Total Absorption Gamma-ray Spectroscopy (TAS) Applications

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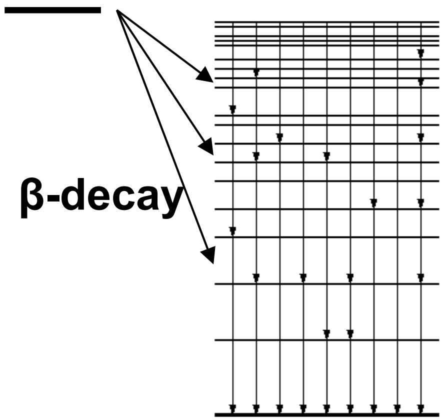
Some basic relations of beta decay



$$ {}_{Z}A_{N} \rightarrow {}_{Z+1}A_{N-1} + e^{-} + \overline{\nu} \qquad \beta^{-} $$

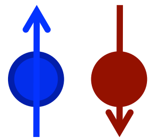
$$ {}_{Z}A_{N} \rightarrow {}_{Z-1}A_{N+1} + e^{+} + \nu \qquad \beta^{+} $$

$$ {}_{Z}A_{N} \rightarrow {}_{Z-1}A_{N+1} + \nu + X_{ray} \qquad \mathrm{EC} $$

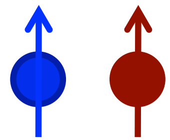
Selection rules of beta decay

The emitted leptons have s=1/2

S=0 (Fermi)



S=1(Gamow-Teller)



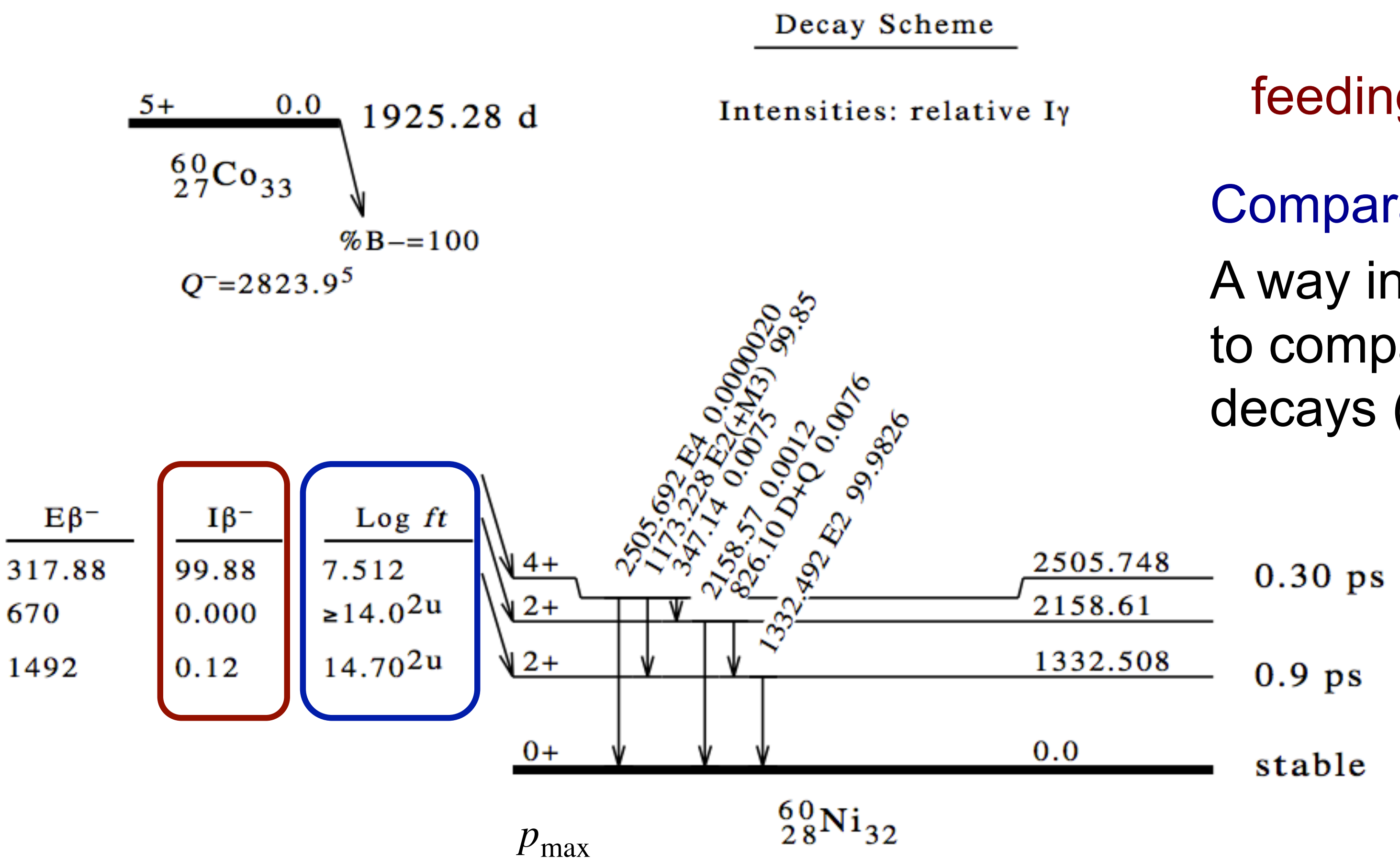
Allowed Transitions (L=0)

$$ \Delta I = \left| I_i - I_f \right| = 0 \quad \text{Fermi} $$

$$ I_i = I_f + 1, \; \Delta I = 0, \, 1 \quad \text{Gamow - Teller} $$

$$ \Delta\pi = (\text{-}1)^{\mathrm{L=0}} = 1, \text{ no change} $$

Example: ^{60}Co decay from http://www.nndc.bnl.gov/



feeding:= $I_\beta = P_f$*100

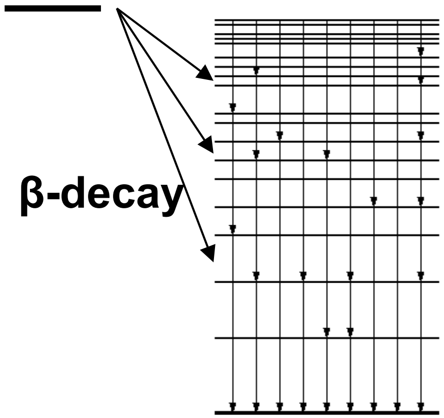
Comparative half-life: ft

A way introduced by Fermi to compare the different decays (Q, Z')

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

$$ft_f = const' \frac{1}{|M_{if}|^2} \qquad t_f = \frac{T_{1/2}}{P_f} \qquad T_{1/2} = \frac{\ln(2)}{\lambda} = \tau \ln(2)$$

Beta decay: feeding /strength distribution



$$ft_f = const' \frac{1}{|M_{if}|^2} = const' \frac{1}{B_{if}}$$

Fermi / Gamow-Teller:

$$B_{i\to f} = \frac{1}{2J_i + 1} \left| \left\langle \Psi_f \right| \tau^{\pm} \ or\ \sigma\tau^{\pm} \left| \Psi_i \right\rangle \right|^2$$

Strength function

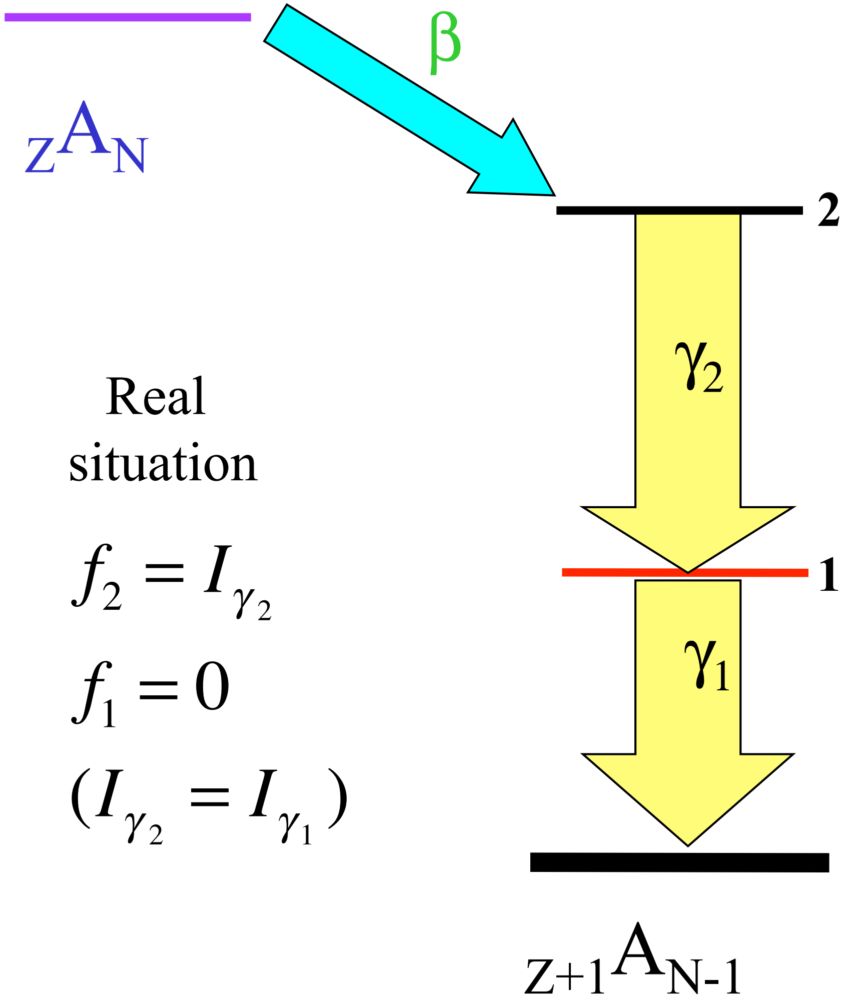
$$S_\beta(E) = \frac{P_\beta(E)}{f(Z', Q_\beta - E) T_{1/2}} = \frac{1}{ft(E)}$$

Beta feeding probability

Relationship

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

The problem of measuring the β-feeding

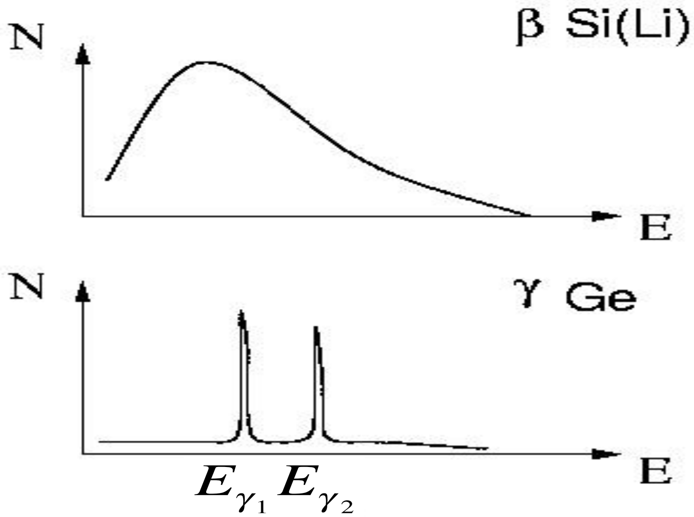


Real situation

$$f_2 = I_{\gamma_2}$$

$$f_1 = 0$$

$$(I_{\gamma_2} = I_{\gamma_1})$$

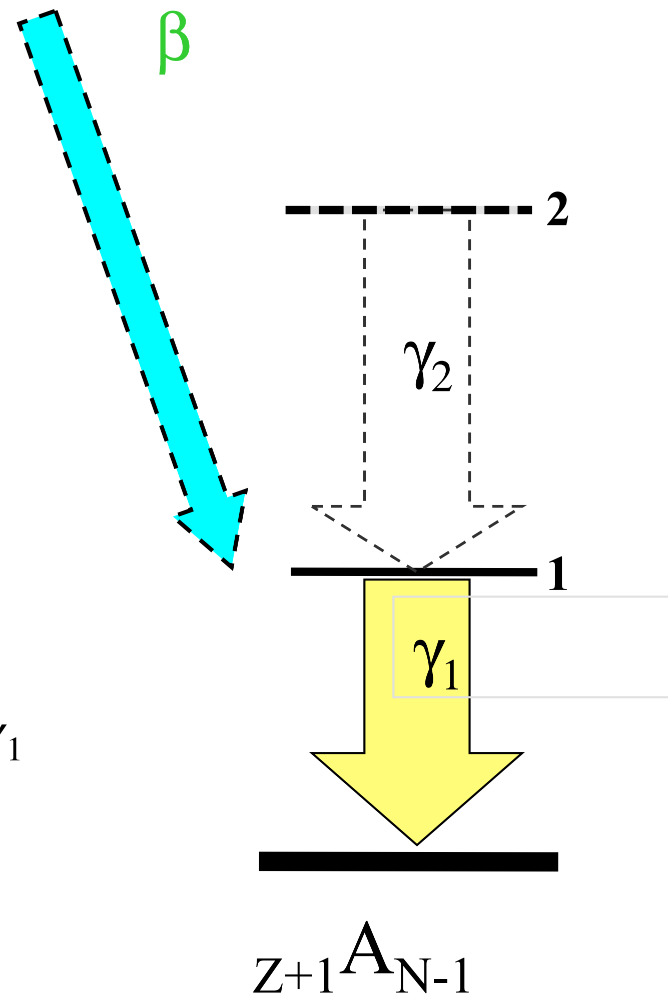


- Ge detectors are conventionally used to construct the level scheme populated in the decay
- From the γ intensity balance we deduce the β-feeding

γ_1

Experimental perspective: the problem of measuring the β- feeding

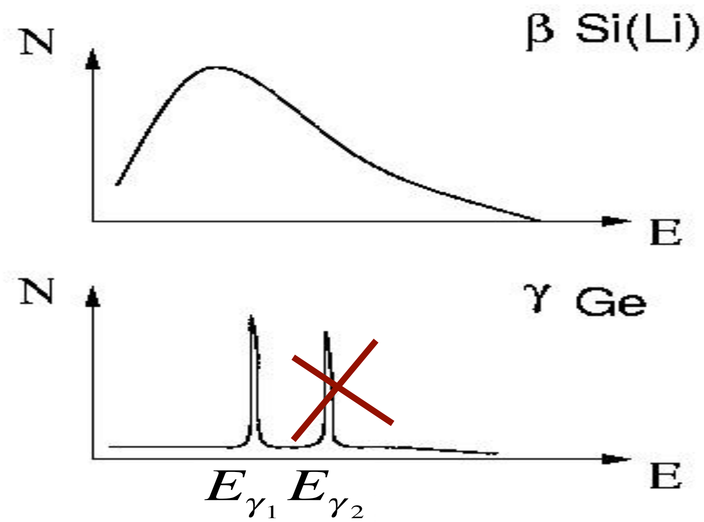
${}_{Z}A_{N}$



Apparent situation

$$f_2 = 0$$

$$f_1 = I_{\gamma_1}$$



- What happens if we miss some intensity

$$Single\ \gamma \sim \varepsilon$$

$$Coinc\ \gamma_1\gamma_2 \sim \varepsilon_1\varepsilon_2$$

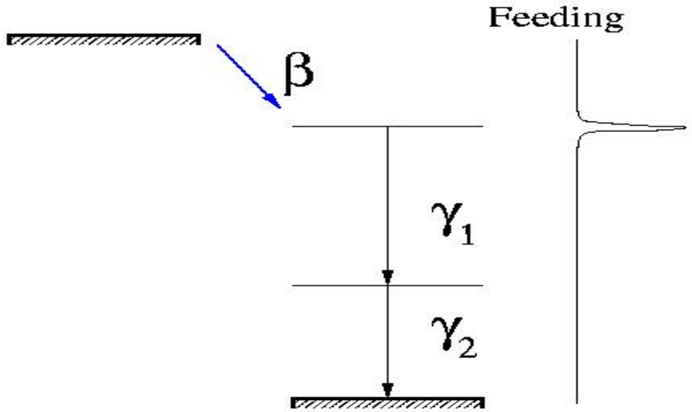
Pandemonium (The Capital of Hell)

introduced by John Milton (XVII) in his epic poem Paradise Lost

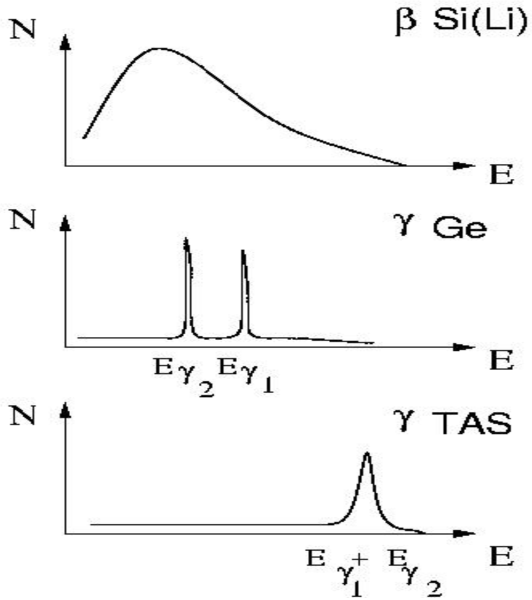
John Martin (~ 1825)

Hardy et al., Phys. Lett. 71B (1977) 307

TAGS measurements



The decay seen by diff. detectors



Since the gamma detection is the only reasonable way to solve the problem, we need a highly efficient device:

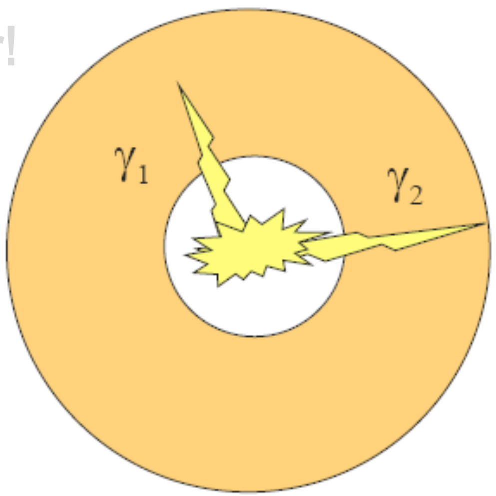
A TOTAL ABSORTION SPECTROMETER

But we need a change in philosophy. Instead of detecting the individual gamma rays we sum the energy deposited by the gamma cascades in the detector.

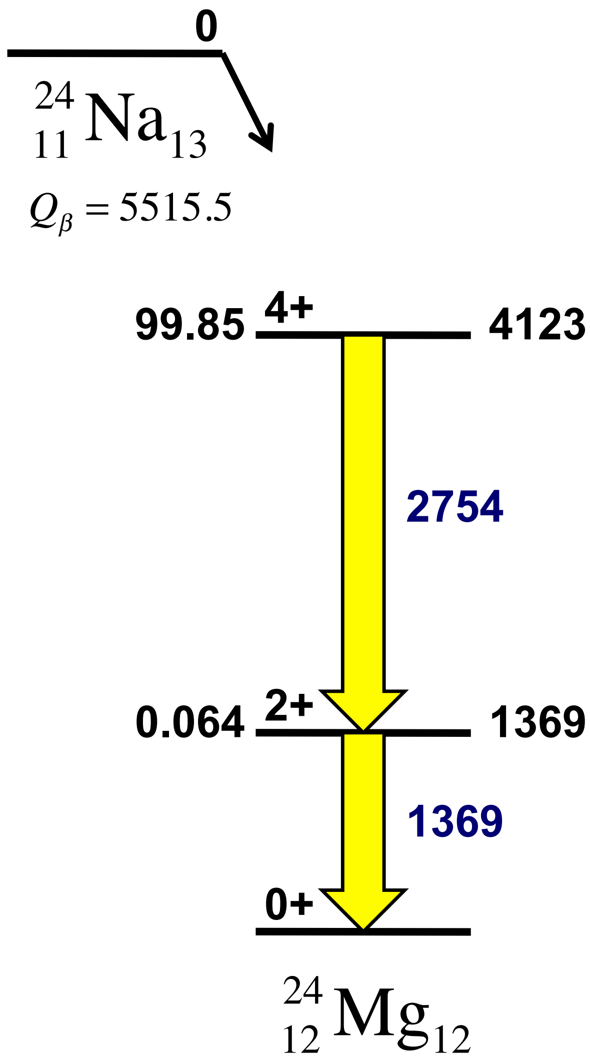
A TAS is like a calorimeter!

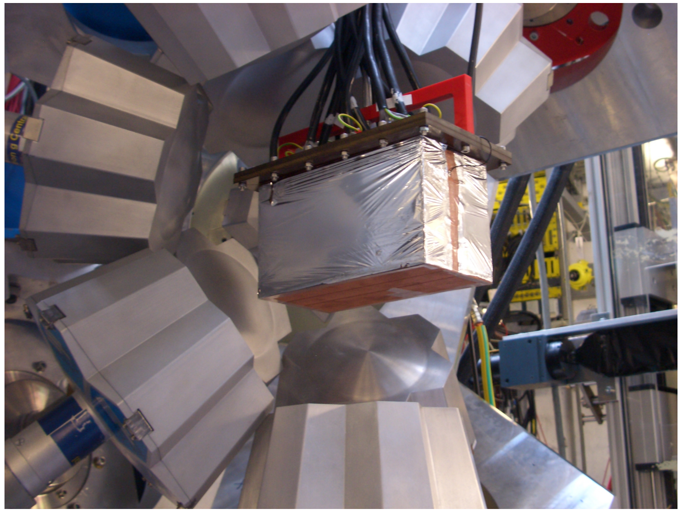
Big crystal, 4π

$$d = R(B) \cdot f$$



Ge detector case: ^{24}Na decay





Stopped Beam Configuration:

15 clusters, 105 Ge capsules

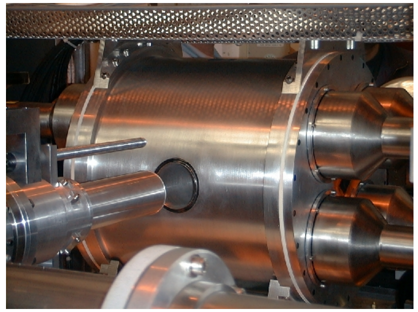
$$\varepsilon_{p1} = 0.10$$ γ$_1$=1369 keV

$$\varepsilon_{p2} = 0.06$$ γ$_2$=2754 keV

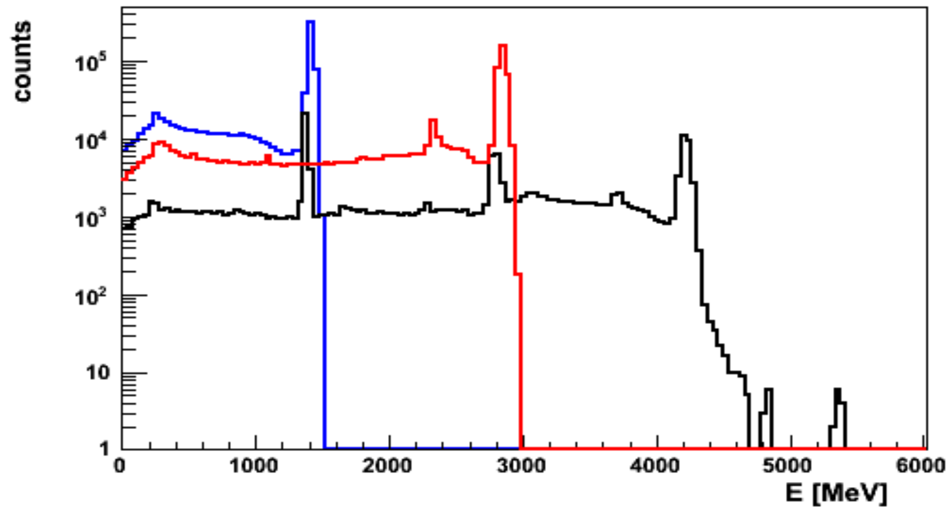
$$\varepsilon_{coinc} = \varepsilon_{p1} \cdot \varepsilon_{p2}$$

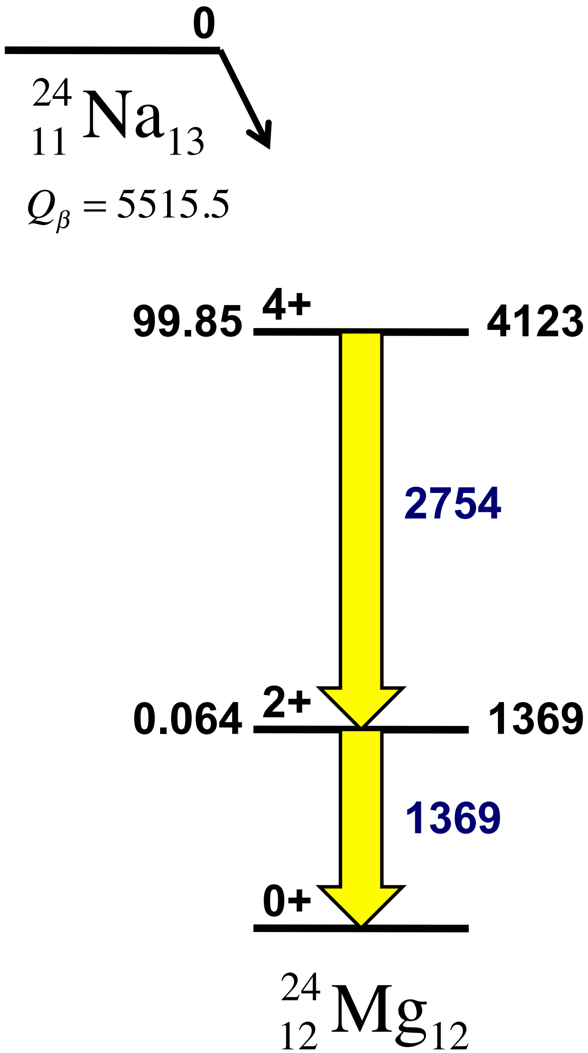
$$\varepsilon_{coinc} = 0.006$$

TAS case: ^{24}Na decay



$$d = R(B) \cdot f$$





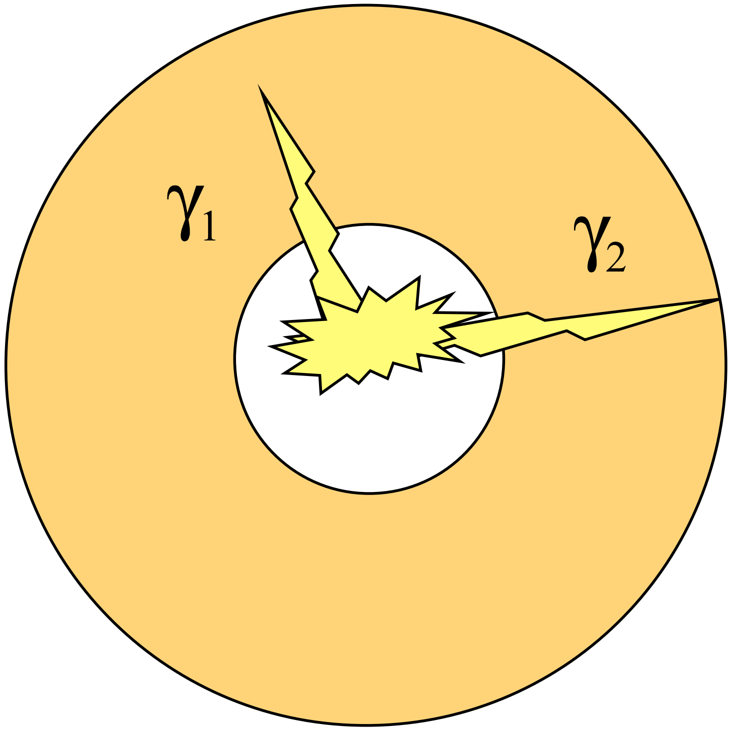
$$\varepsilon_{Total}(1369\ \text{keV}) = 0.81$$

$$\varepsilon_{Total}(2754\ \text{keV}) = 0.72$$

$$\varepsilon_{Total}(cascade) = \varepsilon_{Total}^{\gamma_1}(1-\varepsilon_{Total}^{\gamma_2}) + \varepsilon_{Total}^{\gamma_2}(1-\varepsilon_{Total}^{\gamma_1}) + \varepsilon_{Total}^{\gamma_1}\varepsilon_{Total}^{\gamma_2} = 0.95$$

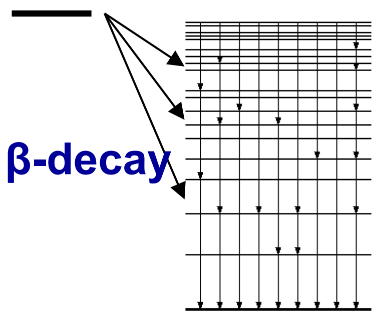
Problems associated with TAS (TAZ)

- The analysis is difficult and lengthy since it requires a careful calculation of the response function of the detector to the decay (but nowadays we have the tools to attack the problem)
- Special care have to be taken with the contaminants



Analysis

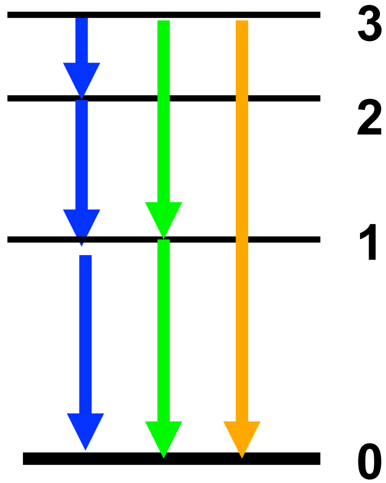
$$d_i = \sum_j R_{ij} f_j \quad or \quad \mathbf{d} = \mathbf{R} \cdot \mathbf{f}$$



R is the response function of the spectrometer, $\boldsymbol{R_{ij}}$ means the probability that feeding at a level ***j*** gives counts in data channel ***i** of the spectrum*

The response matrix $\mathbf{R}$ can be constructed by recursive convolution:

$$\mathbf{R_j} = \sum_{k=0}^{j-1} b_{jk} \mathbf{g_{jk}} \otimes \mathbf{R_k}$$



$\mathbf{g_{jk}}$: γ-response for *j* ➔ *k* transition

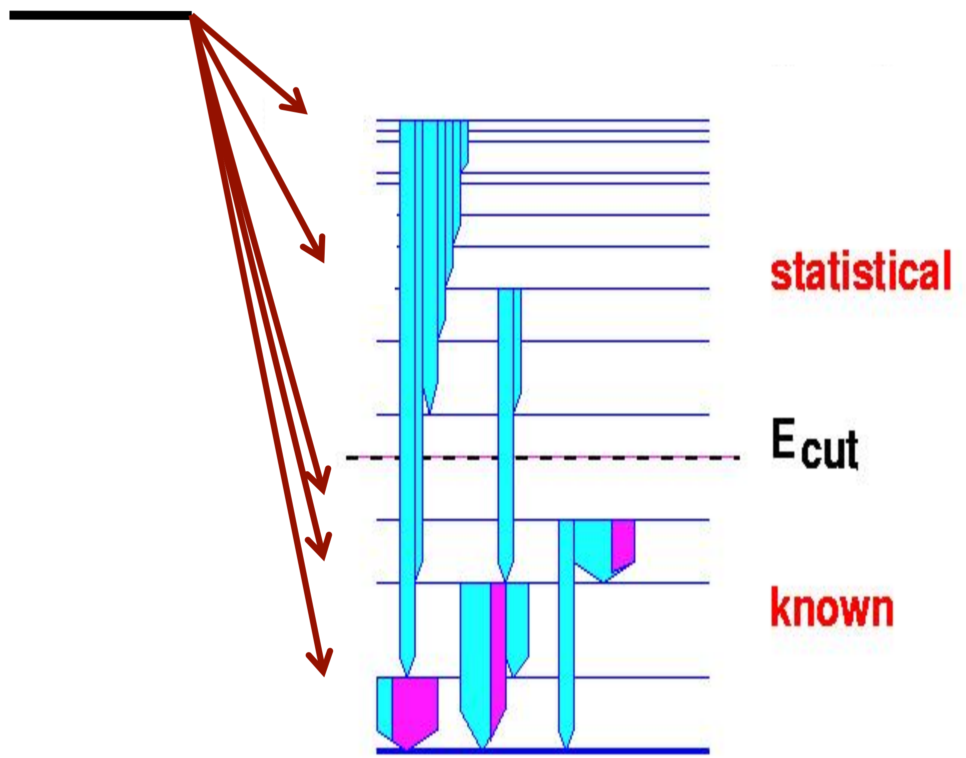
$\mathbf{R_k}$: response for level *k*

b_{jk}: branching ratio for *j* ➔ *k* transition

Mathematical formalization by Tain, Cano, et al.

The complexity of the TAGS analysis: an ill posed problem

$$d = R(B) \cdot f$$

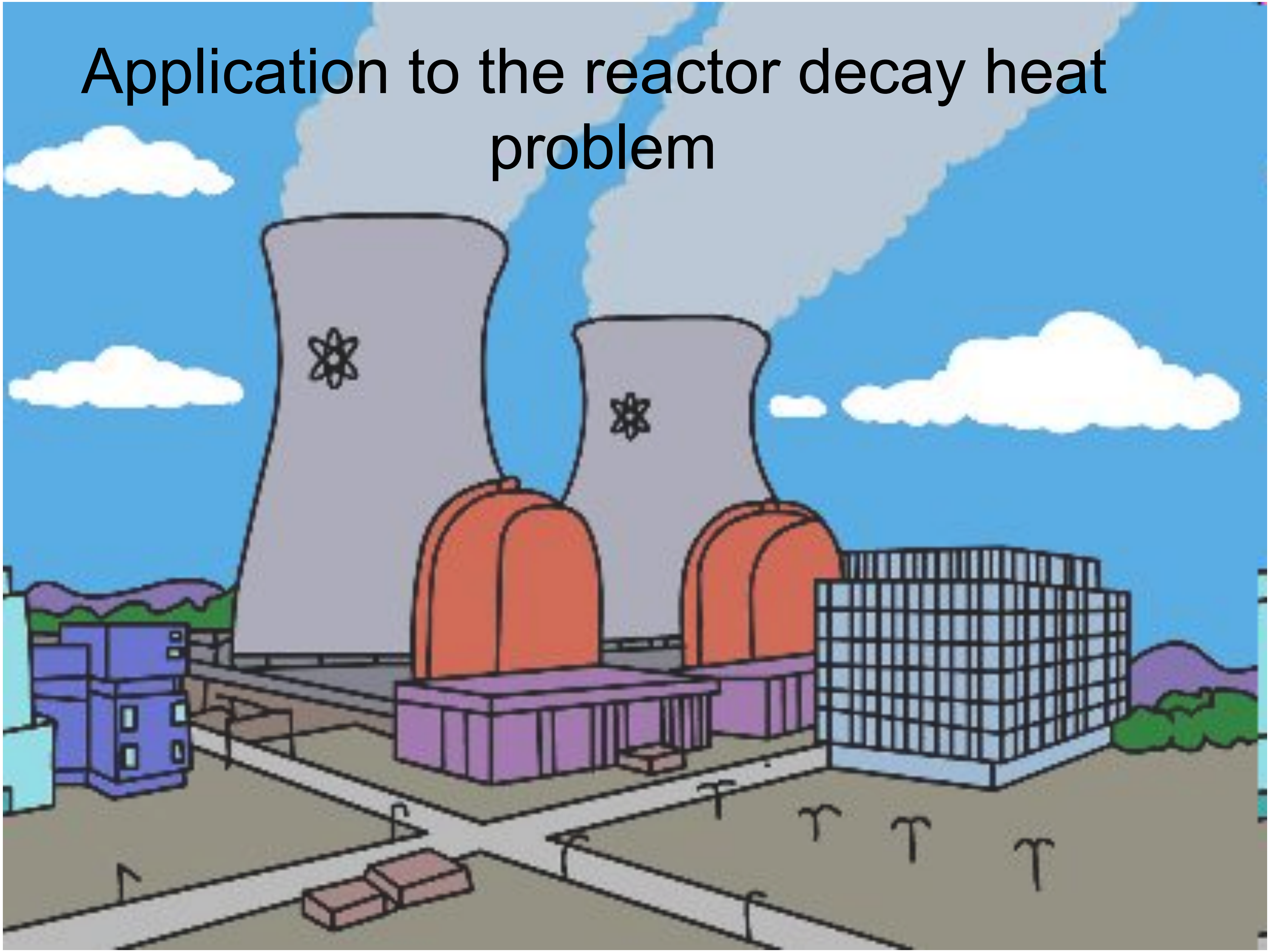


Expectation Maximization (EM) method:
modify knowledge on causes from effects

$$P(f_j | d_i) = \frac{P(d_i | f_j) P(f_j)}{\sum_j P(d_i | f_j) P(f_j)}$$

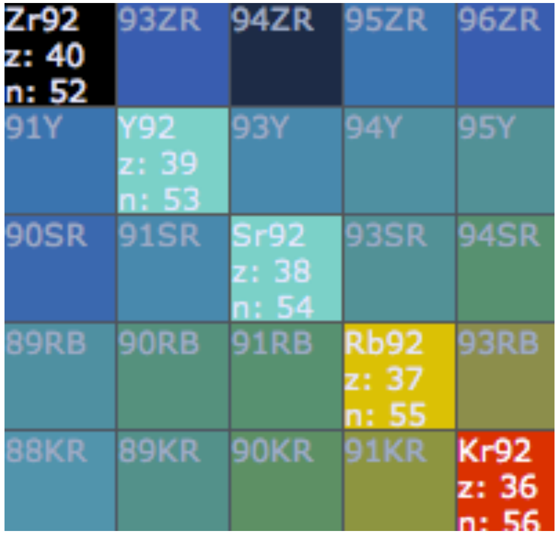
Algorithm: $$f_j^{(s+1)} = \frac{1}{\sum_i R_{ij}} \sum_i \frac{R_{ij} f_j^{(s)} d_i}{\sum_k R_{ik} f_k^{(s)}}$$

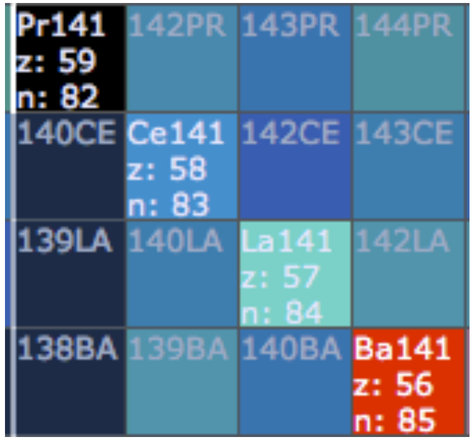
Application to the reactor decay heat problem



Elementary fission

$$n + {}^{235}U \rightarrow {}^{236}U \rightarrow {}^{92}Kr + {}^{141}Ba + 3n$$





$${}^{236}U \qquad Z/N = 92/144 = 0.64$$

$$SN(Z=40) \qquad Z/N = 40/52 = 0.77$$

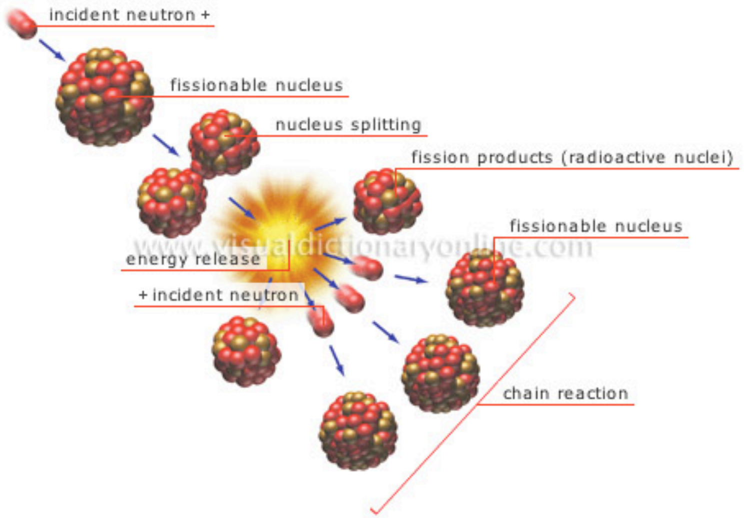
$${}^{92}Kr \qquad Z/N = 36/56 = 0.64$$

$$SN(Z=59) \qquad Z/N = 59/82 = 0.72$$

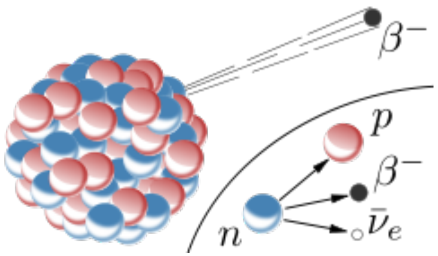
$${}^{141}Ba \qquad Z/N = 56/85 = 0.66$$

Fision products will have a neutron excess compared with stable nuclei around Z=50. So they will decay beta minus

Fission process energy balance and beta decay



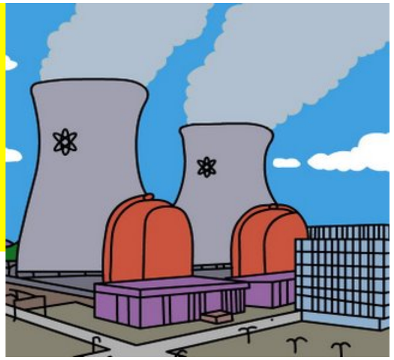
Each fission is approximately followed by 6 beta decays (sizable amount of energy released by the fission products)



Energy released in the fission of ^{235}U	
Energy distribution	MeV
Kinetic energy light fission fragment	100.0
Kinetic energy heavy fission fragment	66.2
Prompt neutrons	4.8
Prompt gamma rays	8.0
Beta energy of fission fragments	7.0
Gamma energy of fission fragments	7.2
Subtotal	192.9
Energy taken by the neutrinos	9.6
Total	202.7

James, J. Nucl. Energy 23 (1969) 517

Decay heat: how to determine it ?



- Measure it (lacks flexibility and it is costly)
- Try to predict or calculate in the best way
  - Statistical method (the first solution)

    Way and Wigner, Phys. Rev. 73 (1948) 1318

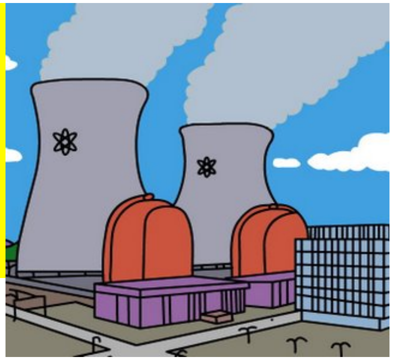
$$B(t) = 1.26t^{-1.2} MeV/s$$

$$\Gamma(t) = 1.40t^{-1.2} MeV/s$$

    later, Griffin, Phys. Rev. 134 (1964) B817

  - Summation calculations (next slide)

Decay heat: summation calculations



$$f(t) = \sum_i E_i \lambda_i N_i(t)$$

E_i Decay energy of the nucleus i (gamma, beta or both)

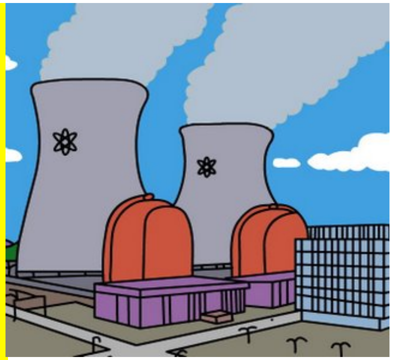
λ_i Decay constant of the nucleus i $\lambda = \frac{\ln(2)}{T_{1/2}}$

N_i Number of nuclei i at the cooling time t

Requirements for the calculations: large databases that contain all the required information (half-lives, mean γ- and β-energies released in the decay, n-capture cross sections, fission yields, this last information is needed to calculate the inventory of nuclides)

The inventory of nuclides:

$$f(t) = \sum_i E_i \lambda_i N_i(t)$$



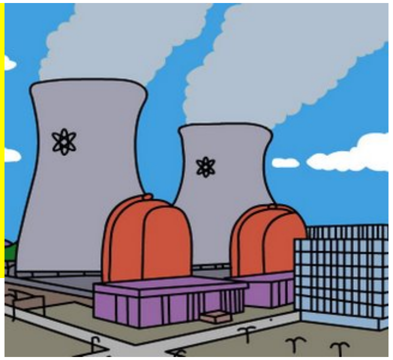
Solve a linear system of coupled first order differential equations

$$\frac{dN_i}{dt} = -(\lambda_i + \sigma_i \phi) N_i + \sum_j f_{j \to i} \lambda_j N_j$$

$$+ \sum_k \mu_{k \to i} \sigma_k \phi N_k + y_i F$$

N_i	Number of nuclides i		$f_{i \to j}$	branching ratio of j to i decay
λ_i	decay constant i		$\mu_{k \to i}$	production rate of i per one neutron capture of k
σ_i	capture cross section i		y_i	fission yield of i
ϕ	neutron flux		F	fission rate

Decay heat: summation calculations



$$f(t) = \sum_i E_i \lambda_i N_i(t)$$

E_i Decay energy of the nucleus i (gamma, beta or both)

λ_i Decay constant of the nucleus i

N_i Number of nuclei i at the cooling time t

The topic of this talk is related basically to the determination of the mean energies released in the decay and their impact.

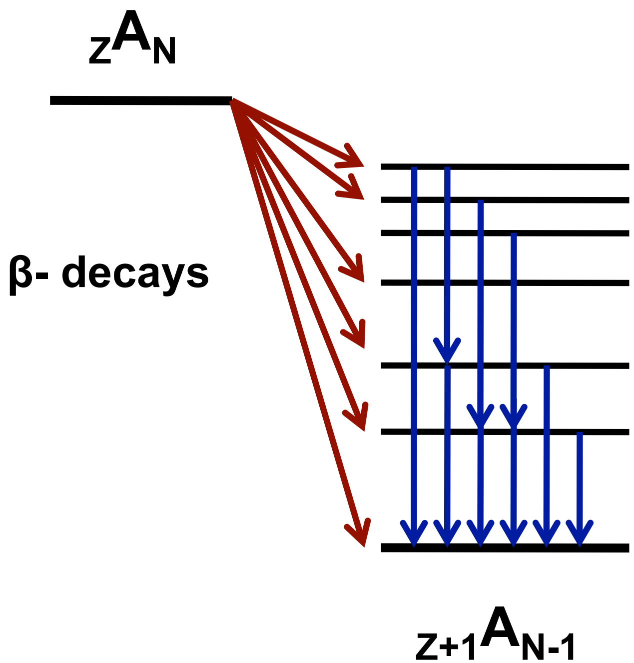
Question, how that is determined?

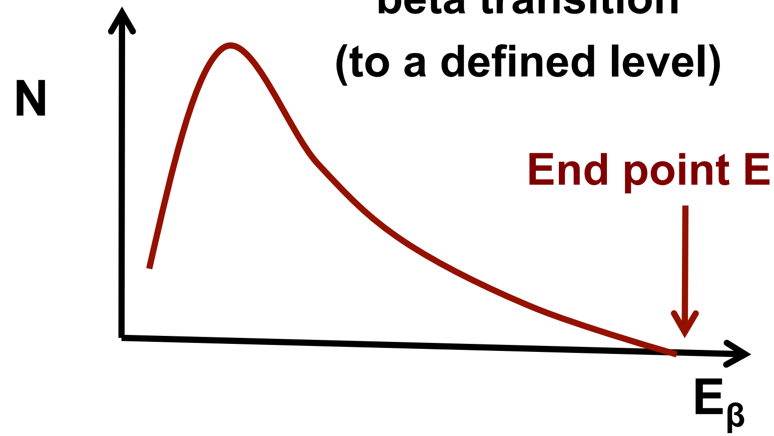
They are based in the data available from conventional nuclear structure databases (formulas later).

How the mean energies are determined ?

$$f(t) = \sum_i E_i \lambda_i N_i(t)$$

DATABASES:
feeding or beta decay prob. distributions

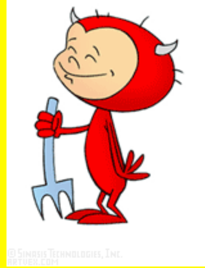




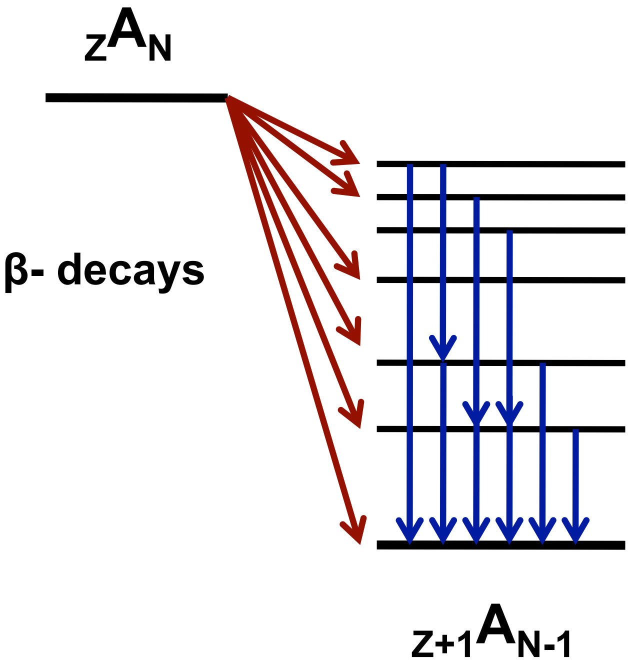
$$\overline{E}_\beta = \sum_i I_\beta(E_i) \langle E_{\beta,i} \rangle$$

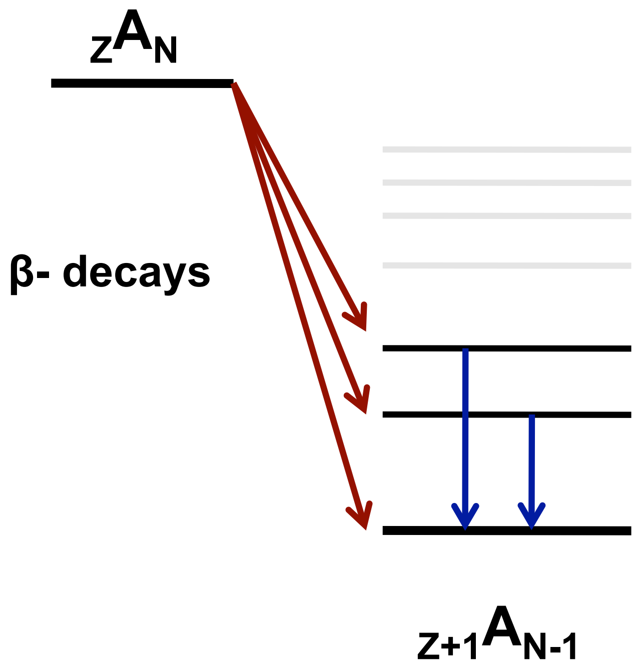
$$\overline{E}_\gamma = \sum_i I_\beta(E_i) E_i$$

Mean energies and Pandemonium



$$f(t) = \sum_i E_i \lambda_i N_i(t)$$





$$\overline{E}_\beta = \sum_i I_\beta(E_i) \langle E_{\beta,i} \rangle$$

$$\overline{E}_\gamma = \sum_i I_\beta(E_i) E_i$$

$\overline{E}_\beta$ overestimation

$\overline{E}_\gamma$ underestimation

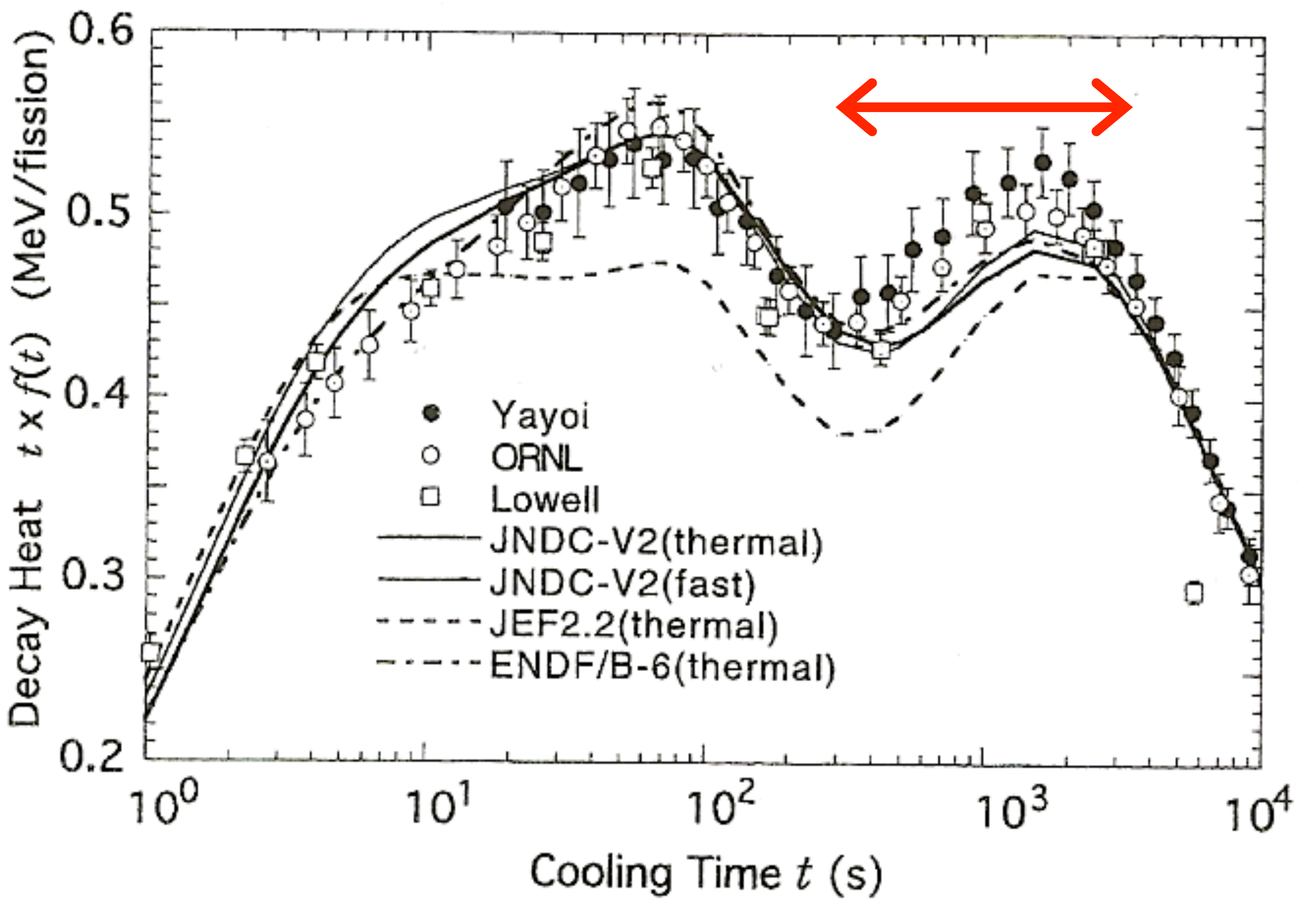
The beginning …

We got interested in the topic after the work of Yoshida and co-workers (Journ. of Nucl. Sc. and Tech. 36 (1999) 135)

^{239}Pu example (similar situation for ^{235,238}U)

Detective work: identification of some nuclei that could be blamed for the anomaly ^{102,104,105}Tc

^{239}Pu example (γ component)




Chair
Alejandro
Algora
Spain
Jose L.
Tain
Spain

The famous list
WPEC-25 (IAEA working group)

Radionuclide	Priority	Radionuclide	Priority	Radionuclide	Priority
35-Br-86	1	41-Nb-99	1	52-Te-135	2
35-Br-87	1	41-Nb-100	1	53-I-136	1
35-Br-88	1	41-Nb-101	1	53-I-136m	1
36-Kr-89	1	41-Nb-102	2	53-I-137	1
36-Kr-90	1	42-Mo-103	1	54-Xe-137	1
37-Rb-90m	2	42-Mo-105	1	54-Xe-139	1
37-Rb-92	2	43-Tc-102	1	54-Xe-140	1
38-Sr-89	2	43-Tc-103	1	55-Cs-142	3
38-Sr-97	2	43-Tc-104	1	56-Ba-145	2
39-Y-96	2	43-Tc-105	1	57-La-143	2
40-Zr-99	3	43-Tc-106	1	57-La-145	2
40-Zr-100	2	43-Tc-107	2		
41-Nb-98	1	51-Sb-132	1		

37 nuclides, of which 23 were given first priority.

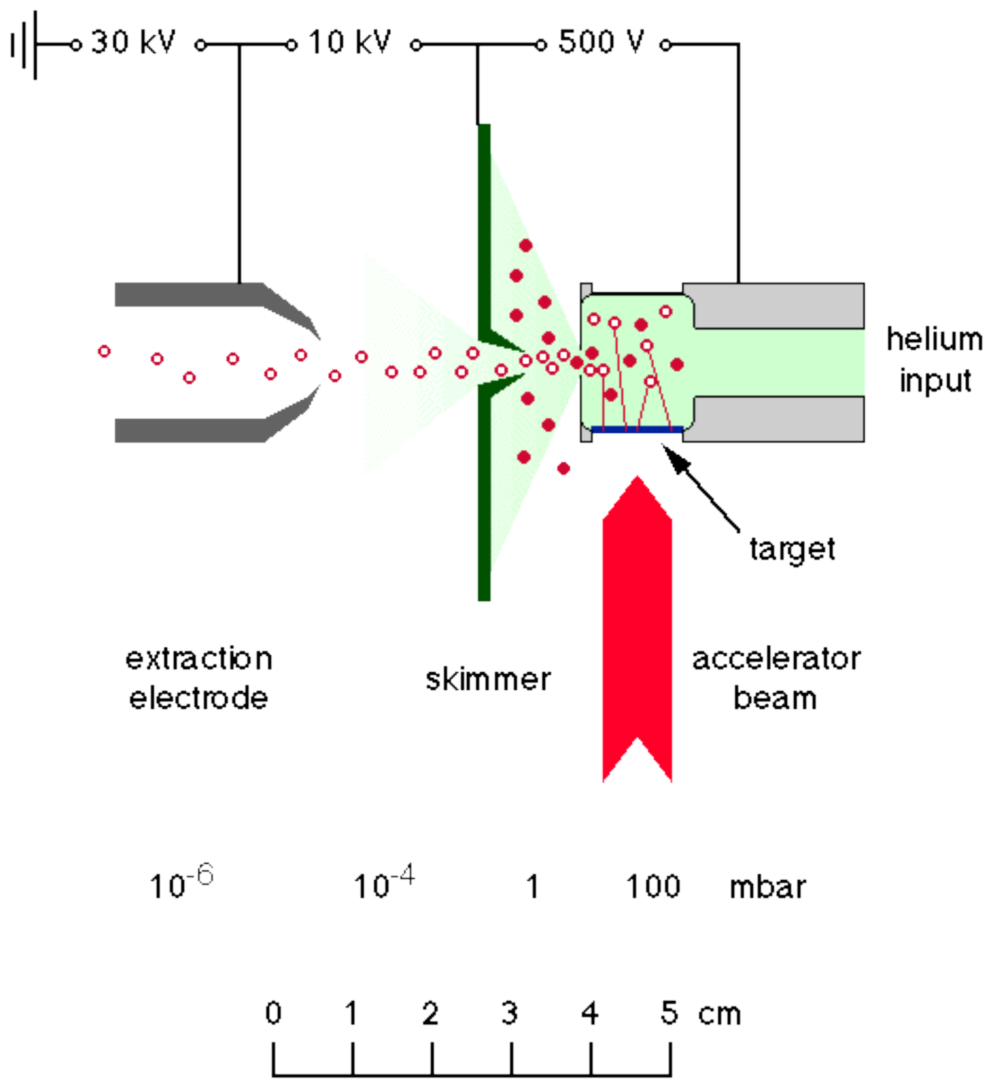
Our favorite place for “polar” experiences

Published cases until know:

Yoshida’s work ($^{102,104,105}Tc$)

WPEC-25 ($^{102,104,105,106,107}Tc$, ^{105}Mo, ^{101}Nb)

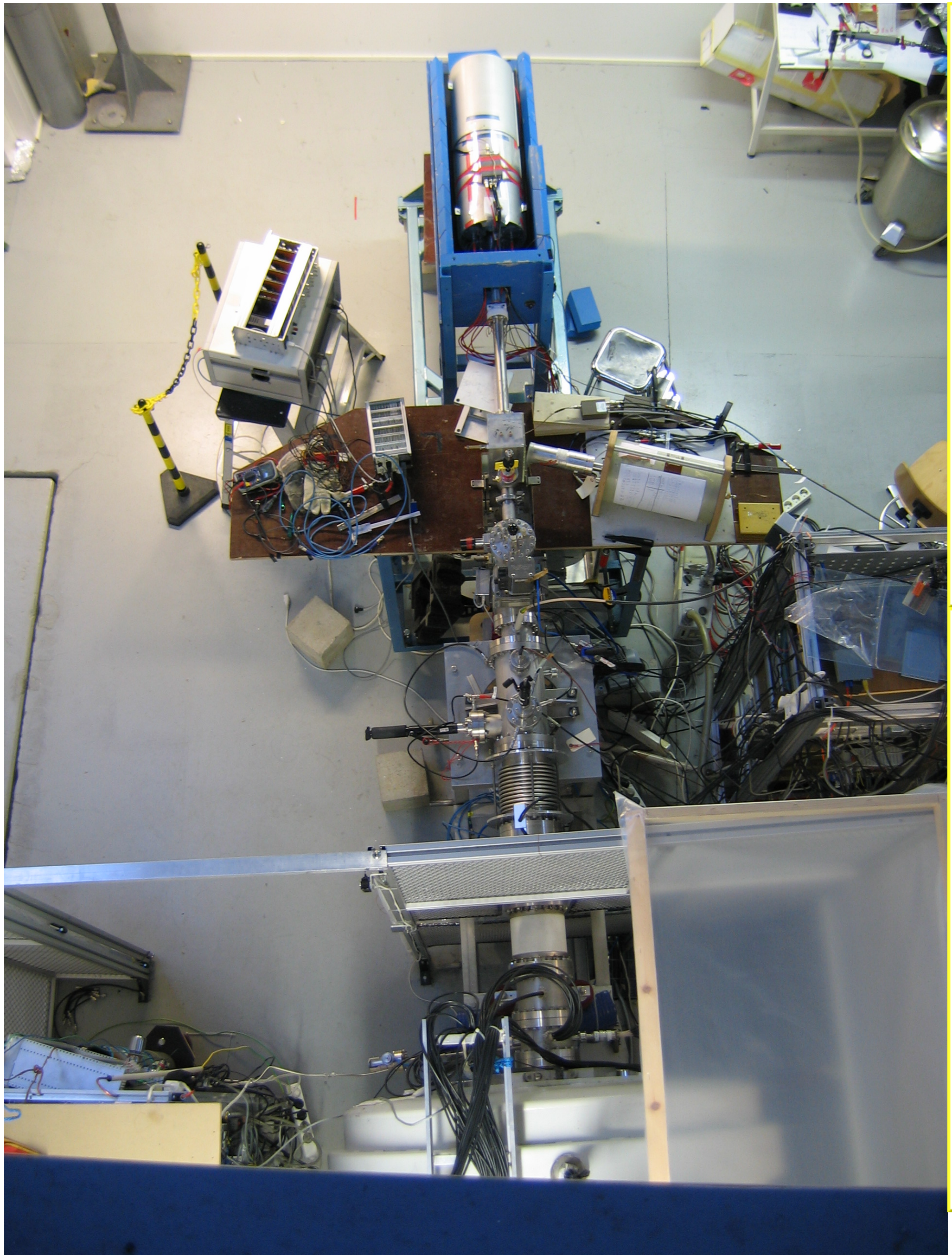
The ion guide technique

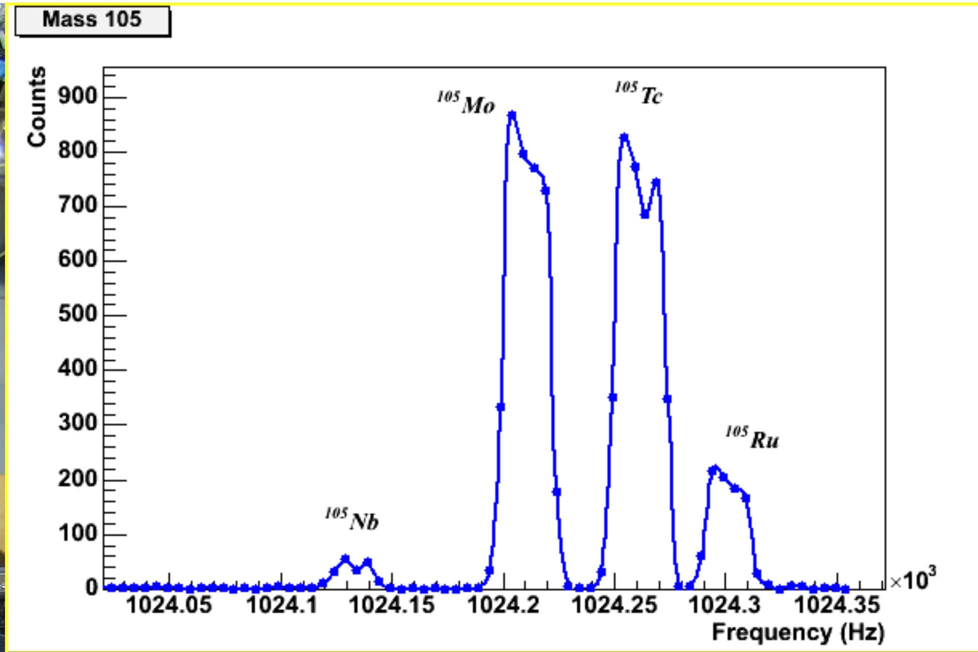


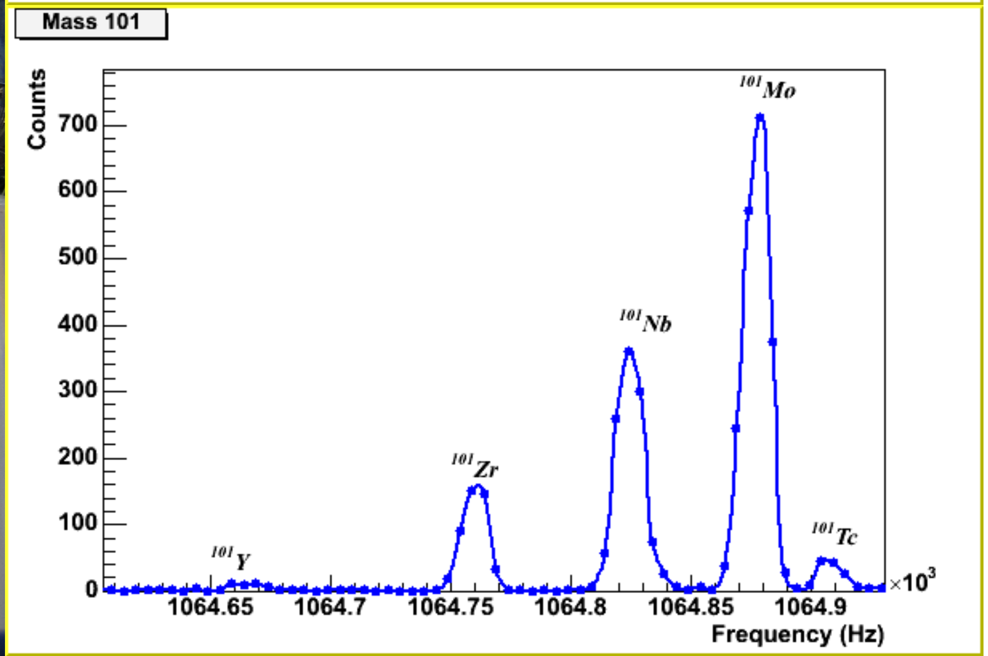
Generic ion guide: the nuclear reaction products are stopped in a gas and are transported through a differential pumping system into the accelerator stage of the mass separator.

The process is fast enough for the ions to survive as single charged ions. The system is chemically insensitive and very fast (sub-ms).

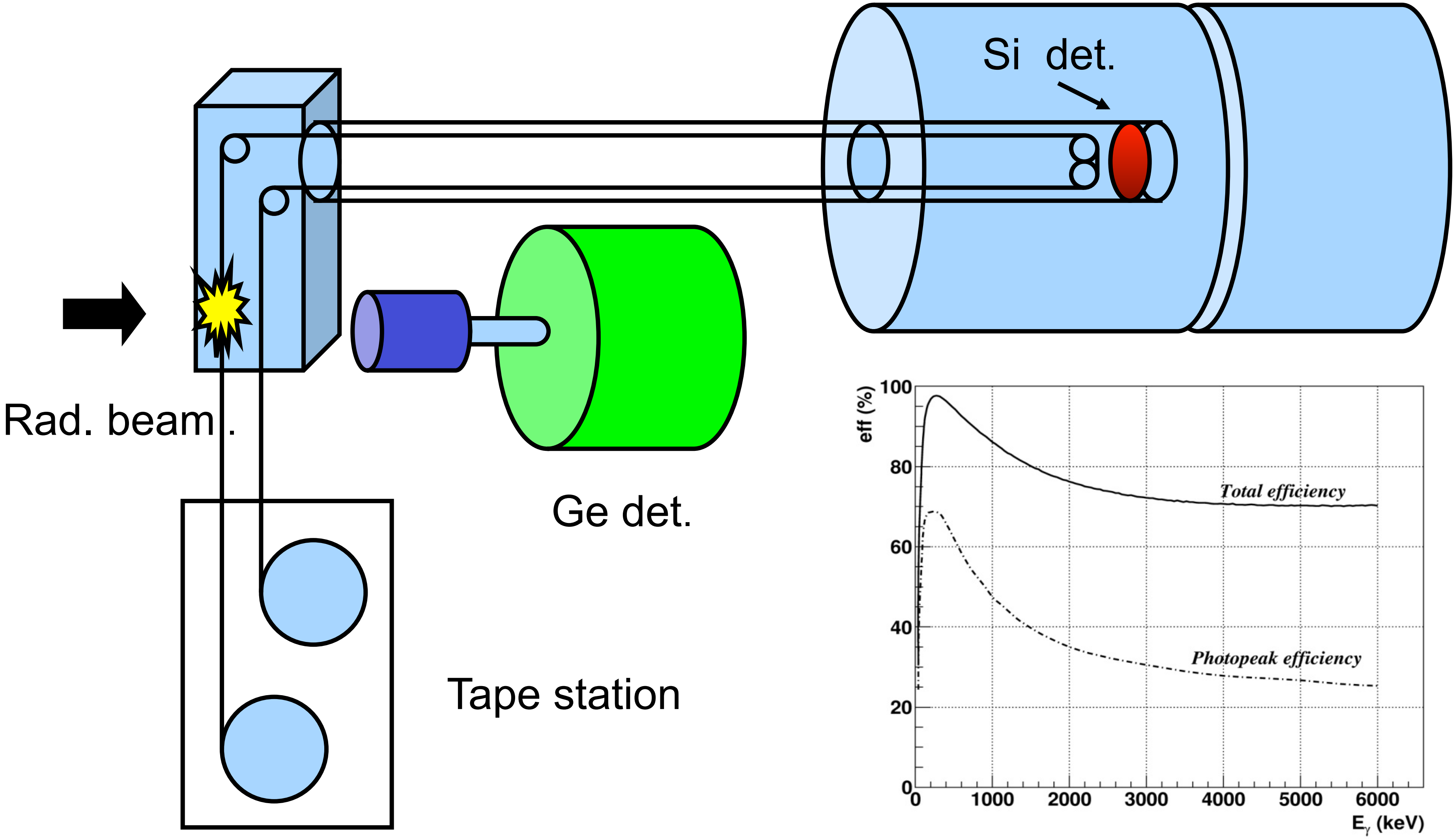
New feature: trap-assisted spectroscopy



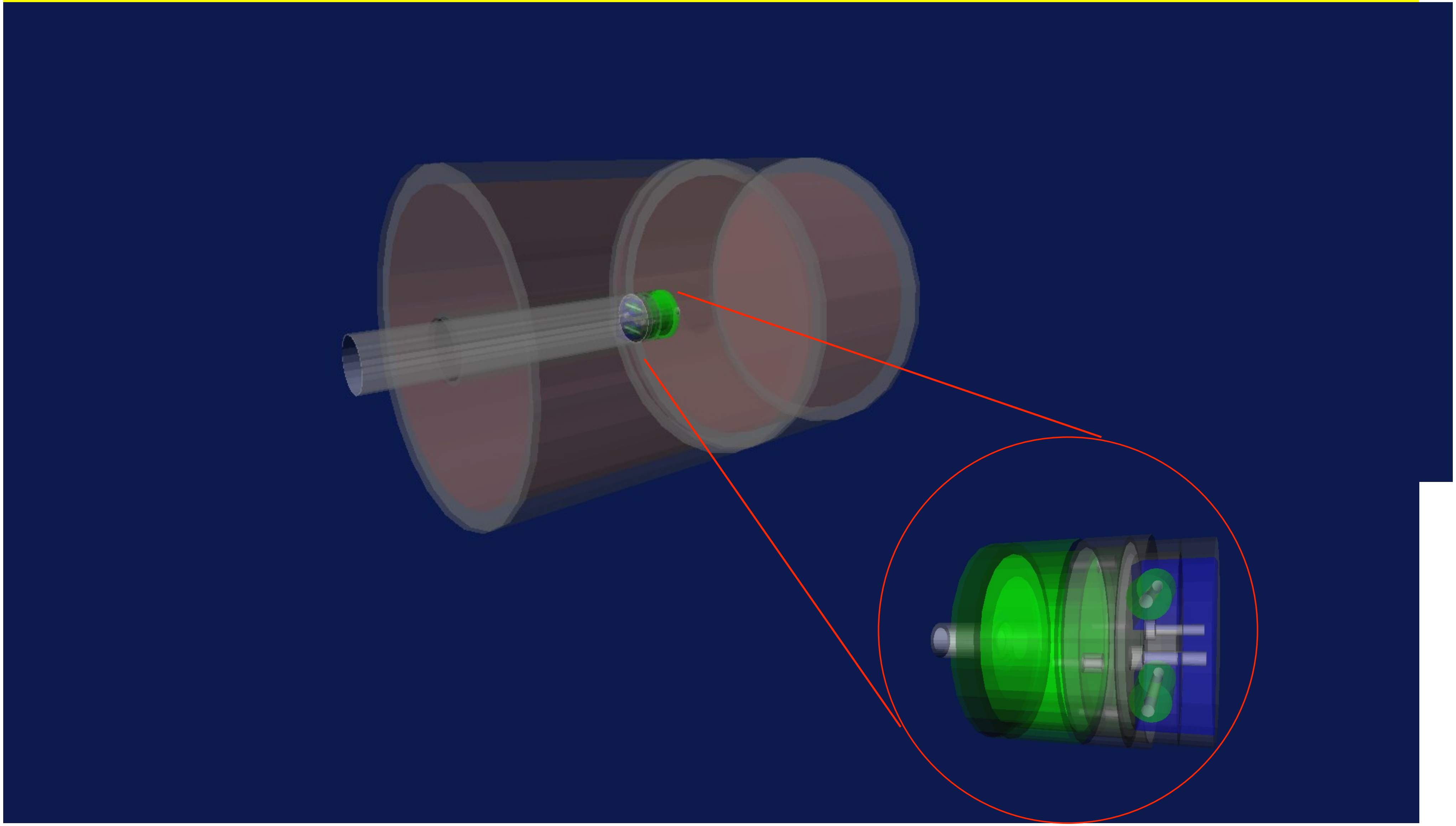




Experimental setup at Jyväskylä



Monte Carlo simulations of the setup: geometry (Geant 4)



Analysis of ^{104}Tc

$$d = R(B) \cdot f$$

Expectation Maximization (EM) method:
modify knowledge on causes from effects

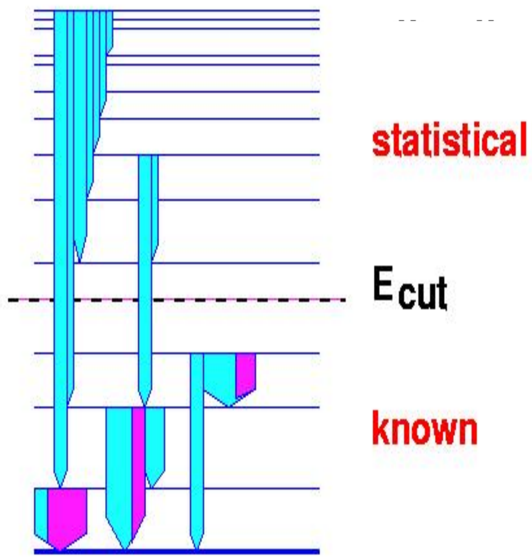
$$P(f_j | d_i) = \frac{P(d_i | f_j) P(f_j)}{\sum_j P(d_i | f_j) P(f_j)}$$

Algorithm: $$f_j^{(s+1)} = \frac{1}{\sum_i R_{ij}} \sum_i \frac{R_{ij} f_j^{(s)} d_i}{\sum_k R_{ik} f_k^{(s)}}$$

Tain et al. NIM A571 (2007) 719,728

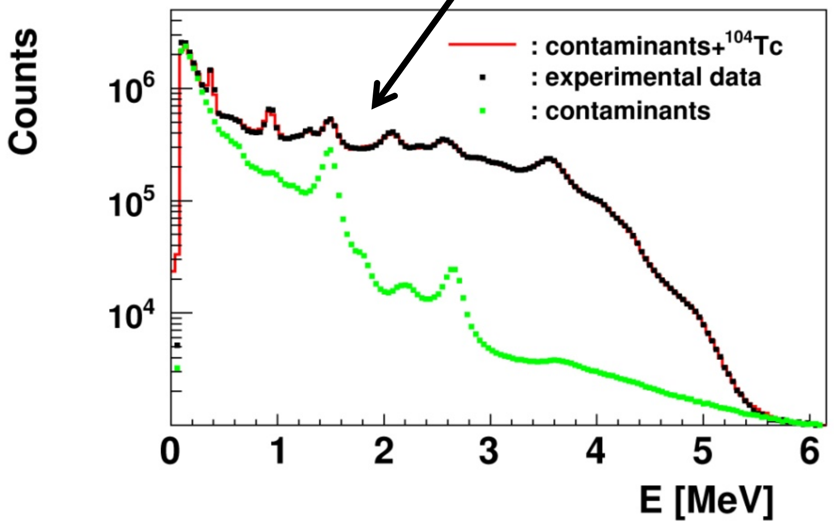
Some details (d=R(B)f)
Known levels up to: 1515 keV excitation

From 1720 keV excitation up to the Q_β =5516(6) value we use an statistical nuclear model to create the branching ratio matrix (Back Shifted Fermi formula for the level density & γ-ray strength functions)



Results of the analysis for ^{104}Tc

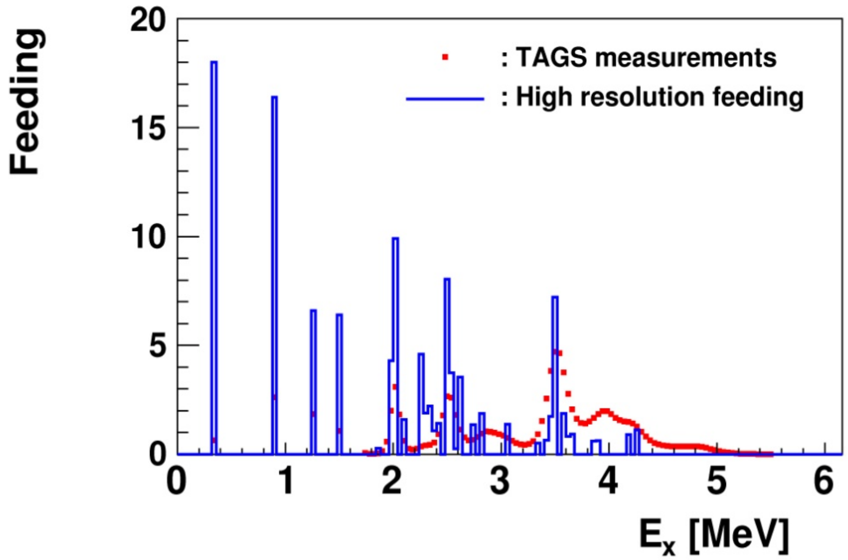
d and R(b)*f^{final}

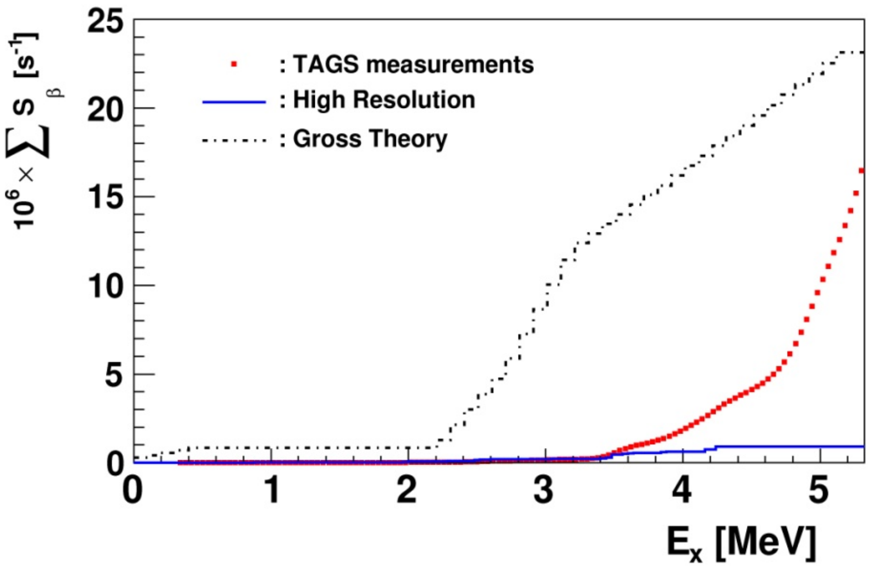


$T_{1/2}$ = 1098(18) s; Q_β= 5516(6) keV

E_β(TAGS) = 931 (10) keV
E_β(JEFF-3.1) = 1595 (75) keV
} ΔE_β = -664 keV

E_γ(TAGS) = 3229 (24) keV
E_γ(JEFF-3.1) = 1890 (31) keV
} ΔE_γ = 1339 keV





D. Jordan, PhD Thesis, Valencia, 2010

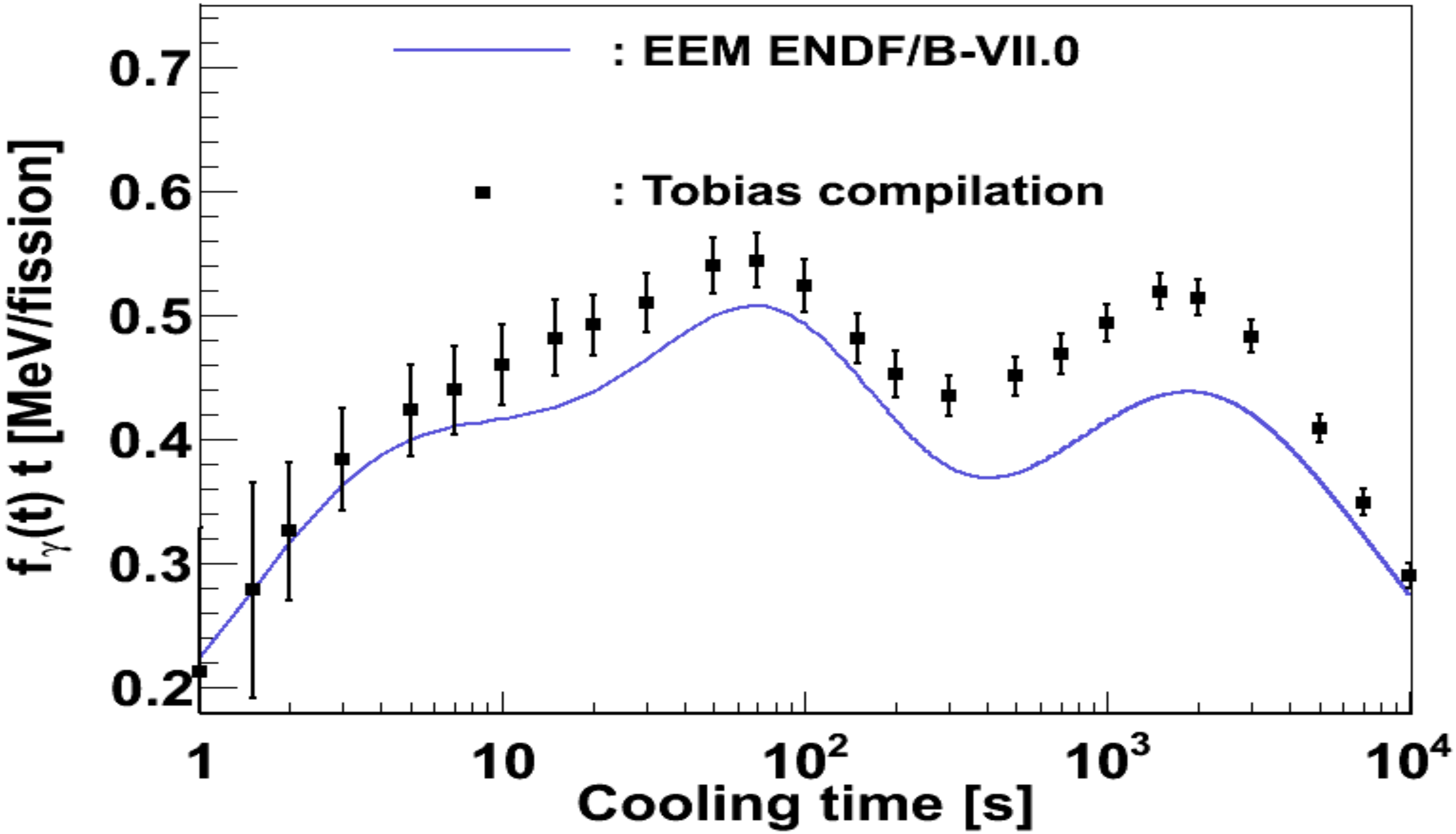
Results published up to now

Isotope	Energy type	TAGS [keV]	JEFF-3.1 [keV]	ENDF/B-VII [keV]	Difference [keV]
^{101}Nb (7.1 s)	beta	1797 (133)	1863 (307)	1966 (307)	-67/-169
	gamma	445 (279)	245 (22)	270 (22)	200/175
^{102}Tc (5.28 s)	beta	1935 (11)	1945 (16)	1945 (16)	-10
	gamma	106 (23)	81 (5)	81 (5)	25
^{104}Tc (1098 s)	beta	931 (10)	1595 (75)	1595 (75)	-664
	gamma	3229 (24)	1890 (31)	1890 (31)	1339
^{105}Tc (456 s)	beta	764 (81)	1310 (173)	1310 (205)	-546
	gamma	1825 (174)	668 (19)	665 (19)	1157/1160
^{105}Mo (35.6 s)	beta	1049 (44)	1922 (122)	1922 (122)	-873
	gamma	2407 (93)	551 (24)	552 (24)	1856/1855
^{106}Tc (35.6 s)	beta	1457 (30)	1943 (69)	1906 (67)	-486/-449
	gamma	3132 (70)	2191 (51)	2191 (51)	941
^{107}Tc (21.2 s)	beta	1263 (212)	2056 (254)	2054 (254)	-793/-791
	gamma	1822 (450)	515 (11)	515 (11)	1307

$$Q_\beta(^{102}Tc \rightarrow ^{102}Ru) = 4532 keV \qquad Q_\beta(^{101}Nb \rightarrow ^{101}Mo) = 4569 keV$$

Impact of the results for ^{239}Pu: electromagnetic component

Motivated by Yoshida *et al.* (Journ. of Nucl. Sc. and Tech. 36 (1999) 135) and WPEC-25



Impact of the results for ^{239}Pu: electromagnetic component

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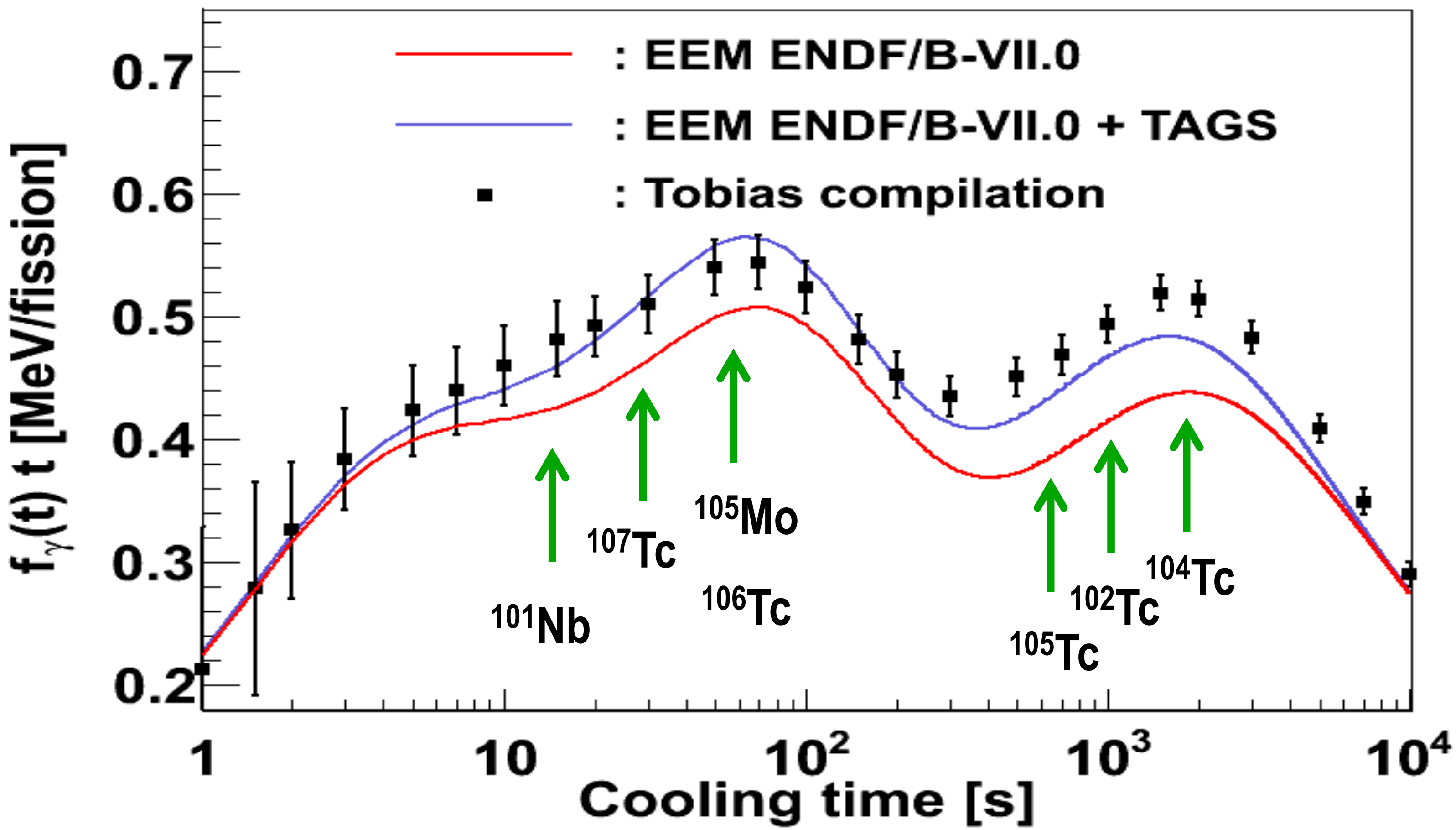


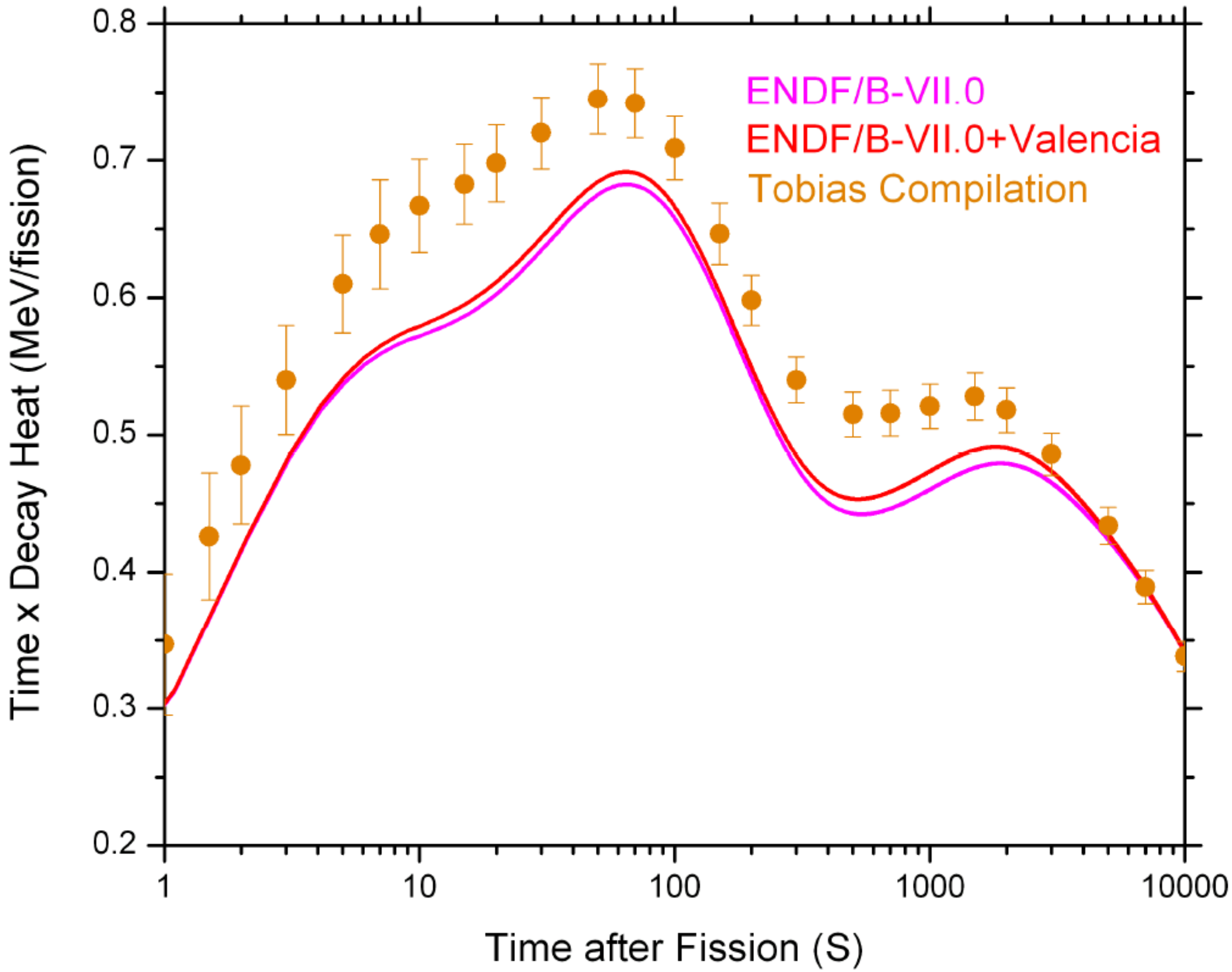
PhD Thesis D. Jordan , A. Algora, Phys. Rev. Letts. 105, 202505,

K. P. Rykaczewsky, Physics 3, 94 (2011)

DH Courtesy A. Sonzogni

Results also confirmed by R. W. Mills using JEFF 3.1

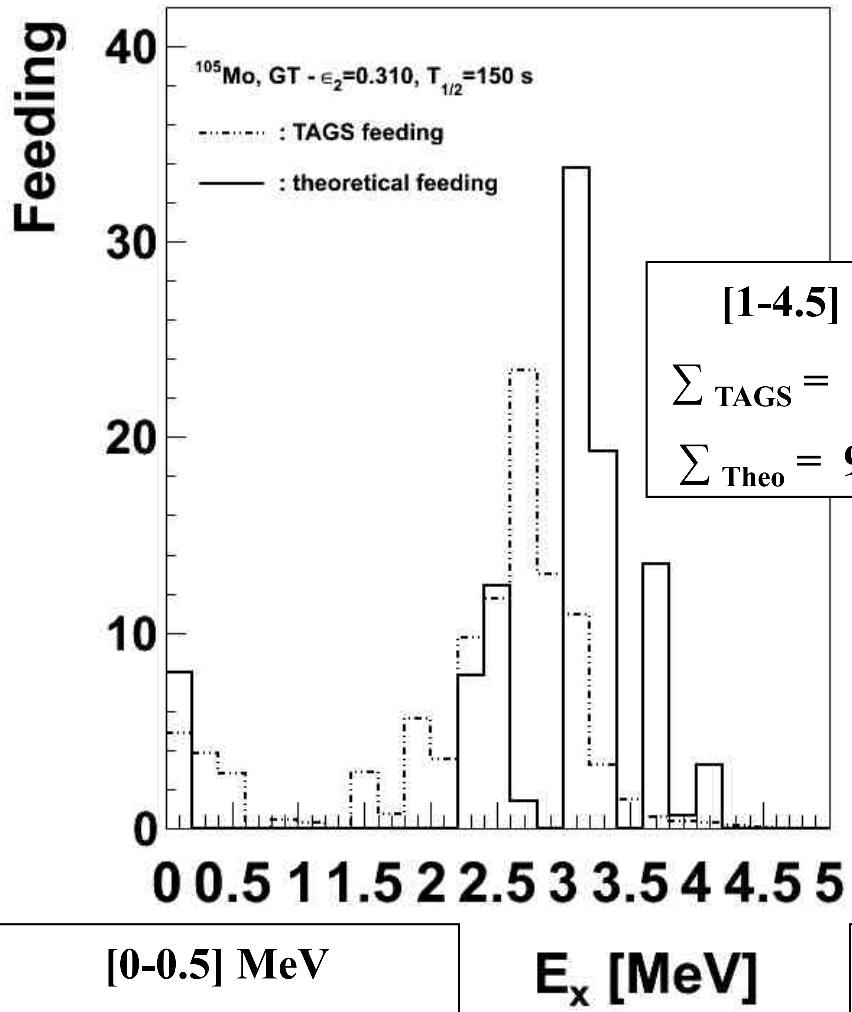
Impact of the results for ^{235}U



Side product: nuclear structure aspects

- **Test of nuclear models (for the moment difficult)**
- **Region where shape effects may be important**
- **Triaxiality has been showed present in the Ru isotopes**
- **Role of FF component**
- **Etc.**

Results of QRPA calculations(I)
$T_{1/2}(exp) = 35.6$ s



[1-4.5] MeV

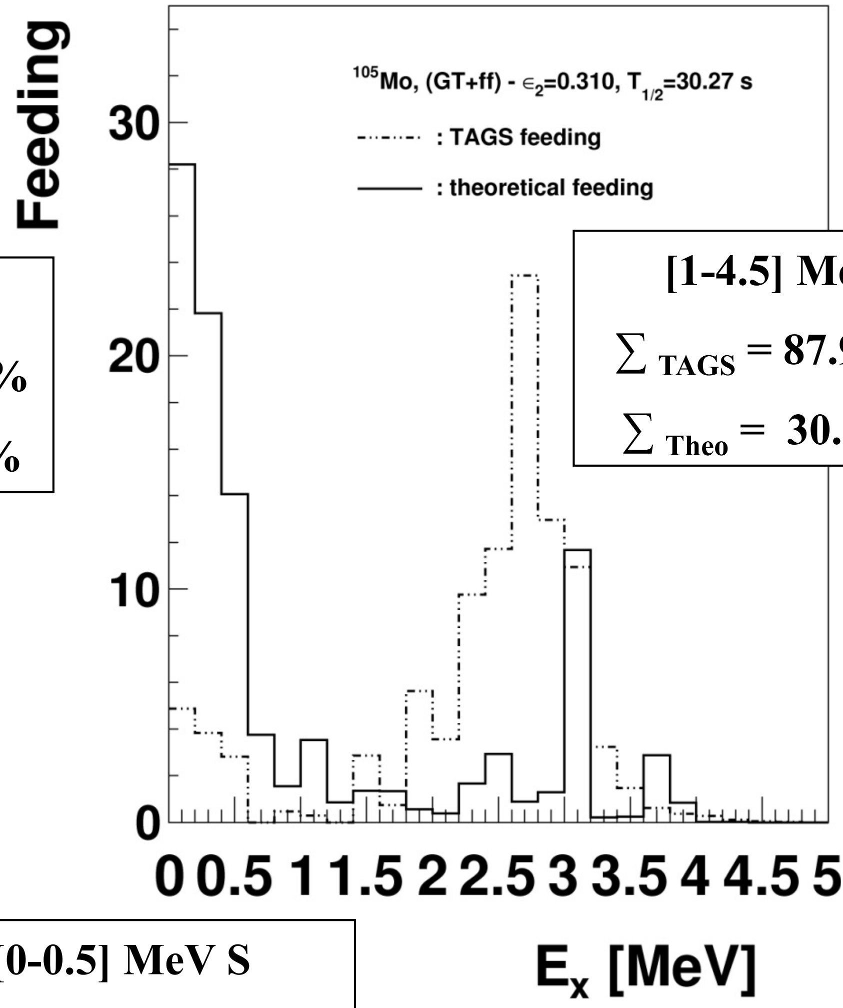
$\sum_{TAGS} =$ 87.99%

$\sum_{Theo} =$ 92.05%

[0-0.5] MeV

$\sum_{TAGS} =$ 11.51%

$\sum_{Theo} =$ 7.94%



[1-4.5] MeV

$\sum_{TAGS} =$ 87.99 %

$\sum_{Theo} =$ 30.62%

[0-0.5] MeV S

$\sum_{TAGS} =$ 11.51%

$\sum_{Theo} =$ 67.84 %

Kratz *et al.*

Nuclear reactors and neutrino phyisics I

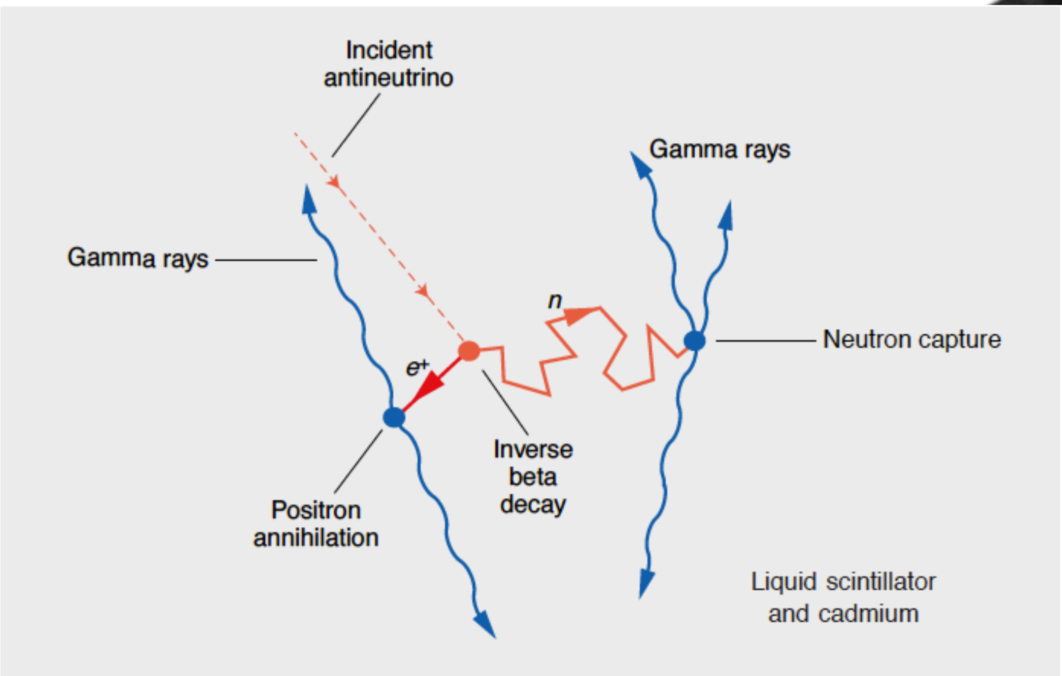
Neutrino postulated by Pauli, 1930

Nuclear reactors are the strongest human source of neutrinos.

Reines, Cowan,1956

$$\bar{\nu} + p \rightarrow e^{+} + n$$

$$n + {}^{108}Cd \rightarrow {}^{109m}Cd \rightarrow {}^{109}Cd + \gamma$$



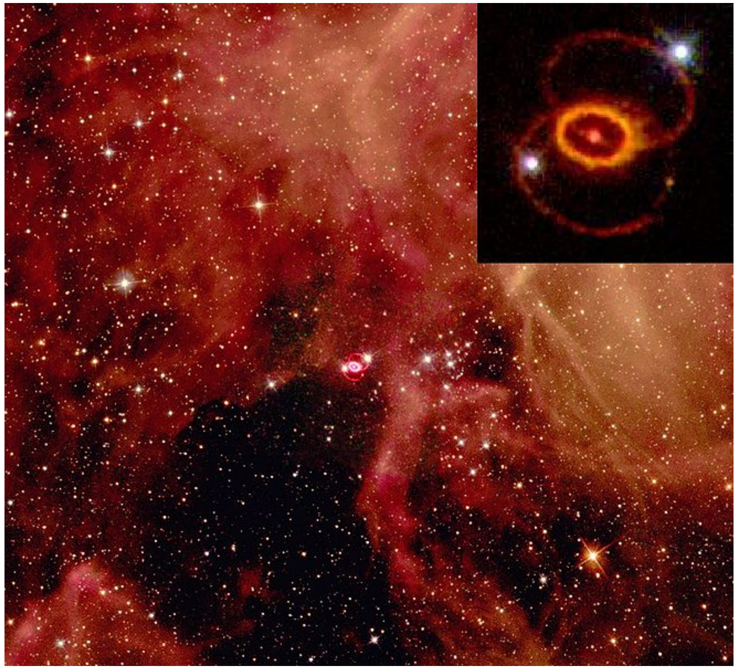
Neutrino flux at the *Savannah River* reactor: 5×10^{13} neutrino/s.cm^2

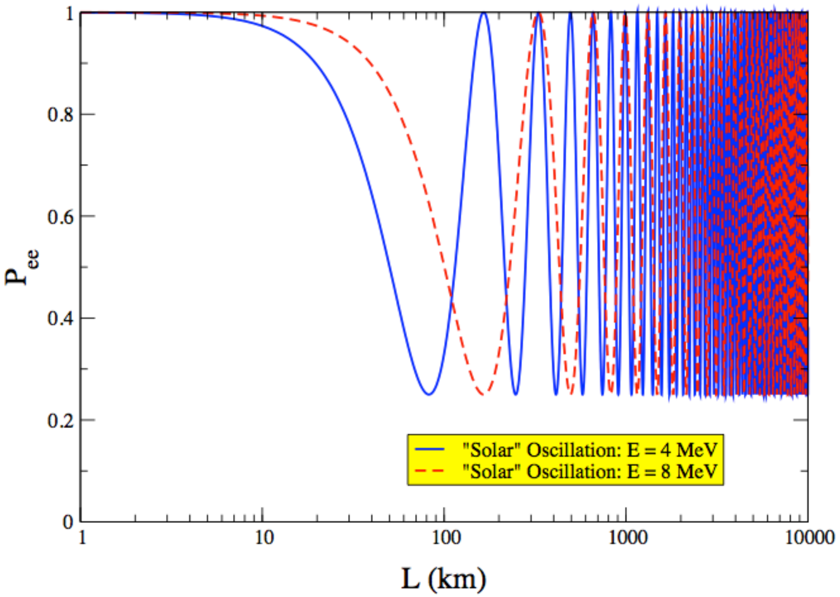
They detected 3 neutrinos/h

Science 20, vol 124 no. 3212 pp. 103-104

Why worth studying: neutrinos as messengers

- We hear about many types of neutrinos: solar neutrinos, geo-neutrinos, atmospheric neutrinos, supernova neutrinos, Big Bang neutrinos, reactor neutrinos, etc., etc.
- They can provide information about the processes that happen inside those objects, because they can travel very long distances without interaction.
- Quantum effects at macroscopic scales

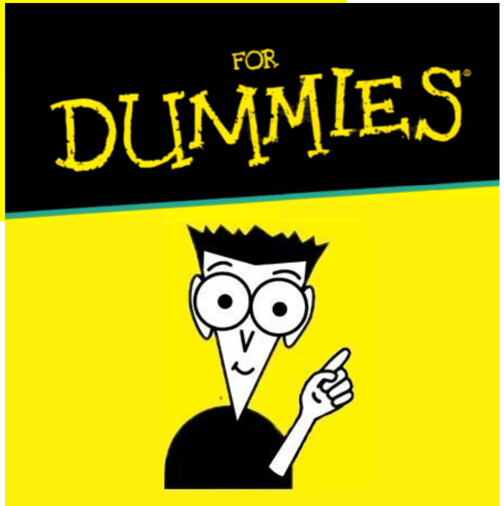




Osscilations !!!

(solar neutrino deficit, atm. neutrino deficit, ^{238}U,^{232}Th, ^{40}K content, etc.)

Neutrino oscillations



(including myself !)

•In the weak interaction neutrinos are produced and detected in flavours (electron, muon, tau)
•The Hamiltonian (of the propagation) depends on mass (free moving particle)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

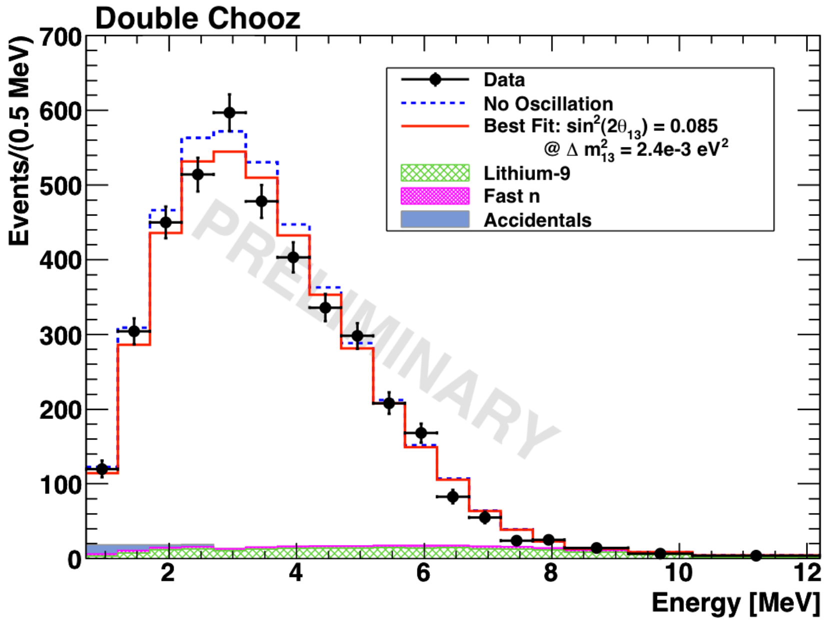
$$P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta)\sin^2(1.27\,\Delta m^2 L / E)$$

$$\Delta m^2 = m_2^2 - m_1^2$$

[L in m, E in MeV, Δm^2 in eV^2]

Example of reactor neutrino oscillation experiment: Double Chooz, Θ_{13}

Reactor neutrino experiments: summation calculations



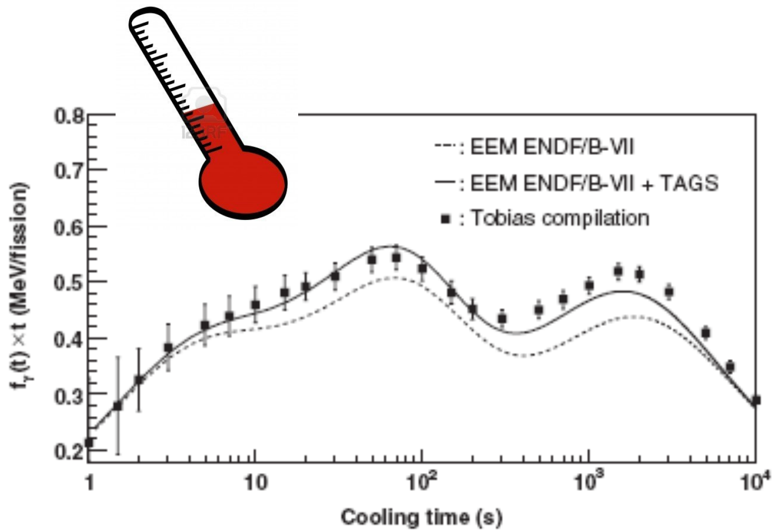
$$N(E_\nu) = \sum_n Y_n(Z,A,t) \cdot \sum_i b_{n,i}(E_0^i) P_\nu(E_\nu, E_0^i, Z)$$

Y_n Number of beta decays per unit time of fragment with Z, A (cumm. Yield)

$b_{n,I}$ branching ratio of the i branch with maximum electron energy E^i_0

$P\nu$ neutrino spectrum of the i branch with maximum electron energy E^i_0

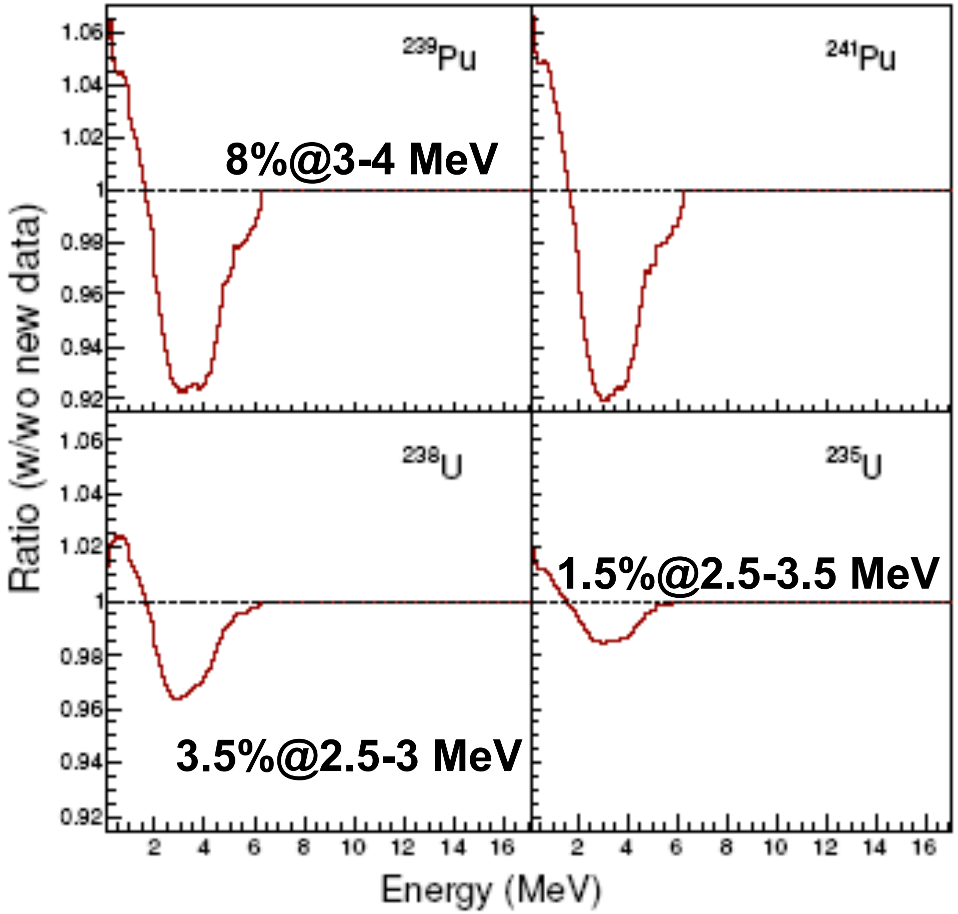
Impact of our data (up to now)



Dolores Jordan, PhD thesis

Algora et al., PRL 105, 202501, 2010

M. Fallot et al., PRL 109.202504



Ratio between 2 antineutrino spectra built with and without the ^{102,104,105,106,107}Tc, ^{105}Mo, ^{101}Nb TAS data

New questions: reactor anomaly ?

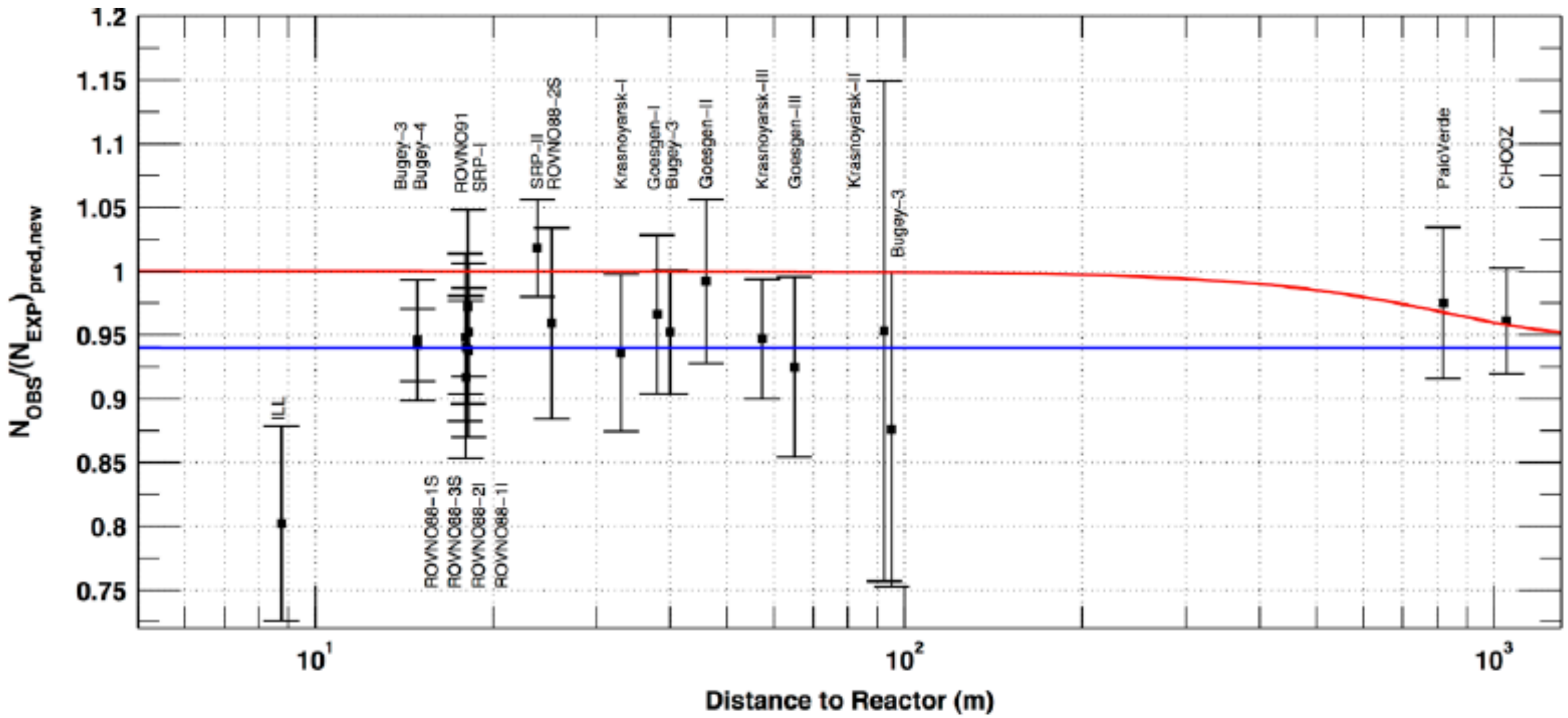


Illustration of the reactor anomaly. Rates in various experiments are compared with the expectations based on the Mueller et al. (2011) spectrum. The mean is 0.943+-0.023.

Possible explanation:

1)Wrong reactor flux or its error

2)Bias in all experiments

3)New physics at short baseline involving a sterile 4th neutrino ν_{new} with $\Delta m^2 \sim 1 eV^2$ and mixing with ν_e with $\theta_{new} \sim 10^0$

The explanation 3) could be supported by several other, so far unconfirmed anomalies. It would involve unexpected but significant "New Physics"

From P. Vogel

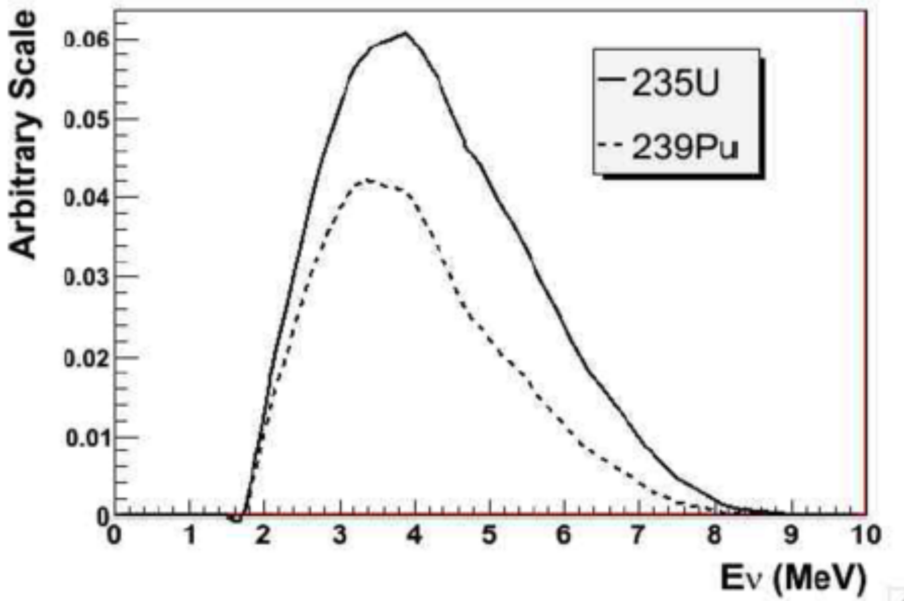
Another application: prediction of the neutrino spectrum from reactors for non-proliferation

	235U	239Pu
Released E per fission	201.7 MeV	210.0 MeV
Mean neutrino E	2.94 MeV	2.84 MeV
Neutrinos/fission >1.8 MeV	1.92	1.45
Aver. Int. cross section	$3.2 \times 10^{-43} cm^2$	$2.8 \times 10^{-43} cm^2$

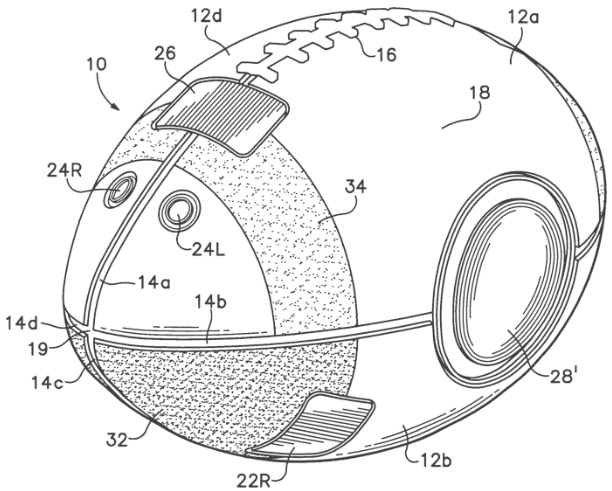
$$\bar{\nu} + p \rightarrow e^{+} + n$$ (threshold 1.8 MeV)

•Relevance for non-proliferation studies (working group of the IAEA). Neutrino flux can not be shielded. Study to determine fuel composition and power monitoring. Non-intrusive and remote method.

•Approved proposal to study some Rb, Sr, Y, Nb, I and Cs (IGISOL, trap assisted TAS) (Fallot, Tain, Algora)



Nuclear Shapes



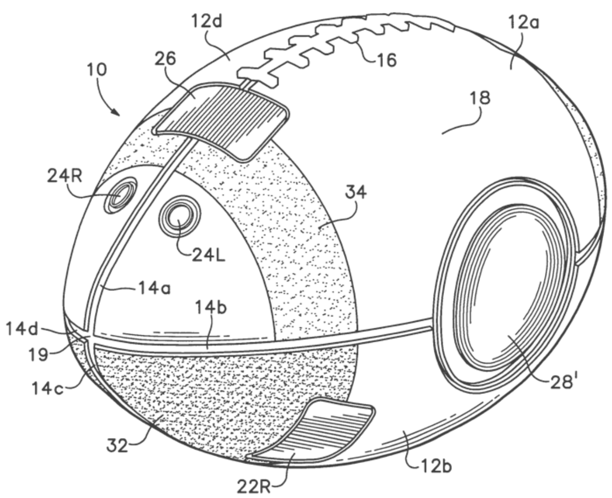
The nuclear shape concept evolution …

- Rutherford model: point like shape (approx. 100 years ago)
- To interpret the binding energies the liquid drop model is created (spherical shapes), later it evolves into the droplet model with diffuse surface
- Revolution in the 50´s: collectivity and static deformed shapes are born. Shape becomes a concept and a tool for testing nuclear models. It is a necessity to interpret data on nuclear multipoles, Coulomb excitation data, etc.
- The interpretation of fission requires the assumption of elongated shapes, or a very drastic shape change.
- Strutinsky shell correction it combination with the liquid drop model predicts deformed minima
- Direct measurements by means of scattering experiments …
- Nilsson model, and shell model relation (Elliot Model), mean field
- Shape coexistence
- SD bands, HD states, etc, etc, etc.

(more than 1144 publications in APS journals 1940-2010)

But experimentally how do we deduce nuclear shapes ?
Are nuclei really deformed?
What can beta decay offer ?

The answer is always model dependent



Nuclear electric quadrupole moment measurements

$$\boldsymbol{Q_z} = \sum_{i=1}^{A} \boldsymbol{Q_z(i)} = \sum_{i=1}^{A} e_i(3z_i^2 - r_i^2)$$

Classical definition (measure of departure from spherical shape)

$$\boldsymbol{Q_2^0} = \boldsymbol{Q_z} = \sqrt{\frac{16\pi}{5}} \sum_{i=1}^{A} e_i r_i^2 Y_2^0(\theta_i, \phi_i)$$

z- component of the quadrupole moment

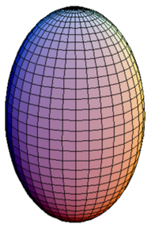
$$Q_s(I) = \langle I, m = I \left| \boldsymbol{Q_2^0} \right| I, m = I \rangle = \sqrt{\frac{I(2I-1)}{(2I+1)(2I+3)(I+1)}} (I \,||\boldsymbol{Q}||\, I)$$

Spect. quadrupole moment of a nucl. state with spin I

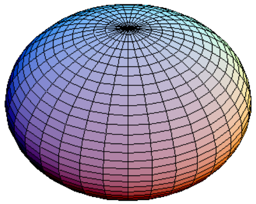
(expectation value)

Under certain assumptions (axially symmetric nuclei, strong coupling)

$$Q_s = \frac{3K^2 - I(I+1)}{(I+1)(2I+3)} Q_0 \qquad Q_0 = \frac{3}{\sqrt{5\pi}} Z R^2 \beta \,(1 + 0.36\beta)$$

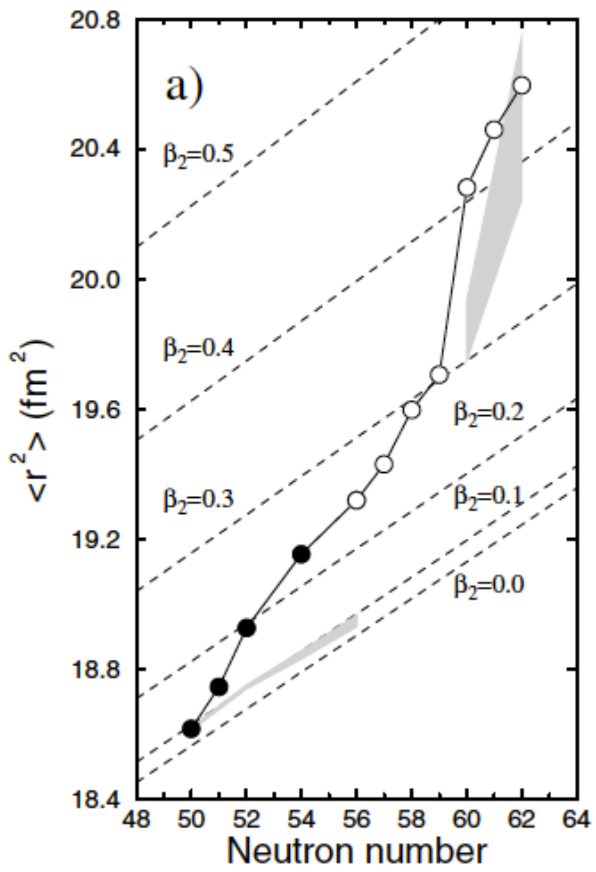


Q>0



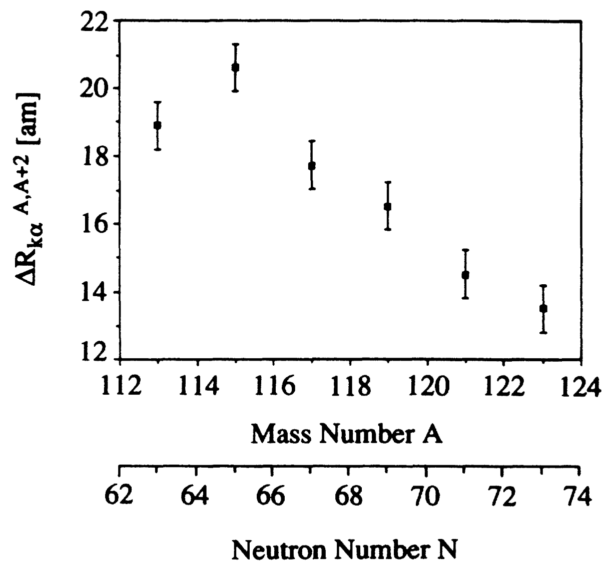
Q<0

Nuclear radii determination by means of isotope shifts (muonic atoms, laser spectroscopy, etc.)



Laser spectroscopy of cooled Zr fission products (Campbell PRL 89, 2002)

Mean square charge radii deduced from the measurements compared with droplet model predictions.

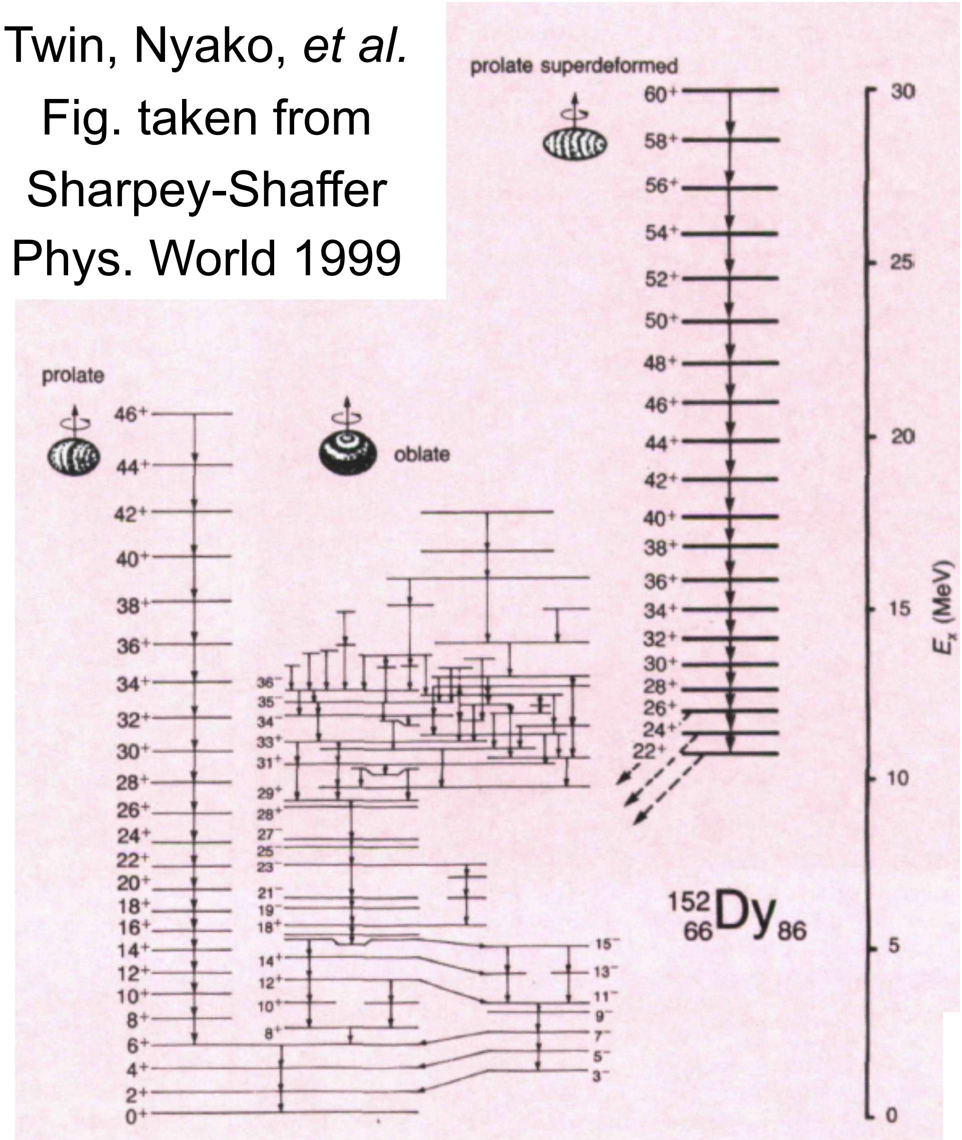


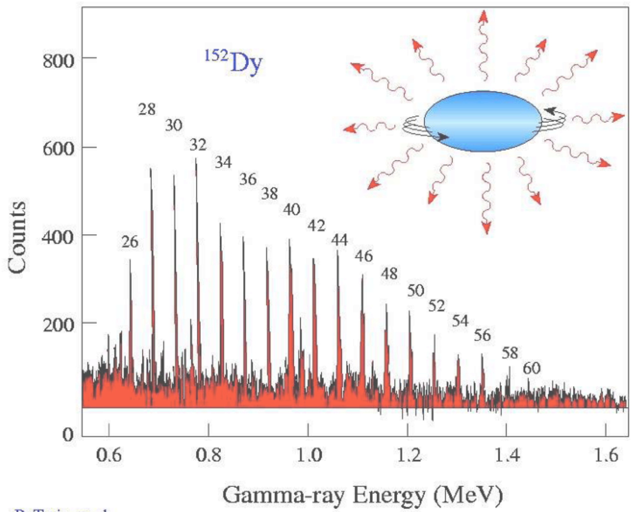
Nuclear charge radii differences in Sn isotopes from muonic atoms

(C. Piller *et al*. PRC 42 , 1990)

Shapes from nuclear spectroscopic information (mainly gamma spectroscopy)

Twin, Nyako, *et al.*
Fig. taken from
Sharpey-Shaffer
Phys. World 1999



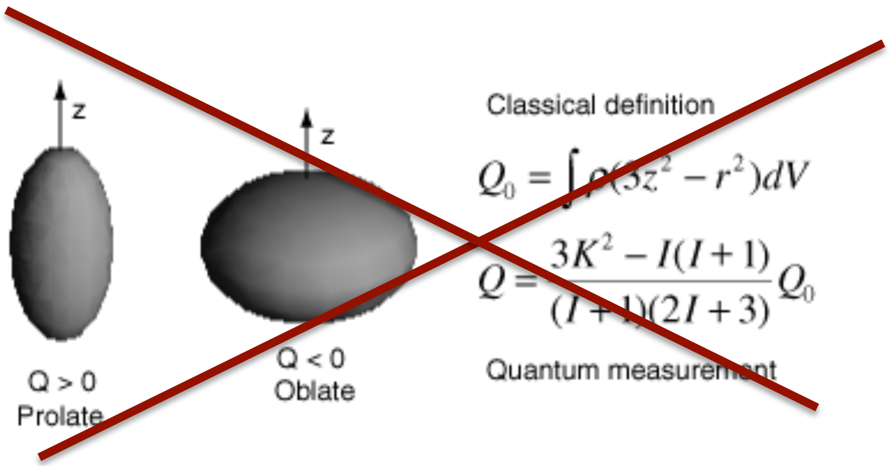


P. Twin et. al
Phys. Rev. Lett. 57 (1986)

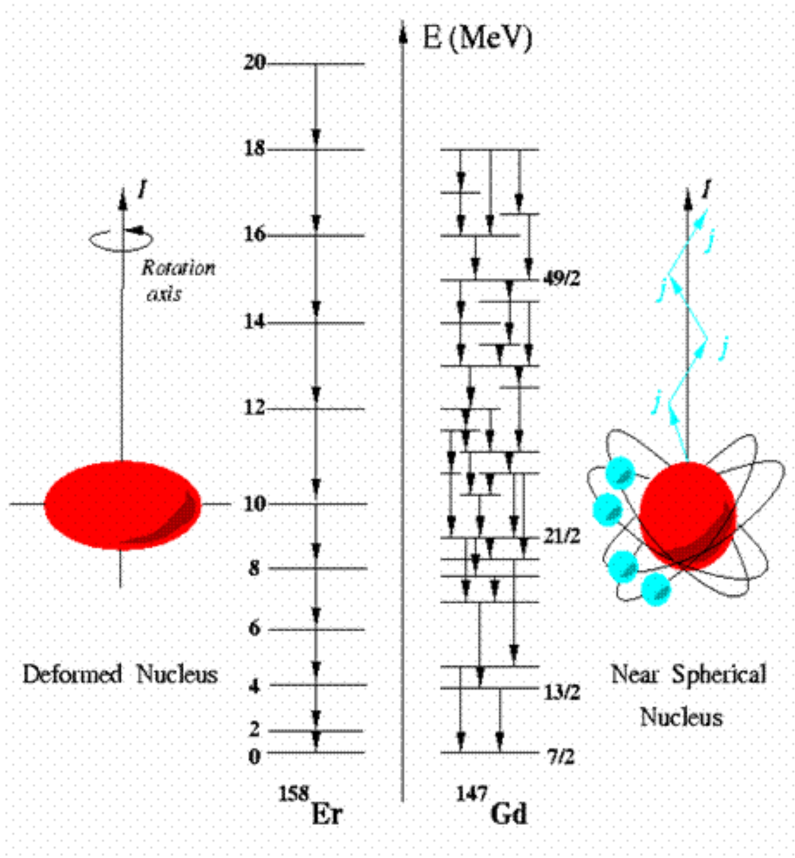
- From level lifetimes, B(E2)-s, deformation can be deduced
- From in-band multipole mixing ratios (angular distributions) the sign of the Q can be deduced
- E0 (electric monopole transitions) are associated with shape changes

$$|Q| = \sqrt{16\pi B(E2{:}2_1^+ \rightarrow 0_1^+)} = \frac{3Ze}{\sqrt{5\pi}} R_0^2(\beta + 0.16\beta^2),$$

How do we deduce the nuclear shape of the ground state when it is a 0+ state …



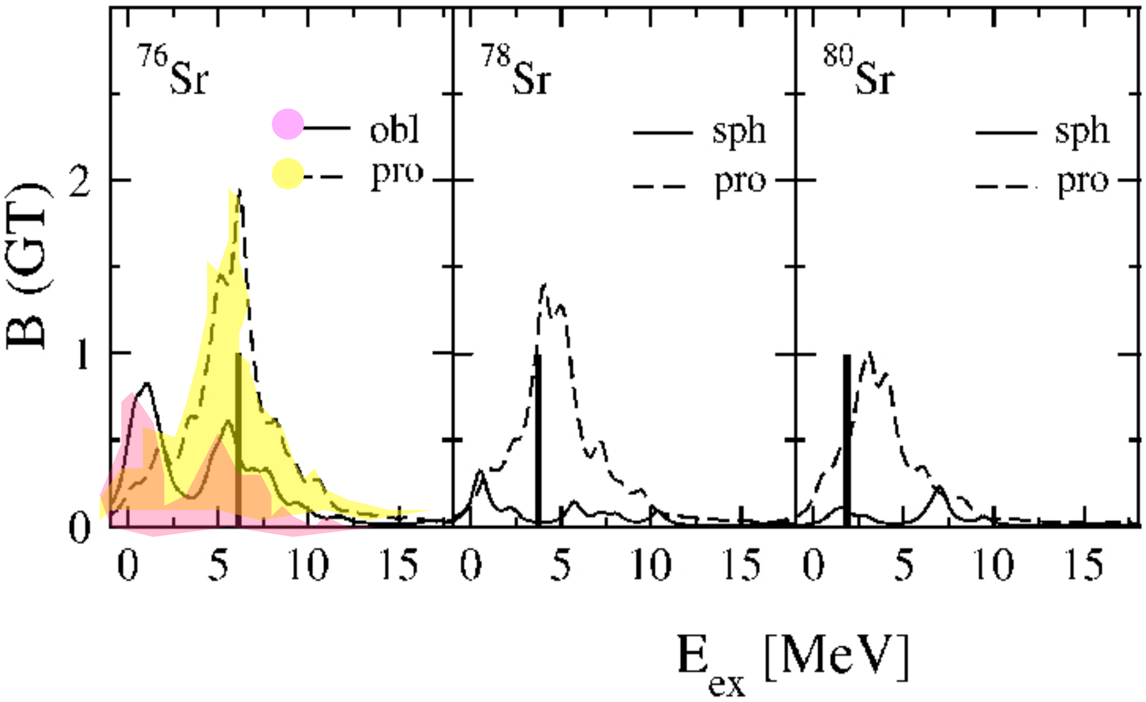
- Nuclear radii determination (isotope shifts)
- Analysis of spectroscopic information (B(E2)-s, $T_{1/2}$ and assuming that we have a band with the same deformation
- ???

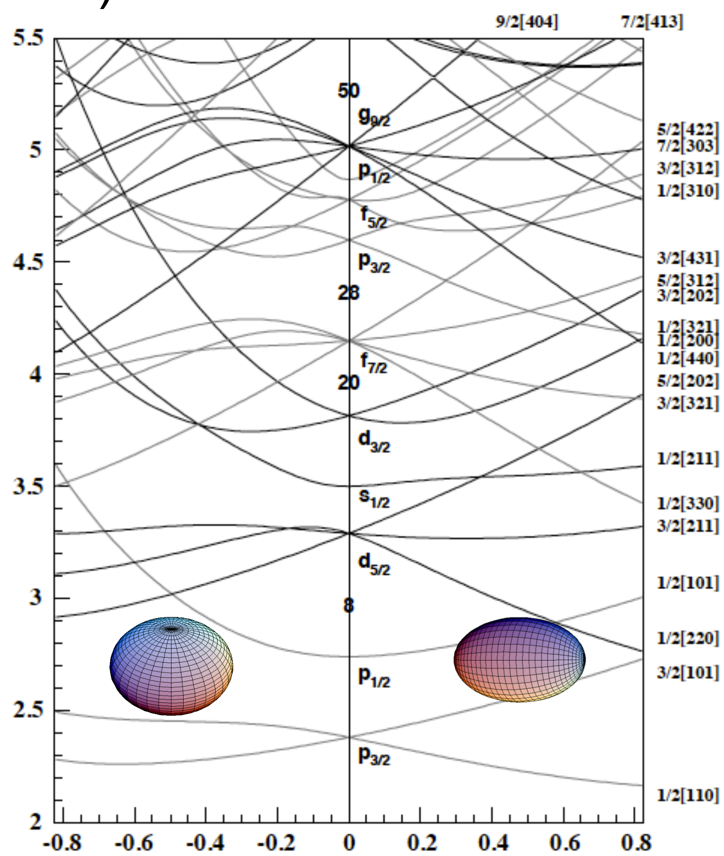


What can beta decay offer apart from spectroscopy …

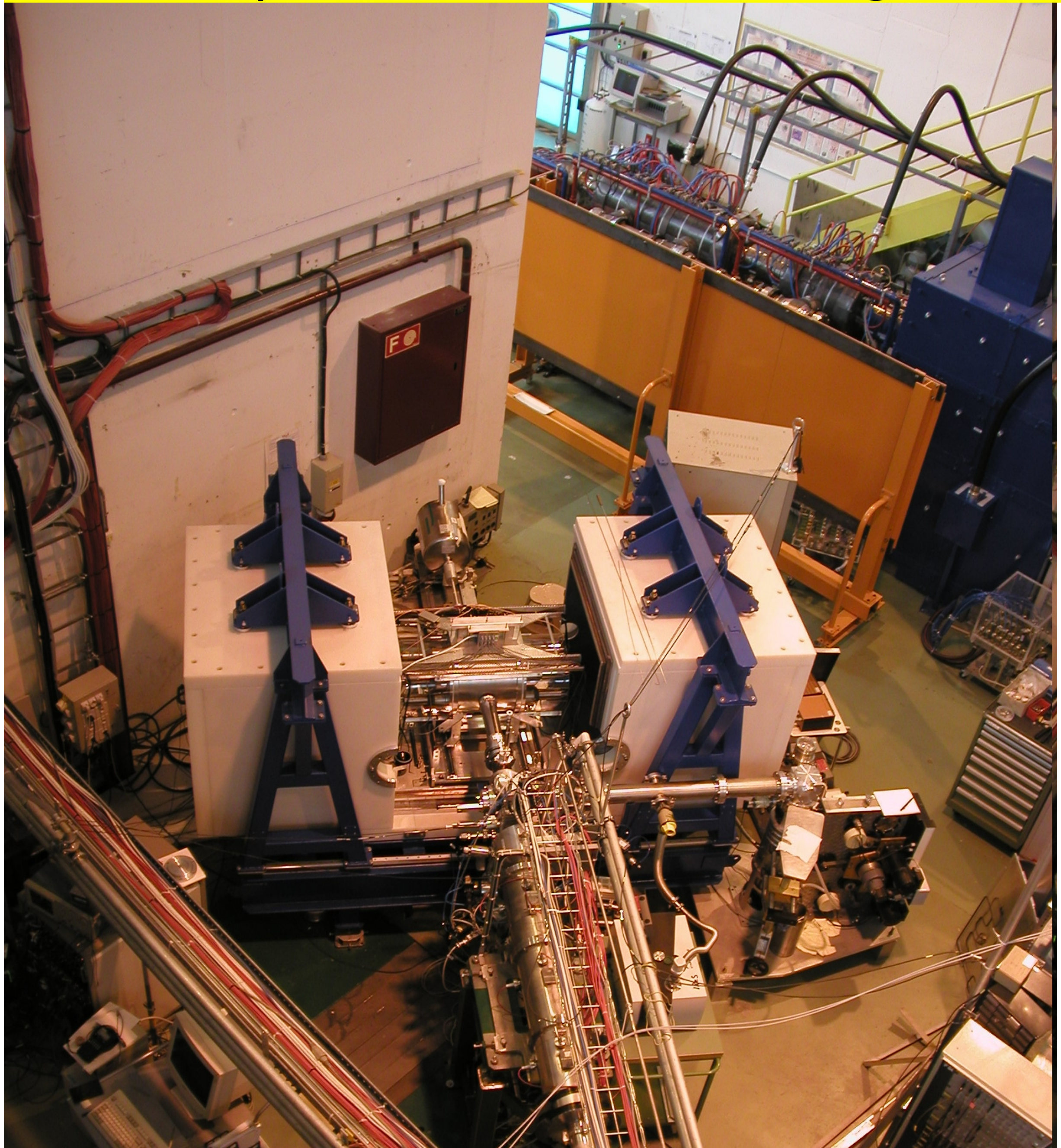
Another alternative, based in the pioneering work of I. Hamamoto, (Z. Phys. A353 (1995) 145) later followed by studies of P. Sarriguren *et al*., Petrovici *et al*. is related to the dependency of the strength distribution in the daugther nucleus depending on the shape of the parent. It can be used when theoretical calculations predict different B(GT) distributions for the possible shapes of the ground state (prolate, spherical, oblate).

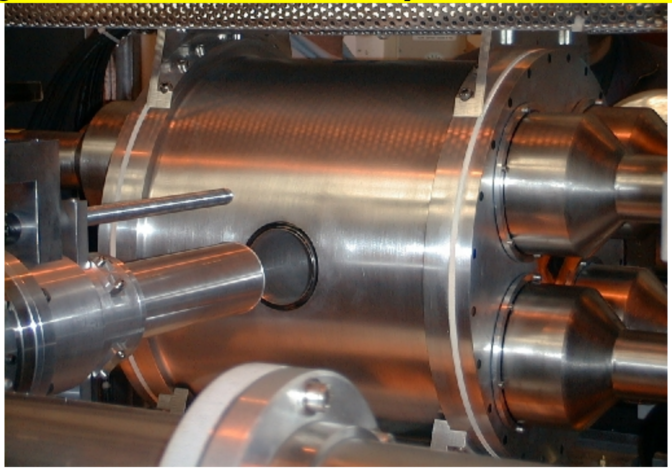
P. Sarriguren *et al*., Nuc. Phys. A635 (1999) 13





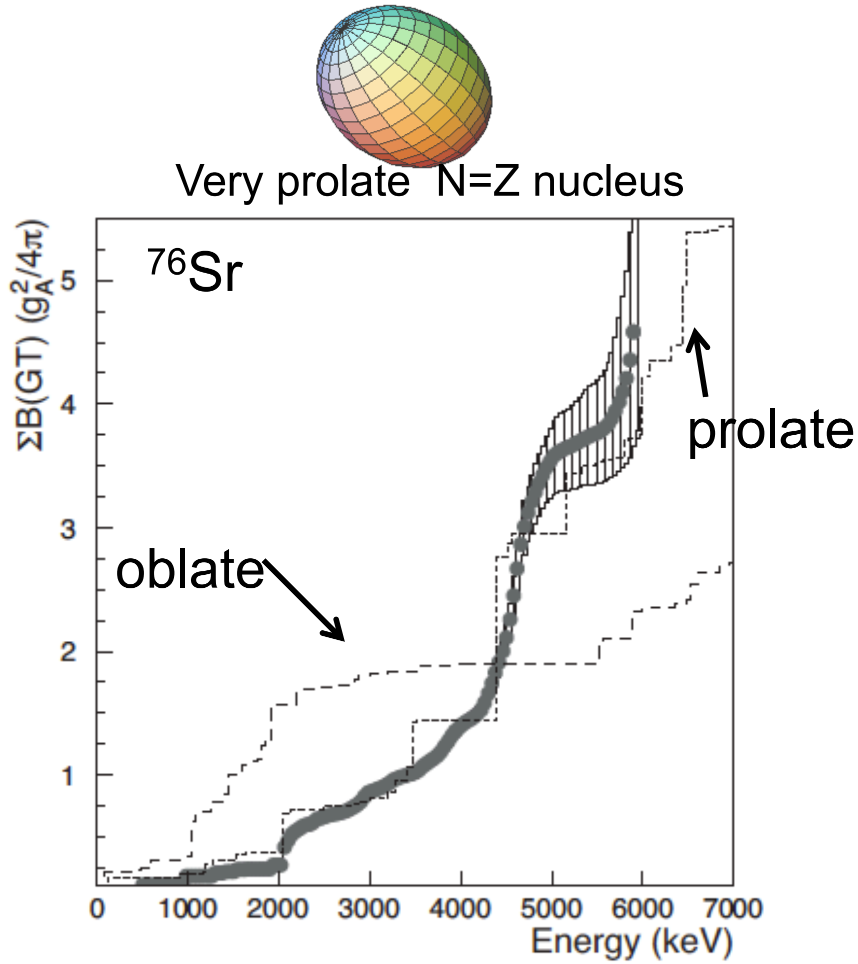
Lucrecia: the TAS at ISOLDE (CERN) (Madrid-Strasbourg-Surrey-Valencia)

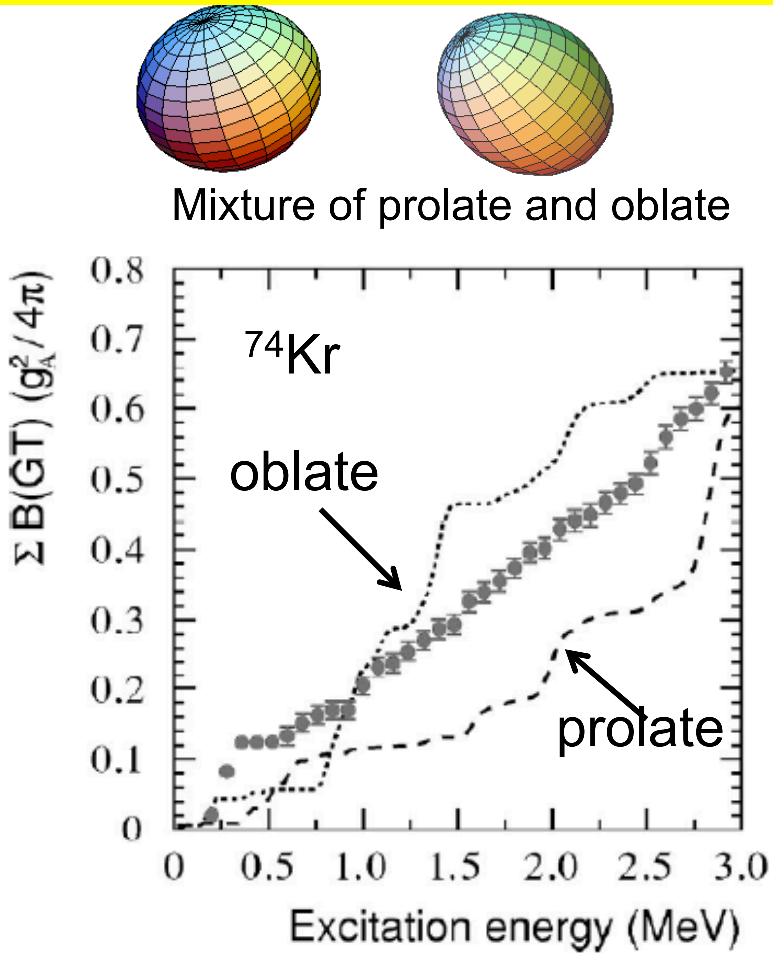




- A large NaI cylindrical crystal 38 cm Ø, 38cm length
- An X-ray detector (Ge)
- A β detector
- Possibility of collection point inside the crystal

Some earlier examples
(proposals of Rubio and Dessagne)





E. Nácher *et al. PRL 92 (2004) 232501 and PhD thesis Valencia*

Ground state of ^{76}Sr prolate (β_2 ~0.4) as indicated in Lister et al., PRC 42 (1990) R1191

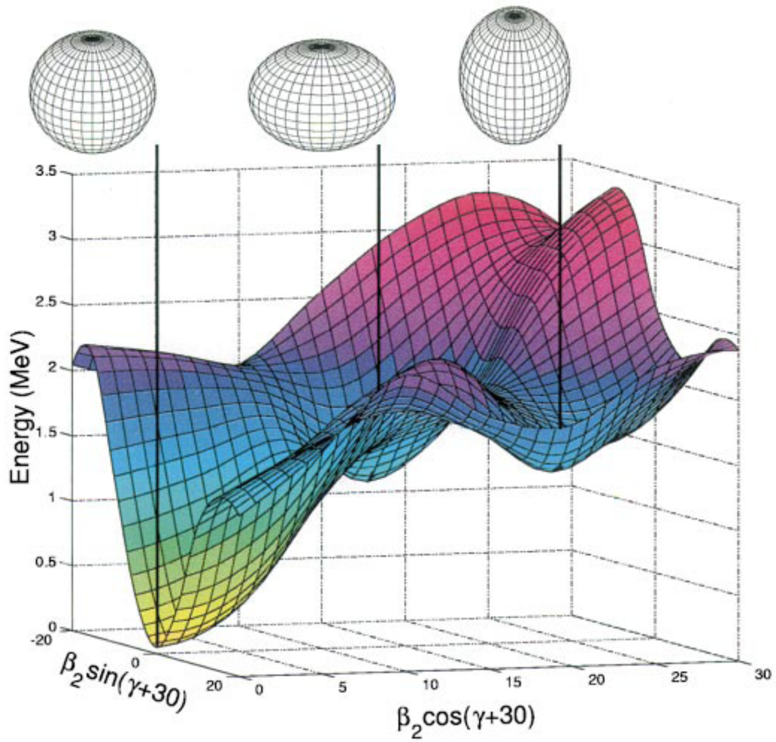
E. Poirier *et al., Phys. Rev. C 69, 034307 (2004) and PhD thesis Strasbourg*

Ground state of ^{74}Kr:(60±8)% oblate, in agreement with other exp results and with theoretical calculations (A. Petrovici et al.)

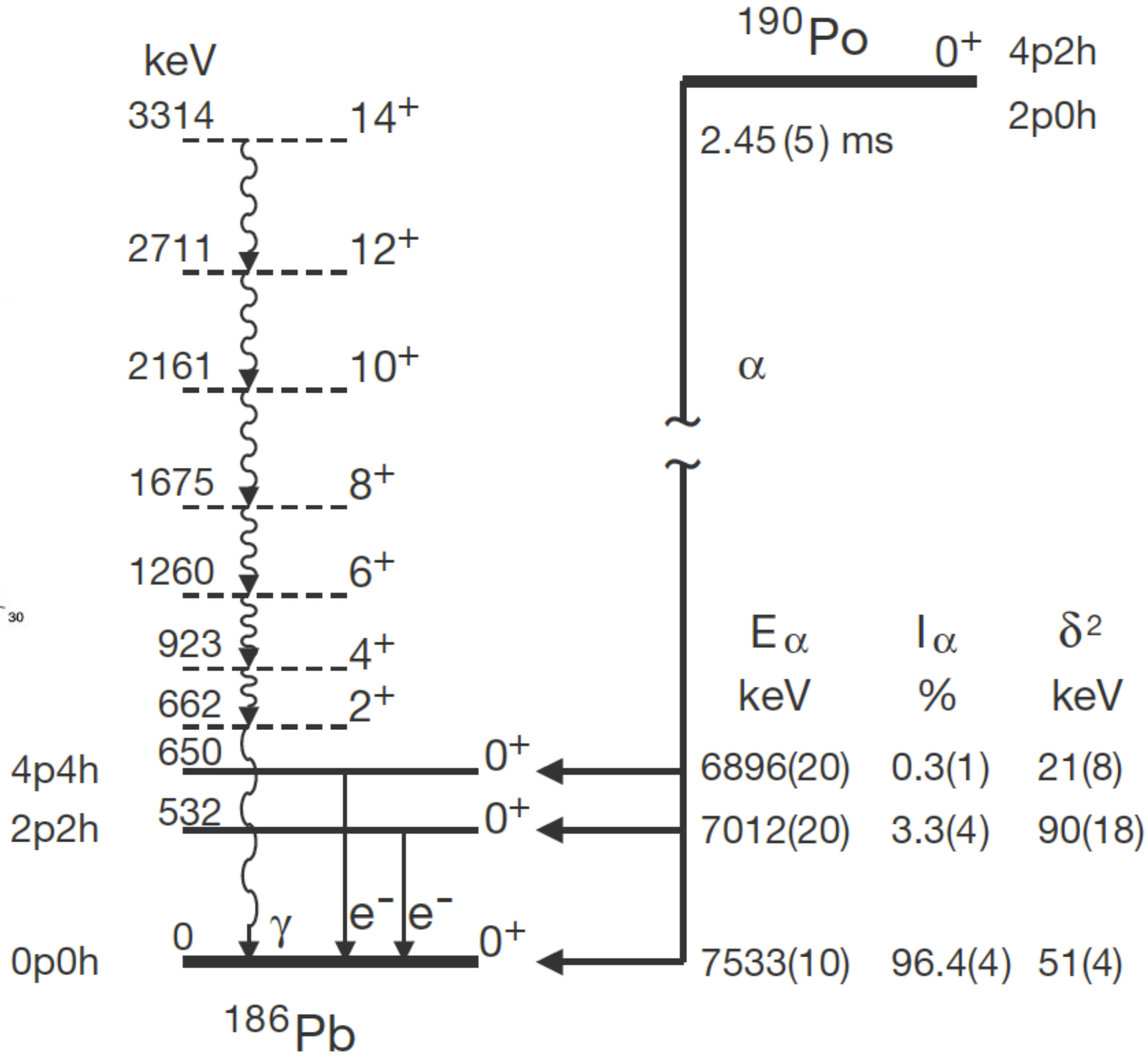
Possible questions

- is the method only valid for A~80 ?
- was the good agreement accidental ?
- because the method can be useful for exotic nuclei
- So it is worth explore heavier domains …

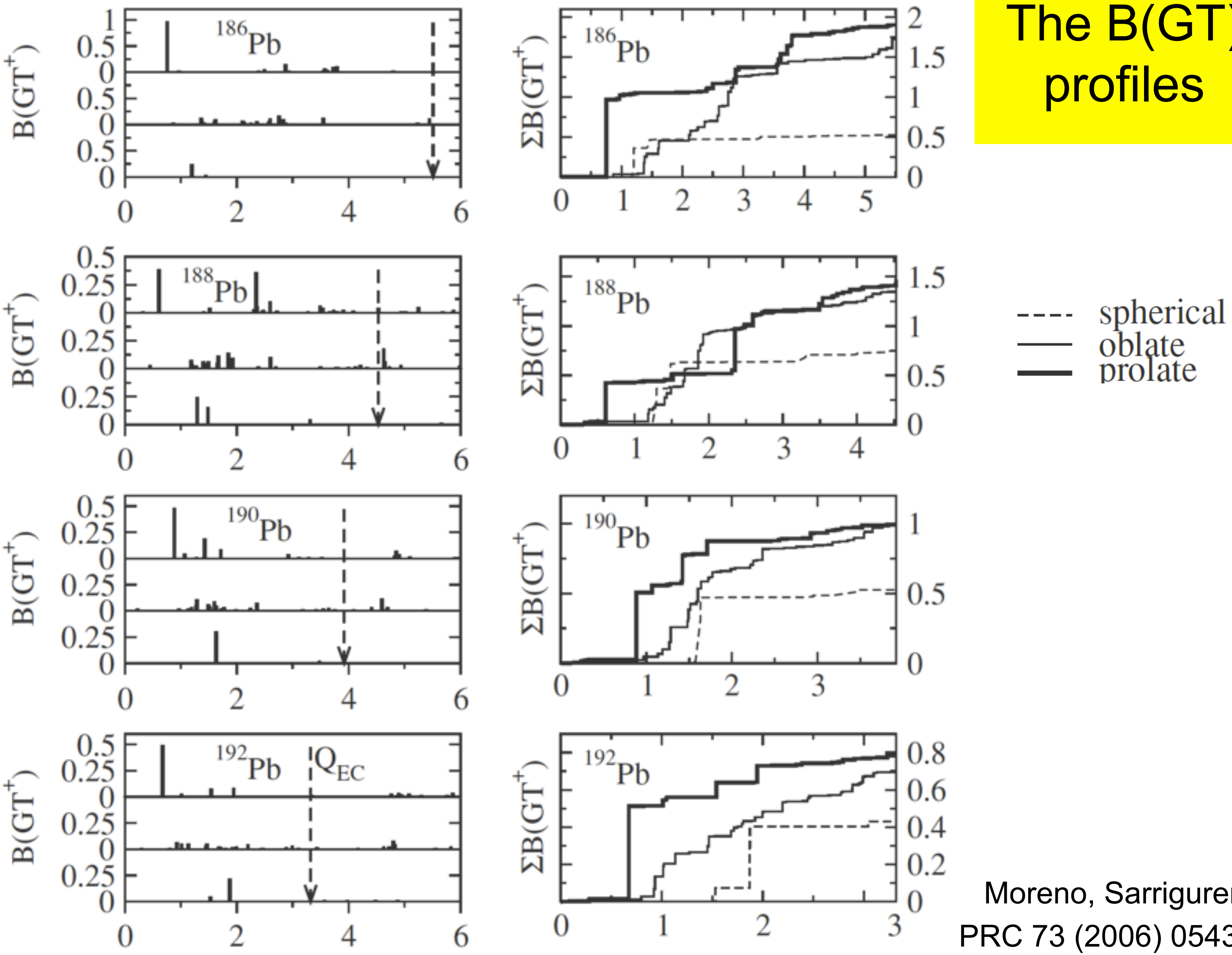
Intruder 0+ states in ^{186}Pb



A. N. Andreyev *et al.*
Nature 405 (2000) 430

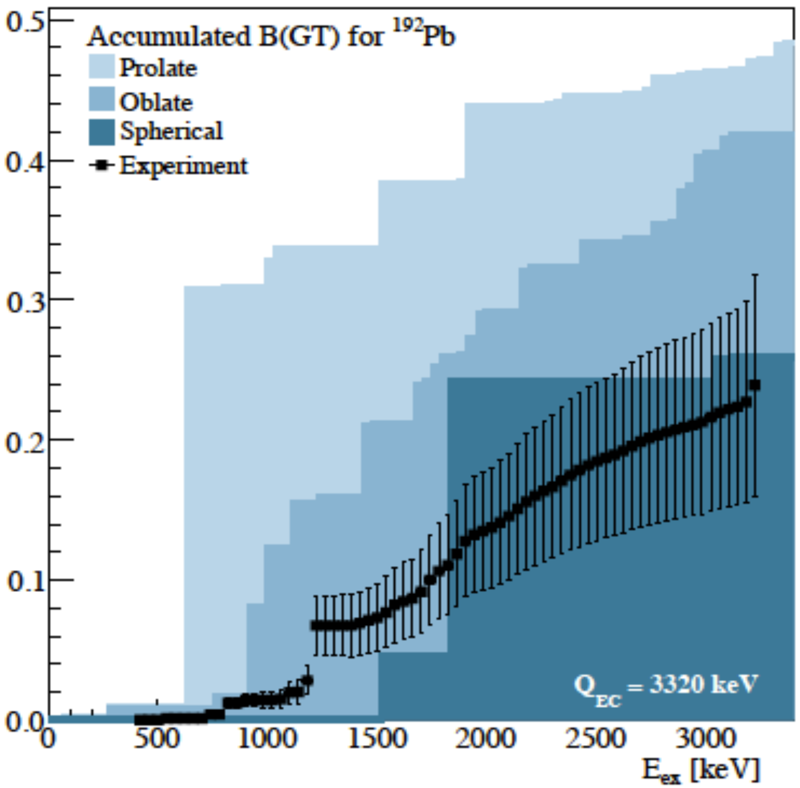


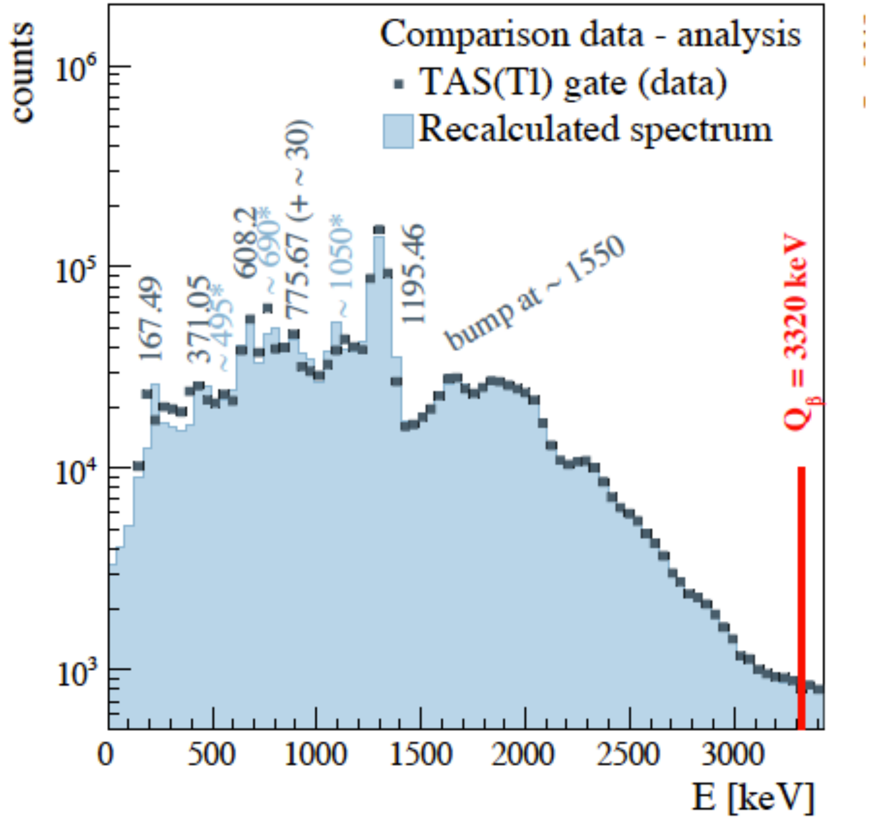
The B(GT) profiles



Moreno, Sarriguren
PRC 73 (2006) 054317

IS440 results: ^{192}Pb example

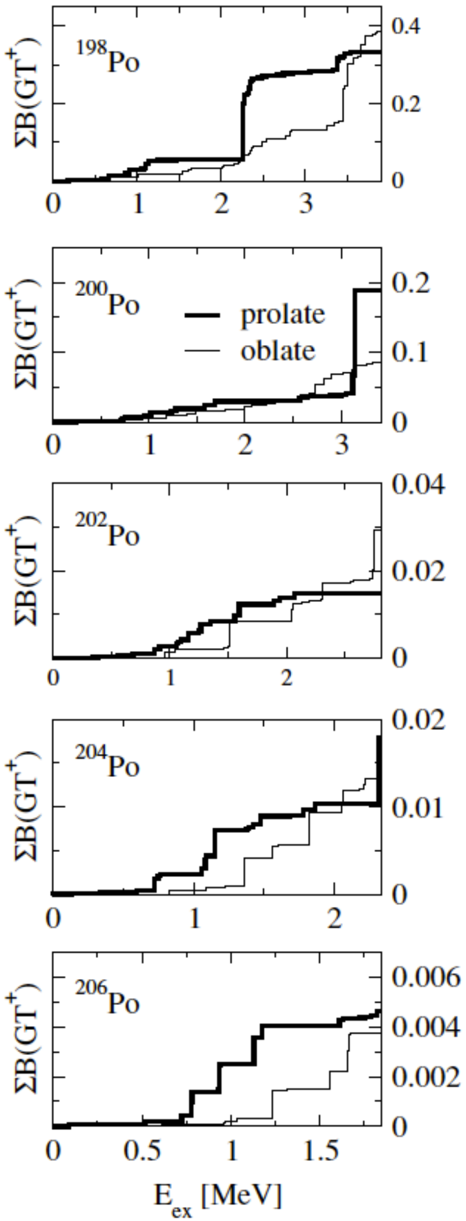




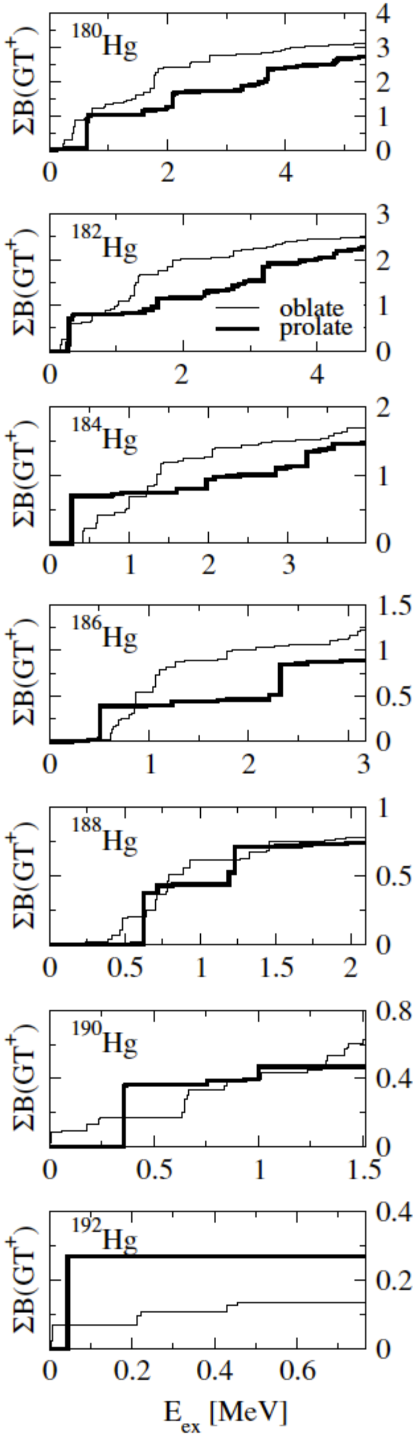
Thesis work of M. E. Estevez 2011, and M. E. Estevez *et al.* in preparation. Theory from PRC 73 (2006) 054317)

Results consistent with spherical picture, but less impressive than in the A≈80 region. Similar situation for ^{190}Pb. *Possible explanation, the spherical character of the Pb nuclei, but requires further testing.*

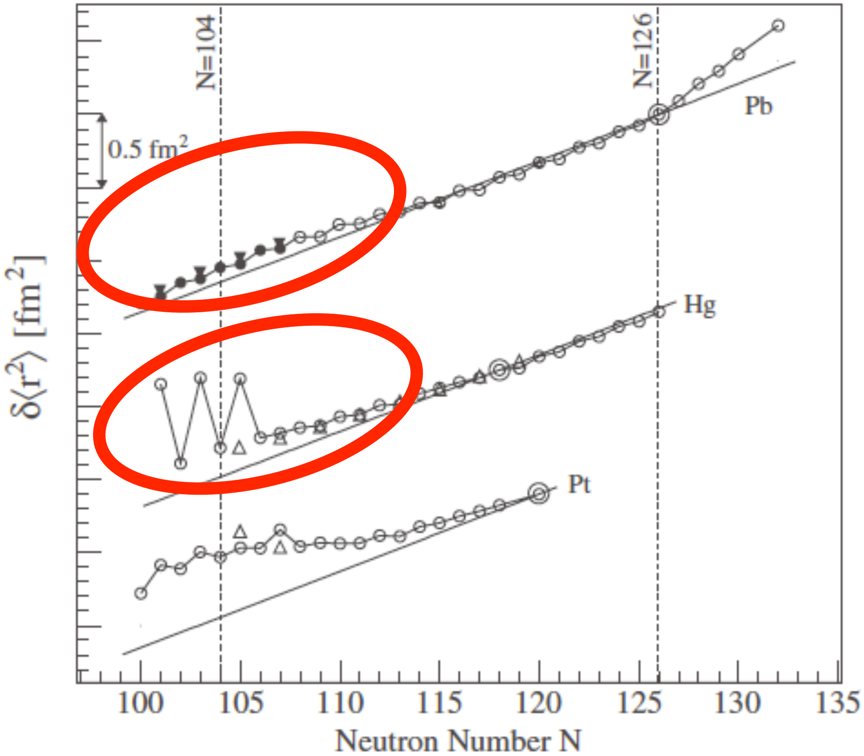
Future studies (exp. recently finished)



O. Moreno *et al.*
PRC 73, 054302



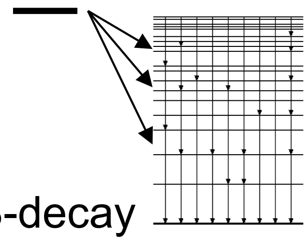
H. De Witte *et al.*
PRL 98, 0112502



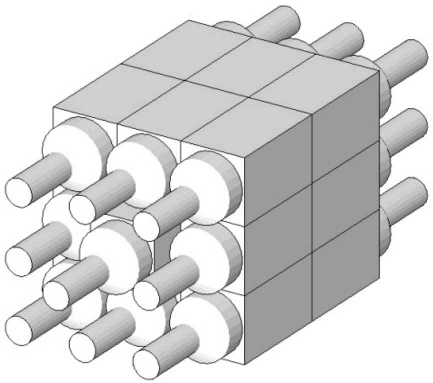
Also T. Cocolios *et al.* *PRL 106, 052503*

Building a Total Absorption Spectrometer for FAIR

DESIGN CHOICES

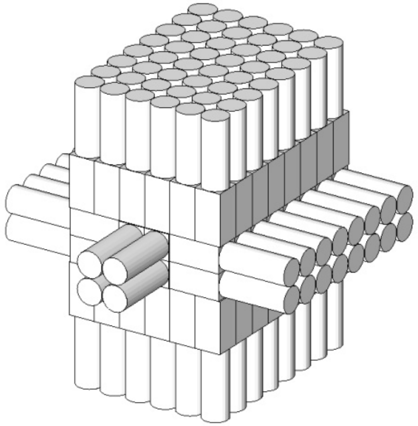

β-decay

16 + 1 modules:
15 x 15 x 25 cm³ NaI(Tl)
+ 5" PMT (50% light col.)
V= 95 L, M= 351 kg



ΔE/E 5%
(@1.3MeV)
Δt ~ 2 ns

128 + 4 modules:
5.5 x 5.5 x 11 cm³ $LaBr_3$:Ce
+ 2" PMT (60% light col.)
V= 44 L, M= 223 kg



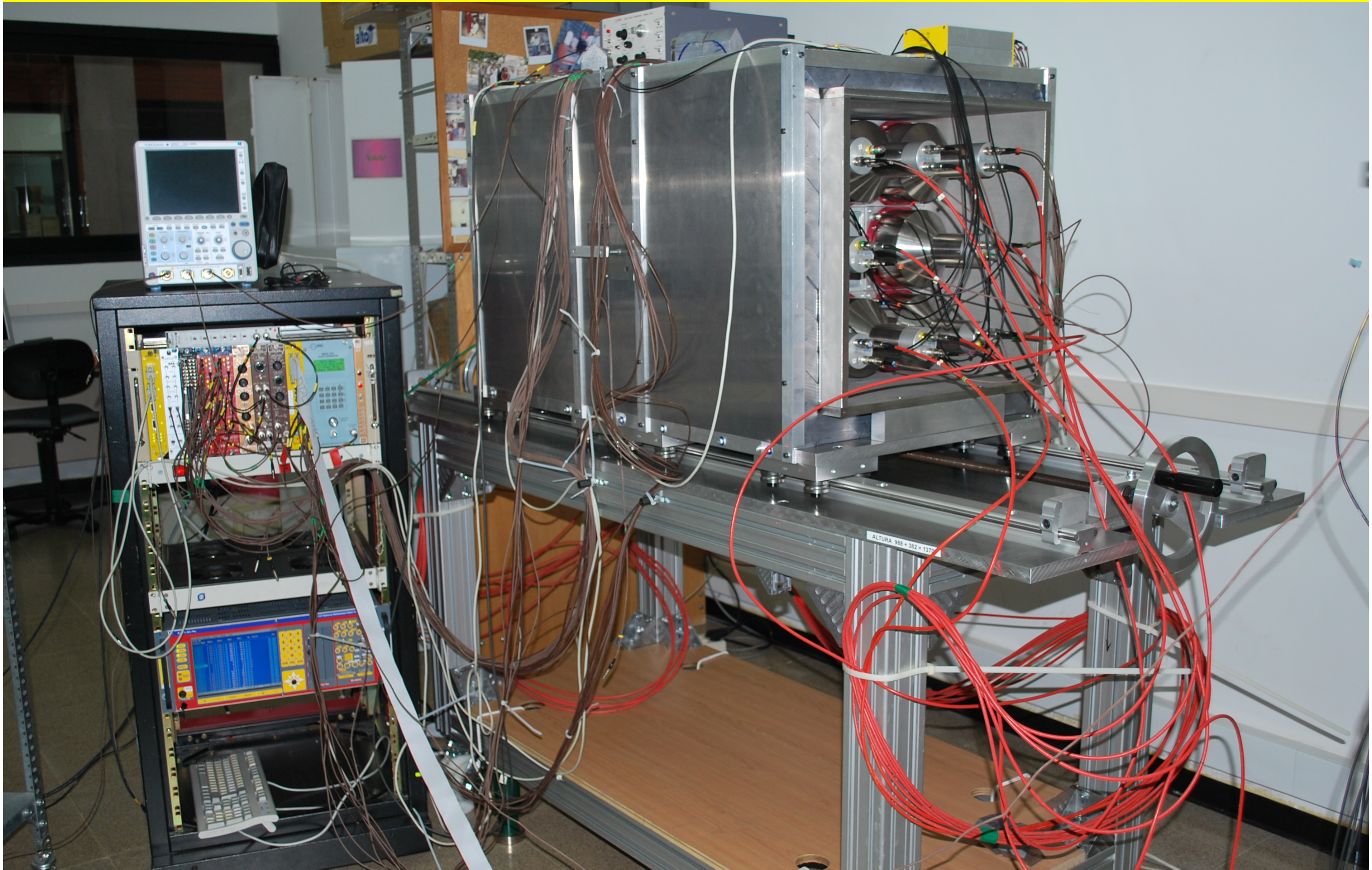
ΔE/E 2%?
(@1.3MeV)
Δt ≤1 ns

- x 2 better energy resolution
- much increased cost

Challenging future experiments in a fragmentation facility !

Figures and numbers from Taín

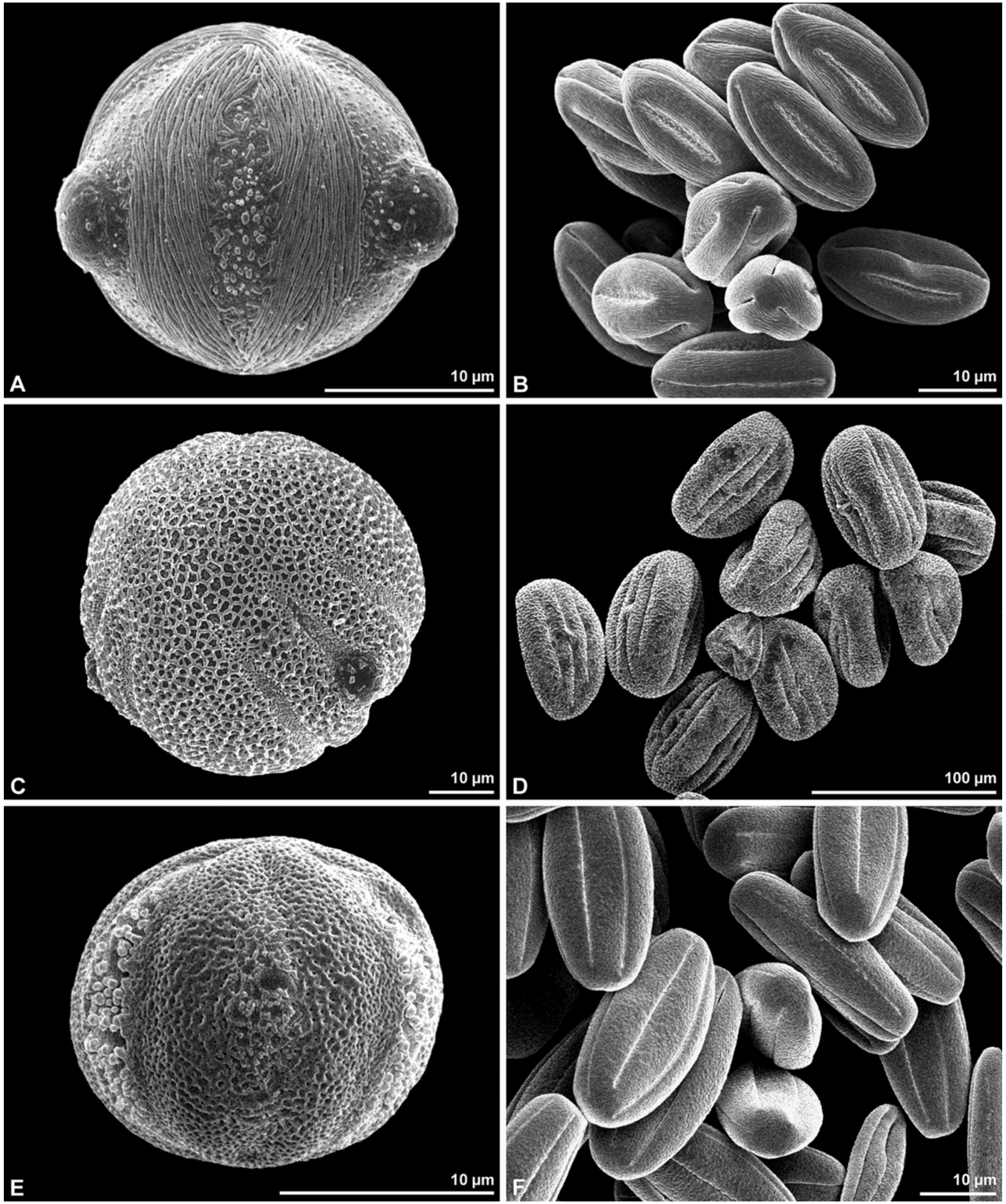
Present status of the DTAS



Conclusions/last comments

- I hope I have shown you the utility of the TAS technique, not only for fundamental research in nuclear structure, but also for practical applications
- Even the results for practical applications can have an impact for nuclear structure.
- We have a long term program for Jyväskylä (decay heat, neutrino spectrum, nuclear structure). Similar research programs at Oak Ridge (USA) and Argonne (USA)
- There is still a lot of work ahead of us, if you consider the challenges for experiments in a facility like FAIR

J.L. Tain, B. Rubio, E. Nácher, L. Caballero, J. Agramunt, A. B. Perez, D. Jordan, F. Molina, W. Gelletly, L. Batist, A. Garcia, J. Äystö, H. Penttilä, I. Moore, P. Karvonen, A. Jokinen, S. Rinta-Antila, A. Kankainen, T. Eronen, U. Hager, T. Sonoda, J. Hakala, A. Nieminen, A. Saastamoinen, J. Rissanen, T. Kessler, C. Weber, J. Ronkainen, S. Rahaman, V. Elomaa, T. Yoshida, F. Storrer, A. L. Nichols, G. Lhersonneau, K. Burkard, W. Huller, A. Krasznahorkay, A. Vitéz, J. Gulyás, M. Csatlos, M. D. Hunyadi, L. Csige, A. Sonzogni, K. Perajarvi, K. L. Kratz, A. Petrovici,, E. Valencia, S. Rice, M. Fallot, A. Porta, Z. A. Aziz, A. Algora



E. Estevez, J .L. Tain, B. Rubio, E.Nácher, J. Agramunt, A. B. Perez, L. Caballero, F. Molina, D. Jordan, A. Krasznahorkay, M. Hunyadi, Zs. Dombrádi, W. Gelletly, P. Sarriguren, O. Moreno, M. J. G. Borge, O. Tengblad, A. Jungclaus, L. M. Fraile, D. Fedosseev, B. A. Marsh, D. Fedorov, A. Frank, A. Algora

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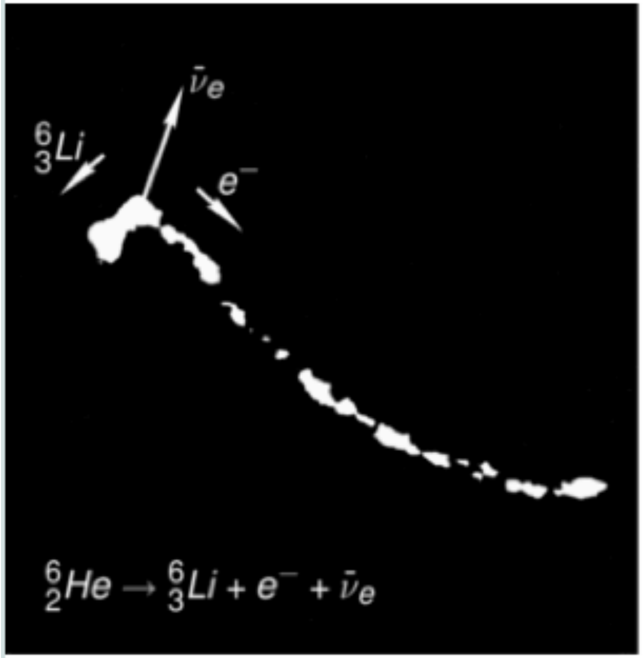

EUROPEAN PHYSICAL SOCIETY – EPS HISTORIC SITE

THE NEUTRINO EXPERIMENT AT MTA ATOMKI

USING A CLOUD CHAMBER LOCATED IN THIS BUILDING, IN 1956 J. CSIKAI AND A. SZALAY PHOTOGRAPHED BETA-DECAY EVENTS. IN SOME CASES THE ANGLE BETWEEN THE TRACKS OF THE ELECTRON AND THE RESIDUAL NUCLEUS IMPLIED THE EMERGENCE OF AN UNDETECTED THIRD PARTICLE IN THE DECAY. THUS CONFIRMING THE EXISTENCE OF THE NEUTRINO, THE DEBRECEN NEUTRINO EXPERIMENT LAID A BRICK OF THE FOUNDATION OF MODERN PHYSICS.

$$^{6}He \rightarrow {}^{6}Li + e^{-} + \overline{\nu}$$

THANK YOU