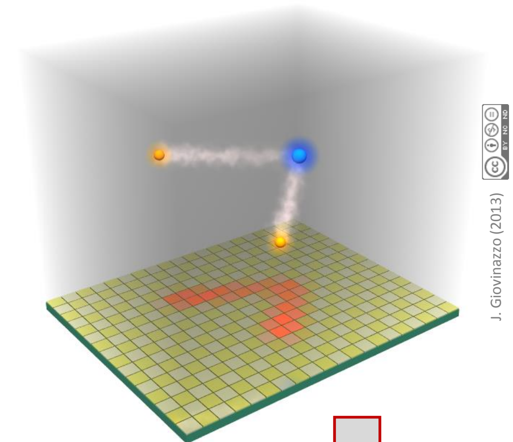
GANIL, CENBG, IPNO (F)
Leuven (B), Santiago de C. (S)

Full 3D + charge reconstruction

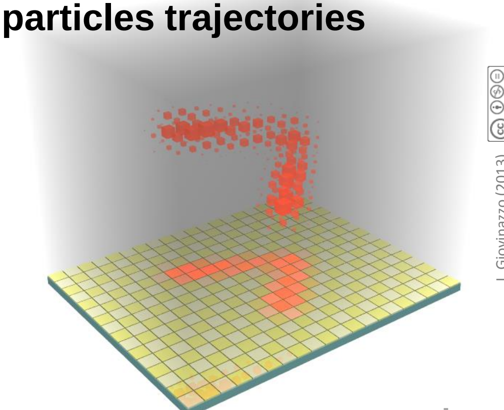
pads plane (signal collection)	TPC principle	time sampling of signal
2D digitization	$z \Leftrightarrow t$	3D digitization

$$\Delta E(x,y,z) \Longleftrightarrow \Delta E[x_i,y_j](z) \Longleftrightarrow \Delta E[x_i,y_j](t) \Longleftrightarrow \Delta E[x_i,y_j,t_k]$$





3D reconstruction of ionizations charges along the particles trajectories

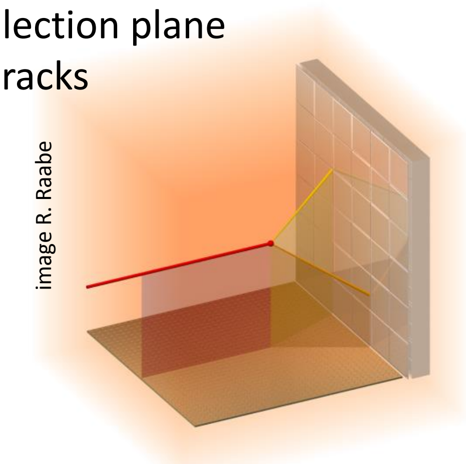


to dem.
to phys.

1 development, 2 chambers

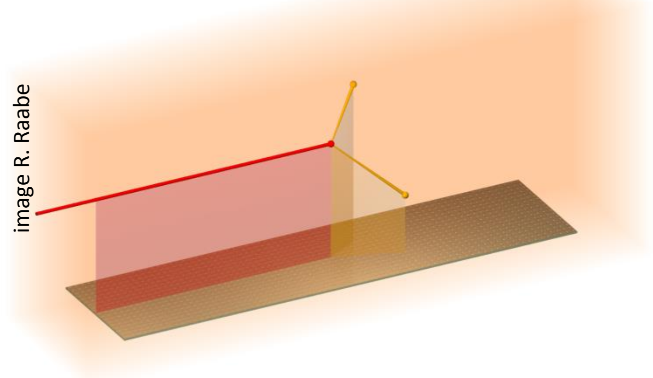
“reaction” chamber

128x128 pads collection plane
large transverse tracks



“decay” chamber

256x64 pads collection plane
short transverse tracks, larger implantation depth



shared design and technology

16384 pads, 2x2 mm^2
2 geometries

→ main funding: ERC
(J.F. Grinyer, GANIL)

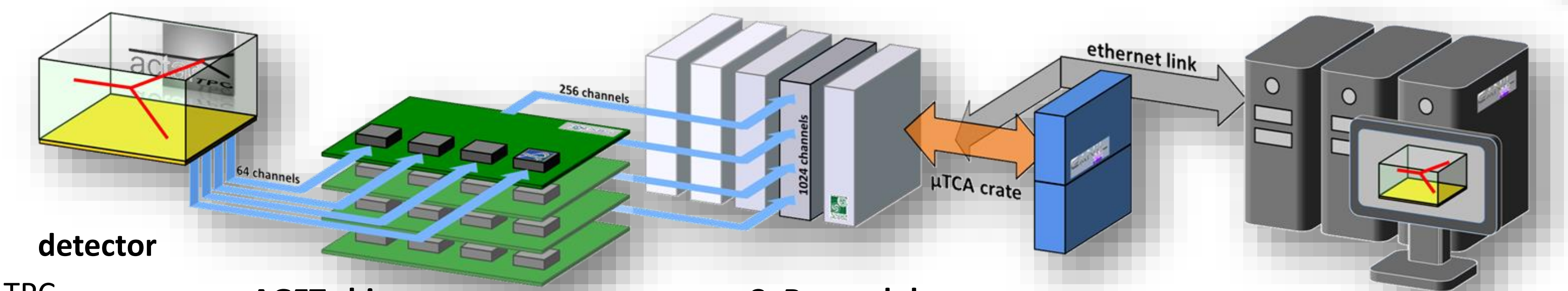
→ decay chamber: Region
pad plane R&D
(J. Giovinazzo, CENBG)

GET electronics
technical solution
for channels readout

Dedicated electronics

IRFU, CENBG, GANIL, MSU
ANR 2011-2015

GET



detector
TPC
16384 pads

AGET chip
64 channels
signal processing (CSA + shaper),
analog memory,
discriminator

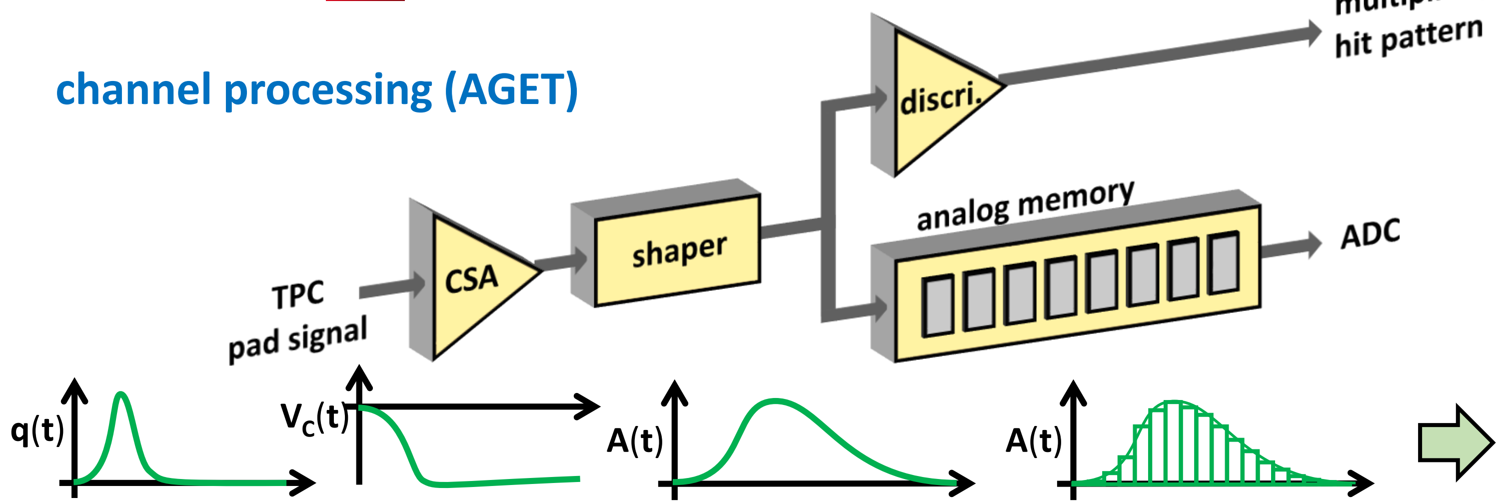
AsAd board
4 chips
(+ config.)
signal & mult. coding (ADC)

CoBo module
4 AsAd boards
digital data management

MuTAnT
clock distrib.,
trigger management (3 levels)

control / acquisition

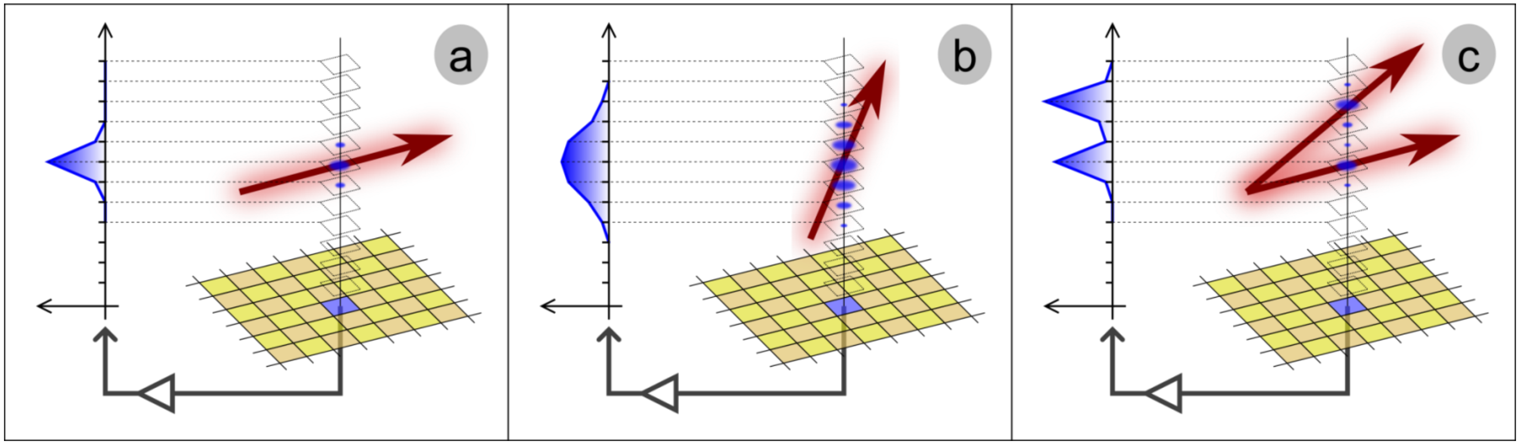
channel processing (AGET)



reconstruction procedure needed

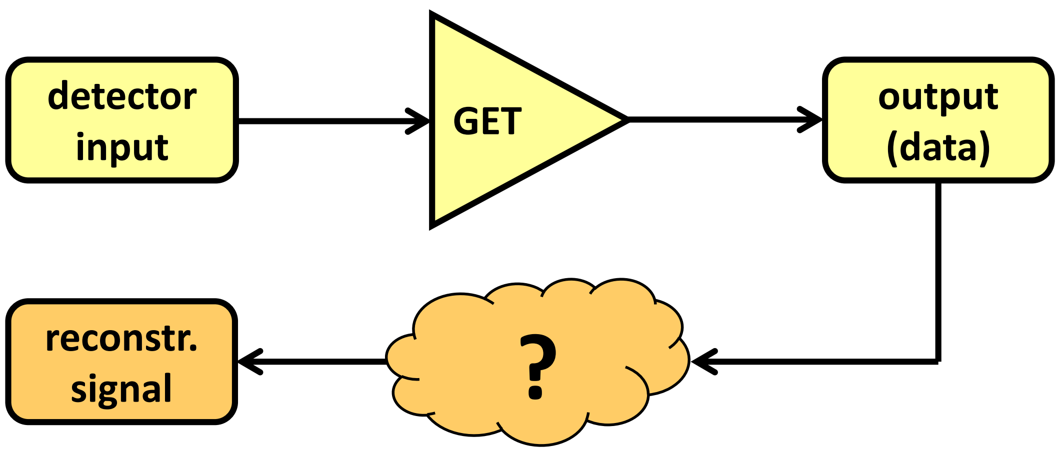
input signal: charge distribution

input charge distribution depends on tracks



but... charge distribution information is “washed out” by AGET shaping

reconstruction principle: deconvolution from AGET response function



to dem.
to phys.

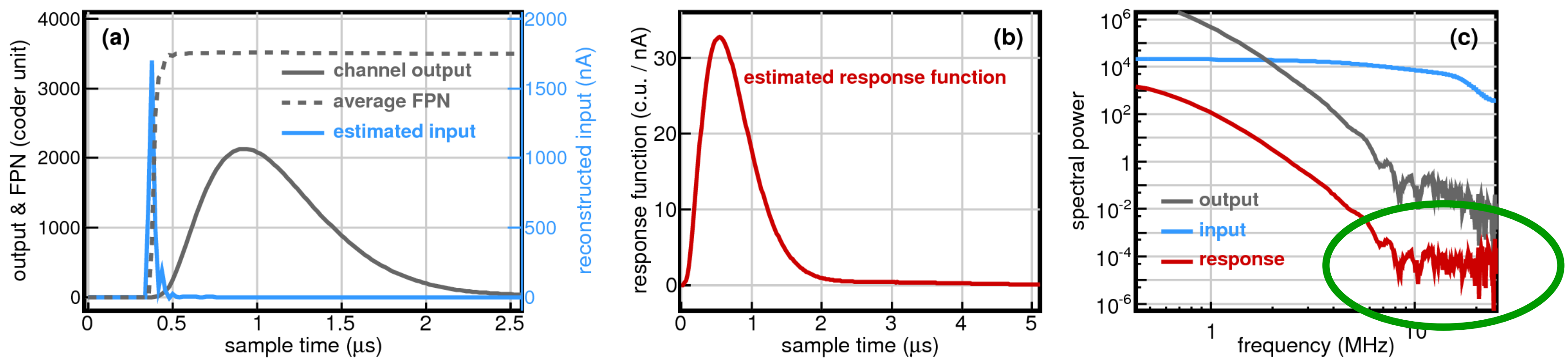
Empirical response function

response function estimate from input pulser

→ AsAd pulser (with FPN channels ≡ input signal)

→ external pulser

de-convolution in Fourier space (use of **FFT**): $\tilde{H}[k] = \dfrac{Out[k]}{\widetilde{In}[k]}$

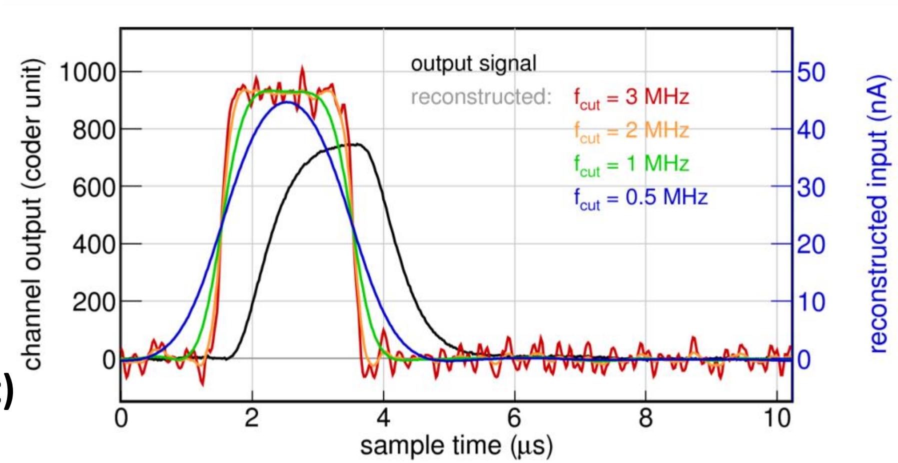


residual noise → need for filtering

→ **low-pass** filter:

$$\tilde{I}_j^{[k]} = \frac{S_j^{[k]}}{\tilde{H}_j^{[k]}} \cdot \Phi^{[k]}$$

single event (square input)



Reconstruction characterization

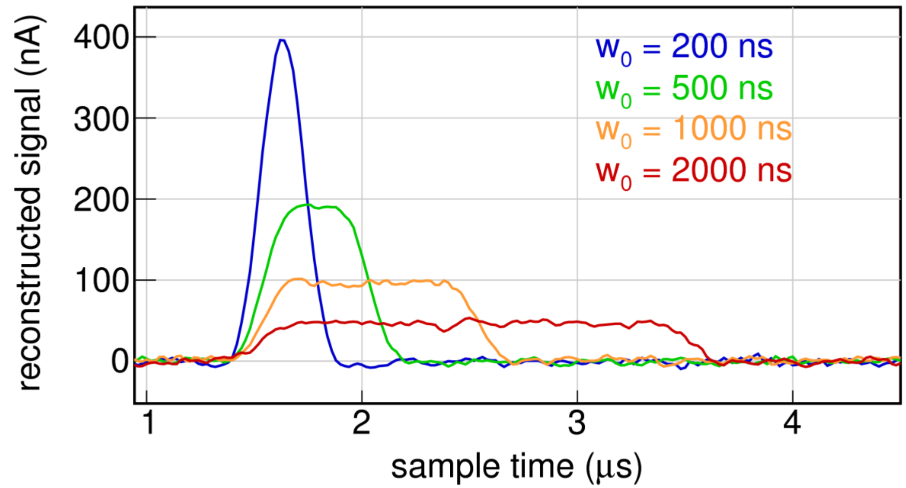
→ **reconstruction fidelity**
difference between reconstructed and input signal

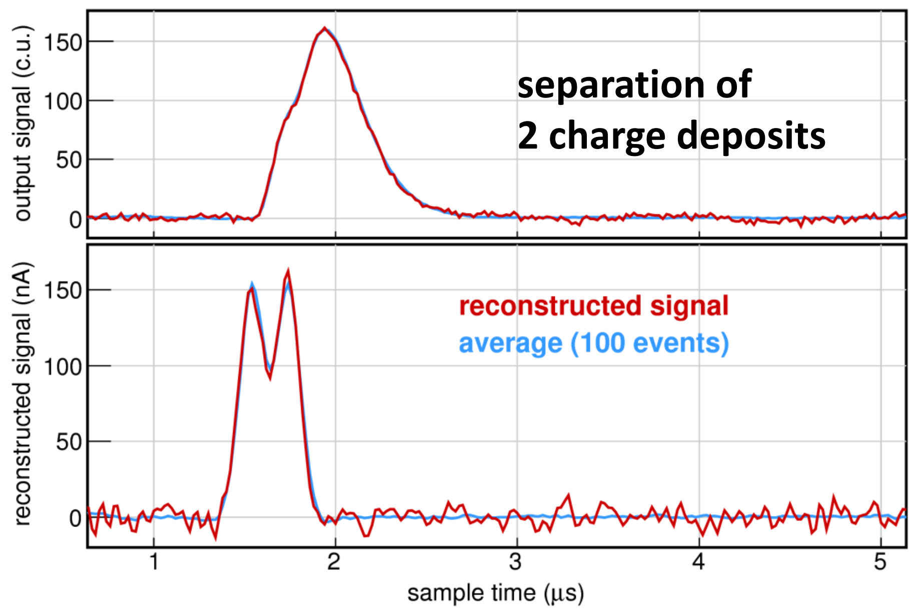
→ **reconstruction resolution**
separation of 2 point charges

→ **timing precision**

results are a compromise between noise and precision

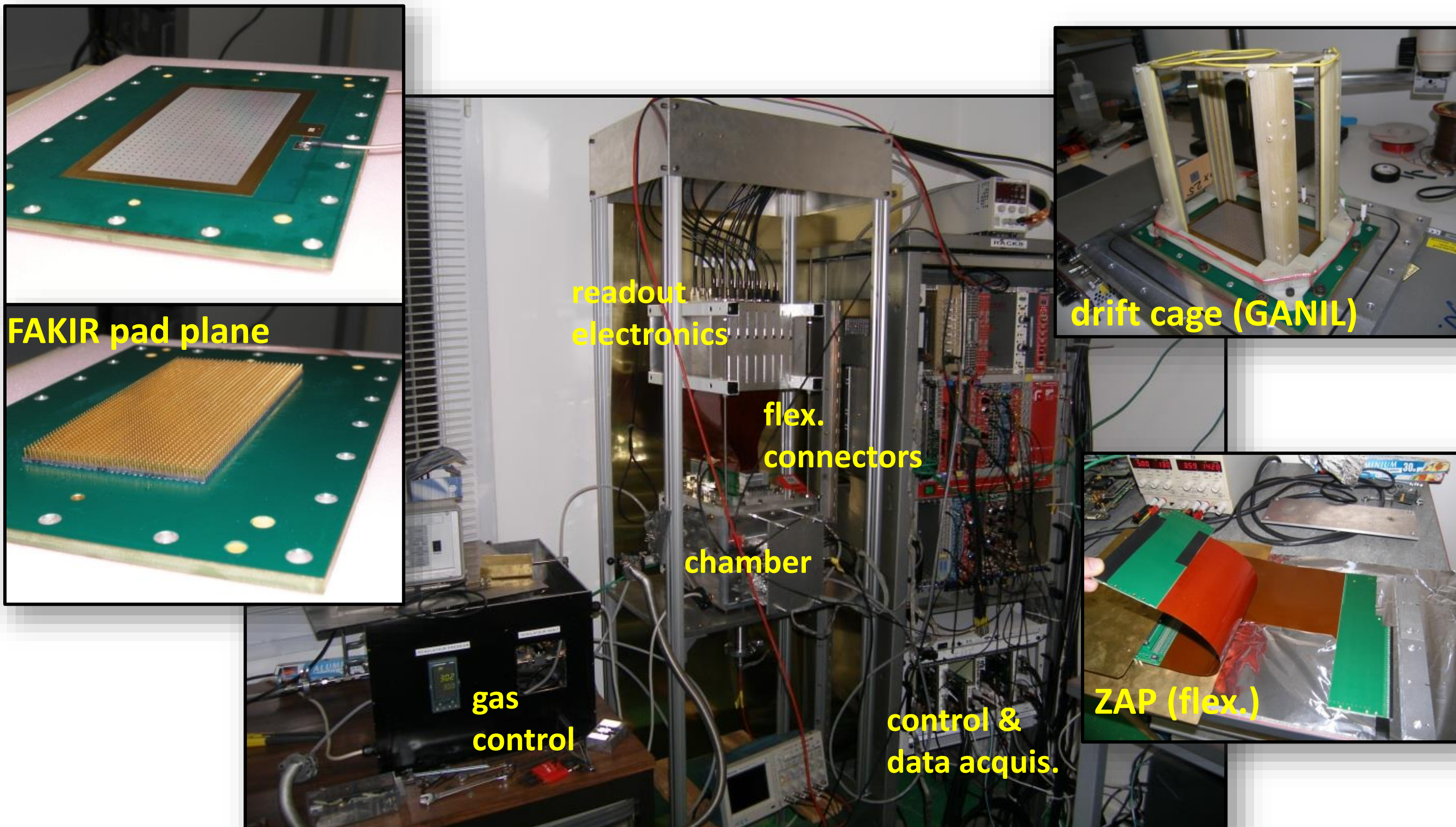
various width square signals



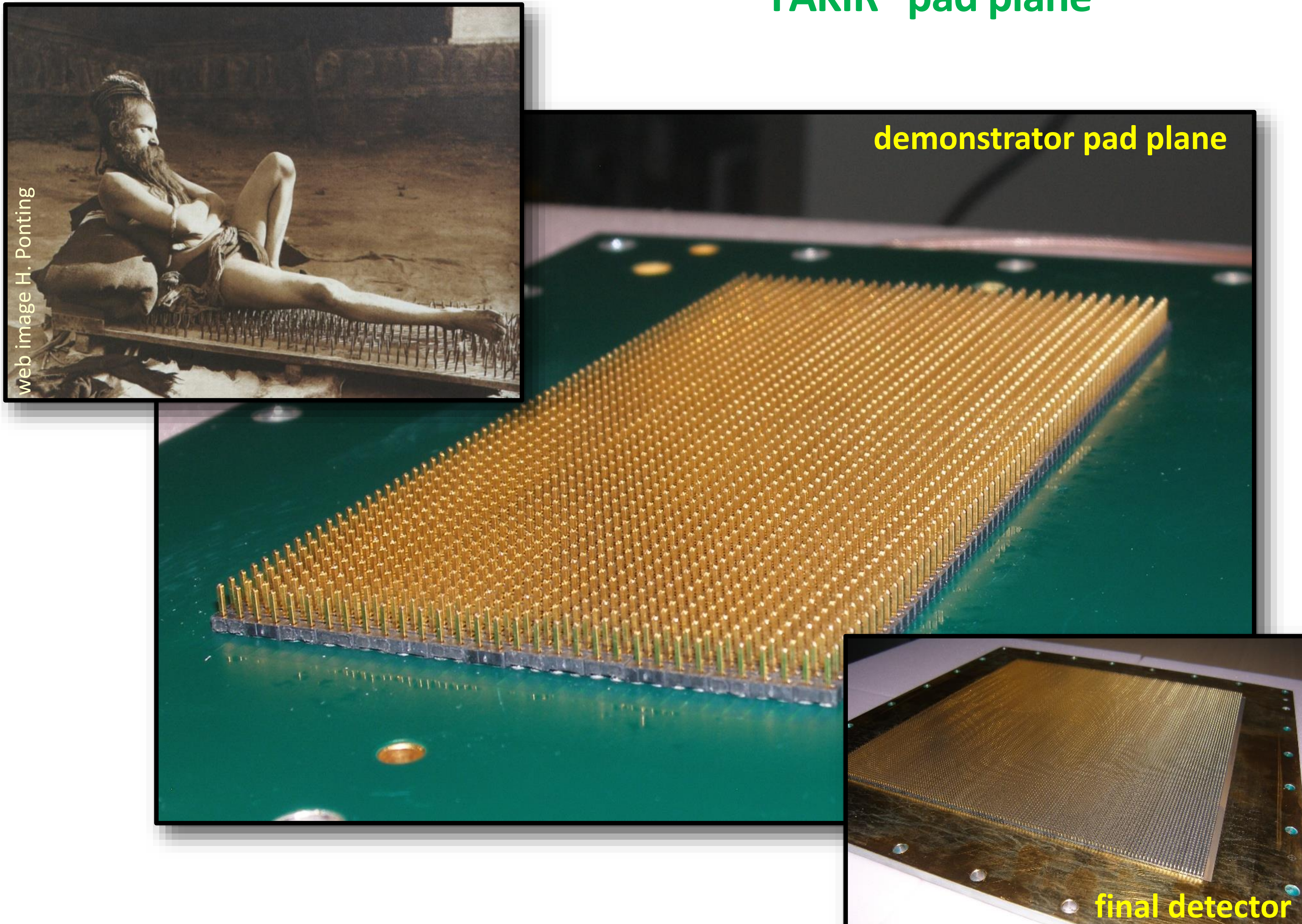


ACTAR TPC demonstrators

2 demonstrators: @ GANIL → tested in-beam (2015), electronics issues…
@ CENBG → new pad plane techno, tested with sources (2016)

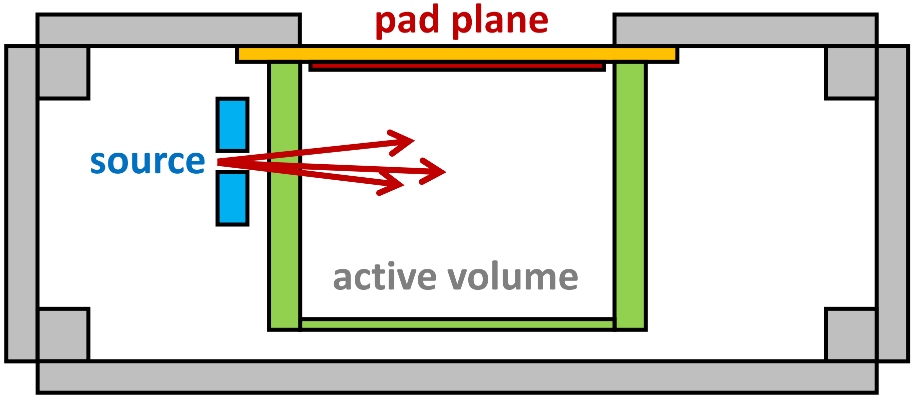


“FAKIR” pad plane

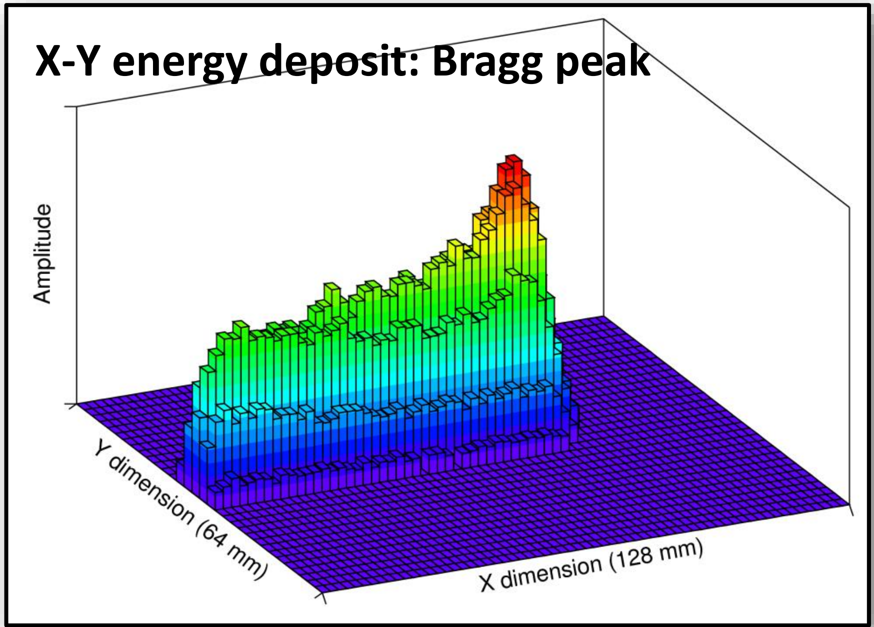


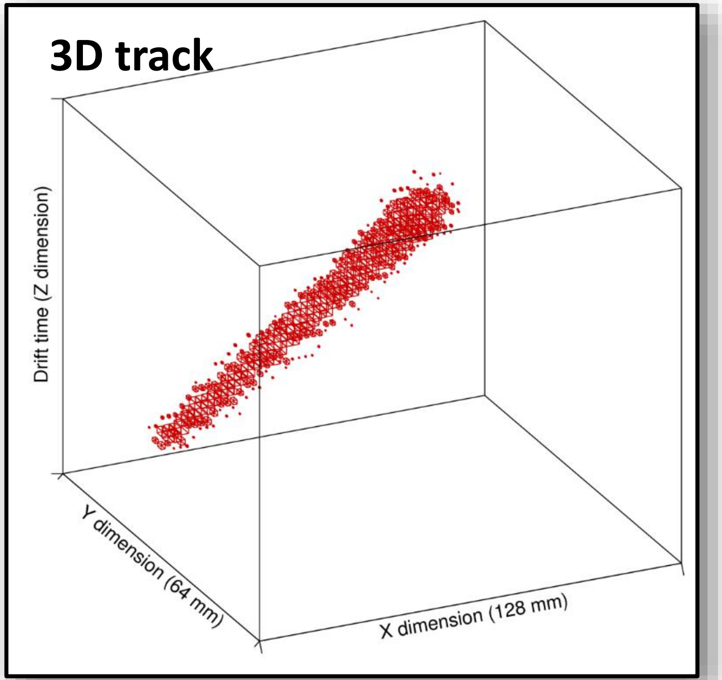
Detector characterization

- **Energy resolution**
- **Tracks reconstruction quality**



single track:
alpha particle, 45° angle





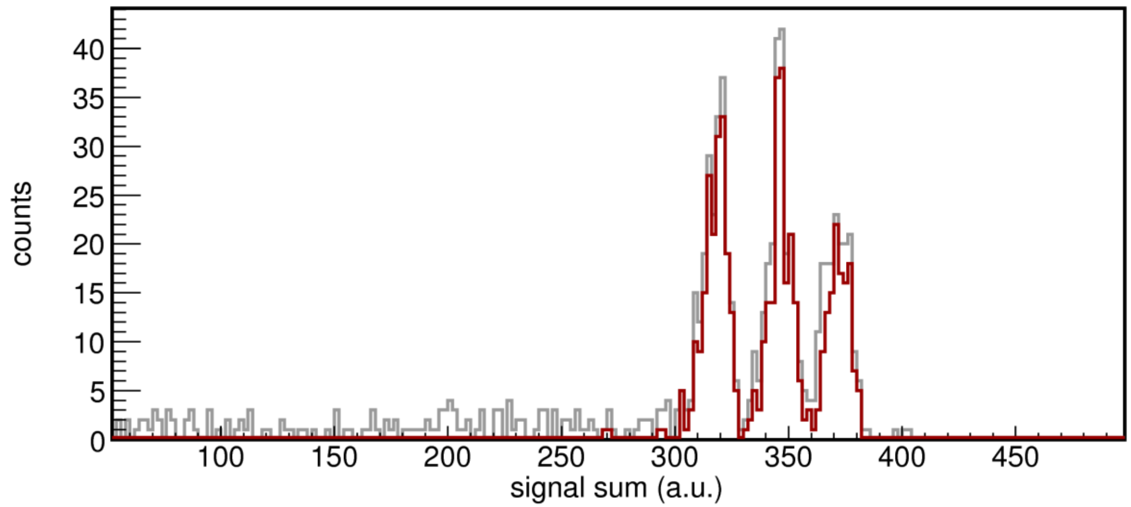
P10 gas (Ar-CH_4), 400 *mbar*

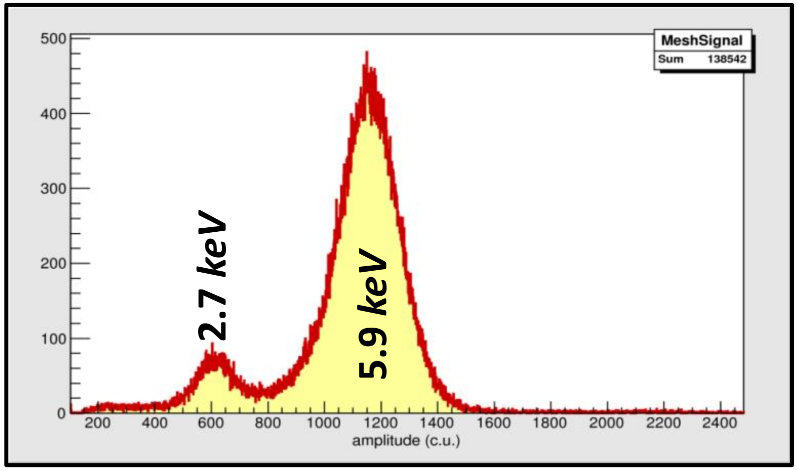
Energy resolution

triple alpha source: 5-6 *MeV*

effective FWHM: **~130 *keV***

→ good resolution for a gas detector (silicon → 25 *keV*)





X-ray source (^{55}Fe): 5.9 *keV*

conversion electron

FWHM: **~20 %**

Tracks reconstruction

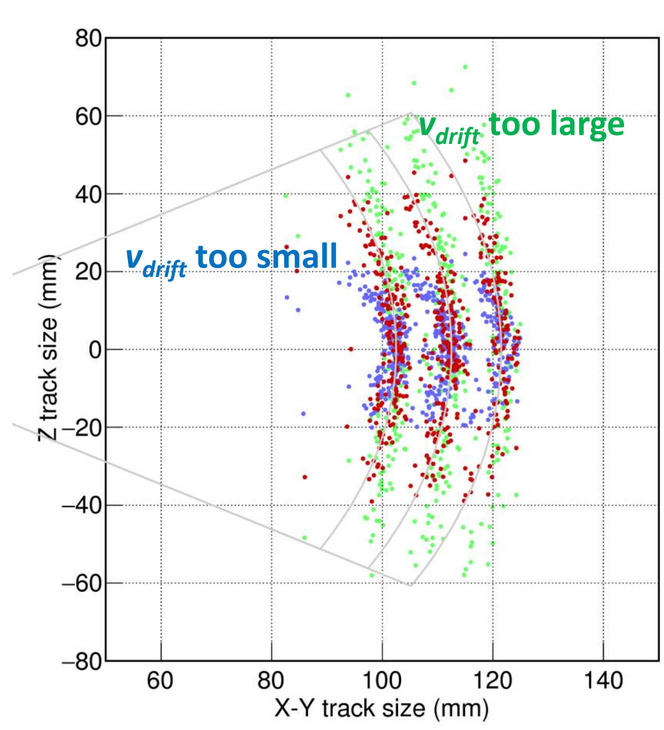
tracks length (end point)

→ Bragg peak fitting

→ signal dispersion along drift

drift velocity

$$L = \sqrt{\Delta X^2 + \Delta Y^2 + (v_{drift} \cdot \Delta T)^2}$$



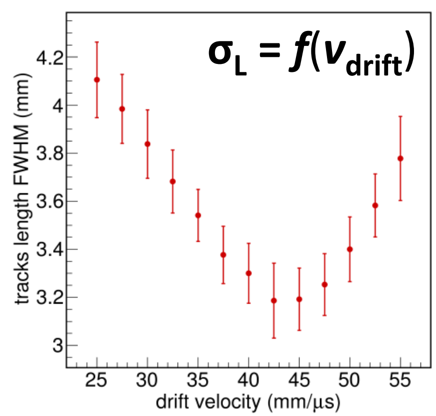
track length precision

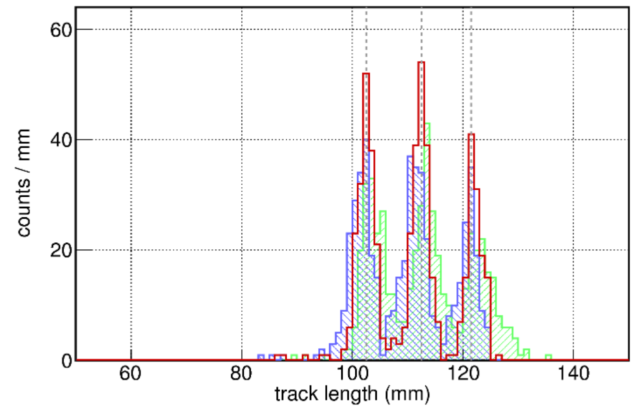
→ simple line trajectory

→ $\sigma_L \sim 3.2$ *mm* ($\sigma_L / L \sim 3\%$)

equiv. to dispersion of alpha in the gas…

⇒ intrinsic resol. < 1 *mm*





ACTAR TPC physics program

- Reaction studies (transfer, inelastic scattering…)
- Nuclear structure

- **Decay studies (for fragmentation experiments)**

  → beta-delayed proton decay for astrophysics

  → proton radioactivity

  → 2-proton radioactivity

Decay studies with ACTAR TPC

beta-delayed proton decay for astrophysics

decay spectroscopy is an access to:

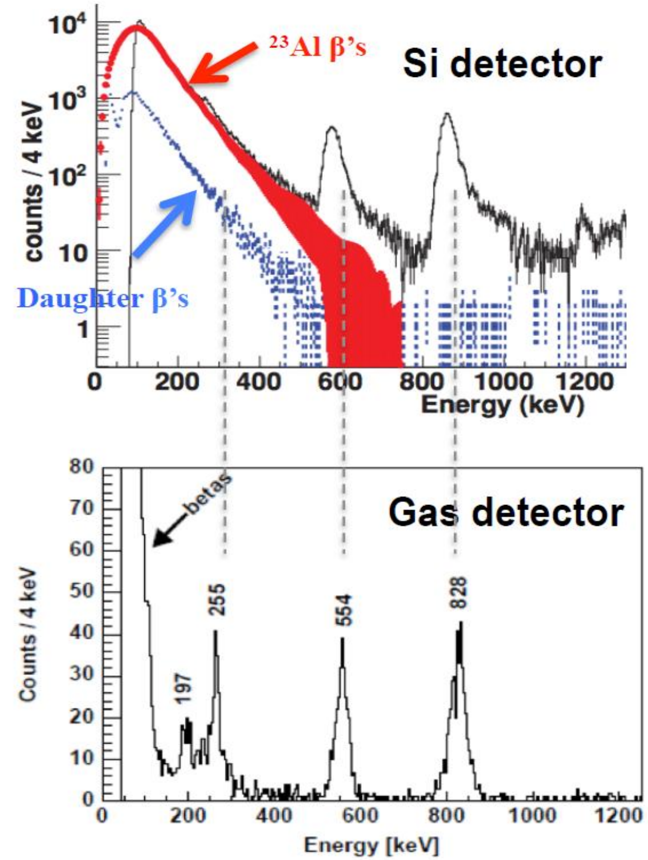
- resonances around $\boldsymbol{S_p}$ populated in ***p***-capture process
- competition with γ de-excitation
- …

ex.: nucleosynthesis in novae

→ $^{22}Na(p,\gamma)^{23}Mg$ reaction

→ ^{23}Mg states around $\boldsymbol{S_p}$: **β-*p*** of ^{23}Al

difficulty: **low energy protons**: 200 *keV* ~ 2 *MeV* in thick DSSSD: beta background



A. Saastamoinen *et al.* PRC 83, 045808 (2011)
E.C. Pollacco *et al.* NIM A 723, 102 (2013)

Decay studies with ACTAR TPC

beta-delayed proton decay for astrophysics

several cases:

nucleosynthesis in novae

^{23}*Al* decay → ^{22}*Na(p,γ)*^{23}*Mg*

^{31}*Cl* decay → ^{30}*P(p,γ)*^{31}*S*

X-ray bursts

^{20}*Mg* decay → ^{19}*Ne(p,γ)*^{20}*Na*

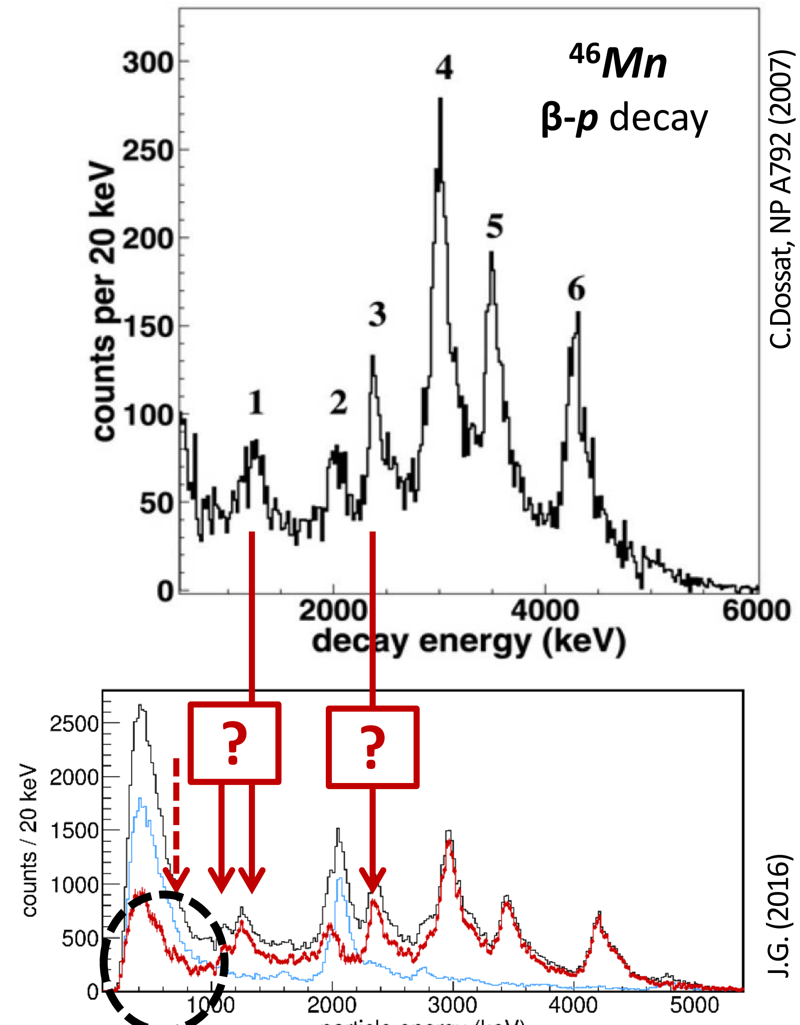
ex. (proposal A.M. Sanchez-Benitez / F. de Oliveira):

^{46}***Mn*** decay: spectro. of ^{46}***Cr***

→ rate of ^{45}***V(p,γ)***^{46}***Cr***

(production of ^{44}***Ti*** in SN-II)

TPC → reduction of β background



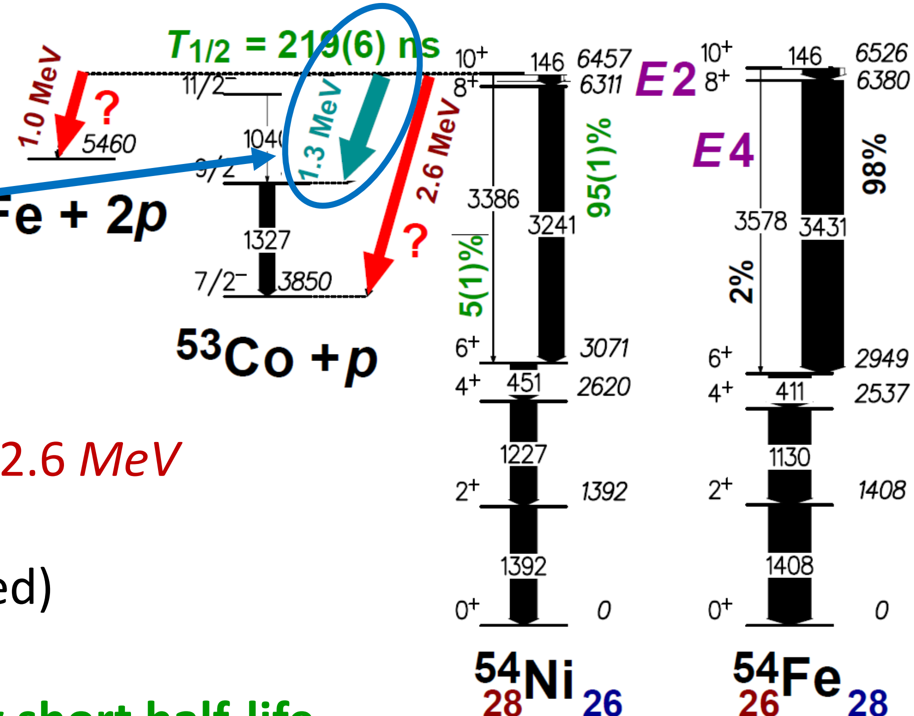
Decay studies with ACTAR TPC

proton radioactivity: decay of ^{54m}*Ni* (10^+)

previous RISING campaign (gamma only)

E_p = 1.3 *MeV* transition

→ **deduced from γ-γ coinc.**

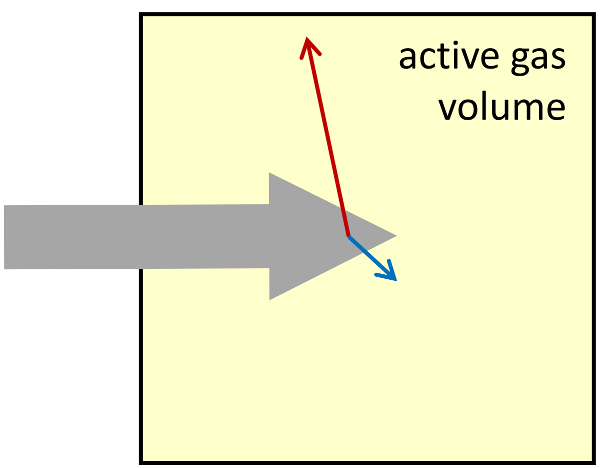


E690: D. Rudolph *et al.*

expected other proton branches

same probability expected for E_p = 2.6 *MeV* (not observed)

possible **2p** branch (low BR expected)



very short half-life

→ **protons** (1-2 *MeV*) come with **implantation** signal (~*GeV*)

→ identified from tracks **out of ion signal**

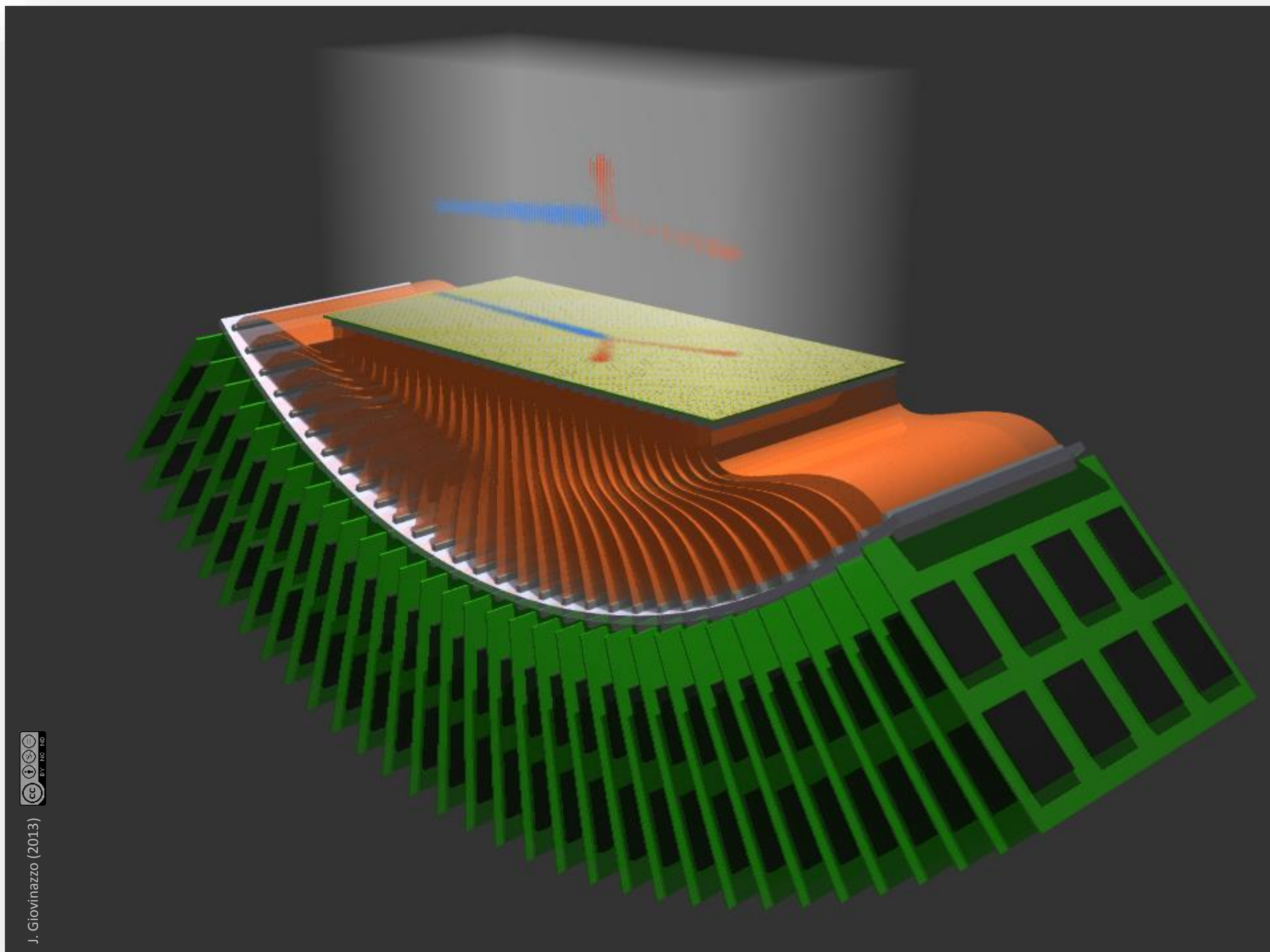
→ for P10 @ 1atm: L(1.3 *MeV*) ~ 4 cm

L(2.6 *MeV*) ~ 12 cm

Decay studies with ACTAR TPC

2-proton radioactivity: proton-proton angular and energy correlations

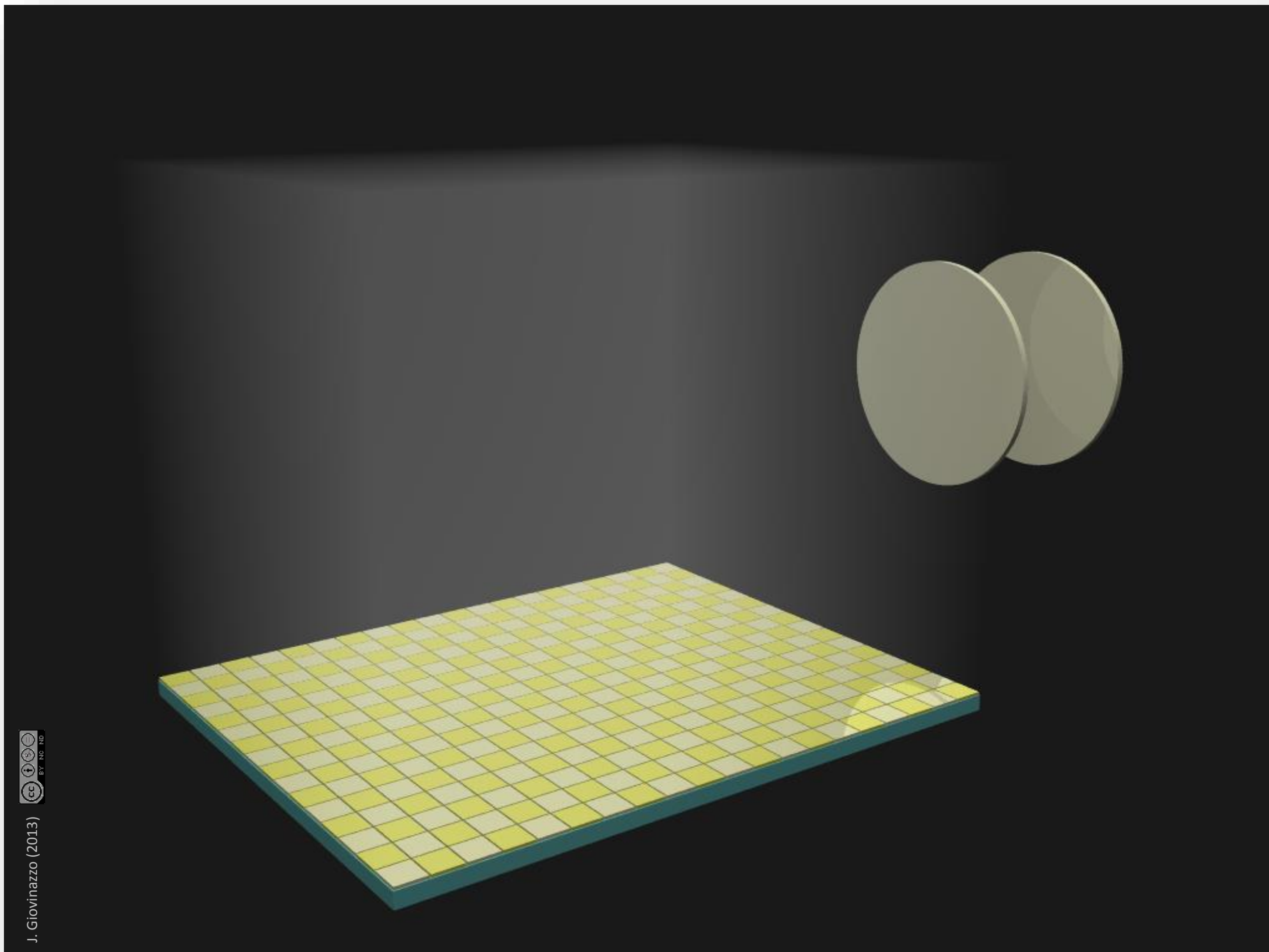
decay of ^{48}***Ni***, ^{54}***Zn***, ^{67}***Kr***… and higher ***Z*** ?



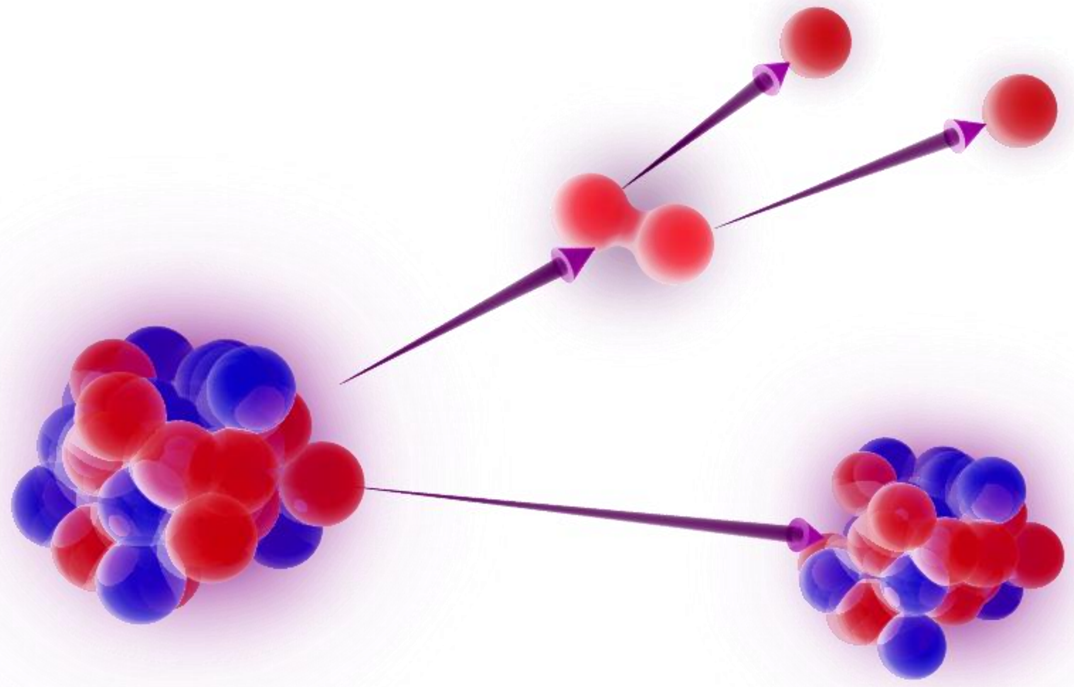
Decay studies with ACTAR TPC

2-proton radioactivity: proton-proton angular and energy correlations

decay of ^{48}***Ni***, ^{54}***Zn***, ^{67}***Kr***… and higher ***Z*** ?



The End !



thank you for you attention