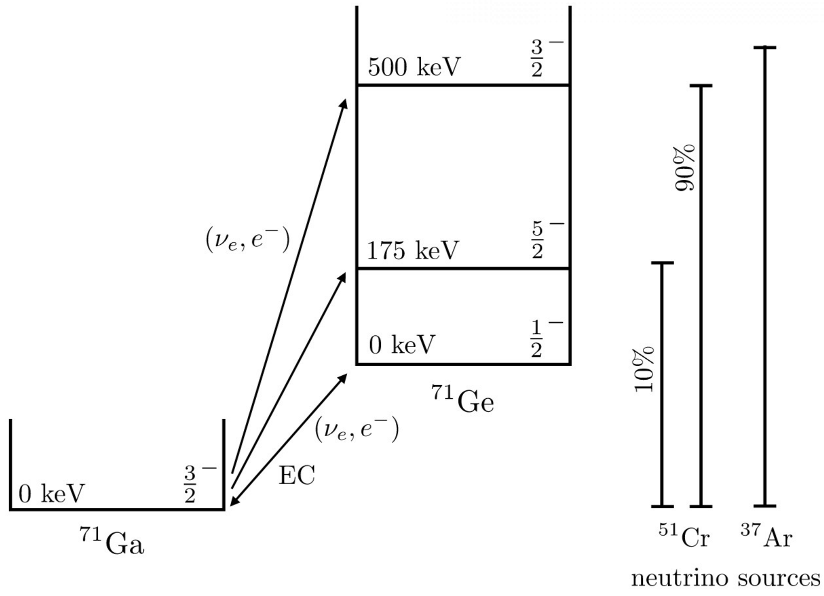
ɣ decay of IAS in ^{71}Ge: a new pathway to Gallium anomaly

D. Stramaccioni and J.J. Valiente-Dobón – June 24th 2025

Inverse Beta Decay - Gallium anomaly

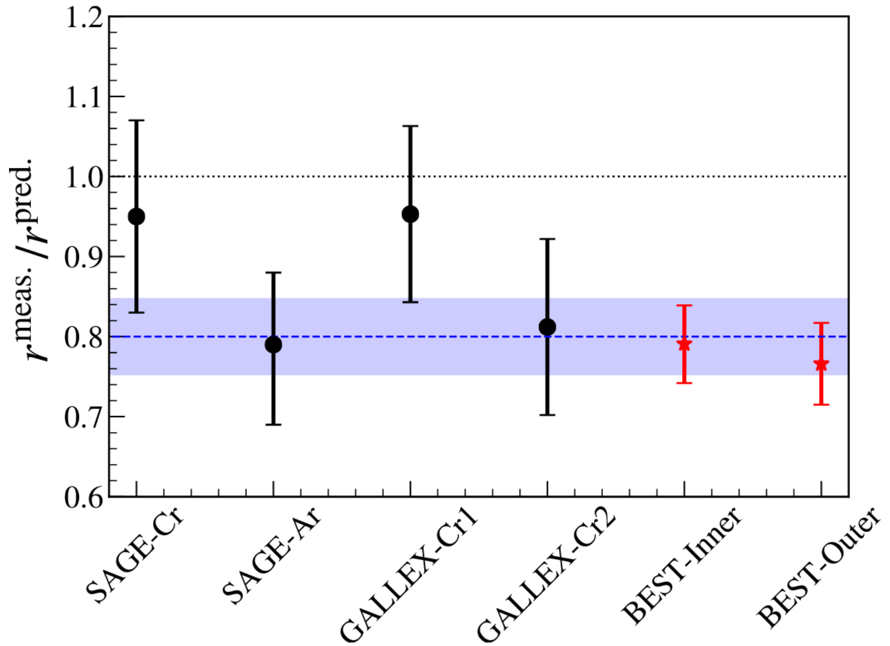
"The measurements of the charged-current capture rate of neutrinos on ***^{71}Ga*** *from* ***strong radioactive sources*** *have yielded* ***results below those expected****"*

Sources: **^{51}Cr** and **^{37}Ar**



$$\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-$$

[S. R. Elliott et al., PRC (2023)]



Hint of **sterile neutrino(s)**?

Need for reliable **ν-nucleus interaction strength** to explore it!

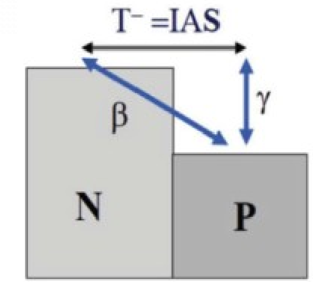
Gamma decays as analogous probe

Interaction Rate

$$R(\nu) = g_W^2 G^\nu I(\nu)\,(2J_i+1)^{-1}|M^\nu|^2$$

Neutrino flux, oscillation effects...

Nuclear physics input



- Same **initial state**
- Same **final state**
- Same **interaction**

$$|i\rangle_\gamma \equiv |i\rangle_{IDB}(\text{IAS}) \propto T^-|i\rangle_{IBD}$$

$$|f\rangle_\gamma \equiv |f\rangle_{IDB}$$

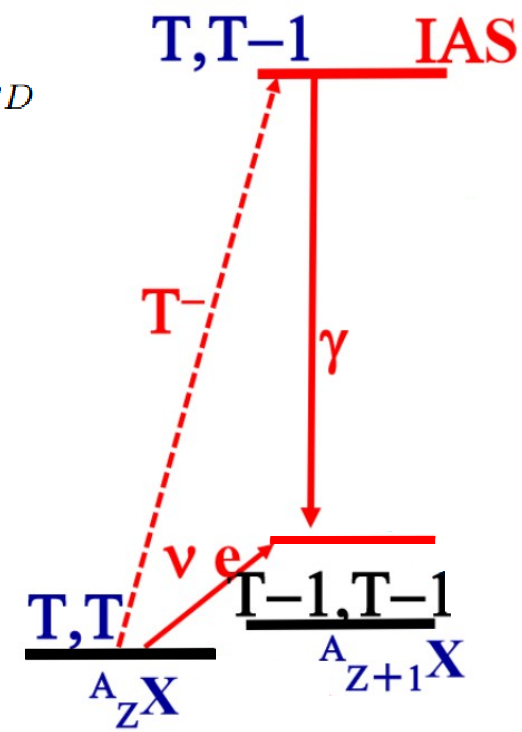
Weak

$$T(AVL) = g_A\tau^i r^{L-1}[\boldsymbol{\sigma}\mathbf{Y}_{L-1}]_L$$

EM

$$T(ML) = g_S r^{L-1}[\boldsymbol{\sigma}\mathbf{Y}_{L-1}]_L + g_L r^{L-1}[\mathbf{j}\mathbf{Y}_{L-1}]_L$$

$$\Rightarrow \langle f|T^W_{1SLJ}|i\rangle \sim \frac{g^W_{1SLJ}}{g^\gamma_{1SLJ}}\sqrt{(2T_i)}\langle f|T^\gamma_{1SLJ}|IAS\rangle$$



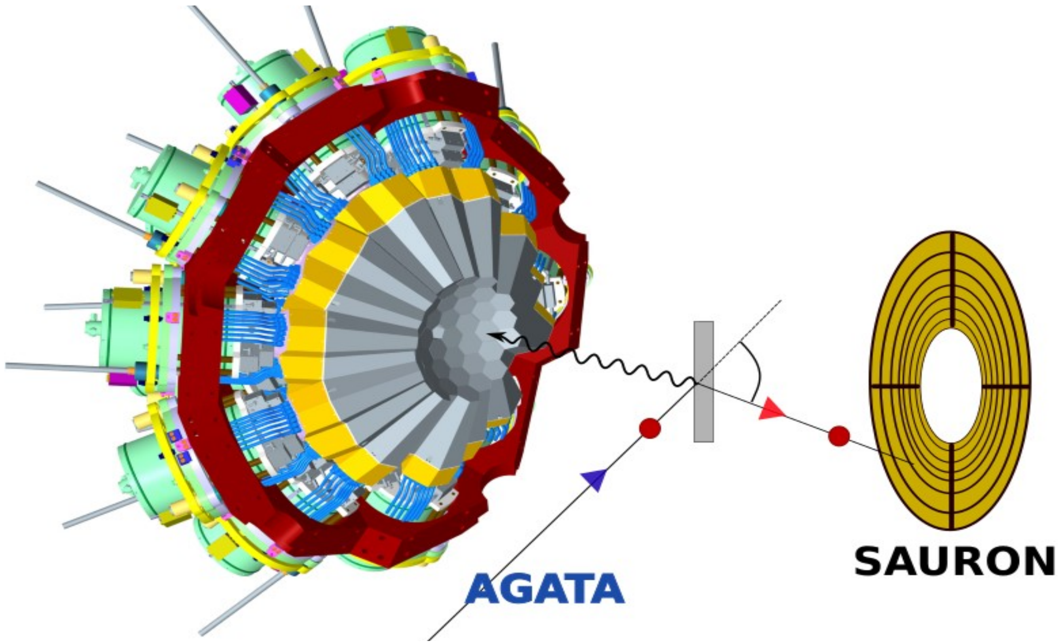
^{71}Ge preparatory experiment

For ^{71}**Ge**, given the **low BR** (10^{-5}), one needs a **long experiment** (3 weeks).

Before running the final experiment we need to know:

- a **reaction** to efficiently **populate the IAS**
- **gamma background** in the region of interest

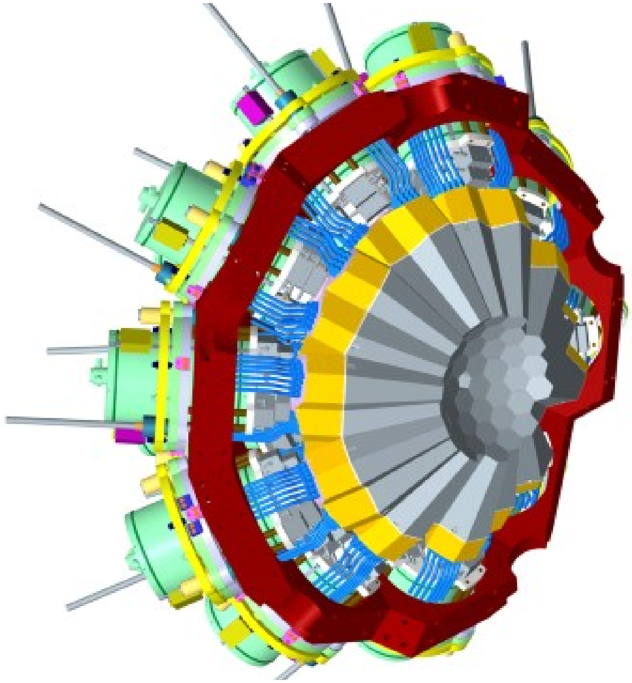
➡ **Test experiment @ LNL!**

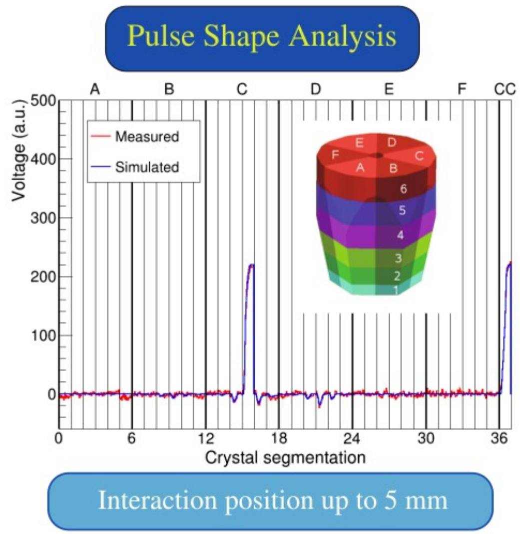


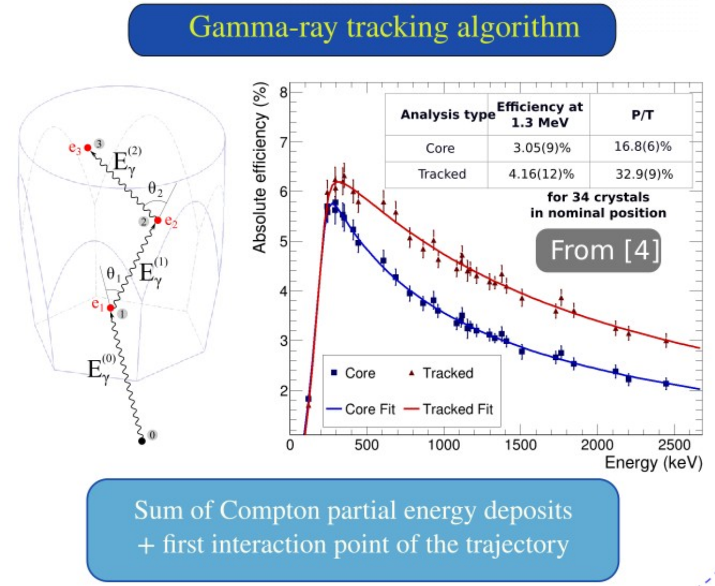
^{72}Ge(p,d)^{71}Ge$_{IAS}$ @28 MeV

- **γ rays** measured in **AGATA**
- **Light charged particles** energies measured in **SAURON Silicon** detector

Why AGATA?

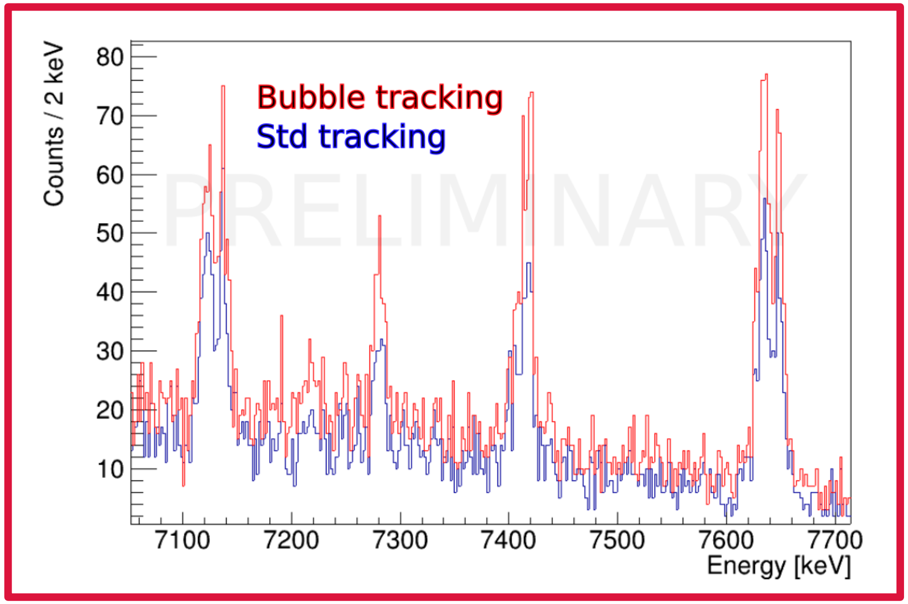




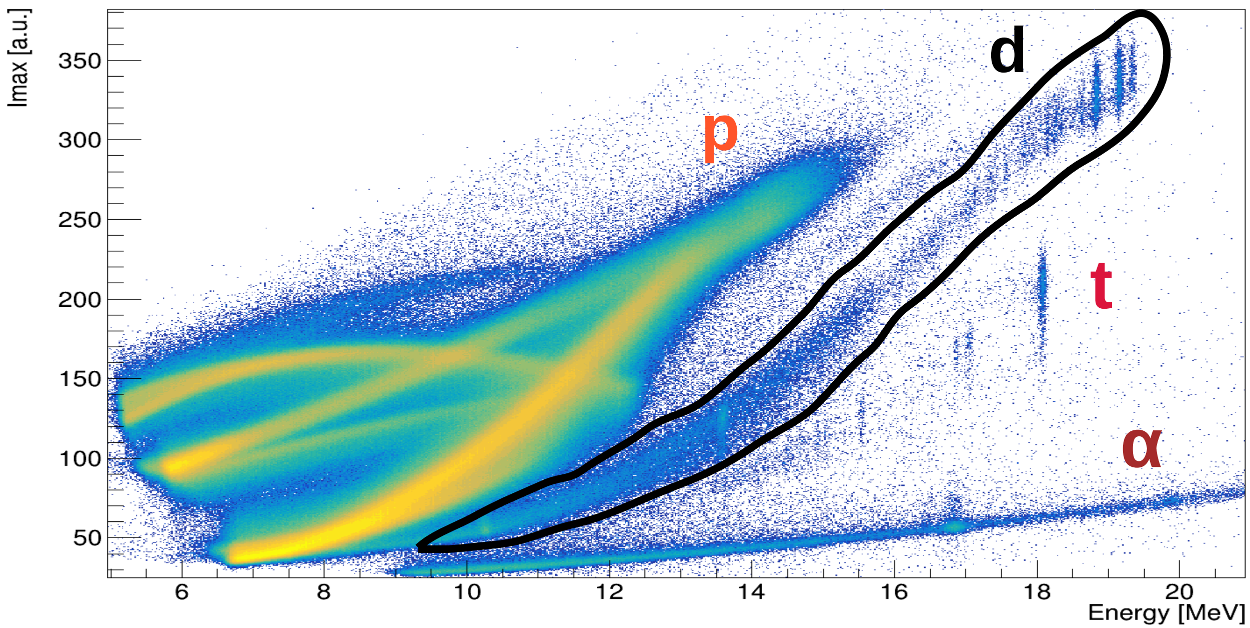


AGATA: State of the art for gamma spectroscopy

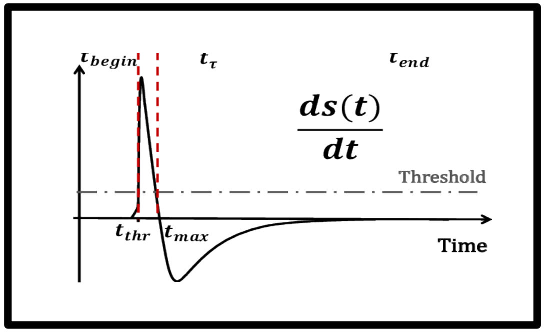
- unprecedented **P/T** and **efficiency**
- newly developed **“Bubble tracking”** improves performance at **high energies (RoI)**

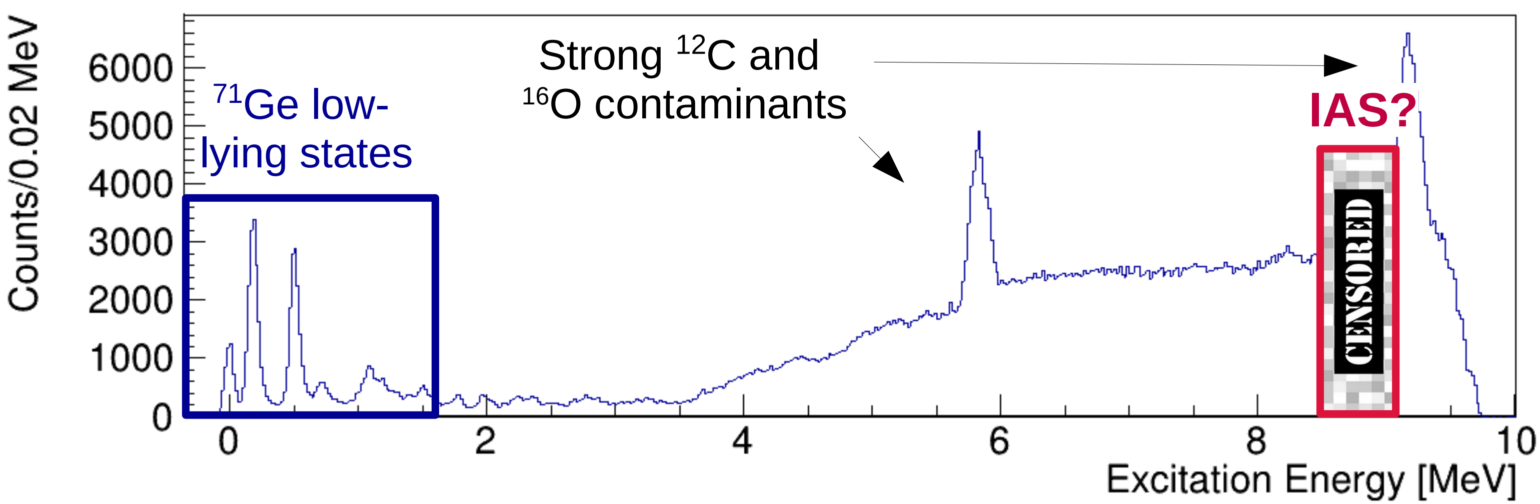


Why SAURON? With preliminary test results..



PID to select deuterons (I_{max} vs E)

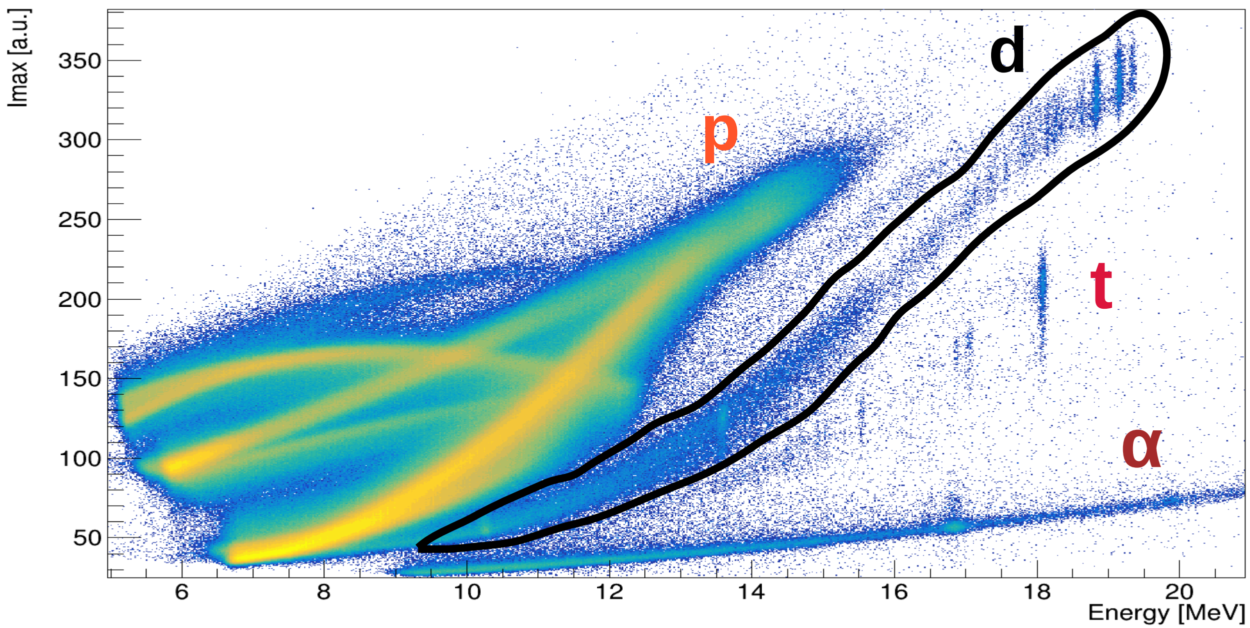




MSc thesis Federico Simioni

→ **Very preliminary** (~5% of statistics)

Why SAURON? With preliminary test results..



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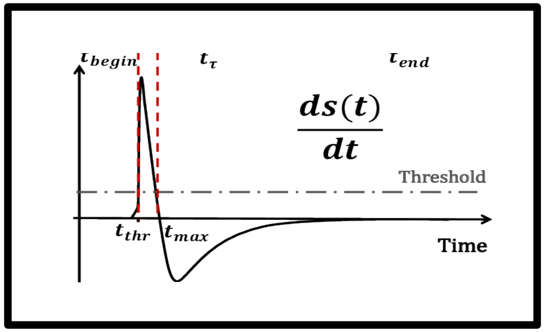
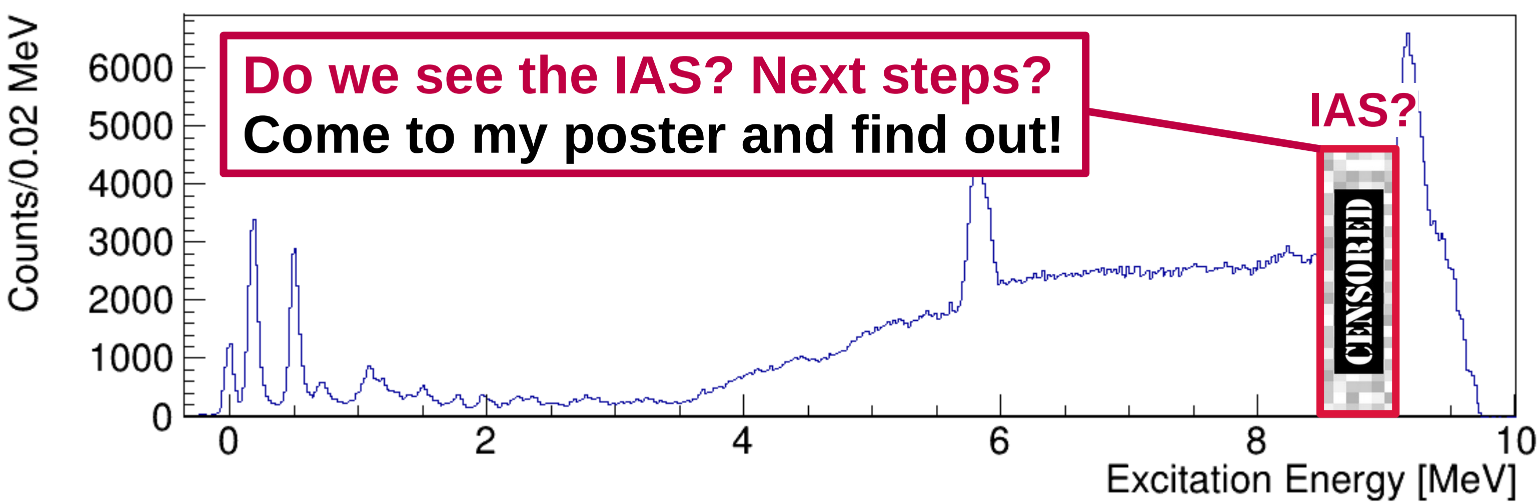


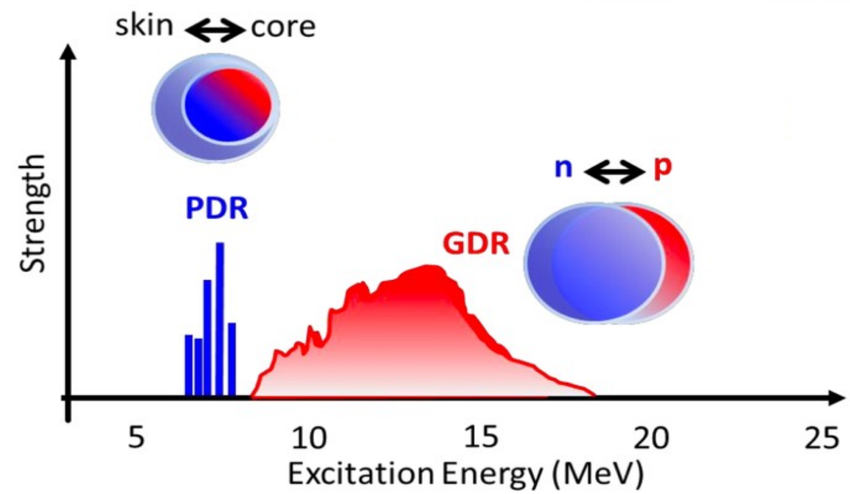


MSc thesis
Federico Simioni

→ **Very preliminary**
(~5% of statistics)

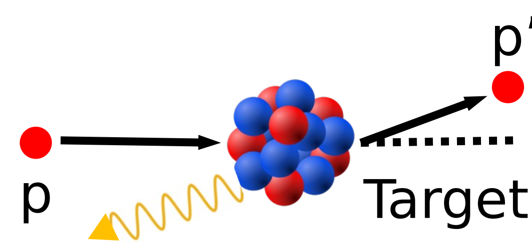
BACKUP SLIDES

PDR has been mostly interpreted as **collective oscillation** of **neutron skin** against the core

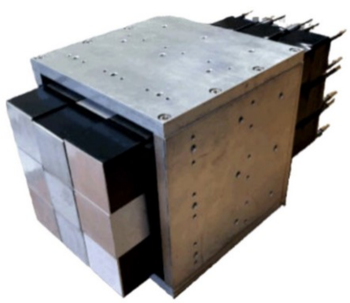


[A. Bracco et al., Prog. Part. and Nucl. Phys. **106** (2019)]

Theory: Different approaches give different predictions on collectivity, strength and line-shape of the PDR.



A **broad systematic multi-messenger** study is necessary using complementary approaches.

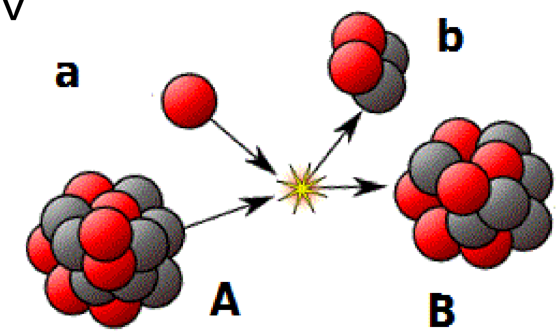


SPES: PDR studies with proton inelastic scattering.

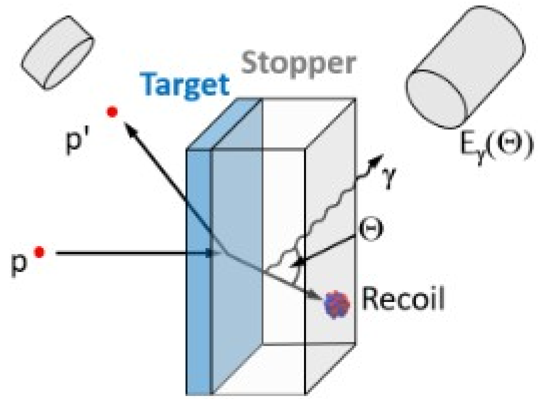
Courtesy of A. Giaz

Cases with this setup: Direct reactions @70 MeV/u

- **(p,^{3}He)**: 0.1 mb (^{58}Ni$\rightarrow$^{56}Co, ^{40}Ca$\rightarrow$^{38}K…): ^{3}He residues @40 MeV
- **(p,3p)**: 10 μb (^{48}Ca$\rightarrow$^{46}Ar, ^{36}S$\rightarrow$^{34}Si, ^{82}Se$\rightarrow$ ^{80}Ge, ^{208}Pb$\rightarrow$^{206}Hg, ^{60}Fe$\rightarrow$^{58}Cr, ^{204}Hg$\rightarrow$^{202}Pt…): diff. c.s. from Seastar
- **(p,t)** on proton-rich nuclei: focus on 2^+ and 0^+ states
- **(p,α)** usually at lower energies… (^{58}Ni$\rightarrow$^{55}Co): ^{4}He residues @40 MeV



- Gamma-ray **spectroscopy of exotic** nuclei
- **Long lifetimes** with **fast timing** (LaBr$_3$)
- Very **short lifetimes** with **centroid shift** method (HpGe)



Courtesy of A. Gottardo

Collaboration – Thanks to everybody!

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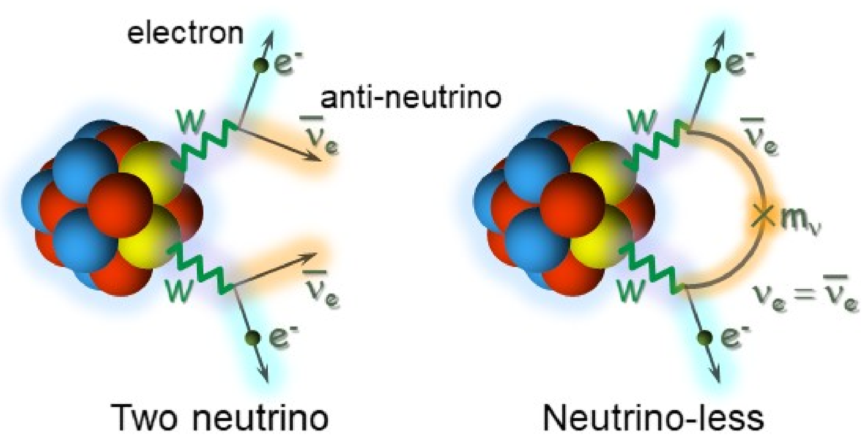
BACKUP SLIDES

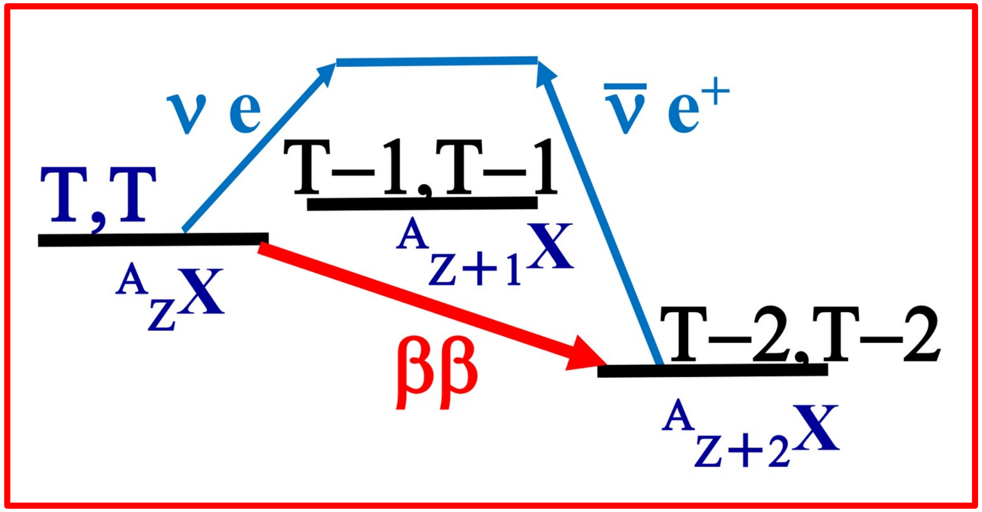
Neutrinoless ββ Decay (0νββ)

Promising **BSM** scenarios:

- **L violation** in laboratory
- **Majorana** nature of ν..

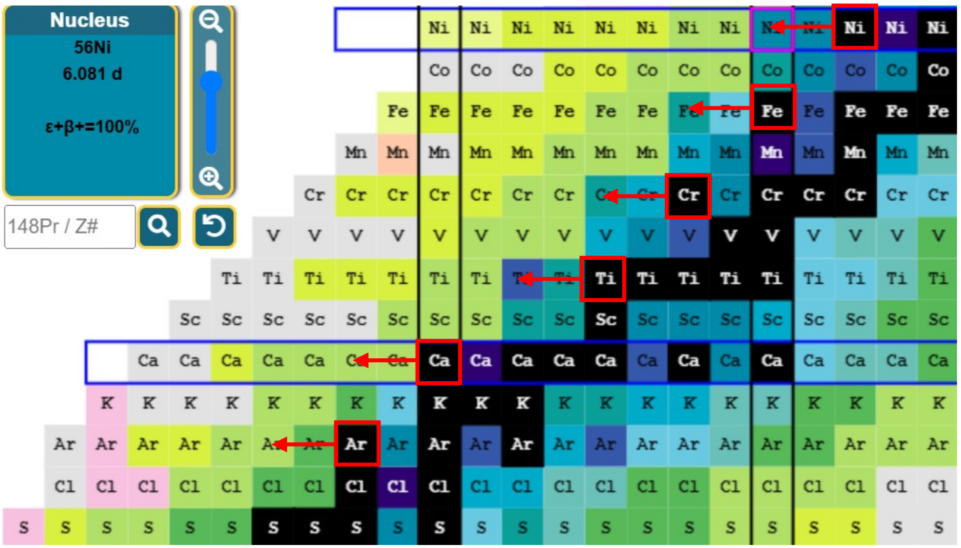
$$ {}^{A}_{Z-2}X_{N+2} \rightarrow {}^{A}_{Z}Y_{N} + 2e^{-} $$





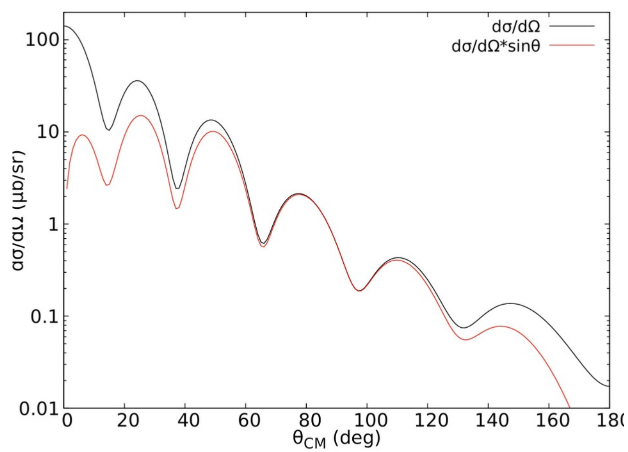
⇨ Virtual **2-step** process of the **same type**!

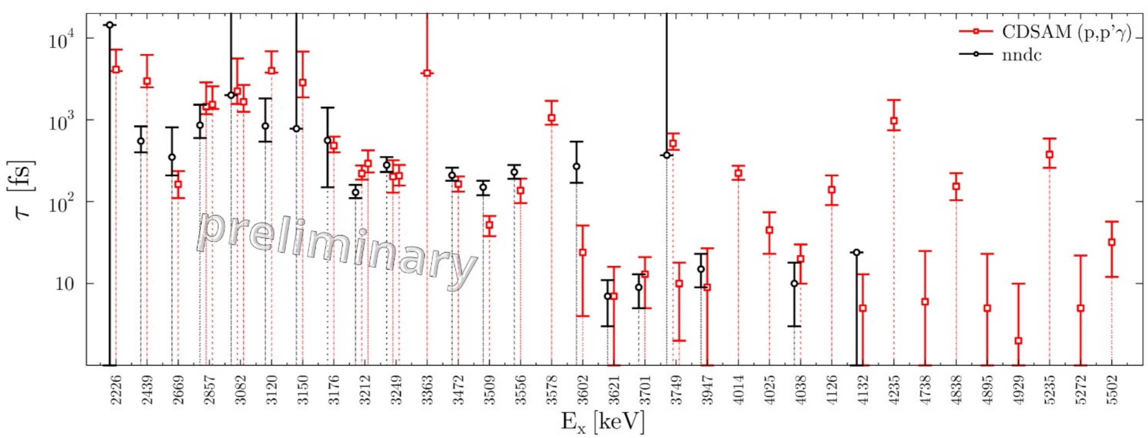
Spectroscopy and lifetime after (p,t) reactions



Characteristics of (p,t) reactions

- Extremely selective for 0^+ and 2^+ states
- Proton energies required: 30-60 MeV
- Cross sections of the order of 10 to 100 ub



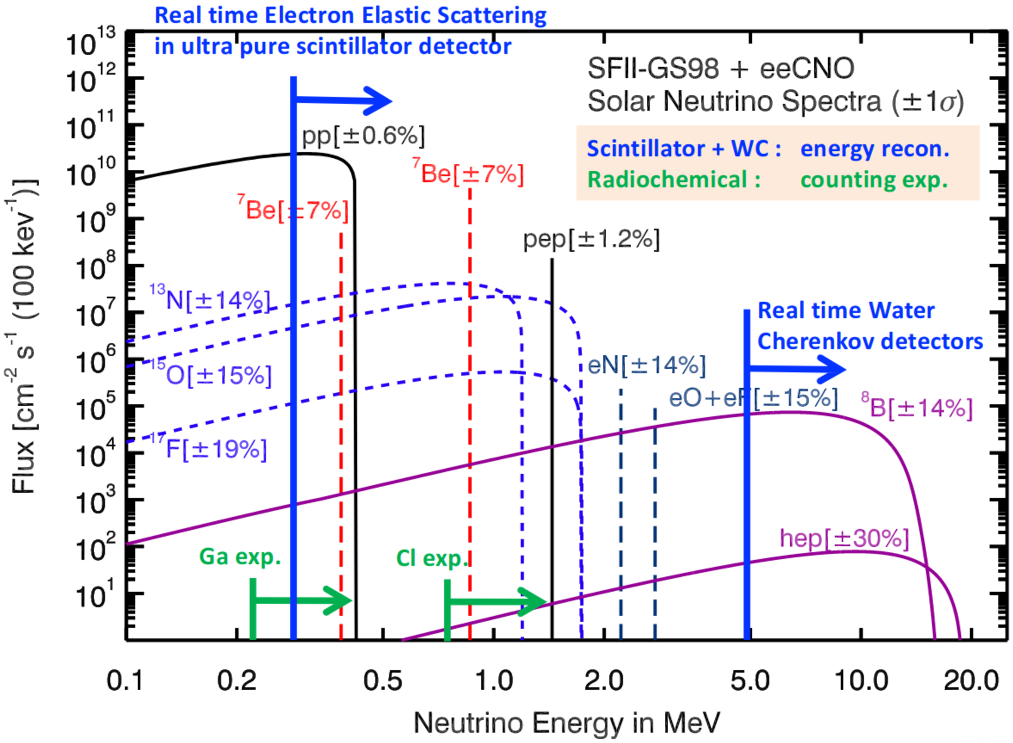


Lifetimes from **10-1000 fs** can be measured with **HPGe** detectors in conjunction with **light-particle detectors**

Inverse Beta Decays for neutrino studies

The **solar-ν** produced in the core of the sun is **mainly ν_e**, since the weak processes involved are the **low-energy nuclear** β decays and electron captures.

Nuclei with **large responses** for the **charged weak currents** are used to detect the **low-energy solar ν_e by inverse β decays**.

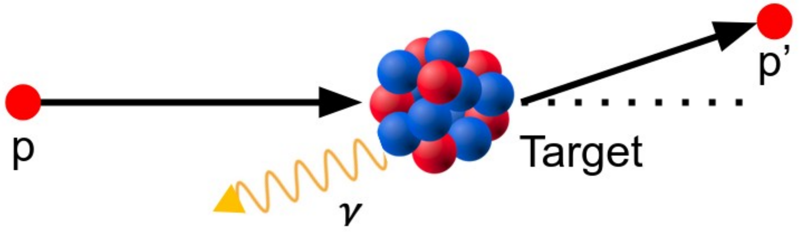


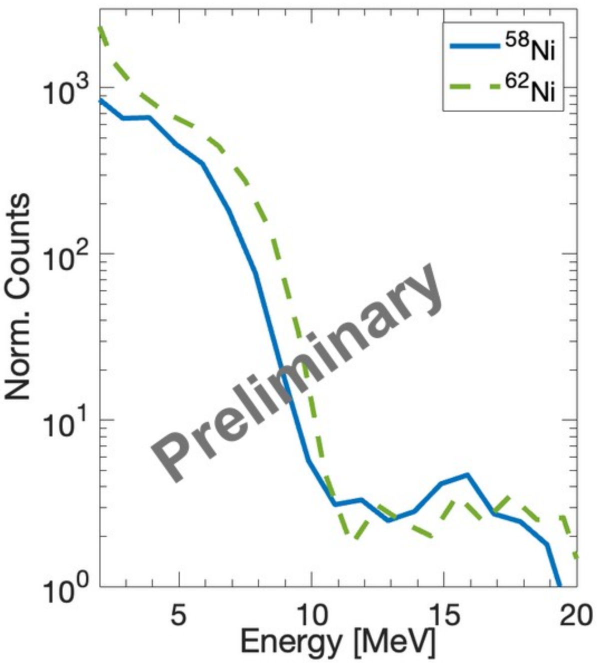
$$\left[\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{71}\mathrm{Ge} + e^-\right]$$

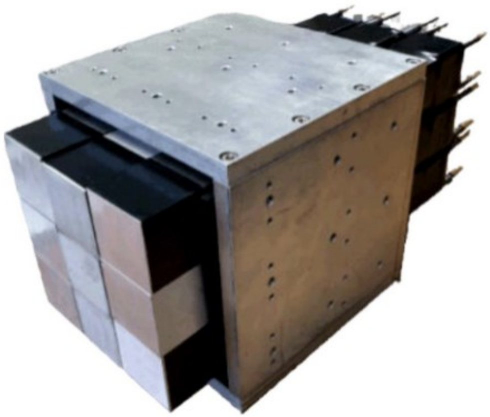
- **^{71}Ga low Q-value** probes uncharted regions of the **pp chain**!

Need for for reliable **ν-nucleus interaction strength** to extract low-energy **ν flux**.

PDR @ SPES: Technique & detector requirements







Proton gate

Scattered protons:

- Energy Resolution: 1 MeV FWHM
- Angular Resolution: 0.8°
- Angular Coverage: 6° (pile-up) - 18°
- Fast Signal
- Very Good Time Resolution < 0.2 ns

High-Energy Gamma Rays:

- Scintillators Detectors → Energy Resolution > 7% @ 662 keV
- High Efficiency (1% at 10 MeV) → Large Volume detectors
- Good Time Resolution < 1ns

Courtesy of A. Giaz

Beam requirements & Setup

We are performing similar measurements at CCB in Krakow with higher energy on Ni isotopes.
With SPES, we propose to measure Nd isotopes.

SPES Specifications	
Energy Range	**35 – 70 MeV**
Current	**min 30 nA**
Beam Spot Size	**?**
Time Micro Structure	**?**

Setup Avalability	
Scintillator Detectors	**PARIS / $LaBr_3$:Ce**
Proton Detectors	**To be build**
Scattering Chamber	**To be build**

With SPES's energies, PDR **cross-section is reduced** by a **factor 2**.

We are using a maximum **current of 2 nA in order** to correlate unequivocally in time protons and gammas. At 30 nA, this seems not possible.

At 30 nA, can we use the proton detectors without pile-up?

We must develop a dedicated detector array.

Courtesy of A. Giaz

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What is the expected timeline of the project? i.e. when can we realistically expect to begin working in the bunker?

What will be a **realistic beam time** assigned for each experiment? A week? A month? A few months?

During and after the experiment (when there is no beam), will we be able to **bring in/out** the detectors/electronics/targets?

Courtesy of A. Giaz

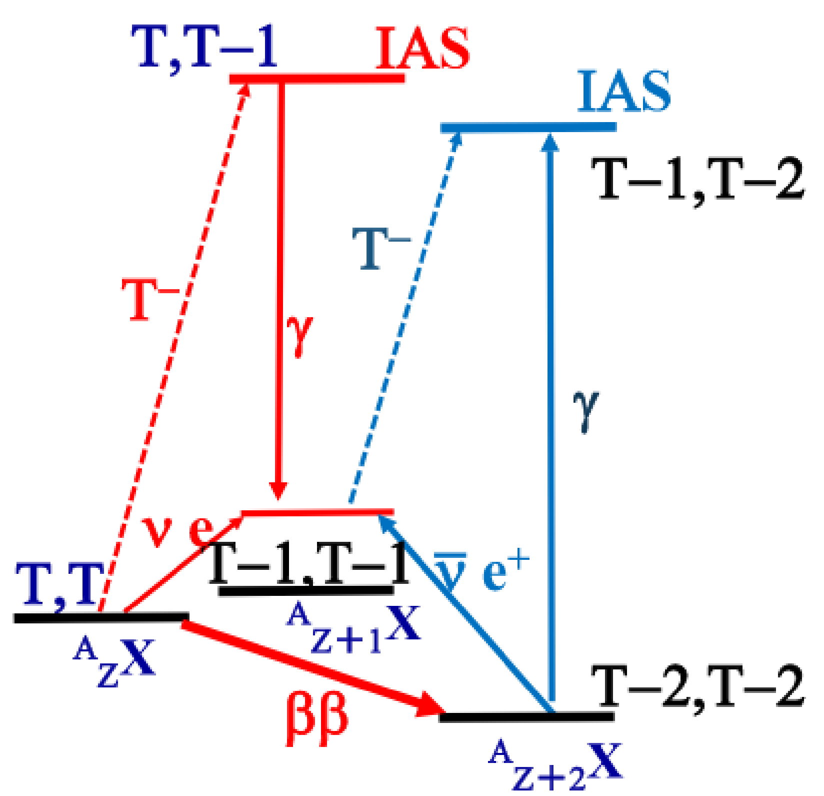
$0\nu\beta\beta$ decay studies with the same method

With the **same setup and methods** discussed before, one can **assess DBD nuclei**

Absolute experimental values for some representative **axial-vector dipole and vector dipole NMEs** can be used to check the **model calculations** and to get the **effective couplings**

$$M^{GT}_{0\nu} = \sum_n \left\langle f \left| \sum_a \vec{\sigma}_a \tau_a^+ \right| n \right\rangle \left\langle n \left| \sum_b \vec{\sigma}_b \tau_b^+ \right| i \right\rangle$$

A	E(IA)	E(GT)	B(GT)	$B^{IA}(M1)$	$\Gamma^{IA}(M1)$	$\sigma^{IA}(M1)$
^{76}Ge	8.31	1.07	0.14	1.45	6.4	41
^{82}Se	9.58	0.075	0.34	3.0	30.0	150
^{96}Zr	10.9	0.69	0.16	1.25	15.3	76
^{100}Mo	11.1	0	0.35	2.7	43.4	170
^{116}Cd	12.1	0	0.14	0.88	18.0	51
^{128}Te	12.0	0	0.079	0.41	8.2	17
^{130}Te	12.7	0	0.072	0.35	8.2	17
^{136}Xe	13.4	0.59	0.23	1.03	25	45
^{150}Nd	14.4	0.11	0.13	0.54	18.0	35
^{71}Ga	8.91	0	0.085	1.2	9.8	51



Double-ɣ spectroscopy for 0νββ - theory

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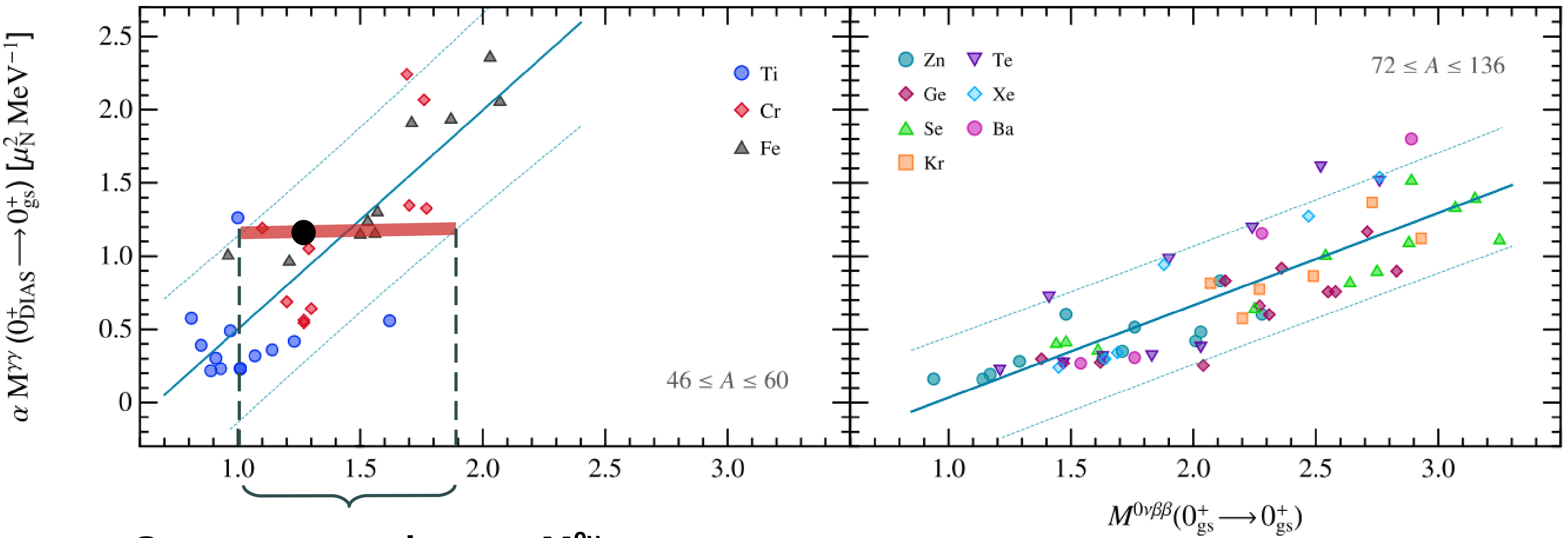


[B. Romeo et al., Phys. Lett. B 827 (2022)]

Strong constraints on $M^{0\nu}$

Considering **analogue initial and final states** as in 0ν2β

$$|0_i^+\rangle_{\gamma\gamma} \equiv |0_i^+\rangle_{\beta\beta}(\mathrm{DIAS}) = \frac{T^-T^-}{K^{1/2}}|0_i^+\rangle_{\beta\beta}$$

$$|0_f^+\rangle_{\gamma\gamma} \equiv |0_f^+\rangle_{\beta\beta}$$

+

Focusing on a **similar transition operator**

For **equal energy** gammas, 2ɣ magnetic dipole operator (**M1**) and the 0νββ Gamow-Teller (**GT**) operator share the same **isovector spin στ** term.

Analogous probes for neutrino studies

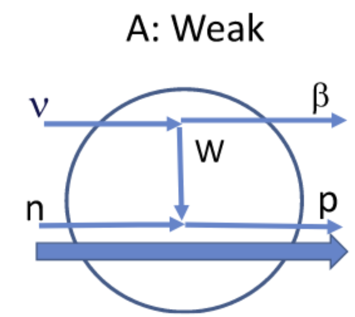
Università degli Studi di Padova

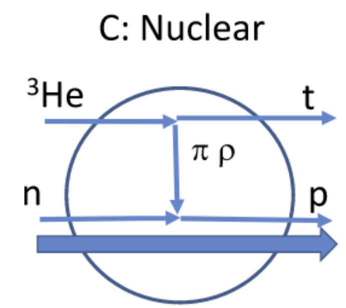
Interaction Rate

$$R(\nu) = g_W^2 G^\nu \, I(\nu) \, (2J_i + 1)^{-1} |M^\nu|^2$$

Neutrino flux, oscillation effects...

Nuclear physics input

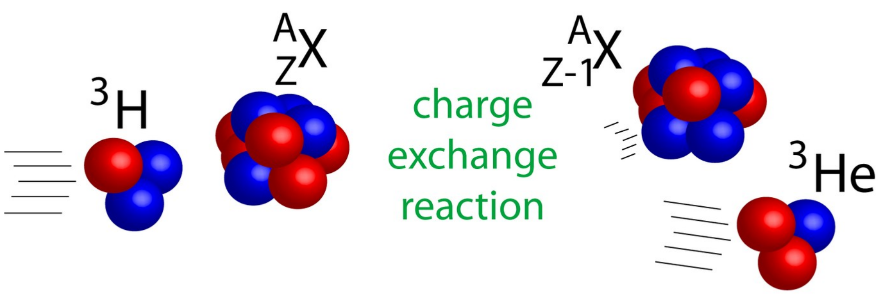




CER

The **charge exchange nuclear reactions** of (^{3}He,^{3}H) / (p,n) have been used widely to **estimate NMEs associated with DBD and IBD GT NMEs**.

- Same **initial state**
- Same **final state**
- Similar **interaction**



Observable for CER

$$\frac{d\sigma_i}{d\Omega} = K_i(\alpha) F_i(\alpha, q) J_i(\alpha)^2 \, (2J_i + 1)^{-1} |M^\nu|^2$$

Analogous probes for neutrino studies - problems

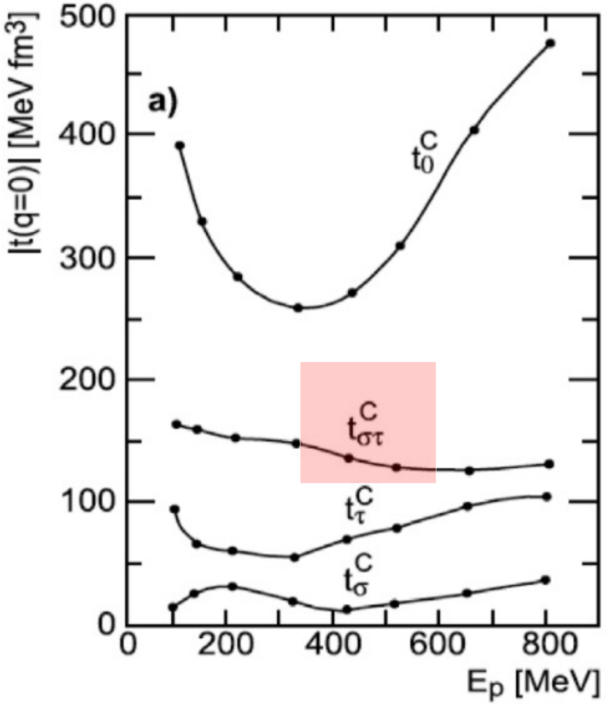
Observable for CER

Kinematical factor — Interaction integral

$$\frac{d\sigma_i}{d\Omega} = K_i(\alpha) F_i(\alpha, q) J_i(\alpha)^2 (2J_i + 1)^{-1} |M^\nu|^2$$

Angular distribution — NME

- The CER includes **mixed interactions** of the **GT(τσ)**, the **tensor ([σ × Y_2]^1)**, and the **vector (τ)** type
- **Angular distribution** depends on the **nuclear distortion**
- **Constant interaction integral** for all states

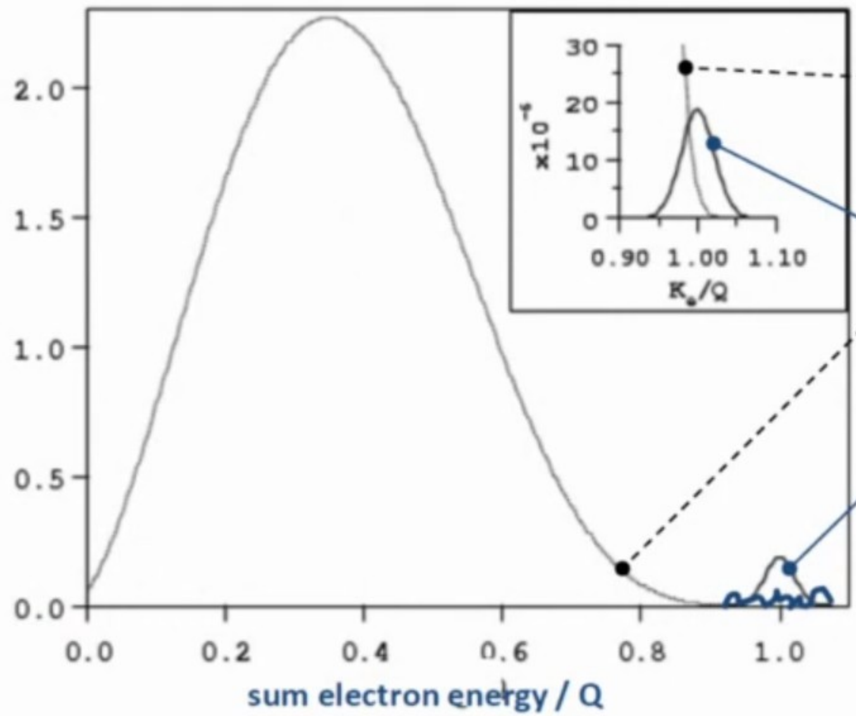


CER data do **not** provide **reliable absolute NMEs values**!

Neutrino physics with nuclei - 0νββ

Università degli Studi di Padova

The shape of the two-electron sum-energy spectrum enables to distinguish between the **0ν** (new physics) and the **2ν** decay modes

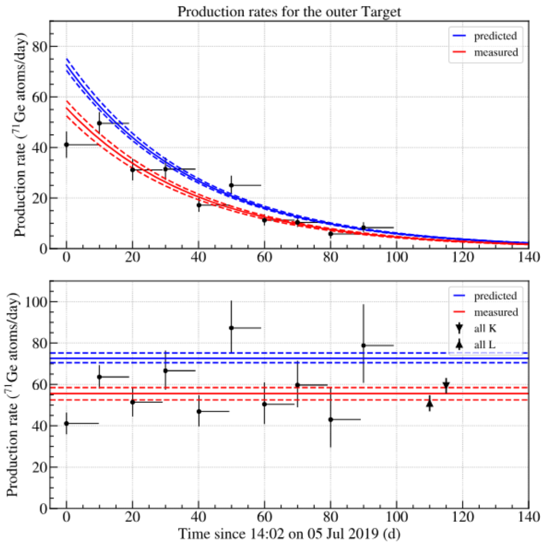


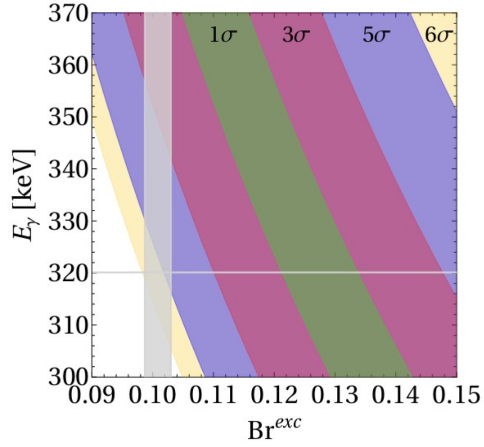
2ν2β : **(A,Z)→(A,Z+2)+2e+2ν**
continuum with maximum at ~1/3 Q

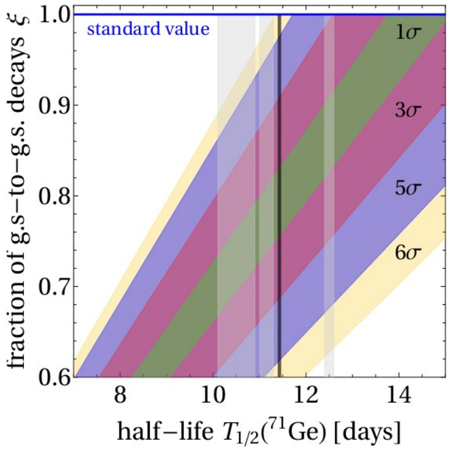
0ν2β : **(A,Z)→(A,Z+2)+2e**
peak enlarged only by
the detector energy resolution

Q ~ 2-3 MeV for the most promising candidates

Gallium anomaly

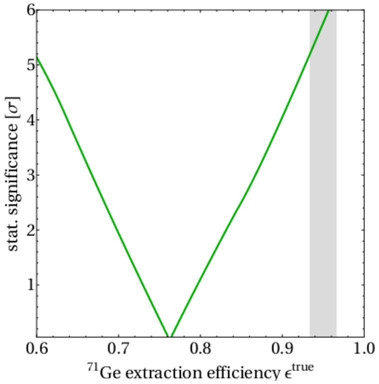






Explanations within the Standard Model

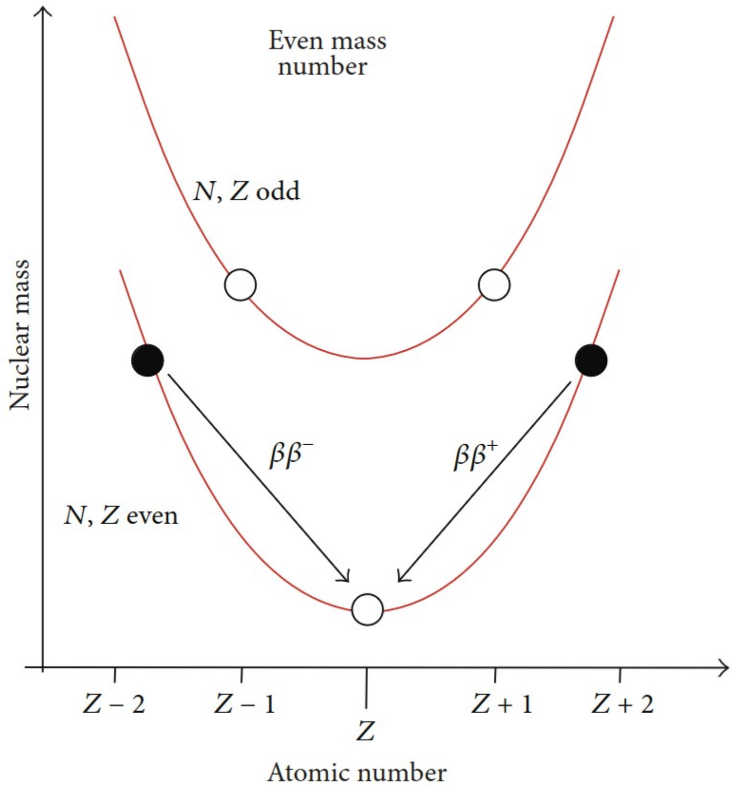
increased ^{71}Ge half-life (section 2.1 and ref. [39])	would lead to smaller matrix element for $\nu + {}^{71}$Ga; but the ^{71}Ge half-life has been measured many times with different methods in [38], all of which yield consistent results. So it is hard to imagine a bias in these measurements.	★★☆☆☆
new ^{71}Ga excited state (section 2.2)	would imply a bias in the extraction of the $\nu + {}^{71}$Ga matrix element from the measured ^{71}Ge half-life. Some very old experiments claim the existence of such a state, but this has not been confirmed in more recent observations.	★★☆☆☆
increased BR(^{51}Cr → ^{51}V*) (section 3)	would cause a bias in translating the heat output of the source to a neutrino production rate. Measurements of BR(^{51}Cr → ^{51}V*) show some tension, but it is far less than the shift required to explain the gallium anomaly.	★★★☆☆
^{71}Ge extraction efficiency (section 4)	one of SAGE's calibration runs has revealed a large bias. Could a small, unnoticed, bias have been present in all gallium experiments?	★★★★☆



0νββ decay and the role of Nuclear Physics

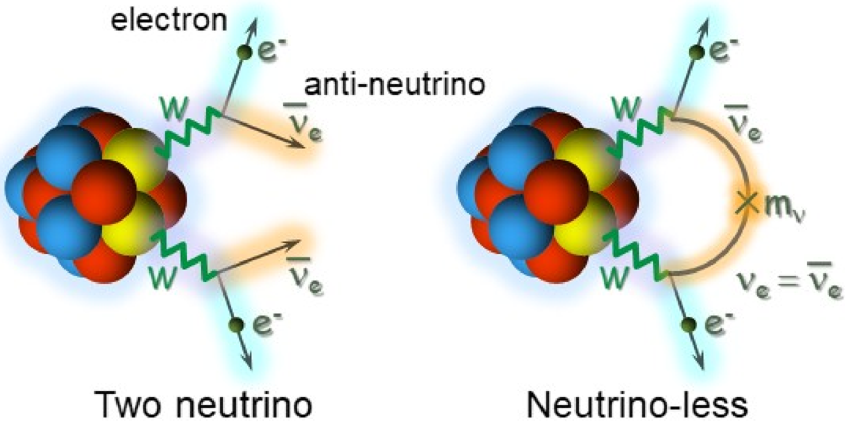
0νββ decay suggested by theories BSM: promising process to observe **L-violation** in laboratory, **ν** a **Majorana** particle, **ν mass**, **matter asymmetry** (leptogenesis)

$$ {}^{A}_{Z-2}X_{N+2} \rightarrow {}^{A}_{Z}Y_{N} + 2e^{-} $$

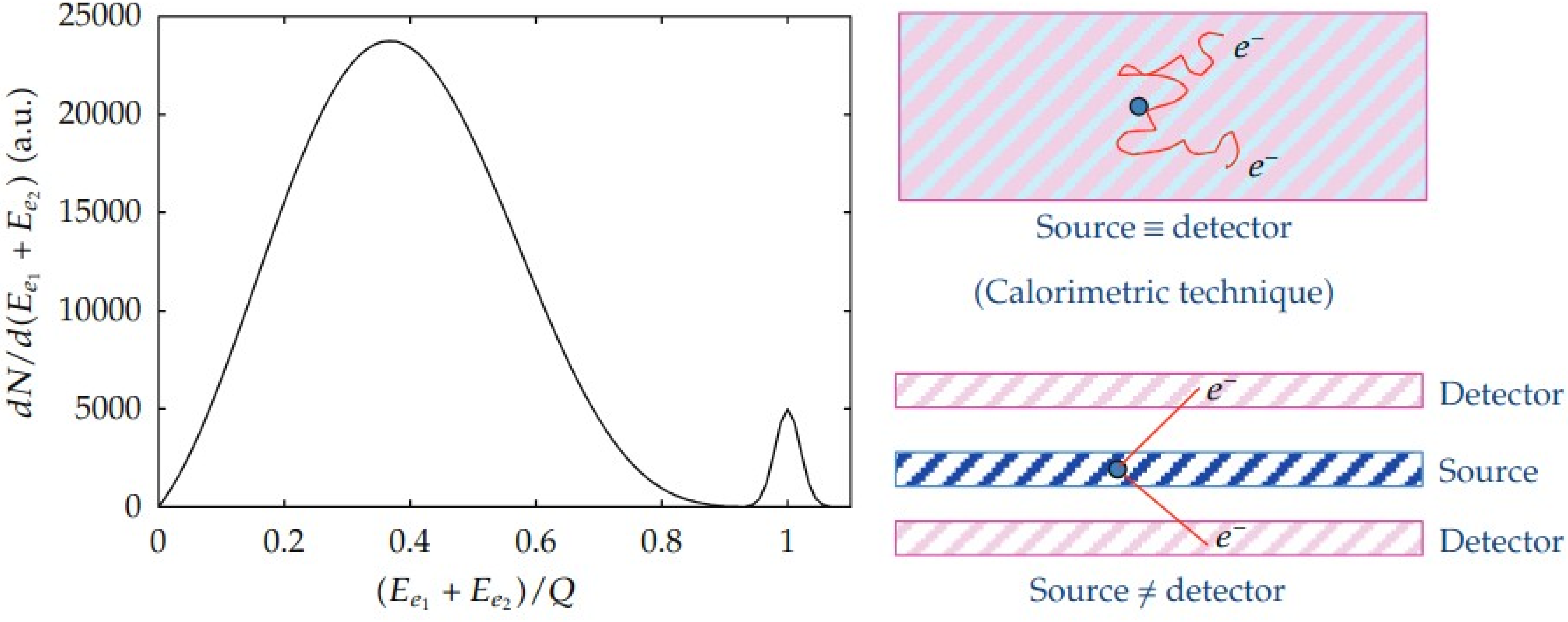


Candidates are **even-even** nuclei which, due to pairing force, are lighter than the odd-odd (A,Z-1) nucleus:

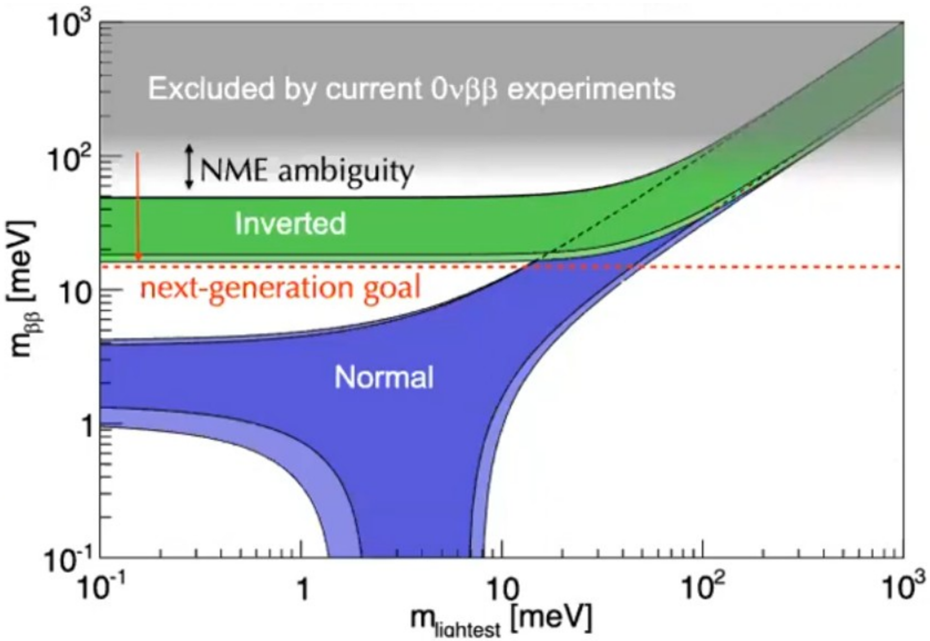
^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{136}Xe, ^{150}Nd

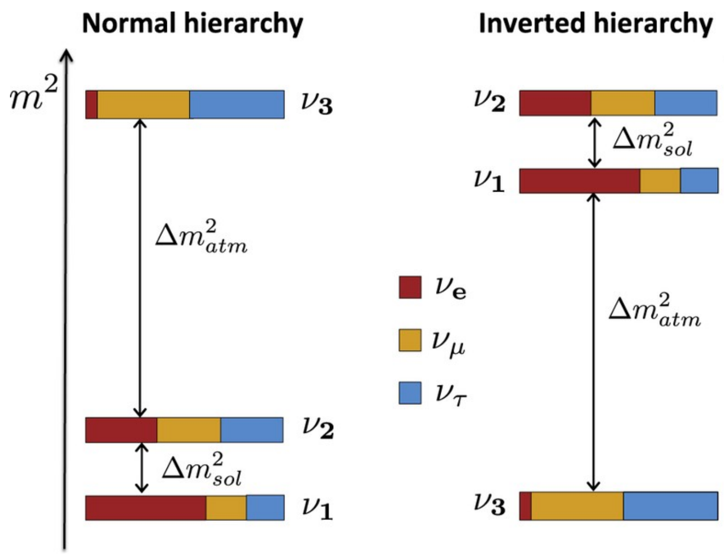


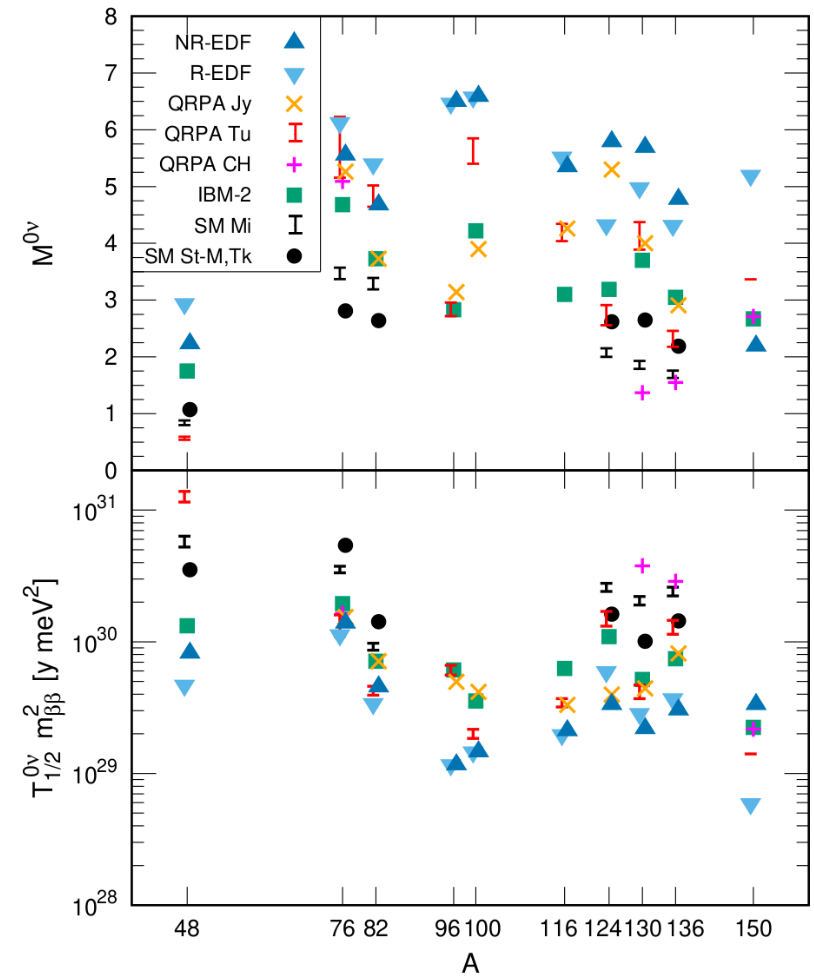
0νββ decay and the role of Nuclear Physics



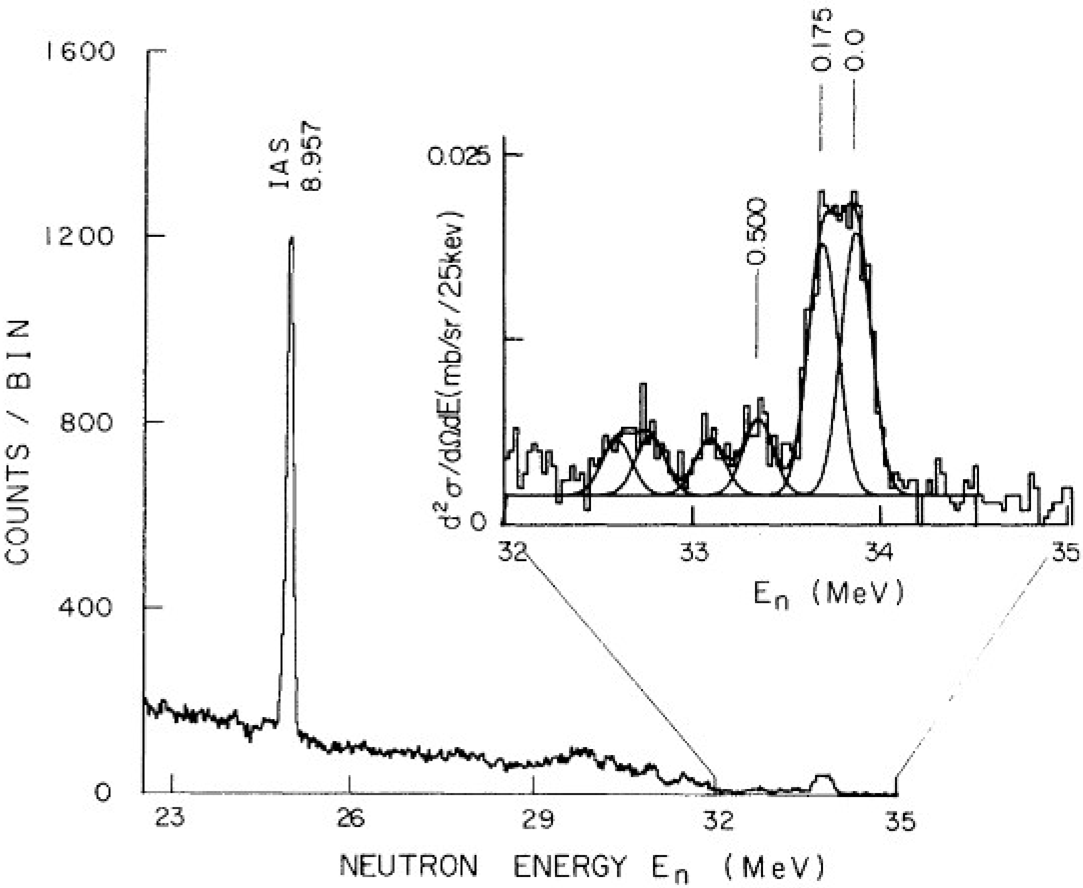
Backup slides: state of the art 0νββ decays

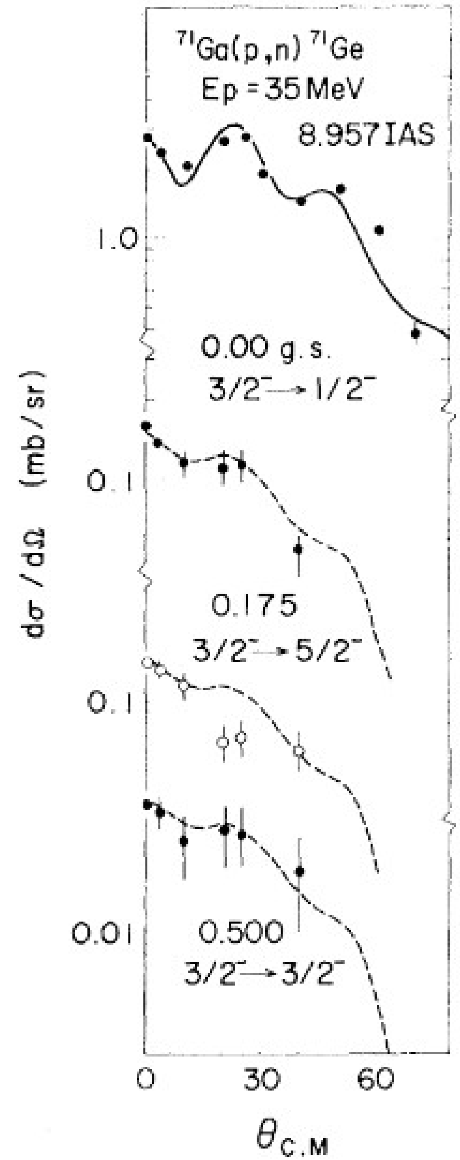




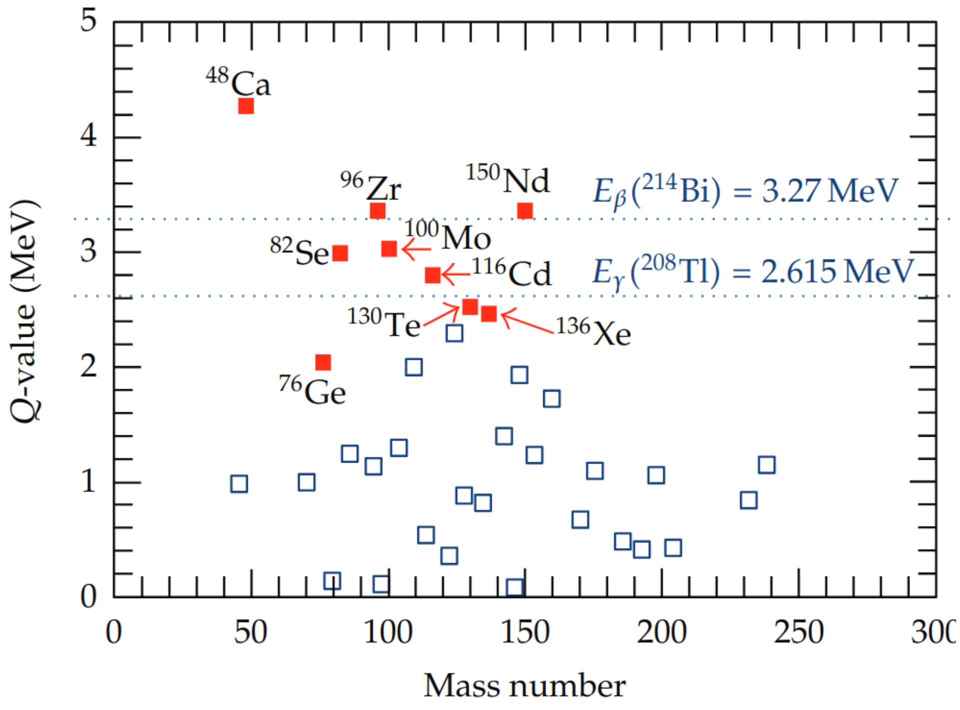


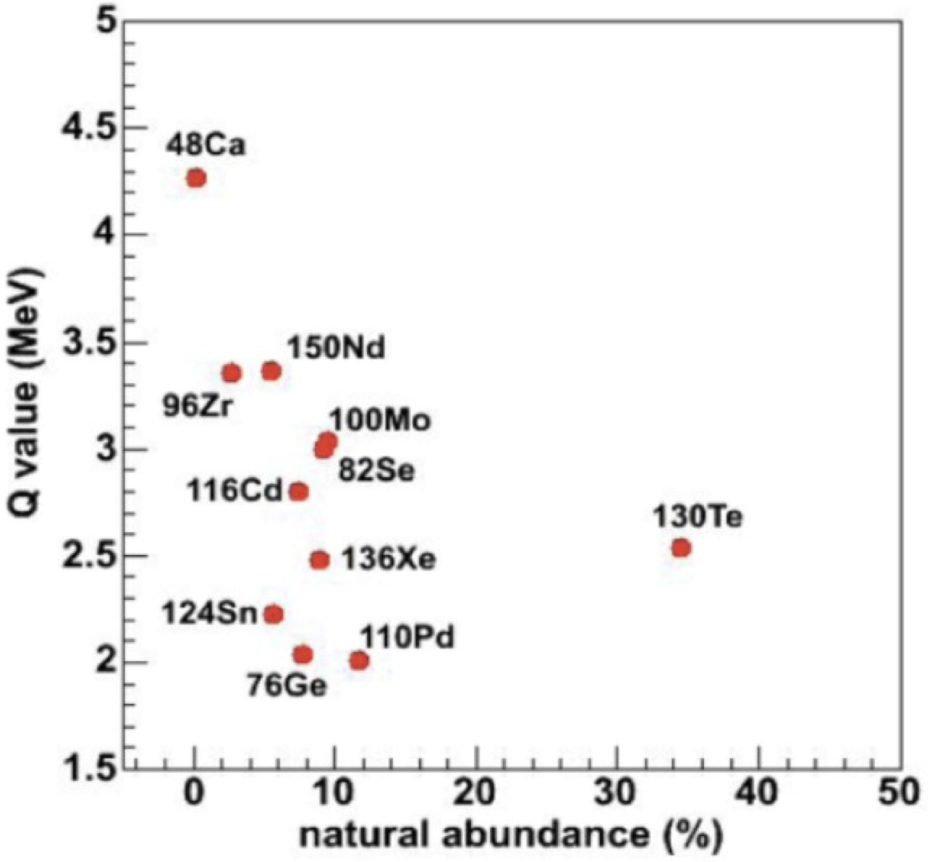
Backup slides: populating the IAS



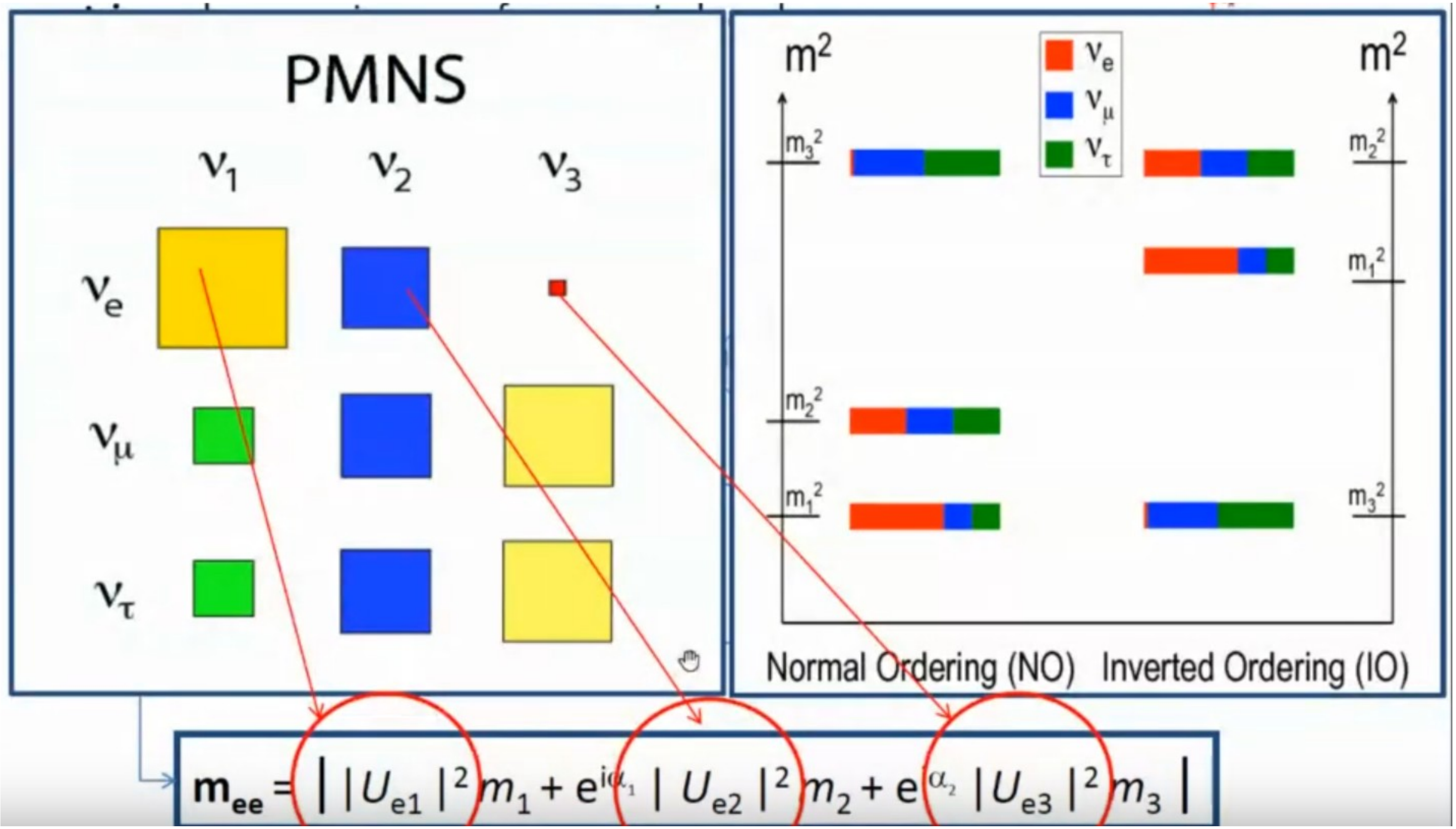


0νββ decay and the role of Nuclear Physics





$0\nu\beta\beta$ decay and the role of Nuclear Physics



Double-gamma decay candidates

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Best candidate: ^{48}Ti → mimic 0νββ ^{48}Ca decay

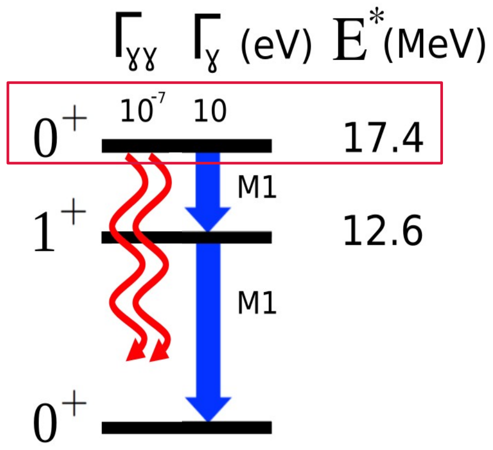
PROS

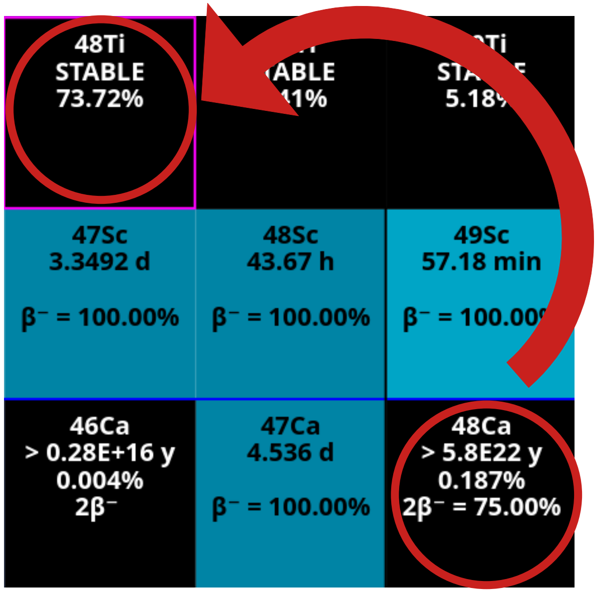
1) The 17 MeV 0^+ **DIAS is known**
2) Particle unbound, but **particle decay is highly suppressed** (isospin forbidden).

CONS

1) **Difficult to populate** (high energy 0^+)
2) Extremely small double-gamma decay width:

$$\Gamma_{\gamma\gamma} / \Gamma_{tot} \approx 10^{-8}$$





- **How to populate the 17 MeV 0^+ DIAS?**

^{50}Ti(p,t)^{48}Ti @ 45 MeV

→ isospin conserving and very selective (light particles)

- **How can we measure the 2γ decay events?**

GEANT4 simulations!

MSc thesis work: GEANT4 simulations

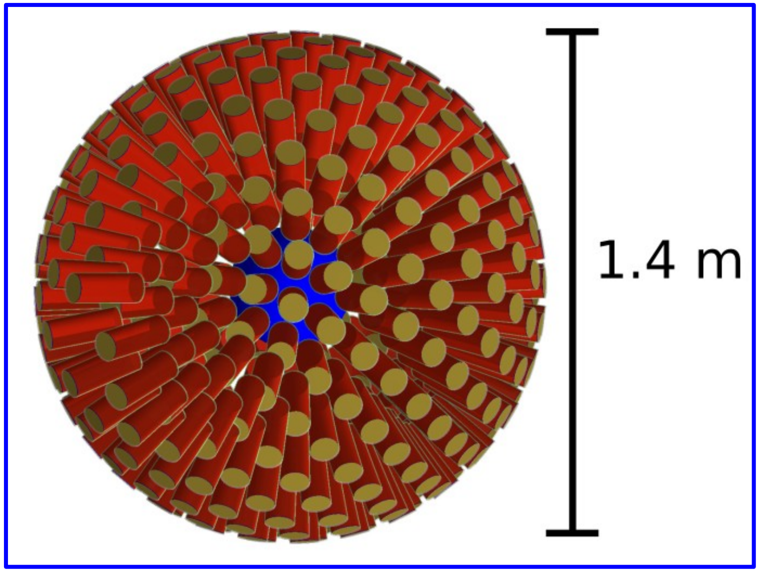
A GEANT4 simulation was designed from scratch:

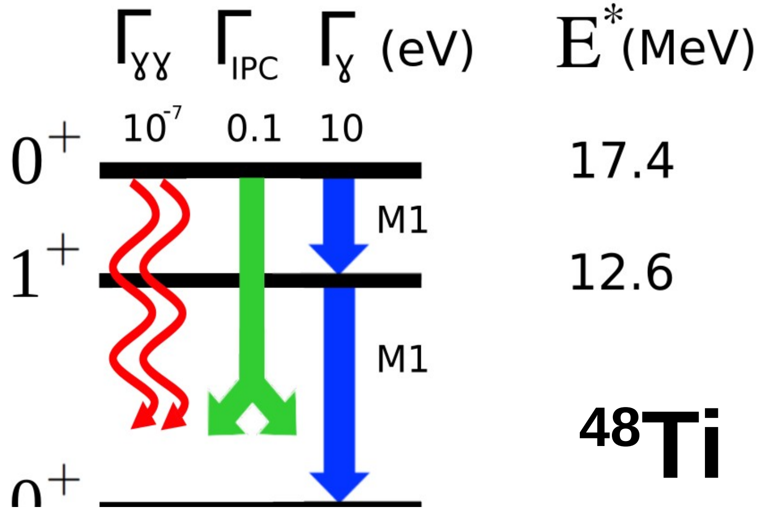
Step 1 **Define setup & data processing**

→ **Maximise the 2ɣ detection efficiency**

Step 2 **Analysis of simulation outputs**

→ **Isolate the M1M1 2ɣ decays, identifying the competing processes**





- **Internal Pair Creation (IPC)**, emission of an e^-e^+ pair — $\Gamma_{\gamma\gamma}/\Gamma_{IPC} \approx 10^{-6}$
- **ɣ-cascade**, 2 consecutive ɣ decays through a 1^+ state — $\Gamma_{\gamma\gamma}/\Gamma_{\gamma} \approx 10^{-8}$

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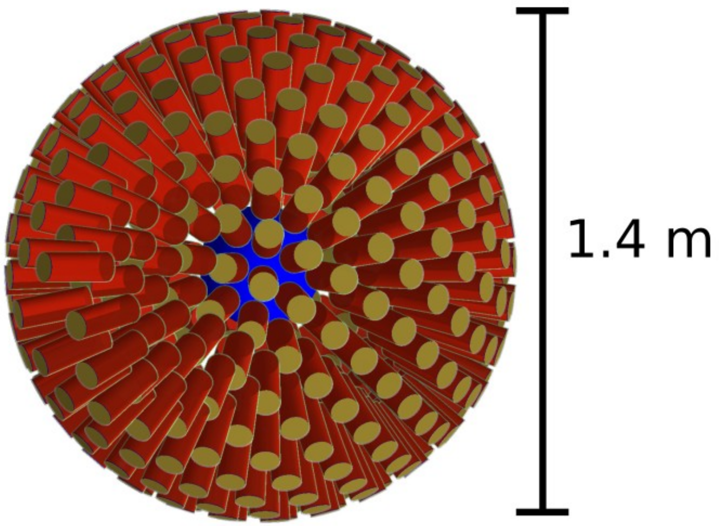

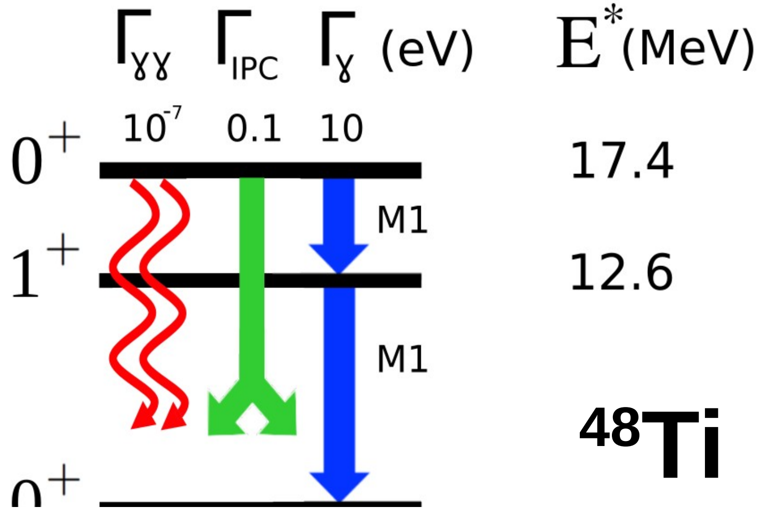

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Competing processes: ɣ-cascade

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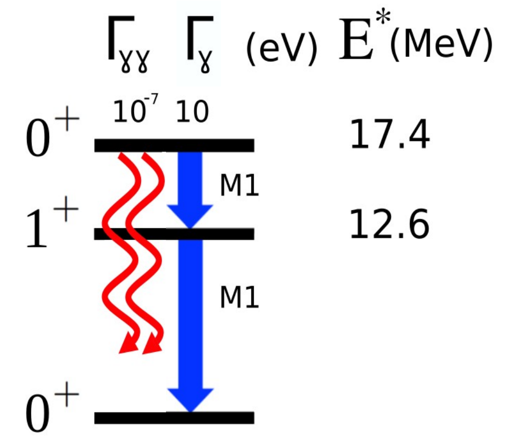
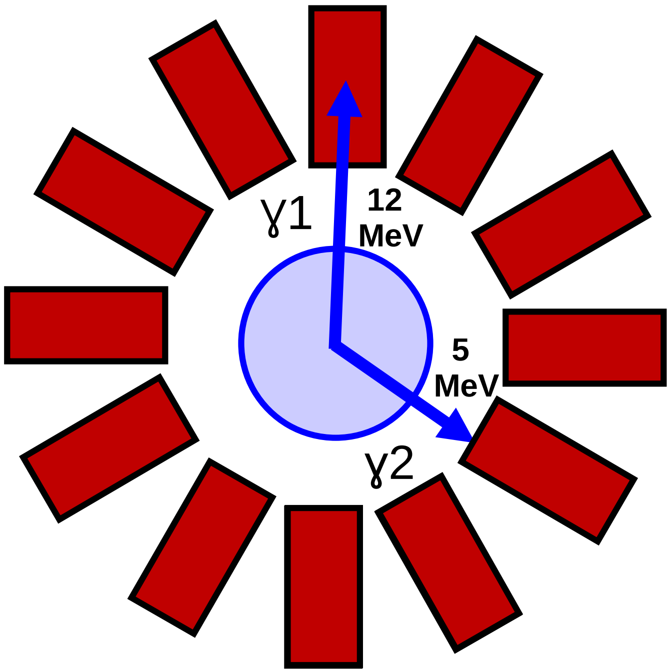
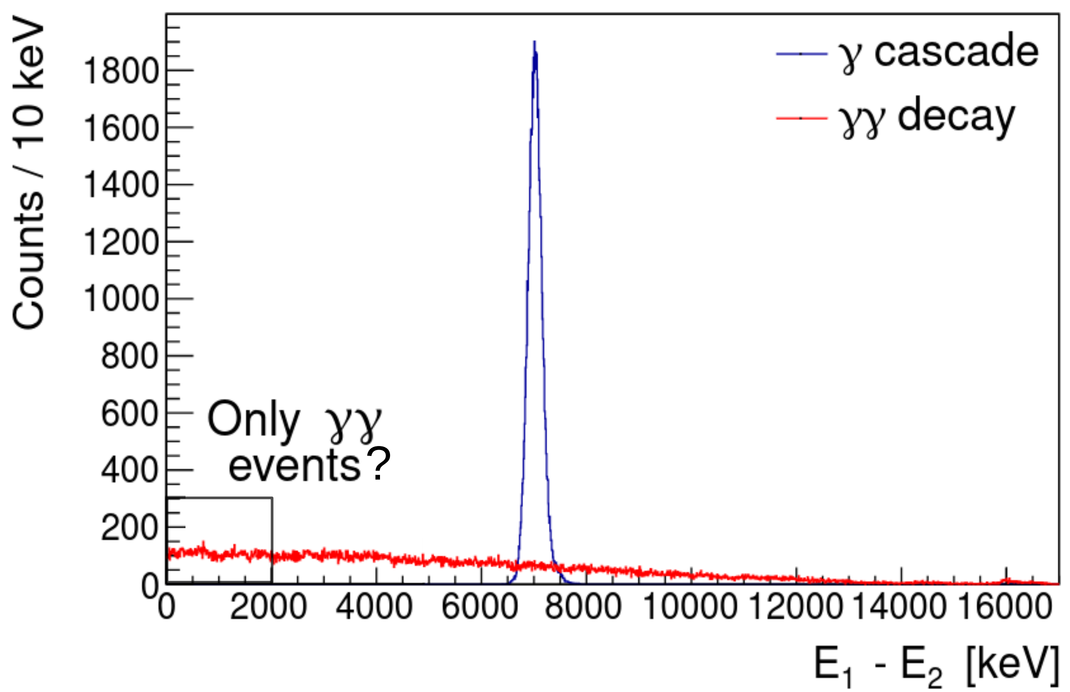
- **ɣ-cascade**: gammas emitted in cascade will have a discrete energy. In most cases 4.8 MeV and 12.6 MeV.



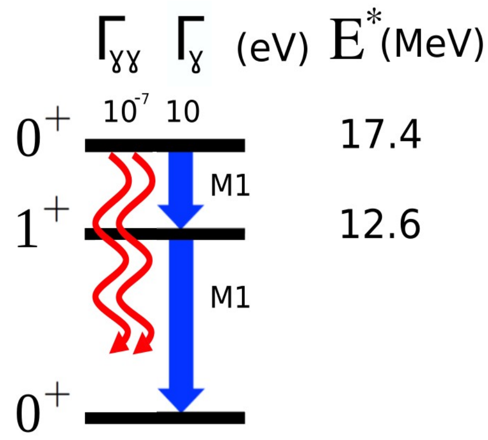
For **multiplicity 2 events** and **setting an energy gate E_1+E_2 > 16.9 MeV, the energy difference E_1-E_2** spectra are quite different





Competing processes: γ-cascade

- **γ-cascade**: gammas emitted in cascade will have a discrete energy. In most cases 4.8 MeV and 12.6 MeV.



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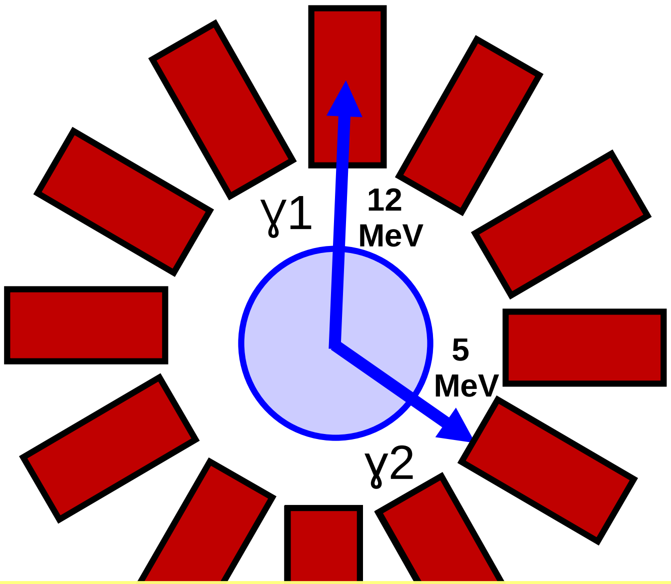

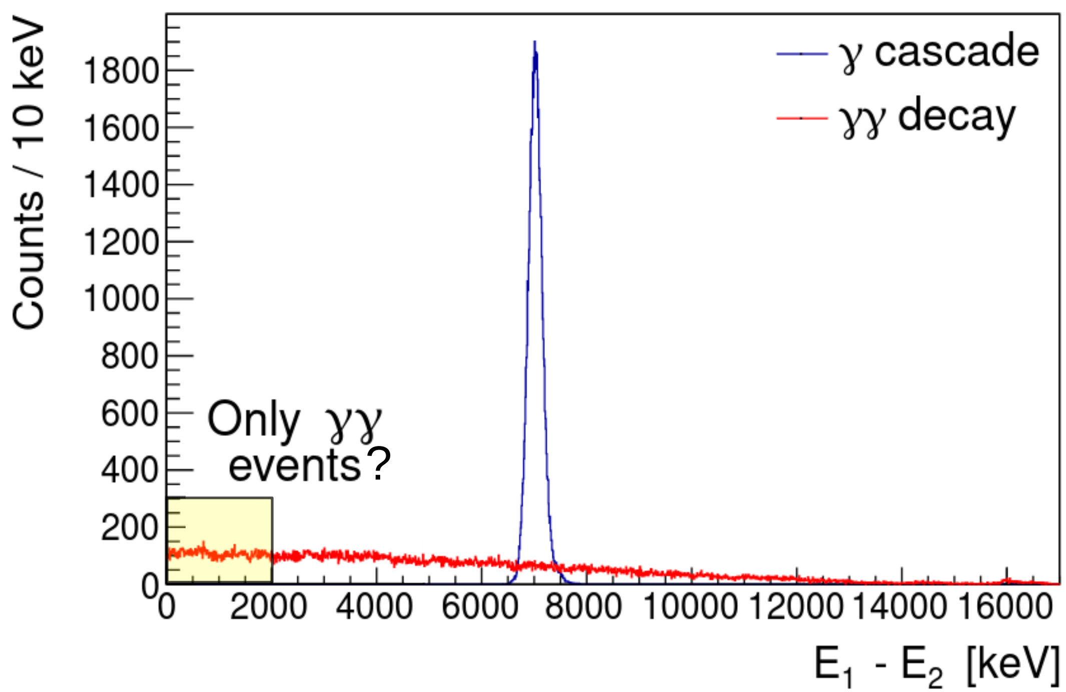

We can remove these events setting an **energy limit E_1 - E_2 < 2 MeV**

Competing processes: ɣ-cascade problems

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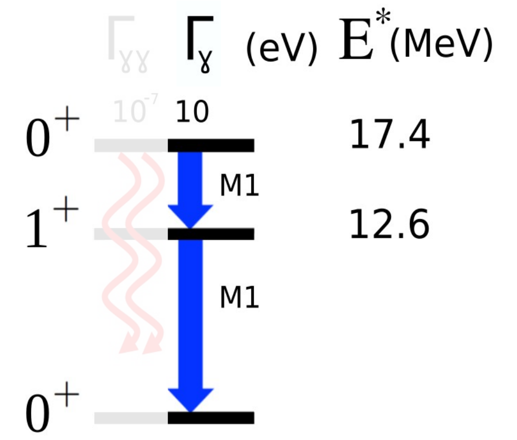
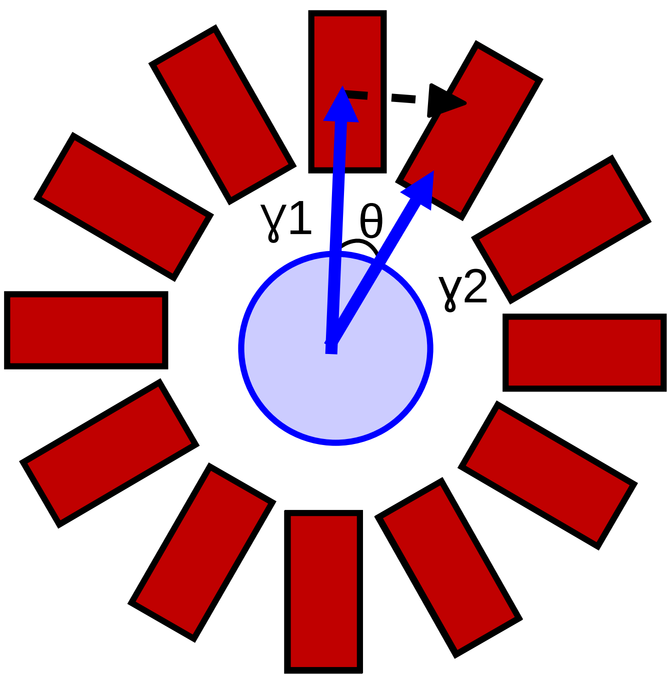
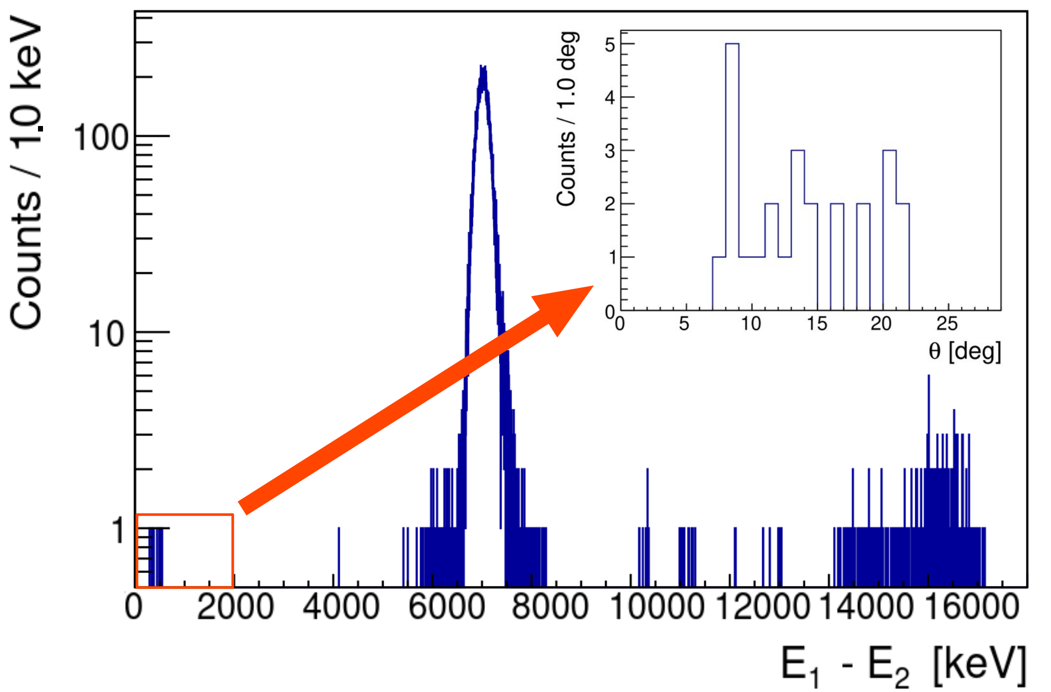
Problem with ɣ-cascade: if **2ɣ correlation angle is low**, the 12.6 MeV gamma can deposit **8.7 MeV in one detector,** scatter on it and deposit **the rest where the other gamma hit**

➡ **Fake 2ɣ events!**







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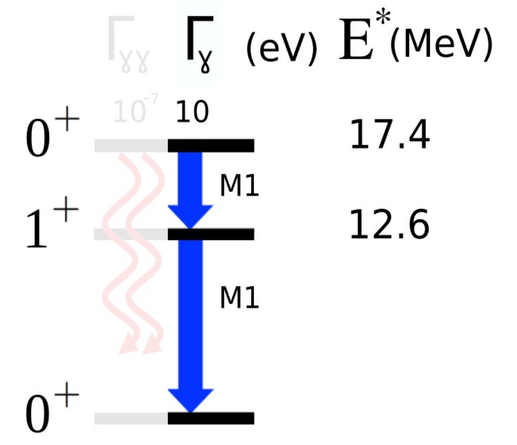

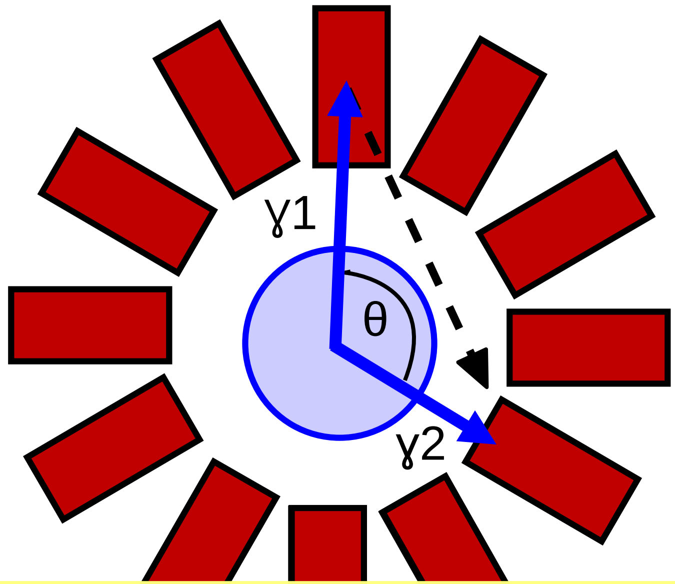

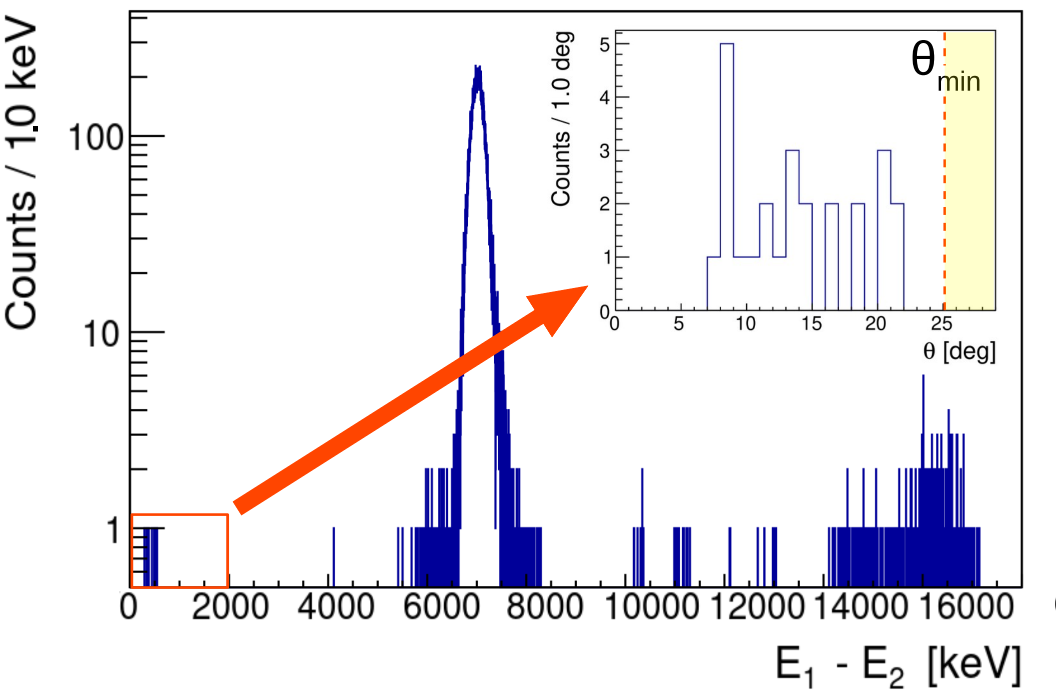

We can remove these events setting an **angle limit θ > 25°**

Extracting multipolarity and double-ɣ decay width

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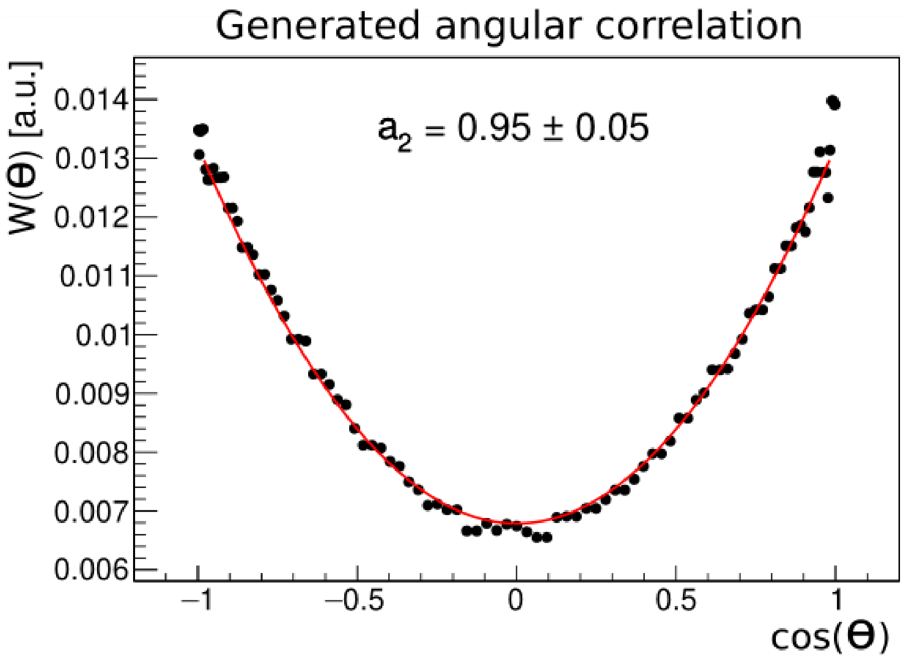
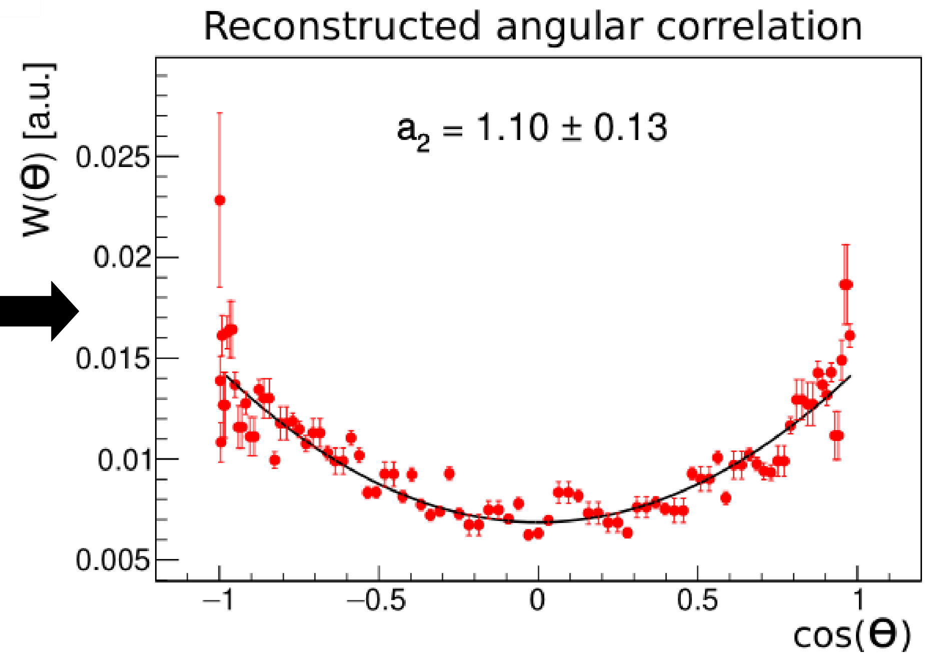
Once only 2ɣ decay events are selected, since we are only interested in **M1M1 decays**, we need to obtain their multipolarity and branching ratio.

With the two gammas angular correlation spectrum we can extract both:

$$W(\theta) = a_0[1 + a_2\cos^2\theta + a_4\cos^4\theta]$$

a_2 **Multipolarity** of the decays





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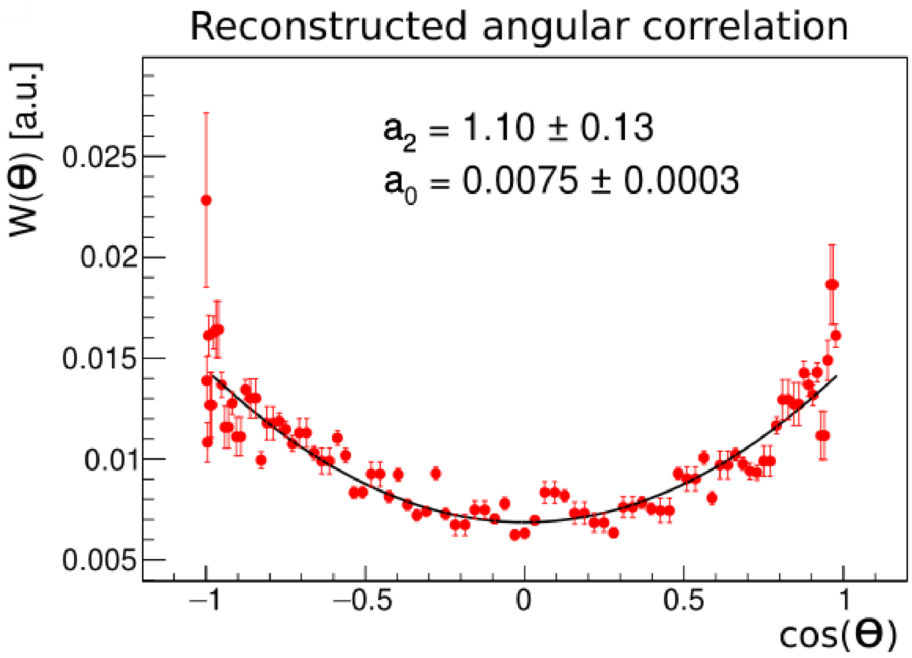
a_2 **Multipolarity** of the decays

a_0 Number of 2ɣ decays / $\varepsilon \rightarrow \Gamma_{\gamma\gamma}$

From the double-ɣ decay width $\Gamma_{\gamma\gamma}$ one can extract the **NME** of interest:

$$\Gamma_{\gamma\gamma}(M1M1) = \frac{8^2 0.22\pi\alpha^2}{3^5 35} \frac{Q^7}{(\hbar c)^4}[M^{\gamma\gamma}(M1M1)]^2$$

and finally determine the **0νββ NME!**



MSc thesis summary

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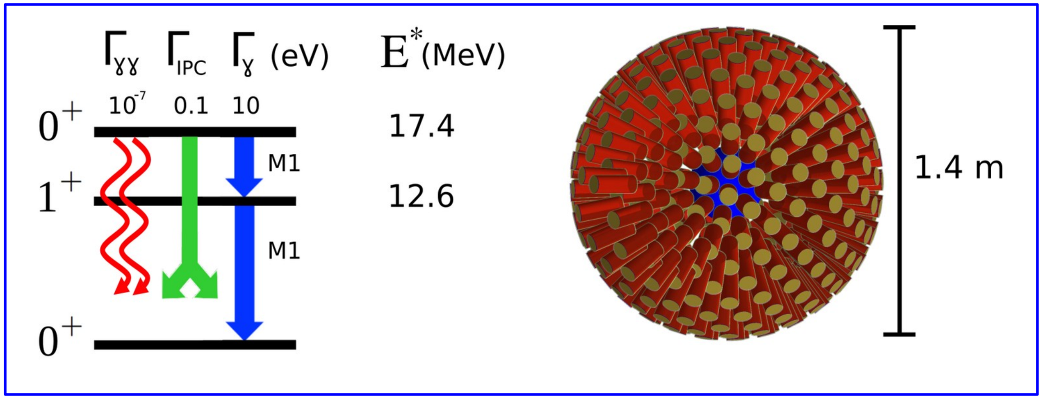
We took the first step...

- **We found a method to isolate and measure 2ɣ-decay NMEs**



Step 1 **Defined setup & data processing**

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→ **Multipolarity and decay width extraction**

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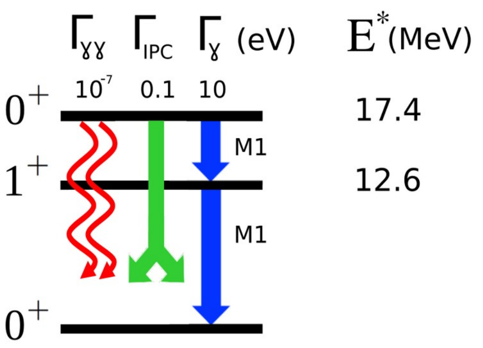

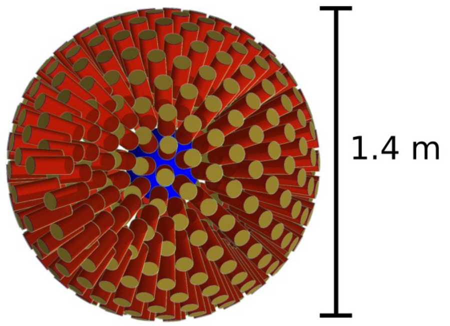

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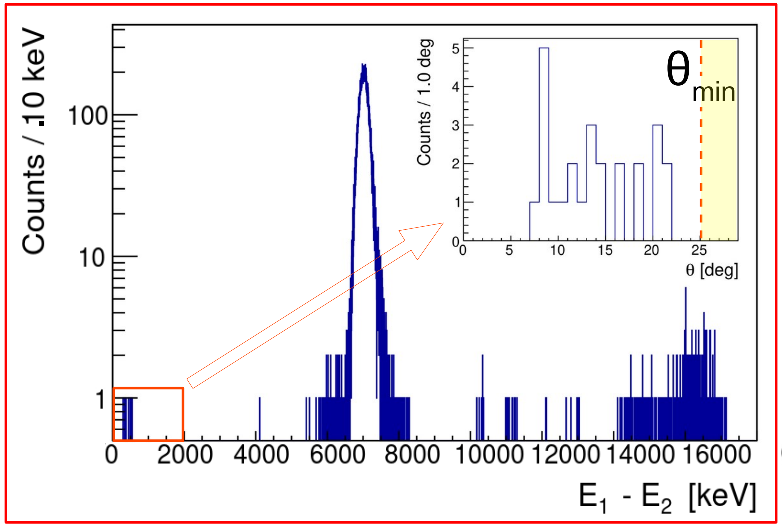

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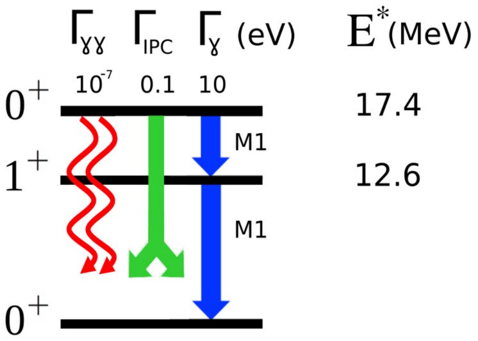

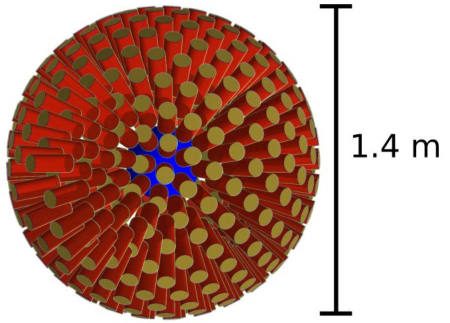

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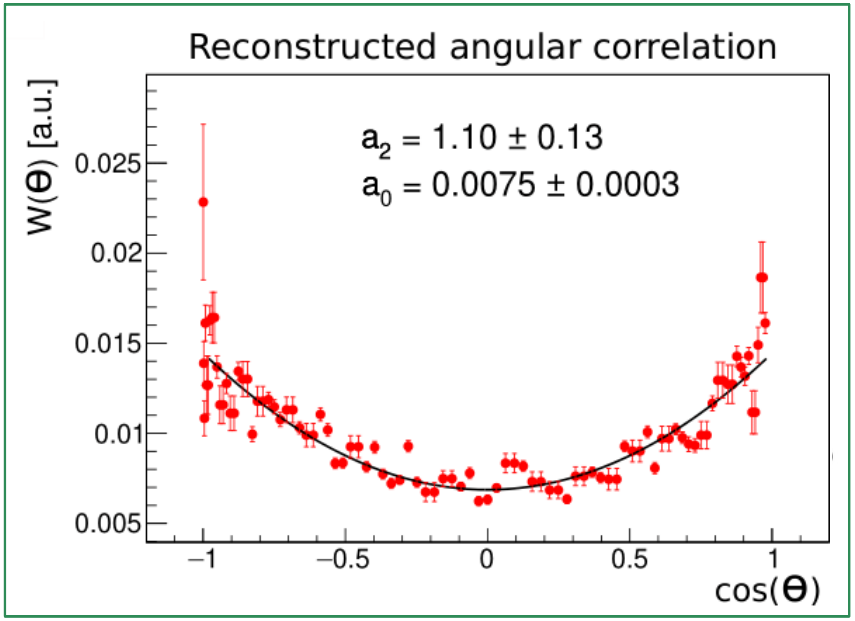
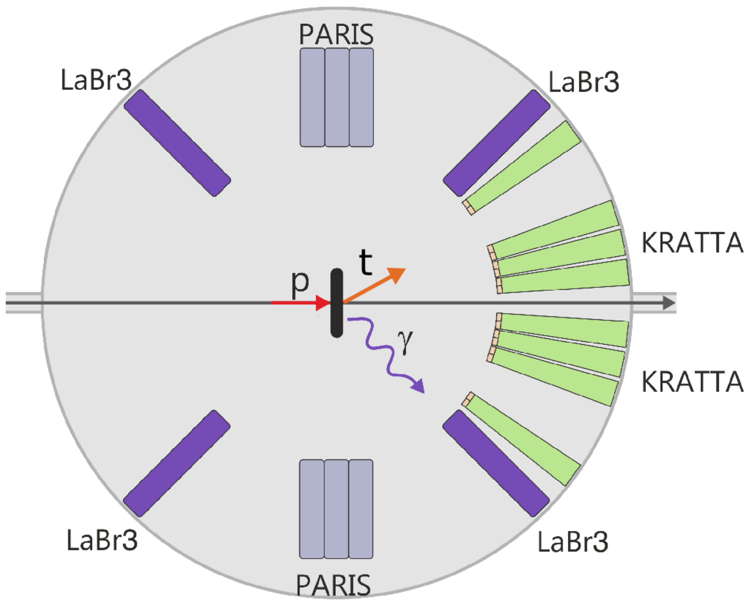


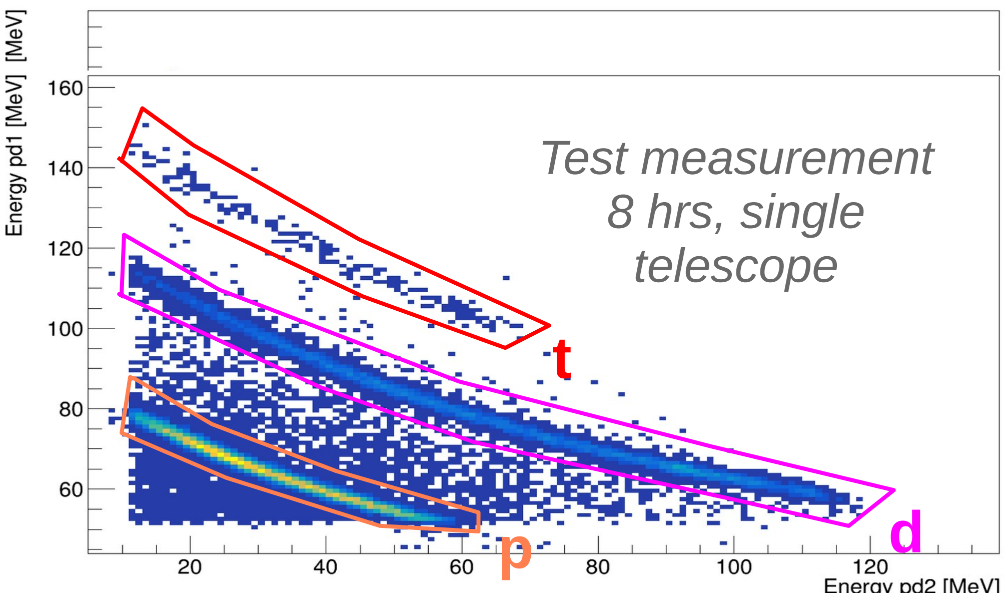
From simulations to experiment

PHASE 0



PHASE 0 - CCB @ Krakow:

- 32 **KRATTA triple telescopes** (with segmented plastic scintillator in front) to measure the **scattered tritons**
- 4 large volume **$LaBr_3$** detectors & 2 **PARIS** clusters for the measurement of **ɣ rays**
- ☹ Low intensity, only weekend runs



1 BTU test in late April:

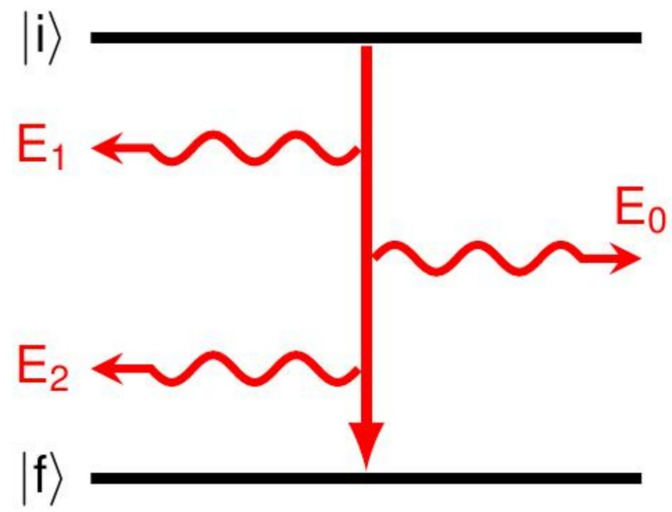
- **Beam**: E=180 MeV and I= 0.4 nA
- **Target**: 100 mg/cm^2 of ^{50}Ti (60%)

✔ We clearly see **tritons** in the energy range of interest

Backup slides: Double gamma decays

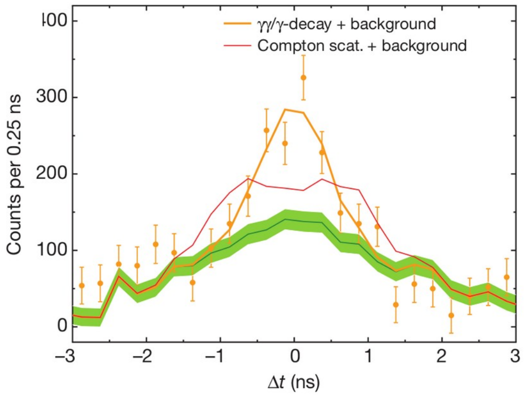
Second order EM process where:

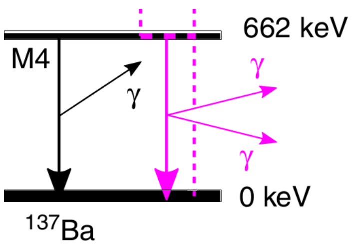
- $E_0 = E_1 + E_2$
- E_1, E_2 are continuous

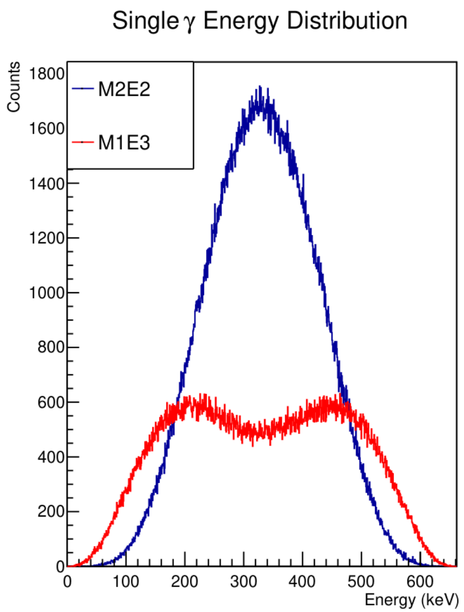


In 2015, a Nature paper reported its observation in **competition with single-gamma decay** in ^{137}Ba: $\Gamma_{\gamma\gamma}/\Gamma_{\gamma} \approx 10^{-6}$

- Using **good time properties** of scintillators







Backup slides: populating DIAS in ^{48}Ti

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^{50}Ti(p,t)^{48}Ti Q = -10.6 MeV

^{46}Ca(^{4}He,2n)^{48}Ti Q = -8.36 MeV

^{48}Ca(^{3}He,3n)^{48}Ti Q = -5.01 MeV

^{48}Ca(^{20}Ne,^{20}O)^{48}Ti Q = -6.50 MeV

…..

1.E.2:
1.E.7

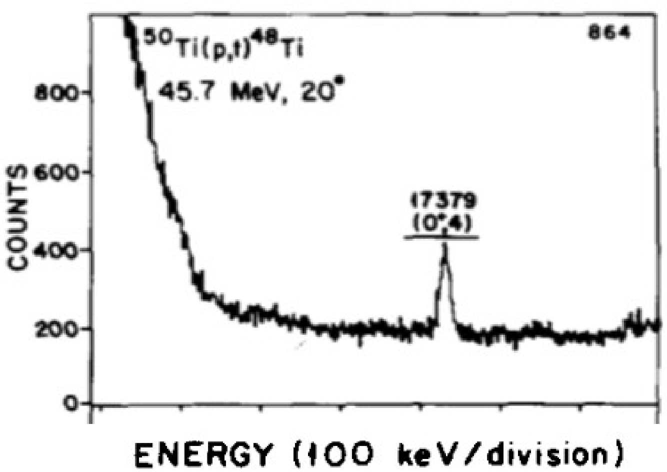
Nuclear Physics A309 (1978) 329 – 343; © North-Holland Publishing Co., Amsterdam

EXPERIMENTAL DISPLACEMENT ENERGIES OF ISOBARIC ANALOG STATES IN THE 1f$_{7/2}$ SHELL †

R. T. KOUZES, P. KUTT, D. MUELLER and R. SHERR

Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540

Received 27 June 1978



DCX ^{48}Ca(π+,π-)^{48}Ti

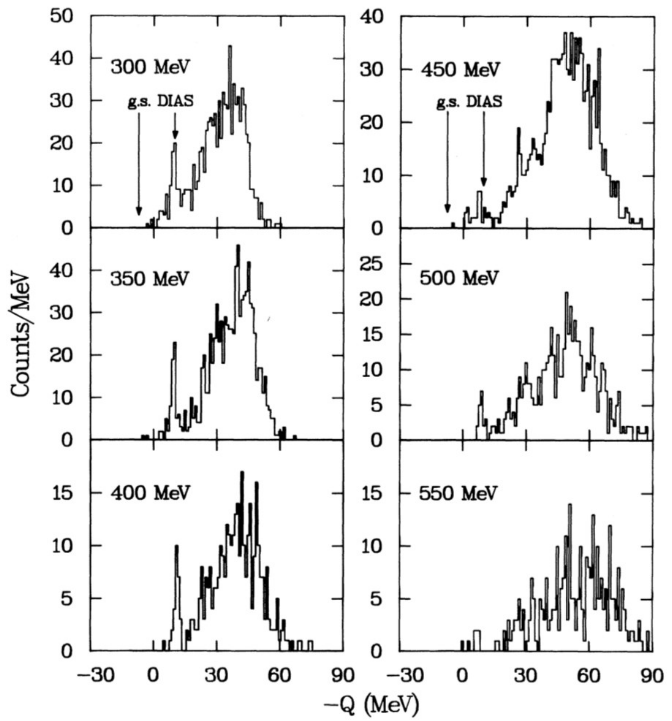


TABLE V. Results of using Eqs. (1) and (2) to calculate cross sections for ^{42,44,48}Ca averaged over 400–500 MeV.[a]

Transition	$d\sigma/d\Omega_{exp}$ (μb/sr)	DIAS only[b] $d\sigma/d\Omega_{calc}$ (μb/sr)	Fit DIAS + g.s.[c] $d\sigma/d\Omega_{calc}$ (μb/sr)	χ^2
^{42}Ca → ^{42}Ti (DIAS)	0.747±0.109	0.747	0.498	5.24
~~^{44}Ca → ^{44}Ti (DIAS)~~	~~0.855±0.125~~	~~0.855~~	~~0.987~~	~~1.12~~
^{48}Ca → ^{48}Ti (DIAS)	2.49±0.284	2.49	2.43	0.04
~~^{44}Ca → ^{44}Ti (g.s.)~~	~~0.094±0.047~~	~~0.418~~	~~0.0901~~	~~0.01~~
^{48}Ca → ^{48}Ti (g.s.)	0.026±0.026	0.308	0.0663	2.37

A.L. Williams PRC43 766 (1991)

Backup slides: detecting the tritons

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Nuclear Inst. and Methods in Physics Research, A 925 (2019) 184–187

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A CsI(Tl) detector array for the measurement of light charged particles in heavy-ion reactions

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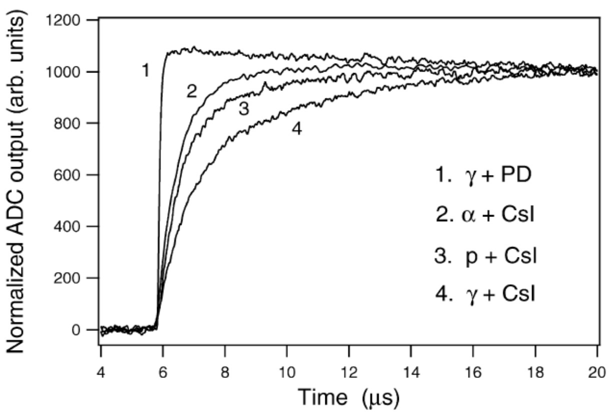


Fig. 1. Selected ADC waveforms show different pulse shape due to protons, α-particles, and γ-rays impinging on the CsI(Tl) crystal. In order to facilitate comparison the waveforms were normalized to the same height at $t = 20$ µs, and their baselines were shifted to zero. The trace number 1 was due to a photon conversion directly in the silicon photodiode. High-frequency noise caused fluctuations clearly discernible in the data.

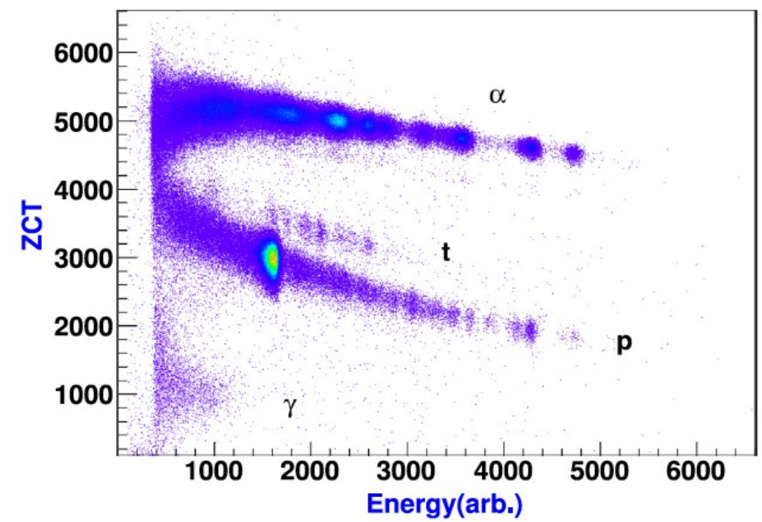
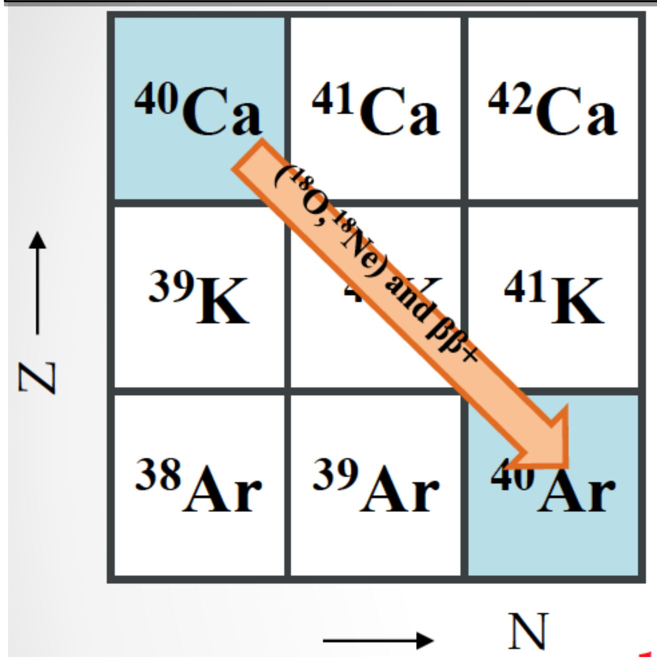


Fig. 4. A 2D spectrum between the ZCT and the energy of CsI(Tl) detector which shows the particles emitted in the $^{12}C + ^{12}C$ reaction are well separated by the pulse shape discrimination technique.

Backup slides: DCX reactions and 0νββ

Feasibility

$^{40}Ca(^{18}O,^{18}Ne)^{40}Ar$ @ 270 MeV



Measured: dσ(DCE)/dΩ= 11μb/sr

Competing processes are at the 1% level

- DCE mediated by strong interaction, ββ0ν by weak interaction
- DCE includes sequential multinucleon transfer mechanism

BUT

- Same initial and final wave functions
- Similar operator …

The idea of NUMEN is to go to more relevant cases such as: ^{76}Ge, ^{116}Cd, ^{130}Te, ^{136}Xe

There are experimental challenges:

- Large beam intensities
- $\beta^-\beta^-$ requires a radioactive beam (^{18}Ne,^{18}O)
- Some cases, not enough energy resolution
  γ detectors

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