EXTENDING GEANT4 "RADIOACTIVE DECAY" FOR THE ANALYSIS OF COMPLEX TOTAL ABSORPTION ANALYSIS CASES

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Use of G4 in Nuclear Physics

- Design and Optimization
  - Best geometry and materials, e.g. R^3B-CALIFA
  - Best configuration, e.g. PRESPEC / AGATA
- Data Analysis
  - Aid the data analysis process, e.g. particle ID plots
  - Key factor in data analysis, e.g. efficiency calculation, data unfolding.

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Outlook of the talk

- Introduction: beta decay measurements
- The TAS inverse problem
- Beta decay of ^{186}Hg
- Summary and Conclusions

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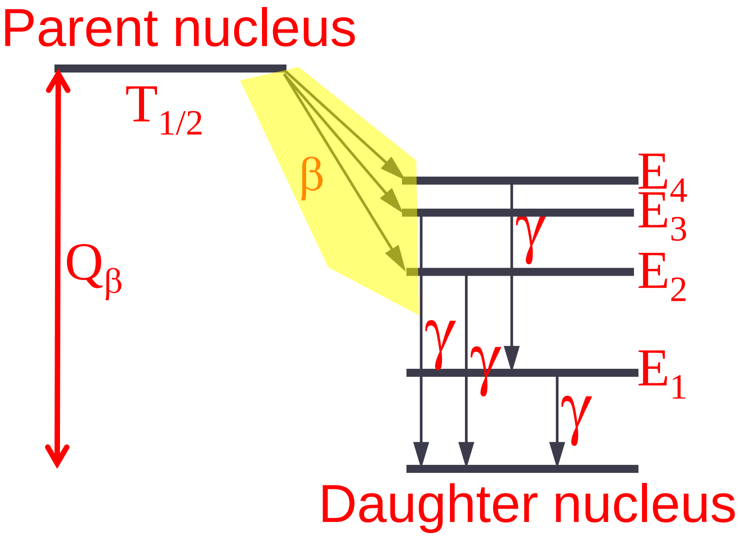
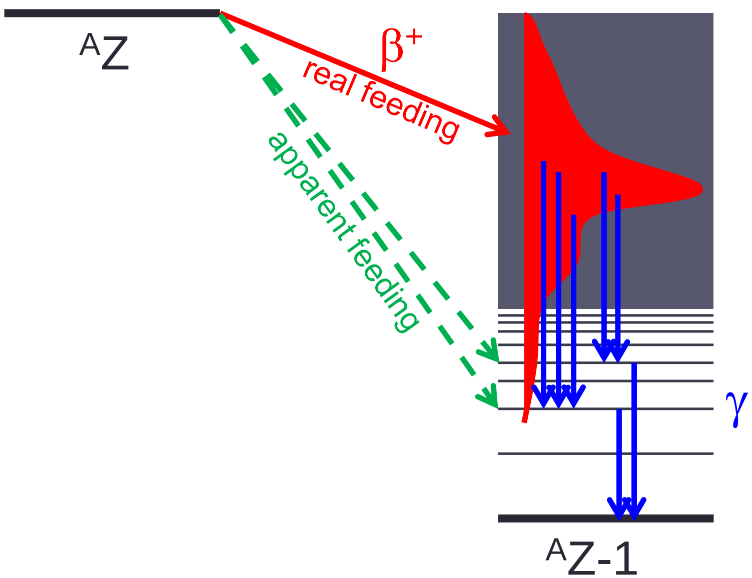
Beta decay measurements

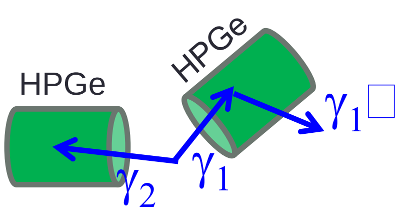
- β-decay is an important source of nuclear structure information.
- From direct measurements one can obtain half-lives, energy levels, Q_β-values (masses), beta intensity distributions (β feeding)…

- Measuring the β feeding distribution is far from being trivial!!



Beta decay measurements





- Medium mass and heavy nuclei: large level density at high energy.
- Very fragmented feeding distr. and γ-deexcitation pattern.
- HPGe arrays fail to detect systematically the upper part of the γ-cascade resulting in a wrong feeding and B(GT) distr.

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THE ESSENTIAL DECAY OF PANDEMONIUM: A DEMONSTRATION OF ERRORS IN COMPLEX BETA-DECAY SCHEMES

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CERN, Geneva, Switzerland

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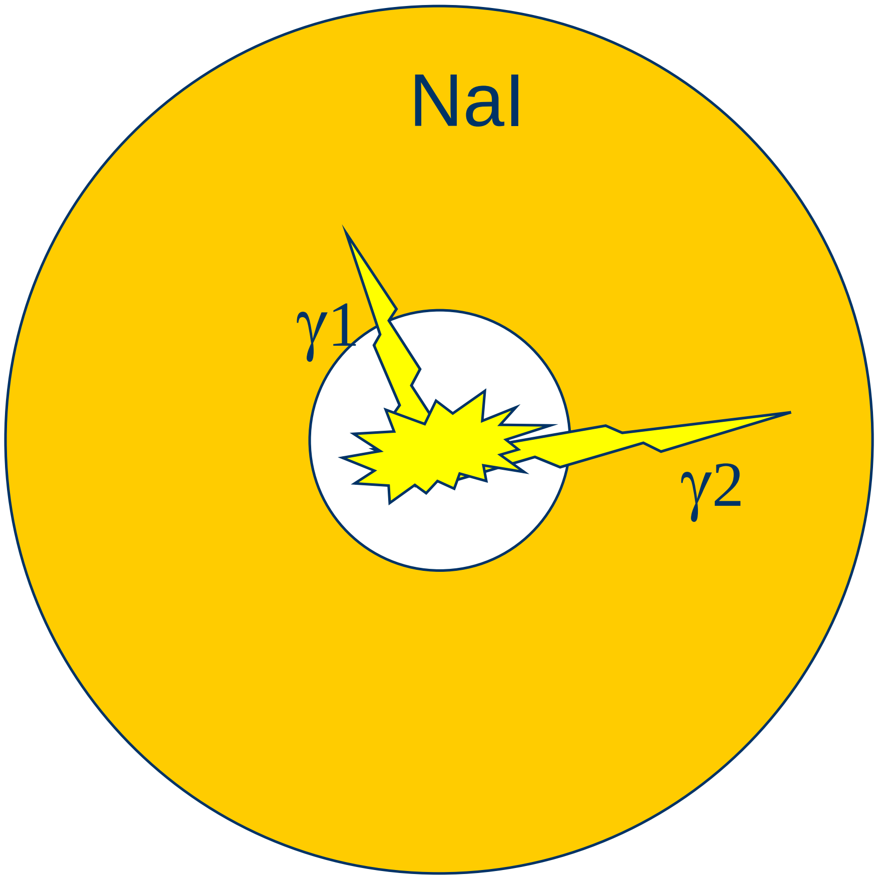
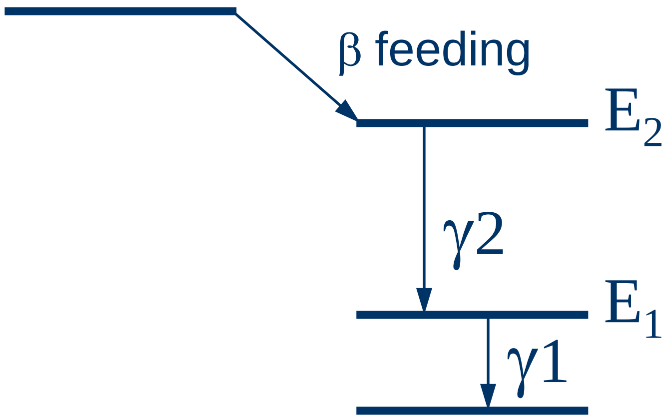
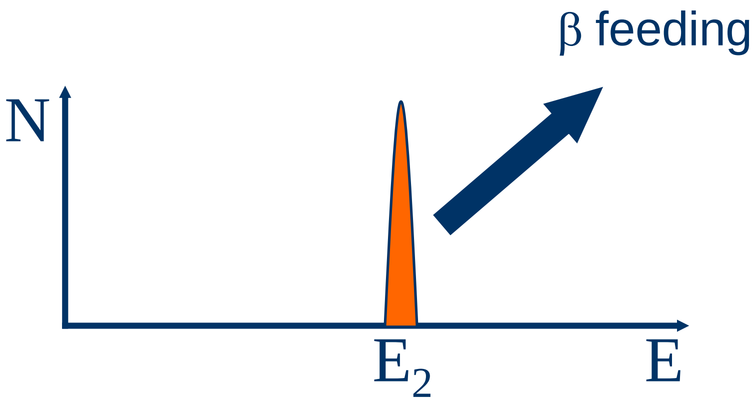
Obviously our results have wider implications than simply to the decay of ^{145}Gd. Every complex β-decay scheme that is based on γ-ray peak analysis and intensity balances must now be regarded as doubtful. In such schemes, the β-decay feeding to each level is assumed to be the difference between the total γ-ray intensity depopulating the level and that seen feeding it. If significant γ-ray intensity remains unobserved, these differences are incomplete and the derived β-decay branching ratios, for all but the strongest transitions, could be wrong by orders of magnitude. In discrediting the "measured" ft values for most β-transitions in complex decay schemes, this conclusion reflects on a large body of existing data, and surely indicates the need to reevaluate the usefulness of a whole class of experiments.

Total Absorption Spectroscopy (TAS)

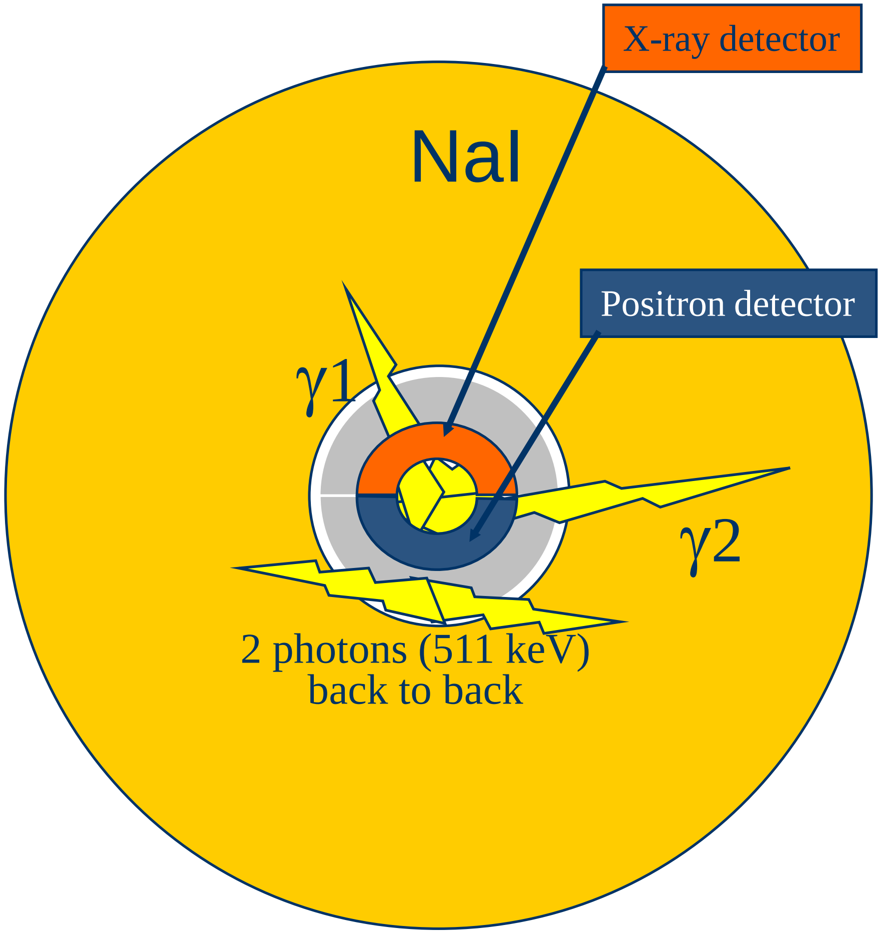


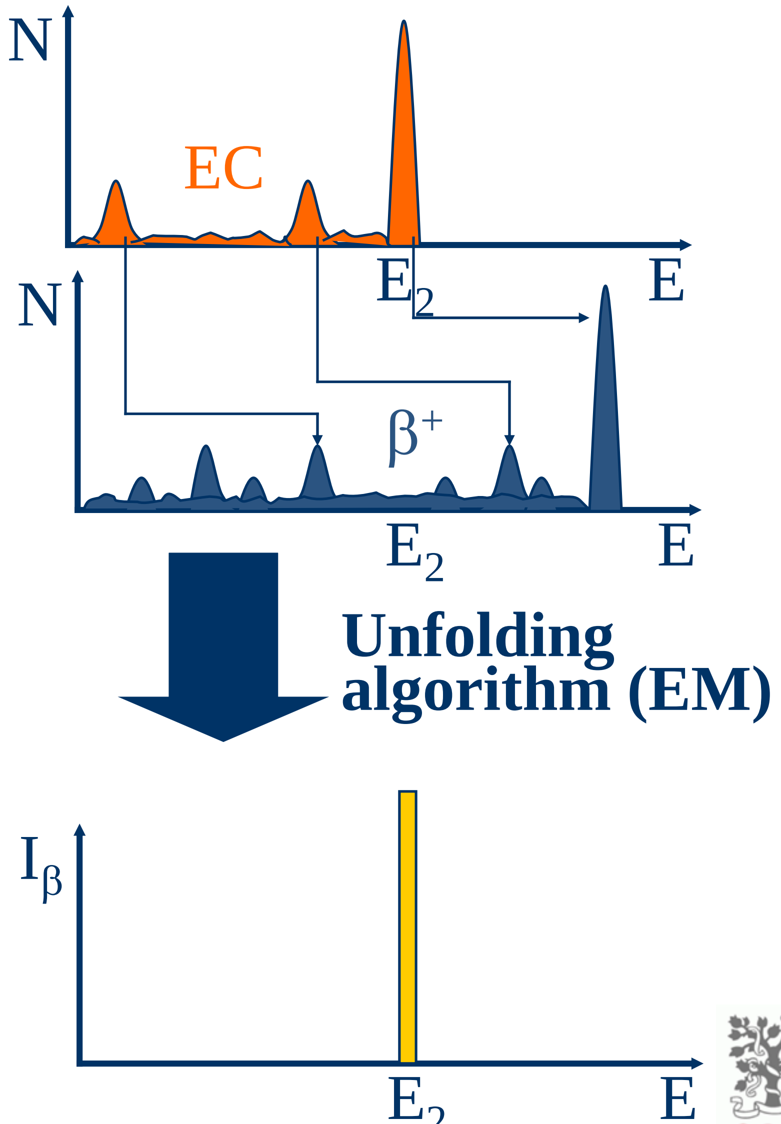




Ideal case

Total Absorption Spectroscopy (TAS)





Real case

The TAS Inverse Problem

- The number of counts detected in channel j relates to the beta feeding to level i through the linear equation:

$$d_j = \sum_i R_{ij} f_i$$

f_i : Feeding to energy level *"i"*

d_j : Counts in channel *"j"* of the spectrum

R_{ij} : Response Function (matrix) to the decay

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The TAS Inverse Problem

No way to measure R_{ij}!!

The only possibility is calculate it using MC simulations: *Geant4*

...nel j relates to the ...equation:

- We can then use the EM algorithm to unfold the data:

$$f_i^{(k)} = \sum_j \frac{R_{ij} f_i^{(k-1)}}{\sum_m R_{mj} f_m^{(k-1)}} d_j \quad , \quad i = 1, \; 2 \ldots m$$

Calculation of R_{ij} from individual γ's and β's: D. Cano, J.L. Taín, NIM A430 (1999) 333

Study of the EM and others applied to TAS: J.L. Taín, D. Cano, NIM A571 (2007) 728

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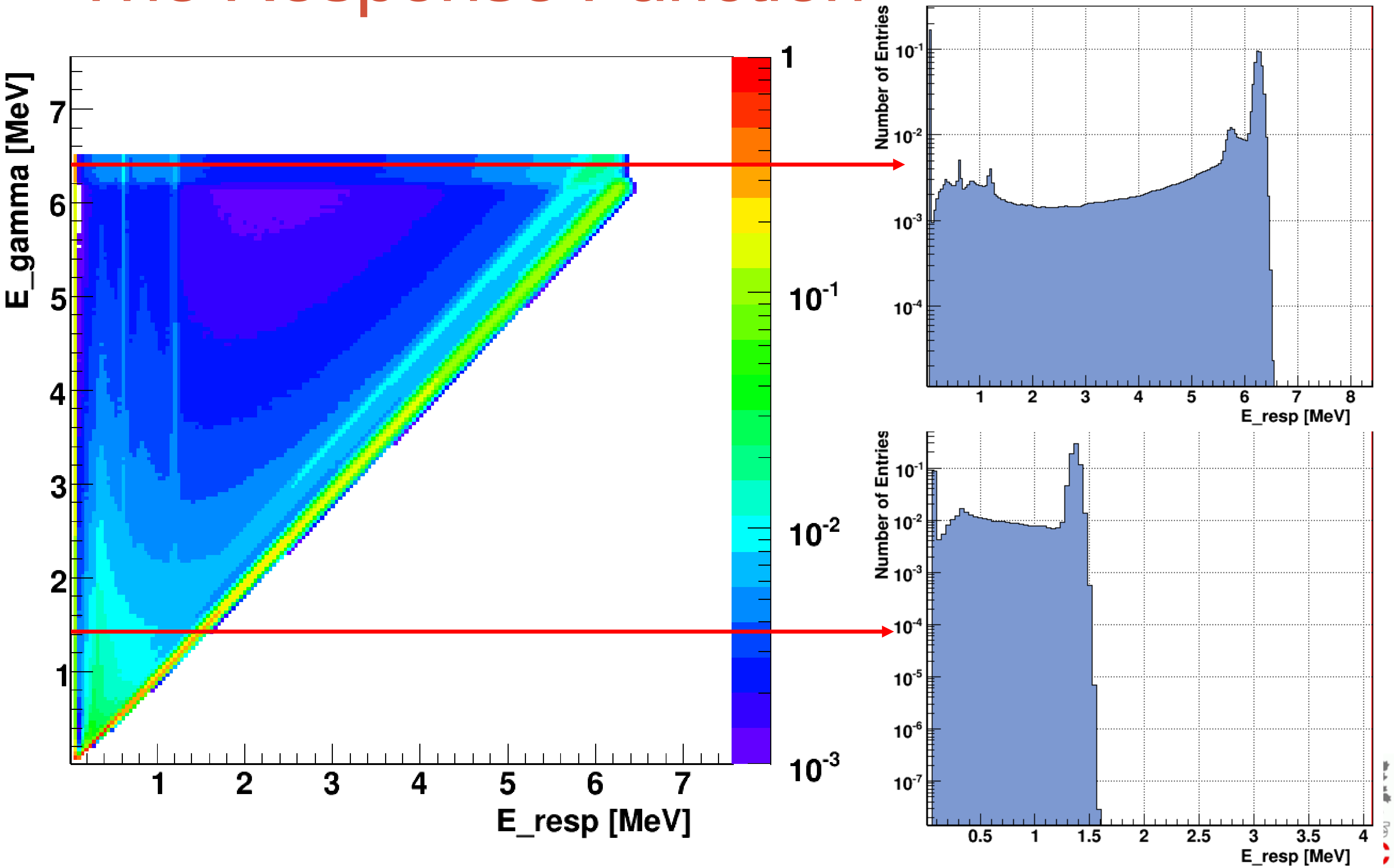
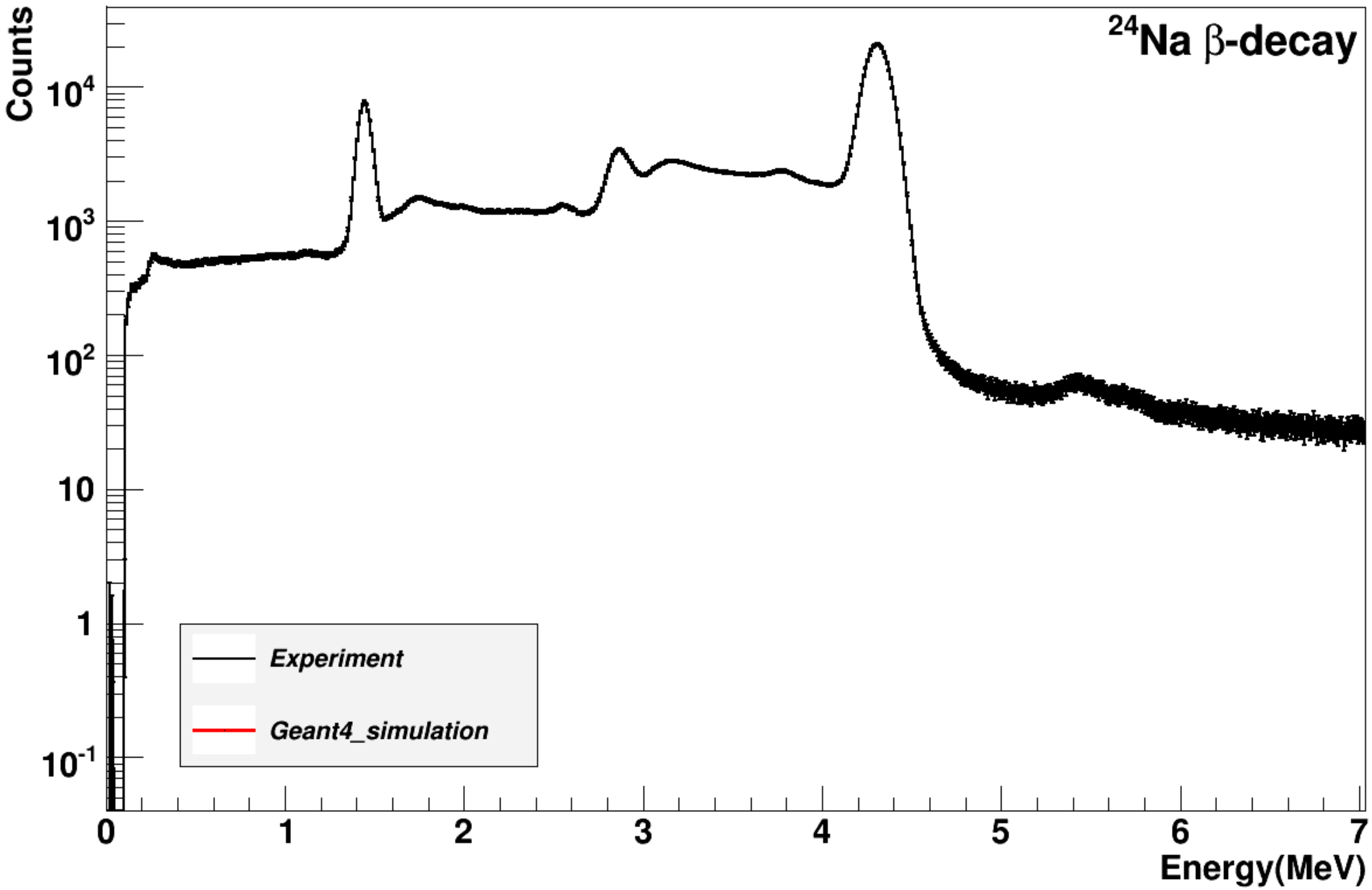
The Response Function

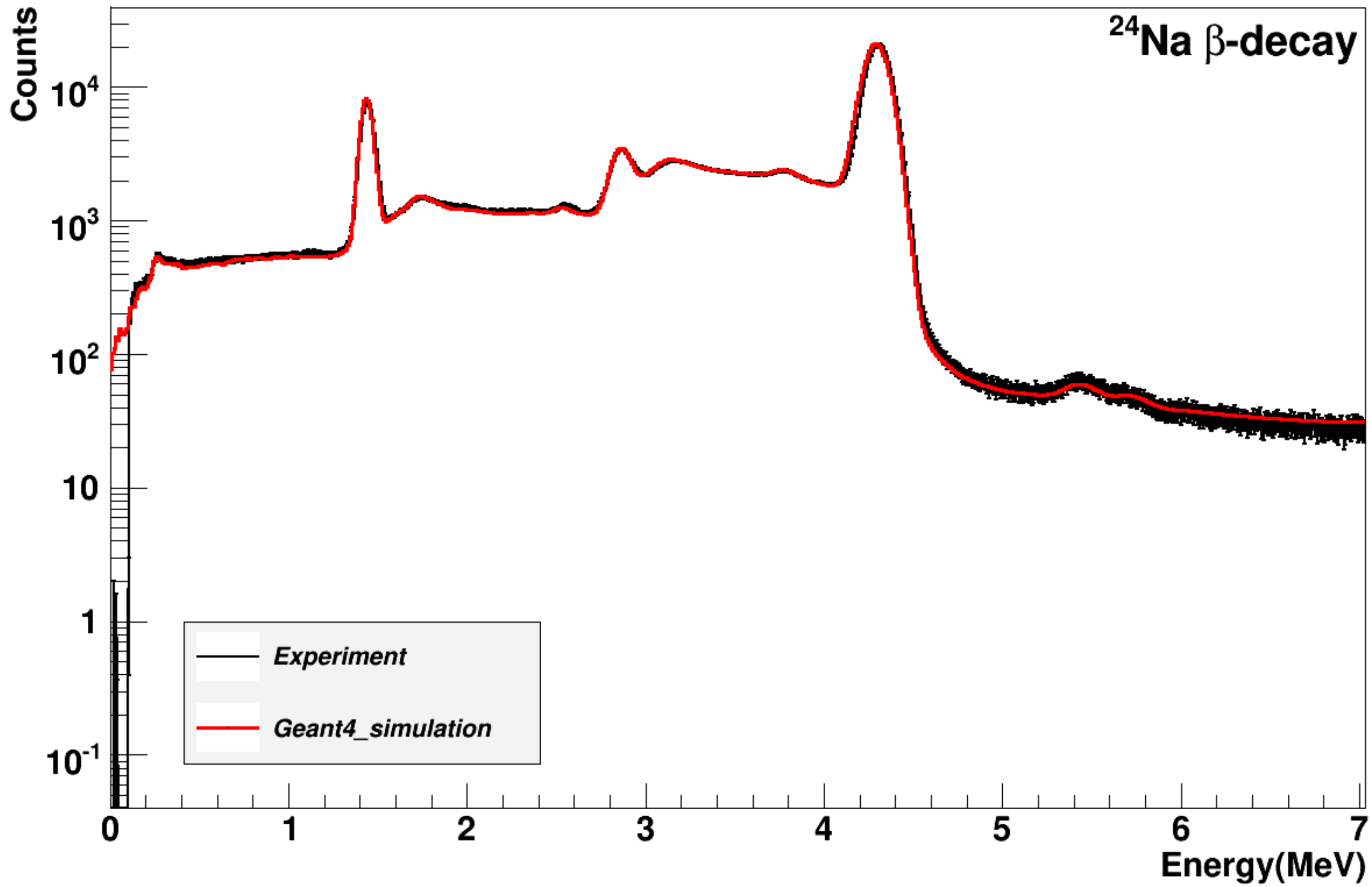


The Response Function



β-decay of ^{24}Na: test bench for our simulations

The Response Function



β-decay of ^{24}Na: test bench for our simulations

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Study case: ^{186}Hg decay

Statistical model:

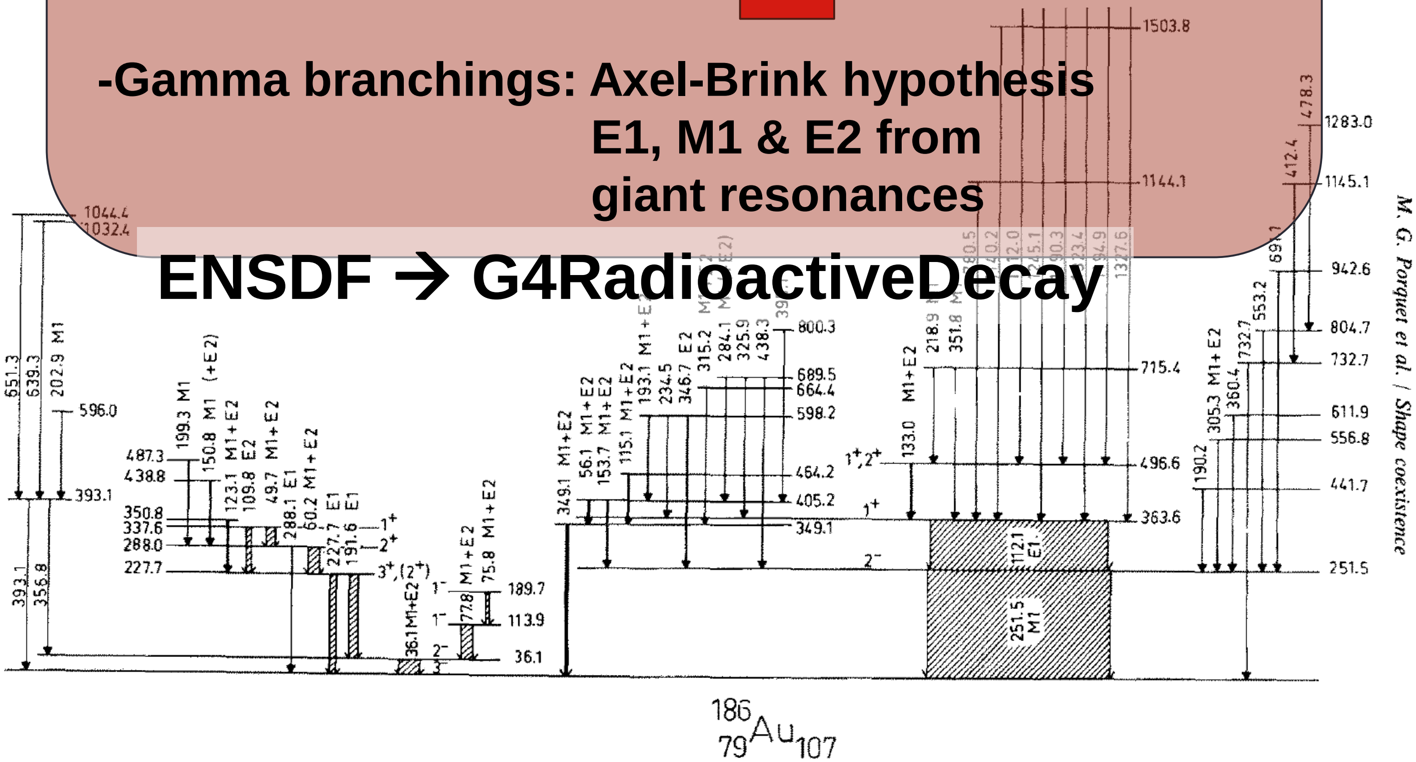
-Level densities: Goriely et al. Phys. Rev. C, 78 (2008)
HFB + combinatorial (RIPL3)
320 positive parity levels 1-3 MeV

-Gamma branchings: Axel-Brink hypothesis
E1, M1 & E2 from
giant resonances

$^{186}_{80}Hg_{106}$ 0+

$Q_b = 3230(140)$

ENSDF → G4RadioactiveDecay



Event generator including the ‘unknown’ part: D. Jordán *et al.*, NIM A828 (2016) 52

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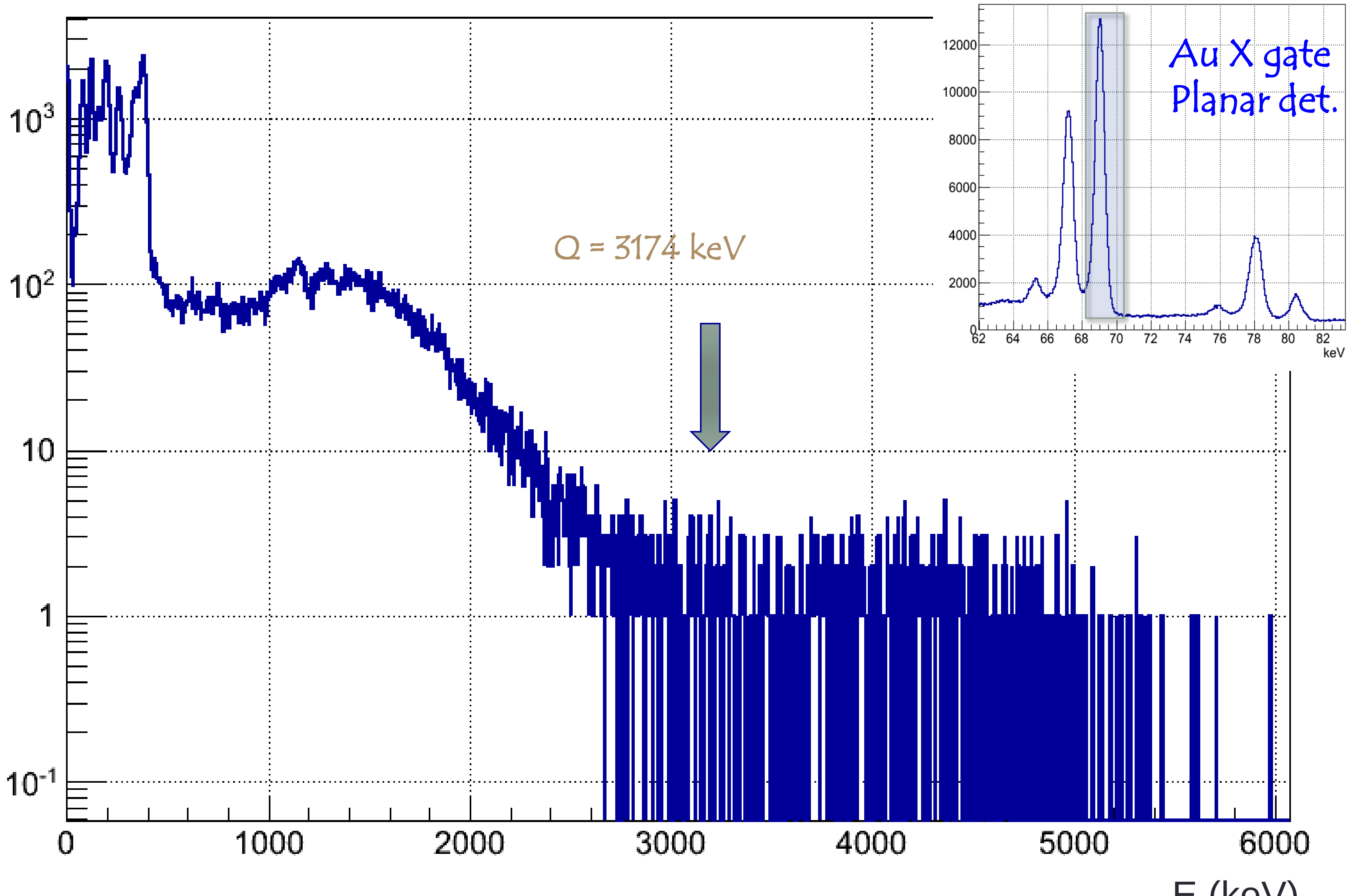
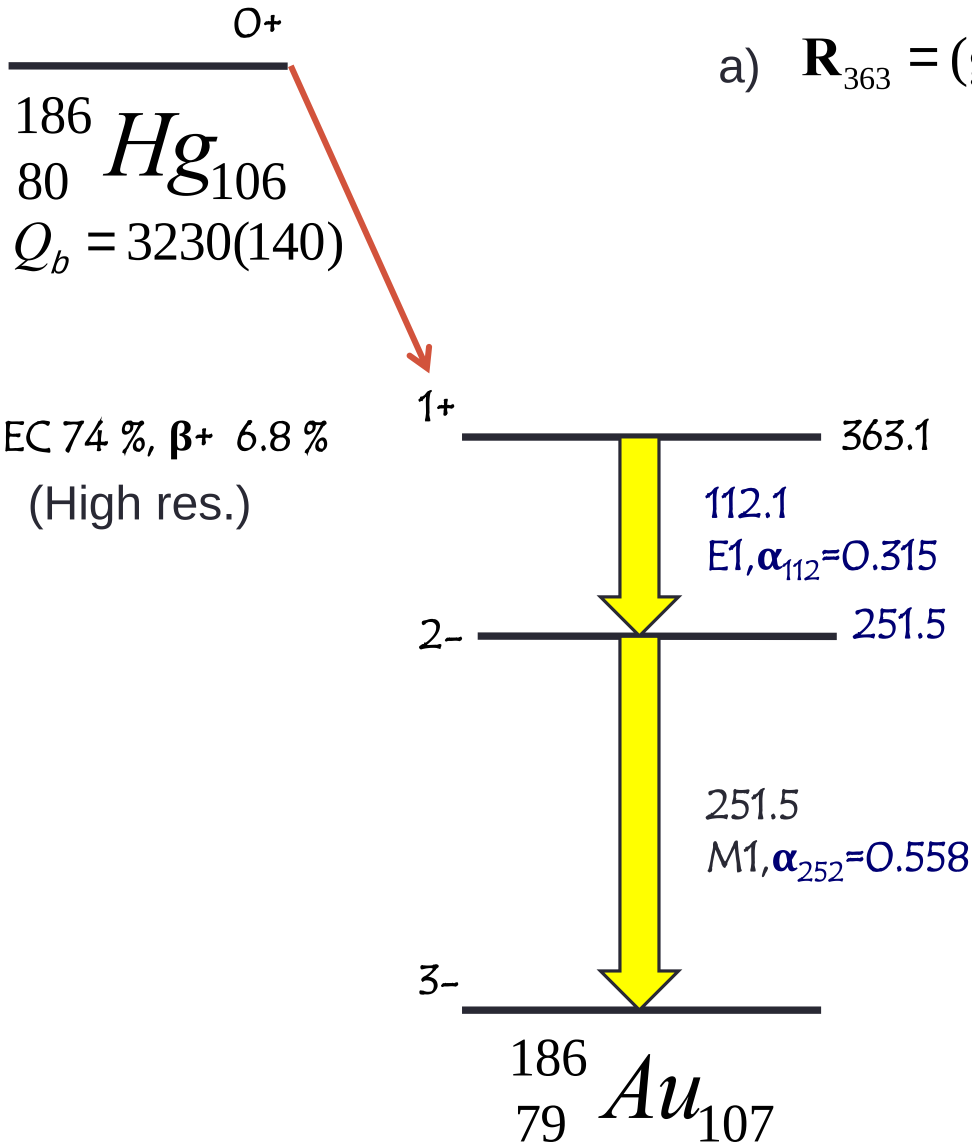
Study case: ^{186}Hg decay



Study case: ^{186}Hg decay

a) $\mathbf{R}_{363} = (\mathbf{g}_{112} \frac{1}{1+a_{112}} + \mathbf{0} \frac{a_{112}}{1+a_{112}}) \text{Ä} \, \mathbf{R}_{252}$



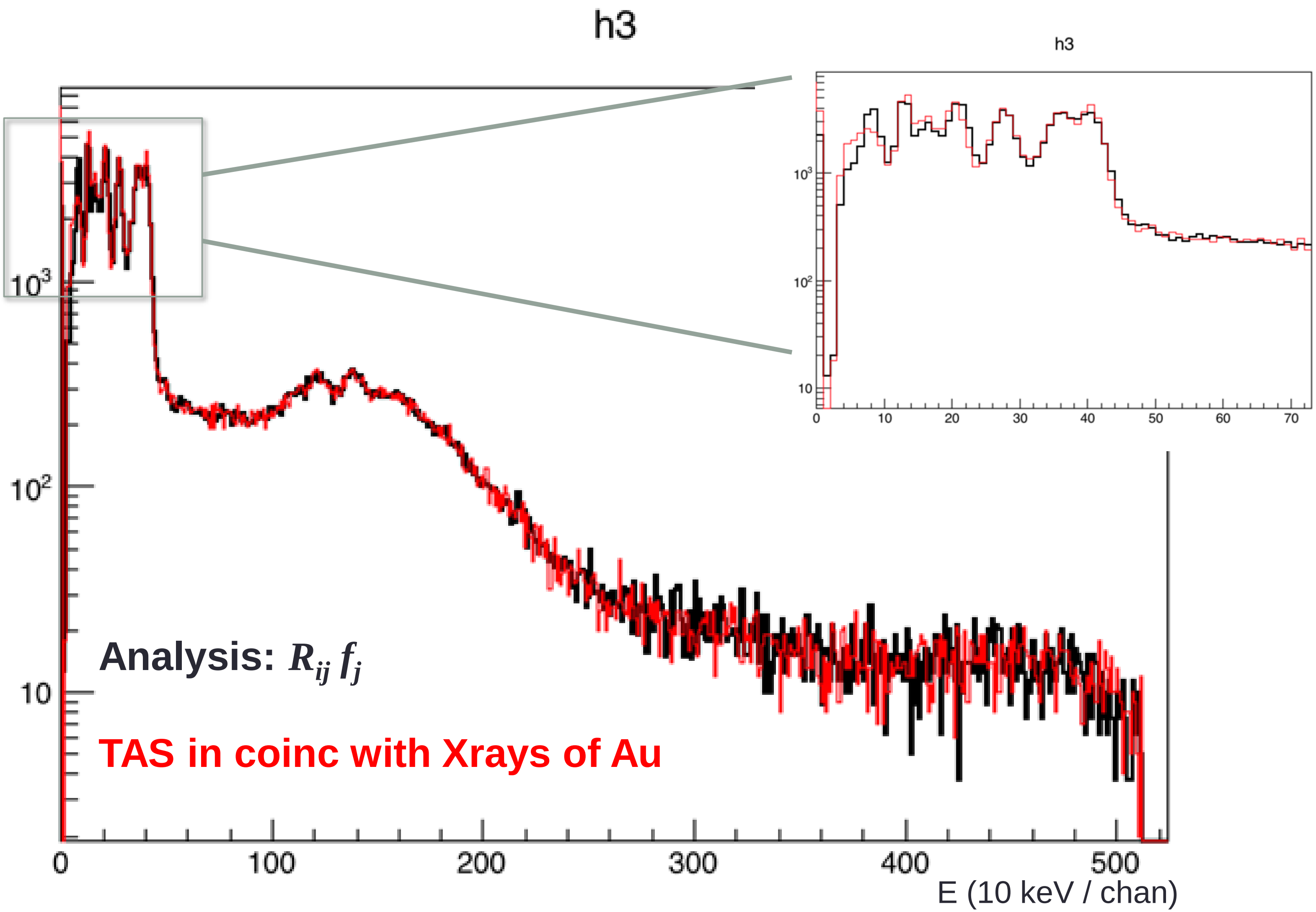
Study case: ^{186}Hg decay

- We calculate the response of the detector to β-feeding, not from individual γ rays plus β particles but from the complete decay generated by G4RadioactiveDecay

- We extend the ENSDF data tables included in RadioactiveDecay5.1.1 and PhotonEvaporation4.3.2 to include the unknown part of the decay / de-excitation (statistical model)

- We analyze the data gated on Au x-rays making sure that this includes the EC component plus the β^+ component. Both contain a proper treatment of CE and the generation of associated X-rays, which is crucial for the description of the experiment (penetration and summing of X-rays).

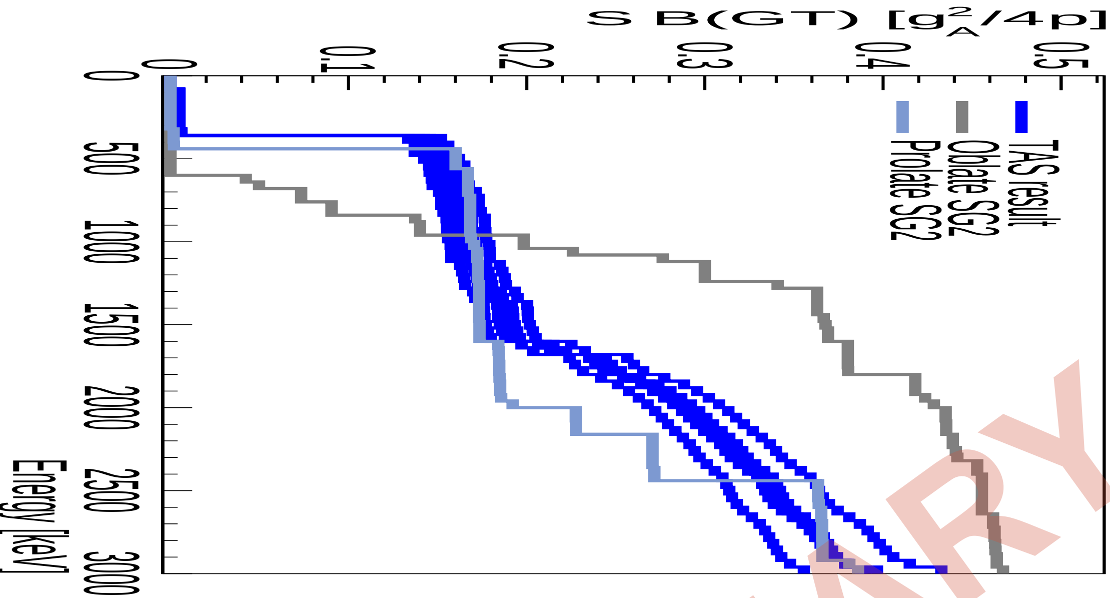
Study case: ^{186}Hg decay



Analysis: $R_{ij}\, f_j$

TAS in coinc with Xrays of Au

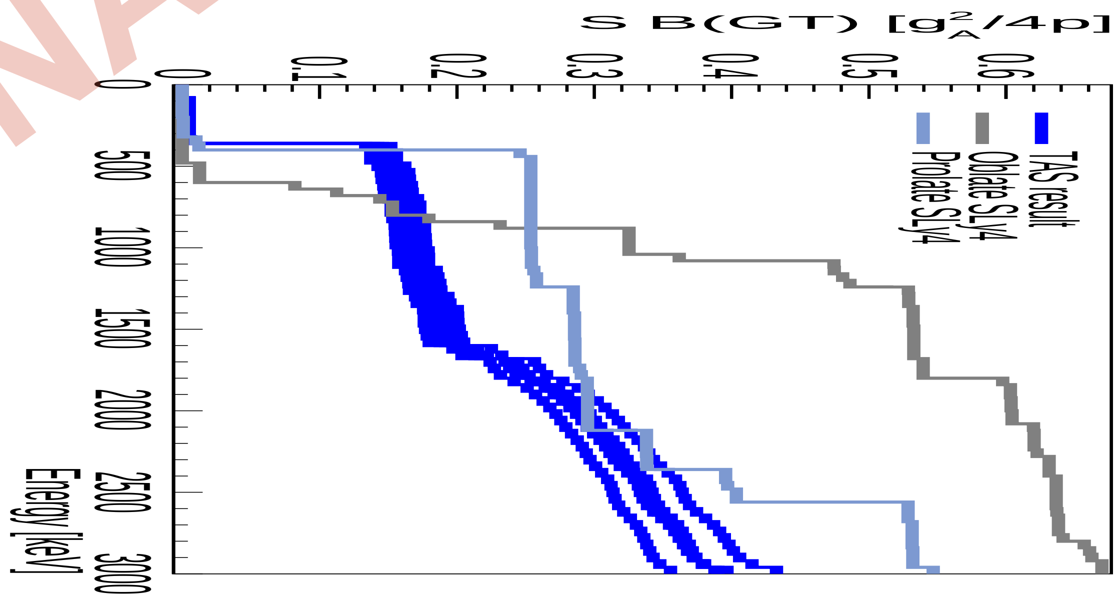
Study case: ^{186}Hg decay



The results are consistent with a **prolate ground state** independent of the force used (SG2, SLy4). Better agreement with SG2

Calculations by P. Sarriguren

Error bands determined by the error in the Q_{EC} value and in the $T_{1/2}$ and by the different possible solutions.



Summary & Conclusions

- To calculate the R_{ij} we count on an event generator that includes the quasi-continuum part (missing in ENSDF). However it does not include the generation of conversion electrons and their subsequent x-ray emission (and some other 2nd order effects…)

- The G4RadioactiveDecay class accounts for the aforementioned effects missing in our event generator. However it is based exclusively on ENSDF and therefore lacks of the quasi-continuum at the upper part of the decay scheme.

- We have merged the two approaches extending the ENSDF data tables included in RadioactiveDecay5.1.1 and PhotonEvaporation4.3.2 using our event generator approach to include the unknown quasi-continuum part of the decay / de-excitation (statistical model).

- We have analyzed the decay of ^{186}Hg gated on Au x-rays that was impossible to analyze with our event generator or with the G4RadioactiveDecay separately. The beta decay of ^{186}Hg shows a strong prolate signature as compared to QRPA calculations

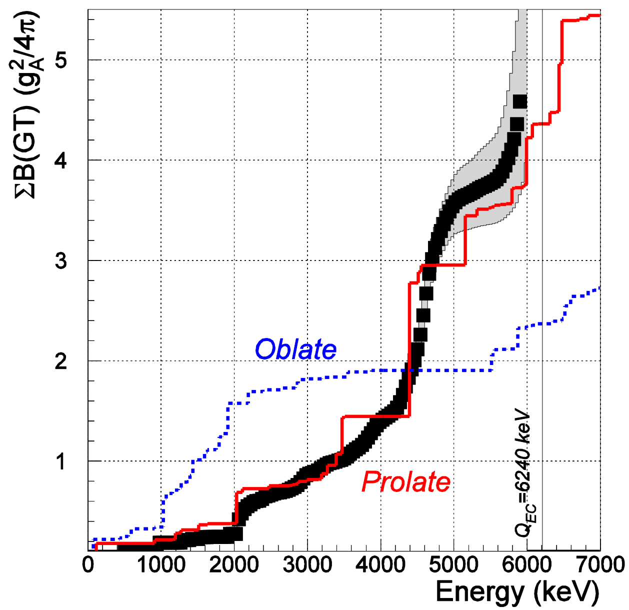
THANKS FOR YOUR ATTENTION!!

What is still missing… and highly desireble!

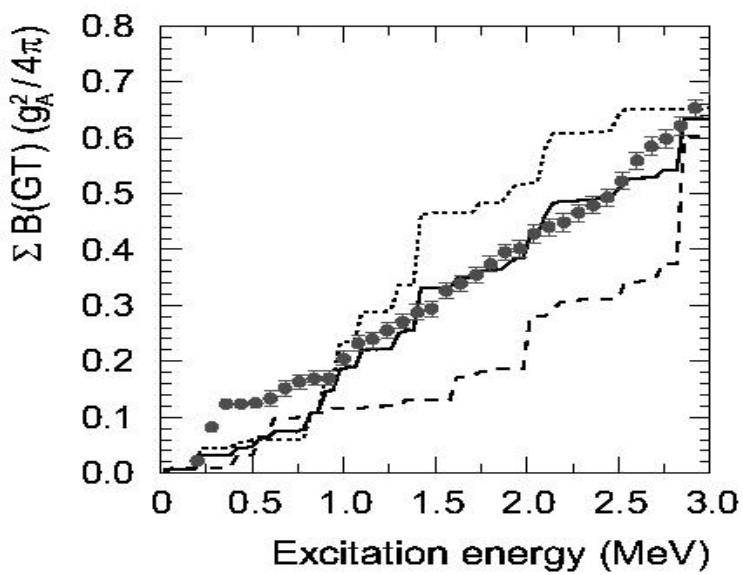
- Beta-delayed particle emission: protons, neutrons and alphas.
- Possibility to include broad resonances above S_p or S_n or S_a rather than discrete levels (e.g. beta decay of ^{8}B in ^{8}Be).

Some other TAS results

- Shape of the g.s. of some N~Z nuclei in the A=70 region inferred from the β-decay
  - E. Nácher, A. Algora *et al*, Phys. Rev. Lett. 92 (2004) 232501
  - E. Poirier, F. Marechal *et al*, Phys. Rev. C69 (2004) 034307



Strong prolate deformation of ^{76}Sr



Shape mixing in the g.s. of ^{74}Kr

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Some other TAS results

- Shap ...) region
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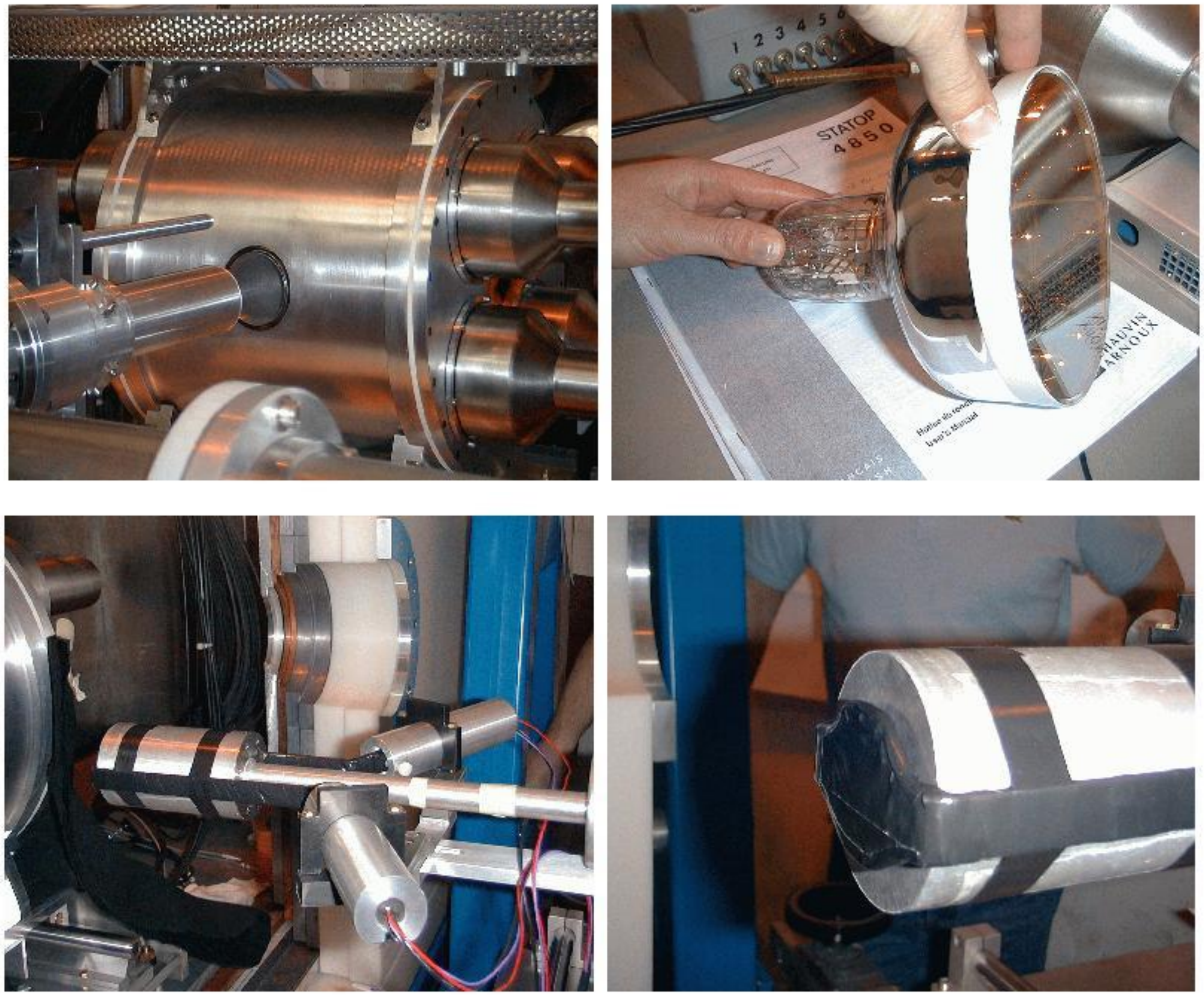
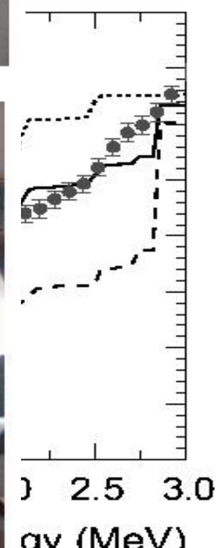
  - E. N ... 2501
  - E. P ... 307





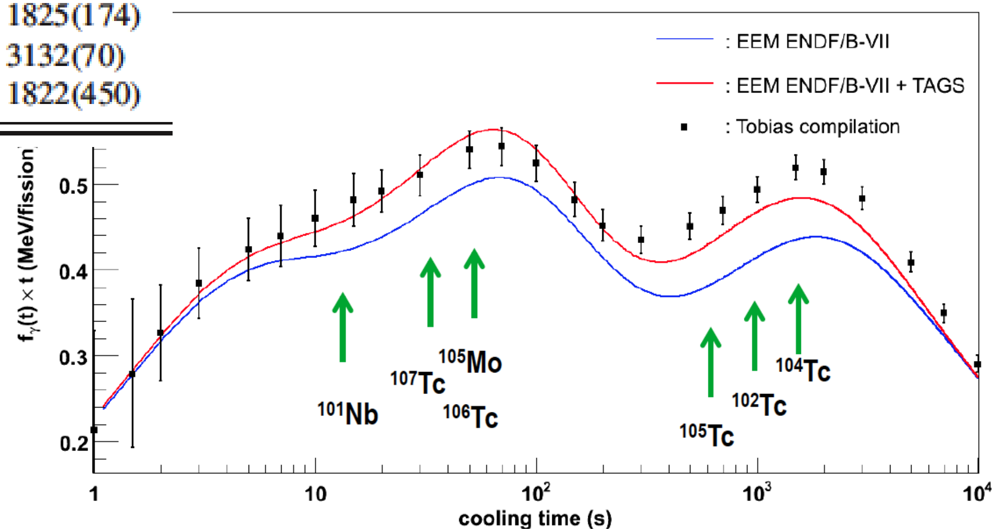
Strong prolate deformation of ^{76}Sr

Shape mixing in the g.s. of ^{74}Kr

Some other TAS results

- Reactor decay heat and related issues
  - A. Algora, D. Jordan *et al*, Phys. Rev. Lett. 105 (2010) 202501

Nuclide	$T_{1/2}$ (s)	$\bar{E}_\gamma$ ENDF	$\bar{E}_\gamma$ TAGS
^{101}Nb	7.1(3)	270(22)	445(279)
^{105}Mo	35.6(16)	552(24)	2407(93)
^{102}Tc	5.28(15)	81(5)	106(23)
^{104}Tc	1098(18)	1890(31)	3229(24)
^{105}Tc	456(6)	668(19)	1825(174)
^{106}Tc	35.6(6)	2191(51)	3132(70)
^{107}Tc	21.2(2)	515(11)	1822(450)



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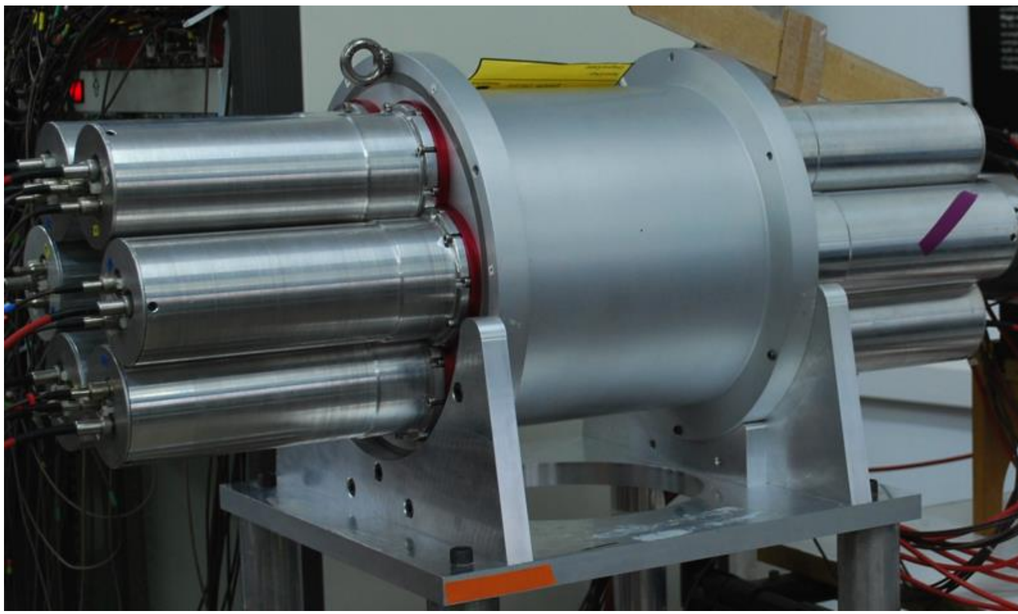
Some other TAS results

- Reactor decay heat and related issu



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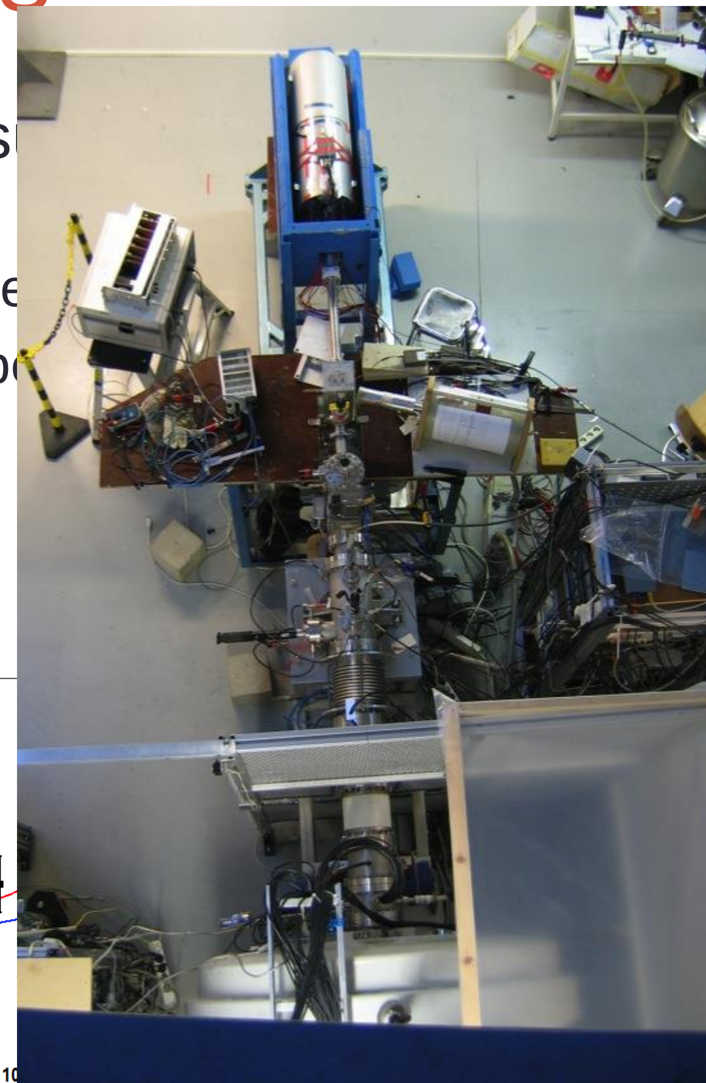
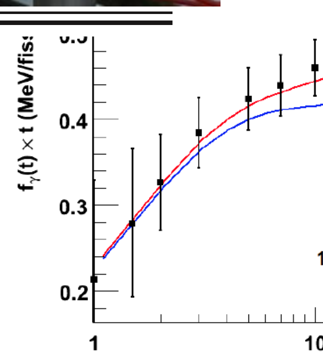
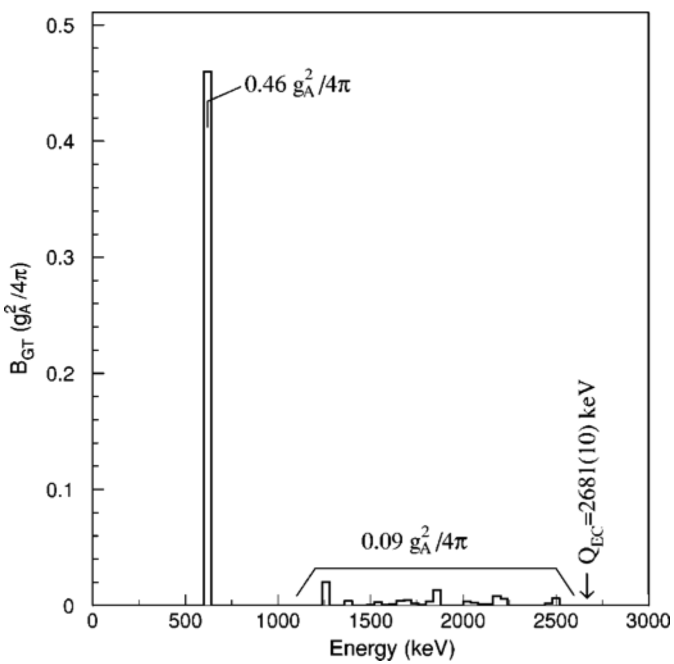


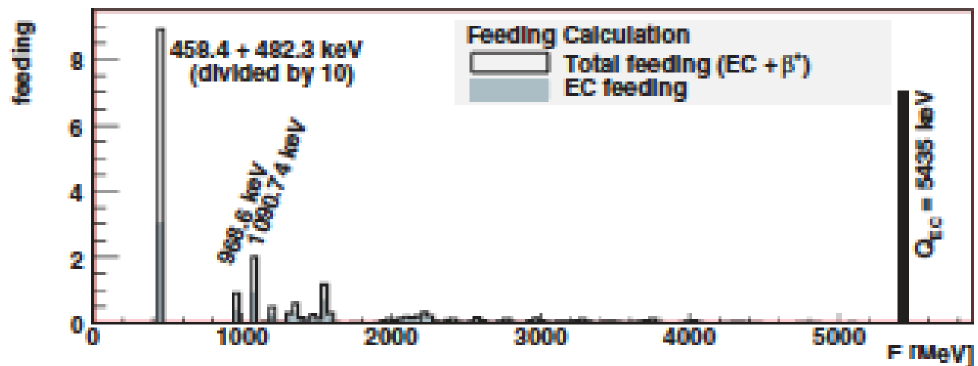


Some other TAS results

- β-decay studies for a Monochromatic beam facility
  - A. Algora, E. Nácher *et al*, Phys. Rev. C 70 (2004) 202501
  - M.E. Estevez A. Algora *et al*, Phys. Rev. C 84 (2011) 034304



β-decay of ^{148}Dy



E_{lev}		I_{EC} (%)		$I_{EC+\beta+}$ (%)	
(keV)	J^π	TAS	HR	TAS	HR
115.2	1^+	41(2)	58.0(13)	60(3)	85.2(5)
317.5	1^+	3.7(7)	3.5(4)	5(1)	4.8(5)
320–Q		22(2)		25(3)	
Total		67(3)	61.5(2)	90(4)	90.0(20)

β-decay of ^{152}Yb

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Some other TAS resul

- β-decay studies for a Monochrom
  - A. Algora, E. Nácher *et al*, Phys. Rev.
  - M.E. Estevez A. Algora *et al*, Phys. Re