From TAGS in β-decay to TAC in (n,γ): a totally absorbing journey

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1994 – 1999

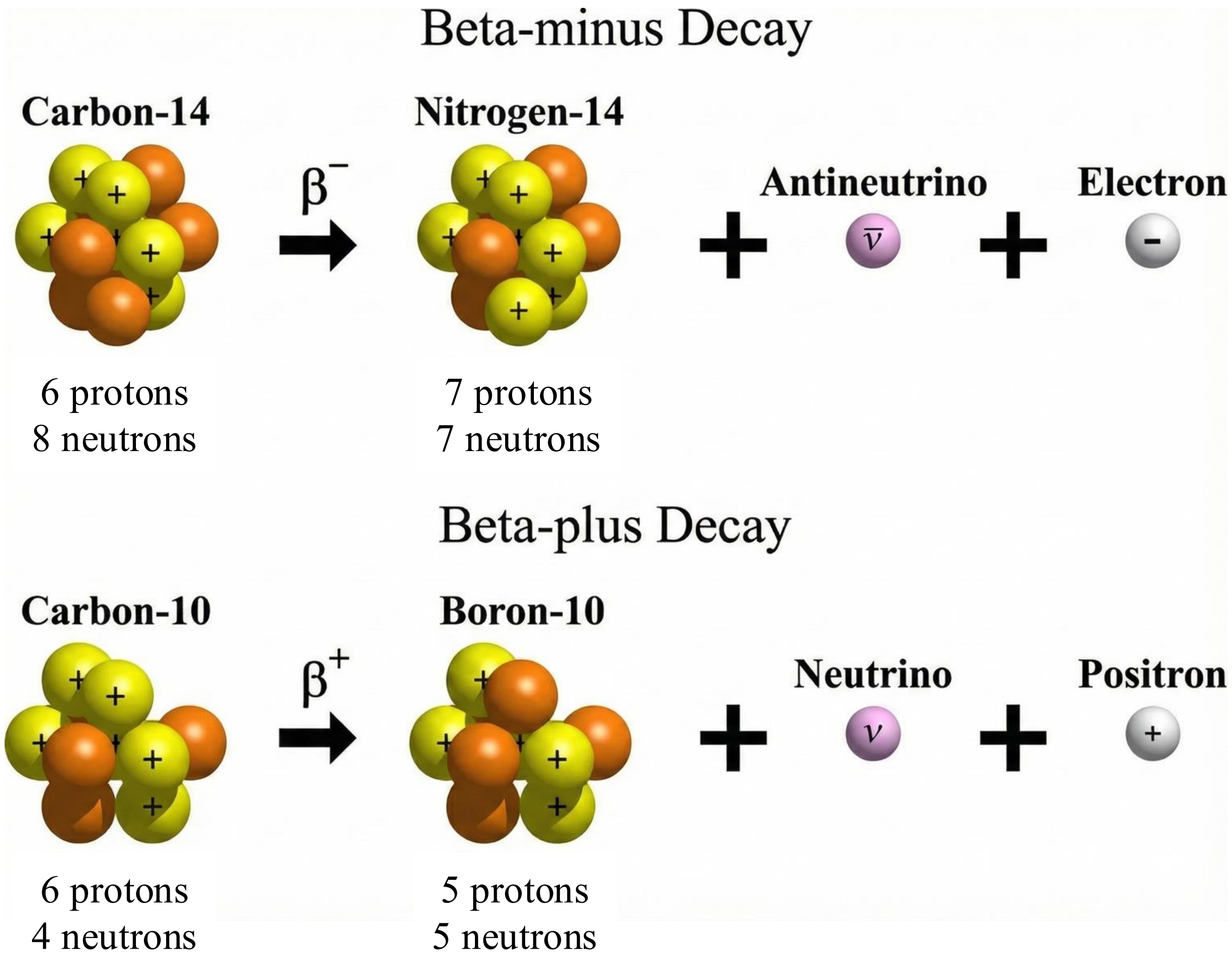
Instituto de Física Corpuscular – CSIC

1999 -> nowadays

Unidad de Innovación Nuclear

Departamento de Fisión Nuclear

Beta decay for dummies



Beta decay experiments are an excellent tool to investigate the electroweak interaction and structure of the nucleus:

- Half-lives, Q-values, nuclear levels, gamma-intensities, particle emission probabilities…

Also provide valuable information for:

- Controlling nuclear reactors, manage nuclear waste, explain how elements were made, cure cancer, develop imaging techniques…

Some β-decay theory

***f* (Fermi integral):** A statistical phase-space factor that accounts for the effects of the nuclear charge (*Z*) and the energy available for the decay (*Q*-value)

$$f(Z,Q) = k\int_0^{p_{max}} F(Z,p)p^2(Q-E_e)dp$$

***t* (Partial half-life):** The half-life specific to a particular transition between a specific initial and final state.

$$t_f = \frac{T_{1/2}}{P_f}$$

$ft_f \propto \frac{1}{|M_{fi}|^2}$ where $|M_{fi}|^2$ is the transition matrix element. The $\log ft$ is commonly used for convenience.

ft **value computed for Gamow-Teller transitions**

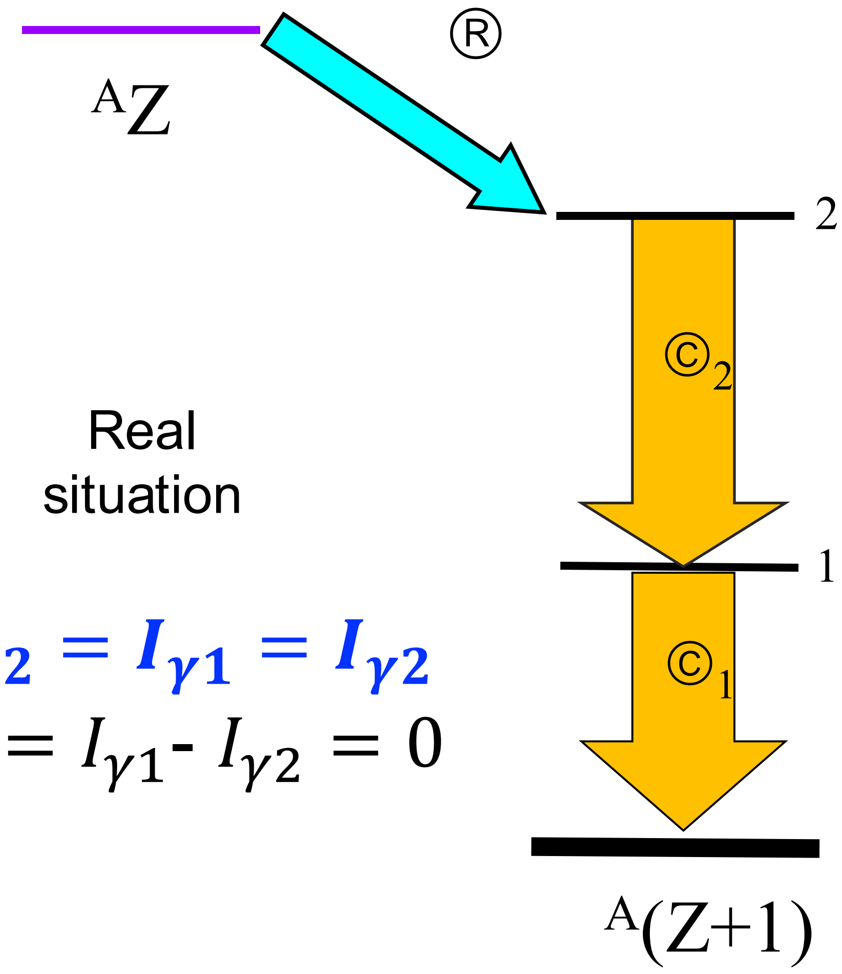
$$ft = \frac{6147 \pm 7}{\left(\frac{g_A}{g_V}\right)^2 B(GT)}$$

β-strength function $\boldsymbol{S_\beta}$

$$S_\beta(E_x) = \frac{I_\beta(E_x)}{f(Q_\beta - E_x)T_{1/2}}$$

Relation between the B(GT) and the $S_\beta(E)$

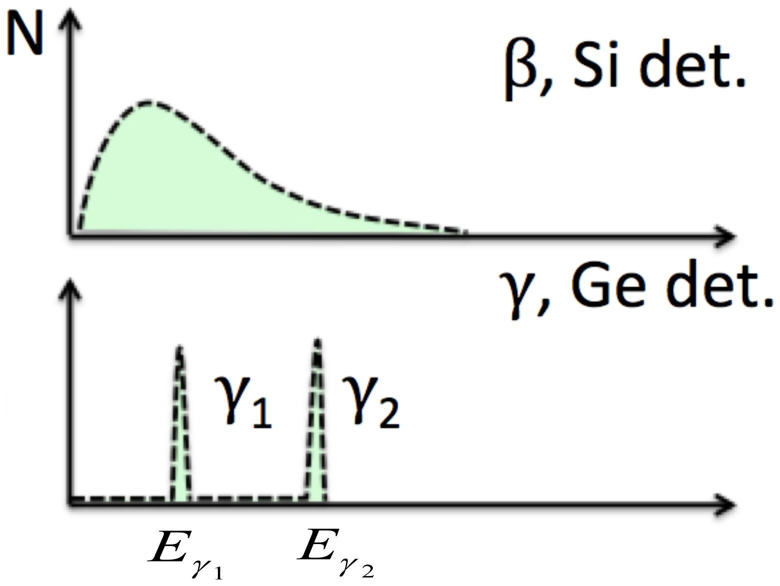
$$S_\beta(E_x) = \frac{1}{6147 \pm 7}\left(\frac{g_A}{g_V}\right)^2 \sum_{E_f \in \Delta E_x} \frac{1}{\Delta E_x} B(GT)_{i \to f}$$



Real situation

$$\boldsymbol{I_{\beta 2} = I_{\gamma 1} = I_{\gamma 2}}$$

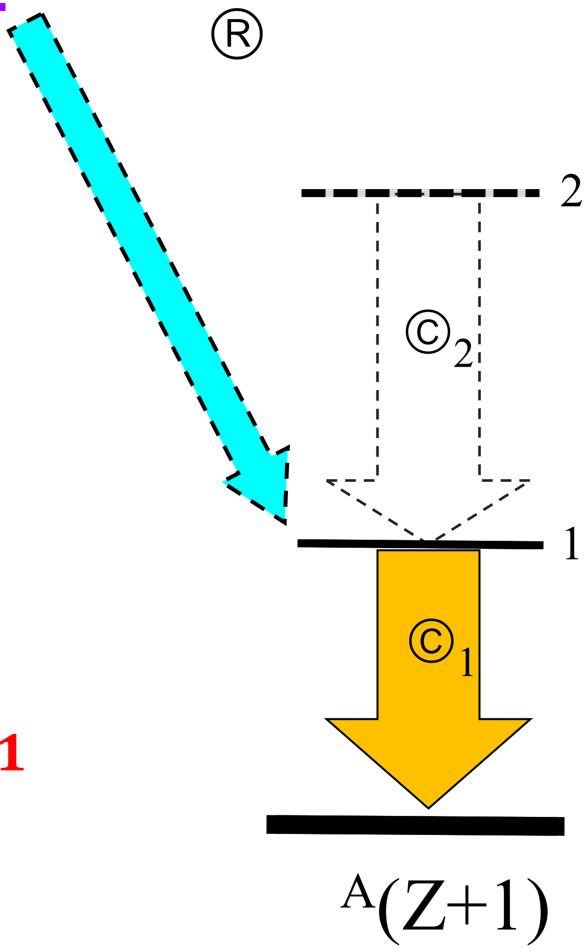
$$I_{\beta 1} = I_{\gamma 1} - I_{\gamma 2} = 0$$



What happens if we miss some intensity?

Courtesy by A. Algora

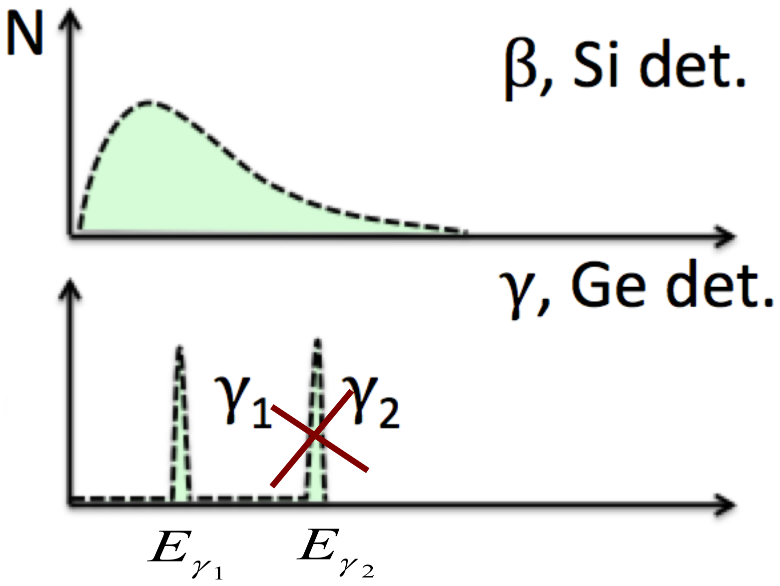
Sometimes things go wrong



Apparent situation

$I_{\beta 2} = 0$

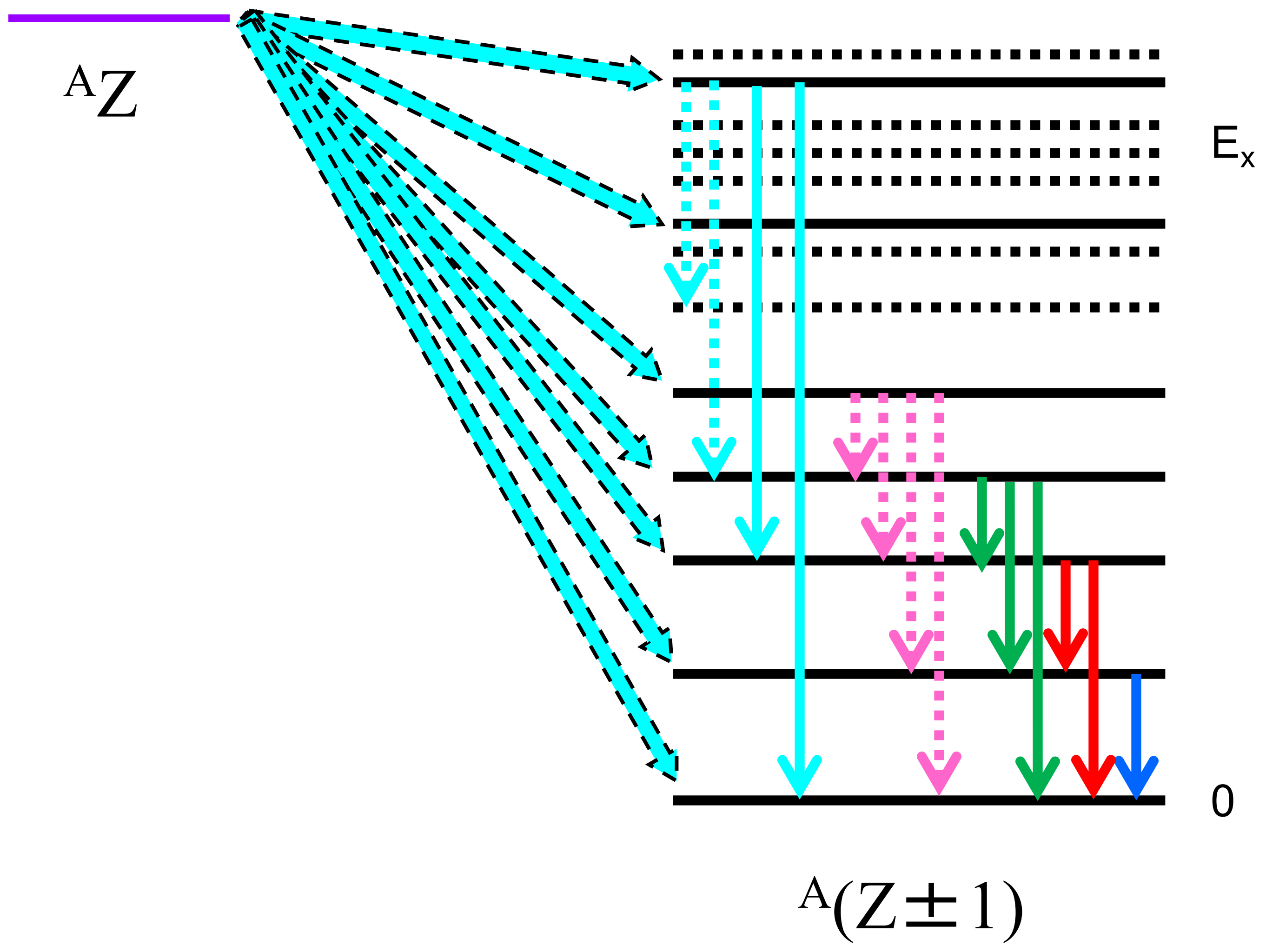
$\boldsymbol{I_{\beta 1} = I_{\gamma 1}}$



We get the wrong feedings -> the wrong **log*ft*** value

Courtesy by A. Algora

Welcome to Plato's cave

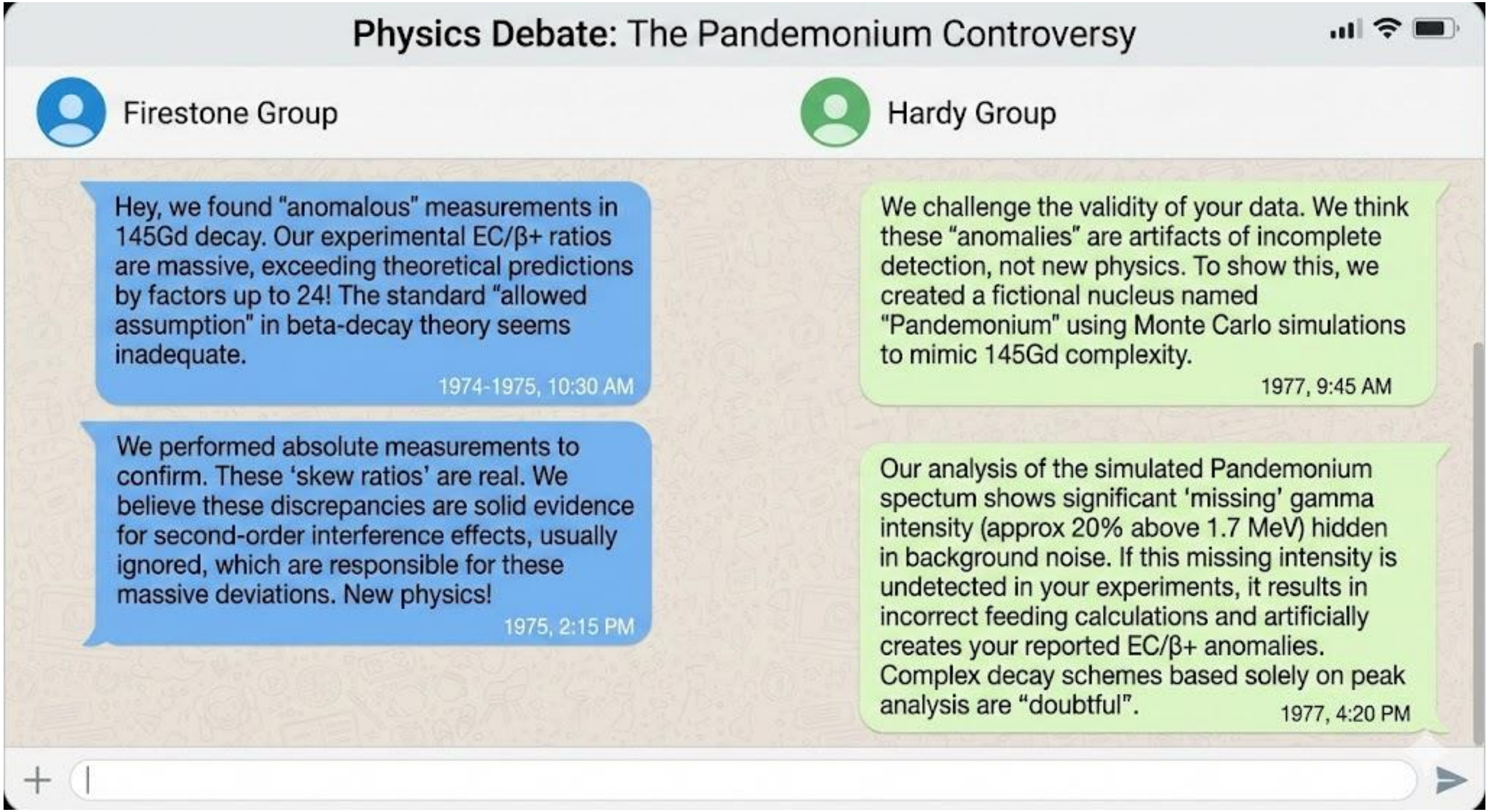


In case of a complex decay, high resolution gamma-ray spectroscopy will always miss intensity.

We just see the shadow of the truth projected on the walls of the cave.

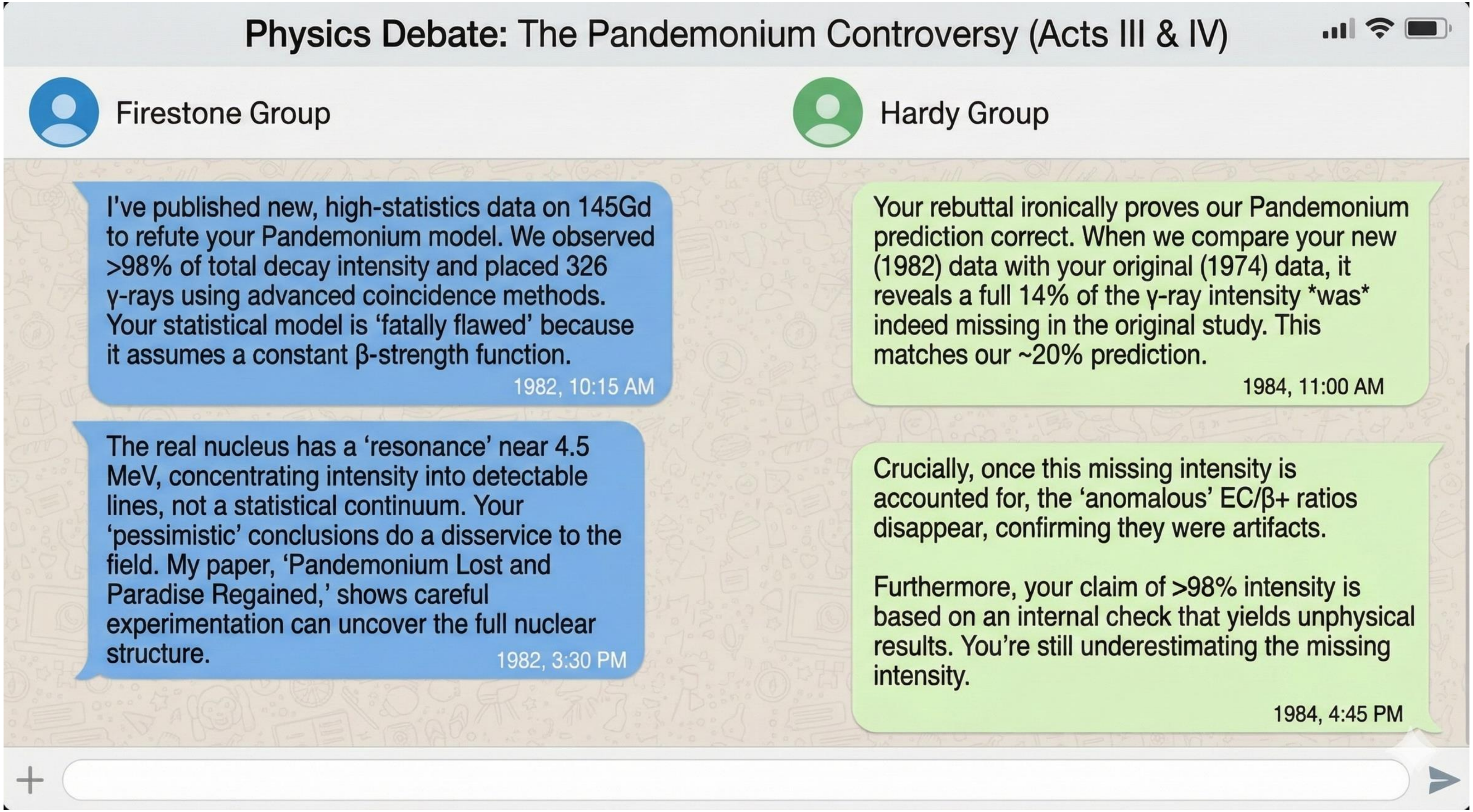
Drama in V acts: how new physics went down the drain

Acts I & II


Physics Debate: The Pandemonium Controversy
Firestone Group
Hardy Group
Hey, we found "anomalous" measurements in 145Gd decay. Our experimental EC/β+ ratios are massive, exceeding theoretical predictions by factors up to 24! The standard "allowed assumption" in beta-decay theory seems inadequate.
1974-1975, 10:30 AM
We challenge the validity of your data. We think these "anomalies" are artifacts of incomplete detection, not new physics. To show this, we created a fictional nucleus named "Pandemonium" using Monte Carlo simulations to mimic 145Gd complexity.
1977, 9:45 AM
We performed absolute measurements to confirm. These 'skew ratios' are real. We believe these discrepancies are solid evidence for second-order interference effects, usually ignored, which are responsible for these massive deviations. New physics!
1975, 2:15 PM
Our analysis of the simulated Pandemonium spectum shows significant 'missing' gamma intensity (approx 20% above 1.7 MeV) hidden in background noise. If this missing intensity is undetected in your experiments, it results in incorrect feeding calculations and artificially creates your reported EC/β+ anomalies. Complex decay schemes based solely on peak analysis are "doubtful".
1977, 4:20 PM


PANDÆMONIUM
G. Doré

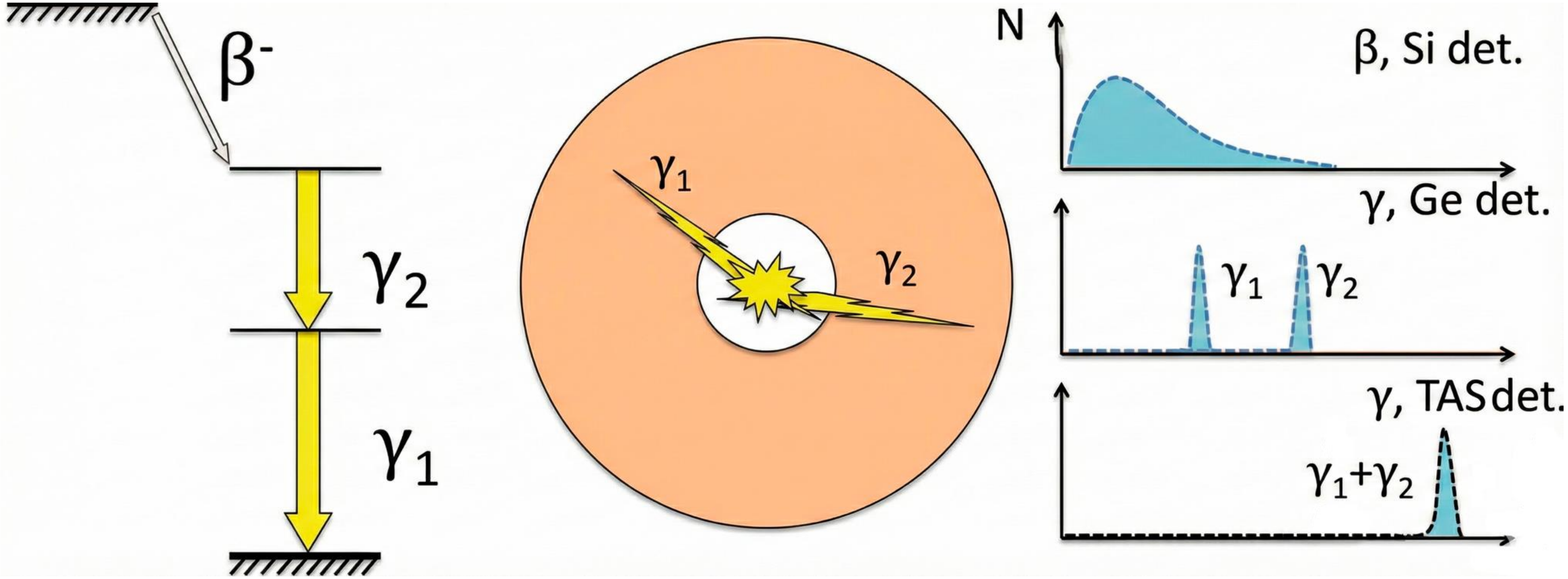
Acts III & IV


Physics Debate: The Pandemonium Controversy (Acts III & IV)
Firestone Group
Hardy Group
I've published new, high-statistics data on 145Gd to refute your Pandemonium model. We observed >98% of total decay intensity and placed 326 γ-rays using advanced coincidence methods. Your statistical model is 'fatally flawed' because it assumes a constant β-strength function.
1982, 10:15 AM
Your rebuttal ironically proves our Pandemonium prediction correct. When we compare your new (1982) data with your original (1974) data, it reveals a full 14% of the γ-ray intensity *was* indeed missing in the original study. This matches our ~20% prediction.
1984, 11:00 AM
The real nucleus has a 'resonance' near 4.5 MeV, concentrating intensity into detectable lines, not a statistical continuum. Your 'pessimistic' conclusions do a disservice to the field. My paper, 'Pandemonium Lost and Paradise Regained,' shows careful experimentation can uncover the full nuclear structure.
1982, 3:30 PM
Crucially, once this missing intensity is accounted for, the 'anomalous' EC/β+ ratios disappear, confirming they were artifacts.
Furthermore, your claim of >98% intensity is based on an internal check that yields unphysical results. You're still underestimating the missing intensity.
1984, 4:45 PM

Act V: the high-resolution catastrophe

Final Verdict. Hardy et al. were right and the statistical warning provided by Pandemonium remains valid.

The solution: a total absorption γ-ray detector

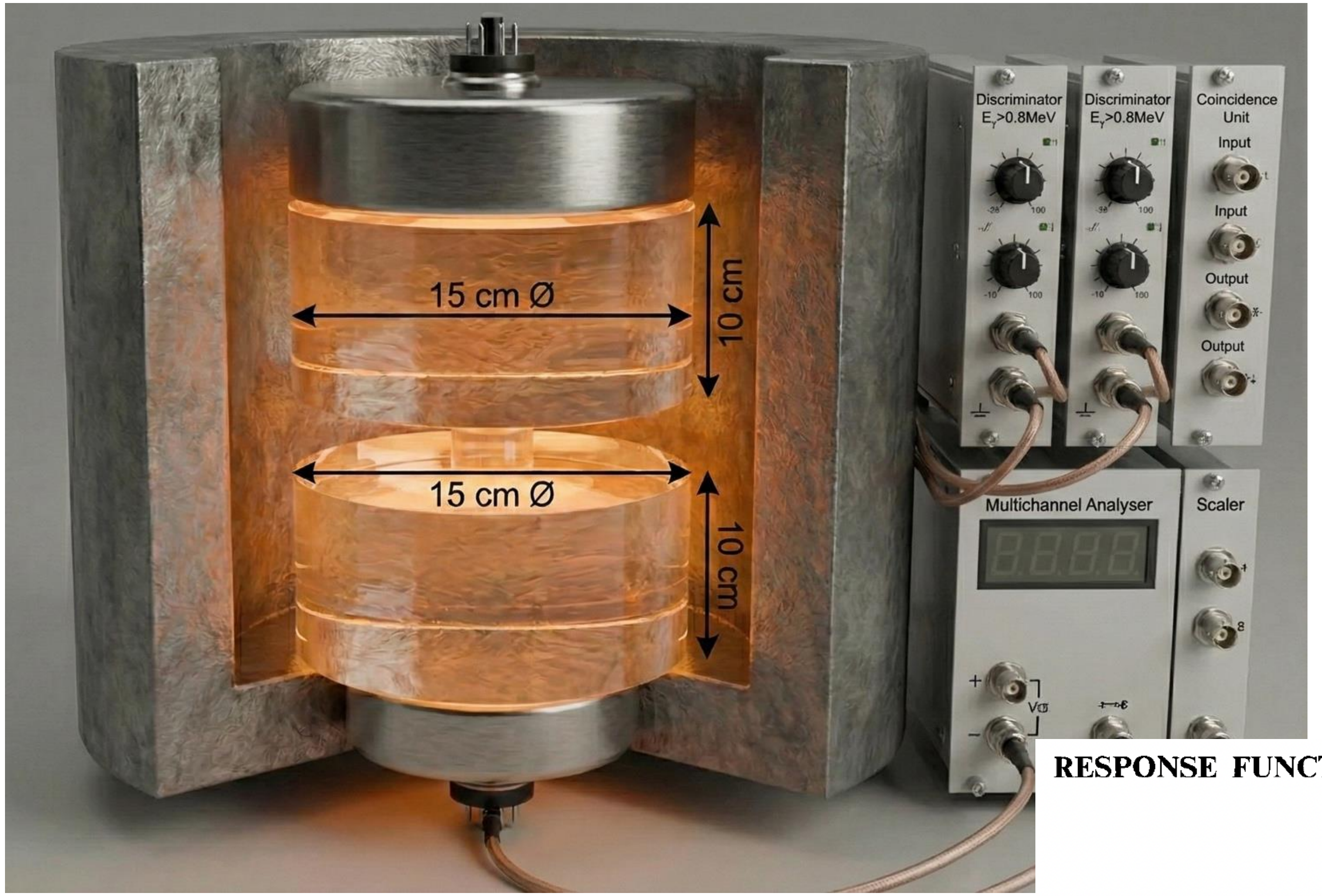


For a 100% peak efficiency detector -> counts in the peaks = feeding to the E_x of the peak.

For an efficiency ≠ 100%, one needs to solve the inverse problem:

$$d = R \cdot f$$

The 1st TAGS at ISOLDE



Pioneering work of B.R. Erdal and G. Rudstam. ISOLDE TAGS, made of two cylindrical NaI(Tl) detectors Φ15 cm × 10 cm thick (before the Pandemonium debate)

RESPONSE FUNCTION OF A GOOD-GEOMETRY DETECTOR FOR A γ-RAY CASCADE

B. R. ERDAL*

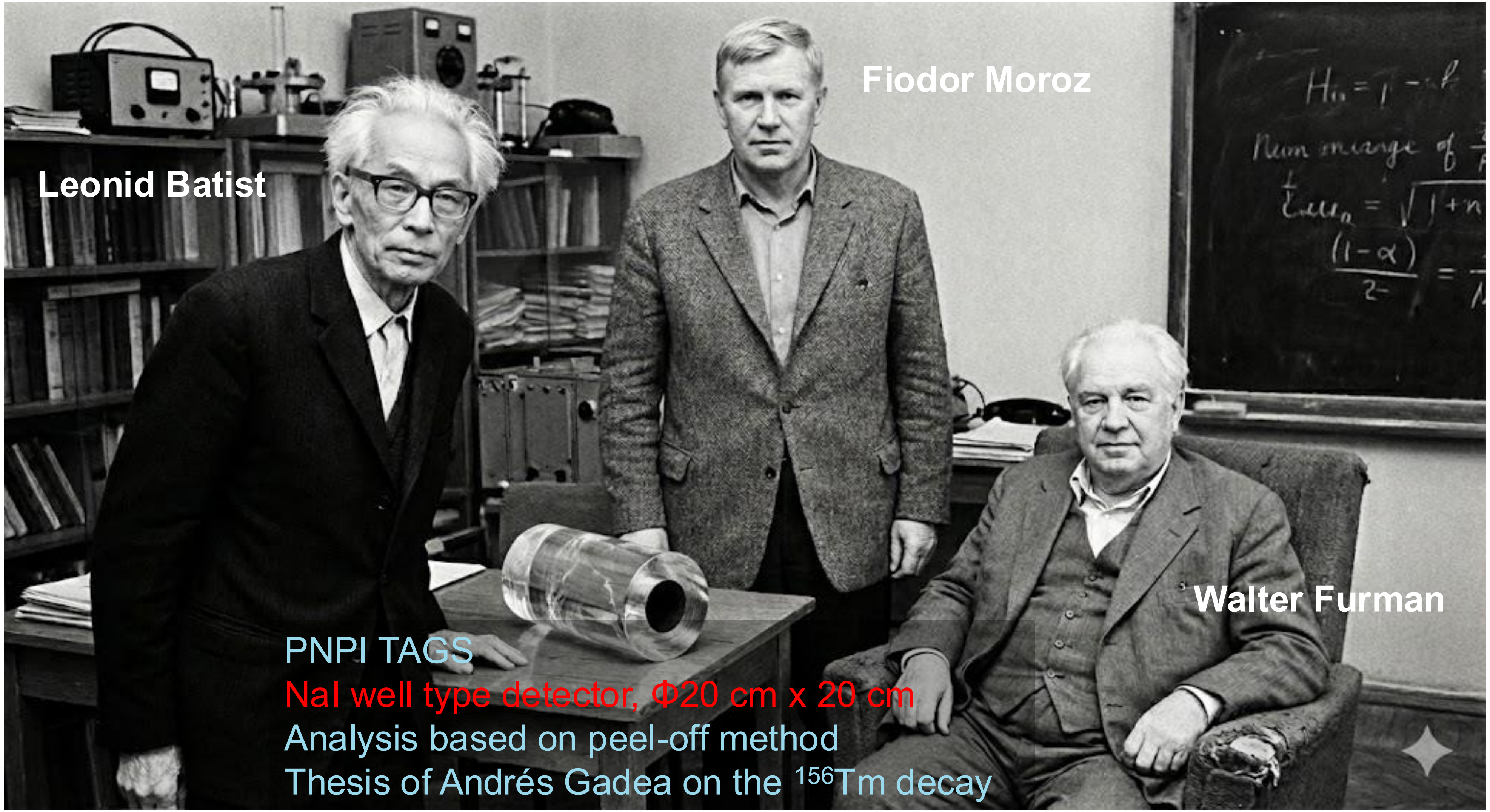
CERN, Geneva, Switzerland

and

G. RUDSTAM

The Swedisch Research Councils' Laboratory, Studsvik, Sweden

The three Russians who came from the cold



The Lawrence Berkeley TAGS moves to Darmstadt (and so do I)

But my heart was warm…

The first days weren't so easy

Spring arrived

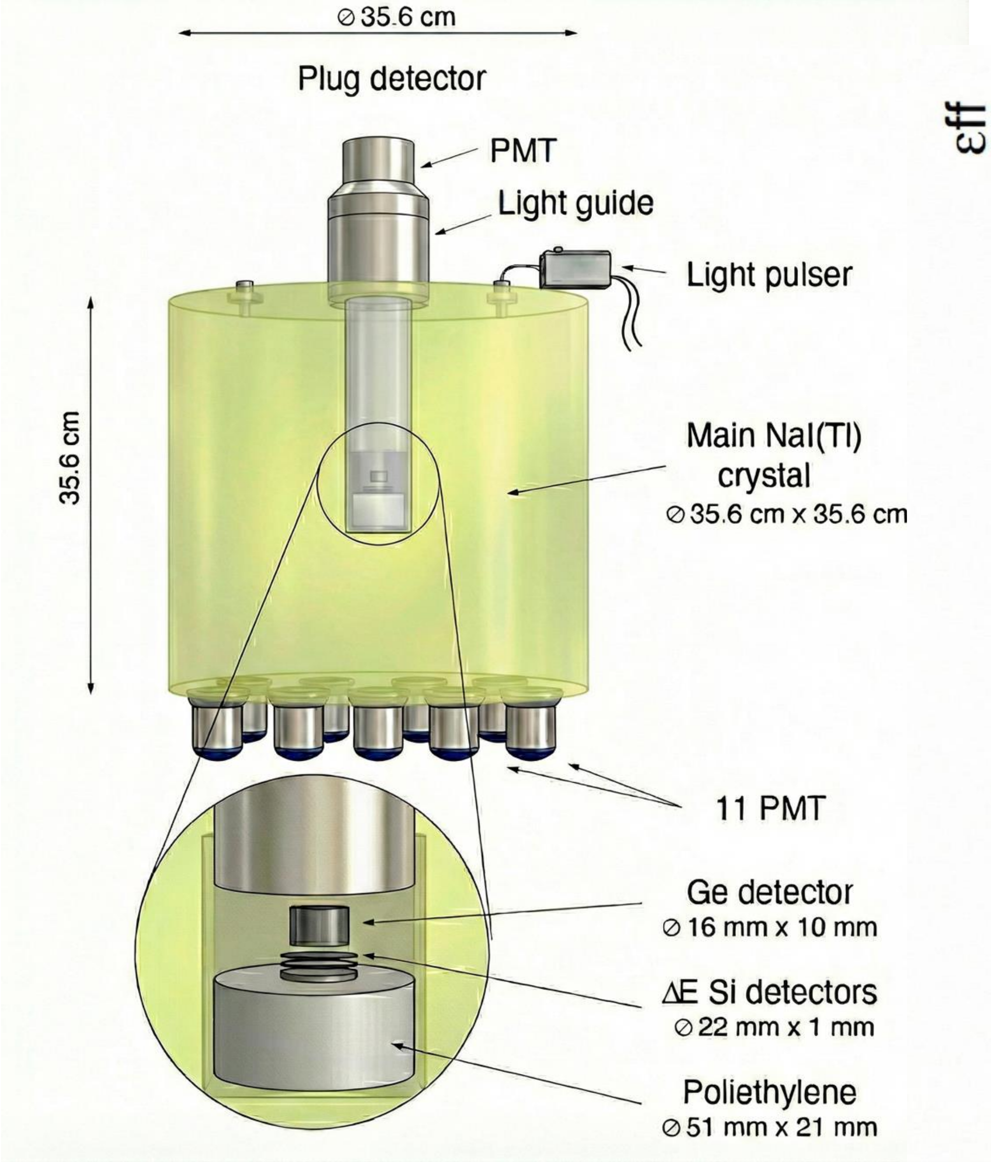
And so did a part of the Valencia team

And so did a part of the Valencia team (unrealistic photo version)

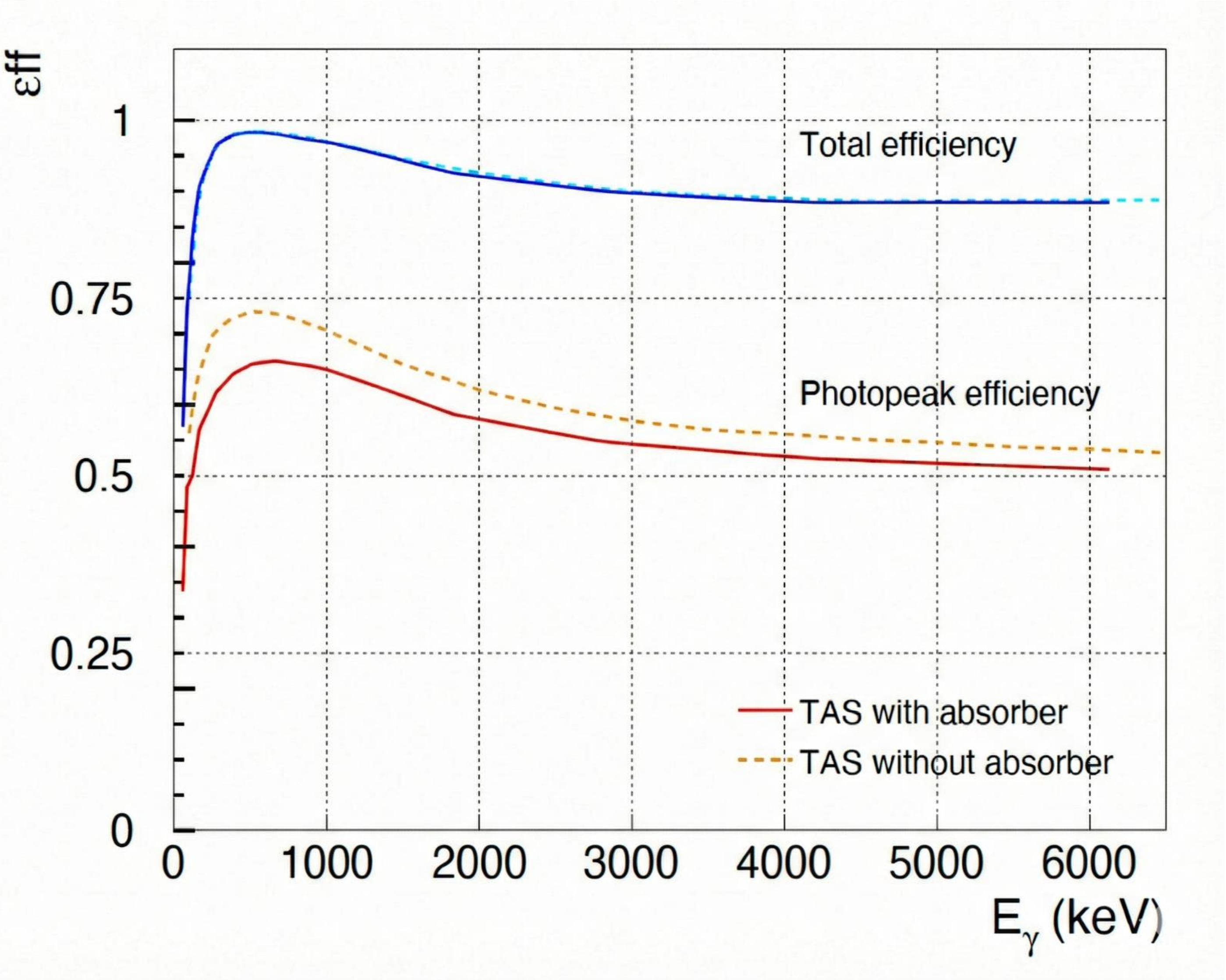
Inside the TAGS hut

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
UIN
CSIC Consejo Superior de Investigaciones Científicas
IFIC Institut de Física Corpuscular

The LBL TAGS



⊘35.6 cm
Plug detector
PMT
Light guide
Light pulser
35.6 cm
Main NaI(Tl) crystal
⊘35.6 cm x 35.6 cm
11 PMT
Ge detector
⊘16 mm x 10 mm
ΔE Si detectors
⊘22 mm x 1 mm
Poliethylene
⊘51 mm x 21 mm



εff
1
0.75
0.5
0.25
0
0
1000
2000
3000
4000
5000
6000
Eγ (keV)
Total efficiency
Photopeak efficiency
TAS with absorber
TAS without absorber

Data analysis: solving the ill-conditioned inverse problem

We collected very nice data from the ^{150}Ho(2^- & 9^+) beta decays, showing wonderful GT resonances.

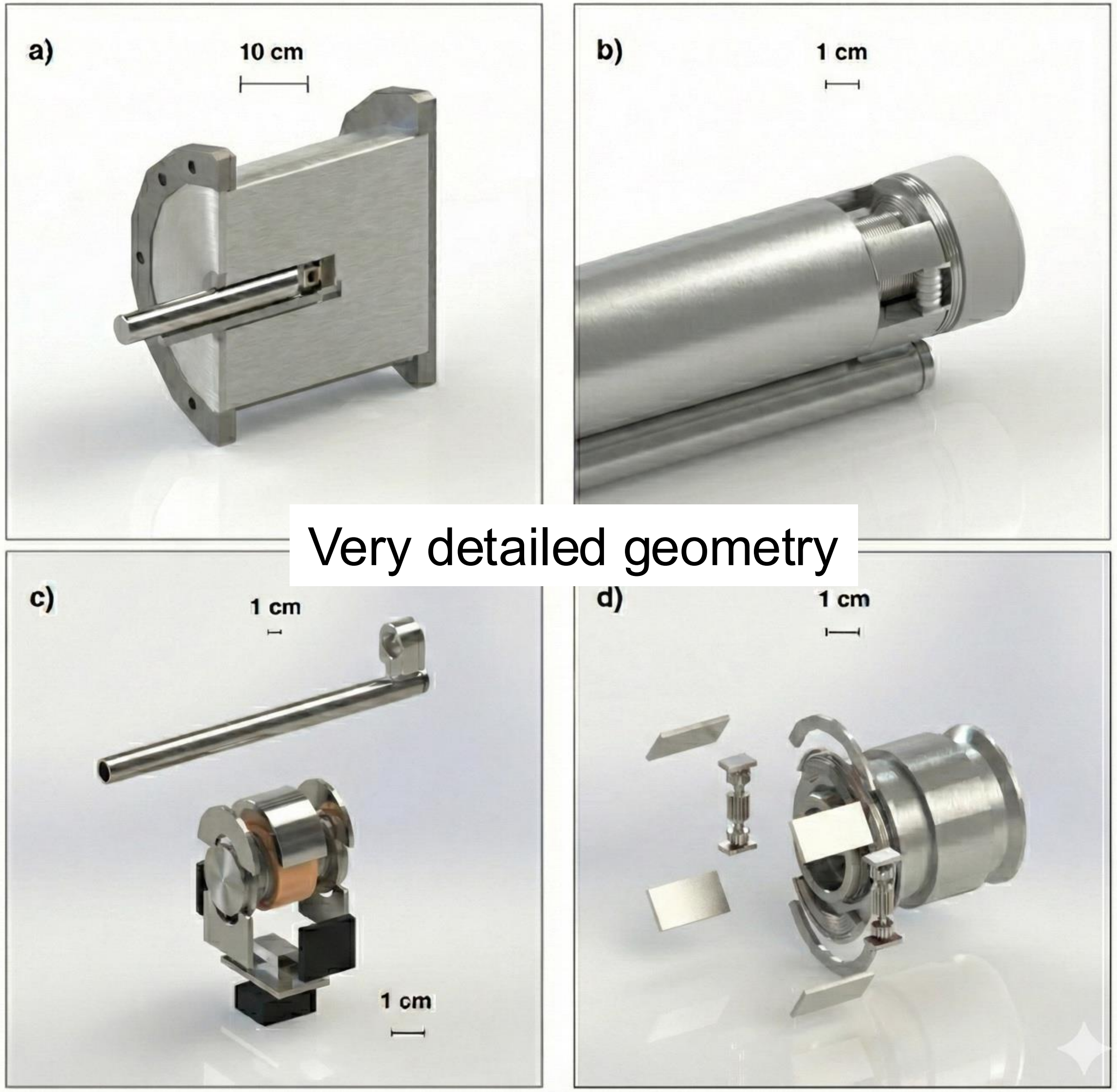
Analysis: finding the feeding distribution ***f*** that reproduces the data ***d*** in a statistical sense.

$$\boldsymbol{d} = \boldsymbol{R} \cdot \boldsymbol{f} \quad \Rightarrow \quad \boldsymbol{f} = \boldsymbol{R}^{-1} \cdot \boldsymbol{d}$$

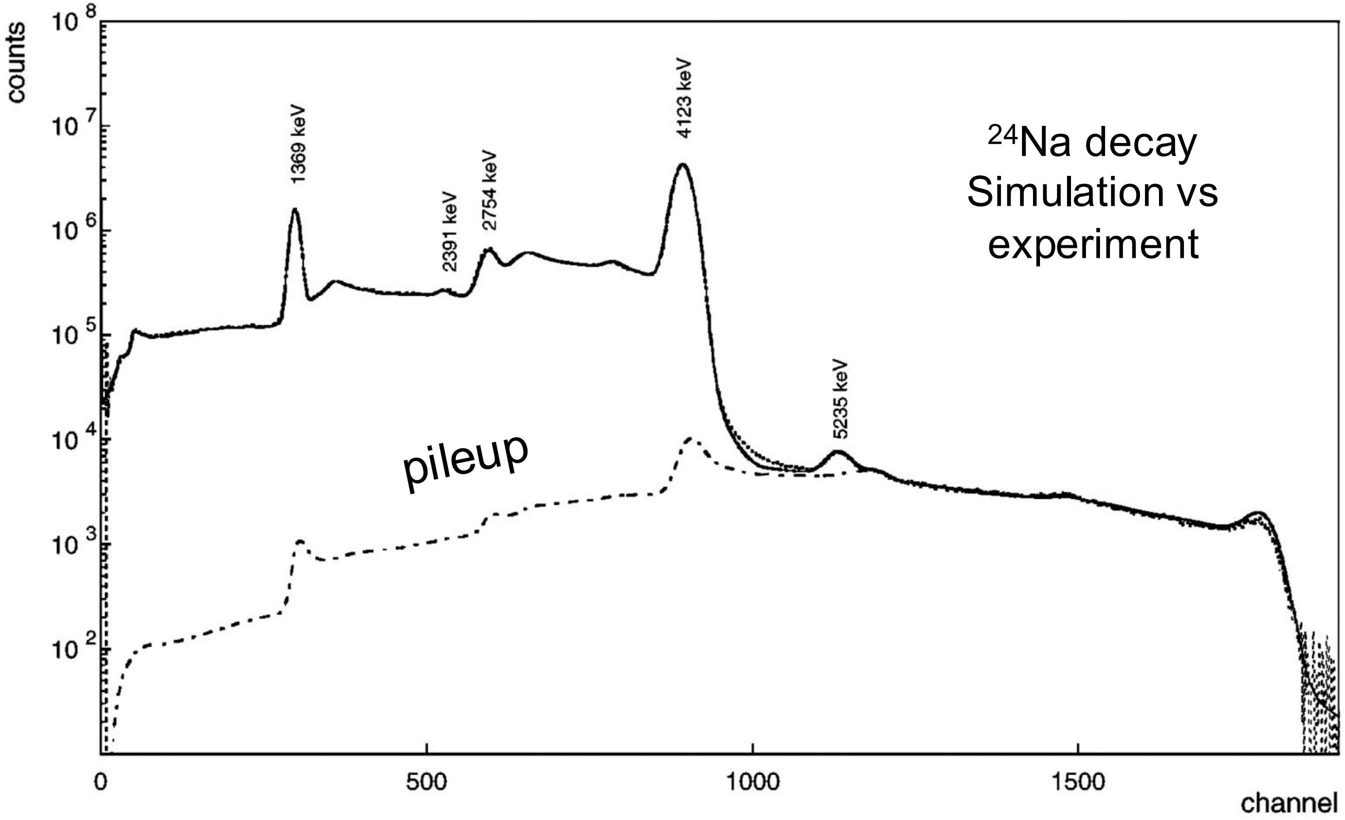
Tiny little problems:

- ***R*** can't really be inverted in a standard way (large quasi singular matrix).
- ***R*** can't be obtained experimentally.
  - ***R*** depends on the level scheme (~N), typically unknown above some excitation energies.
  - ***R*** depends on the branching ratios of transitions connecting the levels (~N^2).
- The spectra have counts beyond the Q_β due to pileup.

Obtaining *R* with accurate Monte Carlo simulations



Very detailed geometry



^{24}Na decay
Simulation vs experiment

Statistical nuclear electromagnetic de-excitation model

Level scheme:

- ENSDF with unambiguous spin and parity at low energies.
- Levels generated from level density formulas (Back-Shifted Fermi Gas) with parameters from RIPL.

Branching ratios:

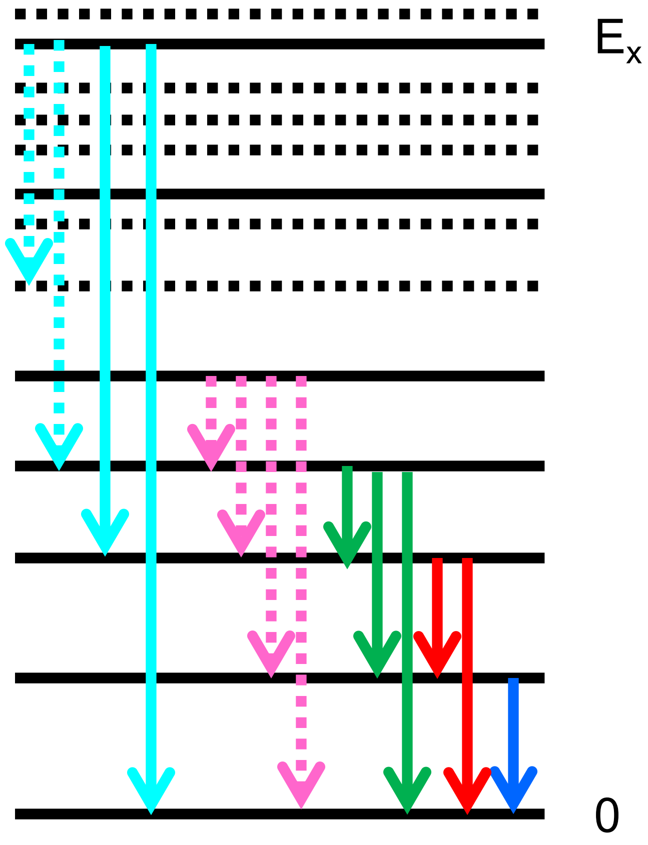
- Known branching ratios from RIPL
- Rest of the branching ratios generated according to:

$$BR_{a\rightarrow b} \propto \varphi \cdot (E_a - E_b)^{2L+1} \cdot PSF^{XL}(E_a - E_b)$$

- PSF functions from RIPL

Internal conversion:

- Known ICC from RIPL
- Rest of the ICC from BrICC



n + ^{A}X → $^{A+1}$X

3 methods for solving the inverse problem

$$d_i = \sum_{j=1}^{j_{max}} R_{ij} f_j \qquad (i = 1 \ldots i_{max})$$

Linear regularisation method (LR):

min:$\chi^2[d - R \cdot f] + \lambda |B \cdot f|^2$

Maximum entropy method (MEM):

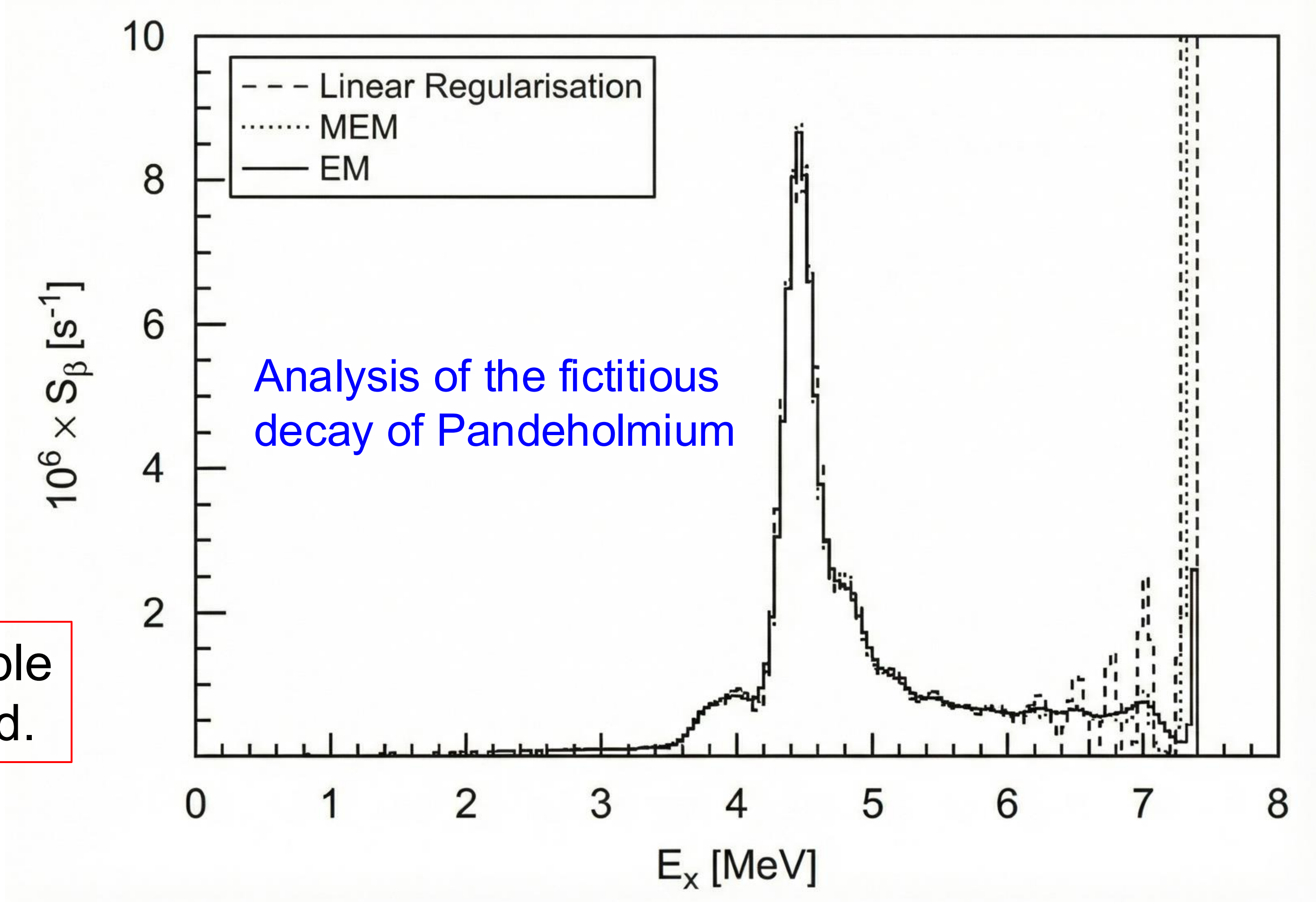
min:$\chi^2[d - R \cdot f] - \lambda S[f]$

Expectation maximisation (EM)

$$P(f_j|d_i) = \frac{P(d_i|f_j)P(f_j)}{\sum_{j=1}^{m} P(d_i|f_j)}$$

EM and MEM provide reasonable solutions, but LR is not so well suited.

Taín, Cano NIMA 571 (2007)



The robustness without knowing *R*

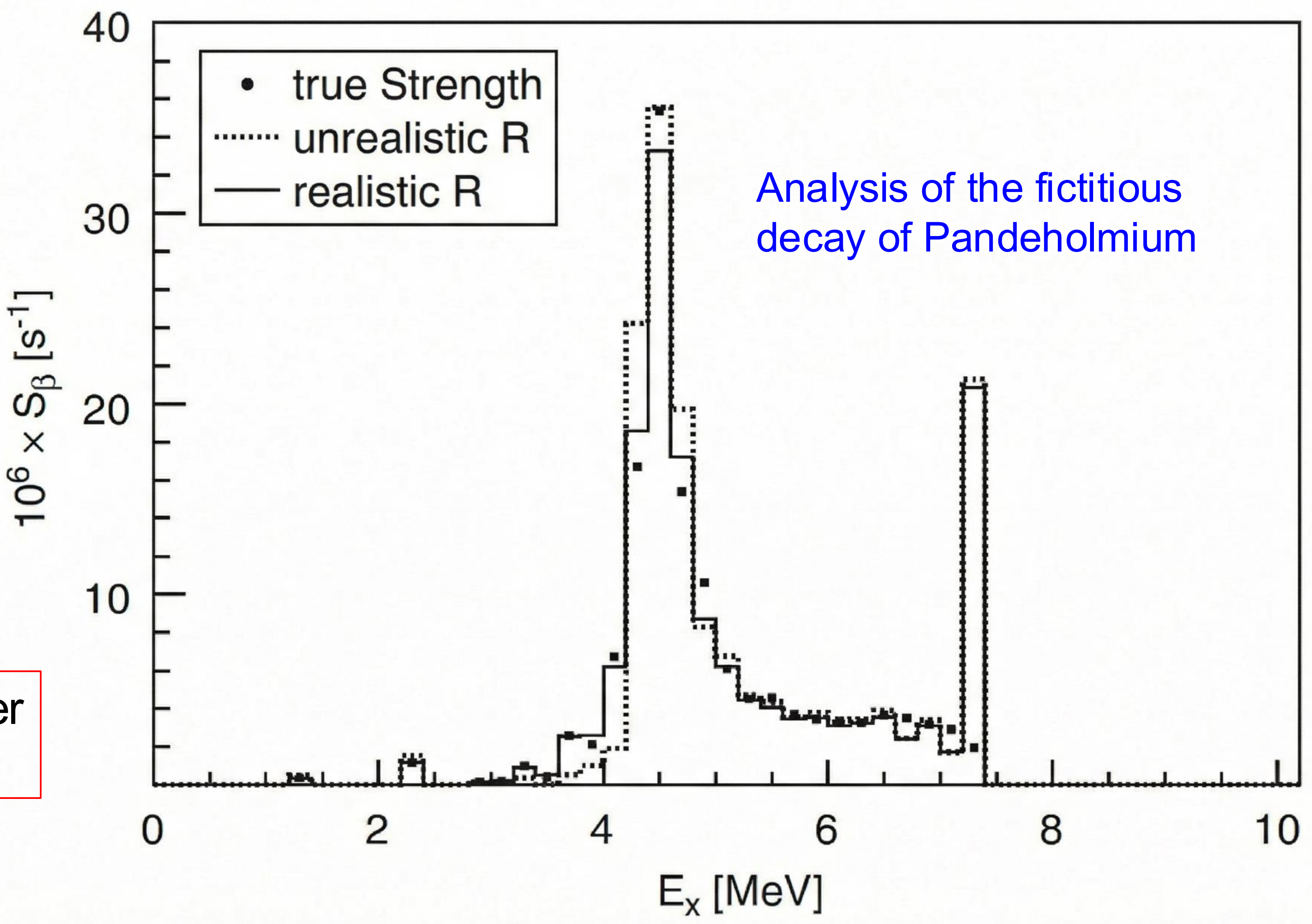
R needs to be built with an electromagnetic de-excitation pattern:

- **Unrealistic** equal probability **branching** ratios from top to bottom levels.

- **Realistic branching ratios**, based on a statistical model with binned levels.

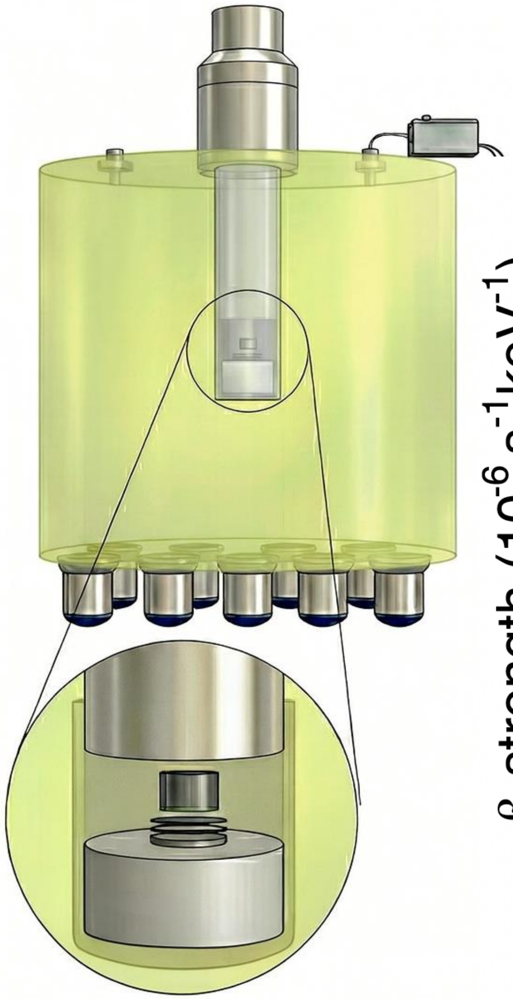
The solution is robust, even under unrealistic assumptions.

Taín, Cano NIMA 572 (2007)

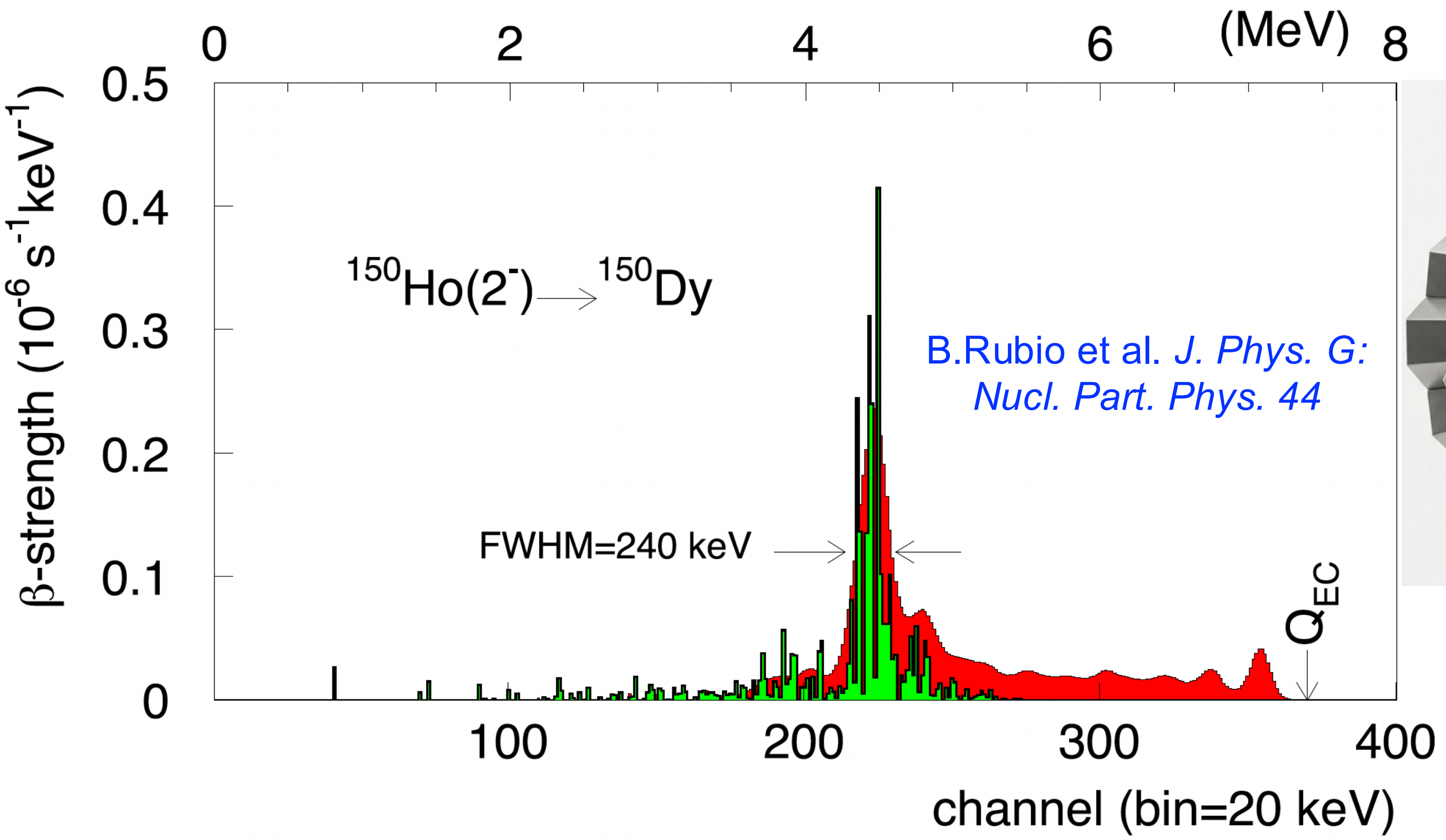


Analysis of the fictitious decay of Pandeholmium

TAGS versus Euroball Cluster Cube: Pandemium is there

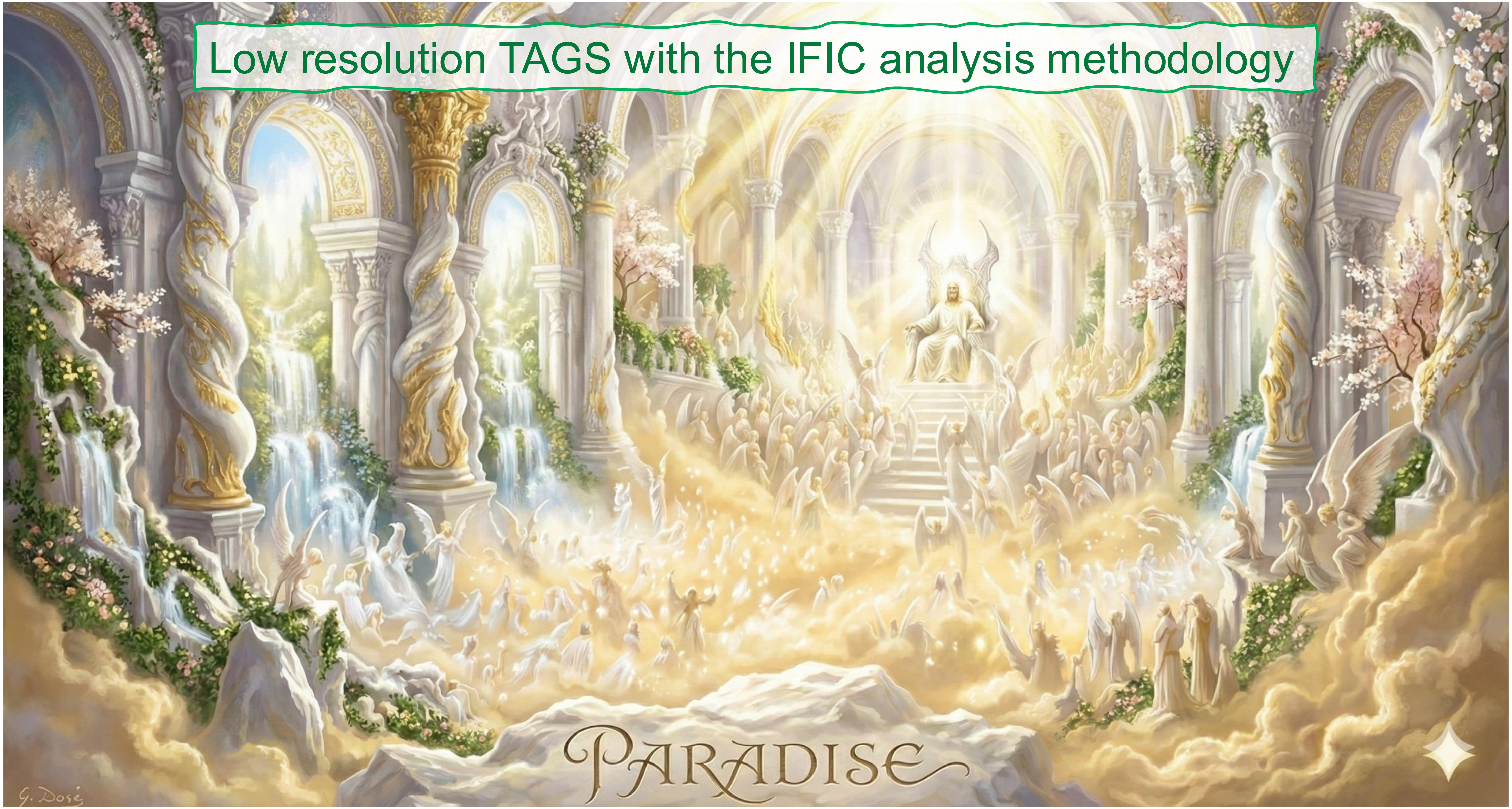


TAGS sees 50% more strength!



High resolution Ge

Low resolution TAGS with the IFIC analysis methodology



The TAGS historic timeline

Detector	Date	Primary Location(s)	Material	Geometry / Segments	Dimensions (Total)	Peak Eff. @ 5 MeV
ISOLDE	70s	ISOLDE	NaI(TI)	2 large cylinders	Φ15 cm×10 cm	Loq
PNPI-TAS	80s	GSI, Jyväskylä	NaI(TI)	1 (Well-type)	Φ20 cm x 20 cm	~30%
LBL/GSI	90s	LBL, GSI	NaI(TI)	1 + Plug	Φ 36 cm x 36 cm	~50%
INEL	90s	Idaho	NaI(TI)	1 (Well-type)	Φ 25.4 cm x 30.5 cm	High
Lucrecia	2000s	ISOLDE (CERN)	NaI(TI)	1 (Through-hole)	Φ 38 cm x 38 cm	~48%
MTAS	2010s	ORNL, ANL	NaI(TI)	19 Hexagonal	1 Ton mass; ~1 m length	~71%
DTAS	2010s	Jyväskylä, GSI, RIKEN	NaI(TI)	18 Rectangular	Reconfigurable block	~48%
Rocinante	2010s	Jyväskylä	BaF_2	12 Cylindrical	Φ 25 cm x 25 cm	~40%
SuN	2010s	FRIB (MSU)	NaI(TI)	8 (orig) / 28 (++)	Φ 40 cm x 40 cm	~45%
(NA)2STARS	Late 2020s	GANIL, SPIRAL2	$LaBr_3$, NaI(TI)	-	-	Large

The TAGS historic timeline and the IFIC legacy

Detector	Date	Primary Location(s)	Material	Geometry / Segments	Dimensions (Total)	Peak Eff. @ 5 MeV
ISOLDE	70s	ISOLDE	NaI(Tl)	2 large cylinders	Φ15 cm×10 cm	Loq
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TAGS and paella, both from Valencia!

Part II: neutron physics or how to live off rent (from what I learned in Valencia)

A new opportunity arises in the Spanish nuclear physics scenario:

The construction of the n_TOF facility at CERN and the creation of the Spanish n_TOF collaboration formed by CIEMAT, CSIC-IFIC, Politechnical University of Catalonia, University of Santiago de Compostela and University of Seville.

Great opportunity for young nuclear physicists!

The n_TOF facility

Spallation source

CERN PS @ 0.8 Hz

p 20 GeV/c, 7ns RMS

$7 \cdot 10^{12}$ p/pulse

$2 \cdot 10^{15}$ n/pulse

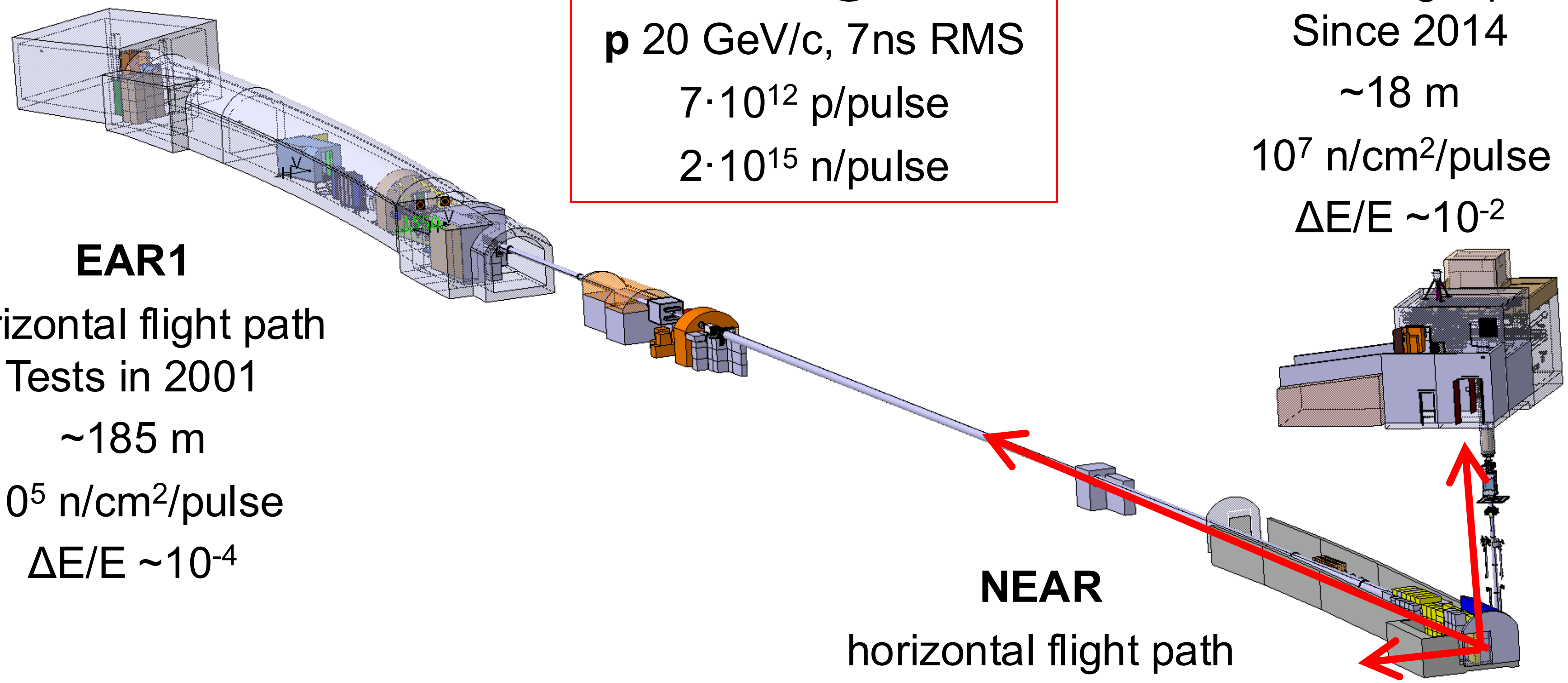
EAR2

Vertical flight path
Since 2014

~18 m

10^{7} n/cm^{2}/pulse

$\Delta E/E \sim 10^{-2}$



EAR1

horizontal flight path
Tests in 2001

~185 m

10^{5} n/cm^{2}/pulse

$\Delta E/E \sim 10^{-4}$

NEAR

horizontal flight path
Tests in 2021

~3 m

10^{8} n/cm^{2}/pulse

World's best and most complete facility for neutron cross section measurements!

Measuring an (n,γ) cross section

Counting rate in γ-ray detector
(γ-ray detector)

Background in the γ-ray detector
Determined from dedicated measurements (sample activity, room background, intrinsic activity of the crystals, neutron beam induced background...)

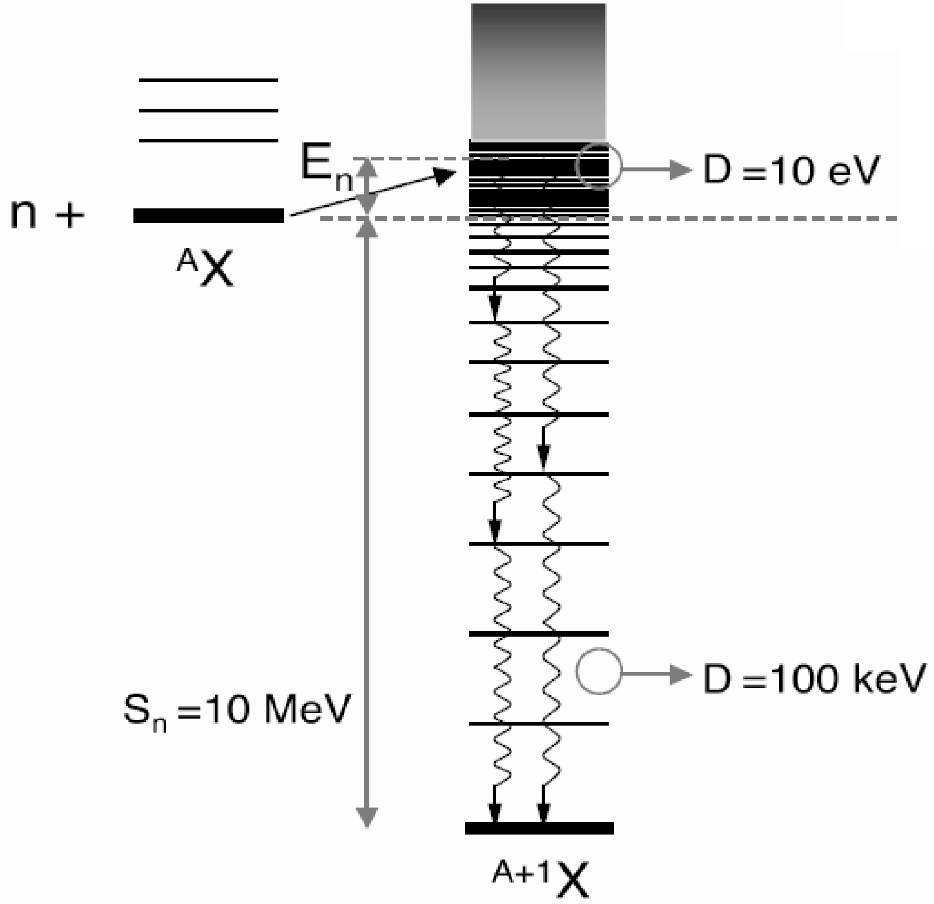
$$\sigma(n,\gamma) = \frac{1}{n_{sample}} \frac{C_\gamma(E_n) - B_\gamma(E_n)}{\varepsilon_\gamma(E_\gamma) \cdot \phi(E_n)}$$

Sample thickness

Detection efficiency
To be determined by Monte Carlo simulation.
Unknown de-excitation scheme.

Neutron energy fluence
-Determined experimentally
-Removed in a relative measurement

Counting cascades without knowing the gammas



Total Energy Detectors (TEDs)

$$\left.\begin{array}{c}\epsilon(E_\gamma) = k \cdot E_\gamma \\ \epsilon(E_\gamma) \ll 1\end{array}\right\} \quad \epsilon_{cascade} \cong \sum \epsilon_{\gamma i} = \sum k \cdot E_{\gamma i} = k \cdot E_{cascade}$$

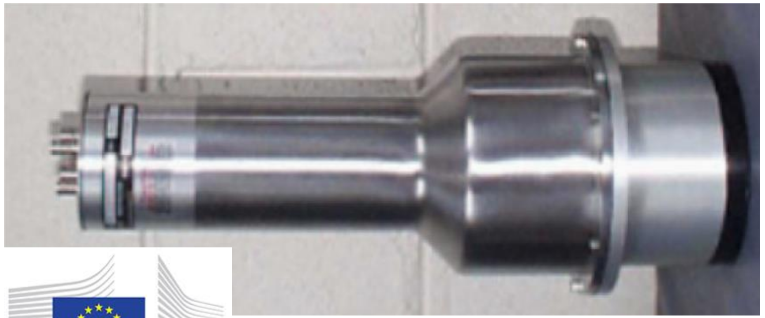
Approximation -> Calculate the detection efficiency with Monte Carlo simulations and application of the pulse height weighting technique.

Total Absorption Calorimeters (TACs)

$$\left.\begin{array}{c}\epsilon_{cascade} = 1 - \prod (1 - \epsilon_{\gamma i}) \\ \epsilon_{\gamma i} = 1\end{array}\right\} \quad \epsilon_{cascade} = 1$$

Approximation -> Calculate the detection efficiency for cascades with Monte Carlo simulations that reproduce the data.

The two (n,γ) setups at n_TOF



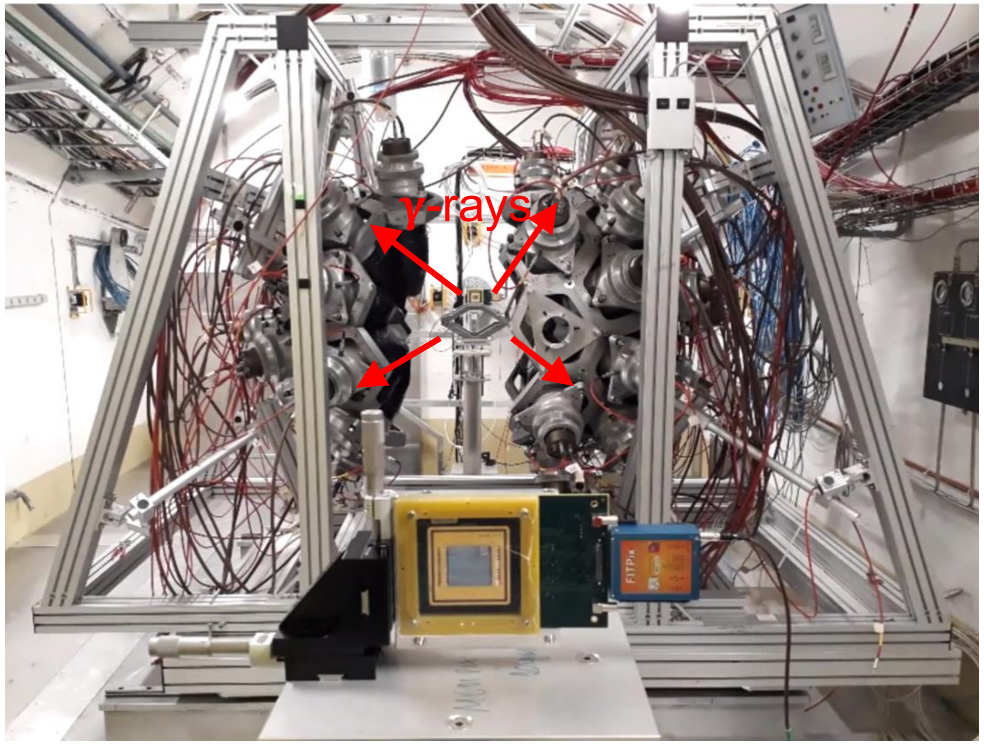
Total energy detectors based on C_6D_6 liquid scintillators.

Monte Carlo based analysis methodology developed by IFIC.

*U. Abbondano… **J.L. Taín** et al. NIMA 521 (2004)*
https://doi.org/10.1016/j.nima.2003.09.066

Total Absorption Calorimeter made of 40 BaF_2 crystals.
Analysis methodology developed by CIEMAT and IFIC.

C. Guerrero et al., NIMA 608 (2009)
https://doi.org/10.1016/j.nima.2009.07.025
C. Guerrero et al., NIMA 671 (2012)
https://doi.org/10.1016/j.nima.2011.12.046



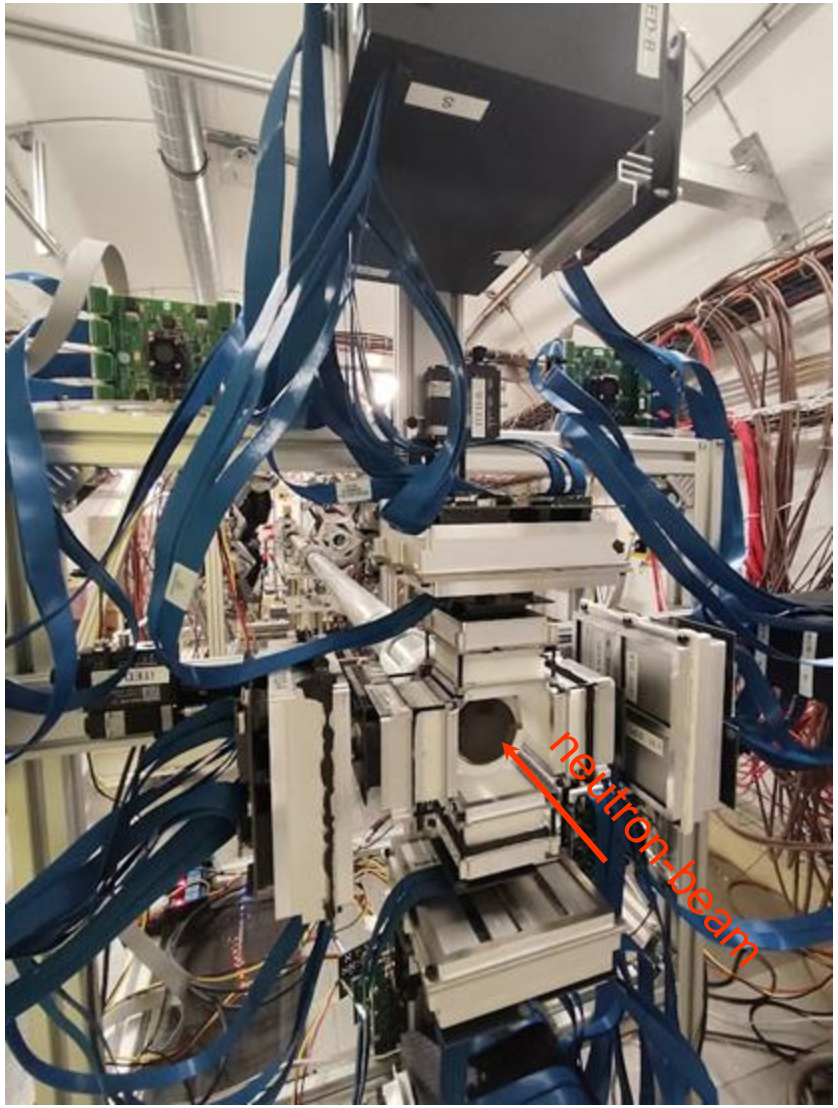
Total energy detectors are also a Valencia thing!

Innovative Idea i-TED: Exploit the Compton Imaging technique to reduce the neutron background and enhance capture detection sensitivity.

C.Domingo-Pardo, "i-TED: A novel concept for high-sensitivity (n,γ) cross-section measurements" NIM-A (2016)
https://doi.org/10.1016/j.nima.2016.04.002

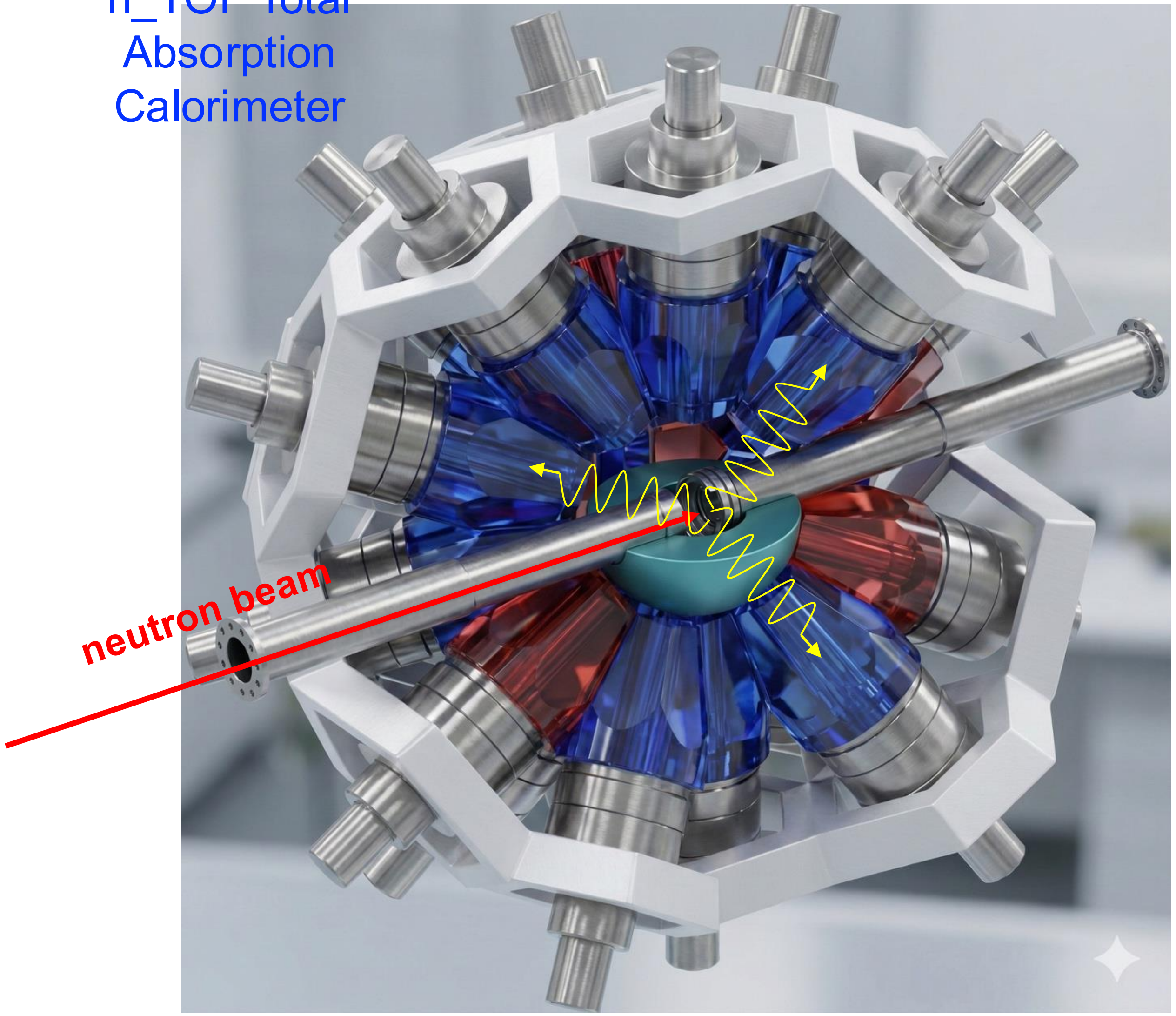
J.Lerendegui-Marco et al., "Imaging neutron capture cross-sections: i-TED proof-of-concept and future prospects based on Machine Learning techniques" EPJ-A (2021) https://doi.org/10.1140/epja/s10050-021-00507-7

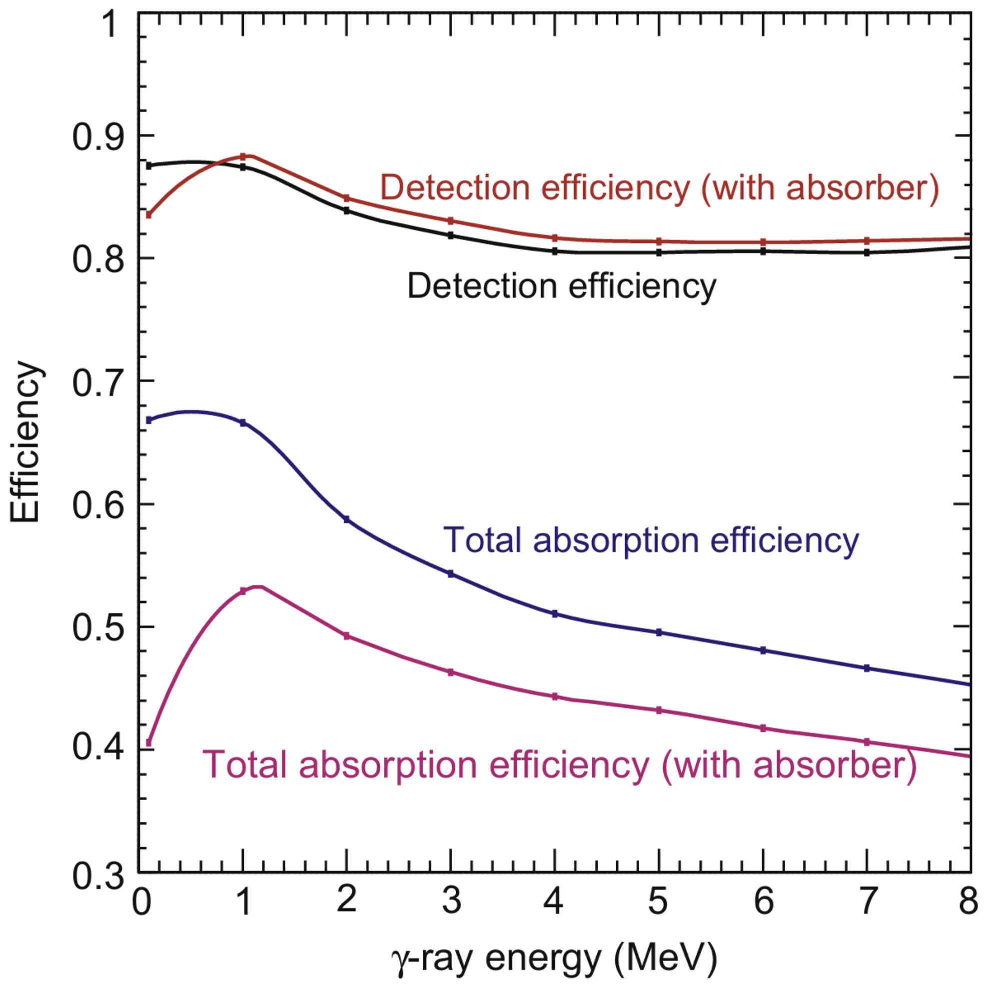
This story of success by César et al. is for another day!



The n_TOF TAC GEANT4 model

n_TOF Total Absorption Calorimeter





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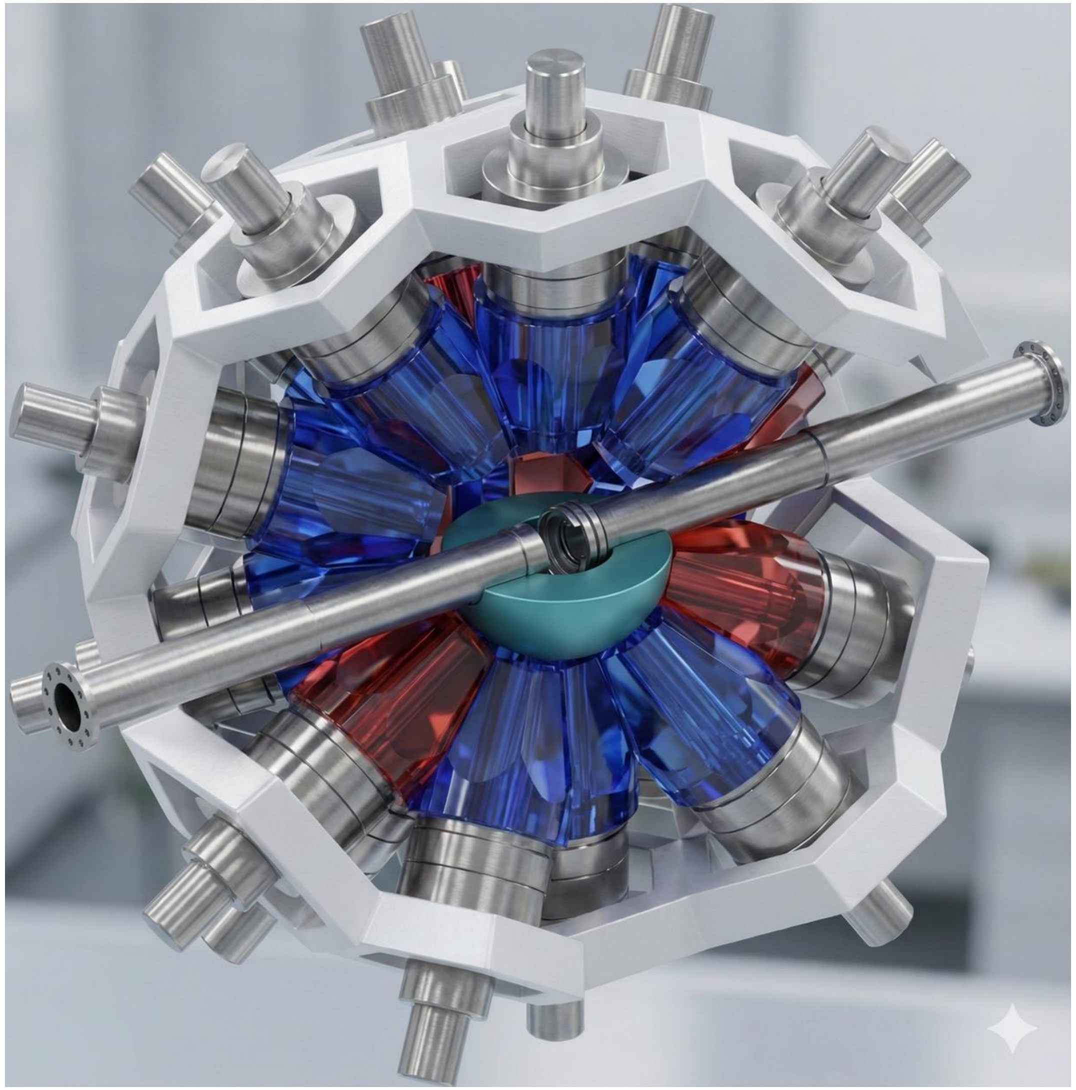
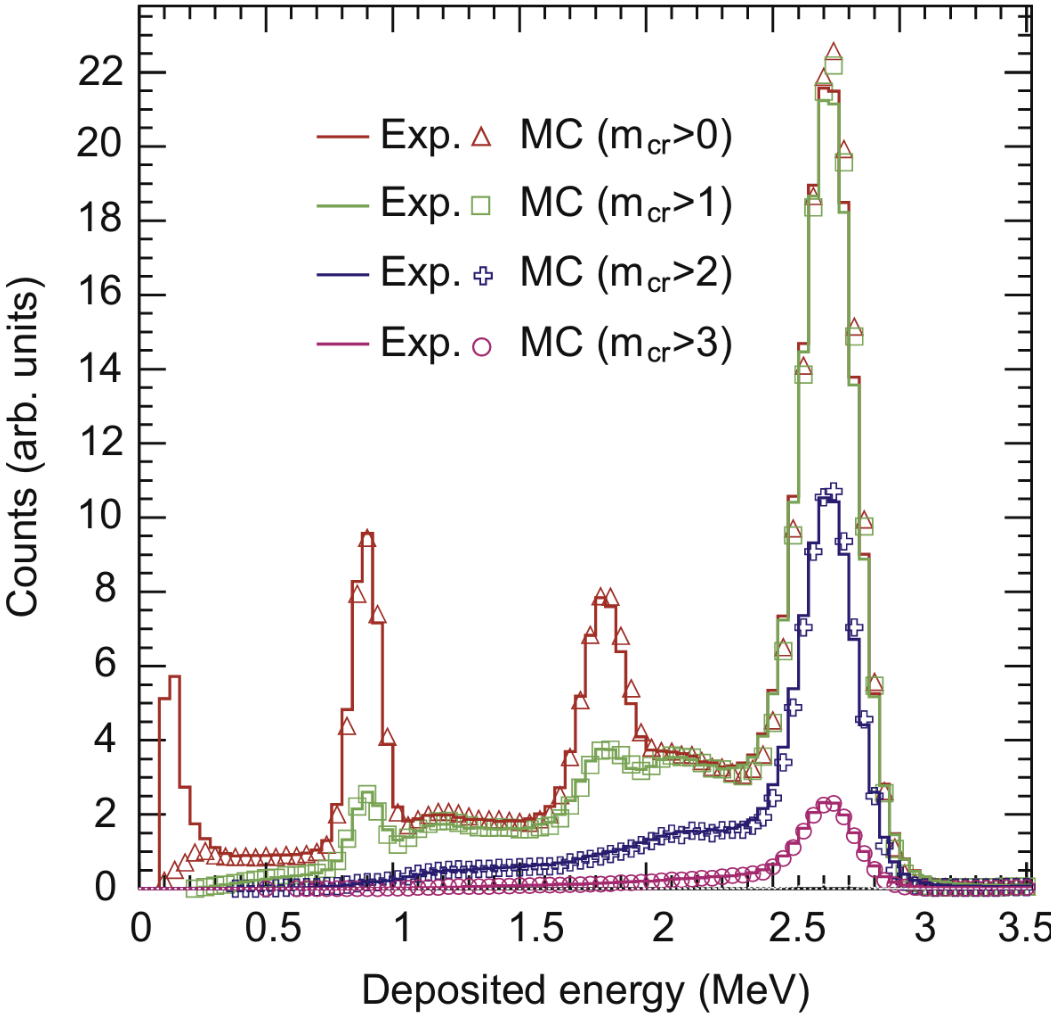
Monte Carlo simulations with GEANT4 of the ^{88}Y decay

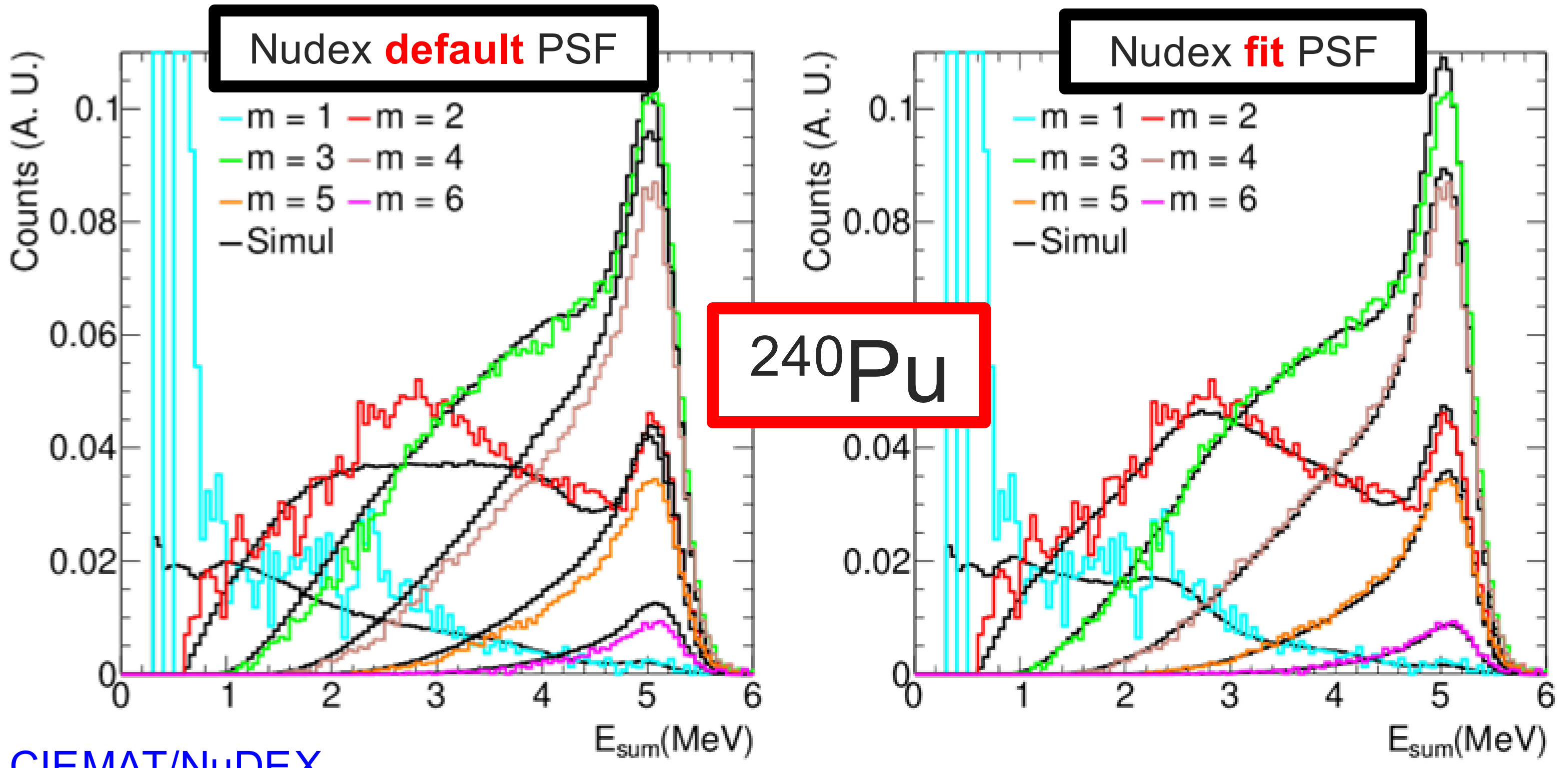




Reproducing the (n,γ) cascades

Nuclear de-excitation model **NuDEX** + GEANT4 A SIMULATION TOOLKIT

fit of the model parameters with a differential evolution algorithm

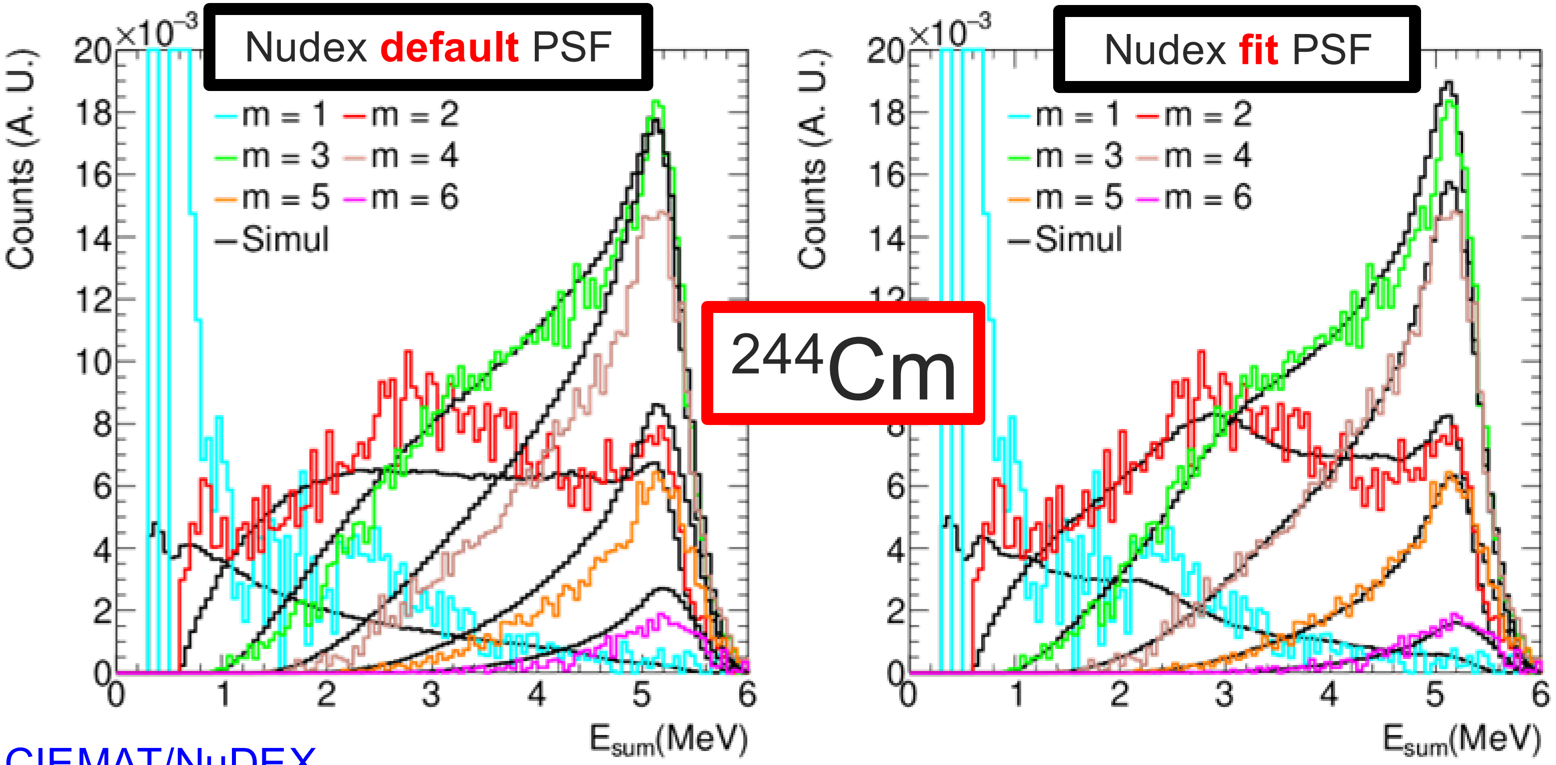


https://github.com/UIN-CIEMAT/NuDEX

Reproducing the (n,γ) cascades

Nuclear de-excitation model **NuDEX** + GEANT4 A SIMULATION TOOLKIT

fit of the model parameters with a differential evolution algorithm



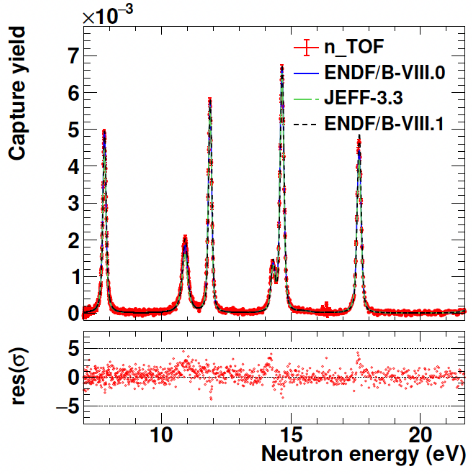
https://github.com/UIN-CIEMAT/NuDEX

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas UIN CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS IFIC INSTITUT DE FÍSICA CORPUSCULAR

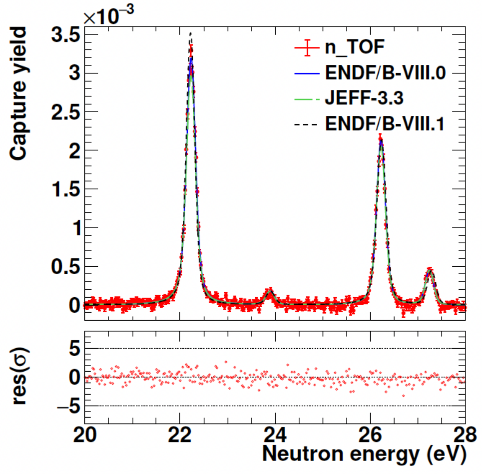
Problem solved!

$$\boldsymbol{\sigma(n,\gamma)} = \frac{1}{n_{sample}} \frac{C_\gamma(E_n) - B_\gamma(E_n)}{\varepsilon_\gamma(E_\gamma) \cdot \phi(E_n)}$$

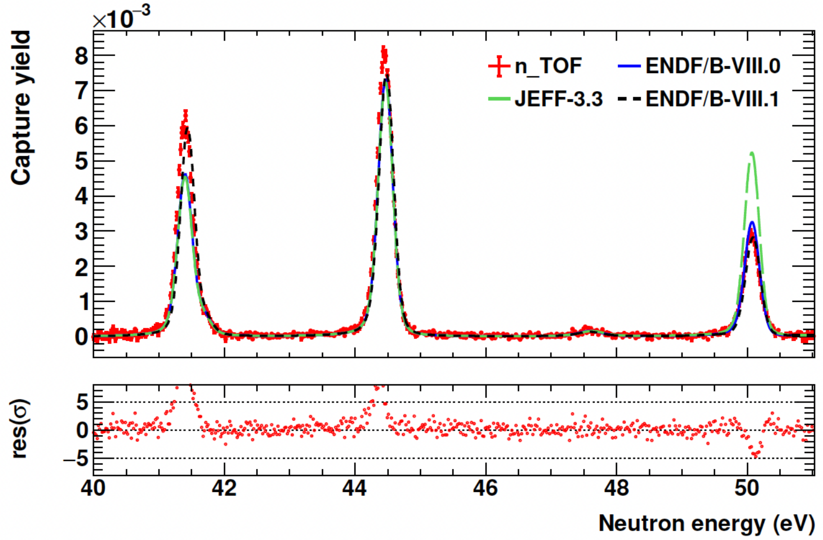
Recent ^{239}Pu(n, γ)



(a)



(b)



(c)

Thesis of Adrián Sánchez (2026)

Actinide $\sigma(n,\gamma)$ cross section data measured after year 2000 (EXFOR)

Isotope	Facility	Detector	E_{low} (eV)	E_{high} (eV)	EXFOR	Publication
U-233	n_TOF-1	TAC	0,7	1000	Yes	E. Berthoumieux et al., Conf. on Nuclear Data for Science and Technology, Nice 2007, p.571 (2007)
U-233	n_TOF-1	TAC	?	?	No	M. Bacak et al., ND2016, EPJ Conf. 146, 03027 (2017)
U-235	LANSCE	TAC + PPAC	4	1,00E+06	Yes	M. Jandel et al., Phys. Rev. Lett. 109, 202506 (2012)
U-235	n_TOF-1	TAC + MGAS	1	22	Yes	C. Guerrero et al., Eur. Phys. Jour. A 48, 29 (2012)
U-235	n_TOF-1	TAC + MGAS	0,2	200	No	J. Balibrea et al., Nucl. Data Sheets 119, 10 (2014)
U-235	RPI	NaI - TAC	0,02	3000	No	Y. Danon, et al., Nucl. Sci. and Eng. 187, 191 (2017)
U-236	LANSCE	TAC	10	11e+03	Yes	B. Baramsai et al. Phys. Rev. C 96, 024619 (2017)
U-238	LANSCE	TAC	1	6,30E+05	Yes	J.L. Ullmann et al., Phys. Rev. C 89, 034603 (2014)
U-238	GELINA	C_6D_6 TED	3,5	1200	Yes	H.I. Kim et al., Eur. Phys. Jour. A 52, 170 (2016)
U-238	n_TOF-1	C_6D_6 TED	1	700	Yes	F. Mingrone et al., Phys. Rev. C 95, 034604 (2017)
U-238	n_TOF-1	TAC	1	8,00E+04	Yes	T. Wright et al., Phys. Rev. C 96, 064601 (2017)
Np-237	KURRI	C_6D_6 - TED	0.005	1,00E+04	Yes	K. Kobayashi et al., Jour. Nucl. Sci. Tech. 39, 111 (2002)
Np-237	KURRI	BGO - TED	0,02	100	Yes	O. Shcherbakov et al., Jour. Nucl. Sci. Tech. 42, 135 (2005)
Np-237	KURRI	Ge	0,02	14	Yes	M. Mizumoto et al., Conf. on Nuclear Data for Science and Technology, Nice 2007
Np-237	LANSCE	TAC	0,02	5,00E+05	Yes	E.I. Esch et al., Phys. Rev. C 77, 034309 (2008)
Np-237	n_TOF-1	TAC	0,7	2000	Yes	C. Guerrero et al., Phys. Rev. C 85, 044616 (2012)
Np-237	J-PARC	NaI - TED	0,01	1000	Yes	K.Hirose et al., Jour. Nucl. Sci. Tech. 50, 188 (2013)
Pu-238	LANSCE	TAC	0,025	3,00E+04	Yes	A. Chyzh et al., Phys. Rev. C 88, 044607 (2013)
Pu-239	LANSCE	TAC	10	1000	Yes	S. Mosby et al., Phys. Rev. C 89, 034610 (2014)
Pu-240	n_TOF-1	TAC	0,7	2000	No	C. Guerrero et al., Conf. on Nuclear Data for Science and Technology, Nice 2007
Pu-242	LANSCE	TAC + PPAC	0,027	3,60E+04	Yes	M.Q. Buckner et al., Phys. Rev. C 93, 044613 (2016)
Pu-242	n_TOF-1	C_6D_6 - TED	2	4000	Yes	J. Lerendegui-Marco et al., Phys. Rev.C 97, 024605 (2018)
Am-241	LANSCE	TAC	0,02	3,20E+05	Yes	M. Jandel et al., Phys. Rev.C 78, 034609 (2008)
Am-241	GELINA	C_6D_6 - TED	0,025	110	No	C. Lampoudis et al., Eur. Phys. J. Plus 128, 86 (2013)
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Am-241	J-PARC	C_6D_6 TED	0,025	100	No	K. Terada et al., Jour. Nucl. Sci. Tech. 55, 1198 (2018)
Am-242m	LANSCE	TAC + PPAC	0,1	8000	Yes	M.Q.Buckner et al., Phys. Rev. C 95, 061602 (2017)
Am-243	n_TOF-1	TAC	0,7	2500	Yes	E. Mendoza et al., Phys. Rev. C 90, 034608 (2014)
Cm-244	J-PARC	Ge	2	300	Yes	A. Kimura et al., Jour. Nucl. Sci. Tech. 49, 708 (2012)
Cm-244	n_TOF-2	C_6D_6 TED	1	300	No	V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018
Cm-244	n_TOF-1	TAC	1	50	No	V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018
Cm-246	J-PARC	Ge	2	300	Yes	A. Kimura et al., Jour. Nucl. Sci. Tech. 49, 708 (2012)
Cm-246	n_TOF-2	C_6D_6 TED	1	300	No	V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018

Contribution of Spanish TAC guys (11 out of 36 – 30%)

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Cm-244	n_TOF-1	TAC	1	50	No	V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018
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Cm-246	n_TOF-2	C_6D_6 TED	1	300	No	V. Alcayne et al., WONDER-2018, Aix-en-Provence France, October 2018

3 totally absorbing decades: Berta and José’s TAGS & TAC disciples

Year	TAS PhDs (IFIC)	TAC PhDs (CIEMAT)
1994	Andres Gadea Raga	
2000	Daniel Cano Ott	
2004	Enrique Nácher González	
2008		Carlos Guerrero
2010	Maria Dolores Jordan	
2012	Ana Belen Perez Cerdán	
2012	María Esther Aguado	
2013	José Antonio Briz Monago (IEM)	
2014	Simon James Rice	Emilio Mendoza
2017	Victor Guadilla Gomez	Javier Balibrea
2022		Victor Alcayne
	Jose Antonio Victoria (on-going)	
2025	David Rodriguez (on-going)	
	Julien Pepin (on-going)	
2026		Adrián Sánchez

The conclusion, after ~30 years of career is that…

size matters…

and having a wonderful scientific family, even more!

Thank for your kindness, hospitality, generosity, friendship, wisdom and support.

As many others in the IFIC family, I owe you a big part of my career and will be grateful for it till my EC/β+ decay!

Act I: The Anomaly and Claims of New Physics (1974–1975)

Firestone, McHarris, and Kelly reported "anomalous" measurements in the decay of nuclei such as ^{145}Gd and ^{143}Sm.

The Findings: Using the gamma-gamma coincidence technique, they measured the EC/β+ ratio. They found that for certain "hindered allowed" transitions, the experimental EC/β+ ratios exceeded theoretical predictions by factors as large as 24.

The Interpretation: Firestone et al. argued that these discrepancies provided "solid experimental evidence" that the standard "allowed assumption" in beta-decay theory was inadequate. They proposed that second-order interference effects, usually ignored in theoretical calculations, were responsible for these massive deviations.

Confidence: In 1975, the group performed absolute measurements which they claimed confirmed the anomalies, asserting the "skew ratios" (experiment vs. theory) were real and significant physical phenomena.

It is always nice to think that one has found new physics but…

Act II: The Counter-Argument & "Pandemonium" Simulation (1977)

Hardy, Carraz, Jonson, and Hansen challenged the validity of Firestone's data, suggesting the "anomalies" were artifacts of incomplete experimental detection rather than new physical effects.

The Simulation: To demonstrate this, Hardy et al. created a fictional nucleus named **Pandemonium**, simulated numerically using Monte Carlo techniques to mimic the complexity of ^{145}Gd.

The "Missing" Intensity: By analysing the simulated γ-ray spectrum of Pandemonium as if it were real experimental data, they discovered that a significant portion of the gamma intensity (approximately 20% above 1.7 MeV) remained undetected. This intensity was hidden in a multitude of weak, unresolved peaks that formed a continuum indistinguishable from background noise.

The Conclusion: Hardy et al. demonstrated that if this "missing intensity" were real but undetected in Firestone’s experiments, it would result in incorrect decay feeding calculations, thereby artificially creating the reported EC/β+ ratio anomalies. They concluded that complex decay schemes based solely on peak analysis were "doubtful" and that the field needed to reevaluate such experiments.

Act III: The Rebuttal attempt & "Paradise Regained" (1982)

Firestone responded with a defense of experimental spectroscopy, publishing new, high-statistics data on ^{145}Gd to refute the Pandemonium model.

New Data: Firestone claimed to have observed greater than 98% of the total decay intensity using advanced coincidence methods, placing 326 γ-rays in the decay scheme.

Critique of the Model: He argued that Hardy's statistical model was "fatally flawed" because it assumed a constant β-strength function. Firestone showed that the real nucleus exhibited a "resonance" (structural peaks) near 4.5 MeV, which concentrated the decay intensity into detectable lines rather than dispersing it into a statistical continuum.

Defense of the Field: Firestone asserted that Hardy's "pessimistic" conclusions did a disservice to nuclear science. He titled his paper "**Pandemonium Lost and Paradise Regained**," arguing that careful experimentation could indeed uncover the full structure of the nucleus without being lost in statistical uncertainty.

Act IV: Pandemonium is there (1984)

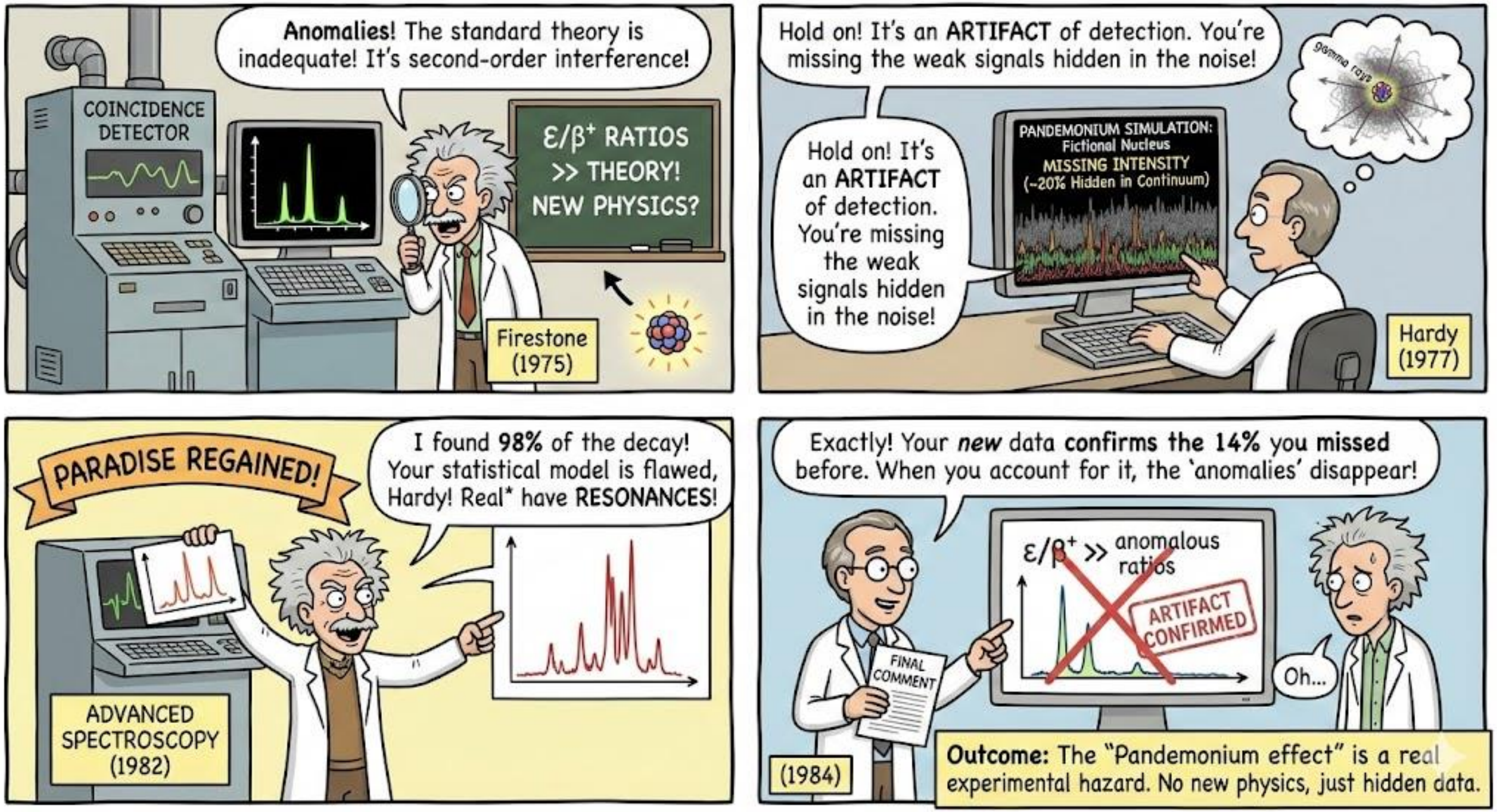
Hardy et al. issued a final comment demonstrating that Firestone's rebuttal ironically proved the original Pandemonium prediction correct.

Vindication by Data: Hardy pointed out that when Firestone's new, more complete data (1982) were compared with his original data (1974), it revealed that a full 14% of the γ-ray intensity had indeed been missing in the original study. This matched the ~20% "missing intensity" predicted by the Pandemonium simulation.

Disappearance of Anomalies: Crucially, once this missing intensity was accounted for in the new experiments, the "anomalous" EC/β+ ratios disappeared, confirming they were artifacts all along.

Flawed "Completeness": Hardy also demonstrated that Firestone's claim of observing >98% of the intensity was based on an internal consistency check that yielded unphysical results (ratios that should be 1.0 were calculated as >1.0 with large uncertainties), suggesting Firestone was still underestimating the missing intensity.

Executive summary



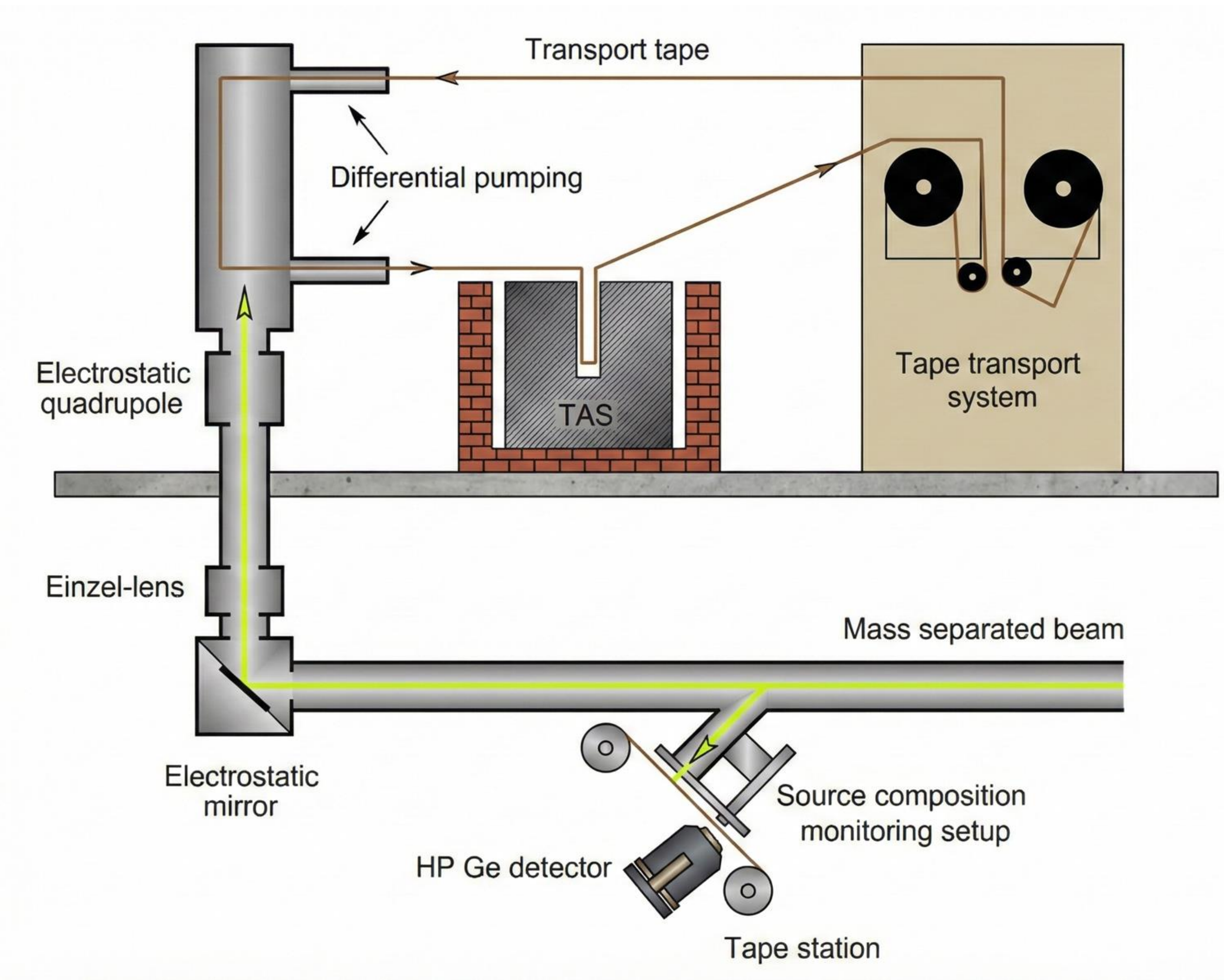
The interaction strength and the beta strength function

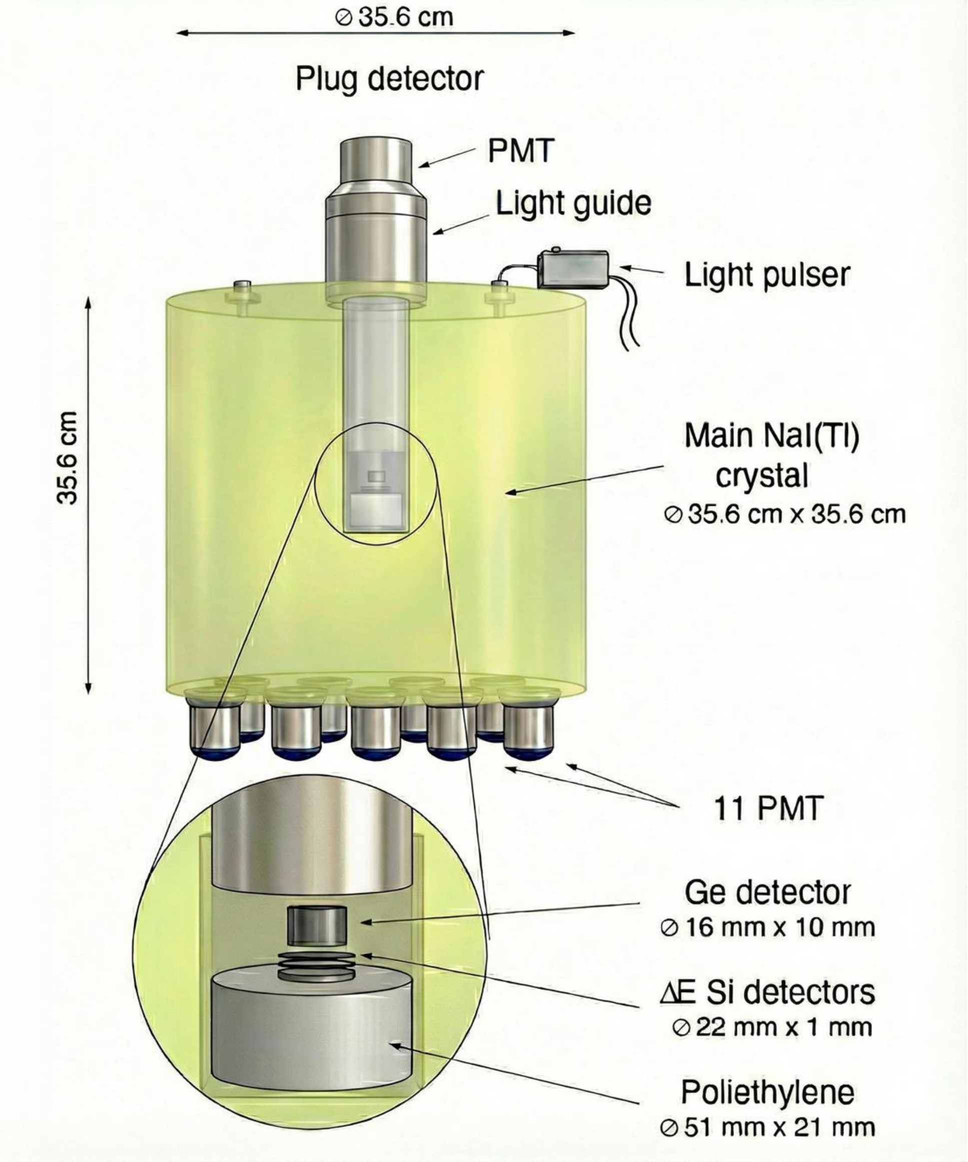
$$ft = \frac{6147 \pm 7}{B(F) + B(GT)} \frac{g_v^2}{4\pi}$$

$$ft = \frac{6147 \pm 7}{\left(\frac{g_A}{g_V}\right)^2 B(GT)}$$

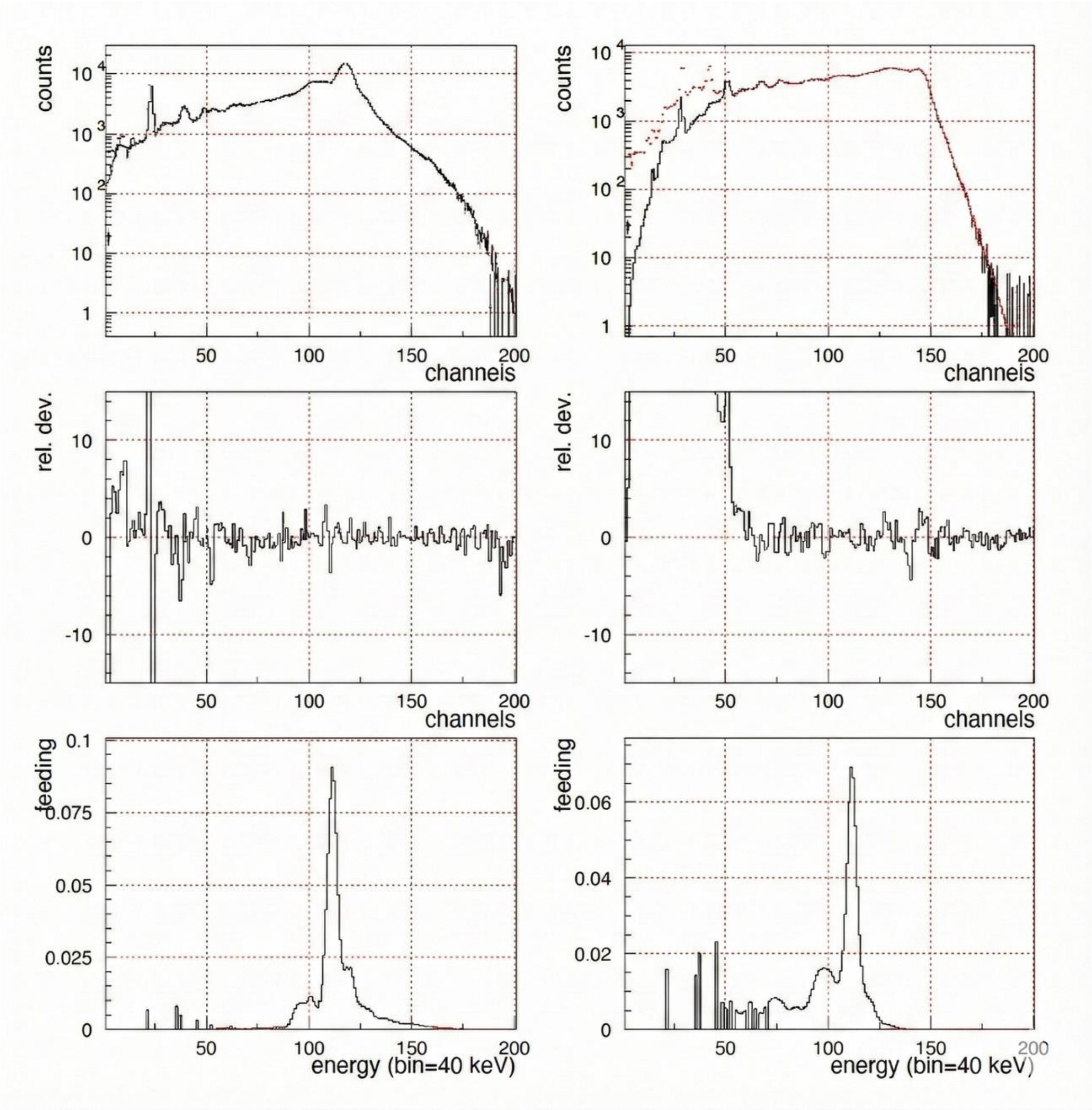
$$S_\beta(E_x) = \frac{I_\beta(E_x)}{f(Q_\beta - E_x)T_{1/2}}$$

The LBL TAGS


Transport tape
Differential pumping
Tape transport system
TAS
Electrostatic quadrupole
Einzel-lens
Mass separated beam
Electrostatic mirror
Source composition monitoring setup
HP Ge detector
Tape station
Up


⌀ 35.6 cm
Plug detector
PMT
Light guide
Light pulser
35.6 cm
Main NaI(Tl) crystal
⌀ 35.6 cm x 35.6 cm
11 PMT
Ge detector
⌀ 16 mm x 10 mm
ΔE Si detectors
⌀ 22 mm x 1 mm
Poliethylene
⌀ 51 mm x 21 mm

Data for the EC & beta+ decays of $^{150}Ho(2^-)$



As a nice Russian lady said once…

A nice Russian lady asked me at the barracks “Where is Don Quijote?”.