RCNP, 21st January 2025

Unlocking the Nuclear Matrix Elements of Neutrinoless Double-Beta Decay: A Novel Experimental Approach

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Laboratori Nazionali di Legnaro (INFN) Padova, Italy.

Overview – Points to be discussed

- Double Isobaric analogue states (DIAS) ^{48}Ti
- Double-gamma decay – HPGe detectors
- Double-gamma decay - scintillators
- Summary

0νββ decay - role of Nuclear Physics

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\ |M^{0\nu}|^2\ m^2_{\beta\beta}$$

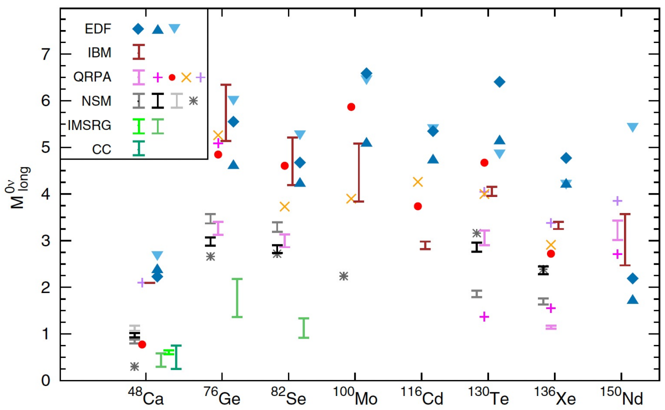
$m^2_{\beta\beta}$ New Physics parameter

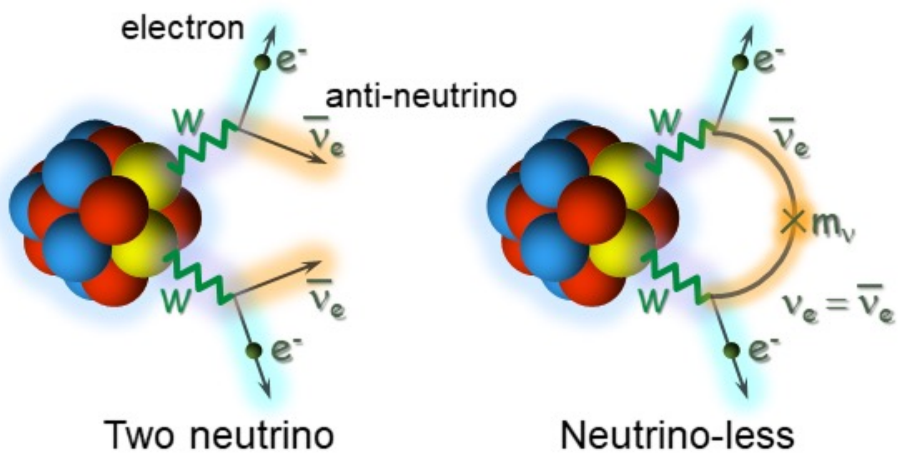
$G_{0\nu}(Q,Z)$ Phase space Factor

$|M^{0\nu}|^2$ Nuclear Matrix Element (NME) brings the **large uncertainties** in DBD half-lifes

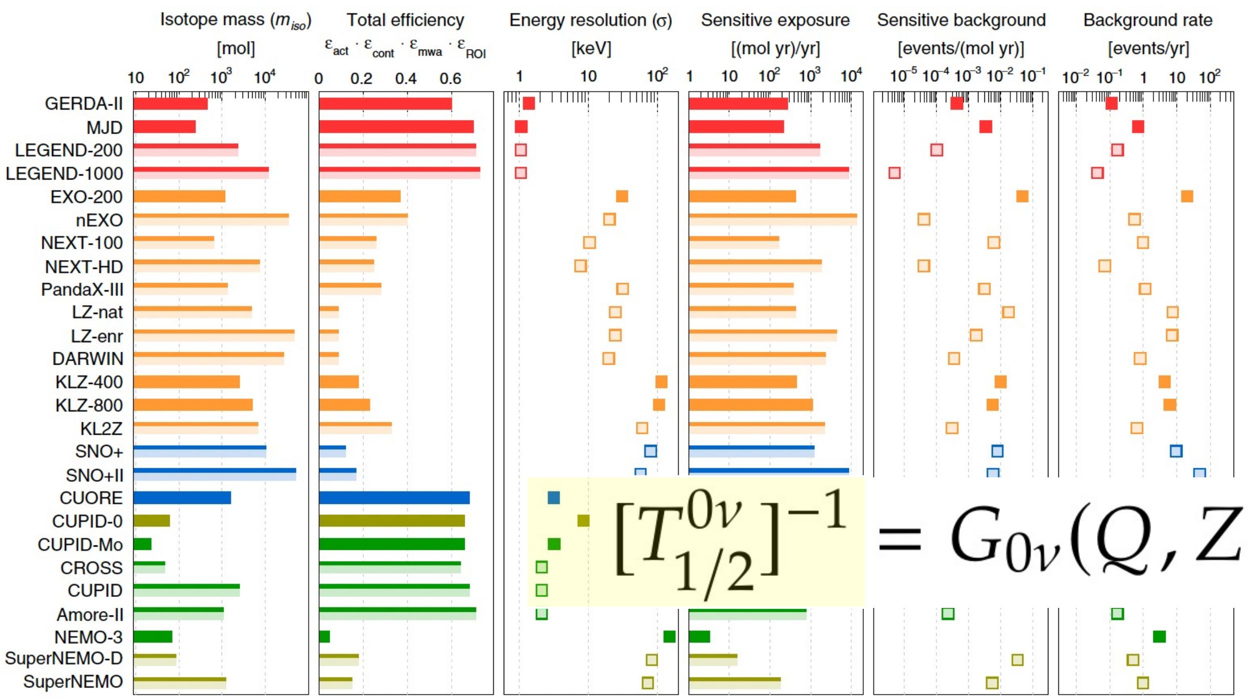
$$^{A}_{Z-2}X_{N+2} \rightarrow {}^{A}_{Z}Y_N + 2e^-$$

Rev. Mod. Phys 95 (2023).





Direct experimental approaches



$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\ |M^{0\nu}|^2\ m^2_{\beta\beta}$$

Agostini, Benato, Detwiler, Menéndez and Vissani Rev. Mod. Phys 95 (2023).

Indirect experimental approaches

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\ \boxed{|M^{0\nu}|^2}\ m^2_{\beta\beta}$$

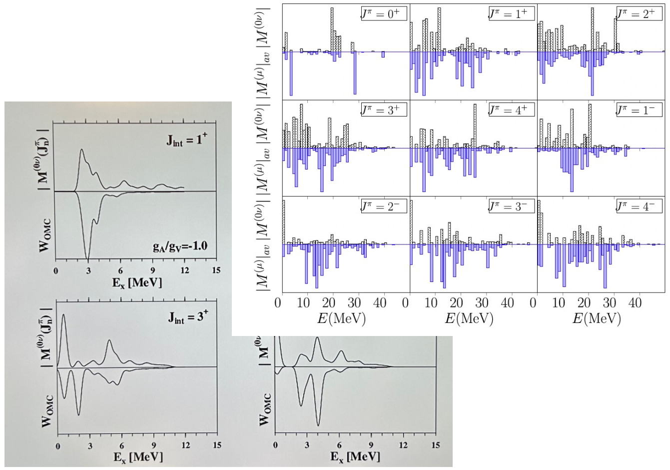
Double Gamow Teller

Double Charge Exchange

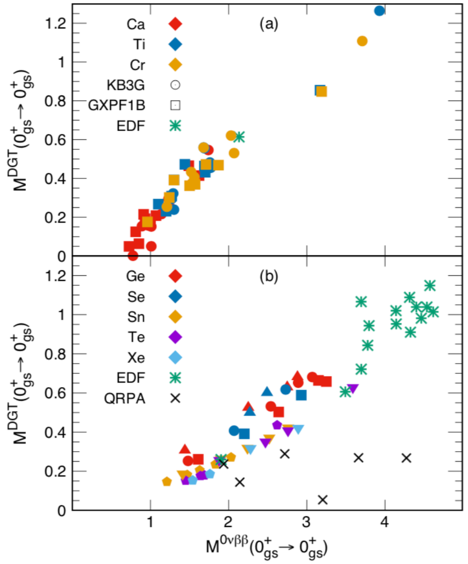
NUMEN

F. Cappuzzello, et al. Eur. Phys. J. A (2015) 51: 145

Muon capture



M. Kortelainen and J. Suhonen J. P. G30 (2004) 2003; L. Jokiniemi and J. Suhonen PR C 102, 024303 (2020)



N. Shimizu J. Menendez, K. Yako PRL120, 142502 (2018)

Indirect experimental approaches

go another way

$$[T^{0\nu}_{1/2}]^{-1} = G_{0\nu}(Q,Z)\ |M^{0\nu}|^2\ m^2_{\beta\beta}$$

Physics Letters B 827 (2022) 136965
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$\gamma\gamma$ decay as a probe of neutrinoless $\beta\beta$ decay nuclear matrix elements

B. Romeo[a,b,*], J. Menéndez[c], C. Peña Garay[b,d]

Phys. Lett. B 860 (2025) 139186
Contents lists available at ScienceDirect
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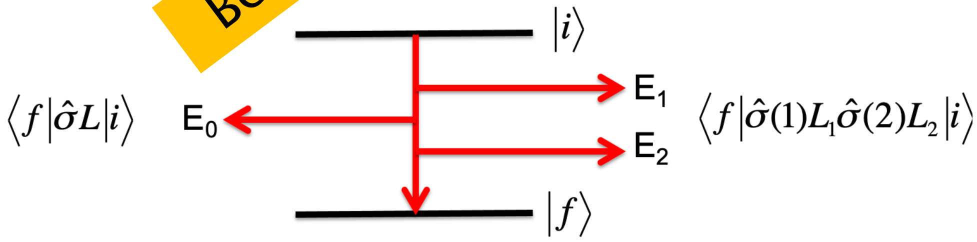
Letter

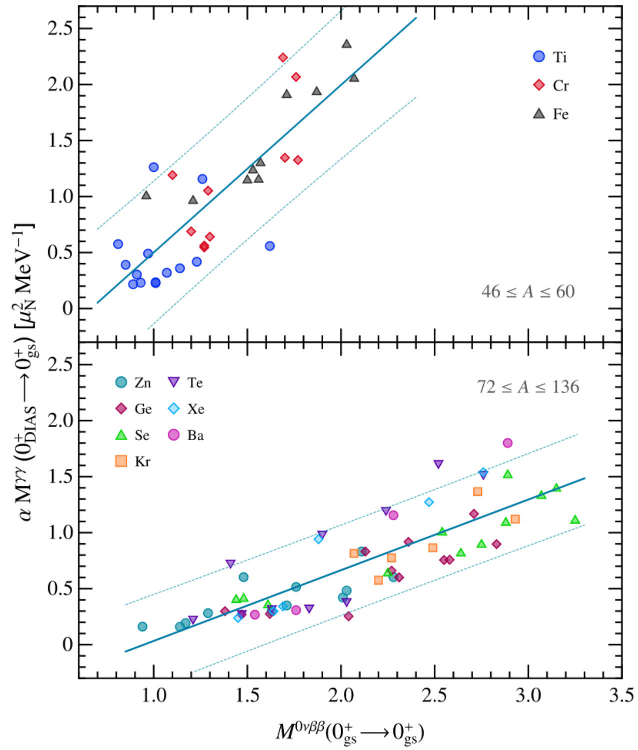
A pathway to unveiling neutrinoless $\beta\beta$ d… …rix elements via $\gamma\gamma$ decay

Beatriz Romeo[a,b,c,d,*], Damiano Strama… …néndez[b,c], Jose Javier Valiente-Dobón[e,g]

Beatriz Romeo and Javier Menendez



Double gamma decay

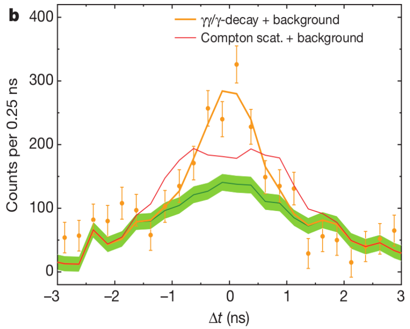


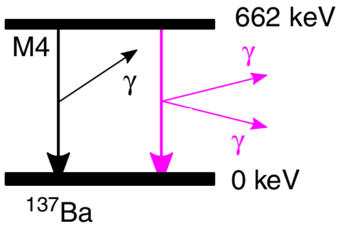
The double γ decay

In 2015, a Nature paper reported its observation in **competition with single-gamma decay** in ^{137}Ba:

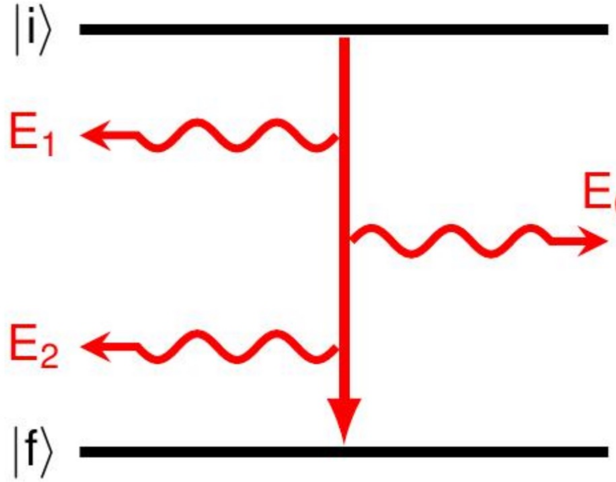
$\Gamma_{\gamma\gamma}/\Gamma_{\gamma} \approx 10^{-6}$

- Using **good time properties** of scintillators





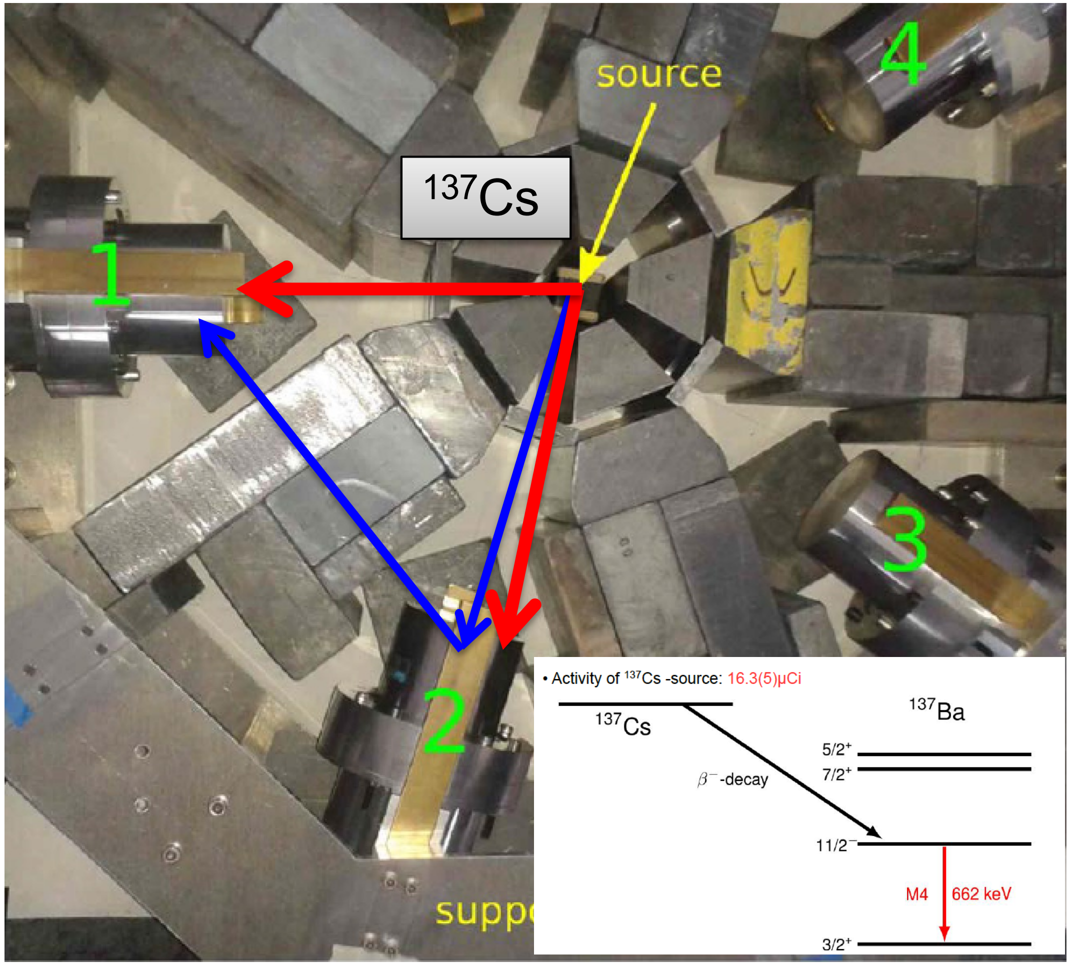
Second order EM



- The two-photon decay process is a second order process in quantum electrodynamics (QED) → excited nuclear state emits two gamma-ray energy-quanta of continuous energy
- Theoretically the γγ-decay process is treated as a second-order perturbation

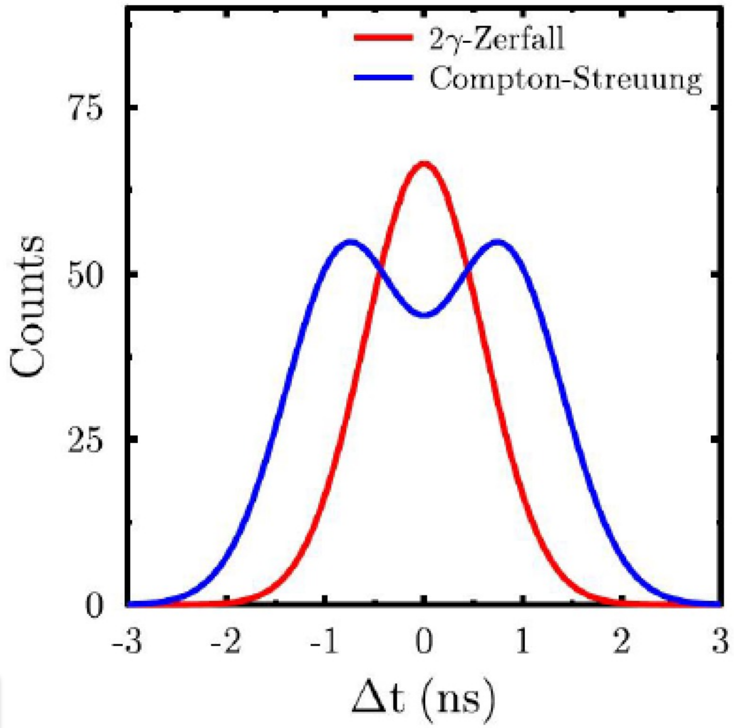
- $E_0 = E_1 + E_2$
- E_1, E_2 are continuous

Overcoming experimental challenges



- 5 detector pairs 72°
- 5 detector pairs 144°

Use of fast $LaBr_3$:Ce scintillators

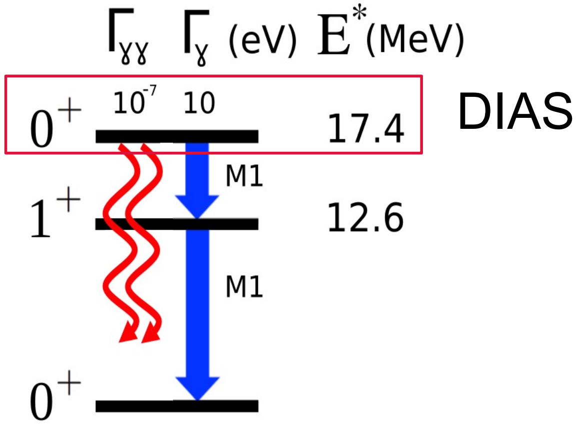


The time spectrum originates from a real double gamma decay and not from Compton scattering

Courtesy of N. Pietralla

DIAS candidates: ^{48}Ti

Best candidate: ^{48}Ti → mimic $0\nu\beta\beta$ ^{48}Ca decay



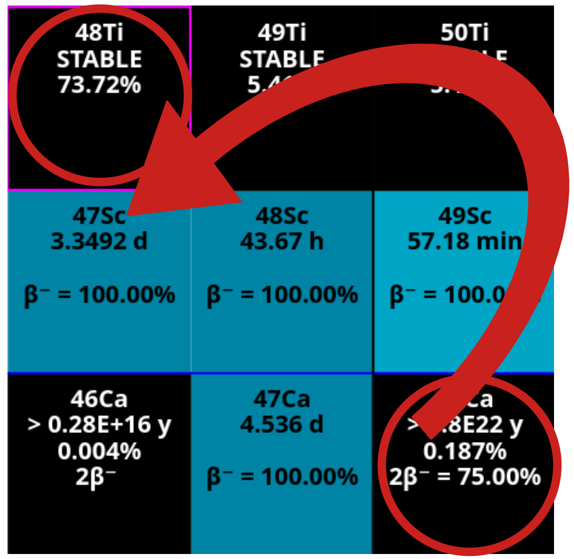
PROS

1) 2γ has the same initial and final states as in $2\beta0\nu$
2) The 17 MeV 0^+ **DIAS is known**
3) 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:

1) $\Gamma_{\gamma\gamma}$ / Γ_{tot} ≈ 10^{-8}

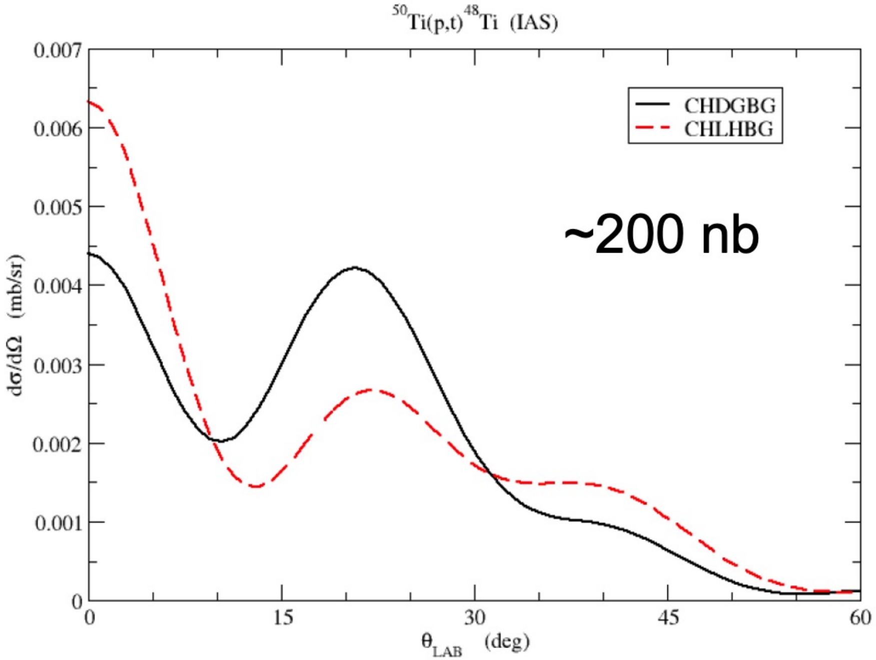


??

- How to populate efficiently the 0^+ (T=4)?
- How to be sensitive to the 2γ?

How to populate the DIAS - 2γ

^{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
…..



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

DCX ^{48}Ca(π+,π-)^{48}Ti

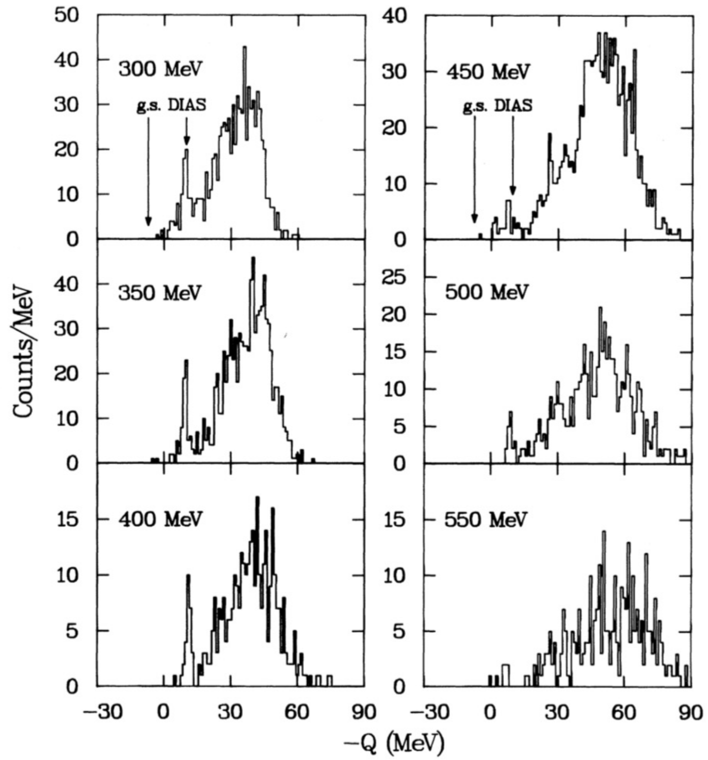


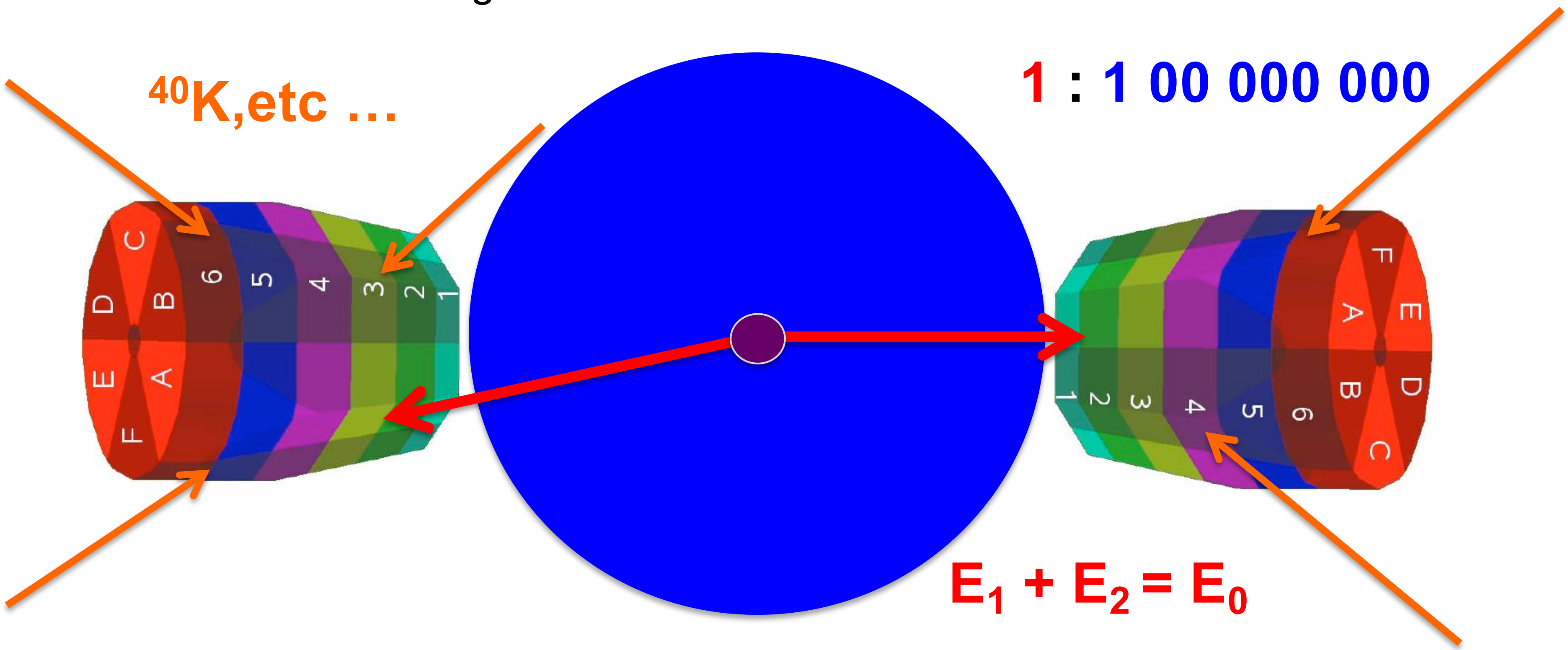
TABLE V. Results of using Eqs. (1) and (2) to calculate cross sections for ^{42,44,48}Ca averaged over 400–500 MeV.[a]

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)

Experimental challenges

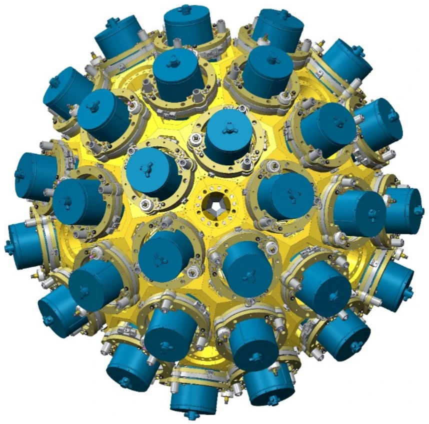
- The competitive γγ/γ decay process is at least seven/eight orders of magnitude smaller than the single gamma decay.
- Due to the nature of gamma radiation with matter, large probability to have a Compton effect that mimics the γγ/γ decay process $E_0 = E_1 + E_2$
- Two gamma rays with E_0 deposit partial energies → $\Sigma E_i = E_0$
- Gamma natural background



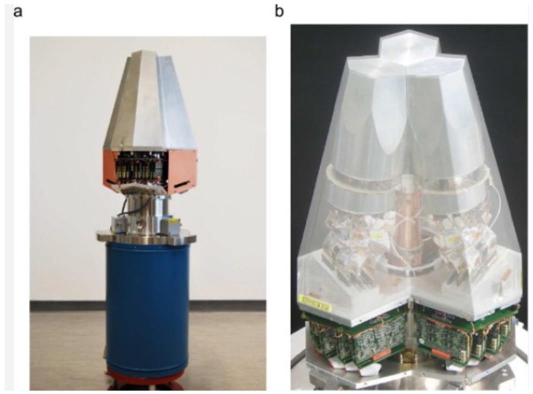
The AGATA spectrometer

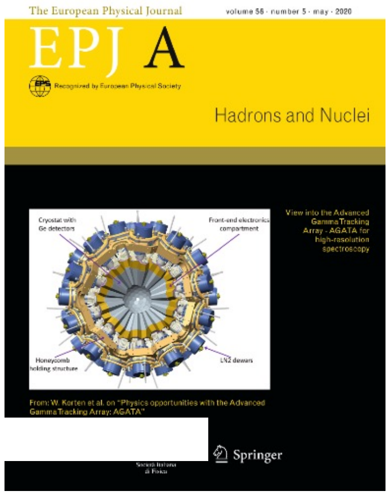
Advanced GAmma-ray Tracking Array

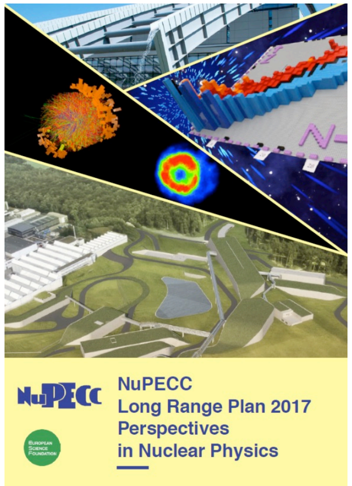
www.agata.org



- 180 (60 triple-clusters) crystals
- Germanium: 362 kg
- Solid angle: 82 %
- acquisition >50 kHz
- efficiency: 43% (M_γ=1)
- Angular resolution : ~1º





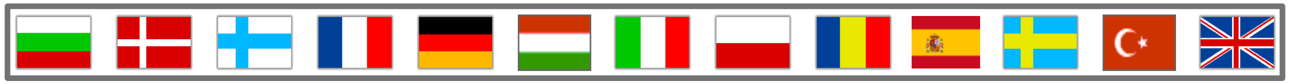


- AGATA technical paper: NIM A 668, 26 (2012).
- Topical Issue EPJA: https://epja.epj.org/component/toc/?task=topic&id=1878
- AGATA White Book: W. Korten et al, Eur. Phys. J. A (2020) 56:137.

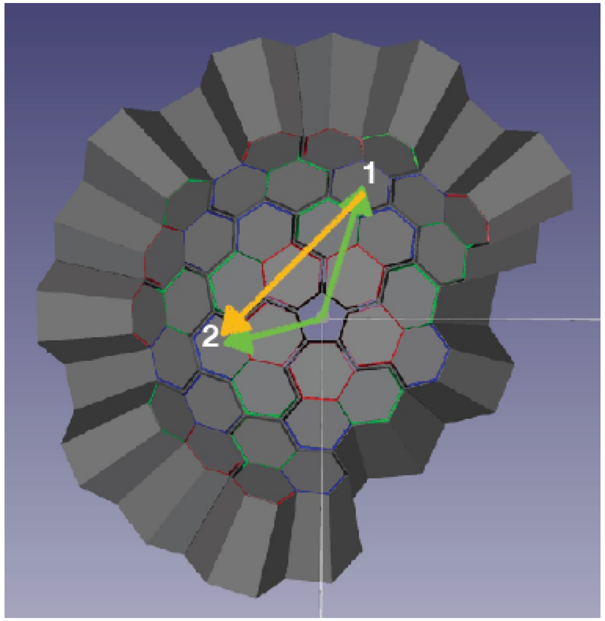
13 countries

41 institutions

~ 160 researchers

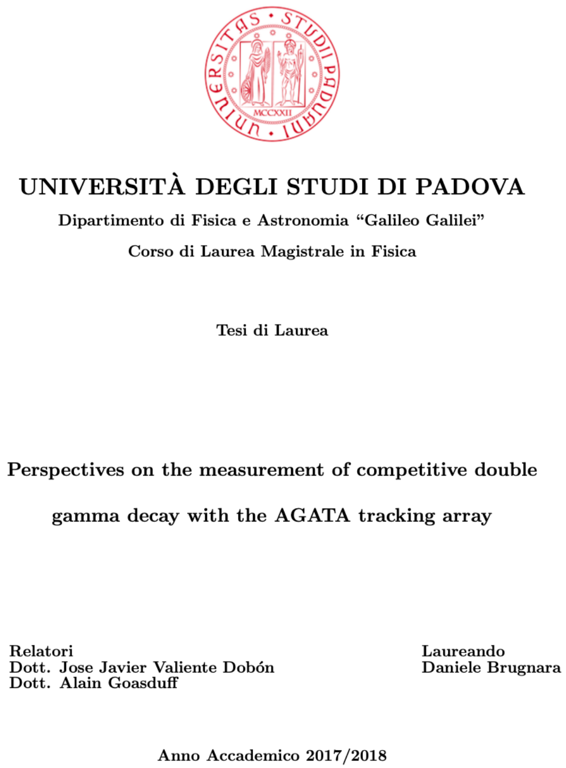


Double γ study with AGATA



Double gamma

Compton scattered


UNIVERSITÀ DEGLI STUDI DI PADOVA

Dipartimento di Fisica e Astronomia "Galileo Galilei"

Corso di Laurea Magistrale in Fisica

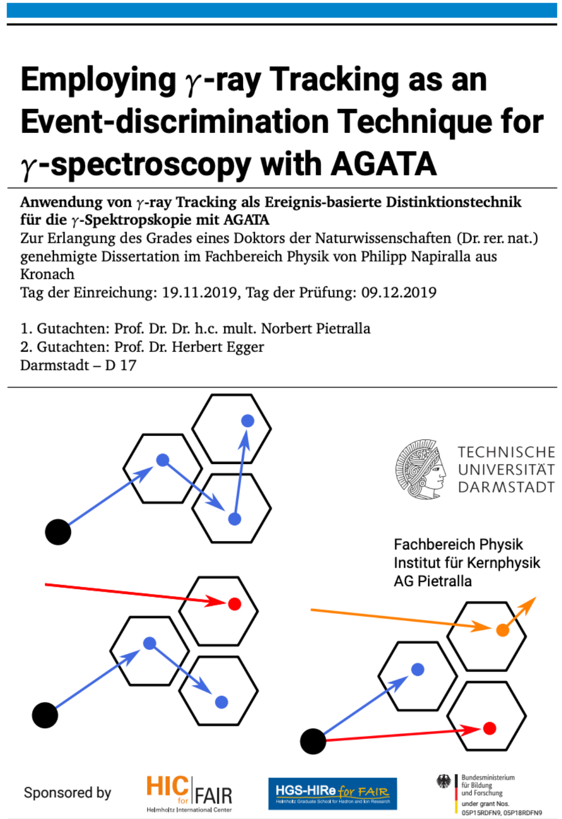
Tesi di Laurea

Perspectives on the measurement of competitive double gamma decay with the AGATA tracking array

Relatori
Dott. Jose Javier Valiente Dobón
Dott. Alain Goasduff

Laureando
Daniele Brugnara

Anno Accademico 2017/2018


Employing γ-ray Tracking as an Event-discrimination Technique for γ-spectroscopy with AGATA

Anwendung von γ-ray Tracking als Ereignis-basierte Distinktionstechnik für die γ-Spektropskopie mit AGATA
Zur Erlangung des Grades eines Doktors der Naturwissenschaften (Dr. rer. nat.)
genehmigte Dissertation im Fachbereich Physik von Philipp Napiralla aus Kronach
Tag der Einreichung: 19.11.2019, Tag der Prüfung: 09.12.2019

1. Gutachten: Prof. Dr. Dr. h.c. mult. Norbert Pietralla
2. Gutachten: Prof. Dr. Herbert Egger
Darmstadt – D 17

TECHNISCHE UNIVERSITAT DARMSTADT

Fachbereich Physik
Institut für Kernphysik
AG Pietralla

Sponsored by HIC for FAIR HGS-HIRe for FAIR

Increasing the experimental position resolution, as well being able to recognize multiple hits within the same segment could be crucial for future measurements.

Double γ study with Scintillators

Phys. Lett. B 860 (2025) 139186

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journal homepage: www.elsevier.com/locate/physletb

Letter

A pathway to unveiling neutrinoless $\beta\beta$ decay nuclear matrix elements via $\gamma\gamma$ decay

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[b] Departament de Física Quàntica i Astrofísica, Universitat de Barcelona, 08028, Barcelona, Spain
[c] Institut de Ciències del Cosmos, Universitat de Barcelona, 08028, Barcelona, Spain
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[e] Laboratori Nazionali di Legnaro, Istituto Nazionale di Fisica Nucleare, 35020, Legnaro, Italy
[f] Dipartimento di Fisica e Astronomia, Università degli Studi di Padova, 35121, Padova, Italy
[g] Instituto de Física Corpuscular, CSIC-Universidad de Valencia, 46980, Valencia, Spain

UNIVERSITÀ DEGLI STUDI DI PADOVA

Dipartimento di Fisica e Astronomia "Galileo Galilei"

Master Degree in Physics

Final Dissertation

Feasibility study of the competitive double-gamma decay measurement

Thesis supervisors
Dr. José Javier Valiente-Dobón
Dr. Matus Balogh

Candidate
Damiano Stramaccioni

Academic Year 2022/2023

Competing processes: IPC & ɣ-cascade

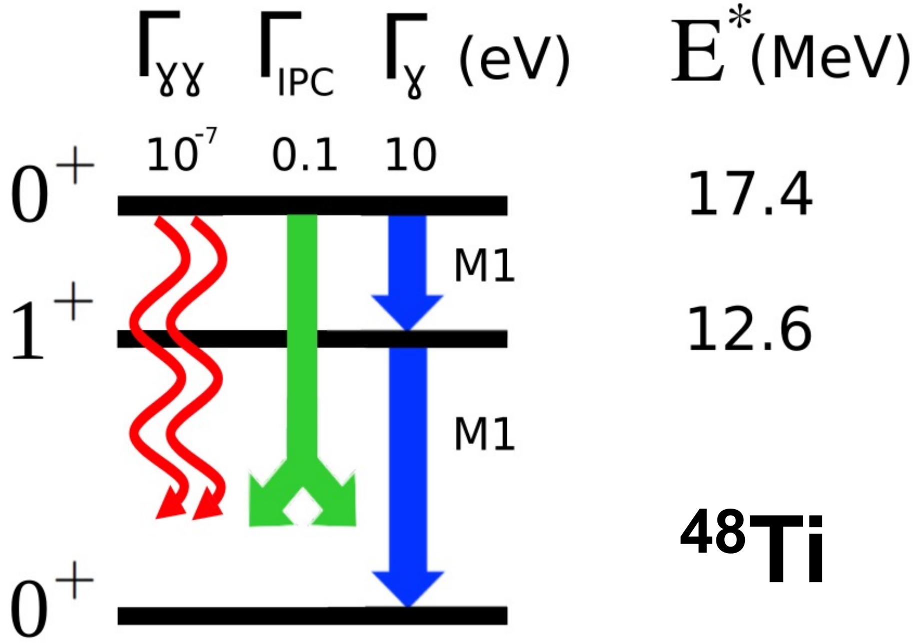
We could extract the **BR** simply measuring how many **2ɣ-decay events are observed**, but two main **competing processes** can mimic them:

- **Internal Pair Creation (IPC)**, i.e. simultaneous emission of an e^-e^+ pair carrying the full transition energy.

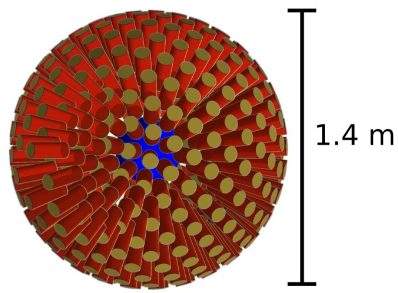
$$\Gamma_{\gamma\gamma}/\Gamma_{IPC} \approx 10^{-6}$$

- **ɣ-cascade**, i.e. 2ɣ cascade through an intermediate state. Theoretical calculations predict most of the intensity to go to the 12.6 MeV state.

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



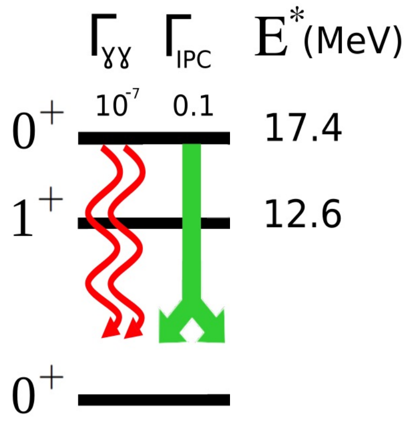
- 302 3.5”x8” cylindrical $LaBr_3$ in spherical configuration
- ΔT = 880 ps
- Detector face is 50 cm from target
-
- Reaction chamber: radius 17cm, 2mm thick

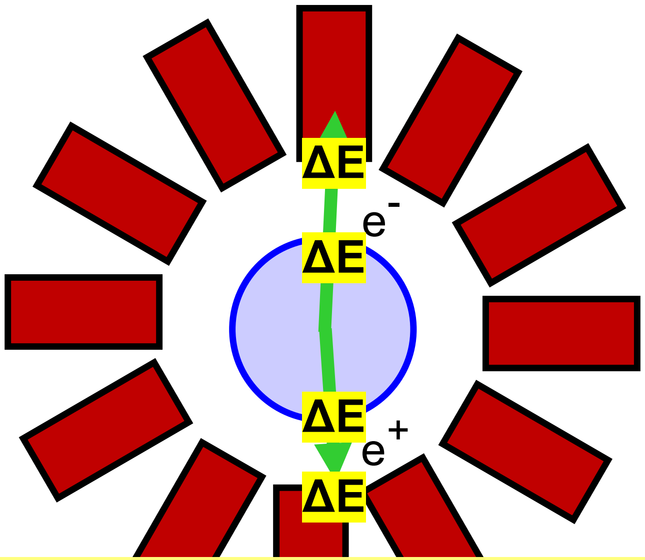


Competing processes: IPC

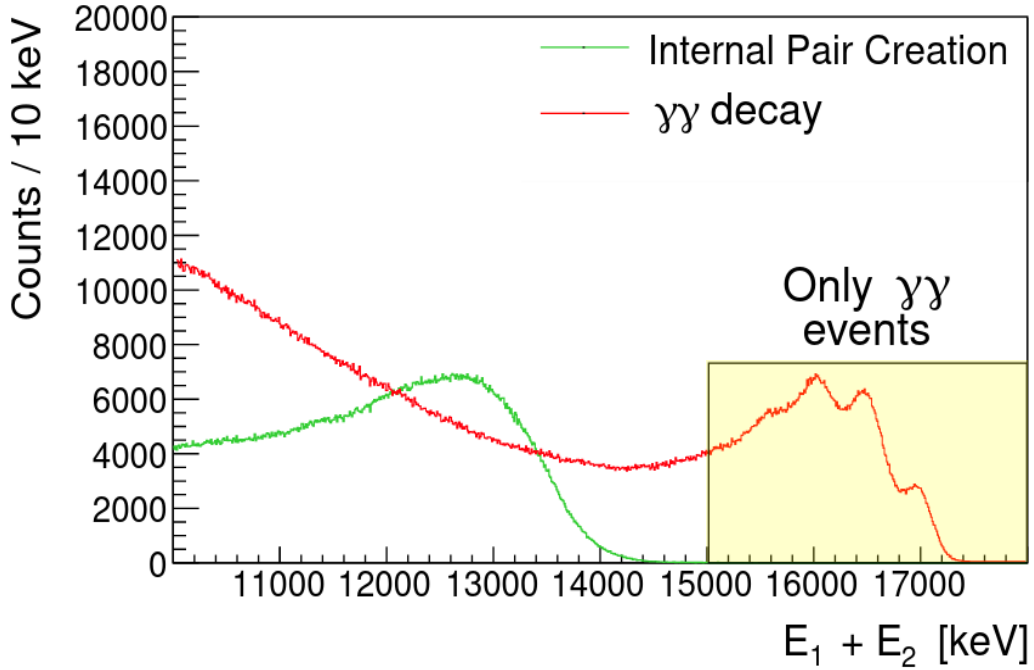
- **IPC**: e^+/e^- charged particles, we expect a total energy loss
  - **ΔE ≈ 2 MeV in scattering chamber + detector capsule**

➡ For **multiplicity 2 events** the energy **E_1+E_2** spectra they deposited in the array are quite different



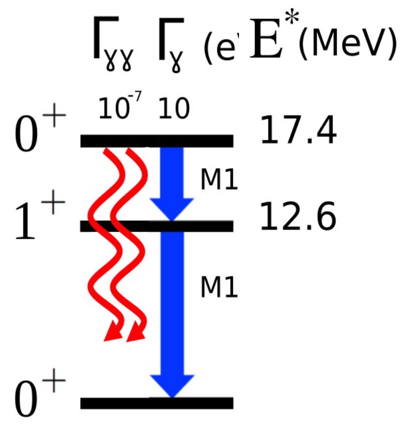


We can remove these events with an **energy threshold E_1+E_2 > 15 MeV**

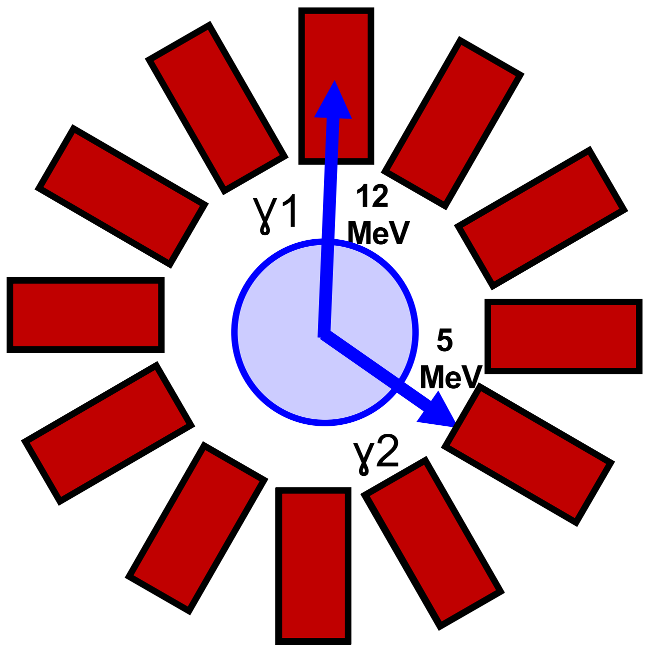


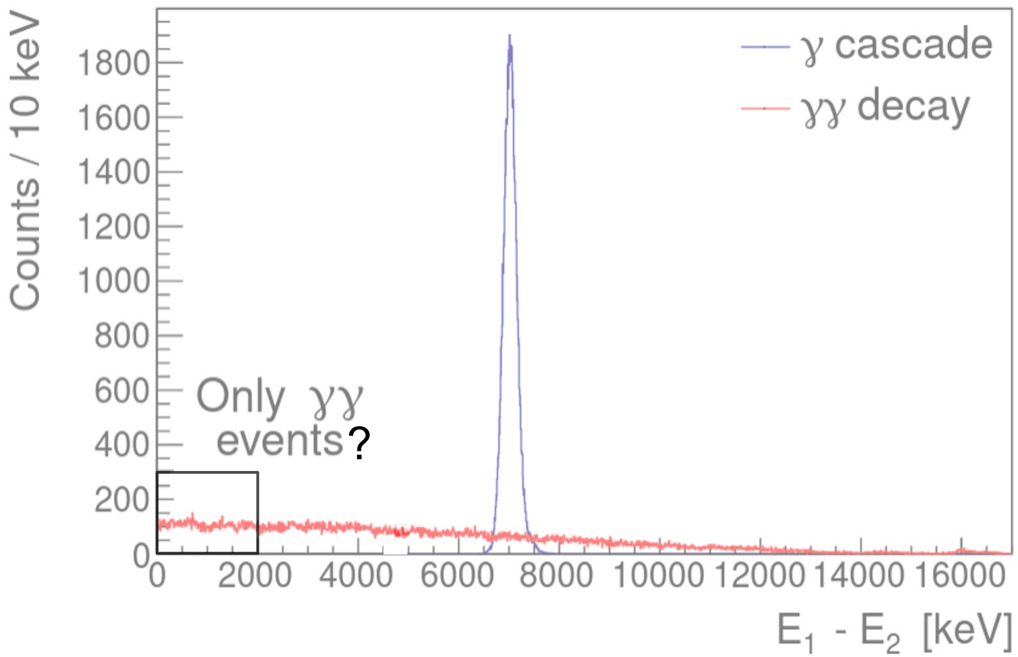
Competing processes: γ-cascade

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



➡ 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: IPC & γ-cascade

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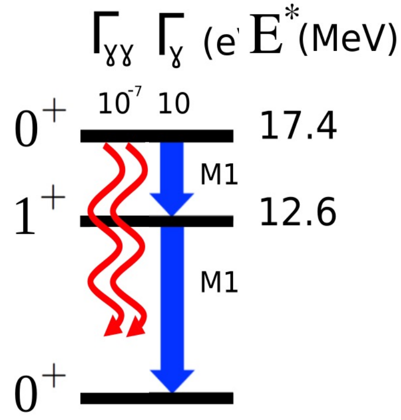
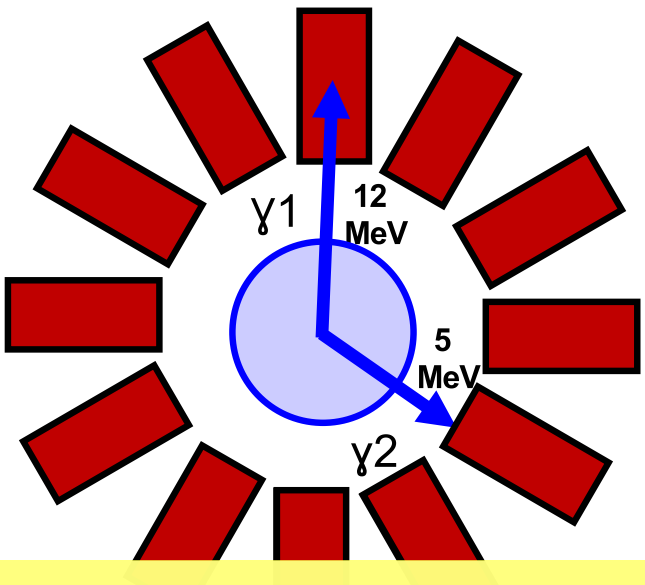
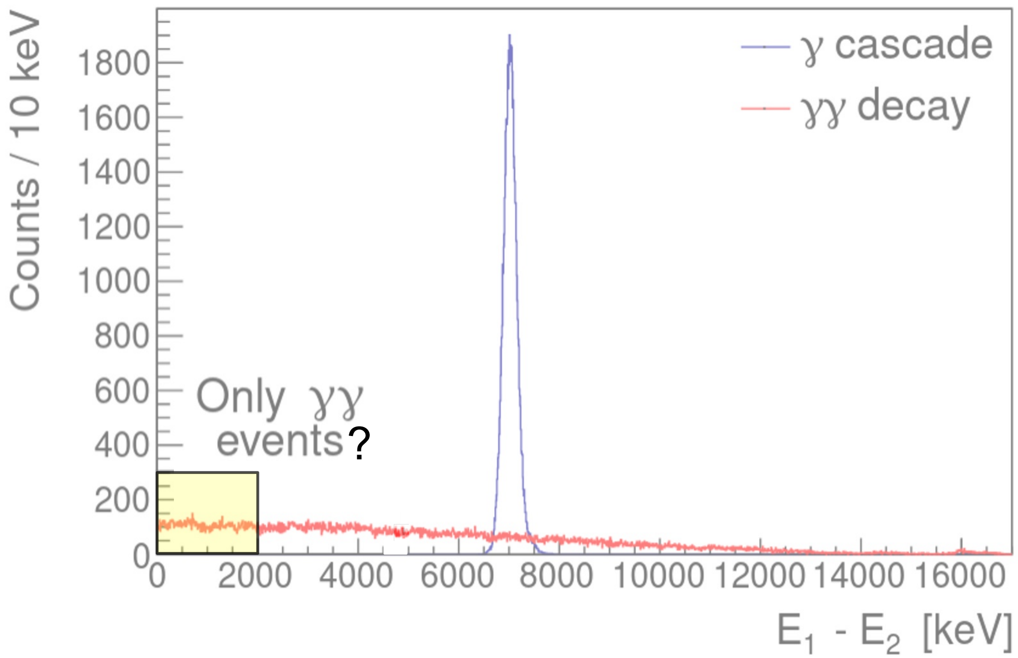


➡ For **multiplicity 2 events** and **setting an energy gate E_1+E_2 > 16.9 MeV, the energy difference E_1-E_2** spectra are quite different





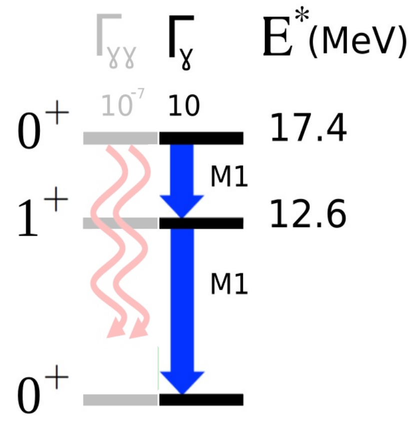
We can remove these events setting an **energy limit E_1 - E_2 < 2 MeV**

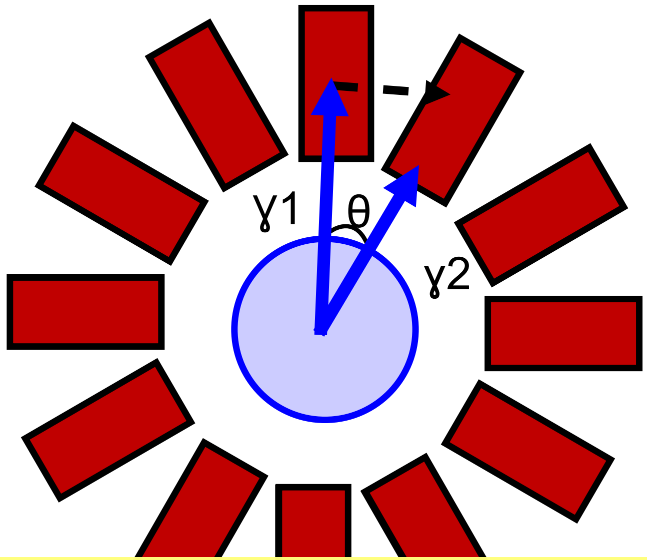
➡ **We are only interested in those!**

Competing processes: ɣ-cascade issues

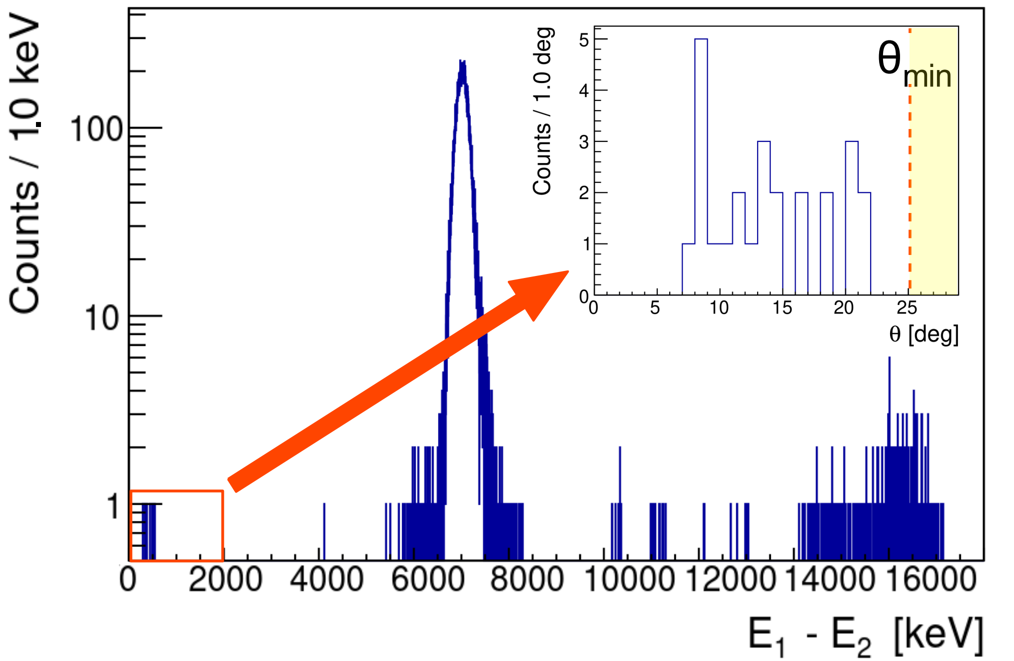
- **Problem with ɣ-cascade**: if **2ɣ correlation angle is low,** the 12.6 MeV gamma can deposit **8.7 MeV in one detector,** scatter on it and deposit **the rest where the other gamma hit**

➡ **Fake 2ɣ events!**





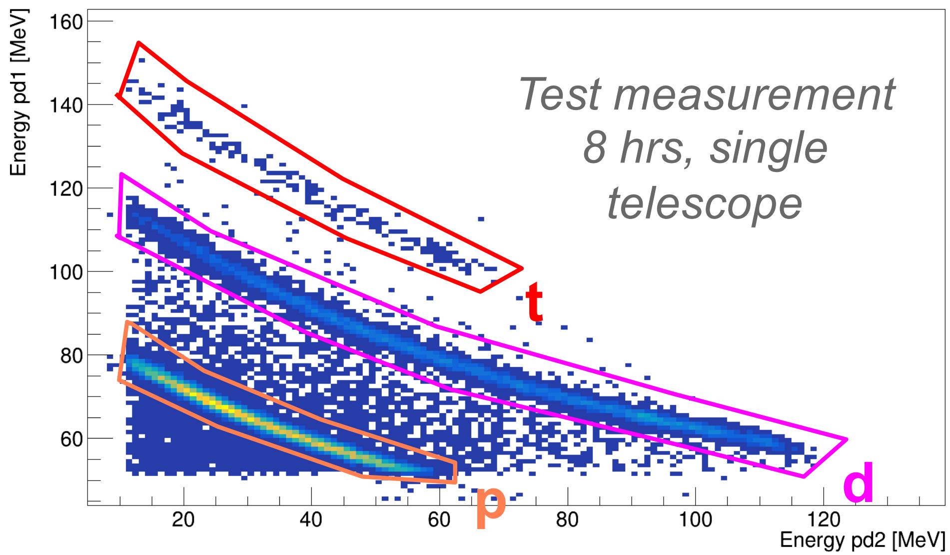
We can remove these events setting an **angle limit θ > 25°**



Test measurement @ CCB

Centrum Cyklotronowym Bronowice IFJ PAN

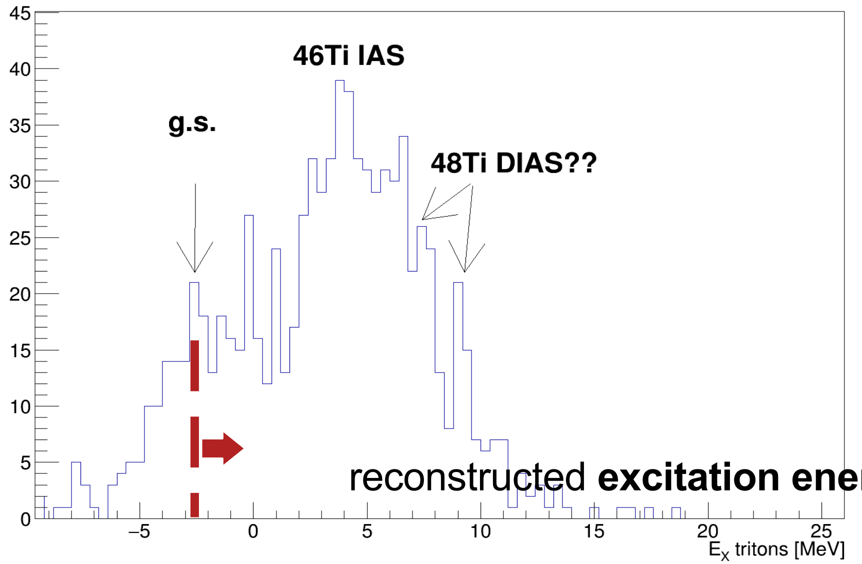
8 hrs test measurement in non-ideal conditions



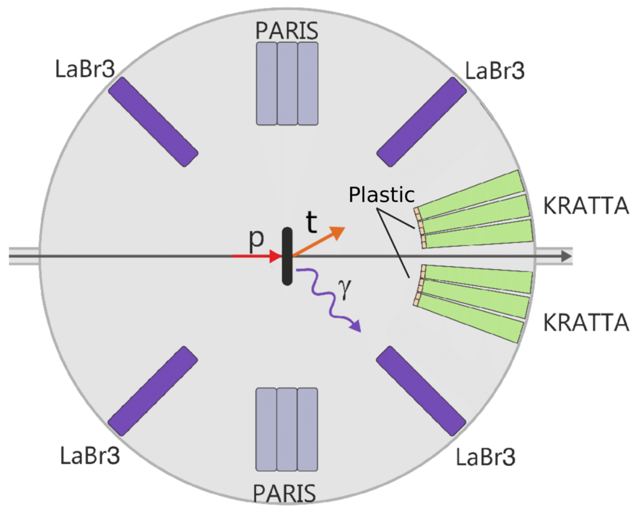
- **Beam**: E=180 MeV and I= 0.4 nA
-
- **Target**: 100 mg/cm^2 of ^{50}Ti (60%)

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

Results consistent with expectations



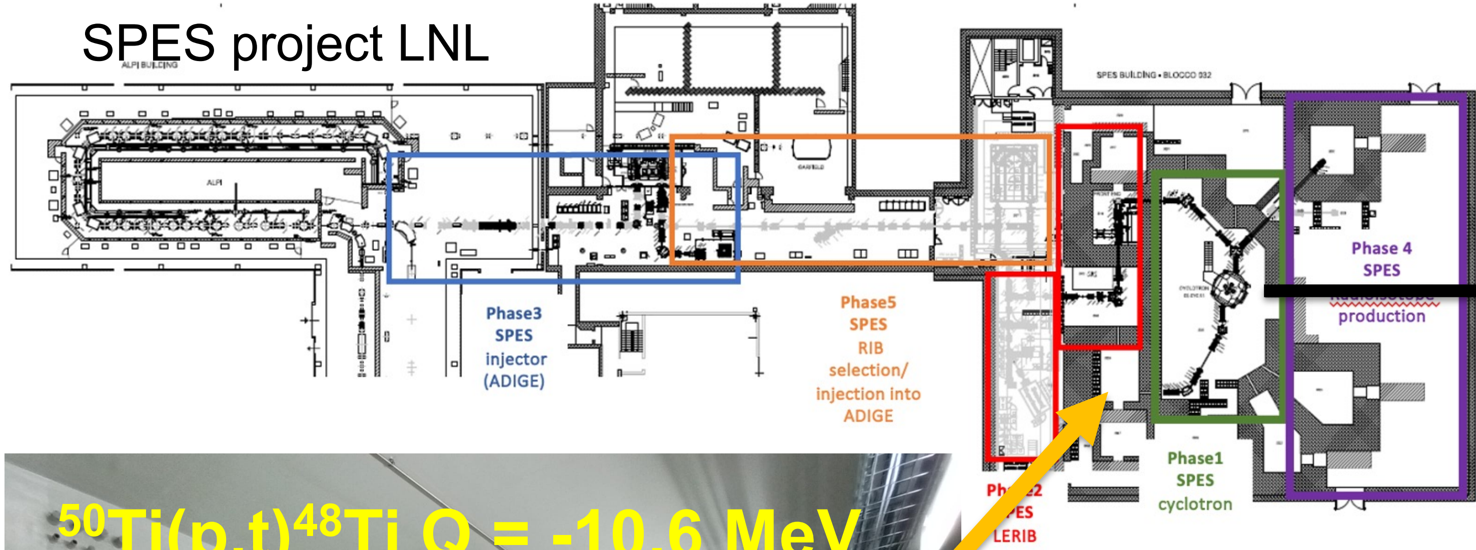
reconstructed **excitation energy** spectrum



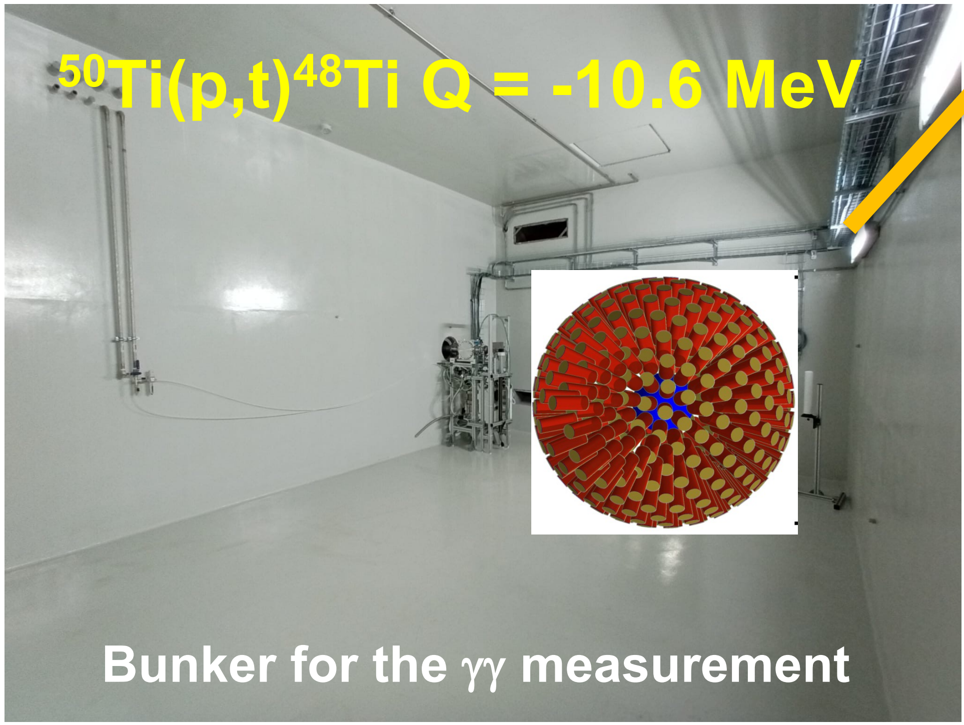
Experimental setup @ SPES

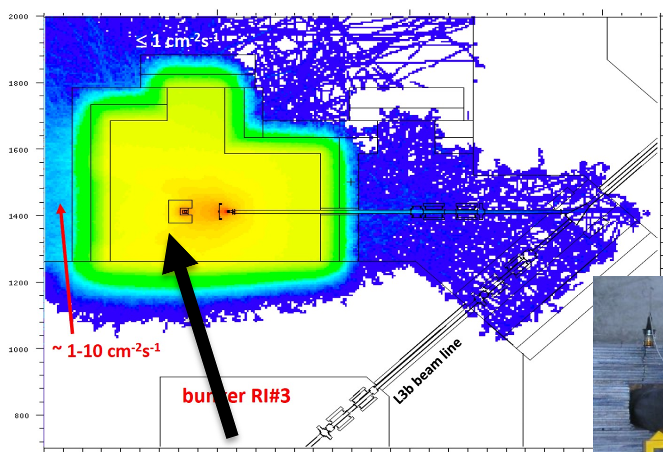
Italy

SPES project LNL



SPES Cyclotron → 40-70 MeV – up to 200 μA of **protons**

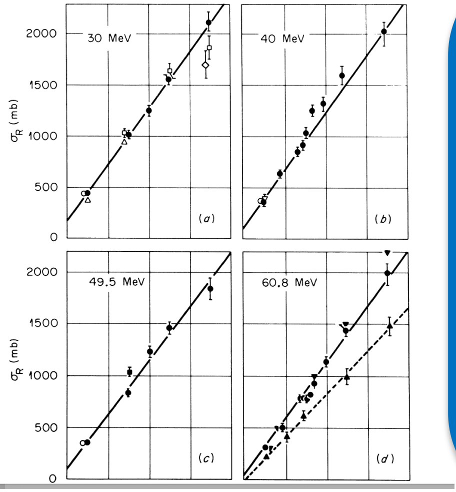




Parafine borate

Beam dump

Large experimental challenges!

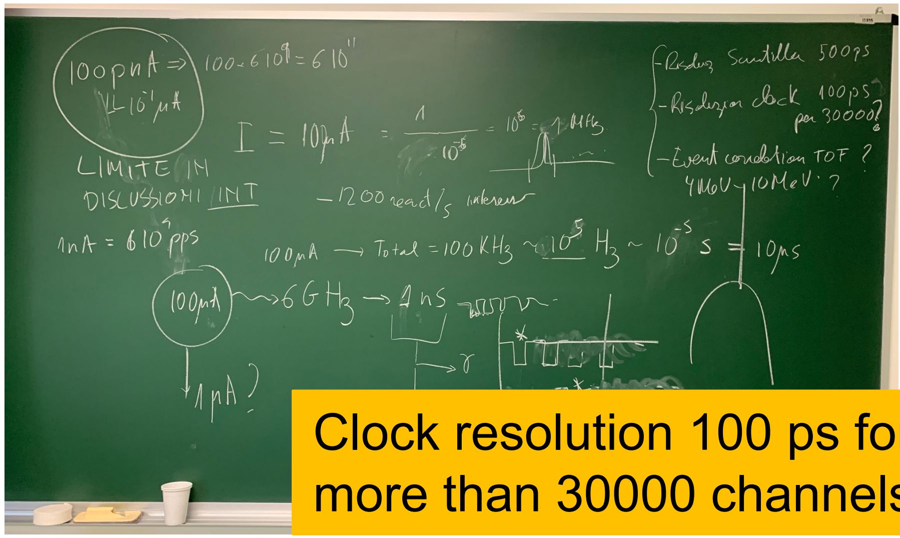


D. Stramaccioni

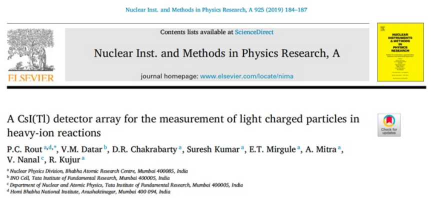
F. Simioni

Total XS = 900 mb

XS $_{\text{(DIAS/ALL)}}$ ~ 10^{-7}



Clock resolution 100 ps for more than 30000 channels!!



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

P.C. Rout, V.M. Datar, D.R. Chakrabarty, Suresh Kumar, E.T. Mirgule, A. Mitra, V. Nanal, R. Kujur

CsI detectors for **trition identification**

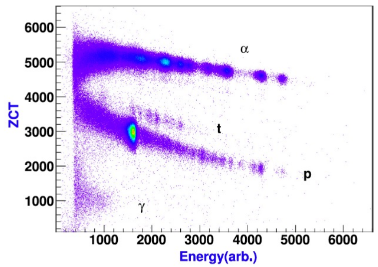

Fig. 4. A 2D spectrum between the ZCT and the energy of CsI(Tl) detector which shows the particles emitted in the ^{12}C + ^{12}C reaction are well separated by the pulse shape discrimination technique.

Summary

- Double-gamma decay process can help on the NME of 0vββ?
  - Experimental study of DIAS double gamma decay
  - Theoretical description → correlation $\gamma\gamma$ and 0vββ
- Observation of the competitive double gamma decay using LaBr:Ce
- Semiconductor detectors like HPGe AGATA might not be the best candidates for the search due to limits in PSA at the 10^{-6} level.
- Scintillators (highly efficient) might be the best experimental setup – Initial preparatory studies ongoing. Genesis.
- Perform the preparatory experiments: determine experimentally the cross sections to populate the DIAS, etc.

END