Proton Rich Ions decaying by EC: A Synergy Between Nuclear and Neutrino Physics

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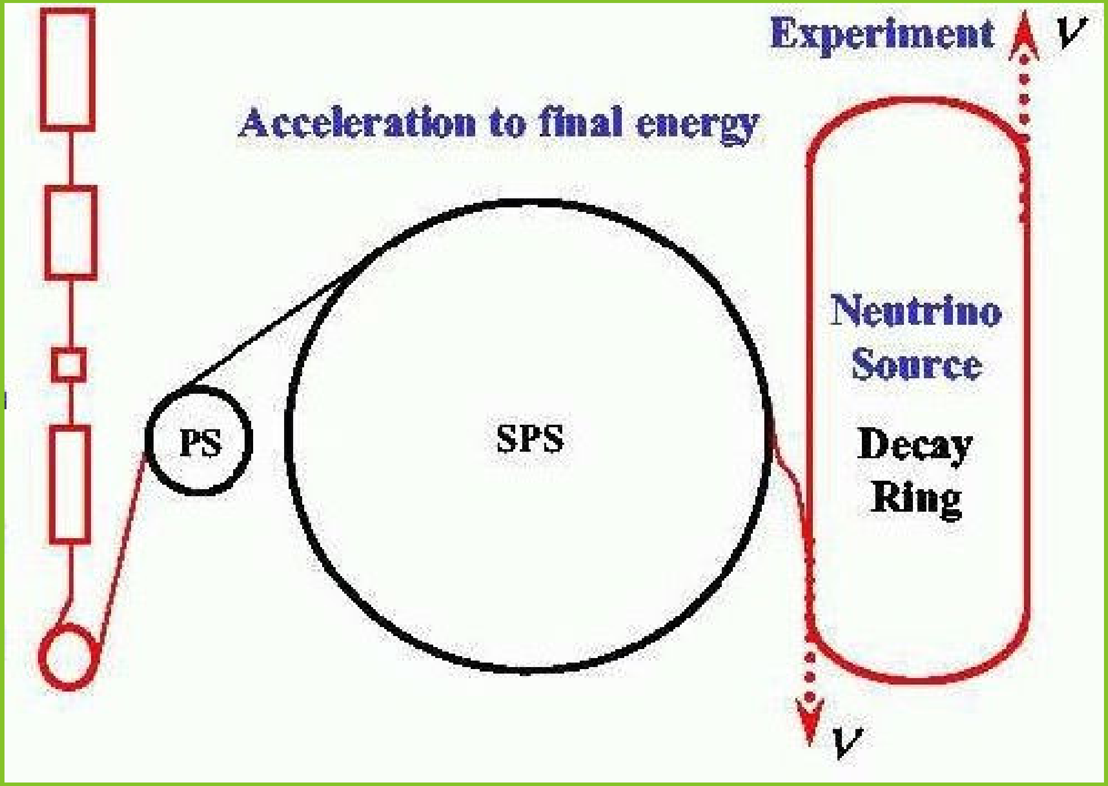
Introduction



Proton Rich Ions: Why are they important?

Nuclear Physics

Gamow Teller Resonance

- Oscillation of spin-isospin mode
- Predicted in 1962 by Ikeda, Fujii and Fujita
- First observed in 1975

- Charge Exchange Reactions (stable nuclei)
- Beta Decay measurements (unstable nuclei)

Missing Strength

- In the Ch-E Rx measurements, the 40% is missing (also in β Decay because of Pandemonium effect)
- One possible explanation is configuration mixing that shifts the strength

- β decay is a forbidden process in general
- Resonance is outside the Q value (except in some cases)
- Rare Earths above ^{146}Gd are one of these exceptions

Introduction

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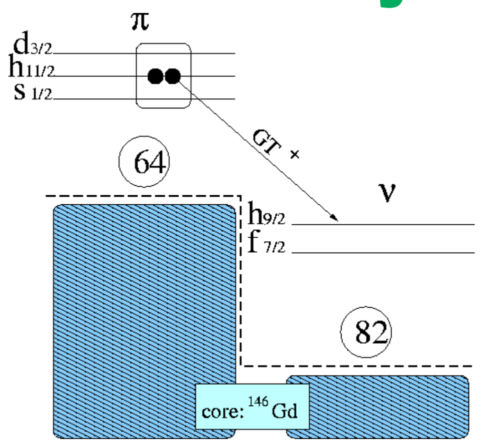


- Quasi-magic in protons, magic in neutrons
- Free neutron orbitals available (Extreme Single Particle Model) lead to a narrow resonance (the narrowest GT resonance observed in heavy nuclei)
- As Z increases, the resonance gets wider
- Would be interesting to go up in protons further than Yb (Systematics)

Some of these nuclei were already measured in the Experimental Program of ISOL, the mass separator at GSI

ISOLDE status

- Rare earths chemically similar: they come together from the ion source
- Nuclei closer to stability are produced in higher amounts

- Saturation of the system and contamination (X ray tagging is not enough to clean)
- Possible solution: laser Ionization (already tested with other nuclei, nice results)

Introduction

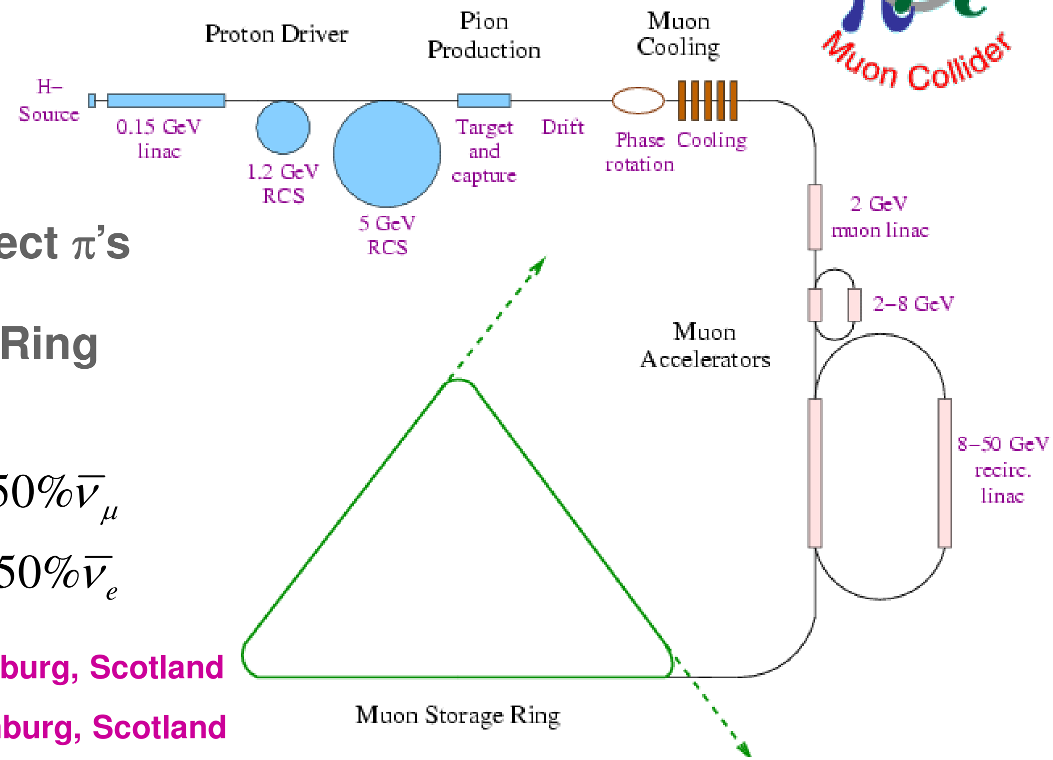
Proton Rich Ions: Why are they important?

Neutrino Physics

Neutrino Factories: Pions and muons

Phases:

- Intense P beam
- Robust target
- Strong magnet to collect π's
- Muon Cooling
- Injection in a Storage Ring



$$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu \Rightarrow 50\% \nu_e + 50\% \bar{\nu}_\mu$$

$$\mu^- \to e^- \nu_\mu \bar{\nu}_e \Rightarrow 50\% \nu_\mu + 50\% \bar{\nu}_e$$

M. S. Zisman et al, *Proceedings of EPAC* 2006, Edinburg, Scotland

A. Blondel et al, *Proceedings of EPAC* 2006, Edinburg, Scotland

Proton Rich Ions: Why are they important?

Neutrino Physics

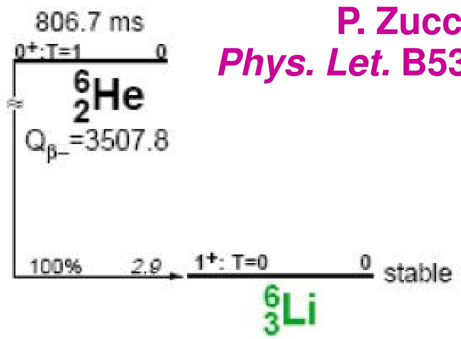
Beta Beams: ^{6}Li and ^{18}Ne

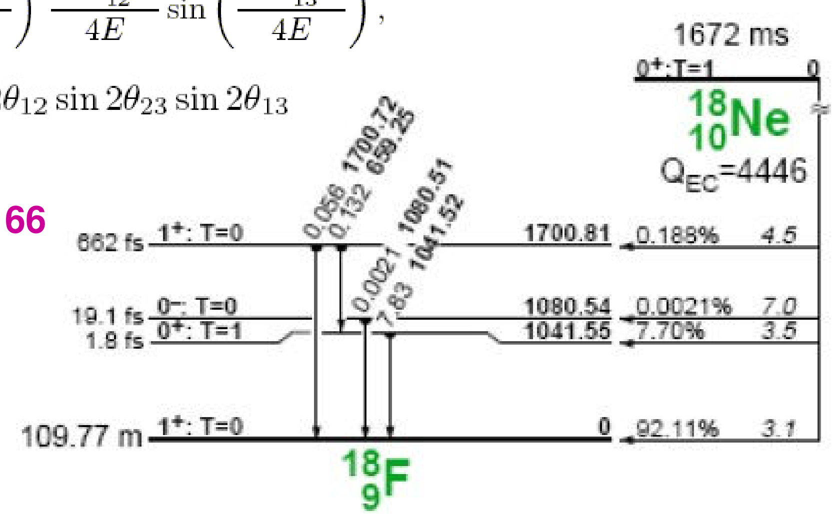
The decay of a beta unstable nucleus is even simpler !!

Apearance Probability

$$P(\nu_e \to \nu_\mu) \simeq s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right) + c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right) +$$
$$+ \tilde{J} \cos\left(\delta - \frac{\Delta m_{13}^2 L}{4E}\right) \frac{\Delta m_{12}^2 L}{4E} \sin\left(\frac{\Delta m_{13}^2 L}{4E}\right),$$
$$\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$

P. Zucchelli, ***Phys. Let.*** **B532 (2002) 166**





$$^{6}_{2}He \to ^{6}_{3}Li + e^{-} + \overline{\nu}_e$$

Average E_{cms} = 3.51 MeV

$$^{18}_{10}Ne \to ^{18}_{9}F + e^{+} + \nu_e$$

Average E_{cms} = 1.86 MeV

Proton Rich Ions: Why are they important?

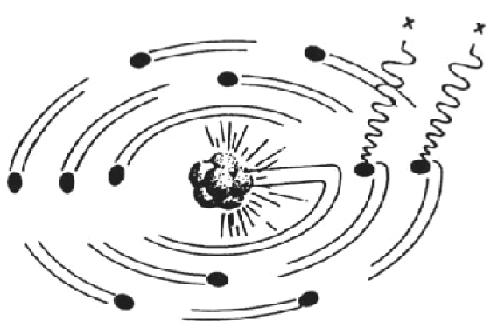
Neutrino Physics

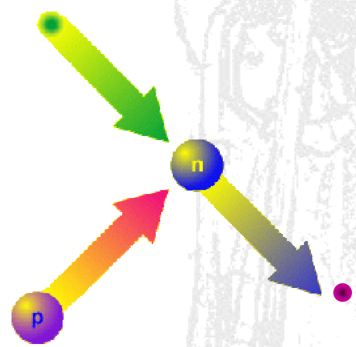
The synergy:
Rare Earths over ^{146}Gd

The decay of a beta unstable nucleus is even simpler !!

Apearance Probability

$$P(\nu_e \to \nu_\mu) \simeq s_{23}^2 \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{13}^2 L}{4E}\right) + c_{23}^2 \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{12}^2 L}{4E}\right) +$$
$$+\tilde{J} \cos\left(\delta - \frac{\Delta m_{13}^2 L}{4E}\right) \frac{\Delta m_{12}^2 L}{4E} \sin\left(\frac{\Delta m_{13}^2 L}{4E}\right),$$
$$\tilde{J} \equiv c_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13}$$





Feasible ν's source:

Nuclei that EC decay

$$^{152}_{70}Yb + e^- \rightarrow ^{152}_{69}Tm + \nu_e$$

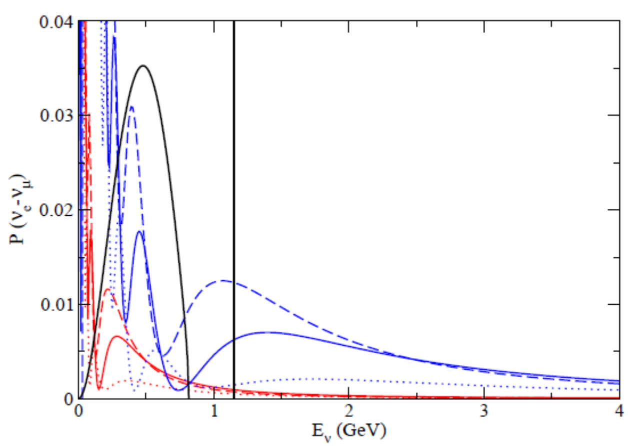
Q_{EC} = 5.47 MeV

Proton Rich Ions: Why are they important?

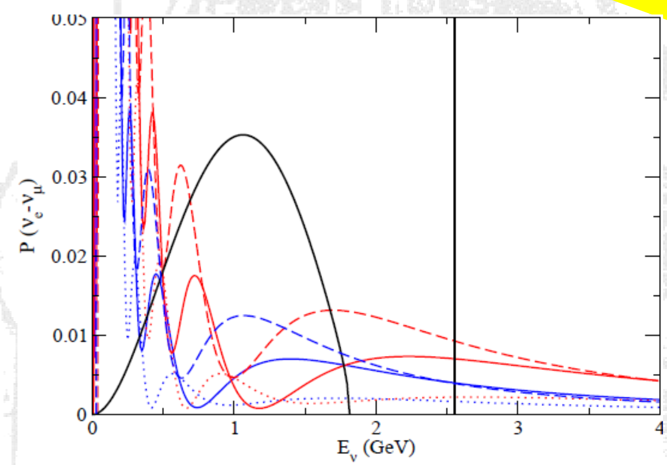
Neutrino Physics

The synergy:
Rare Earths over ^{146}Gd

The decay of a beta unstable nucleus is even simpler !!



Red: CERN-Frejus (130 km)
Blue: CERN-Canfranc (650 km)
$\gamma = 166$, $\sin^2 2\theta_{13} = 0.01$



Blue: CERN-Canfranc (650 km)
Red: CERN-Boulby (1050 km)
$\gamma = 369$, $\sin^2 2\theta_{13} = 0.01$

J. Bernabeu, C. Espinoza
arXiv:0905.2913v1
[hep-ph] 18 May 2009

$${}^{152}_{70}Yb + e^- \rightarrow {}^{152}_{69}Tm + \nu_e$$

$Q_{EC} = 5.47$ MeV

Candidates

Rare Earths above ^{146}Gd

Introduction

Candidates

Measures

Analysis

Results

- Radioactive nuclei
- Good production (I will show it later)
- One single state mainly populated
- Small amount of other decay modes
- $T_{1/2}$ small enough for reasons related to the design of the ring (acceleration, vacuum loses, etc)
- Larger percentage of EC than β^+

J. Bernabeu et al, *JHEP* **12** (2005) 14

Proton Rich Ions: Why are they important?

Nuclear Physics

- Open problems
- Interesting region to be studied
- Proton rich nuclei (X-ray selectivity)
- Nuclear Structure Physics
- Missing Strength
- The narrowest GT resonance observed in heavy nuclei
- Development of new experimental techniques

Neutrino Physics

- Beta beams
- Neutrino Factories
- Study of Neutrino Oscillations
- Physics beyond the SM
- Neutrino Cross-sections
- Good EC candidates for producing monochromatic neutrino beams
- Development of new experimental techniques

Candidates

ytterbium
70
Yb
173.04(3)
erbium
68
Er
167.259(3)
thulium
69
Tm
168.93421(2)
thulium
69
Tm
168.93421(2)

Candidates

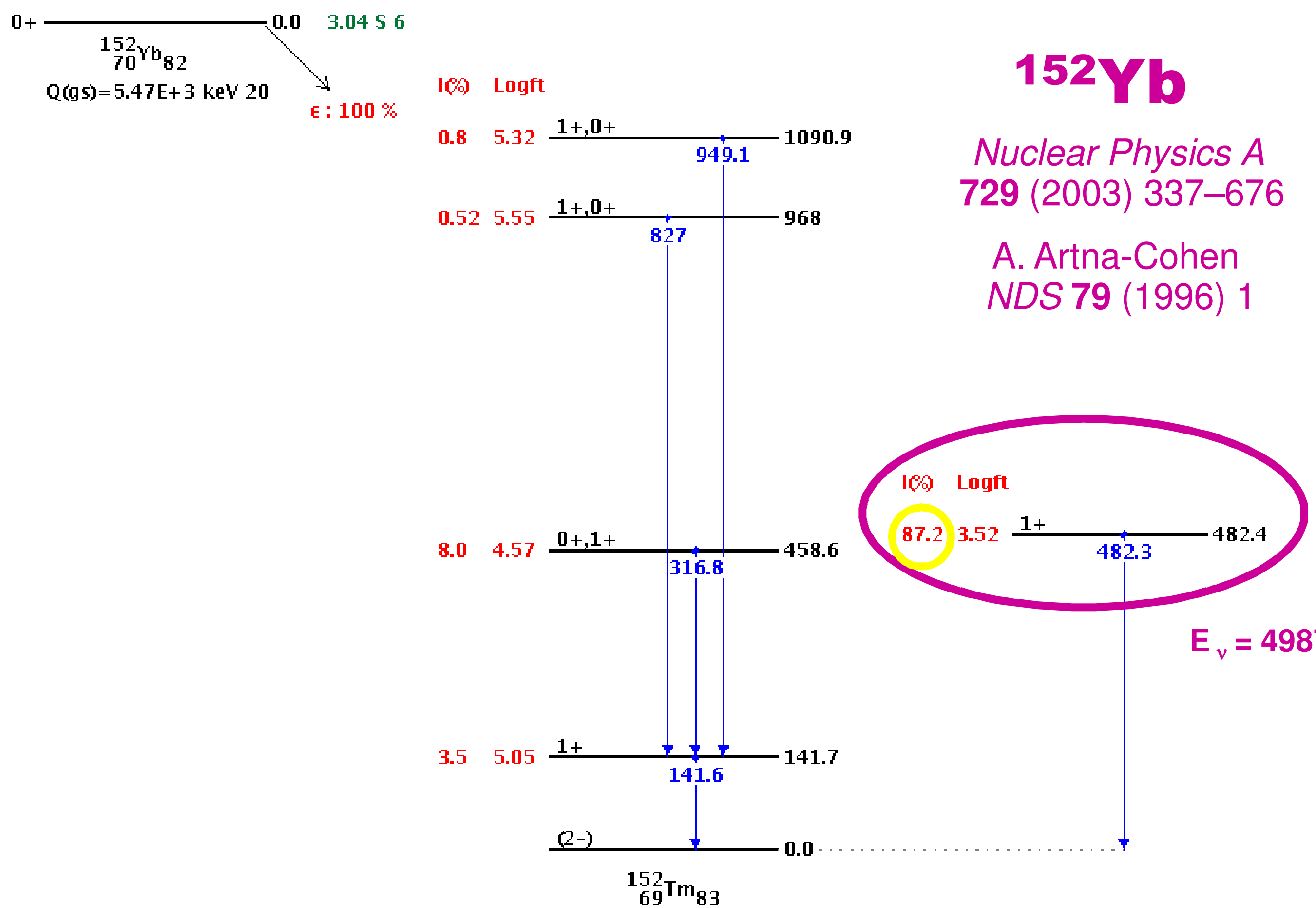
Table of candidates (ENSDF[1])

ID	Parent Nucleus	Daugther Nucleus	Half-life	$(EC+\beta^+)/\alpha$ branch of the decay	EC int. [%] (to the level of interest)	Ex Daugther Level [keV]	I [%]	Q value [keV]	Yield (ISOLDE) [atoms/μC]
1	$^{148}_{66}Dy_{82}$	$^{148}_{65}Tb_{83}$	3.1 m	100*	92.5	620	96	2678	2.9×10^8
2	$^{148}_{68}Er_{80}$	$^{148}_{67}Ho_{81}$	4.6 s	100*	8.8	0.0 (+?)	70 (+?)	6800	-
3	$^{150}_{68}Er_{82}$	$^{150}_{67}Ho_{83}$	18.5 s	100*	59.4*	476+X	99.6	4108	7×10^6
4	~~$^{150}_{66}Dy_{84}$~~	~~$^{150}_{65}Tb_{85}$~~	~~7.17m~~	~~64/36~~	~~64.0*~~	~~397+Y~~	~~64~~	~~1794~~	~~2.4×10^9~~
5	$^{152}_{70}Yb_{82}$	$^{152}_{69}Tm_{83}$	3.1s	100*	29.0	482	88	5470	-
6	$^{152}_{69}Tm_{83}$	$^{152}_{68}Er_{84}$	8s	100*	50	4300	Res.	8700	-
7	$^{152}_{68}Er_{84}$	$^{152}_{67}Ho_{85}$	10.3s	(10/90)	8.0	179.4	10%	3105	7×10^7
8	$^{154}_{72}Hf_{82}$	$^{154}_{71}Lu_{83}$	2s	100*	-	-	-	6700	(Difficult)
9	$^{154}_{70}Yb_{84}$	$^{154}_{69}Tm_{85}$	0.404s	(7.2/92.8)	3.3	133.2	7.2	4490	2×10^3
10	~~$^{154}_{68}Er_{86}$~~	~~$^{154}_{67}Ho_{87}$~~	~~3.73m~~	~~99.53/0.47~~	~~96.8~~	~~26.9~~	~~99.53~~	~~2032~~	~~6×10^8~~
11	$^{156}_{72}Hf_{84}$	$^{156}_{71}Lu_{85}$	25ms	(alpha>81%)	-	-	-	5910	-
12	$^{156}_{70}Yb_{86}$	$^{156}_{69}Tm_{87}$	26.1s	90/10	61.0	115.2	90	3570	3.2×10^7
13	~~$^{156}_{68}Er_{88}$~~	~~$^{156}_{67}Ho_{89}$~~	~~19.5m~~	~~100*~~	~~58 (+38)~~	~~82.1 (+87.5)~~	~~58 (+38)~~	~~1370~~	~~6×10^8~~

[1]Evaluated Nuclear Structure Data Files

Candidates

Known information (high resolution measurements)

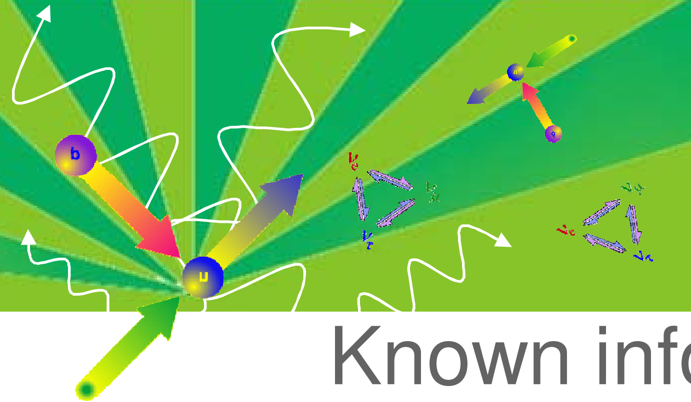


^{152}Yb

Nuclear Physics A **729** (2003) 337–676

A. Artna-Cohen
NDS **79** (1996) 1

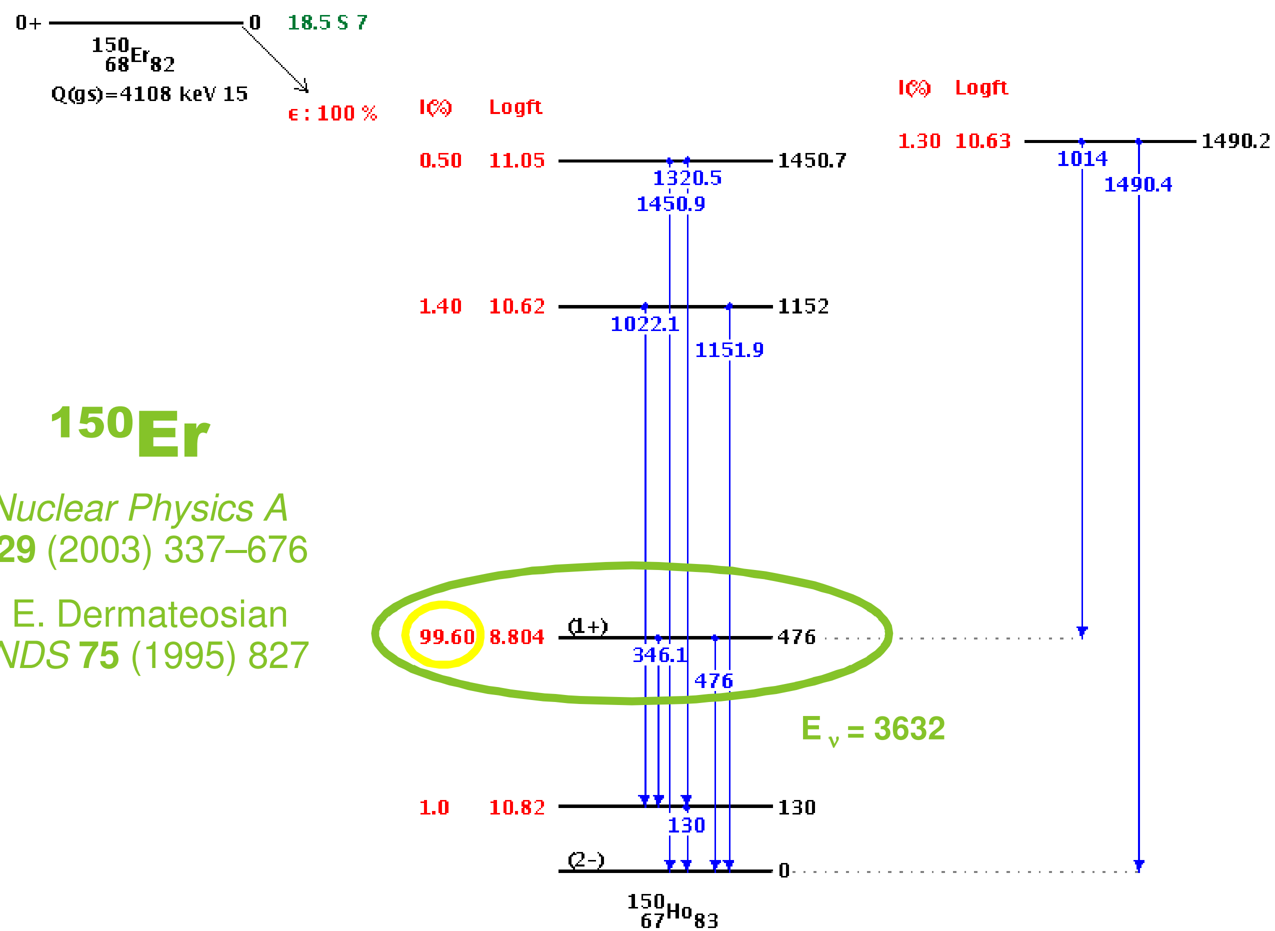
E_{ν} = 4987.6



Candidates

Known information (high resolution measurements)

- Introduction
- **Candidates**
- Measures
- Analysis
- Results



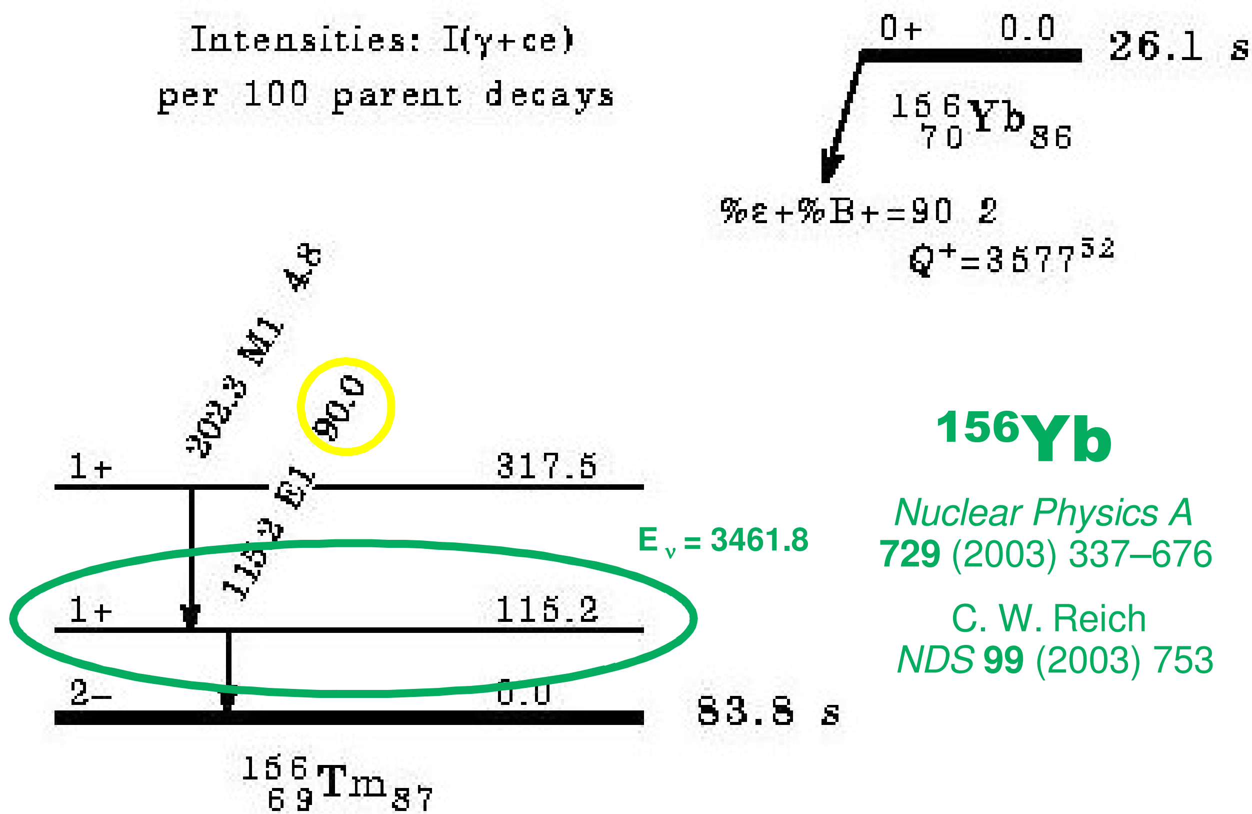
^{150}Er

Nuclear Physics A **729** (2003) 337–676

E. Dermateosian *NDS* **75** (1995) 827

E_{ν} = 3632

Known information (high resolution measurements)



^{156}Yb

Nuclear Physics A **729** (2003) 337–676

C. W. Reich

NDS **99** (2003) 753

About Production Rates

ISOLDE Yields (in atoms/microC):

^{6}He	1.6×10^{7}
^{18}Ne	3.5×10^{6}
^{150}Er	7.0×10^{6}
^{152}Yb	No info. available
^{156}Yb	3.2×10^{7}

Looking at the ISOLDE yields we see that there is no real difference in terms of production under the present ISOLDE conditions.

Calculated using a p beam of 600 MeV and 6×10^{12} particles per second (1μA)

It is possible to have better numbers in the future if these nuclei are to be used in the new facility. Even if more exotic isotopes are needed, techniques to produce them are in hand. A future beta or EC beam facility will need higher intensities and will demand a MW driver any way.

- We need detailed experimental results on the properties of the EC- β^+ transitions occuring in these ions.
- We need to involve the persons that can provide a realistic estimate of the production rate of these ions with the advent of the MW proton driver, and its comparison with the production rate for light ions.

Candidates

Table of candidates (ENSDF)

ID	Parent Nucleus	Daugther Nucleus	Half-life	(EC+β^+) / α branch of the decay	EC int. [%] (to the level of interest)	Ex Daugther Level [keV]	I [%]	Q value [keV]	Yield (ISOLDE) [atoms/μC]
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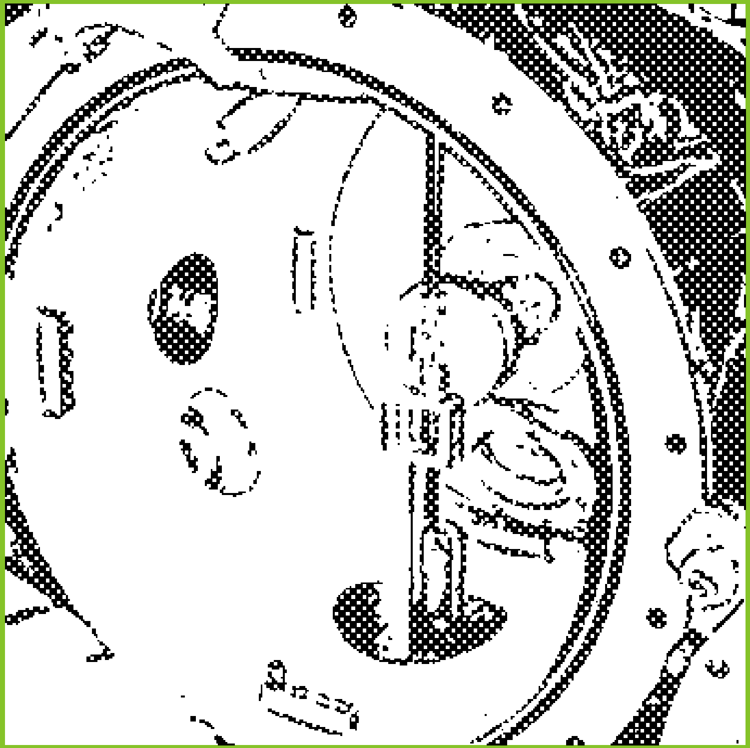
^{152}Yb Already measured !!

^{150}Er Already measured !!

^{156}Yb Already measured !!

Measurements



Measurements

Introduction

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Measures

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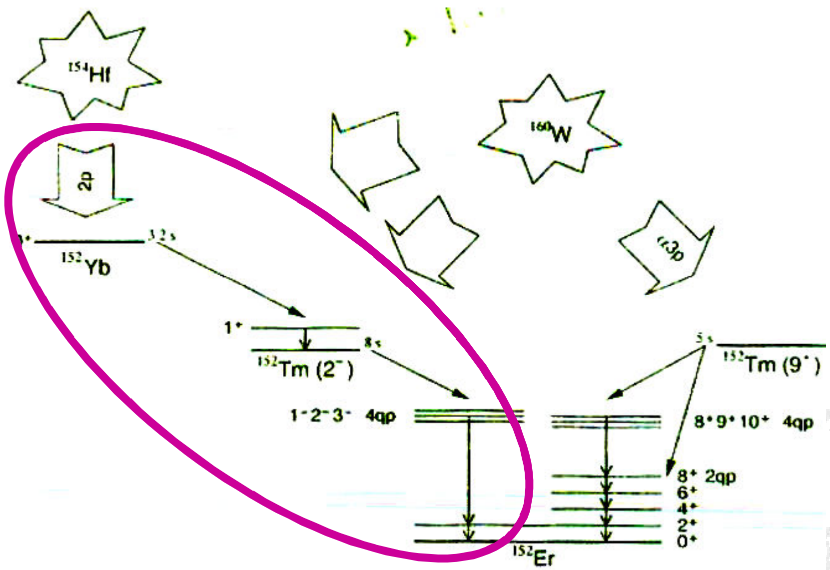
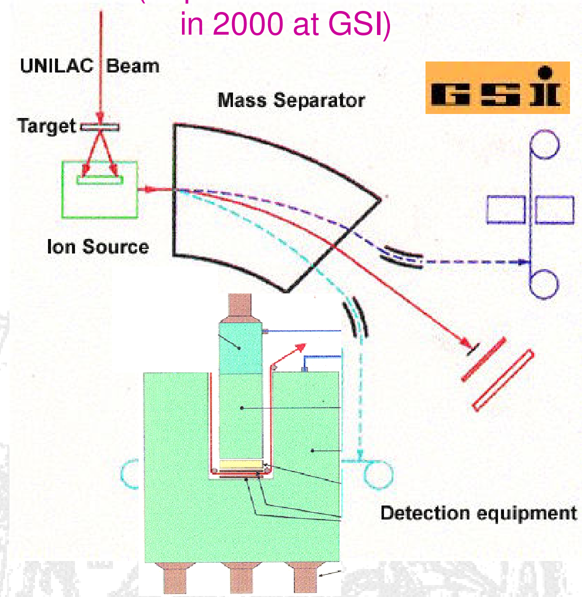


(Experiment realized in 2000 at GSI)



Beam: ^{58}Ni a **T = 4,53 MeV/u**

Target: ^{96}Ru (96.53%) 2 mg/cm^2

$$^{96}_{44}Ru_{52}(^{58}_{28}Ni_{30},2p)^{152}_{70}Yb_{82}$$

PARENT: $T_{1/2}$ (Yb) = 3.1s

DAUGHTER: $T_{1/2}$ (Tm 2$^-$) = 8s, $T_{1/2}$ (Tm 9$^+$) = 5.2s

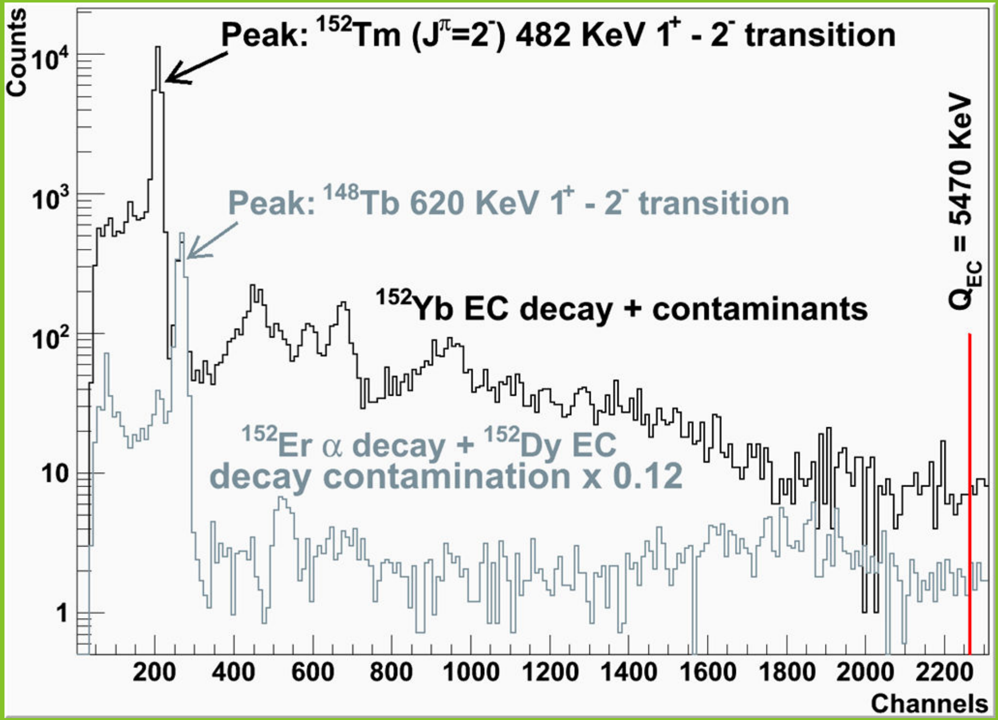
GRAND-DAUGHTER: $T_{1/2}$ (Er) = 10.3s

cycle:16s

(optimized for the prodruction of Er)

at least 3 isobars in the spectra!!!

Analysis and Results



Analysis and Results

Calculating the feeding

(D. Cano et al, NIM A 430 (1999) 333)

$$d_i = \sum_{j=1}^{j_{max}} R_{ij} f_j$$

Nº of counts in i

Nº of events that go to E_j

Prob. of having a count in i when there has been feeding to E_j
RESPONSE FUNCTION
(unique for each level scheme and detector)

Introduction

Candidates

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$d_i \rightarrow$ Measurements

$R_{ij} \rightarrow$ MC (resp.to individual γ)

$f_j \rightarrow$ Is not possible to invert R !!
(Similar response to the feeding of adjacent energy beams)

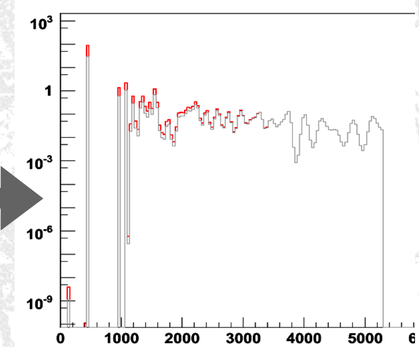
Expectation-Maximisation Method
(**BAYES THEOREM**)

Thesis of D. Cano
(J. L. Tain et al, NIM A 571 (2007) 738)

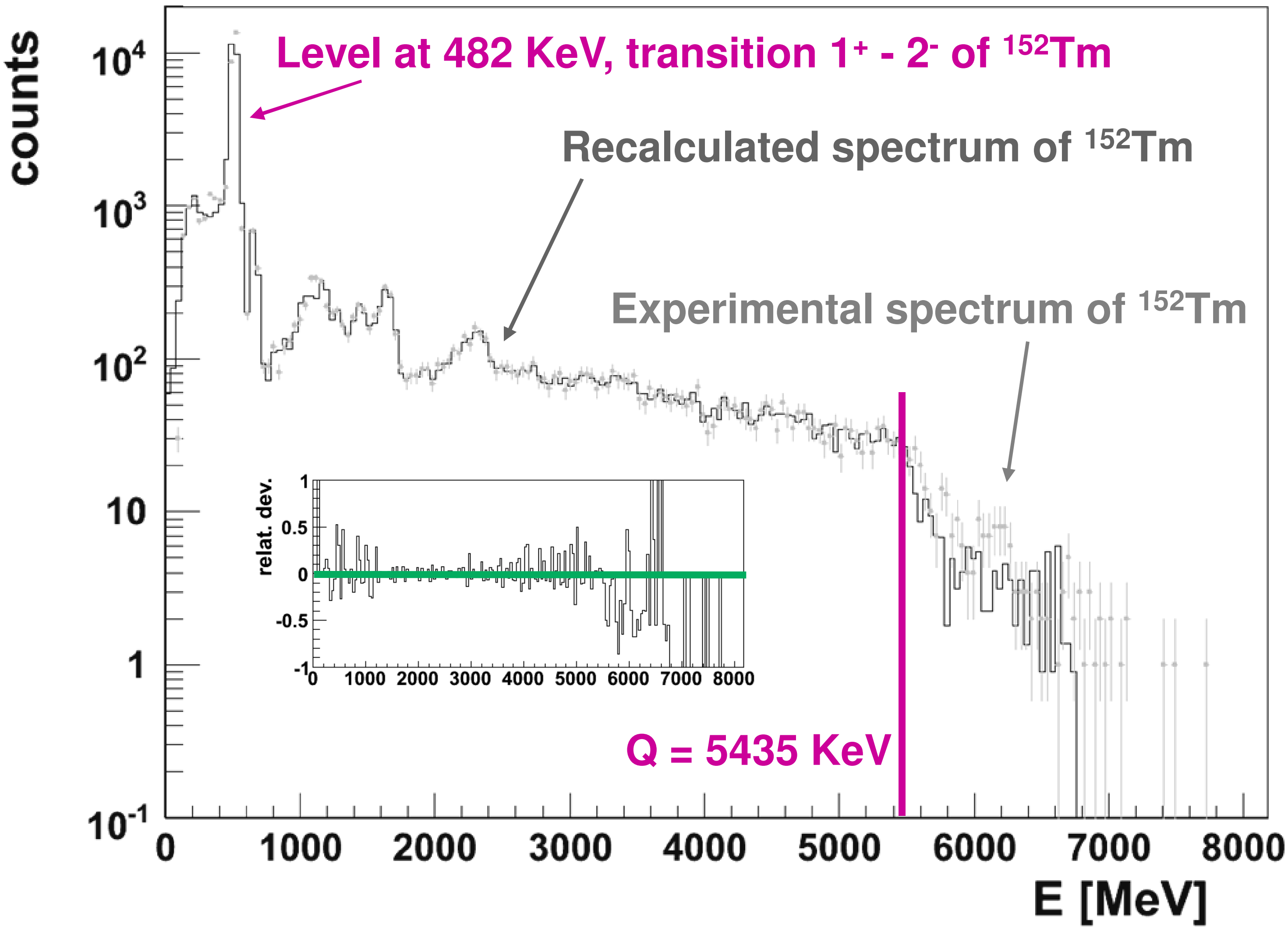
d_i (rebinned 40 keV)
Resp. MC
Contaminants
(…pileup, background…)
Known levels
+statistical model
+ gamma strength function

input

$$f_j = \frac{1}{\sum_{i=1}^{n} R_{ij}} \sum_{i=1}^{n} \frac{R_{ij} \hat{f}_j}{\sum_{k=1}^{m} \frac{R_{ij} f_j}{\sum_{k=1}^{m} R_{ik}}}$$



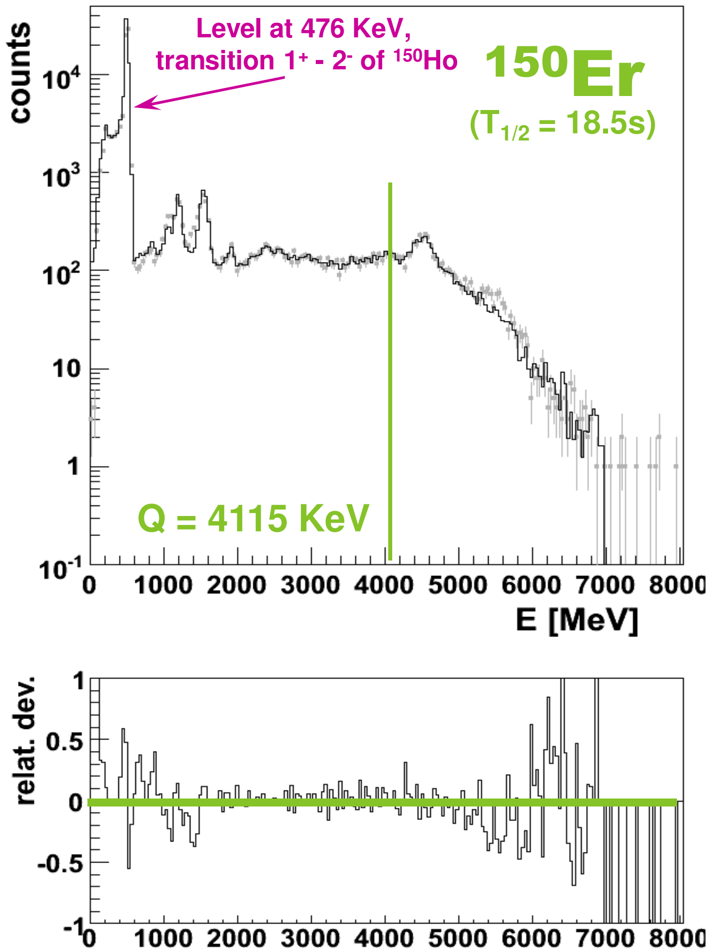
Analysis and Results

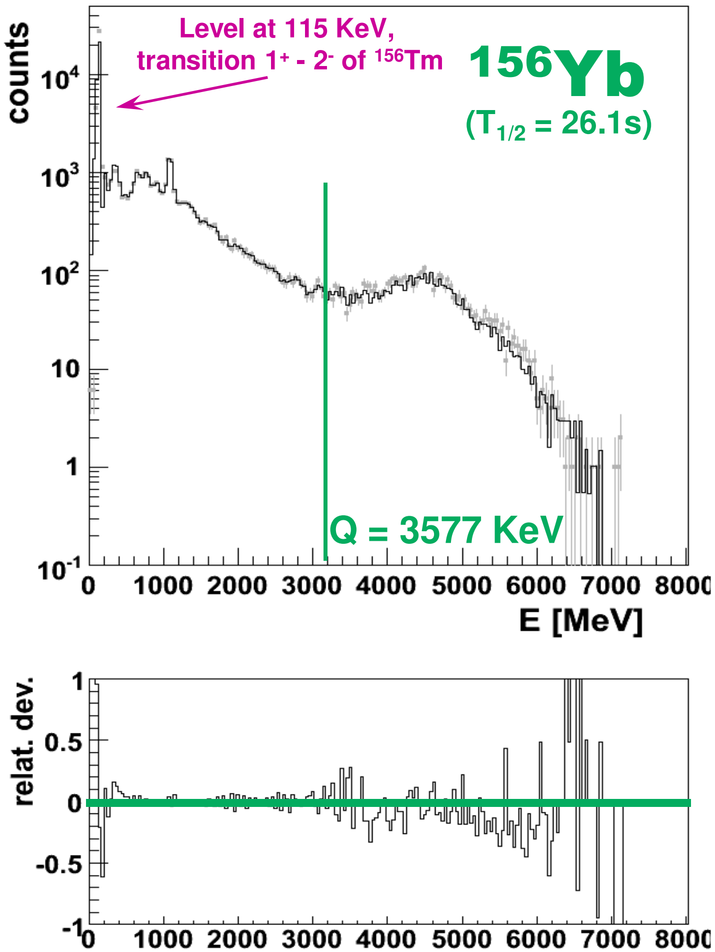


^{152}Yb

($T_{1/2}$ = 3.1s)

Analysis and Results





Analysis and Results

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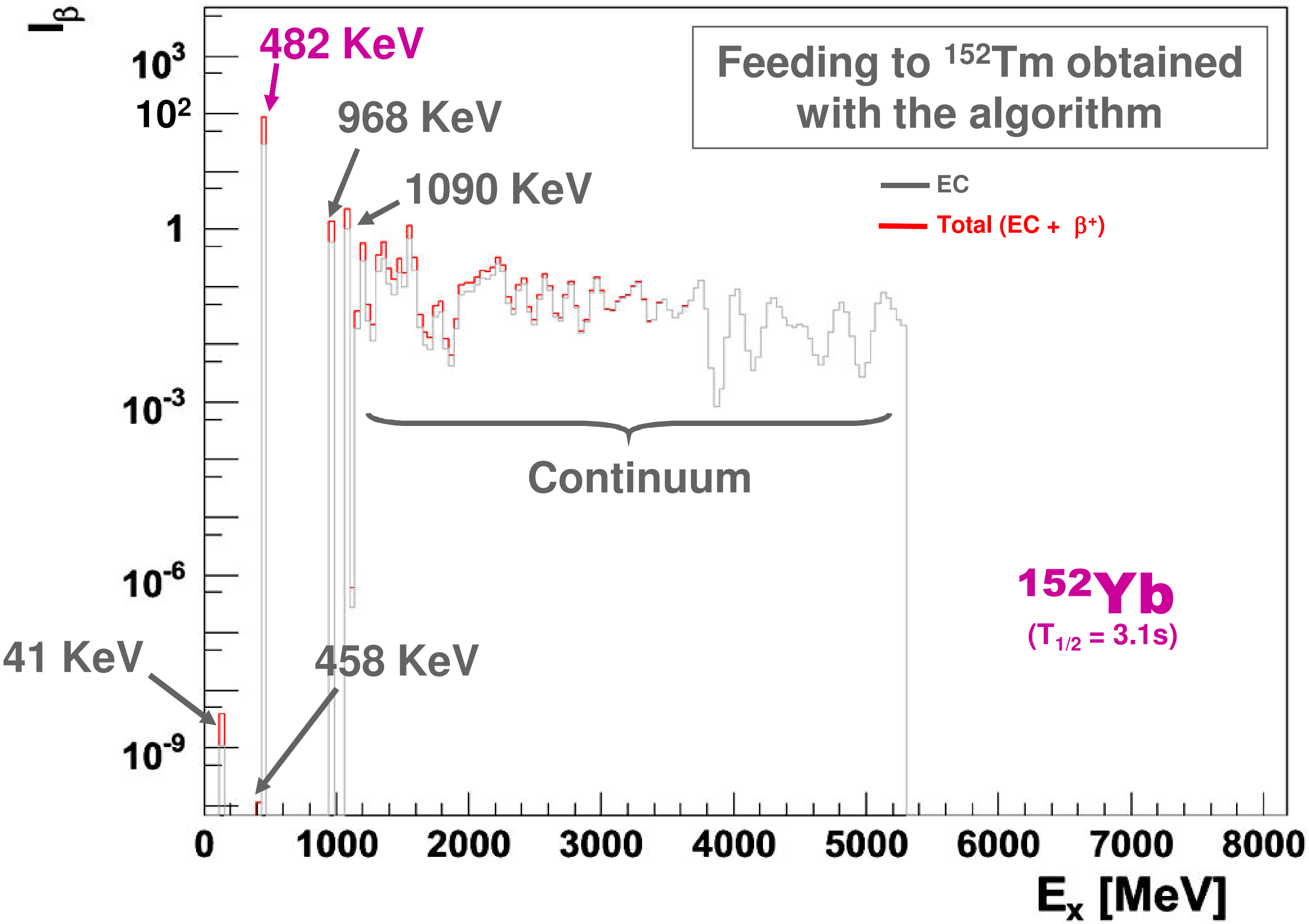
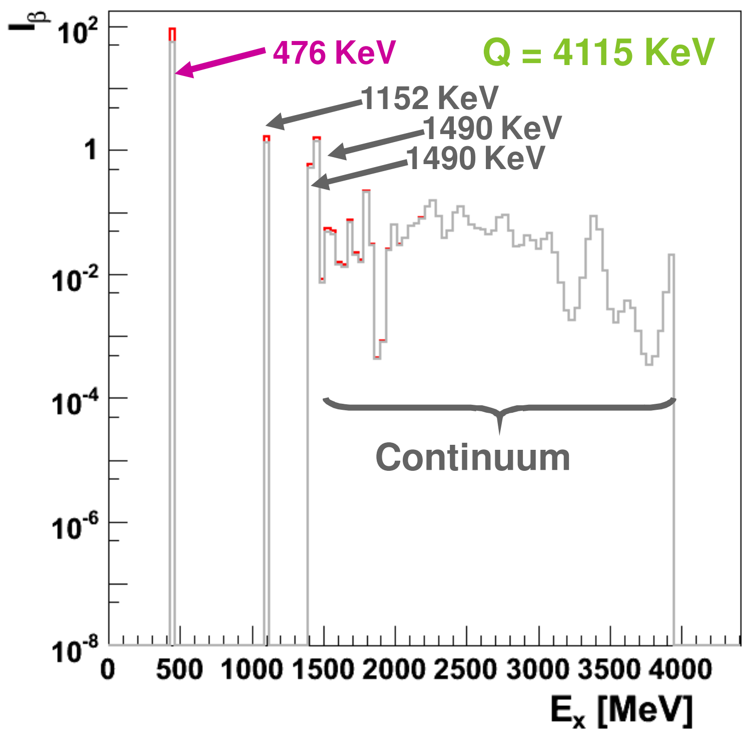


Analysis and Results

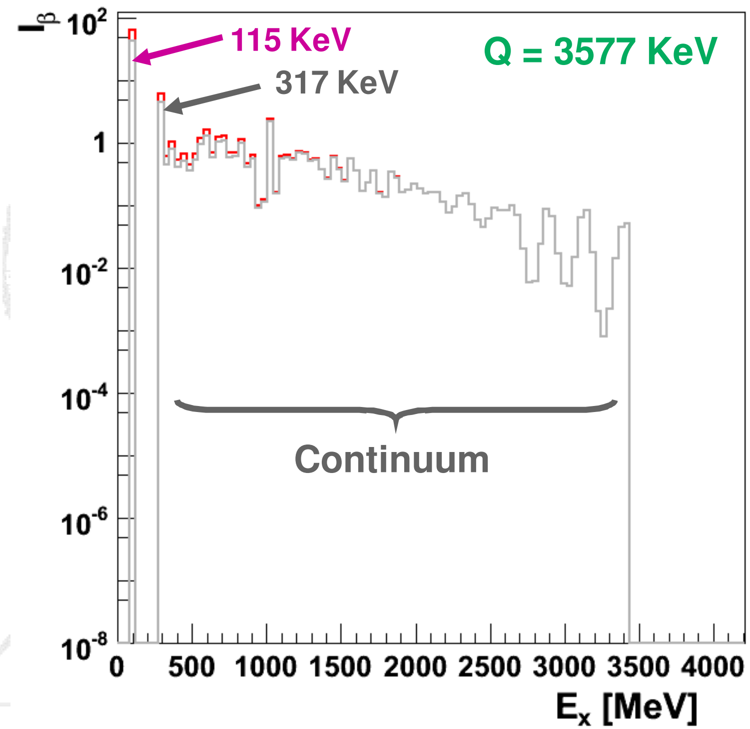
Feeding to ^{150}Ho obtained with the algorithm

^{150}Er
($T_{1/2}$ = 18.5s)



Feeding to ^{156}Tm obtained with the algorithm

^{156}Yb
($T_{1/2}$ = 26.1s)



EC
Total (EC + β^+)

Analysis and Results

Introduction

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Measures

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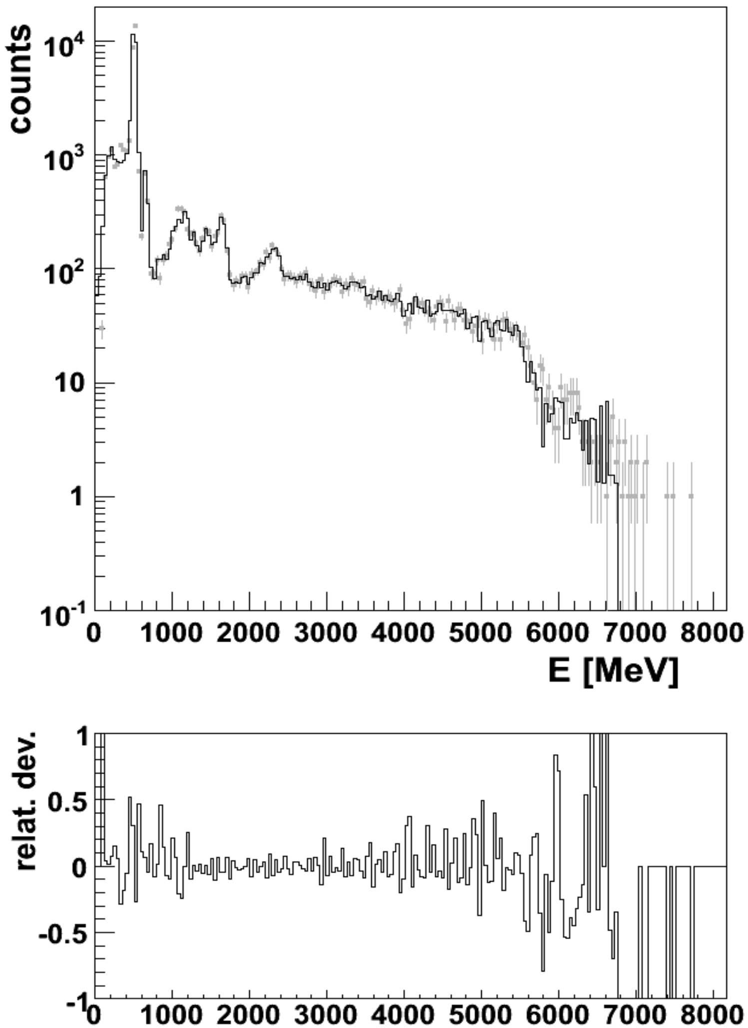
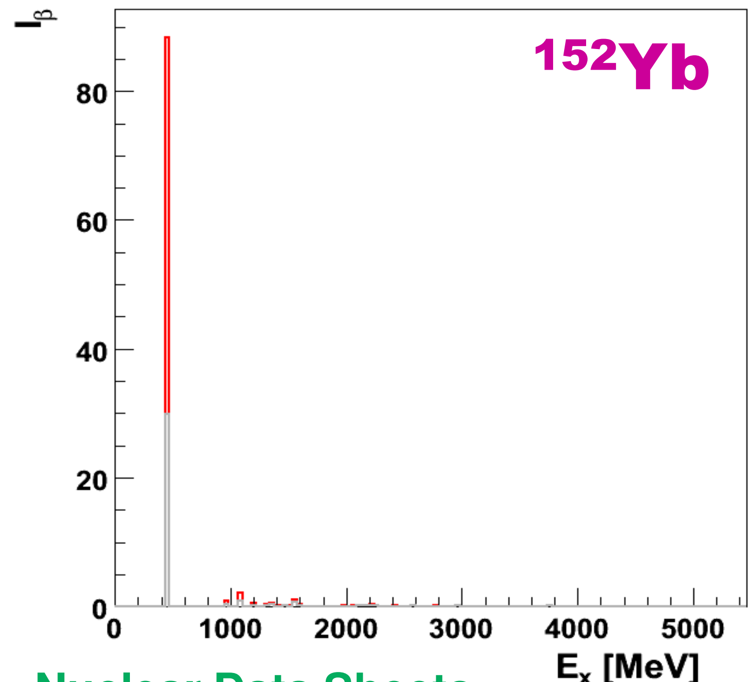




Nuclear Data Sheets

EC + β^+ = 87.2 %

EC = 29.3 %

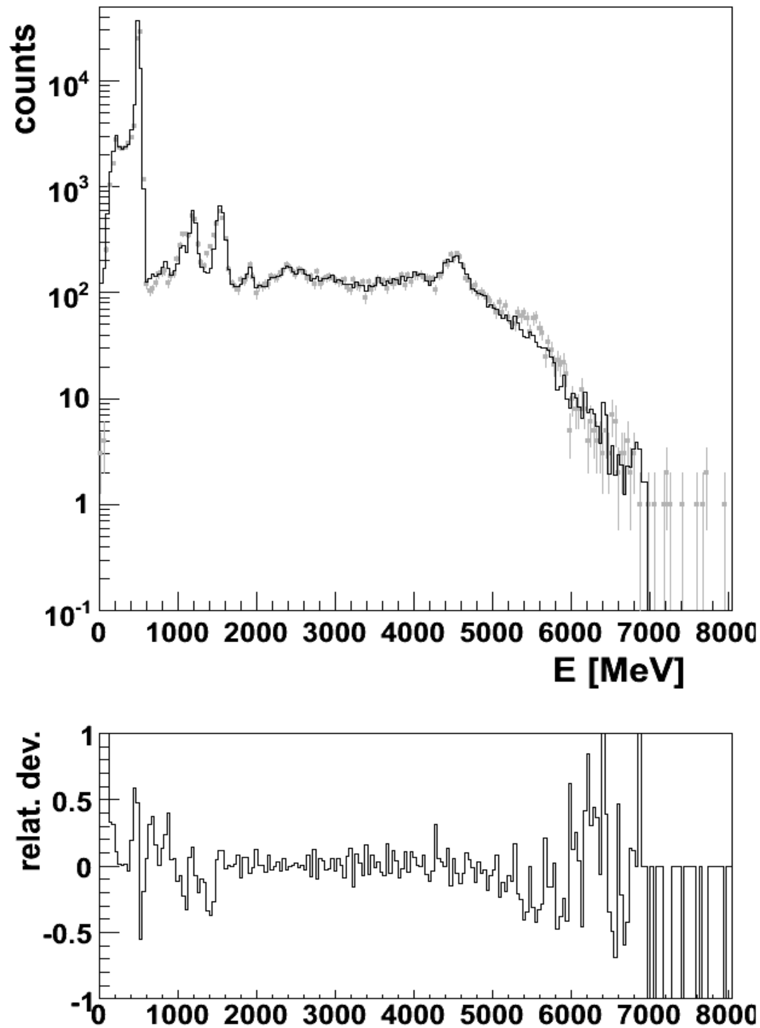
A. Artna-Cohen *NDS* **79** (1996) 1

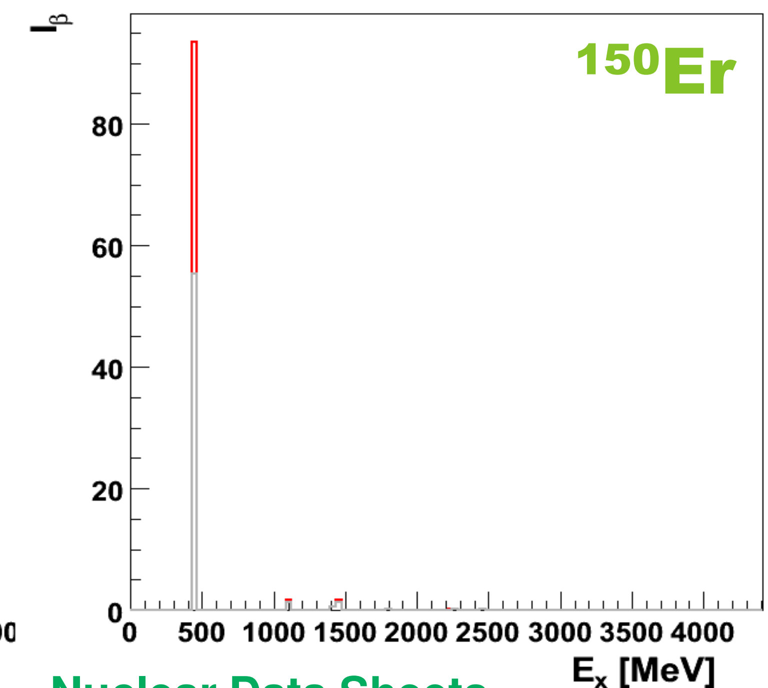
Our Data:

EC + β^+ = 88.3 $\pm$ 0.7 %

EC = 29.9 $\pm$ 0.2 %

Analysis and Results





Nuclear Data Sheets

EC + β^+ = 99.6 %

EC = 54.0 %

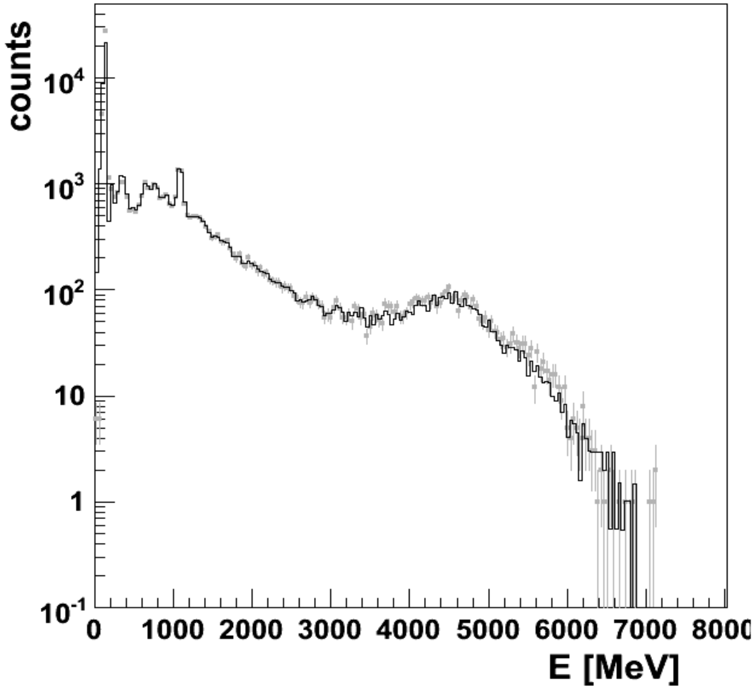
E. Dermateosian *NDS* **75** (1995) 827

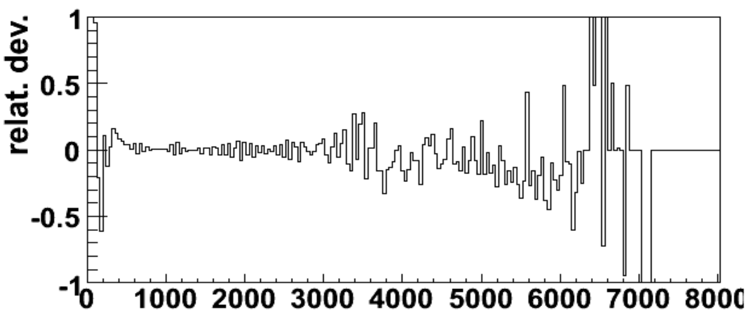
Our Data:

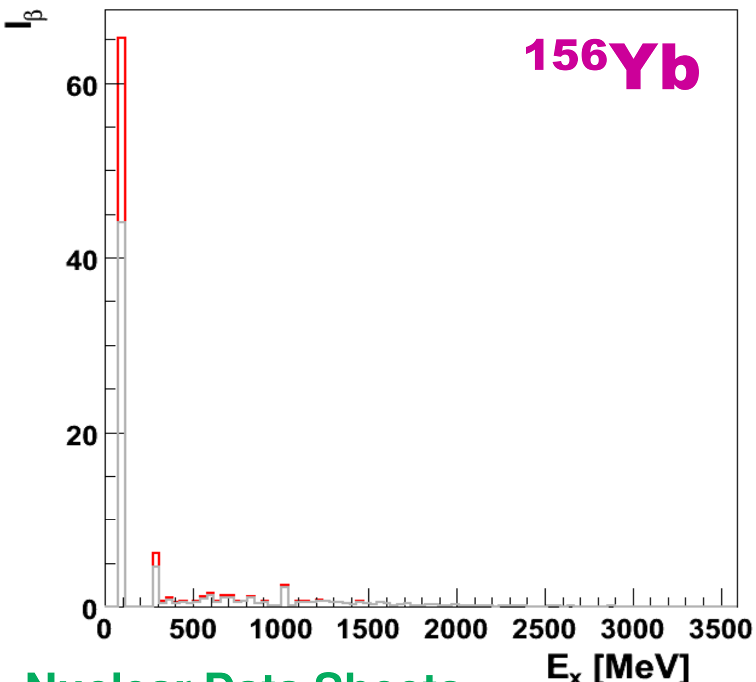
EC + β^+ = 93.0 $\pm$ 1.0 %

EC = 55.4 $\pm$ 0.6 %

Analysis and Results







Nuclear Data Sheets

$EC + \beta^+ = 90\ \%$

$EC = 61\ \%$

C. W. Reich
NDS **99** (2003) 753

Our Data:

$EC + \beta^+ = 65.1 \pm 1.0\ \%$

$EC = 44.1 \pm 0.5\ \%$

Analysis and Results

Conclusions

- The study of the phenomena of **neutrino oscillations** is of great interest and is one of the physical motivations for the construction of a neutrino beam facility.
- As a source for this beams it has been proposed to use nuclei that decay by means of the **electron capture** process, given that it is a two body process so the neutrino energy will be well defined..
- These nuclei should decay mainly to one state of the daughter nuclei, have a bigger EC than β^+ component, a short half life, a good production and small amount of other radioactivities (alphas, etc). In this talk we presented 3 candidates in the region of the **rare earths over ^{146}Gd**, that fullfill these requirements: **^{152}Yb**, **^{150}Er** and **^{156}Yb**.
- For the design of the facility we need good numbers that we can trust, specifically the feedings to the level of interest from which the neutrinos will be produced. This information is already known from the HR technique, so we determined these numbers for the three candidates with a different experimental technique, the **Total Absorption Spectroscopy**, which is assumed to not suffer from the *Pandemonium* effect.
- Our study **confirmed the values** for the feedings to the levels of interest in the selected nuclei, except for the case of ^{156}Yb, for which there is incomplete data available, suggesting that **this nuclei should be revisited** using the high resolution technique.

Acknowledgements

- Algora A.
- J. Bernabeu
- B. Rubio
- J. L. Tain
- E. Nacher
- D. Cano
- A. Gadea
- J. L. Tain
- L. Batist
- K. Burkard
- J. Döring
- M. Gierlik
- W. Hüller
- R. Kirchner
- I. Mukha
- C. Plettner
- E. Roeckl
- J. J. Valiente

This work was supported by the following projects: Spanish MEC FPA 2002-04181-004-03, FPA 2005-03993 and FPA2008-06419-C02-01; Hungarian OTKA K72566. A. Algora recognizes support from the Spanish Ramón y Cajal fellowship.

"…If you want to make an *apple pie* from scratch, you must first create the *universe*…"

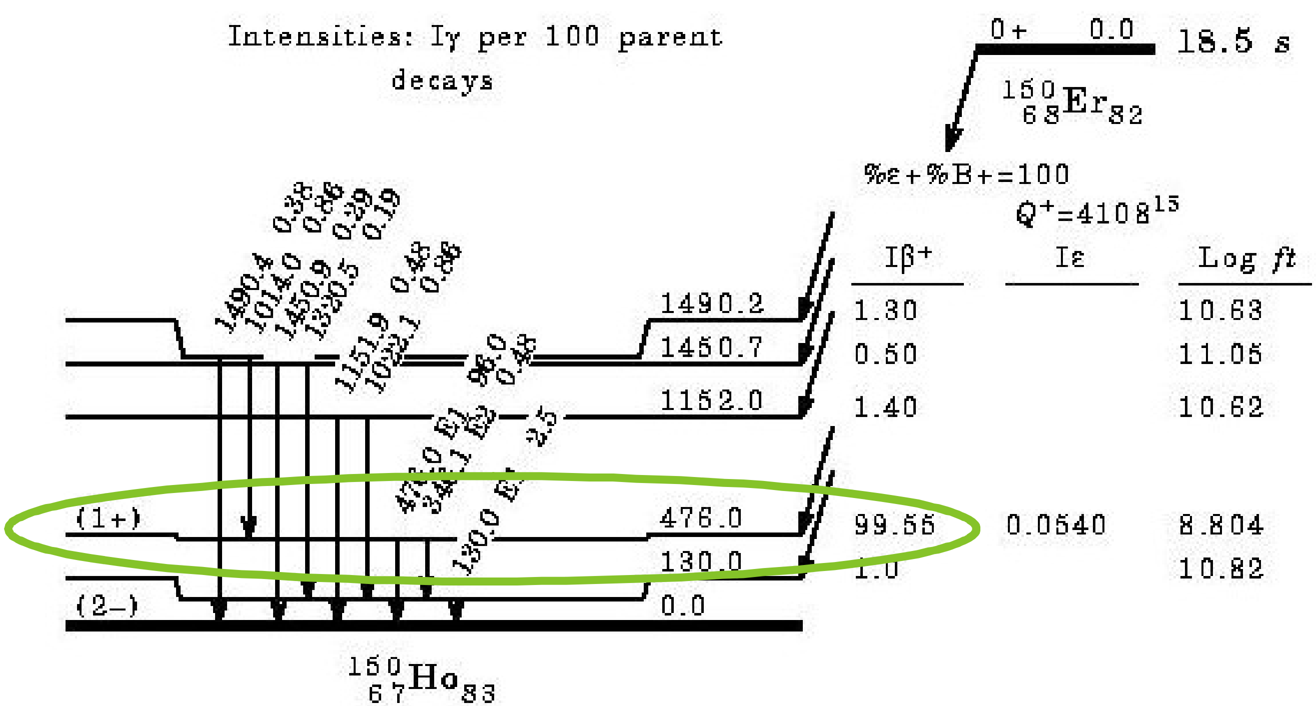
Carl Sagan

Candidates

Known information (high resolution measurements)

^{150}Er *Nuclear Physics A* **729** (2003) 337–676 E. Dermateosian *NDS* **75** (1995) 827

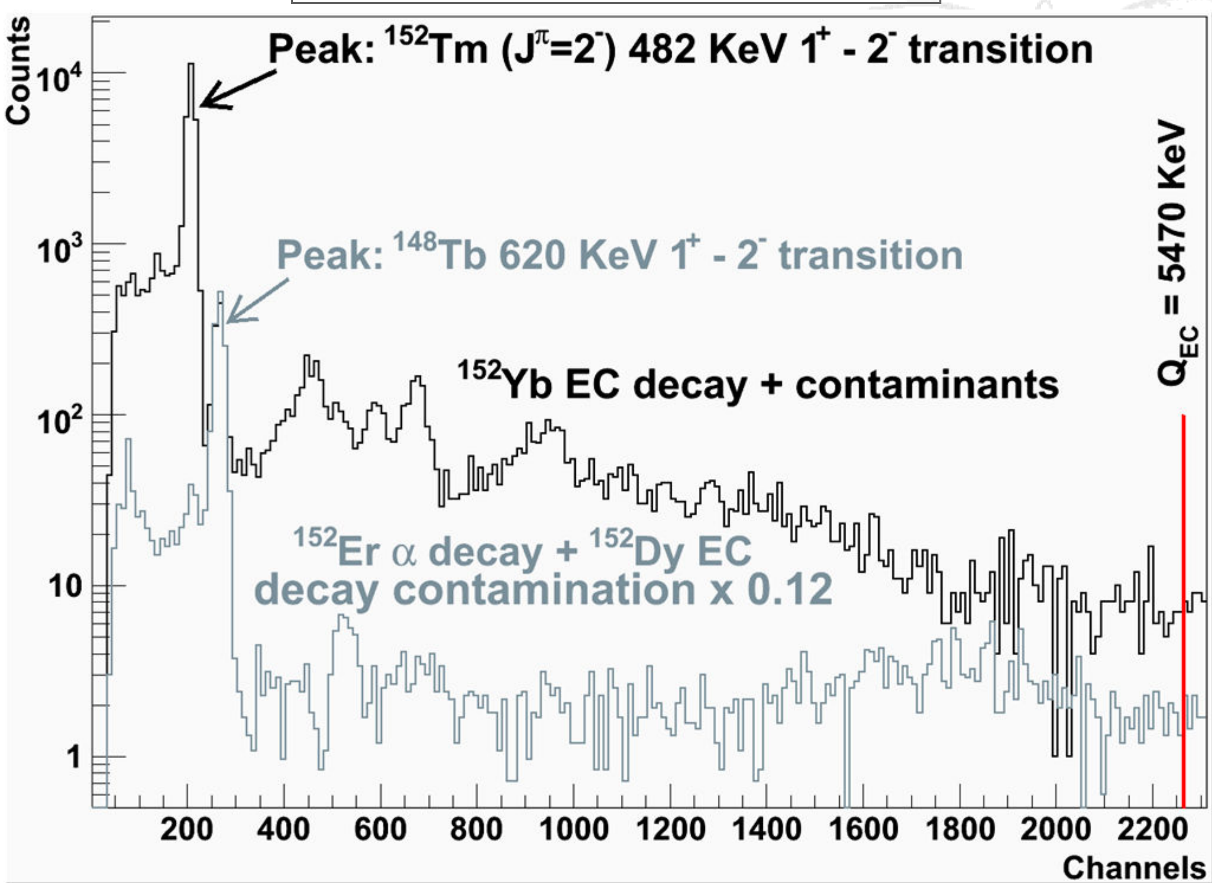
- Introduction
- **Candidates**
- Measures
- Analysis
- Results



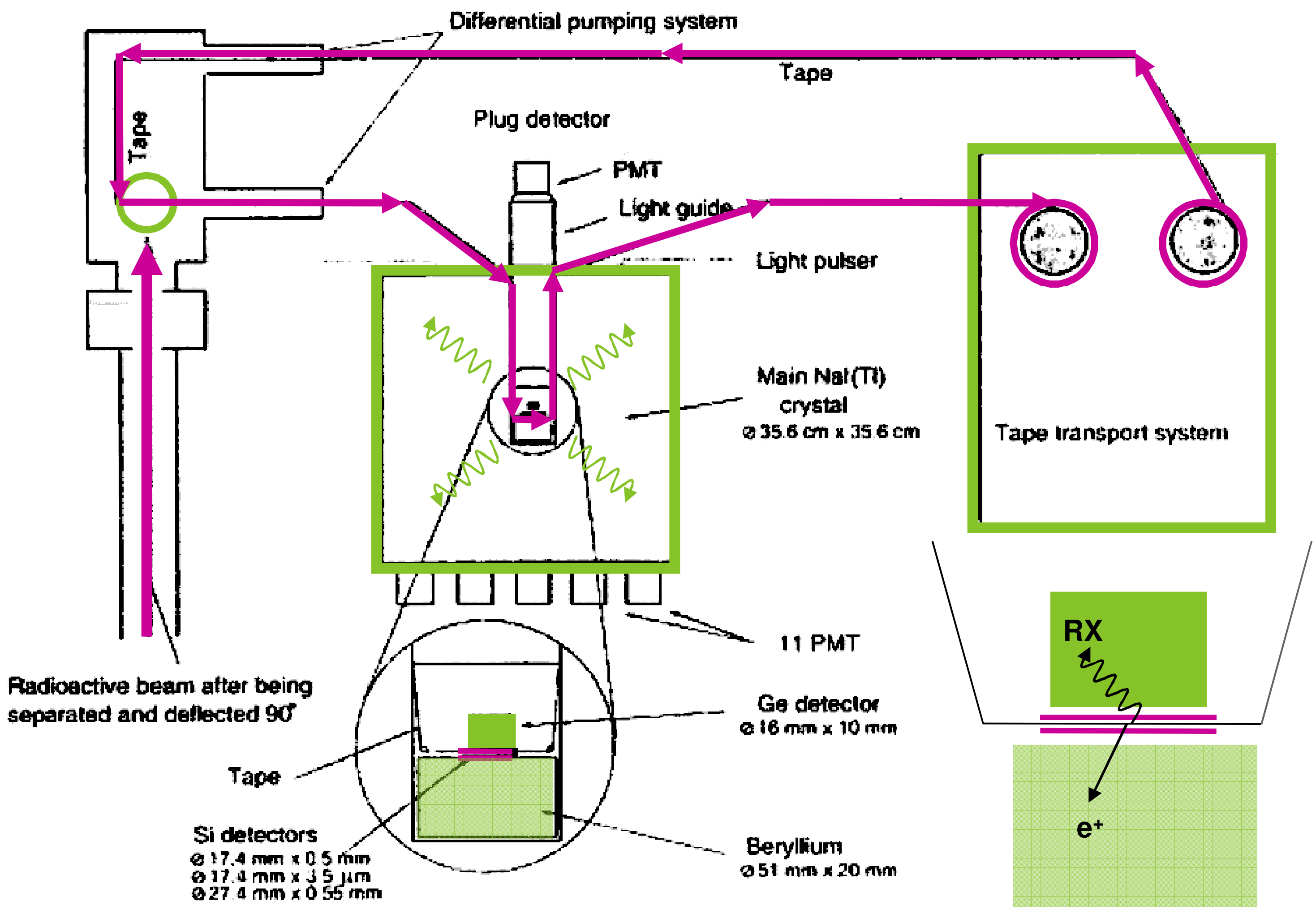
Análisis

^{152}Er (t½ = 10,3s) —90% α, Q_α = 4934 keV→ ^{148}Dy (t½ = 3,1 m) —100% EC, Q_{EC} = 2678 keV→ ^{148}Tb (t½ = 1h)

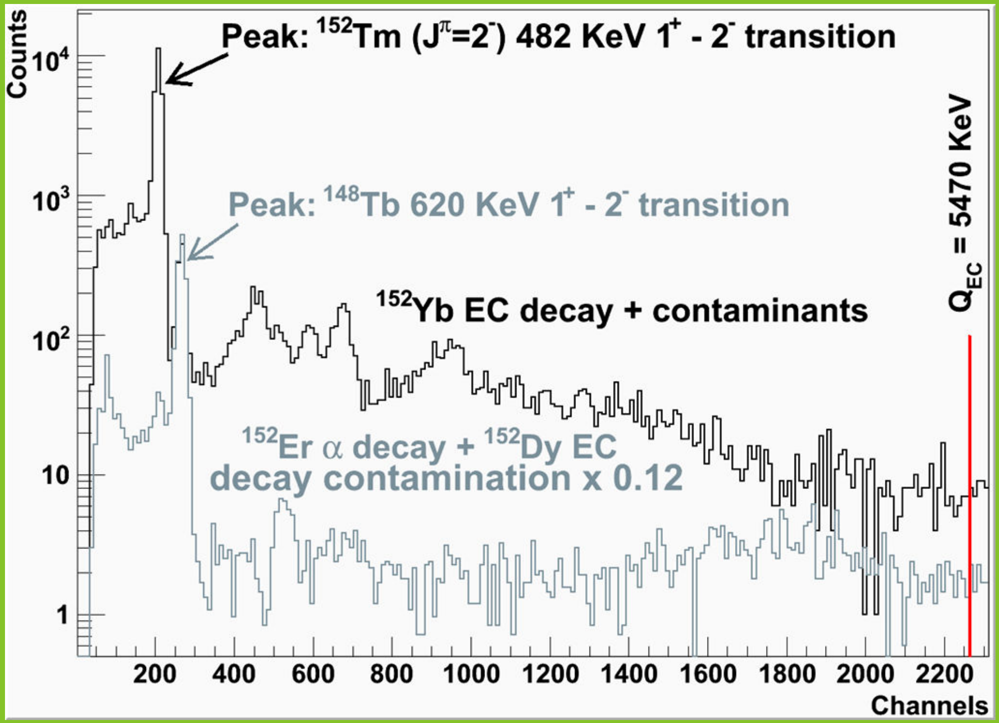
E ($^{148}Tb_{1+} \rightarrow {}^{148}Tb_{2-}$) = 620 keV



Measurements

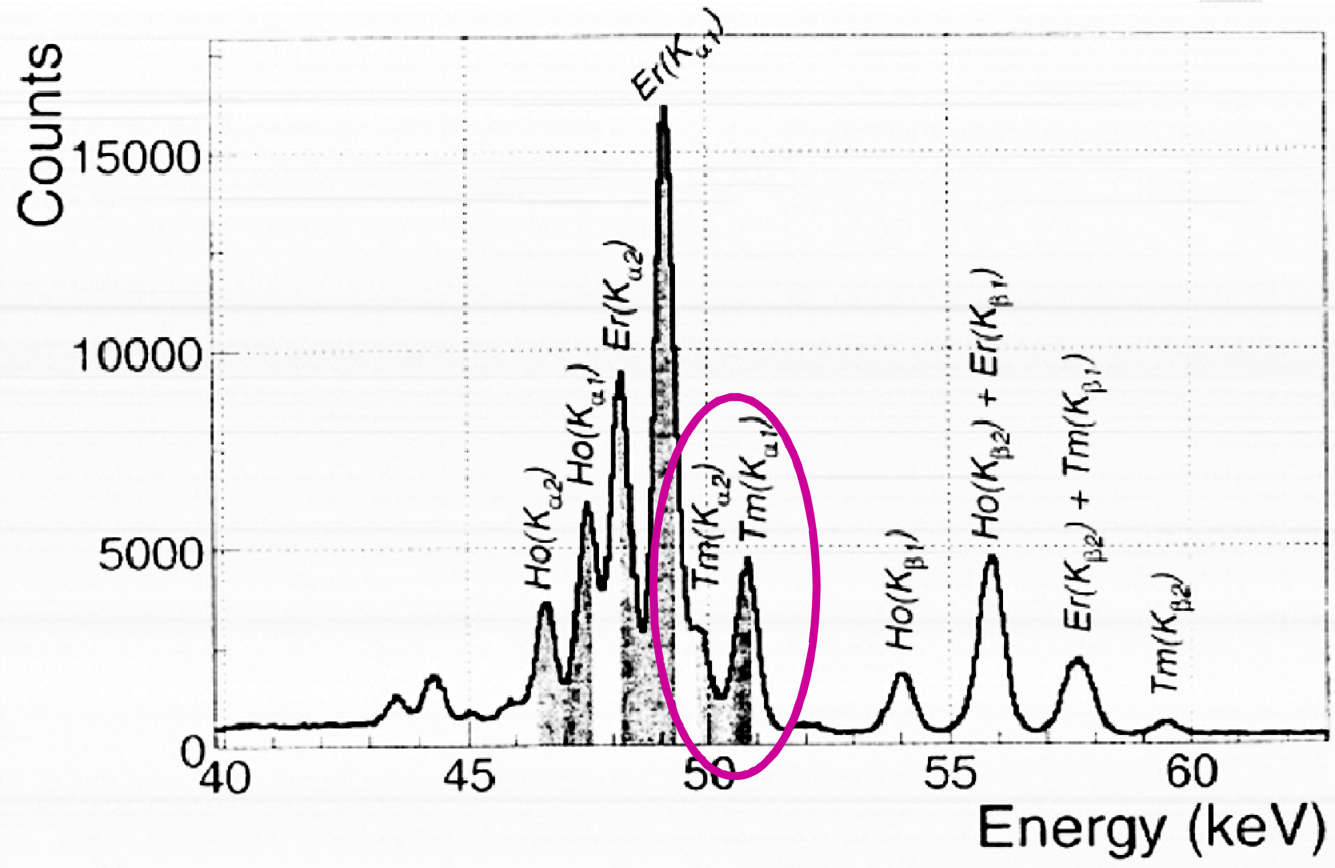


Analysis


Peak: 152Tm (Jπ=2-) 482 KeV 1+ - 2- transition
Peak: 148Tb 620 KeV 1+ - 2- transition
152Yb EC decay + contaminants
152Er α decay + 152Dy EC
decay contamination x 0.12
QEC = 5470 KeV
Counts
Channels
10^4
10^3
10^2
10
1
200
400
600
800
1000
1200
1400
1600
1800
2000
2200

Generating the spectra

- EC Component → coinc. with XR



Analysis and Results

- Introduction
- Candidates
- Measures
- Analysis
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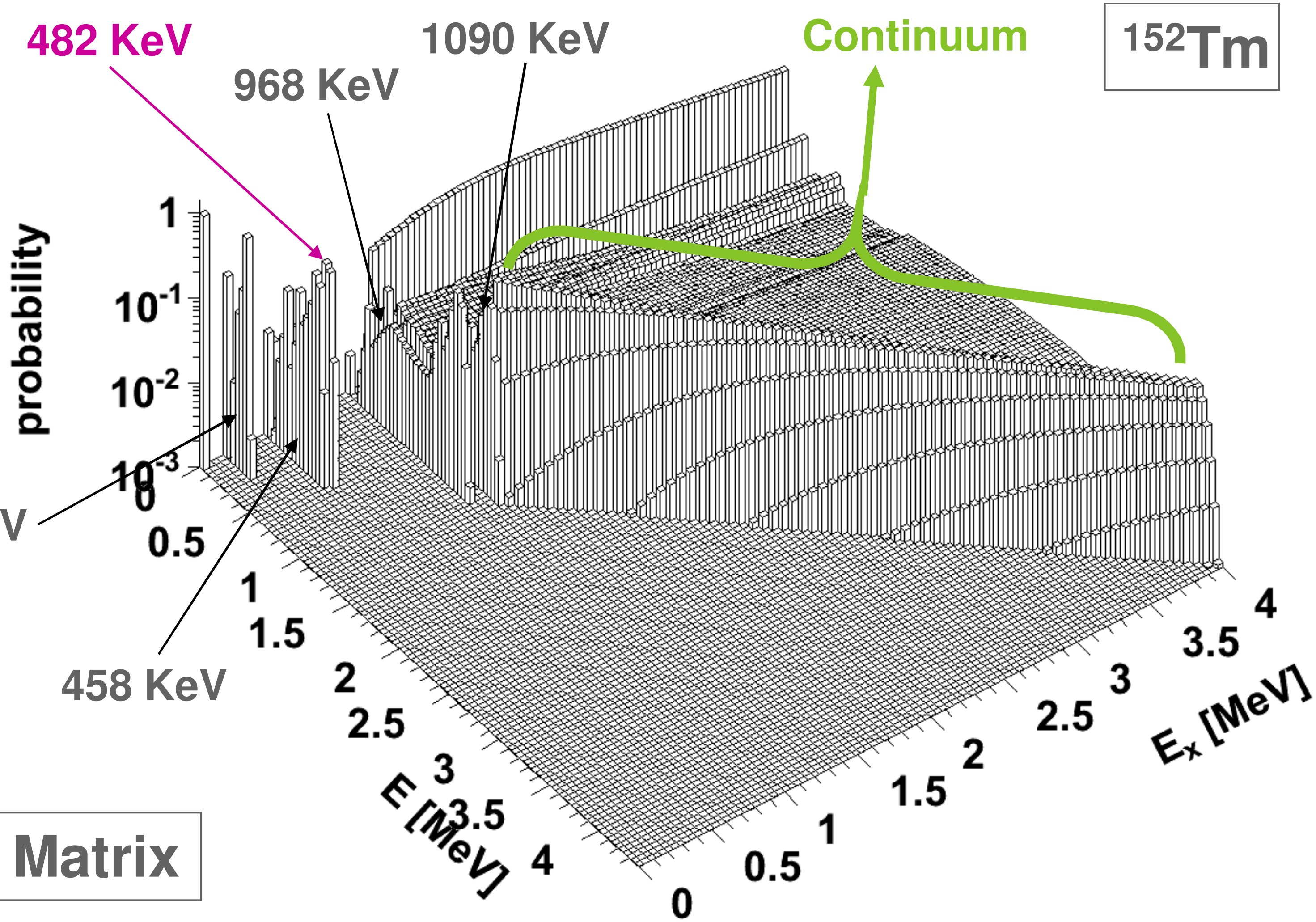
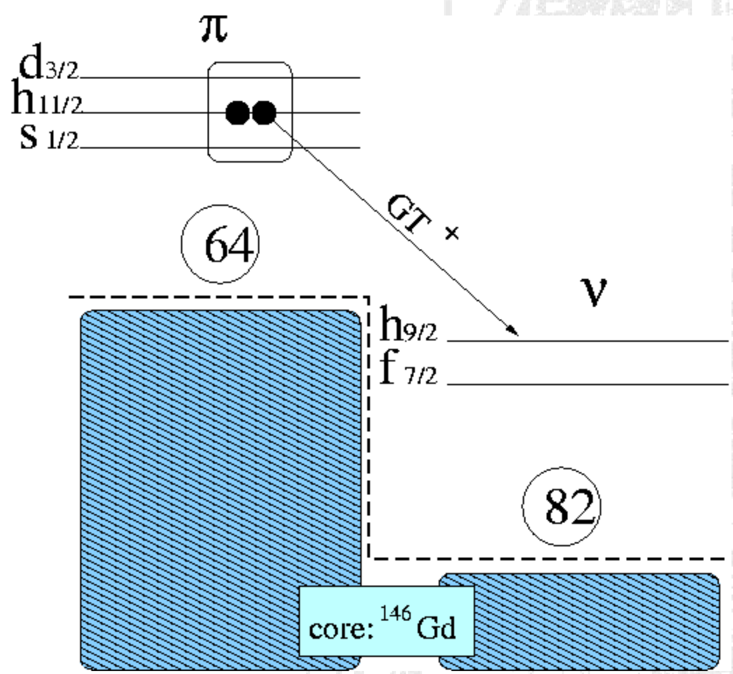


Response Matrix

	HR		TAS			
NUCLEUS	EC	TOT	EC	TOT	T1/2	Q
152Yb	29	88,0	29,9 ± 0,2	88,3 ± 0,7	3,1	5435
150Er	54	99,6	55,4 ± 0,6	93,0 ± 1,0	18,5	4115
156Yb		90,0	44,1 ± 0,5	65,1 ± 1,0	26,1	3577

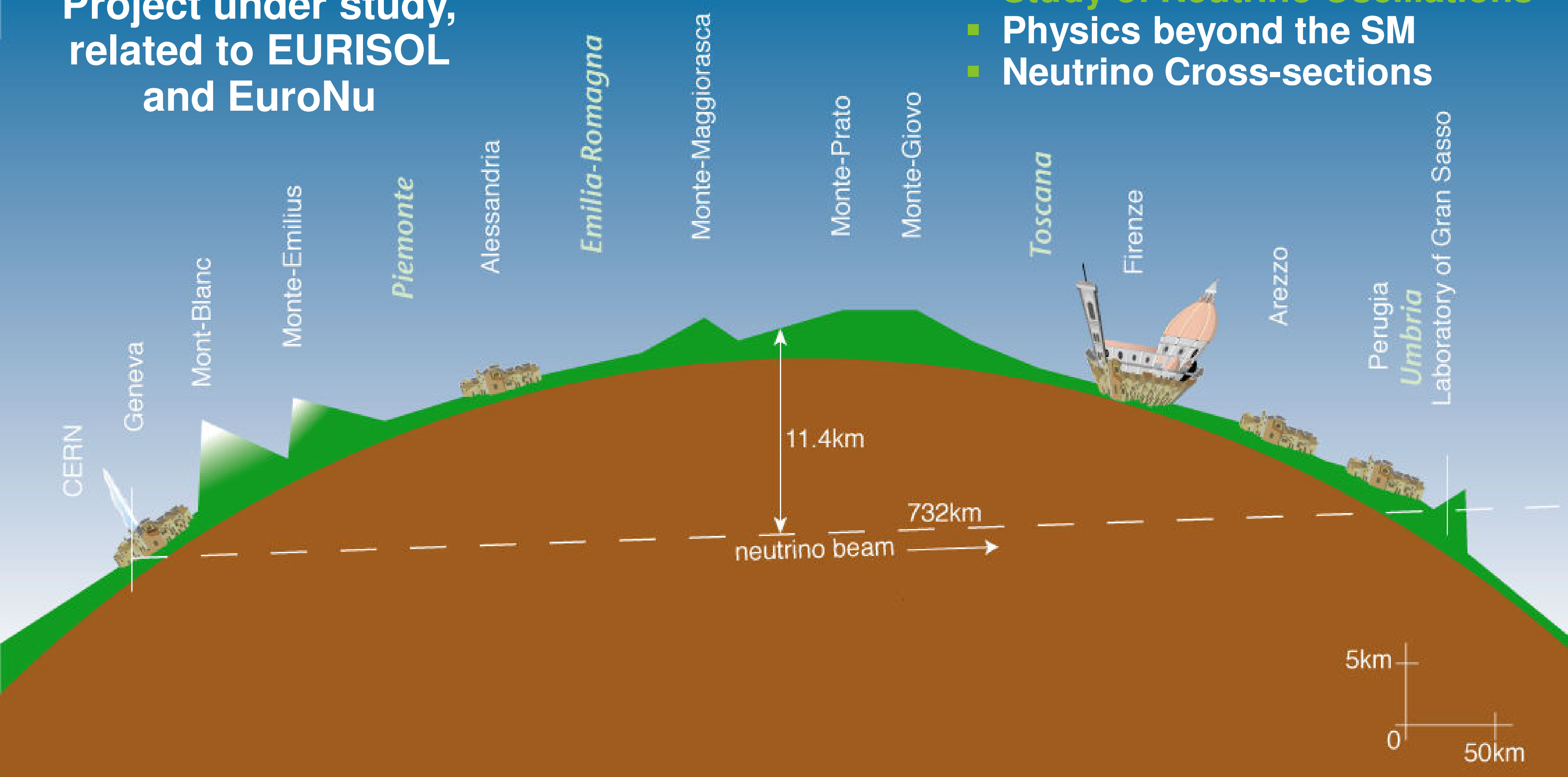


Introduction

P. Zucchelli, *Phys. Let.* B532 (2002) 166

Project under study, related to EURISOL and EuroNu

- **Study of Neutrino Oscillations**
- **Physics beyond the SM**
- **Neutrino Cross-sections**

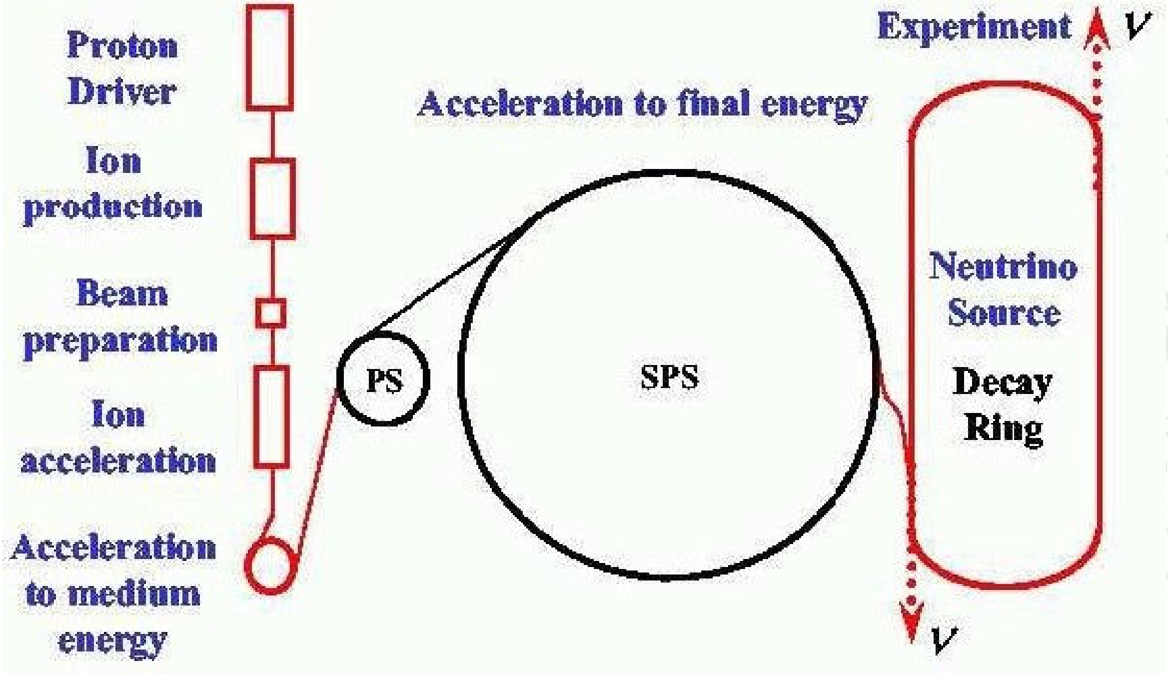


The Idea

J. Bernabeu et al, *JHEP* **12** (2005) 14

- These nuclei produce monochromatic beams when they decay at high energies in a long section storage ring.

- Controlling the energy of the leaving neutrino is possible to measure with precision the oscillation paremeters.



Experimental Techniques

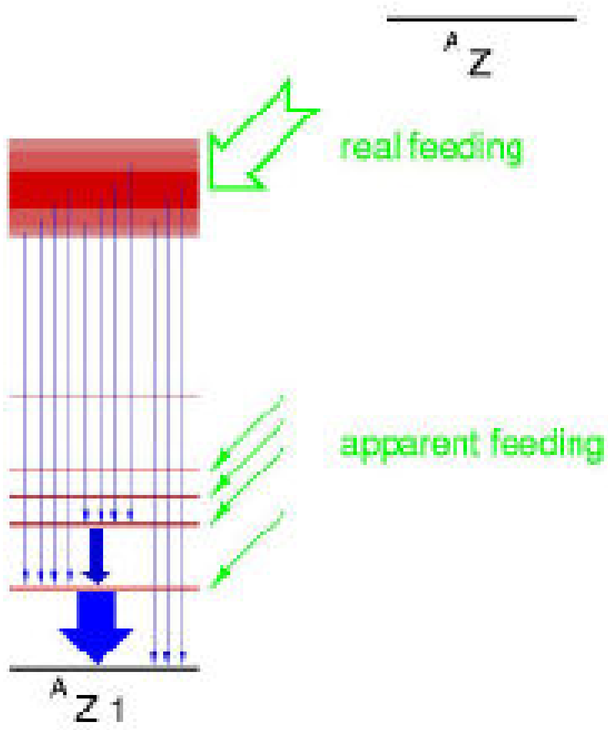
Gamma Detectors

- We use Ge detectors to construct the level scheme populated in a decay
- From the γ intensity balance we deduce the β-feeding:

$$S_i = \frac{I_i}{f(Q_\beta - E_i)T_{1/2}}$$

- What happens if we miss some gamma intensity???

Eff ~ 1% some gamma intensity is missed!!!



Pandemonium effect

Introduced by the work of Hardy *et al* (*Phys. Lett*. 71B (1977) 307).

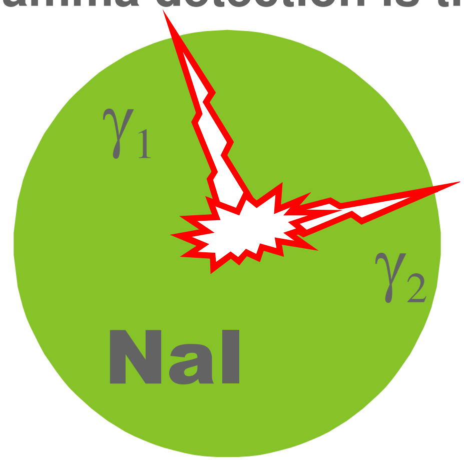
Several factors can contribute to this problem:

- Feeding at high energy, high level density, many decay paths, fragmentation
- Low efficiency of Ge detectors
- Gamma rays of high energy, which are hard to detect

Experimental Techniques

Pandemonium effect

Since the gamma detection is the only reasonable way to solve the problem

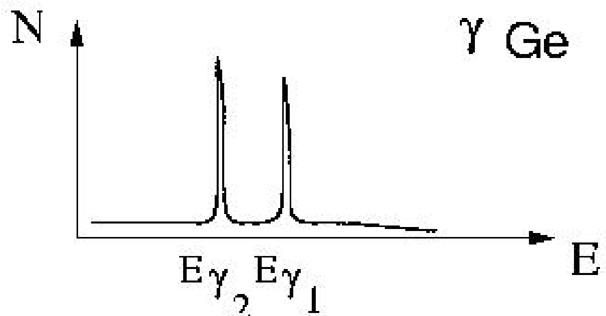


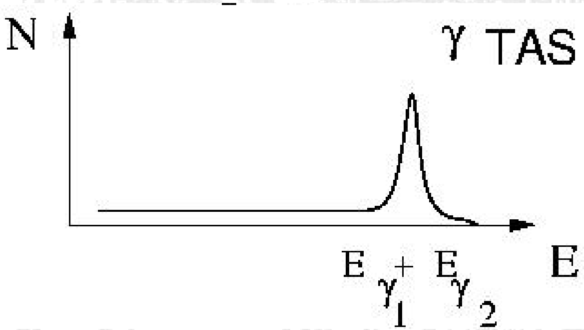
we need a highly efficient device:

A TOTAL ABSORTION SPECTROMETER

TAS

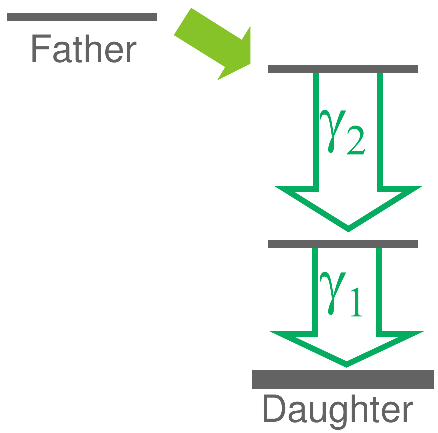
But we need a change in philosophy. Instead of detecting the individual gamma rays we sum the energy deposited by the gamma cascades in the detector. A TAS is like a calorimeter !





Candidates

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

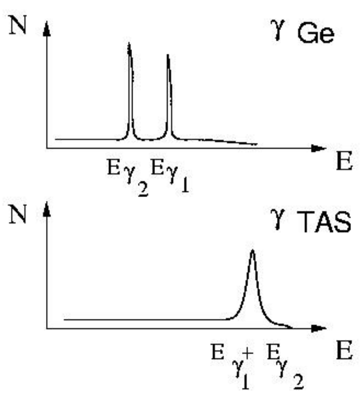


Ge → construct level scheme

γ intensity balance → β-feeding

Eff ~ 1% some gamma intensity is missed!!!

- fragmentation of the strength: detection of the weak gamma rays difficult
- gamma rays of high energy are hard to detect



we need a highly efficient device:

A TOTAL ABSORTION SPECTROMETER

TAS