Gamma spectroscopy at ISOLDE for isospin mirror asymmetry studies

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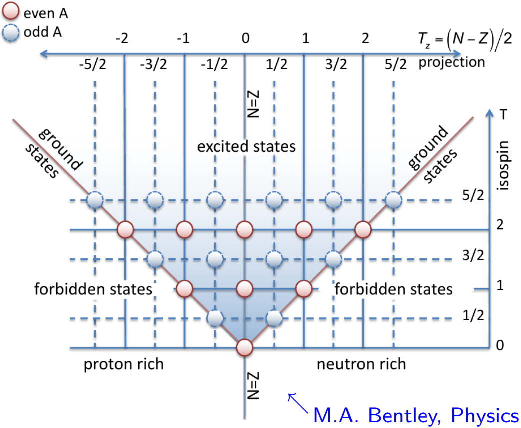
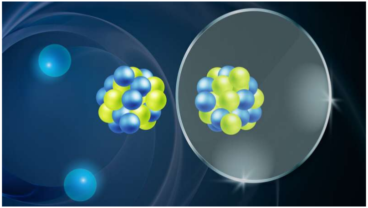
1. Isospin asymmetry
2. Gamma spectroscopy
3. β decay of ^{27}Na
4. Conclusions and outlook

Isospin formalism





↖M.A. Bentley, Physics 4, 995 (2022)

- Heisenberg (1932) and Wigner (1937)
- Mass difference quarks u and $d \ll$ binding energy of hadrons
- Symmetry conserved under strong interaction

Isospin mirror asymmetry

$$MED(A,T) = E_{ex}(T, T_z = T) - E_{ex}(T, T_z = -T)$$

Isospin mirror asymmetry

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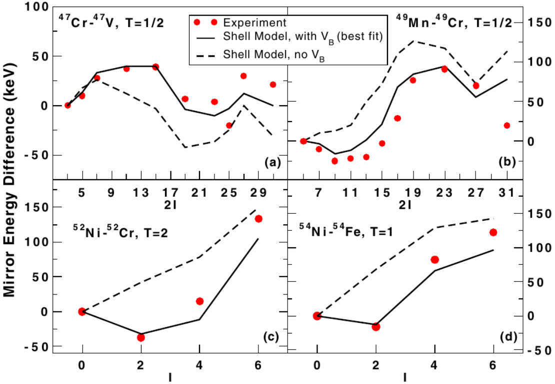


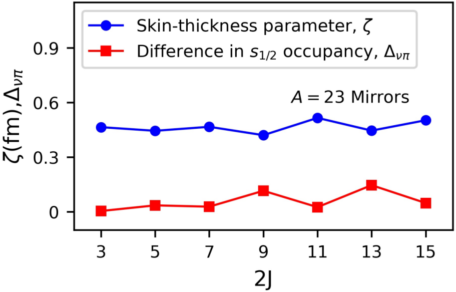
M.A. Bentley et al., PRC 92, 024310 (2015)

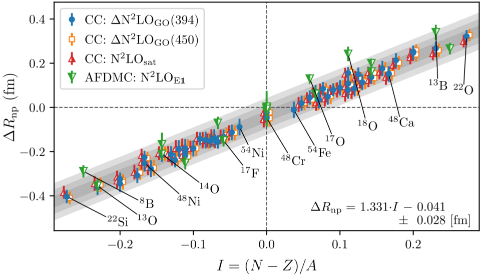
- electromagnetic effects
- isospin-symmetry-breaking effective interaction V_B

Isospin mirror asymmetry

Connection between MED and neutron skin

$$\Delta R_{np} = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle} \propto \zeta$$





A. Boso, PRL 121, 032502 (2018)

M.A. Bentley, Physics 4, 995 (2022)

S.J. Novario et al., PRL 130, 032501 (2023)

Isospin mirror asymmetry in β decay

Isospin-symmetry-breaking corrections, δ_C, for superallowed Fermi decays

$$\mathcal{F}t = ft(1+\delta_R^{'})(1+\delta_{NS}-\delta_C) \propto G_V^{-2}$$

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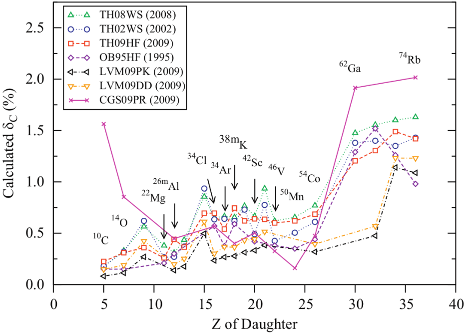
$$\mathcal{F}t = ft(1+\delta'_R)(1+\delta_{NS}-\delta_C) \propto G_V^{-2}$$

Conserved Vector Current hypothesis → constraint different models:

$$\delta_C = 1+\delta_{NS}-\frac{\overline{\mathcal{F}t}}{ft(1+\delta'_R)}$$



G.F. Grinyer et al., NIMA 622, 236 (2010)

Reminder ft: Fermi theory

→ Experimental ingredients: Q_β, $T_{1/2}$ and I_β

$$f(Q_\beta, Z) = \int_1^{\varepsilon_{max}} F(Z,\varepsilon)\varepsilon\sqrt{\varepsilon^2-1}\left(\frac{Q_\beta}{m_e c^2} - \varepsilon + 1\right)^2 d\varepsilon$$

$$t = \frac{T_{1/2}(1+P_{EC})}{I_\beta}$$

→ Theoretically: sensitivity to initial and final wave functions

$$ft = \left(\frac{2\pi^3\hbar^7 ln2}{m_e^5 c^4}\right)\frac{1}{g_V^2|\langle\psi_f\,|\,\tau\,|\,\psi_i\rangle|^2 + g_A^2|\langle\psi_f\,|\,\tau\sigma\,|\,\psi_i\rangle|^2}$$

Isospin mirror asymmetry in β decay

$$\delta = \frac{ft^+}{ft^-} - 1$$

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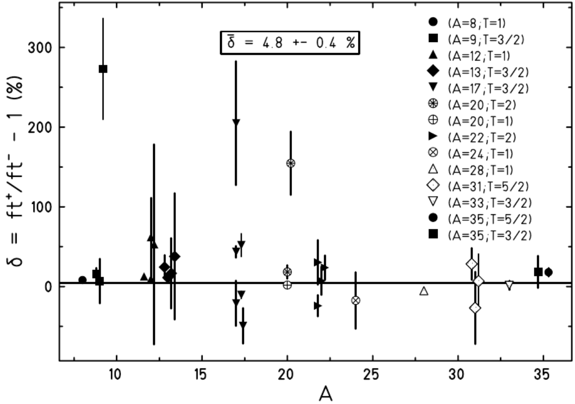
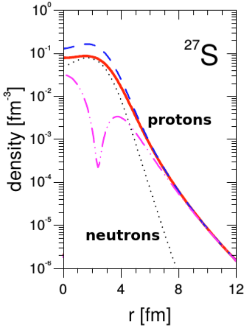
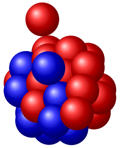
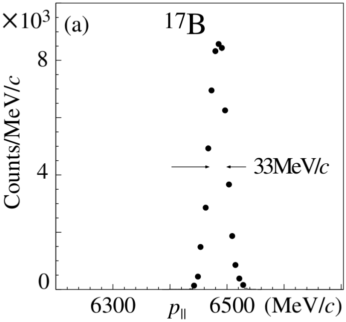


J.-C. Thomas et al., EPJA 21, 419 (2004)

Halo nuclei







B.Q. Chen et al., JPG 24, 97 (1998)

T. Suzuki et al., PRL 89, 012501 (2002)

- Low neutron/proton separation energies
- Extended neutron/proton matter densities
- Narrow momentum distributions and low angular momentum

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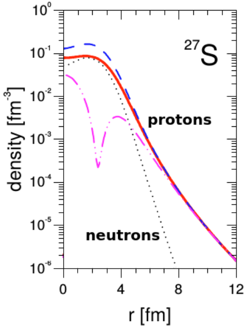

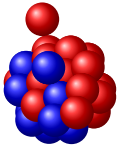

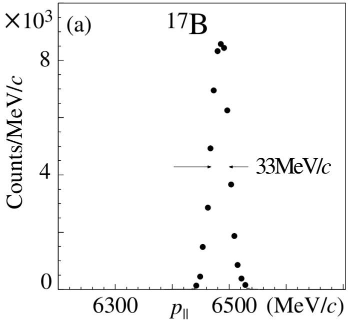

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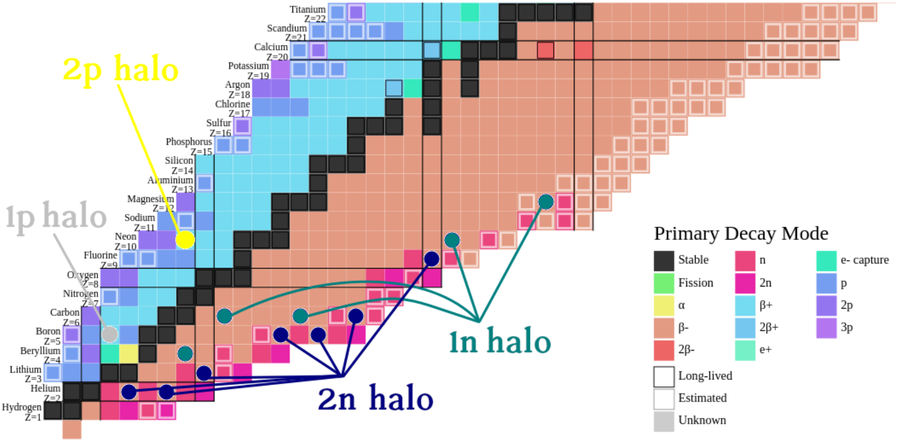
Theoretical and experimental efforts to identify and confirm new cases

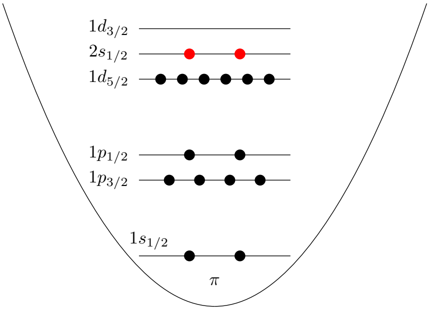
Halo nuclei



⋆ More difficult to investigate proton halo cases (Coulomb barrier)

⋆ 2p halo: ^{17}Ne best candidate but: C. Lehr et al., PLB 827, 136957 (2022)

Proton halo candidates in the *sd* shell



$\downarrow$

Possible protons in the $2s_{1/2}$ orbital

Low proton separation energies:

- ^{26}P(Z=15):
  S_{1p}=140(200) keV
- ^{27}S(Z=16):
  S_{1p}=581(214) keV
  S_{2p}=727(78) keV
- ^{22}Al(Z=13)
  S_{1p}=-7(400) keV
- ^{23}Al(Z=13)
  S_{1p}=140.9(4) keV

Isospin mirror asymmetry in the *sd* shell

- ^{26}P-^{26}Na:

  D. Pérez-Loureiro et al. PRC 93, 064320 (2016)

  + K. Kaneko et al. NPA 986, 107 (2019)

  $$\delta(2_1^+) = 51(10)\%$$

  H. Jian et al., Symmetry 13, 2278 (2021)

  $$\delta(2_1^+) = 46(13)\%$$

- ^{27}S-^{27}Na:

  Ł. Janiak et al., PRC 95, 034315 (2017) +

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  $$\delta(3/2_1^+) = 38(26)\%$$

- ^{22}Si-^{22}O:

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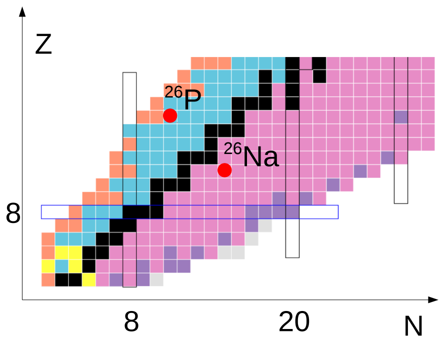

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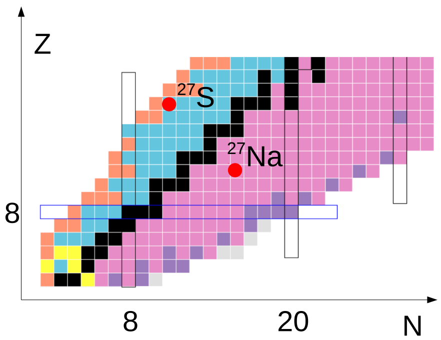

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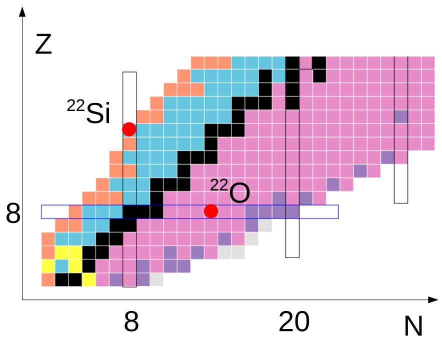

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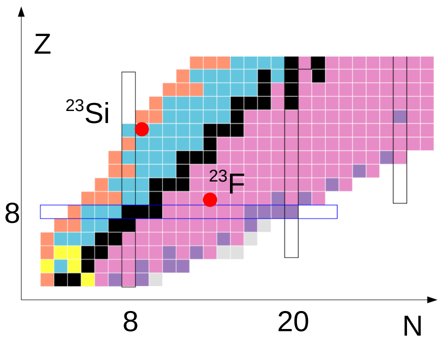
Recently: ^{23}Si-^{23}F

$$\delta(5/2_2^+) = 201(108)\%$$

H. Jian et al.,



Halo character: isospin mirror asymmetry (theory)

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$\star$ Shell-model calculation with Coulomb + isospin-nonconserving forces

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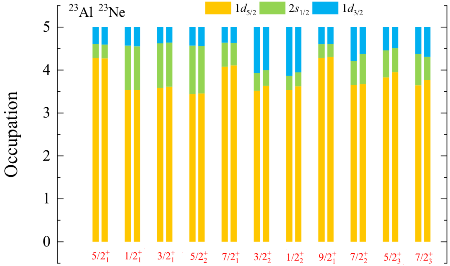
H. H. Li et al., PRC 107, 014302 (2023)



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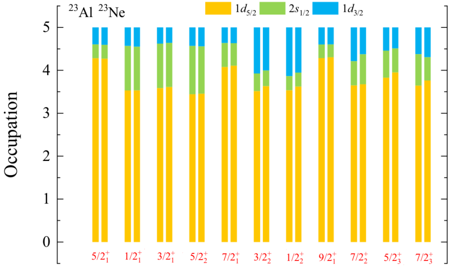

Large mirror asymmetries due to large occupations of $2s_{1/2}$ orbitals

Halo character: isospin mirror asymmetry (experiment)

Completeness of β intensity distributions?

β-decay spectroscopy data of mirror nuclei may explain the isospin mirror asymmetry values

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^{27}Na

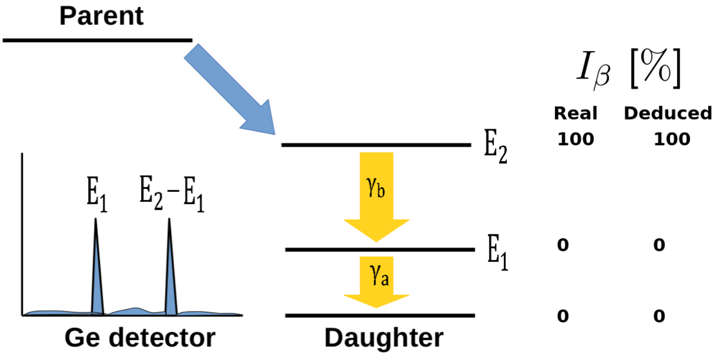
I_β $(3/2^+_1)$ [%]	*logft*	δ [%]
85.8	4.30	38
80	4.33	29
75	4.36	20
70	4.39	12
65	4.42	5
60	4.46	-5

^{22}O

I_β (1^+_1) [%]	*logft*	δ [%]
29	4.59	216
25	4.65	175
20	4.75	119
15	4.87	66
10	5.05	10
5	5.35	-45

Determining I_β

Traditional approach: I_β deduced from γ-intensity balance of the cascades that follow the β decay, using **HPGe detectors**:



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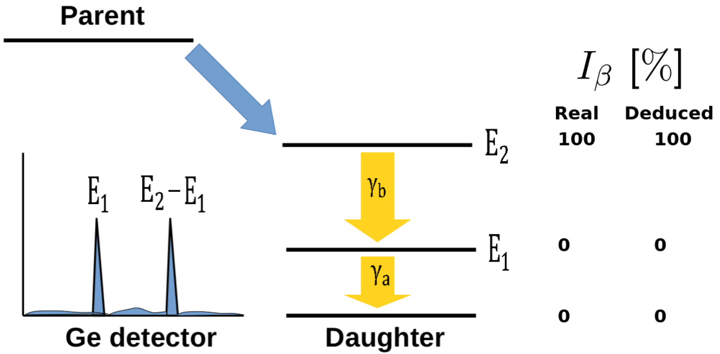

Low efficiency of HPGe detectors → what happens if we miss a γ-ray?

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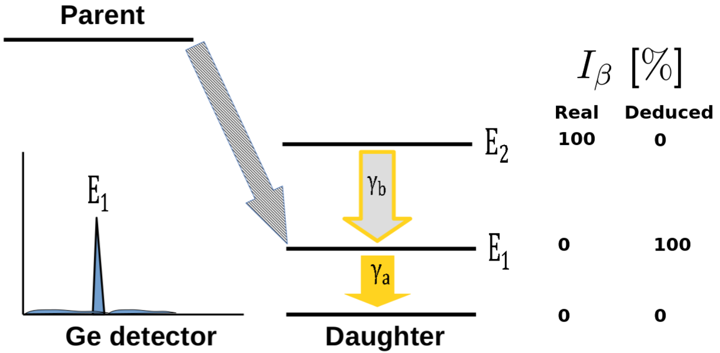


Low efficiency of HPGe detectors $\rightarrow$ what happens if we miss a γ-ray?

Pandemonium effect J.C. Hardy et al., PLB 71 (1977) 307

Pandemonium

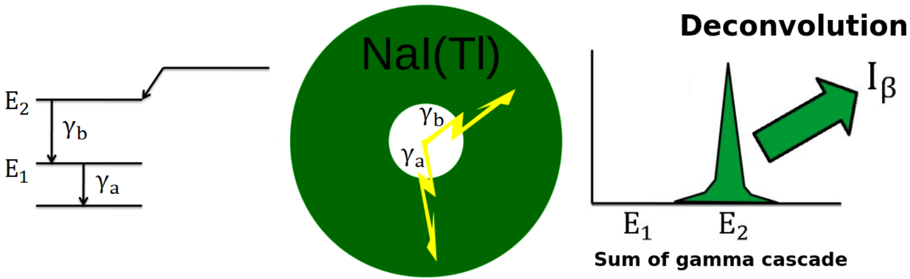
“The rest were all
Far to the inland retired, about the walls
Of Pandemonium city and proud seat
Of Lucifer.”

J. Milton in Paradise Lost X (1667) line 424

John Martin, Pandaemonium, 1825 (source Wikipedia)

Total Absorption γ-Ray Spectroscopy (TAGS)

A **T**otal **A**bsorption **S**pectrometer (TAS) acts as a **calorimeter**, absorbing the full energy released in the β-decay process.



It requires:

Large scintillation crystals covering a solid angle of $\sim 4\pi$ in order to maximize the γ-ray detection **efficiency**.

TAGS analysis

Inverse problem:

$$d_i = \sum_{j=1}^{m} \boldsymbol{R_{ij}}(\boldsymbol{B}) f_j$$

- $j \rightarrow$ levels, $i \rightarrow$ experimental bins
- f_j: $I_\beta(E)$ distribution
- d_i: experimental spectrum
- R_{ij}: response matrix of the detector
- B: branching ratio matrix (depends on the decay)

A deconvolution process to extract f_j

J.L. Tain and D. Cano-Ott NIMA 571 (2007) 728

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Expectation-Maximization (EM) algorithm

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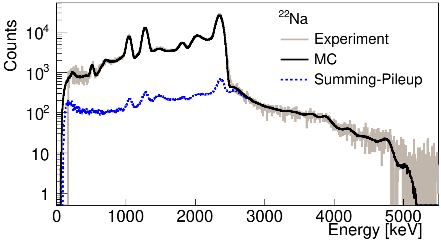
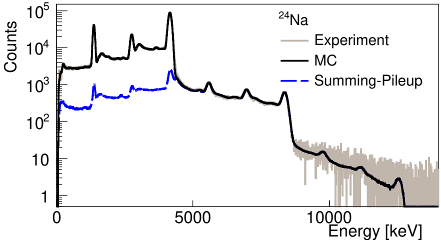
TAGS analysis

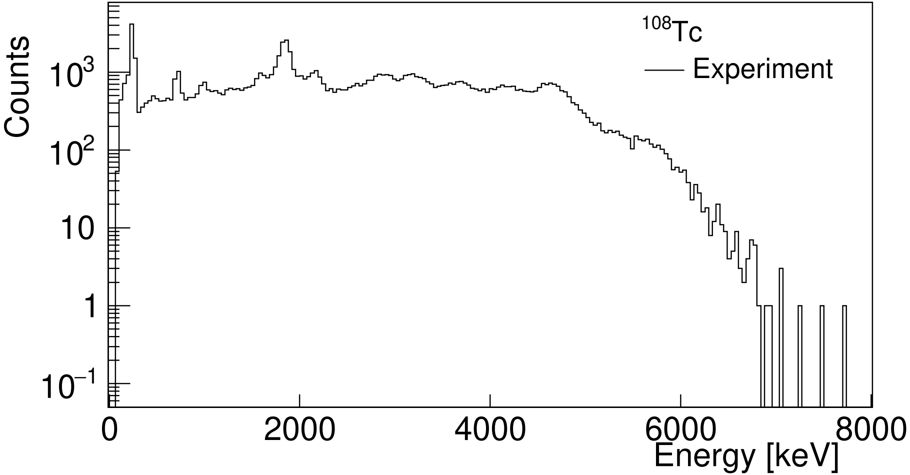
Characterization of the detector $\rightarrow R_{ij}$





V. Guadilla et al., NIMA 910, 79 (2018)

Example of TAGS deconvolution



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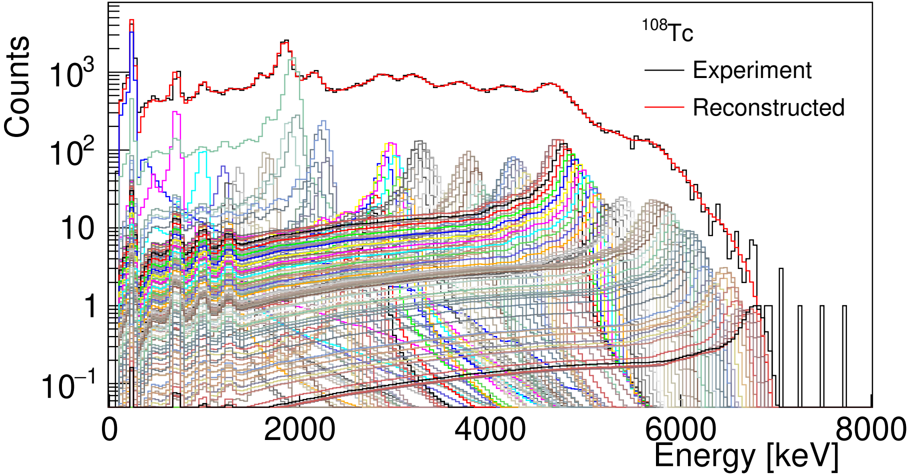
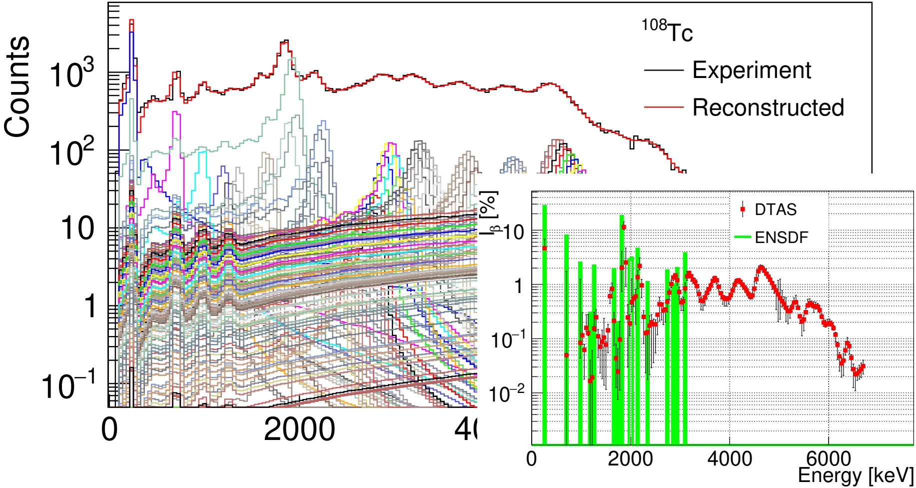


→ Reconstructed: $\sum_{j=1}^{m} \boldsymbol{R_{ij}}(\boldsymbol{B}) f_j$

Example of TAGS deconvolution



V. Guadilla et al., in preparation

How to foresee Pandemonium?

→ **Case dependent!**

- Q_β
- Last level known to be populated in β decay
- Density of levels
- γ multiplicity of cascades (spin-parities of mother and daughter)
- β-delayed particle emission
- Ground state feeding
- ft values

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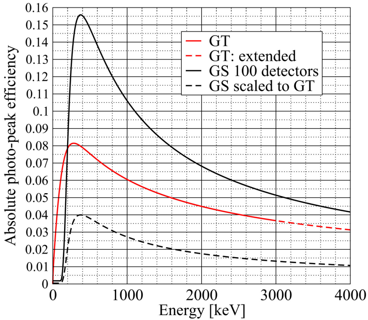
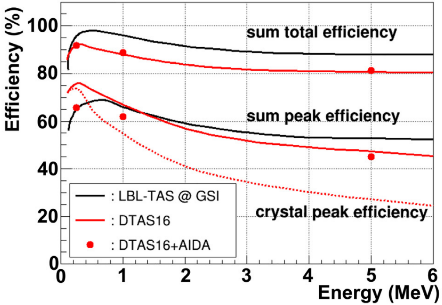
Reflection on efficiencies



GRETINA and Gammasphere

T. Lauritsen et al., NIMA 836,46 (2016)



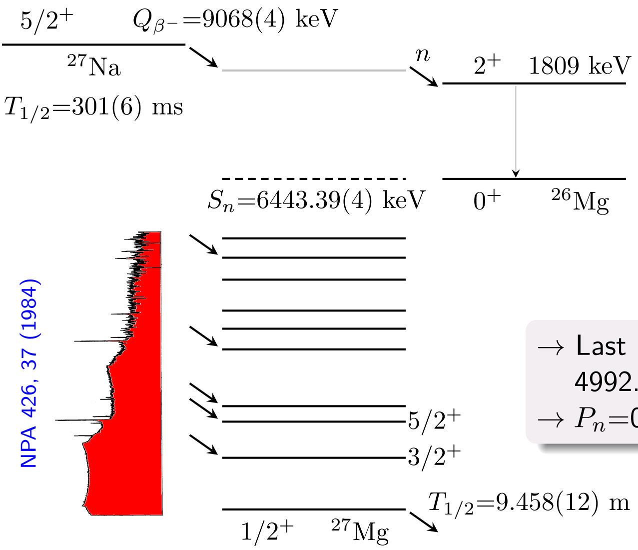
LBL-TAS and DTAS

A.K. Mistry et al., NIMA 1033, 166662 (2022)

Example: cascade of 3 γ-rays of 1 MeV each

0.12% vs. 82%

What was known in the β decay of ^{27}Na



D. Guillemaud-Mueller et al.
NPA 426, 37 (1984)

→ Last level: 4992.6 keV
→ P_n=0.13(4)%

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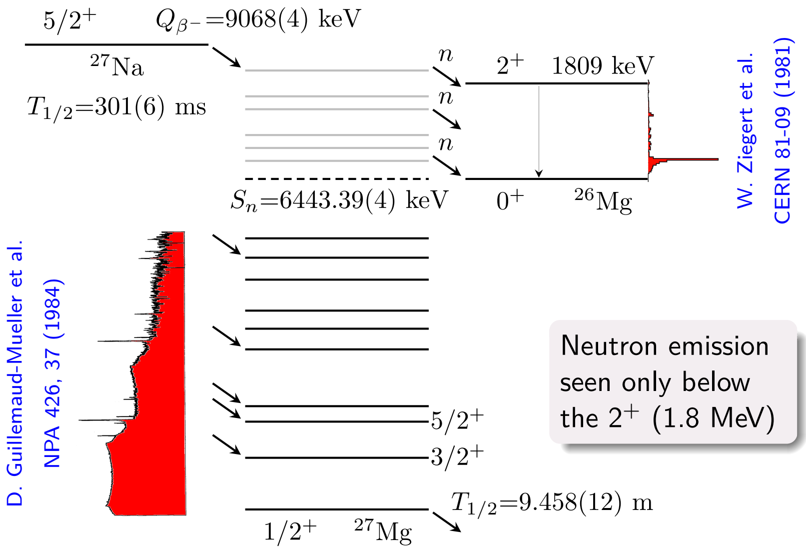
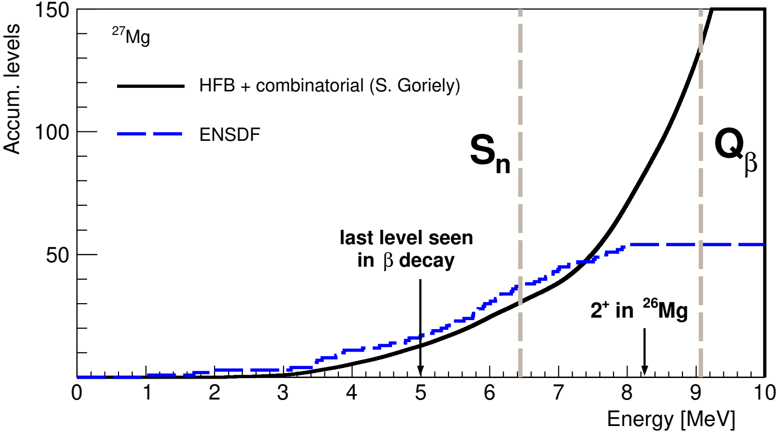


Neutron emission seen only below the 2^+ (1.8 MeV)

What was known in the β decay of ^{27}Na

Accumulated level density:



TAGS measurement of ^{27}Na at ISOLDE

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

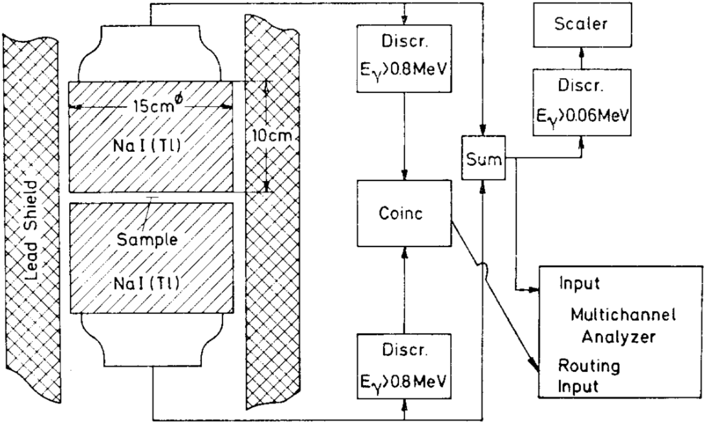
Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Beta-decay spectroscopy of ^{27}Na and ^{22}O for isospin asymmetry studies in the *sd* shell

January 5, 2021

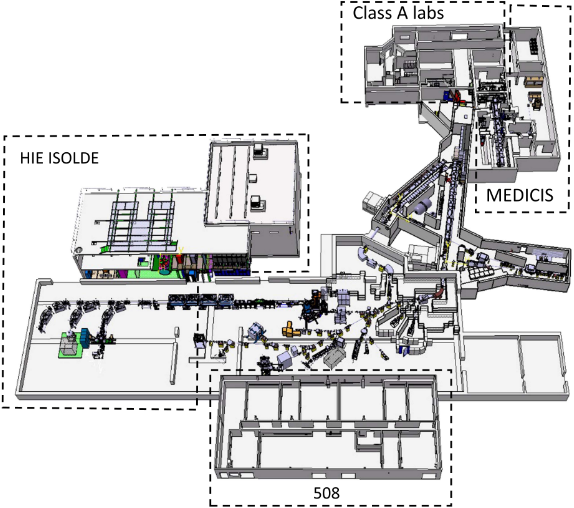
History: TAS@ISOLDE

→ Pioneering TAGS experiments:



C.L. Duke et al., NPA 151, 609 (1970)

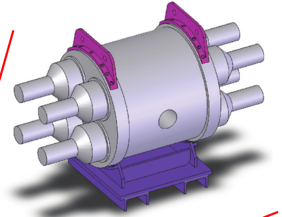
Lucrecia: TAS@ISOLDE

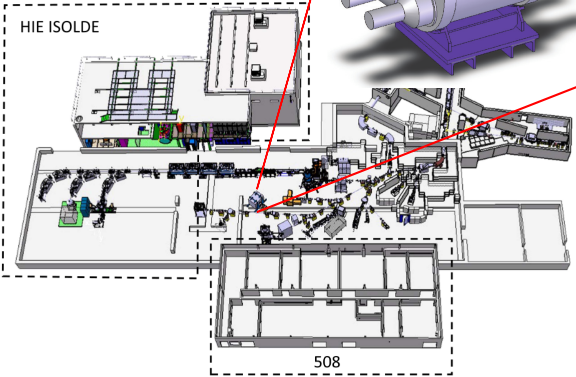


R. Catherall et al., JPG 44, 094002 (2017)

Lucrecia: TAS@ISOLDE

NaI(Tl) 38 cm length, 38 cm diameter
internal hole of 7.5 cm diameter





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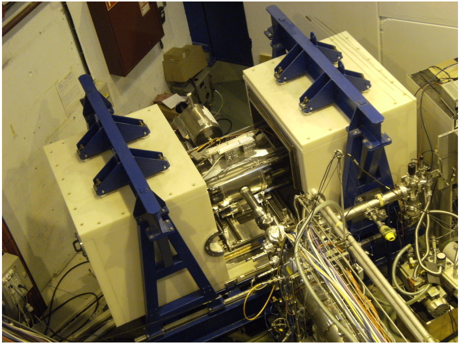
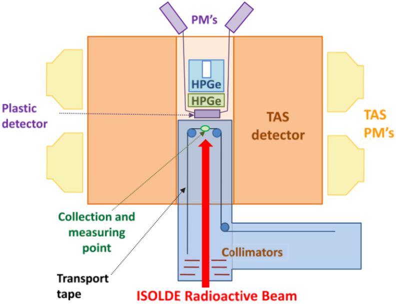
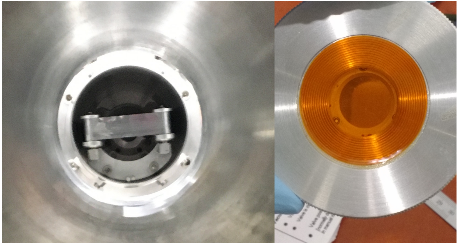


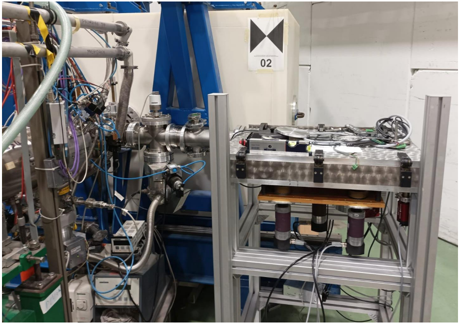


J. A. Briz et al. PRC 92, 054326 (2015)

- 20 years operational: B. Rubio et al., JPG 44, 084004 (2017)
- Total efficiency ~90%
- Coincidences with β detector and x-ray detector
- Shielding: boron, polyethylene, lead, copper and aluminium

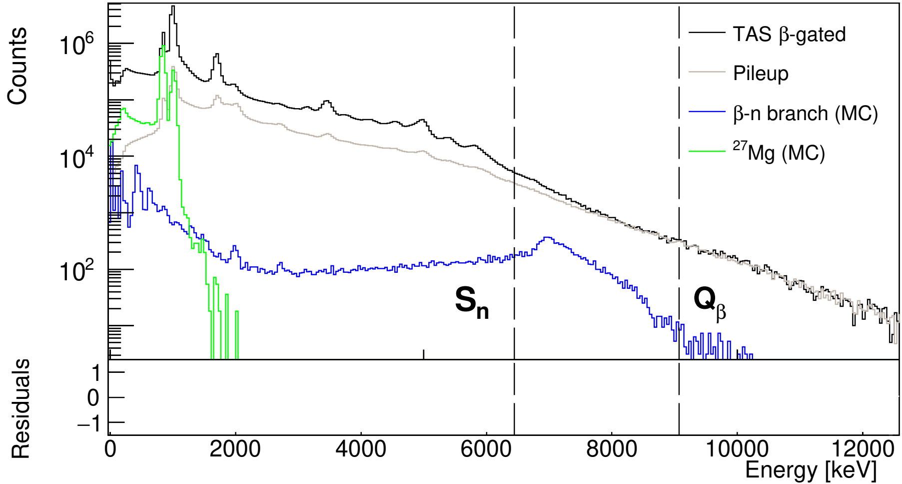
Experiment ^{27}Na β decay





- UC target and HRS separator
- Beam: ^{27}Na + ^{27}Mg
- Cooling down beam transfer line reduced contamination of ^{27}Mg
- New (refurbished) tape transport system for implantation and removal of the activity + vacuum system (IFIC)

TAGS analysis of ^{27}Na β decay



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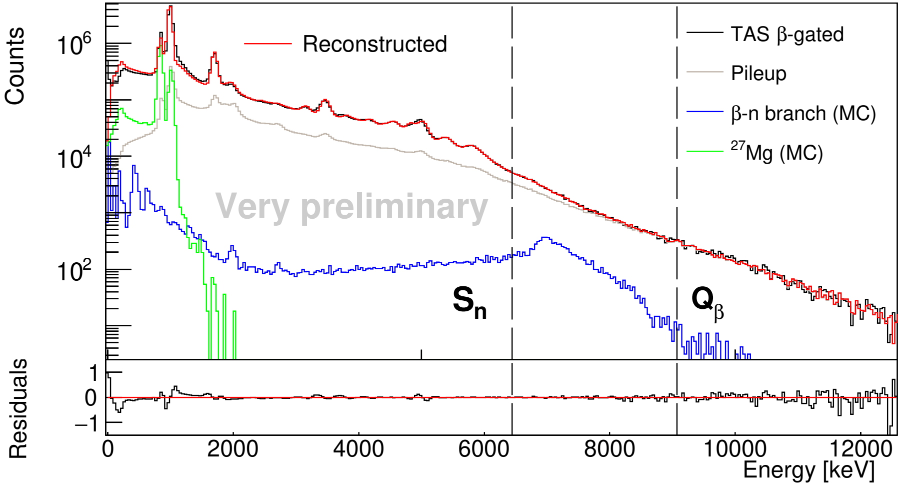

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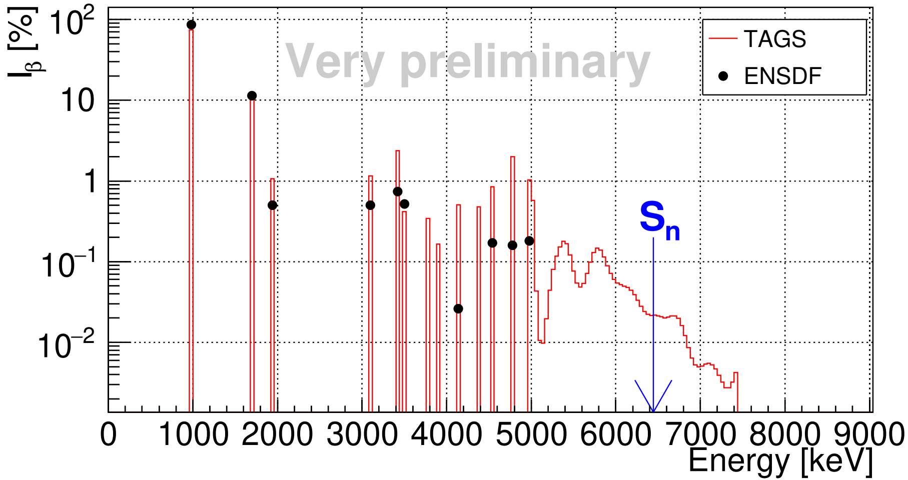


Neutron-γ competition

Hauser-Feshbach statistical model calculations

J.L Tain et al. PRL 115, 062502 (2015)

E. Valencia et al., PRC 95, 024320 (2017)

V. Guadilla et al., PRC 100, 044305 (2019)

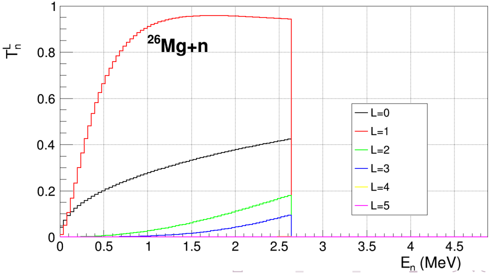
$$\left\langle \frac{\Gamma_\gamma}{(\Gamma_\gamma + \Gamma_n)} \right\rangle \leftrightarrows \frac{I_{\beta\gamma}}{(I_{\beta\gamma} + I_{\beta n})}$$

Ingredients:

⋆ Nuclear level densities

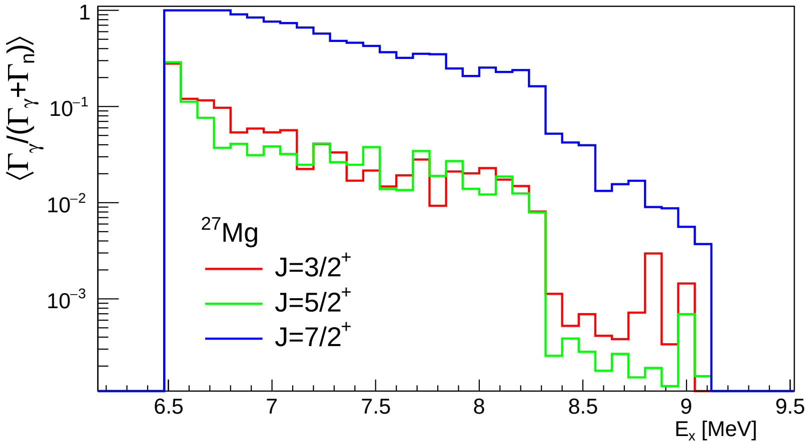
⋆ Photon strength functions

⋆ Neutron transmission coefficients



Neutron-γ competition

Possible hindrance of neutron emission up to the energy of the first 2^+ state in ^{26}Mg: large angular momentum needed, l=2,4



Conclusions

- Isospin mirror asymmetry in β decay and proton halo nuclei
- TAGS technique: **powerful** tool for decay spectroscopy studies
- New decay data for ^{27}Na point to previously **unknown** β intensity
- Final calibration ongoing $\rightarrow$ Master Thesis Piotr Bielak
- First confirmation of Pandemonium in a **light nucleus**!
- I_{β} $(3/2^+_1) \downarrow \Rightarrow \delta(3/2^+_1) \downarrow$
- Neutron unbound states populated: neutron-γ **competition**

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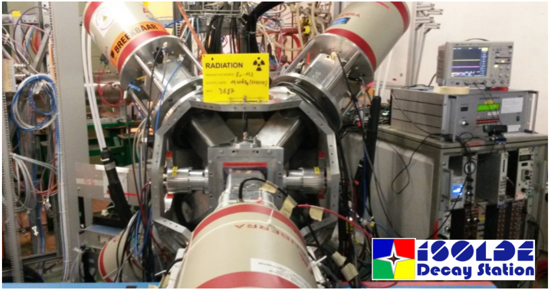
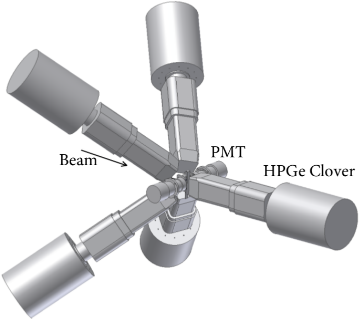
Outlook: β decay of ^{22}O





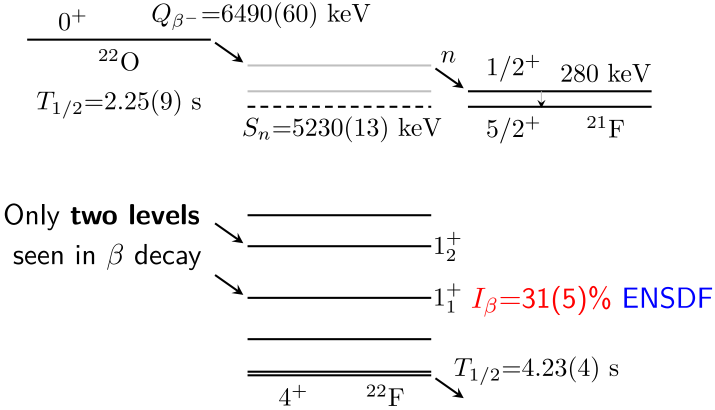
R. Lică et al., PRC 100, 034306 (2019)

- **High efficiency** β-γ configuration:

  5 clovers + β detector (NE102 plastic scintillator covering $\simeq 4\pi$)

- Movable tape for implantation and removal of the activity

Outlook: β decay of ^{22}O

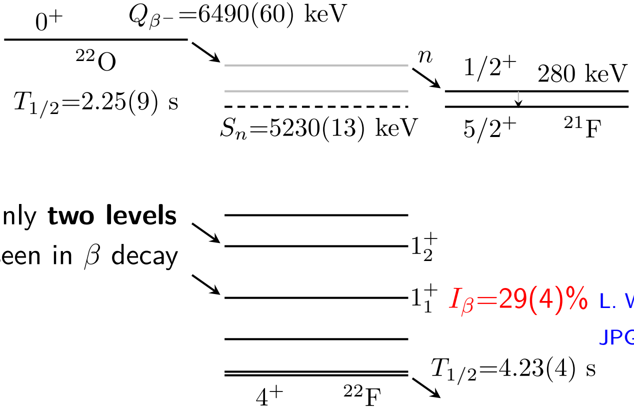


Shell model calculations predict $I_\beta(1_1^+)$=13-45%

(USD effective interaction predicts 0.04%!)

L. Weissman et al., JPG 31, 553 (2005)

Outlook: β decay of ^{22}O



Only **two levels** seen in β decay

I_β=29(4)% L. Weissman et al., JPG 31, 553 (2005)

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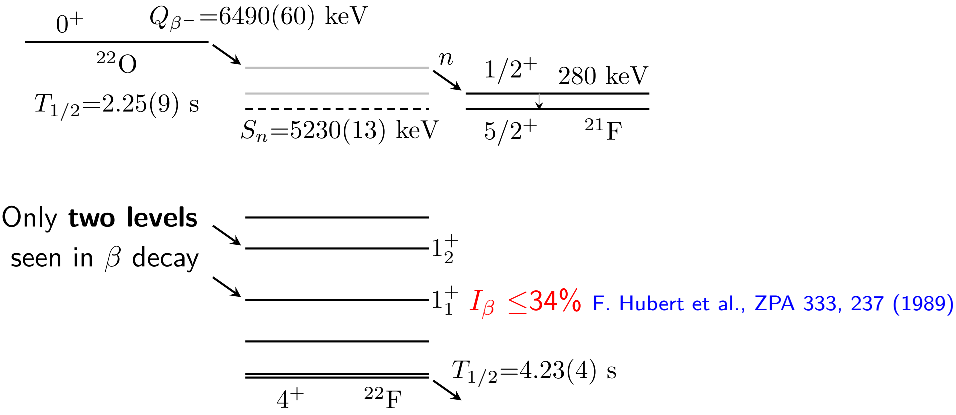

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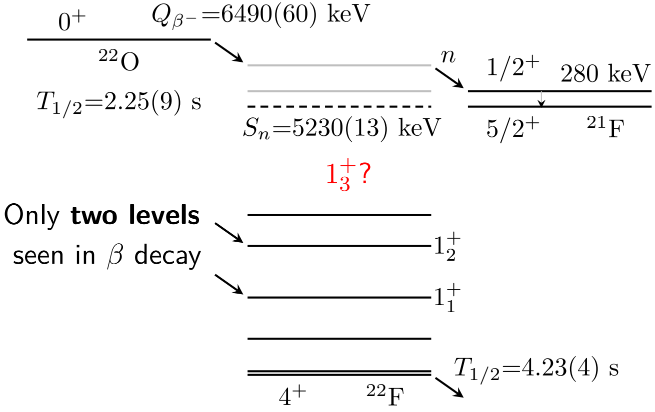


Shell model and HFB calculations predict extra 0^+ and 1^+ levels

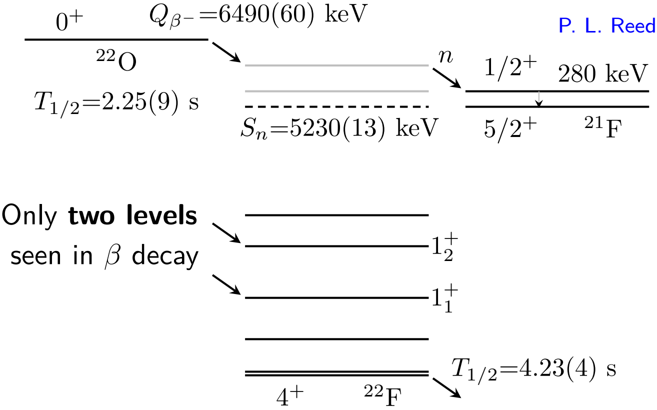
Shell model calculations predict $I_\beta(1_3^+)$=0.2-15%

L. Weissman et al., JPG 31, 553 (2005)

Outlook: β decay of ^{22}O

P. L. Reeder et al., PRC 44, 1435 (1991)

P_n <22%



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Outlook: superallowed transitions

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Direct measurement of superallowed β transitions with Lucrecia

September 26, 2023

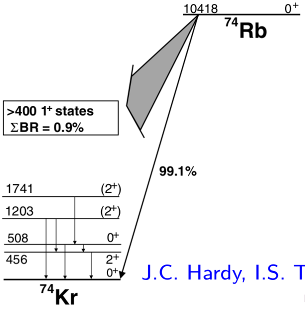
Outlook: superallowed transitions

Ground state feeding determination

- In high-resolution γ-spectroscopy:

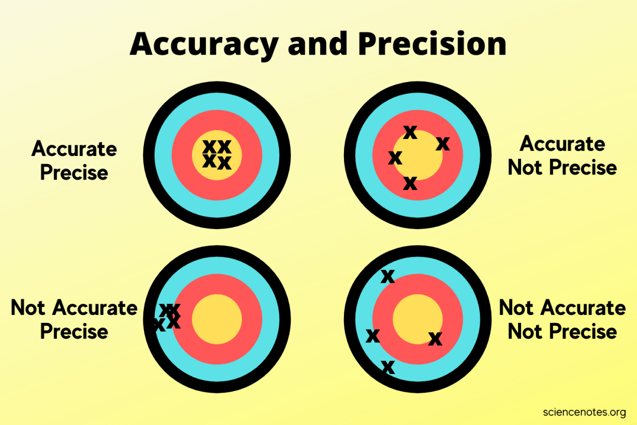
$$\boxed{I_{\beta}^{g.s.} = 1 - I_{\beta\gamma}}$$

- A>62: large amount of 1^+ states $\rightarrow$ up to 1% β-decay feeding numerous Gamow-Teller transitions $\Rightarrow$ possible **Pandemonium**



J.C. Hardy, I.S. Towner, PRL 88, 252501 (2002)

Outlook: superallowed transitions



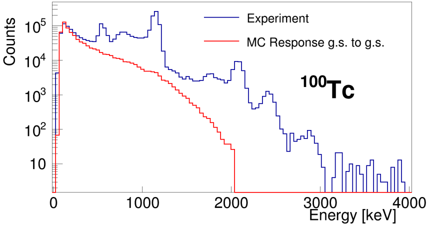
^{62}Ga
$99.8577^{+0.0023}_{-0.0029}$%
MacLean et al., PRC 102, 054325 (2020)

^{74}Rb
99.545(31)%
Dunlop et al., PRC 88, 045501 (2013)

Outlook: superallowed transitions

Ground state feeding determination

- TAGS technique naturally gives a value due to the β penetration!



$I_\beta^{g.s.}$ value:
93.3(1)% ENSDF
93.9(5)% TAGS

V. Guadilla et al., Phys. Rev. C 96, 014319 (2017)

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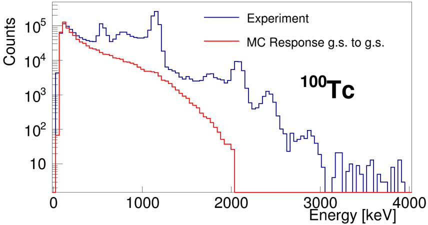

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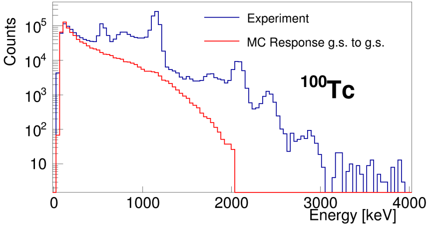

$I_\beta^{g.s.}$ value:
93.3(1)% ENSDF
93.9(5)% TAGS
92.8(5)% $4\pi\gamma - \beta$

V. Guadilla et al., Phys. Rev. C 96, 014319 (2017)

- Counting method: Greenwood et al., Nucl. Instrum. Methods A 317, 175 (1992)
- Recently revised: $4\pi\gamma - \beta$

ratio $N_{\beta\gamma}/N_\beta$ (exp.) + ratios of β efficiencies (MC)

V. Guadilla et al., Phys. Rev. C 102, 064304 (2020)

IS687-^{27}Na collaborators

V. Guadilla[1], P. Bielak[1], J. A. Briz[2], A. Fijałkowska[1], L. M. Fraile[2], A. Korgul[1], U. Köster[3], E. Nácher[4], Zs. Podolyák[5], W. Poklepa[1], K. Solak[1]

[1]Faculty of Physics, University of Warsaw, 02-093 Warsaw, Poland
[2]Universidad Complutense de Madrid, CEI Moncloa E-28040 Madrid, Spain
[3]Institut Laue-Langevin, 38042 Grenoble, France
[4]Instituto de Fisica Corpuscular, CSIC-Universidad de Valencia, E-46071, Valencia, Spain
[5]University of Surrey, Guildford, GU2 7XH, UK

Thank you very much for your attention!

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