Beta decay of the *N=Z*, rp-process waiting points: ^{64}Ge, ^{68}Se and the *N=Z+2*: ^{66}Ge, ^{70}Se for accurate stellar weak-decay rates

E. Nácher
Instituto de Estructura de la Materia – CSIC, Madrid (Spain)
C. Domingo, A. Algora
Instituto de Física Corpuscular – CSIC, Valencia (Spain)
et al.

Outline of the presentation

- Introduction: the physics case
- The experimental technique
- Beam-time request

Introduction: The physics case

Type I X-ray bursts

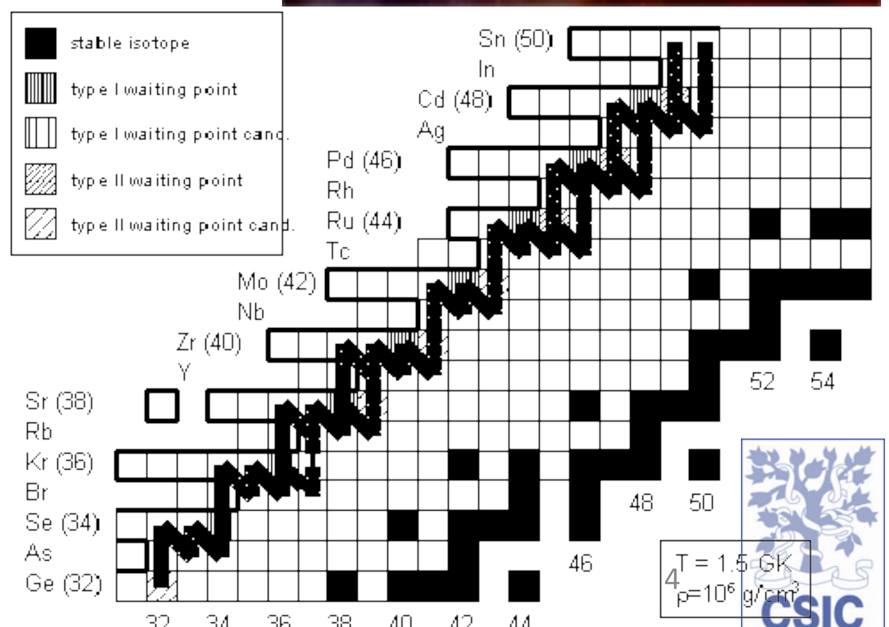
- Binary systems: a neutron star accretes hydrogen-rich material from a low-mass companion (Red-Giant or Main-Seq. star)

- T_{peak} = 1 – 3 GK and $\rho = 10^6 - 10^7$ g cm^{-3}
- Breakout from the hot CNO cycle -> rp-process

Introduction: The physics case

Type I X-ray bursts

- Nucleosinthesys pushed towards the proton drip-line through rapid proton capture reactions (rp)
- When β-decay competes with p capture: Waiting Point (WP)



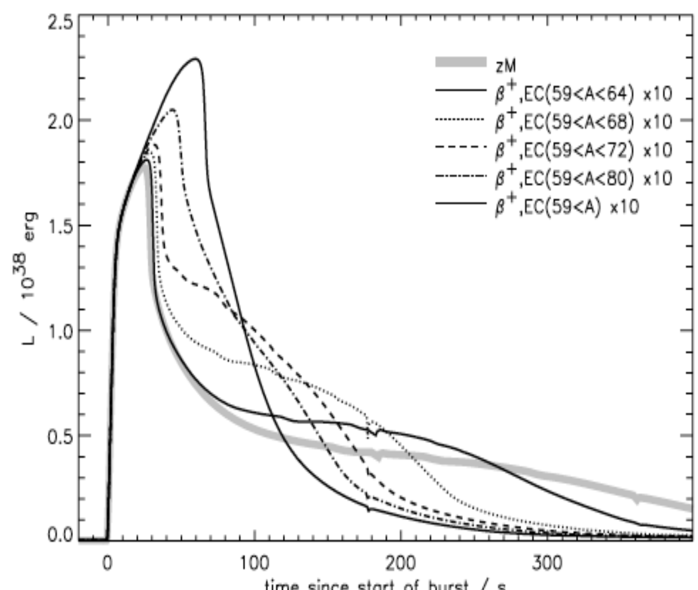
Introduction: The physics case

Physical observable:

- Luminosity curve
- No matter is released

Network calculations:

- Decay and reaction rates
- 1300 isotopes included, e.g. in *Woosley et al. ApJS 151 (2004)*



Introduction: The physics case

…but, what is really in?

- Masses/Binding energies
- Reaction rates: (p,γ), (α,γ), (p,α), CNO cycles…
- Decay rates: β^+-decay, p-decay, α-decay…

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- From experiment, when available
- From theory (SM, QRPA, Hauser-Feshbach…)
- From systematics

Introduction: The physics case

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Introduction: The physics case

EC rates have been neglected so far for N≈Z, A≥60

Schatz et al. Phys. Rep 294 (1998)
Woosley et al. ApJS 151 (2004)

Introduction: The physics case

EC rates have been neglected so far for N≈Z, A≥60

- At XRB peak conditions atoms are fully ionized
- Q values are so big that β^{+}-decay dominates

Introduction: Sci. Motivation

Recent calculations show that this is not a good approximation for the N=Z waiting points and their N=Z+2 neighbours: ^{64,66}Ge, ^{68,70}Se, ^{72,74}Kr, ^{76,78}Sr.

In these cases Continuum EC dominates weak decay rates over the β^+ and should not be neglected

Sarriguren, Physics Letters B 680 (2009)
Sarriguren, Phys. Rev. C 83 (2011)
Jameel-Un Nabi, Astrophys. Space Sci. 339 (2012) } → *QRPA*

Mishra et al., Phys. Rev. C 78 (2008) *-> Deformed SM*

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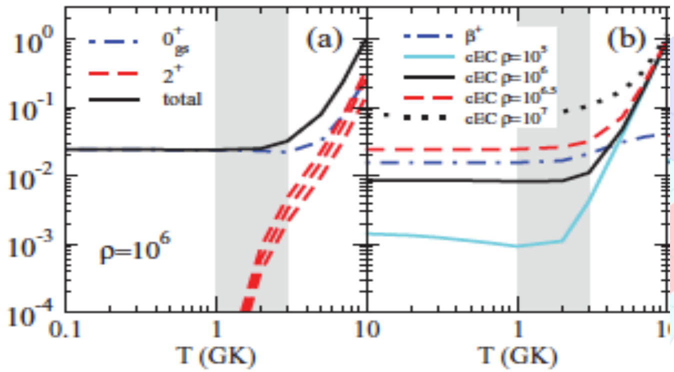
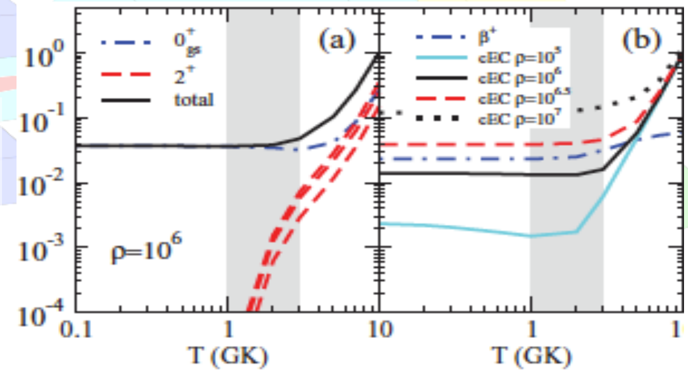
Introduction: Sci. Motivation

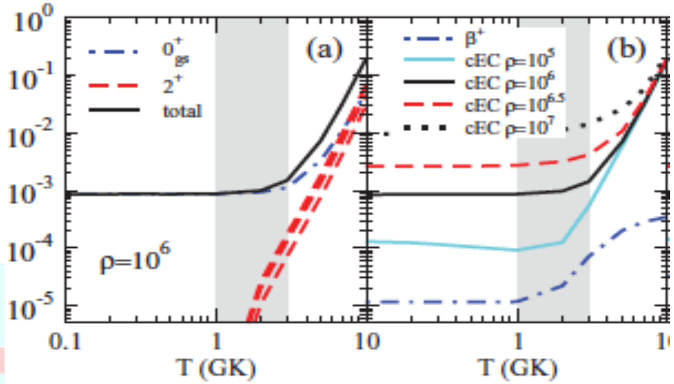
^{64}Ge



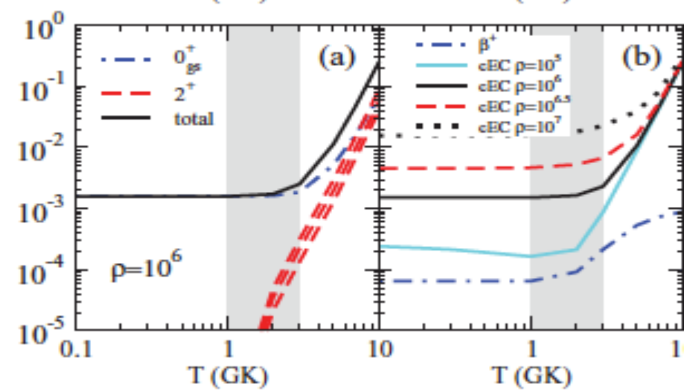
^{68}Se



^{66}Ge



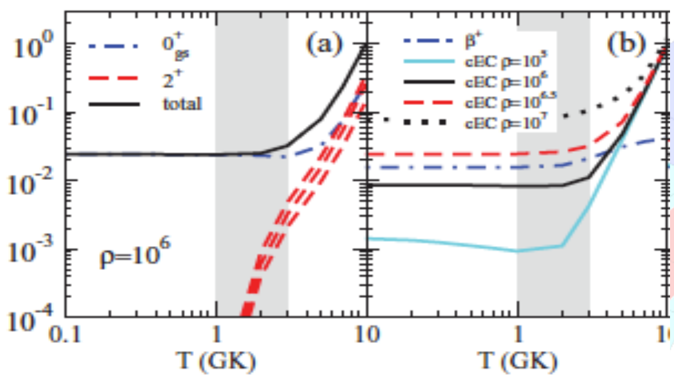
^{70}Se



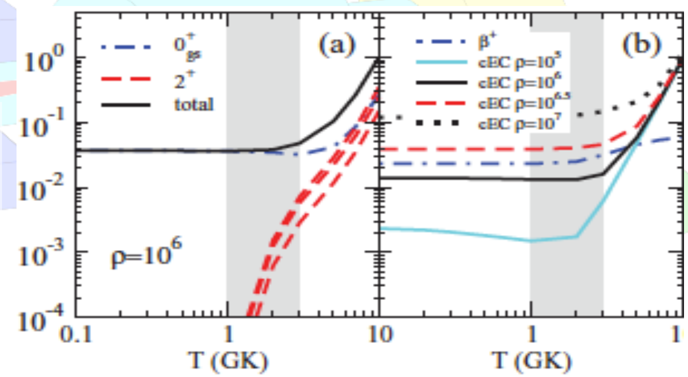
Sarriguren, Phys. Rev. C 83 (2011)

Introduction: Sci. Motivation

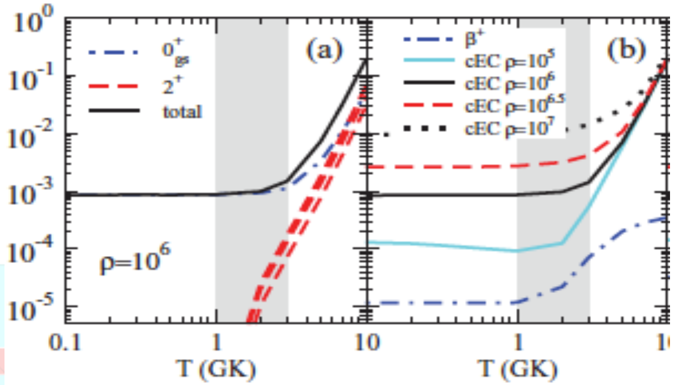
^{64}Ge



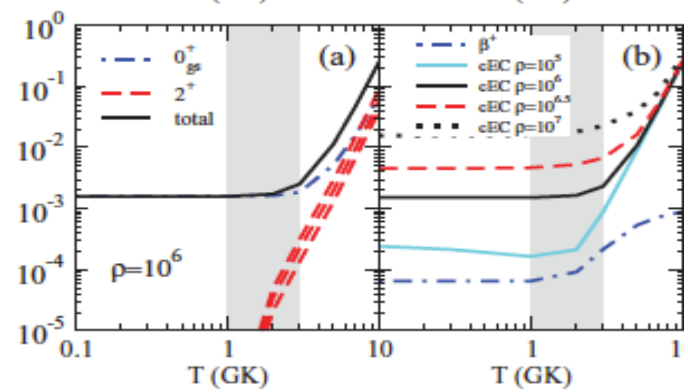
^{68}Se



^{66}Ge



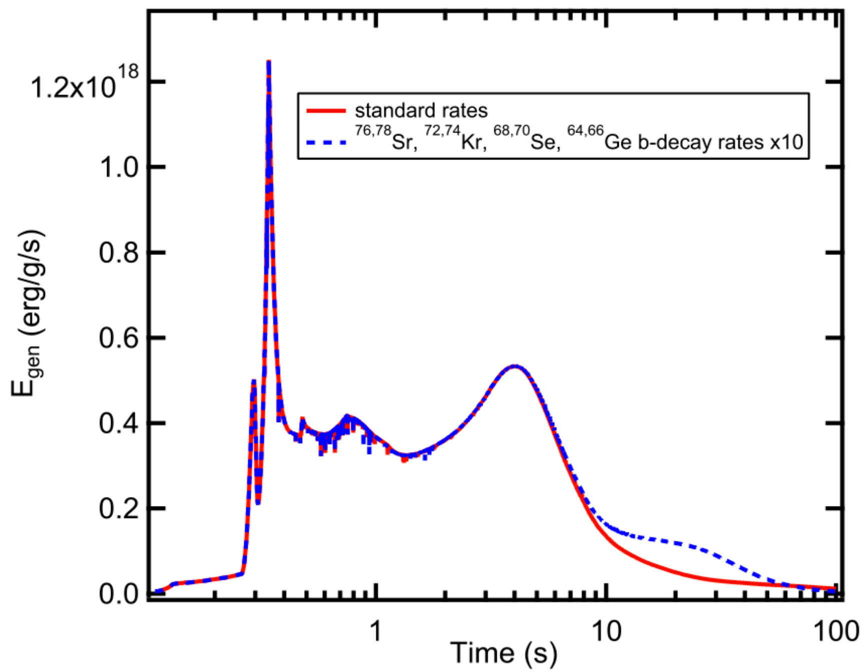
^{70}Se



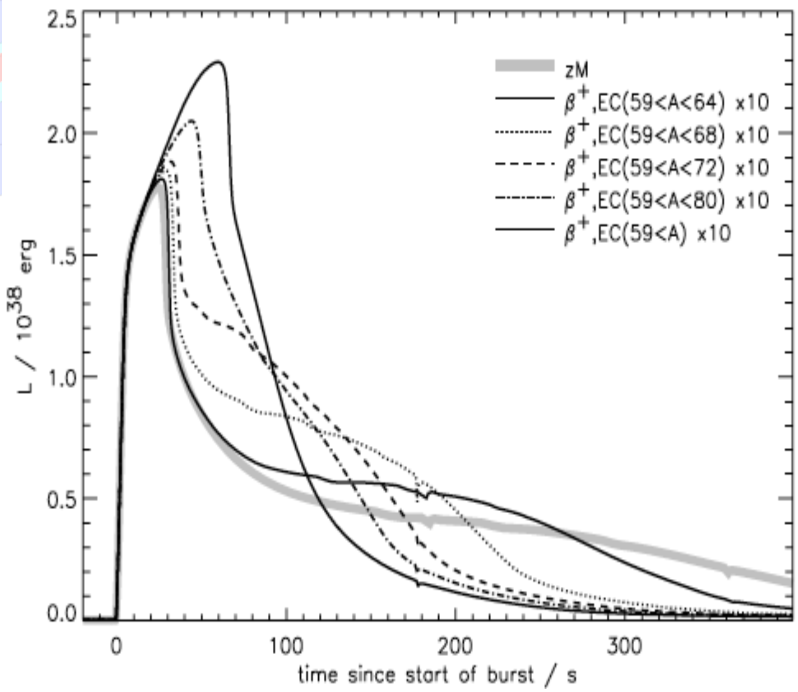
Sarriguren, Phys. Rev. C 83 (2011)

-> NEED FOR VALIDATION AT TERRESTRIAL CONDITIONS

Introduction: Sci. Motivation



Nuclear energy generated in one XRB model (K04 in Parikh et al., ApJS 178 (2008) 110)



Luminic curve of 1st pulse in model Zm from Woosley et al. ApJS 151 (2004)

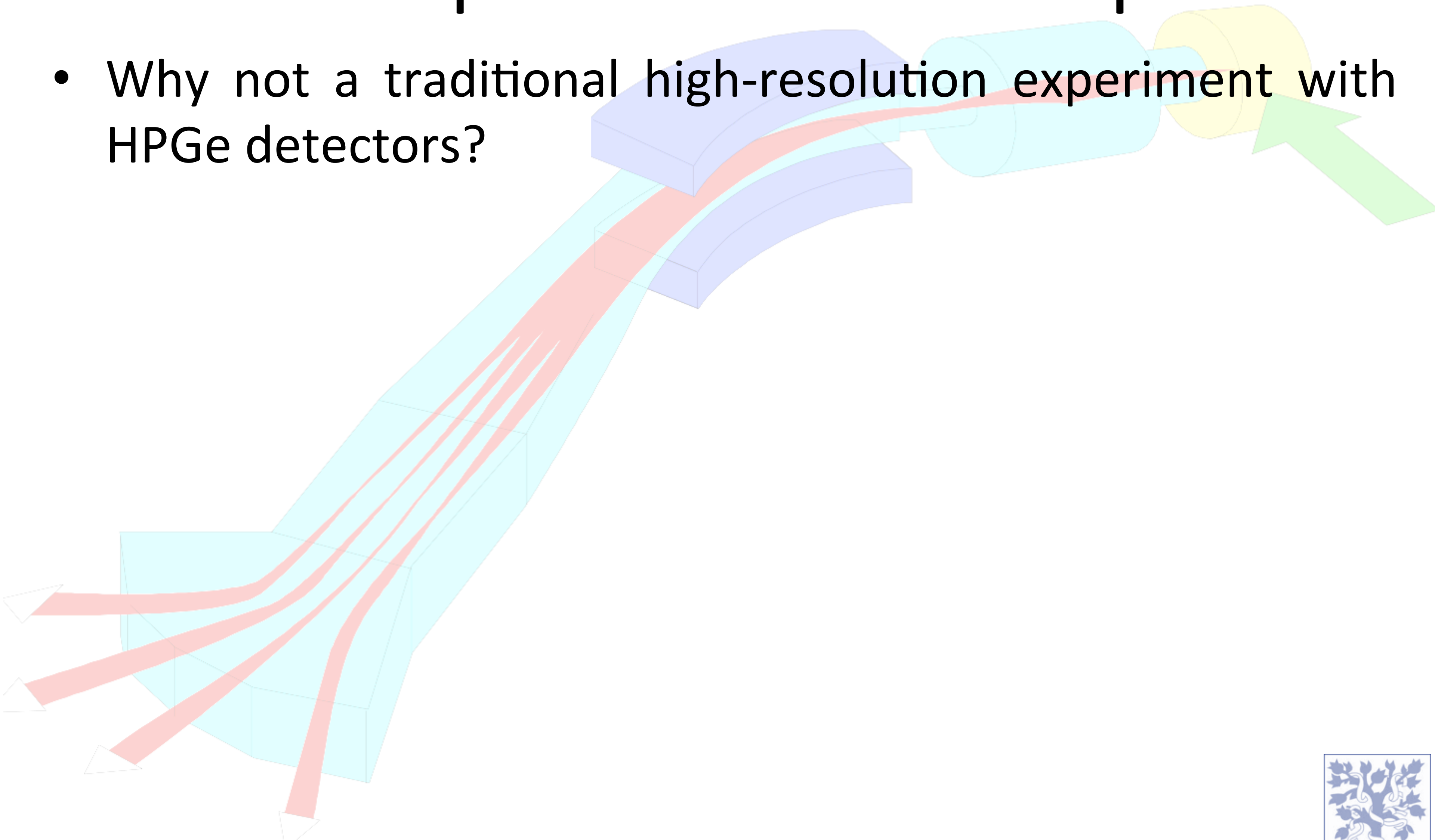
The experimental technique

- We propose to measure accurately the B(GT) distribution in the β^+/EC-decay of ^{64,66}**Ge** and ^{68,70}**Se** using the **Total Absorption Spectroscopy** (TAS) technique.

- In the TAS technique we measure entire γ cascades rather than individual γ-rays since this allows for the 'direct' determination of the β^+/EC intensities and therefore the B(GT) distribution in the decay of interest.

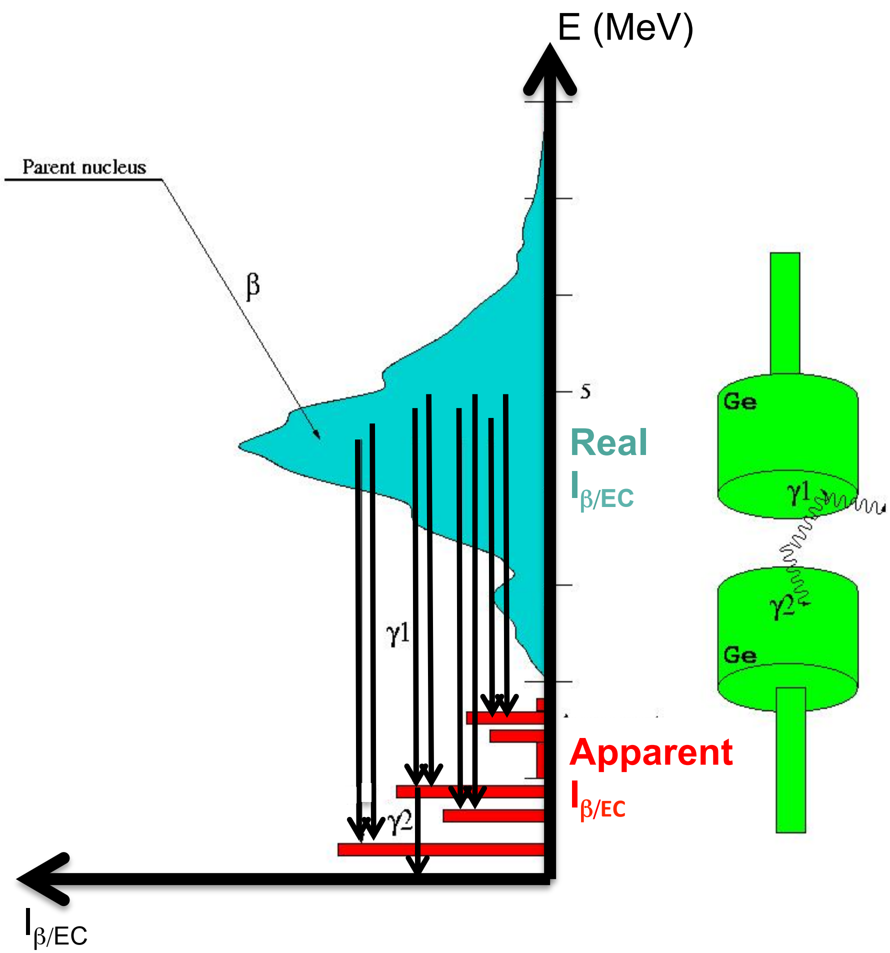
The experimental technique

- Why not a traditional high-resolution experiment with HPGe detectors?



The experimental technique

- Why not a traditional high-resolution experiment with HPGe detectors?
  - Medium mass and heavy nuclei: large level density at high energy.
  - Very fragmented $I_{\beta/EC}$ distribution and γ-deexcitation pattern.
  - HPGe arrays fail to detect the upper part of the γ-cascade resulting in a wrong $I_{\beta/EC}$ and B(GT)



Hardy et al., Physics Letters B 71 (1977)

The experimental technique

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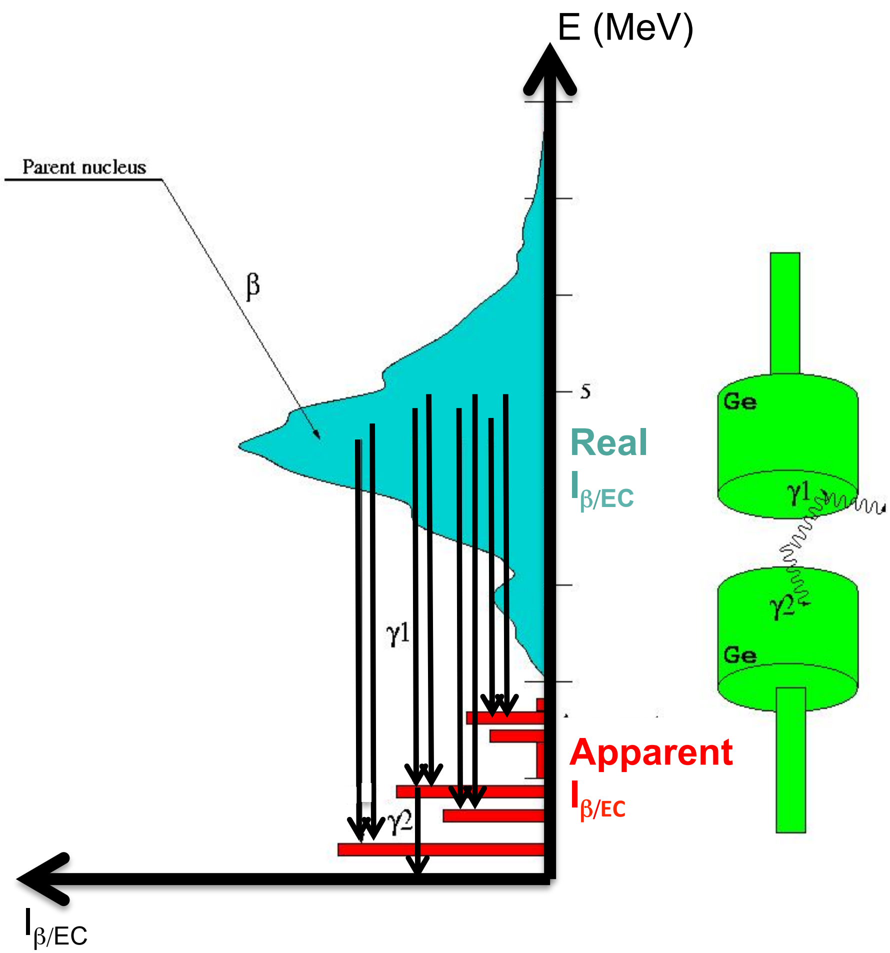
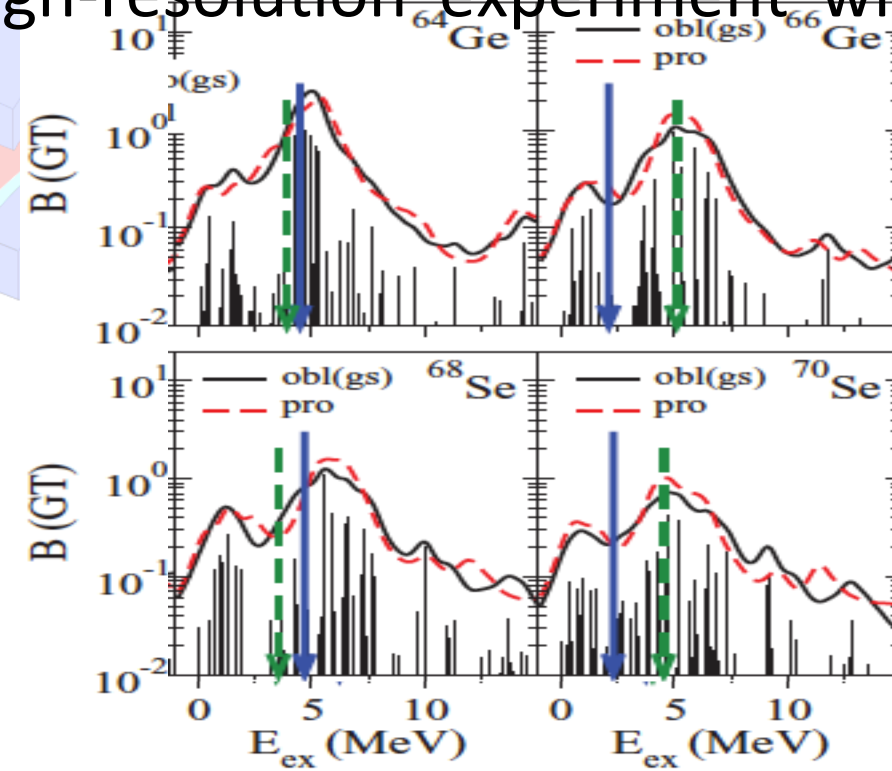
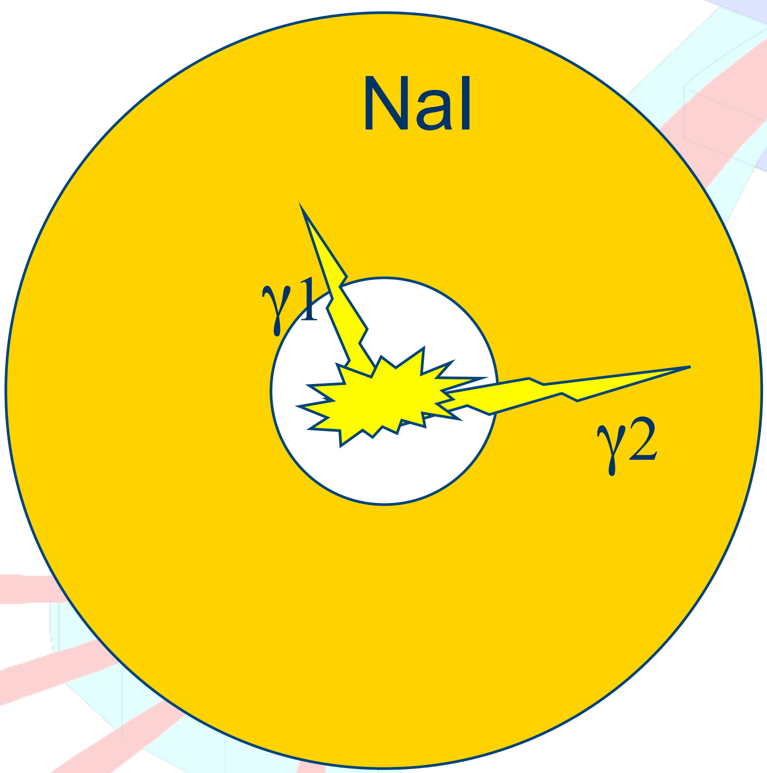


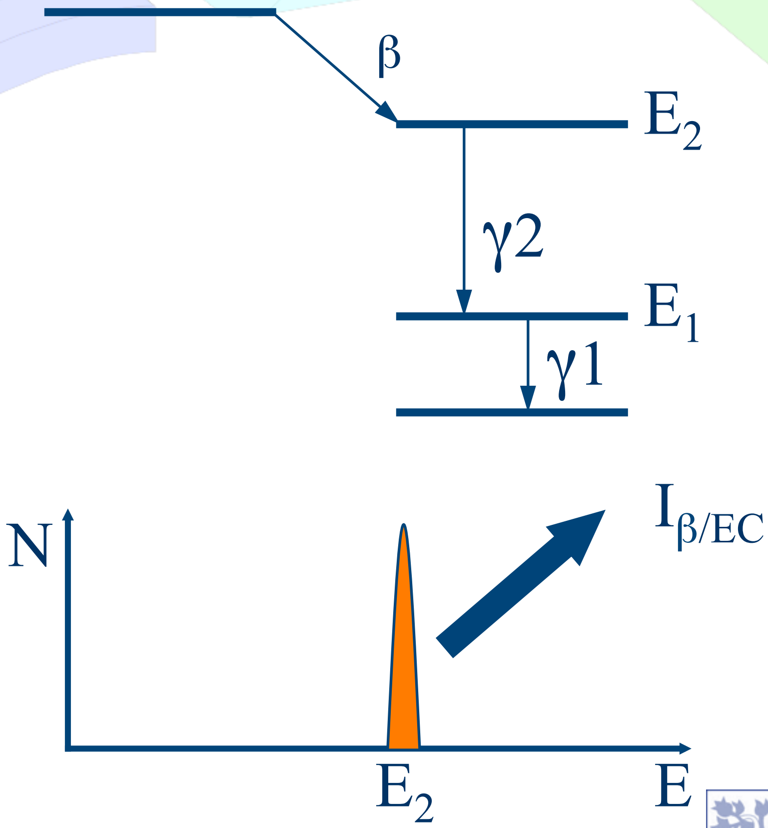


Last level seen in the decay of ^{68}Se is at 426 keV but Q_{EC}=4705 keV!!

The experimental technique

- Total Absorption Spectroscopy (Ideal case)

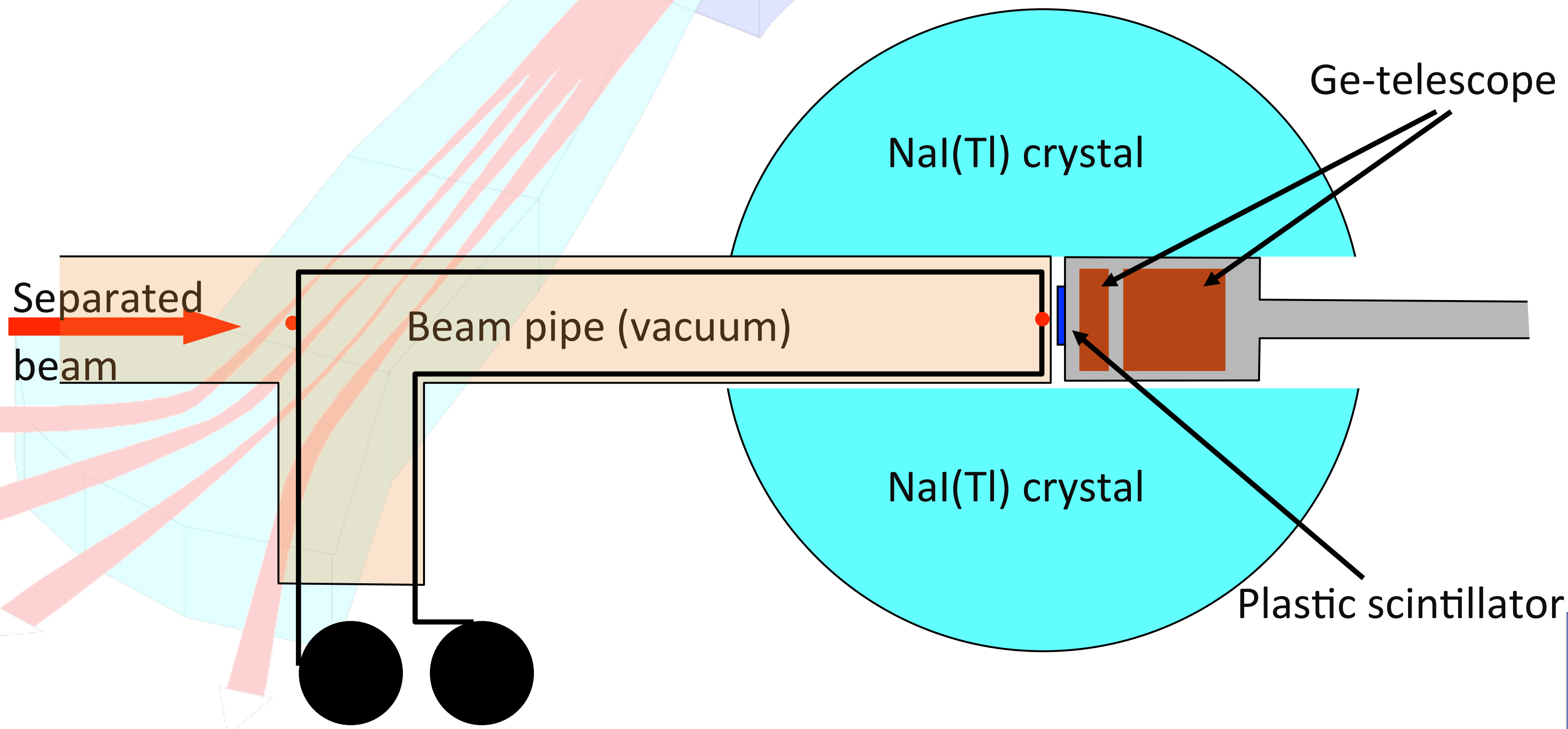




For a comprehensive review of the TAS technique see: Rubio et al., J. Phys. G 31 (2005)

The experimental technique

- Lucrecia, the TAS at ISOLDE
  - Main NaI(Tl) cylinder: Ø38 cm x 38 cm
  - Ancillary detectors: Ge telescope + plastic scintillator



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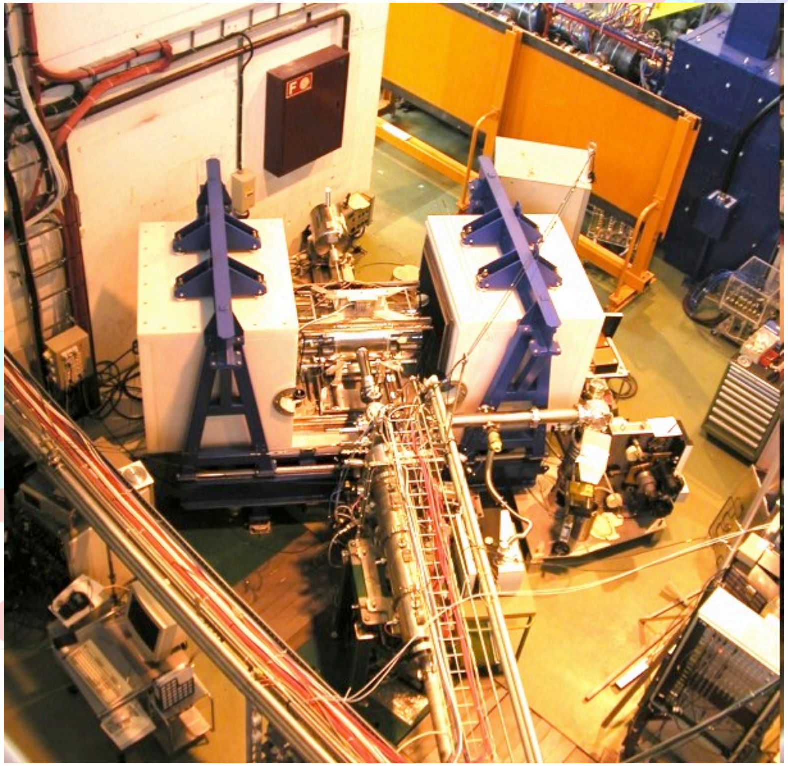
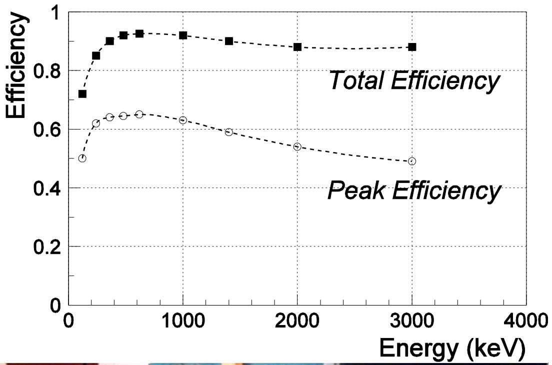
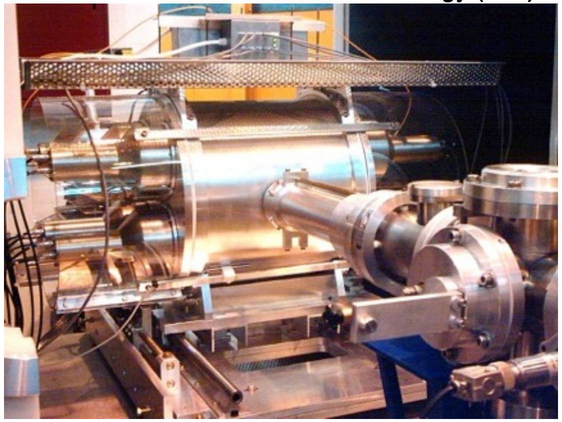






The experimental technique

- Production and Separation:

  - ^{68,70}Se: Y_2O_3 nanomaterial or ZrO_2 fibre target coupled to the arc discharge VD5 source (VADIS). Extraction as molecule: $SeCO^+$ to avoid Ga contaminant.

  - ^{64,66}Ge: can be produced with the same combination of target - ion source but a different molecular compound: GeS^+. Another possibility to produce/select these isotopes is with the RILIS ion source + the LIST suppressor for Ga (possible at ISOLDE, but not done before).

Beam-time request

- Within the TISD program (T. Stora): some beam-time should be allocated to assess the production of $^{68,70}Se$ and $^{64,66}Ge$ with the YO-VD5 (2 leaks for CO and S). Some more beam-time should be allocated to assess the production of $^{64,66}Ge$ with the RILIS + LIST system. We will ask for more beam time to measure ^{64}Ge based on the results from this test.

- **We request:**
  - **6 shifts** to measure ^{68}Se and its daughter.
  - **3 shifts** to measure ^{70}Se and its daughter.
  - **3 shifts** to measure ^{66}Ge and its daughter.

Beta decay of the *N=Z*, rp-process waiting points: ^{64}Ge, ^{68}Se and the *N=Z+2*: ^{66}Ge, ^{70}Se for accurate stellar weak-decay rates

E. Nácher, J.A. Briz, M. Carmona, A. Illana, A. Jungclaus, A. Perea, V. Pesudo, G. Ribeiro, J. Sánchez-del-Río, P. Sarriguren, J. Taprogge, O. Tengblad

Instituto de Estructura de la Materia – CSIC, Madrid (Spain)

C. Domingo, A. Algora, J. Agramunt, G. Giubrone, V. Guadilla, A. Montaner, S.E.A. Orrigo, B. Rubio, J. L. Taín

Instituto de Física Corpuscular, CSIC – Universidad de Valencia (Spain)

J. José, A. Parikh

Universitat Politècnica de Catalunya, Barcelona (Spain)

L.M. Fraile, I. Marroquín, O. Moreno, B. Olaizola, V. Paziy, J.M. Udías, V. Vedia

Universidad Complutense de Madrid (Spain)

M.J.G. Borge, C. Guerrero, T. Day Goodacre, V. Fedosseev, B. Marsh, E. Rapisarda, T. Stora

CERN, Geneve (Switzerland)

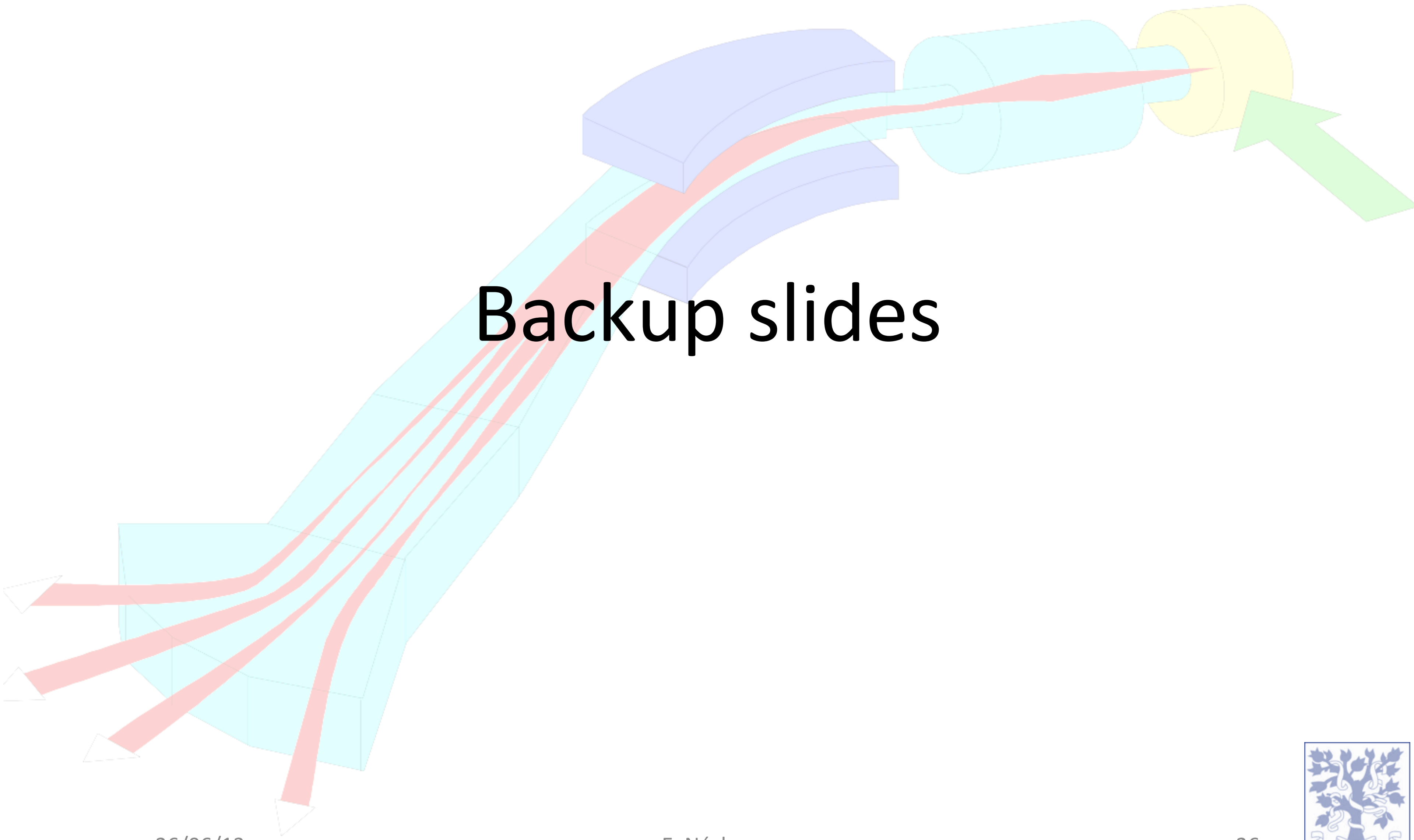
W. Gelletly, P. Regan, Z. Podolyák, S. Rice

University of Surrey, Guildford (United Kingdom)

R. Orlandi

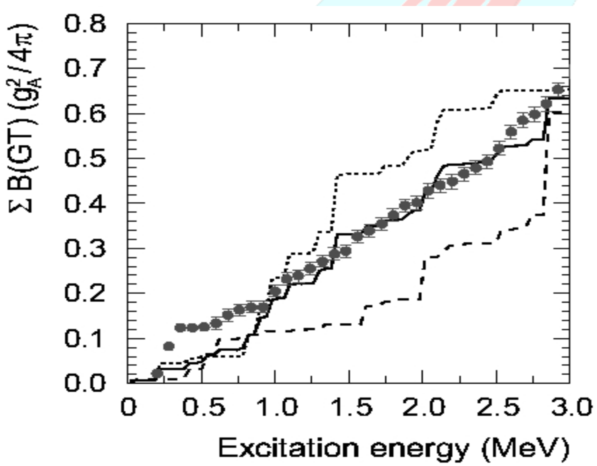
Katholieke Universiteit Leuven (Belgium)

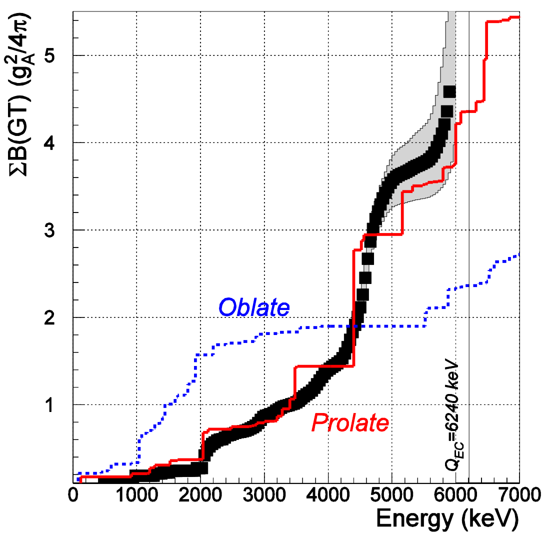
Backup slides



Nuclear deformation around A=70

- β-decay of ^{72,74}Kr and ^{76,78,80}Sr measured in different runs during 2001-2002 at ISOLDE.
- The shape of the ground state can be inferred from the B(GT) distribution.

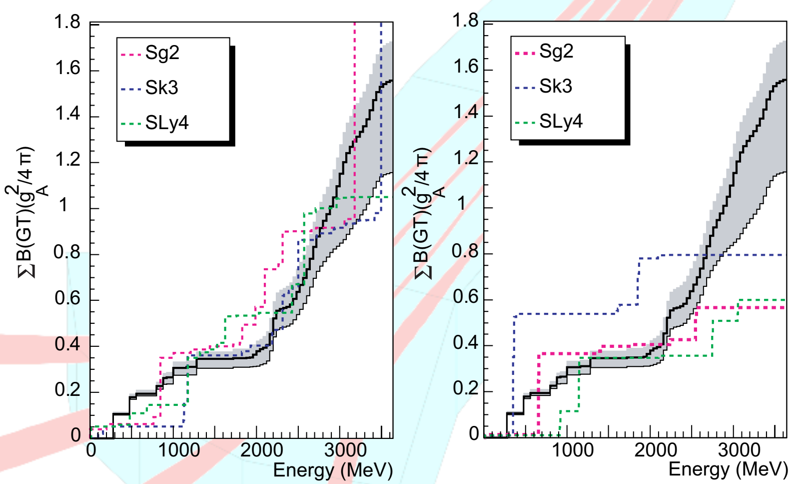


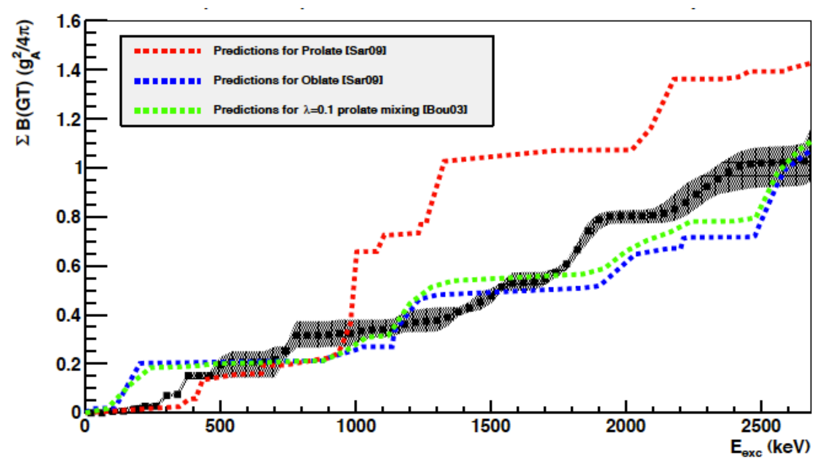


- E. Nácher, A. Algora *et al*, Phys. Rev. Lett. 92 (2004)
- E. Poirier, F. Marechal *et al*, Phys. Rev. C69 (2004)

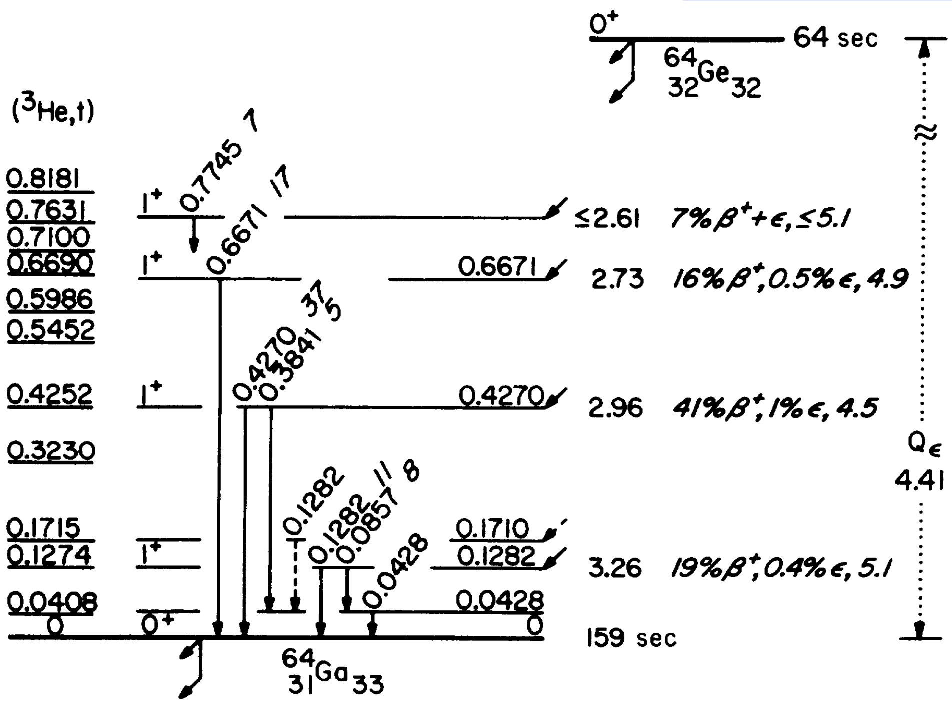
Nuclear deformation around A=70

- β-decay of ^{78}Sr: A. Perez PhD thesis (2012), sent for publication.
- β-decay of ^{72}Kr: J.A. Briz PhD thesis (next september).





What is known so far…

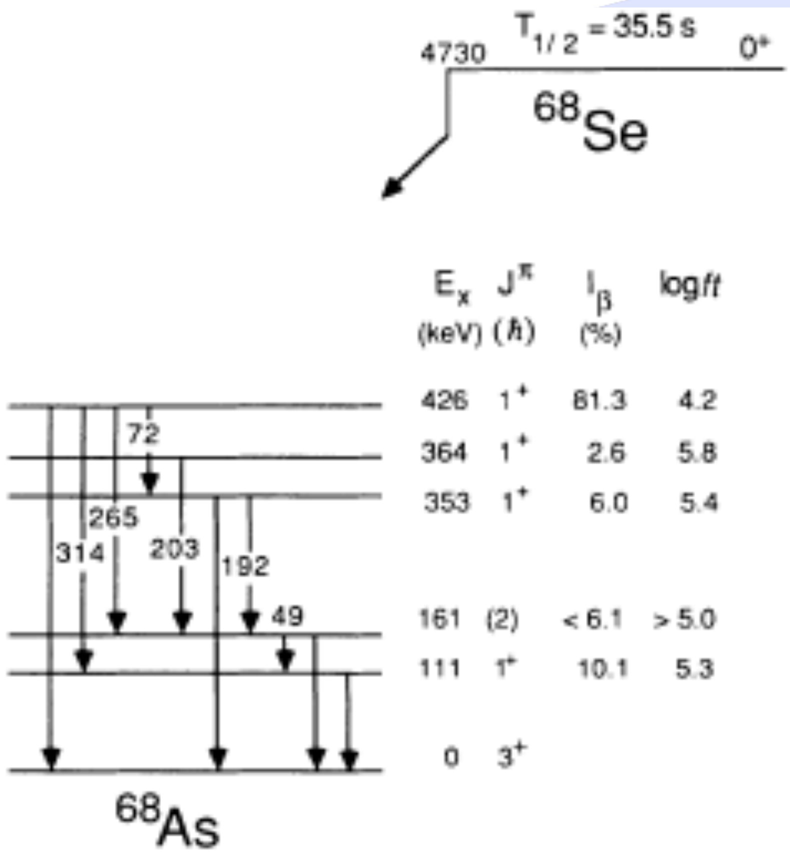


Last level seen in the decay of ^{64}Ge is at 818 keV.

Q_{EC}=4410 keV

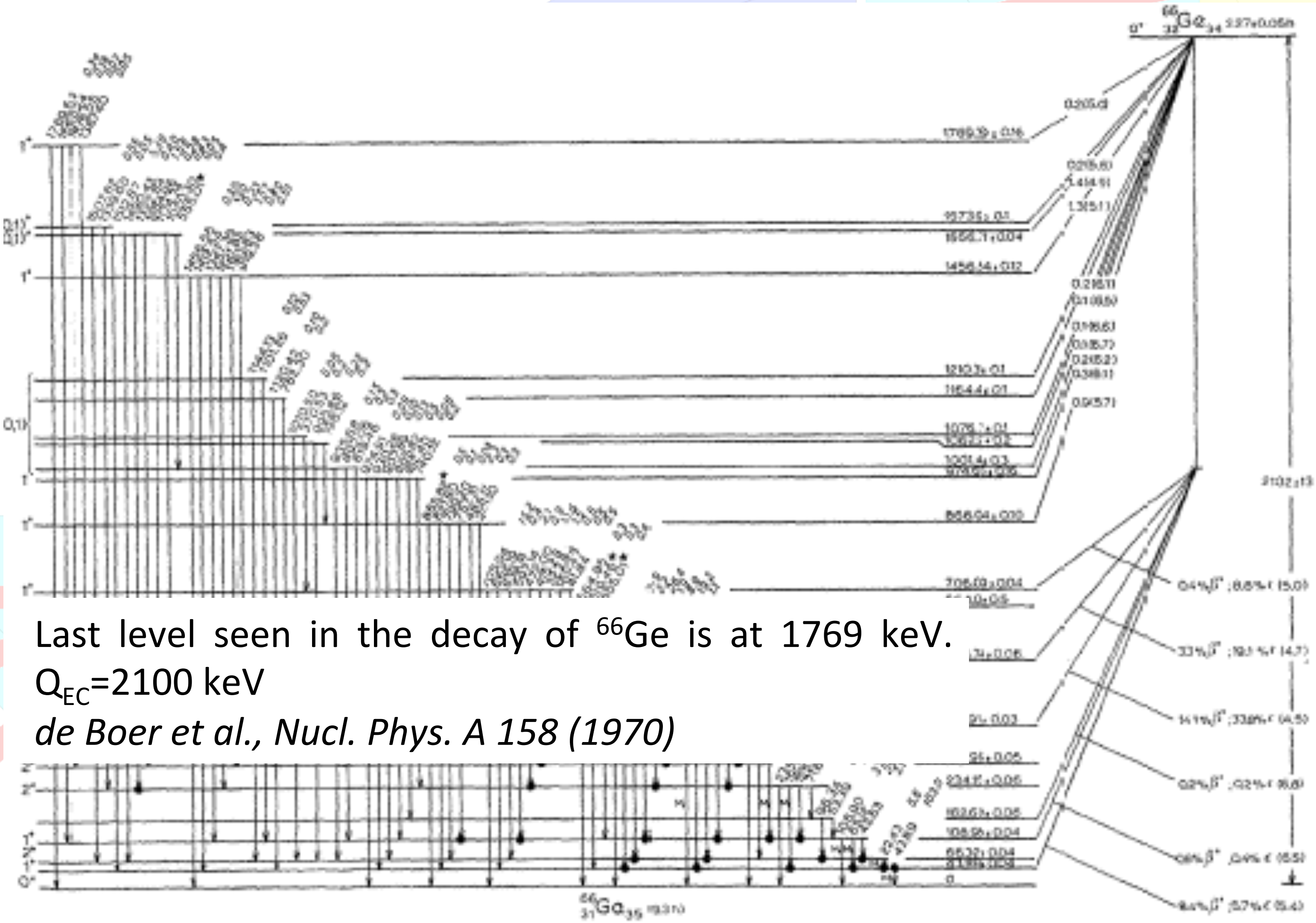
Robertson et al., Phys. Rev. C 9 (1974)

What is known so far…



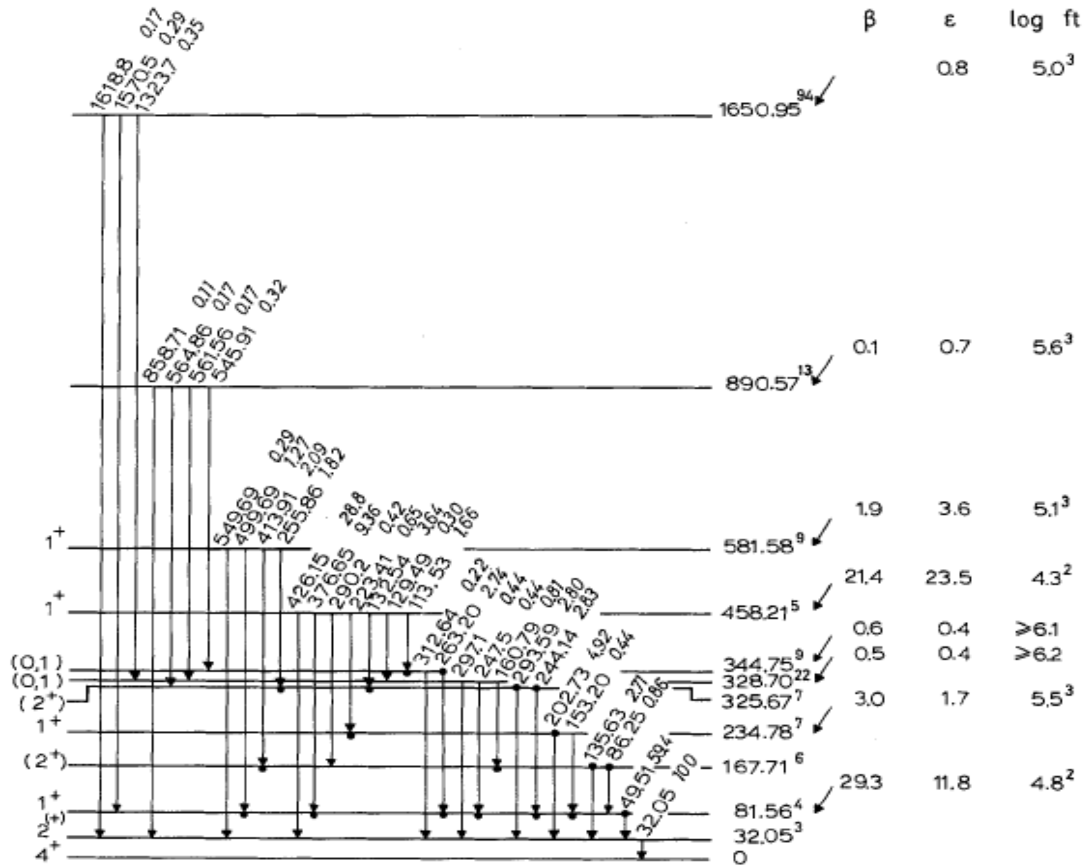
Last level seen in the decay of ^{68}Se is at 426 keV.
Q_{EC}=4705 keV
Baumann et al., Phys. Rev. C 50 (1994)

What is known so far…



Last level seen in the decay of ^{66}Ge is at 1769 keV. Q_{EC}=2100 keV
de Boer et al., Nucl. Phys. A 158 (1970)

What is known so far…



Last level seen in the decay of ^{70}Se is at 1619 keV. Q_{EC}=2412 keV

B.O. ten Brink et al., Z. Physik 270 (1974)

Level densities

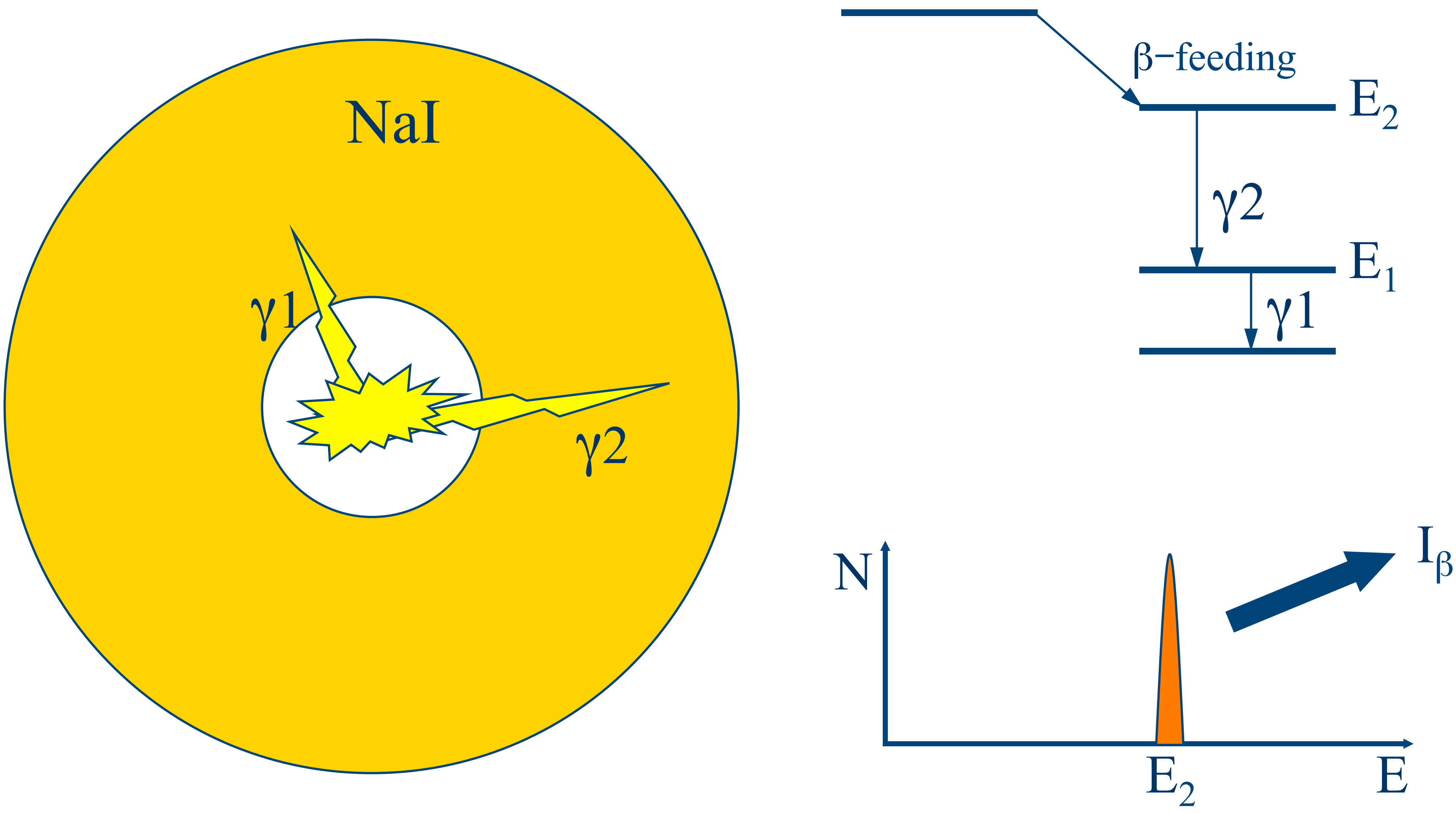
	^{66}Ga (^{66}Ge decay)	^{70}As (^{70}Se decay)
Q_{EC} (MeV)	2.1	2.3
N(0.5 MeV)	11.5	16.4
N(1.0 MeV)	38.6	65.5
N(1.5 MeV)	108	193
N(2.0 MeV)	240	497
N(2.25 MeV)	339	749
N(2.5 MeV)		1090

Table 1: N(E) is the cumulative number of predicted levels up to energy E. Experimentally one obtains 21 for ^{66}Ge and 11 for ^{70}Se.

RIPL2: HF-BCS Total Level Densities

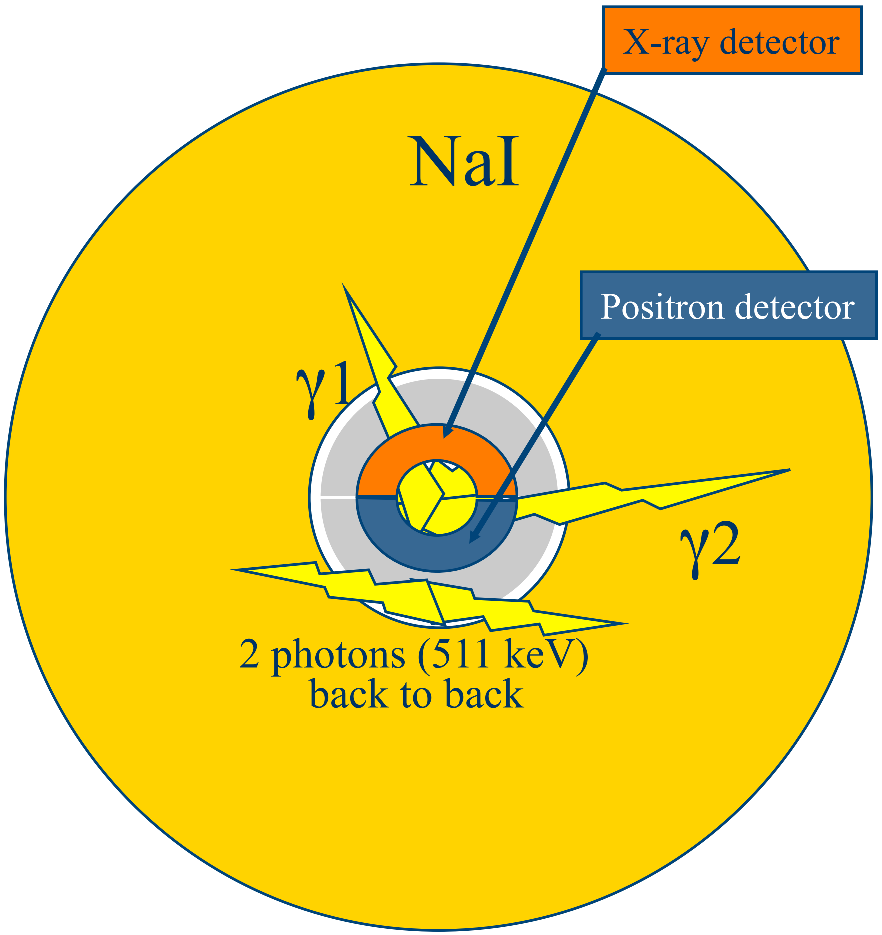
Total nuclear level densities predicted within the statistical partition function approach. The calculations are based on the realistic microscopic single-particle level schemes determined within the HF-BCS model using the MSk7 Skyrme force (*S. Goriely, et al., Atomic Data Nuclear Data Tables 77 (2001)*).

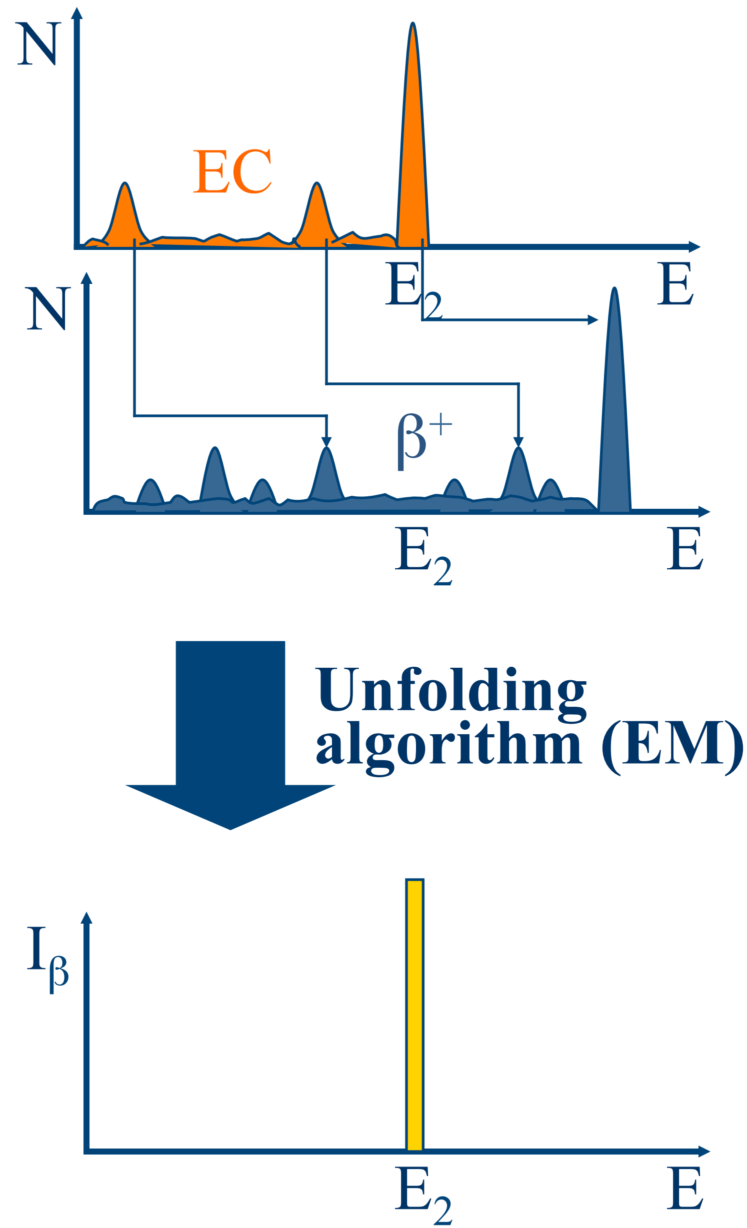
Total Absorption Spectroscopy



Ideal case

Total Absorption Spectroscopy





Real case

Analysis of TAS data

- The TAS inverse problem [1]:

$$d(i) = \sum_j R(i,j) f(j)$$

- Expectation-Maximisation algorithm [2] applied to this problem [1]:

$$f_k(j) = \frac{1}{\sum_i R(i,j)} \sum_i \frac{R(i,j) f_{k-1}(j) d(i)}{\sum_j R(i,j) f_{k-1}(j)}$$

[1] J. L. Taín et al., Nucl. Inst. and Methods A 571 (2007) 728
[2] A. P. Dempster et al., J. R. Statist. Soc. B 39 (1977) 1.

ISOSPIN MIXING

Next, we present the amplitudes of the $T=1$ component admixed into the $T=0$ ground state of $N=Z$ even-even nuclei, which are estimated in our HF+TDA (or HF+RPA) calculations using Skyrme-type interactions. In the literature the isospin-mixing amplitude has been discussed a lot for years. In Fig. 3 we plot our calculated probabilities of the isospin mixture. The probabilities are obtained from the calculated sum of reduced probabilities of the Fermi transitions of $N=Z$ even-even nuclei, assuming that the admixture of the $T>1$ component into the ground state of the $N=Z$ nuclei can be neglected. Since the main $T=0$ component cannot make a contribution to any Fermi transitions to the neighboring $(Z\mp1, N\pm1)$ nuclei which have $|T_Z|=1$, the whole Fermi strength has to come from small isospin-impurity components with $T>0$. When RPA is used instead of

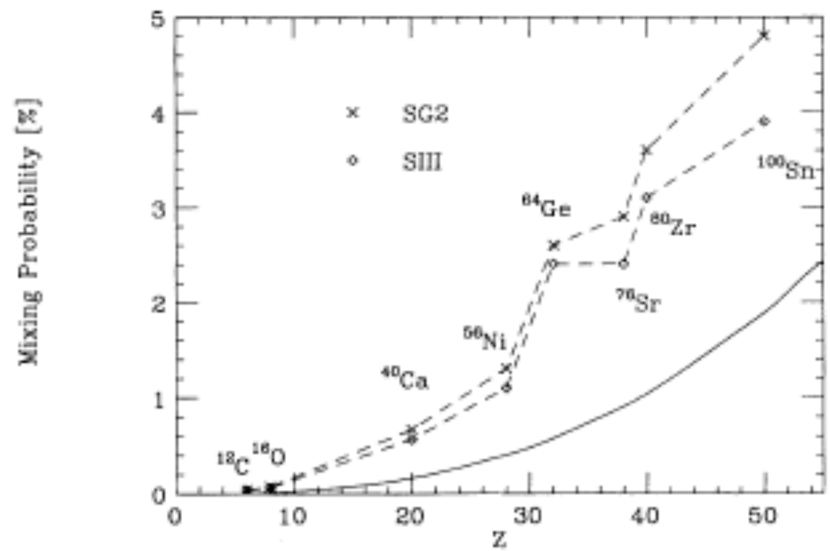


FIG. 3. The isospin-mixing probabilities calculated by the HF+TDA approximation with the Skyrme interactions, SIII (open diamonds) and SG2 (crosses), for $N=Z$ even-even nuclei. The solid curve is taken from Ref. [9].

- *Hamamoto & Sagawa, Phys. Rev. C 48 (1993) R960*