Prospects for neutrino mass in other isotopes

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Mini Workshop: Direct Neutrino Mass Measurements

SnowMass2021

NF05: Neutrino properties

outline

- *skip pros and cons of calorimetric measurements*
- *skip low temperature detector (LTD) calorimeters*
- calorimetric neutrino mass measurements
  - statistical m_ν sensitivity
  - the ^{187}**Re** case: MANU, MIBETA, and MARE
  - **other isotopes** (mostly?) for calorimetry
- other ideas for **(ultra)low *Q* isotopes**
  - not only calorimetry
- other ideas …

calorimetry

resolving time τ_R

analysis interval ΔE

source activity A_β

pile-up fraction $f_{\text{pile-up}}=\tau_R A_\beta$

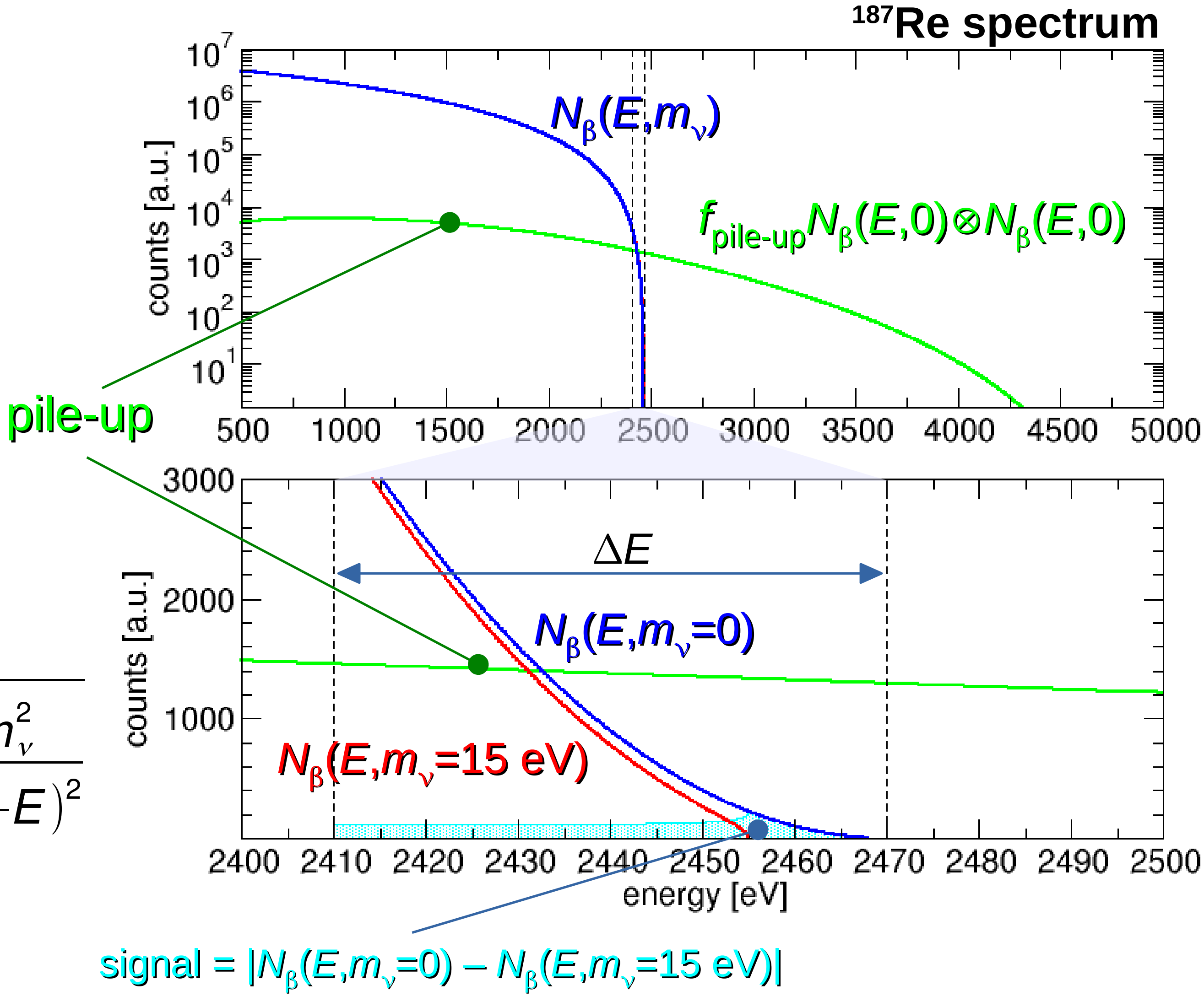
measuring time T_M

number of detectors N_{det}

exposure $t_M=T_M\times N_{det}$

$$N_\beta(E,m_\nu)\approx\frac{3}{Q^3}(Q-E)^2\sqrt{1-\frac{m_\nu^2}{(Q-E)^2}}$$

$$F_{\Delta E}(m_\nu)\approx\left(\frac{\Delta E}{Q}\right)^3\left(1-\frac{3m_\nu^2}{2\Delta E^2}\right)$$



calorimetry statistical sensitivity

$$f_{pile-up} = \tau_R A_\beta \ll \frac{\Delta E^2}{Q^2} \Rightarrow \text{pile-up is negligible}$$

$$\Delta E \approx \Delta E_{FWHM}$$

$$\Sigma_{90}(m_\nu) \approx 0.89 \sqrt[4]{\frac{Q^3 \Delta E}{A_\beta t_M}}$$

experimental challenges

- energy resolution $\boldsymbol{\Delta E_{FWHM}}$
- time resolution $\boldsymbol{\tau_R}$
- exposure $\boldsymbol{t_M = N_{det} \times T_M}$
- single channel activity $\boldsymbol{A_\beta}$

$$\Sigma_{90}(m_\nu) \propto \sqrt[4]{\frac{Q^3}{N_{ev}}}$$

for given $\boldsymbol{T_M}$ $\Sigma_{90}(m_\nu) \propto \sqrt[4]{\frac{Q^3}{A_\beta N_{det}}}$

$$A_\beta N_{det} = \lambda N_{nuclei} = \lambda \frac{M}{A} N_{Av}$$

for a target $\boldsymbol{\Sigma_{90}(m_\nu)}$

$$M \propto \frac{Q^3}{\lambda(Z,Q,S(Q))} \propto \approx \frac{1}{Q^2}$$

for LTDs calorimeters

$$\Delta E_{FWHM} \propto \sqrt{\frac{\boldsymbol{M}}{N_{det}} T^2}$$

A. Nucciotti et al., Astropart. Phys. 34, 80 (2010).

Rhenium-187

$$^{187}_{75}\mathrm{Re} \rightarrow\, ^{187}_{76}\mathrm{Os} + e^- + \bar{\nu}_e$$

- $5/2^+ \rightarrow 1/2^-$ unique first forbidden transition $\Rightarrow S=S(E)$
- end point Q = 2.47 keV
- half-life time $\tau_{1/2}$ = 43.2 Gy
- natural a.i. = 63%

  → 1 mg metallic Rhenium → ≈1.0 decay/s

metallic rhenium single crystals

superconductor with T_c=1.6K

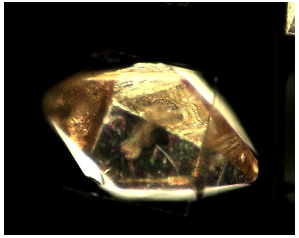
Ge NTD thermistors

MANU exp. (Genova)

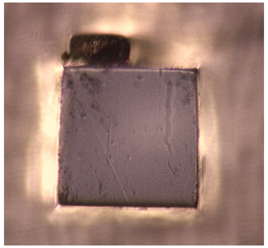
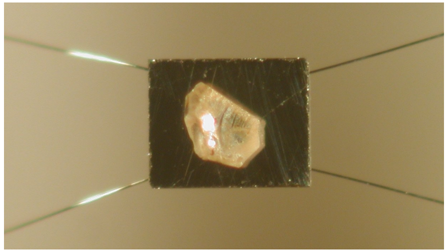
dielectric rhenium compound ($AgReO_4$) crystals

Si implanted thermistors

MIBETA exp. (Milano)



Rhenium-187 experiments

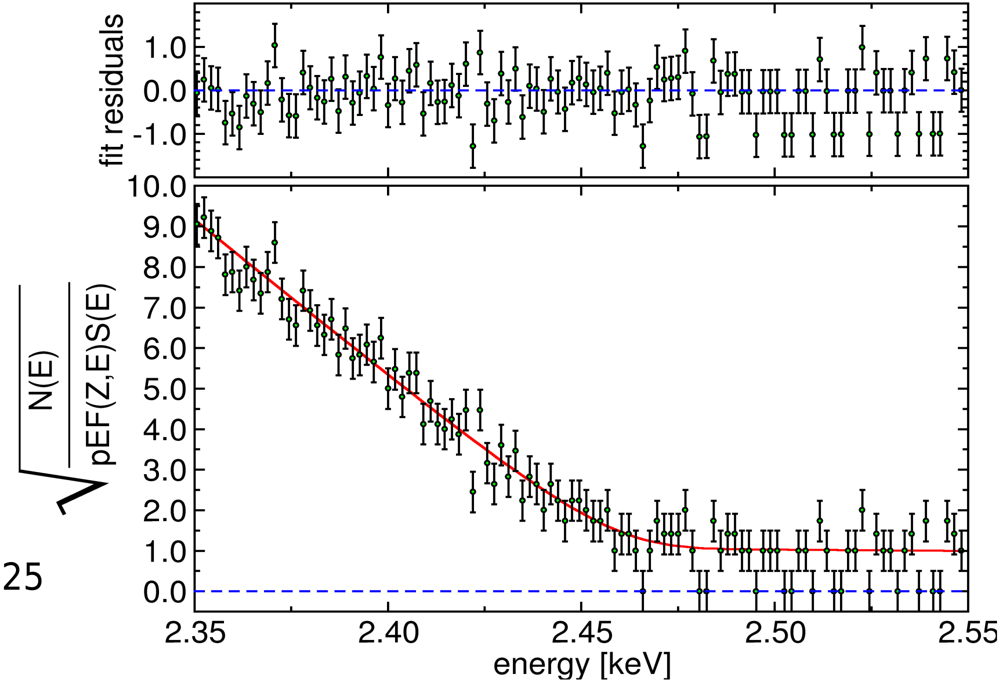
first ^{187}Re experiments: $N_{ev} \approx 10^7$ events

- MIBETA@MiB with $AgReO_4$

m_ν< 15 eV 90% C.L. M.Sisti et al., NIM A 520 (2004) 125

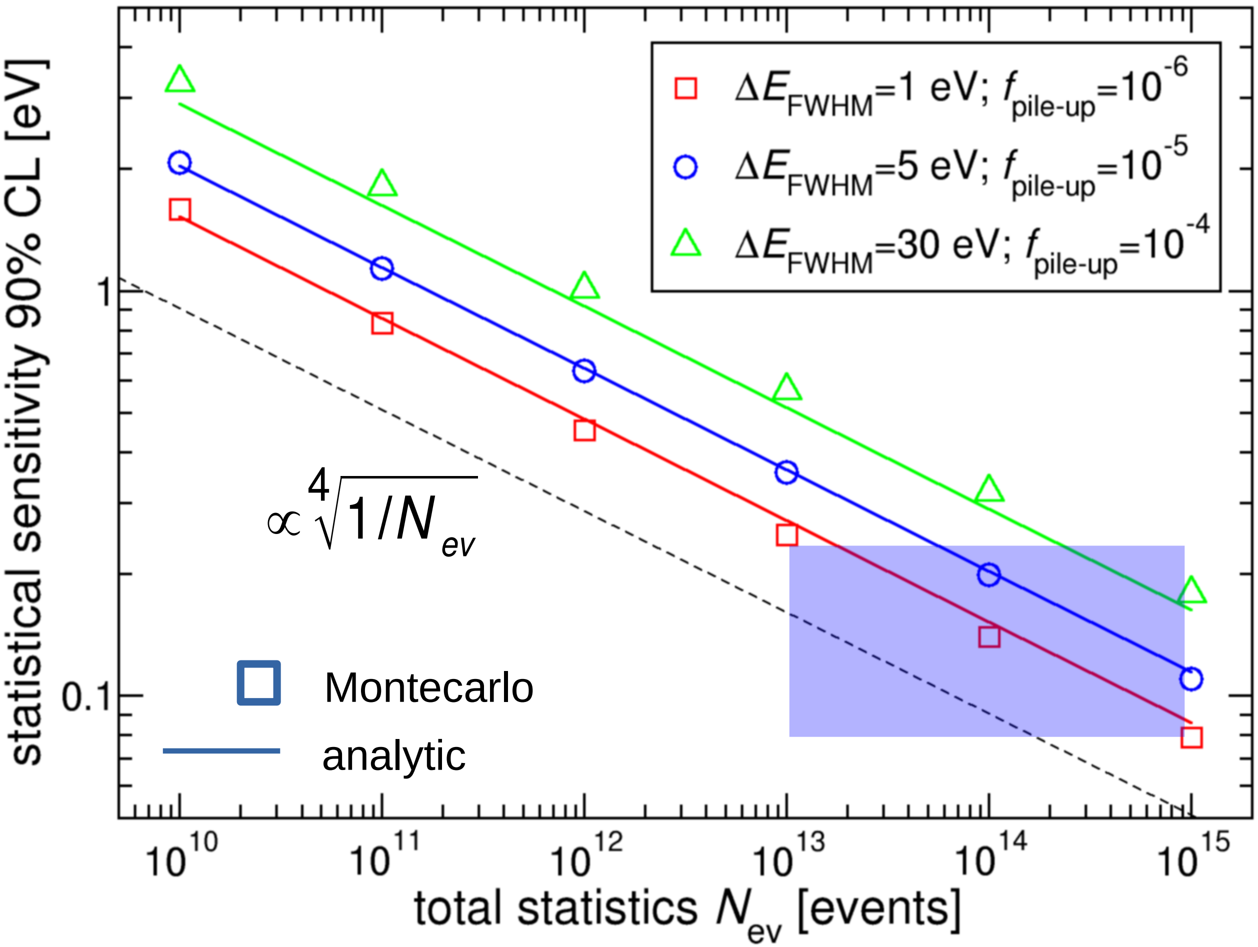
- MANU@Ge with metallic Re

m_ν< 26 eV 95% C.L. F.Gatti et al., Nucl. Phys. B91 (2001) 293



1990 → 2006	MIBETA (Milano/MilanoBicocca) + MANU (Genova)
	^{187}Re → m_ν<15 eV (+ BEFS...)
2006	MARE (Microcalorimeter Array for a Rhenium Experiment) int'l project
2007 → 2013	MARE R&D for phase 1→ Re+TES/MMC / $AgReO_4$+Si-Impl

Rhenium-187: MARE project



A. Nucciotti et al., Astropart. Phys. 34, 80 (2010).
https://doi.org/10.1016/j.astropartphys.2010.05.004

MARE

Microcalorimeter Array for a Rhenium Experiment

ITALY:

INFN / Univ. di Genova / Univ. di Milano-Bicocca / Univ. dell'Insubria / Univ. di Roma “La Sapienza / FBK, Trento / SISSA, Trieste

GERMANY:

Universität Heidelberg / PTB, Berlin / GSI, Darmstad

USA:

University of Miami / Wisconsin University, Madison / GSFC/NASA / NIST, Boulder Co / JPL/Caltech

PORTUGAL:

Universidade de Lisboa and ITN

FRANCE:

CNRS, Grenoble

http://crio.mib.infn.it/wig/silicini/proposal/proposal_MARE_v2.6.pdf

Rhenium-187: MARE project

exposure required for 0.1 eV m_ν sensitivity

A_β [Bq]	τ_R [μs]	ΔE [eV]	N_{ev} [counts]	exposure [det×year]
1	0.1	0.1	1.7×10^{14}	5.4×10^{6}
10	0.1	0.1	5.3×10^{14}	1.7×10^{6}
10	1	1	10.3×10^{14}	3.3×10^{6}
10	3	3	21.4×10^{14}	6.8×10^{6}
10	5	5	43.6×10^{14}	13.9×10^{6}

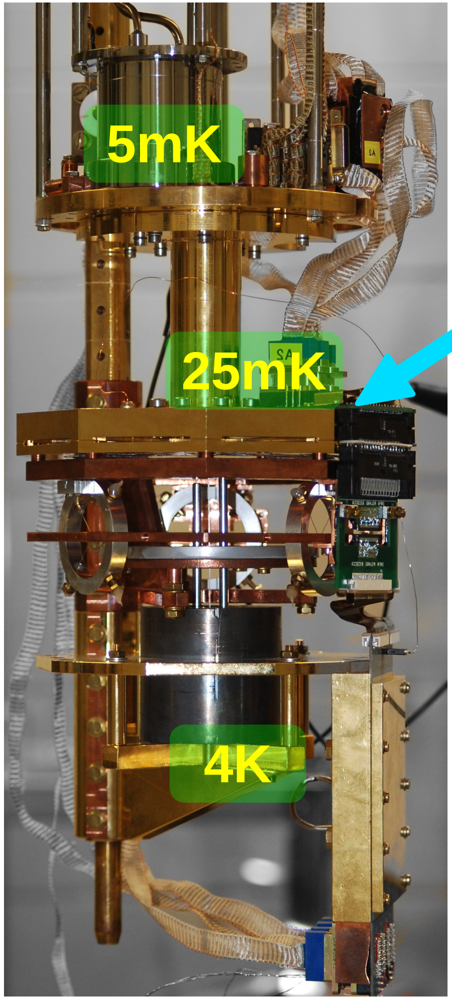
***bkg* = 0**

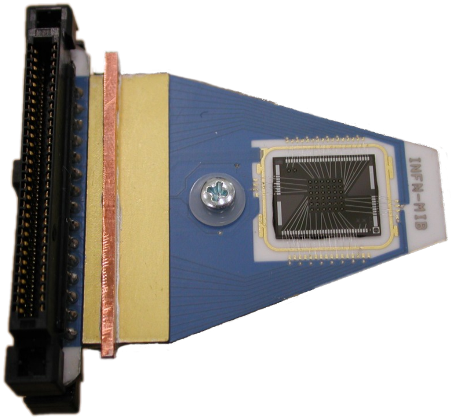
320000 detectors

10 years

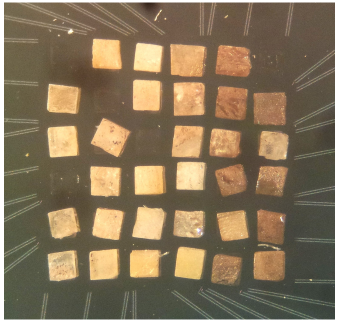
3.2 kg ^{nat}Re

Rhenium-187: MARE project

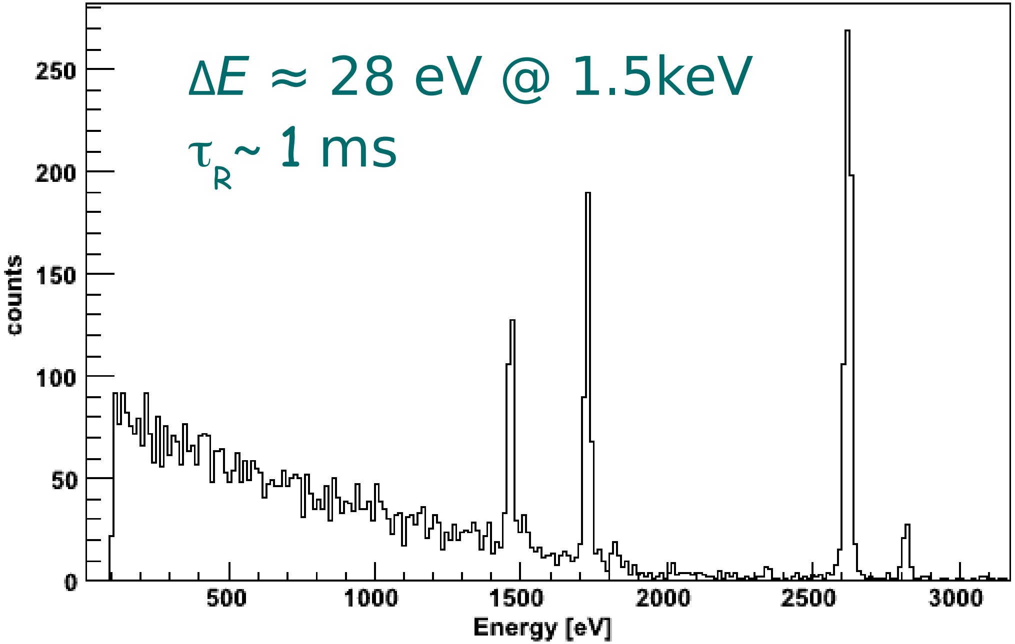




detector array



E. Ferri et al., J. of Low Temp. Phys., 176(5-6) (2014) 885



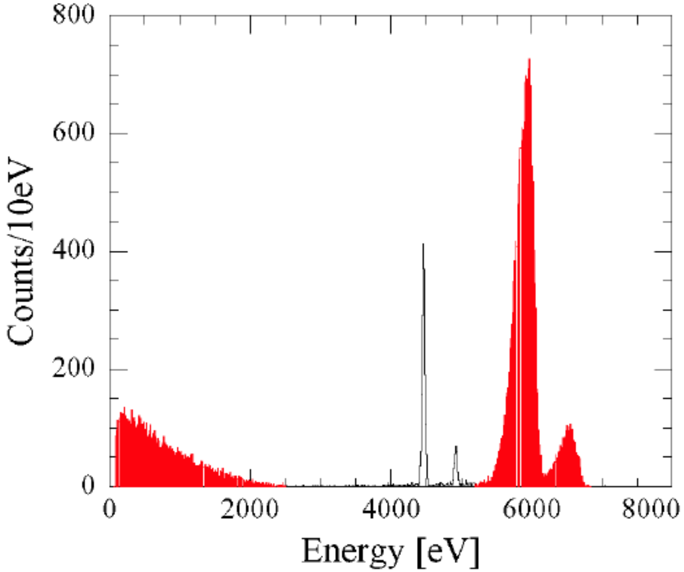
- 31 ≈500µg AgReO4 crystals → 0.3Bq
- 16 usable:
  - ⟨ΔE⟩ ≈ 47 eV @ 2.6 keV, $\tau_R \approx$ 1 ms

$AgReO_4$ best detectors cannot provide the perfomances for sub-eV sensitivity

Rhenium-187: MARE project

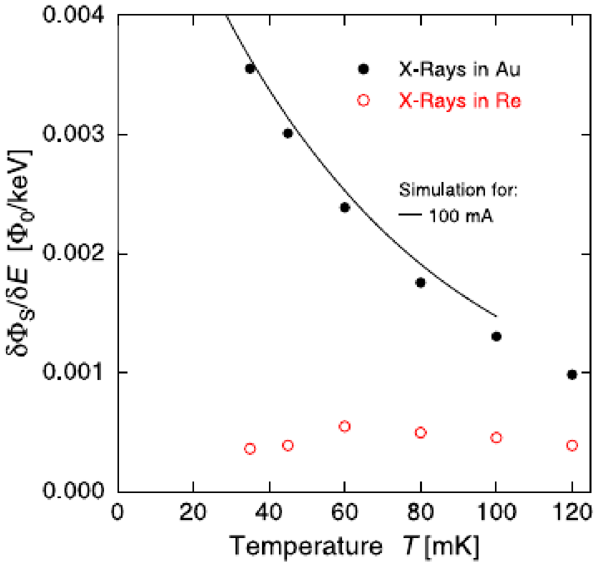
- **metallic Re + MMC** studies @ Heidelberg University (2007-2012)
- poor energy thermalization in superconducting Re
  - 95% of the energy missing
  - small pulses → poor energy resolution
  - long decay time constants

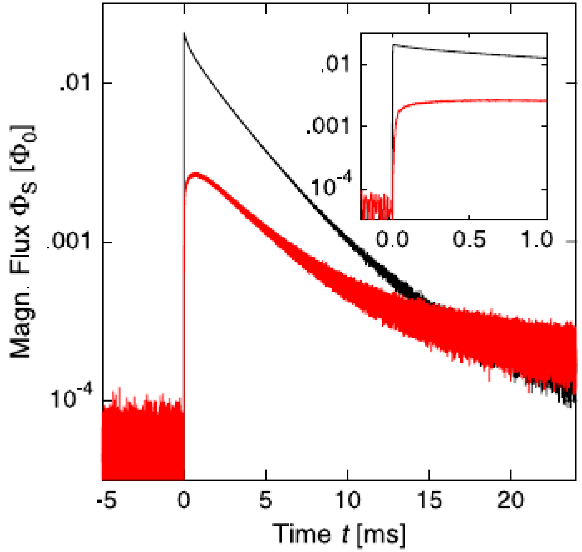
200×200×500µm^3 Re crystal→ 0.4Bq



L. Gastaldo et al. AIP Conf. Proc. 1185, 607 (2009); https://doi.org/10.1063/1.3292415

240×240×500µm^3 Re crystal → 0.6Bq





P. C.-O. Ranitzsch et al., J. of Low Temp. Phys, 167(5-6) (2012) 1004.

Rhenium-187: conclusions

- Re detector development → no satisfactory results with Si/Ge thermistors, TES, MMCs... in about **20 years** of testing (1990-2010) at Standford, Genova, Milano, Heidelberg
  - no clear understanding of Re absorber physics
  - purity and superconductivity?
  - extra *C* due to nuclear quadrupole moment?
- low specific activity → “large” masses → fabrication issues
- possibly large systematics
  - Beta Environmental Fine Structure (BEFS)
  - detector response function
- MARE project shifted to ^{163}**Ho** → ECHo and HOLMES

A. Nucciotti, Adv. High Energy Phys. 2016, 9153024 (2016).
https://doi.org/10.1155/2016/9153024

other isotopes for calorimetry

good isotope requires low Q_{exc} (→ $Q \approx E^*$), "long" half life and favorable B.R.

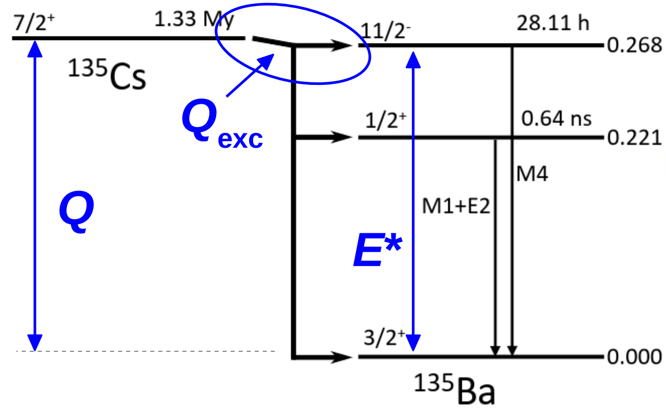
Q (and Q_{exc}) have errors ($\mathcal{O}$(keV) or more), B.R. not known ...

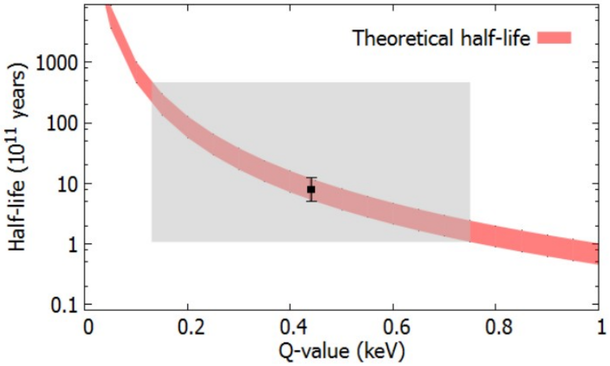
Q → systematic measurements with traps, B.R. → theory/measurements

*** hypothesis**

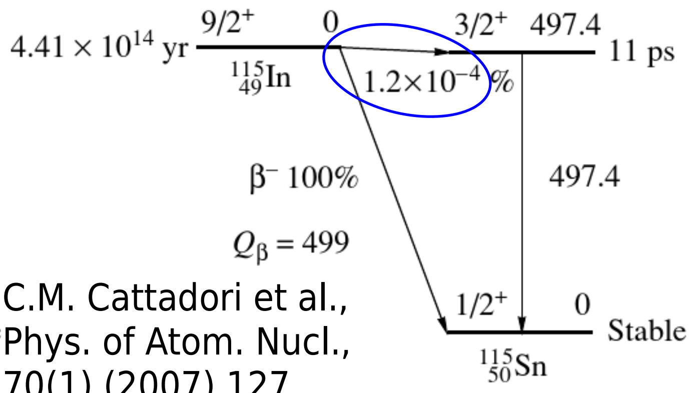
- ^{187}Re shape
- negligible pile-up
- no background
- 100% enrichment

	a.i. [%]	half-life [y]	Q [keV]	B.R. (→ E^*)	Q_{exc} [eV]	half-life (→ E^*) [y]	N_{ev} for $\Sigma(m_\nu)$=0.1eV *	Mass for T_M=10y * [g]	Activity (→ E^*) [1/s]	Activity main [1/s]
^{187}Re	63	4.3E+10	2.47	1	2470	4.3E+10	9.5E+13	182	298258	0
^{115}In	96	4.0E+14	499	1.1E-06	155	3.7E+20	2.3E+10	2.38E+08	74	6.8E+07
^{135}Cs	0	1.3E+06	270	1.6E-06	440	8.0E+11	5.3E+11	14	1686	1.0E+09
^{135}Cs	*0*	*1.3E+06*	*270*	*1.3E-05* *4.3E-08*	*750* *130*	*1.0E+11* *3.0E+13*	*2.6E+12* *1.4E+10*	*9 – 13*	*8350 – 43*	*1.0E+09*





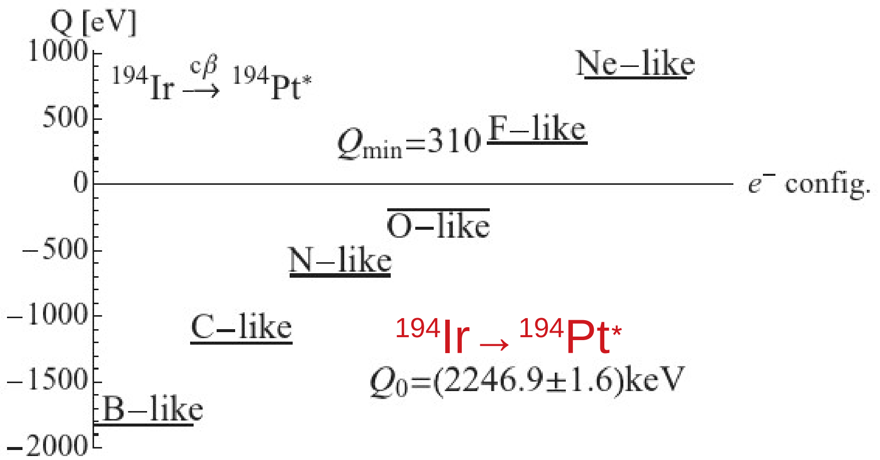
A. de Roubin et al. Phys. Rev. Lett. 124, 222503 (2020)



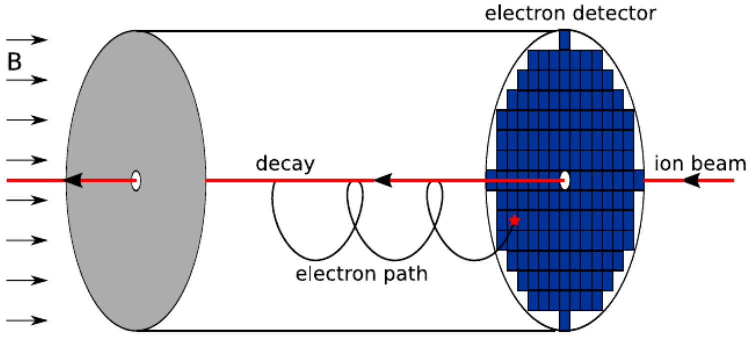
C.M. Cattadori et al., Phys. of Atom. Nucl., 70(1) (2007) 127

other ideas for (ultra)low Q isotopes

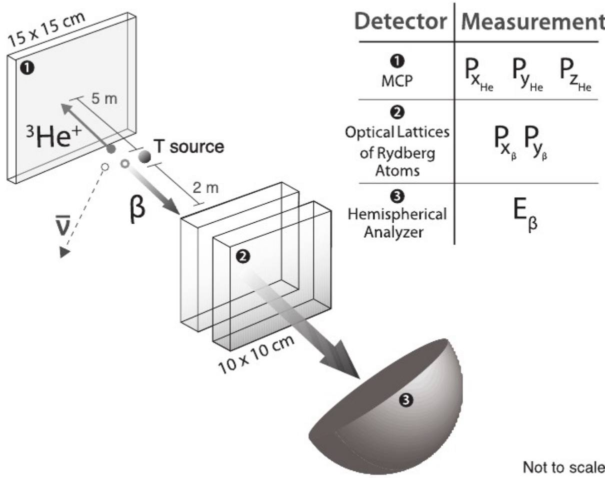
- bound and continuum β and EC low *Q* decays
  - "adjust" Q_{exc} to E^* by ionizing the atoms
- bound β and EC decays
  - measure decay rate of stored nuclei (X/γ emission)
  - signal $[\Gamma(m_\nu=0)-\Gamma(m_\nu)]/\Gamma(m_\nu=0)$
- continuum β decays
  - end point electron spectroscopy
  - add electron TOF (tagging with X/γ)
  - add recoil spectroscopy
- store ions in rings or traps
- solid/liquid/gas for neutrals



J. Kopp and A. Merle Phys. Rev. C 81, 045501 (2010)



M. Lindroos et al., Eur. Phys. J. C (2009) 64: 549–560



Detector	Measurement
❶ MCP	$P_{x_{He}}$ $P_{y_{He}}$ $P_{z_{He}}$
❷ Optical Lattices of Rydberg Atoms	P_{x_β} P_{y_β}
❸ Hemispherical Analyzer	E_β

M. Jerkins et al., New J.Phys.12:043022,2010

other ideas for (ultra)low Q isotopes

$\tau_{1/2} \rightarrow E^*$?

Decay	$t_{1/2}$	Q_0 (keV)	E^* (keV)	Q (eV)	Comment
Continuum β^- decay					
$^{188}W \rightarrow {}^{188}Re$	69.4 d	349 ± 3	346.58	80^{+150}_{-80}	Decay to E^* not yet observed Decay impossible for unfavorable Q_0 daughter spin uncertain
$^{193}Os \rightarrow {}^{193}Ir^*$	30.5 h	1140.6 ± 2.4	1, 131.2	50^{+1150}_{-50}	Decay to E^* not yet observed
$^{194}Ir \rightarrow {}^{194}Pt^*$	19.15 h	2246.9 ± 1.6	2, 239.8	310^{+200}_{-310}	Decay to E^* not yet observed
Bound state β^- decay					
$^{163}Dy \rightarrow {}^{163}Ho$	stable	-2.576 ± 0.016	0	$\approx 1,500$	
Continuum β^+ decay					
$^{189}Pt \rightarrow {}^{189}Ir^*$	10.87 h	1971 ± 14	958.6	1880^{+670}_{-1180}	Allowed background modes with %-level Q_0 branching ratio Decay impossible for unfavorable Q_0
Electron capture decay					
$^{159}Dy \rightarrow {}^{159}Tb^*$	144.4 d	365.6 ± 1.2	363.51	130^{+1200}_{-130}	Might not require ionization
$^{163}Ho \rightarrow {}^{163}Dy$	4570 yr	2.833 ± 0.033	0	≈ 540	Might not require ionization

J. Kopp and A. Merle
Phys. Rev. C 81, 045501 (2010)

bound β and EC decays

- Q = 100eV → $[\Gamma(0)-\Gamma(m_\nu=0.2\text{eV})]/\Gamma(0) \approx 10^{-6}$
- 10^{20} nuclei/ions and 10^{12} decays
- must know $\Gamma(m_\nu)$ precisely!

continuum β decays

- end point rate doesn't depend on Q (neglecting nuclear matrix elements!)
- m_ν=0.2eV → 10^{19} nuclei/ions (≈KATRIN)

beyond present storage technology capability for ions
continuous unstable isotope production

one more idea…

coherently amplified
Radiative Emission of Neutrino Pairs (RENP)

$\gamma_0 + |e\rangle \rightarrow |g\rangle + \gamma + \nu\bar{\nu}$

low energy atomic process
to measure neutrino mass

- atoms in a macro-coherent excited state $|e\rangle$
- RAman stimulated Neutrino Pair emission (RANP)
- measure "end-points" related to $m_{\nu i}$
  - in γ angular distribution
  - γ emission vs. γ_0 energy
- QED backgrounds to be understood
- no real experimental layout proposed yet…

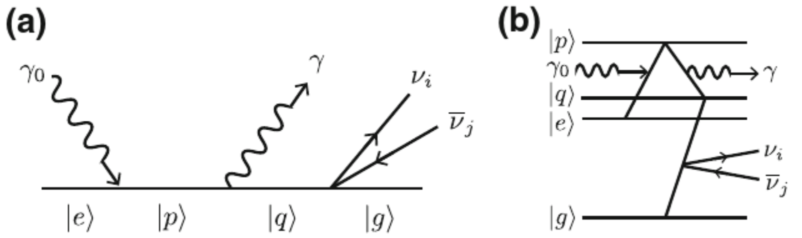


Fig. 1 **a** Feynman diagram of $\gamma_0 + |e\rangle \rightarrow \gamma + |g\rangle + \nu_i \bar{\nu}_j$. There are five more diagrams that contribute off resonances, as in Eq. (3). **b** Corresponding energy levels indicating absorption and emission of photons and a neutrino-pair

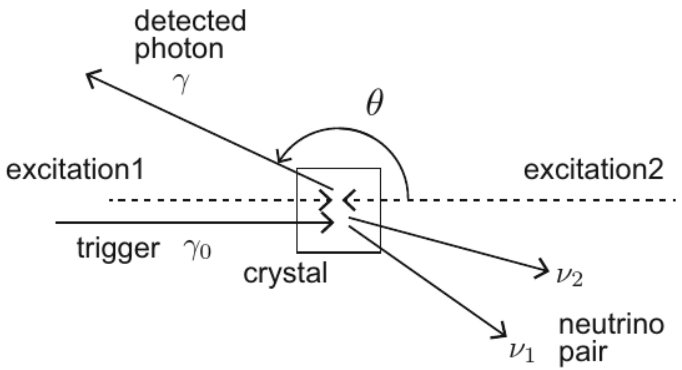


Fig. 2 Schematics of experimental layout

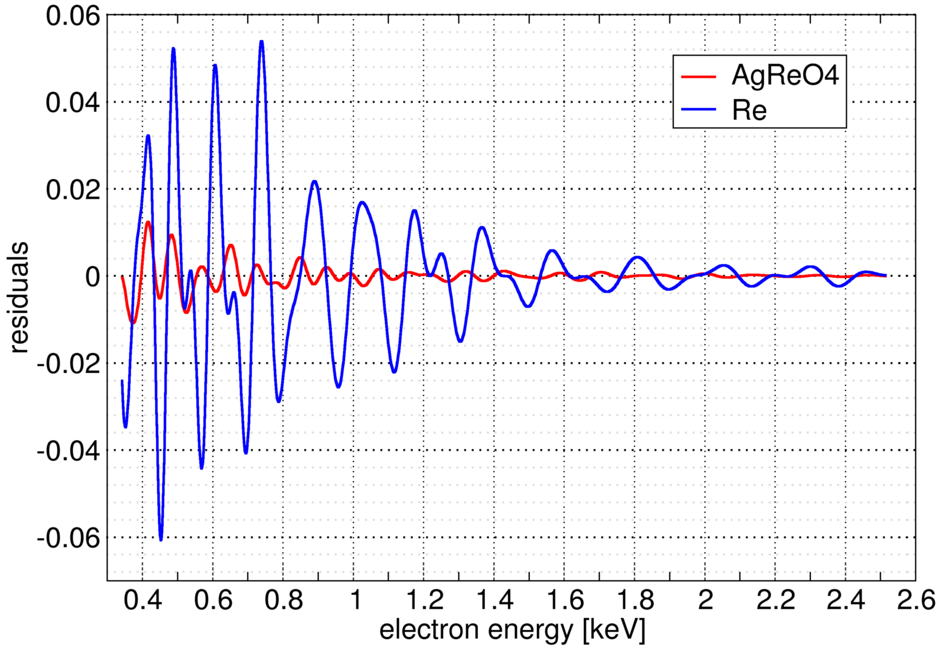
Hideaki Hara, Motohiko Yoshimura, Eur. Phys. J. C (2019) 79:684 https://doi.org/10.1140/epjc/s10052-019-7148-y
M. Tashiro et al., Eur. Phys. J. C (2019) 79:907 https://doi.org/10.1140/epjc/s10052-019-7430-z

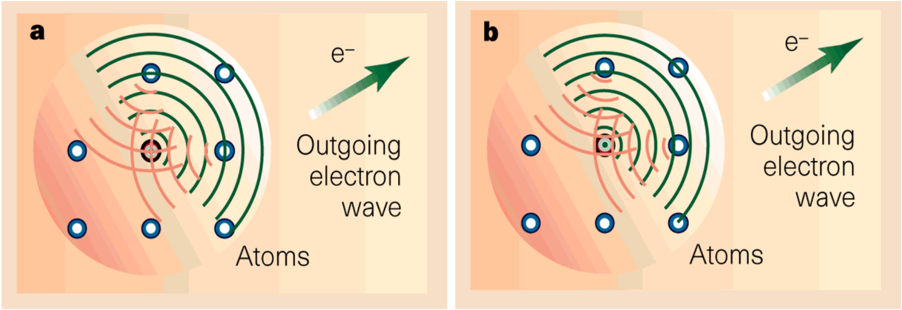
conclusions

- no convincing isotope alternative to ^{3}H and ^{163}Ho yet
- ^{187}Re has too low specific activity and under-performing detectors
- isotopes decaying to excited state:
  - ^{115}In and ^{135}Cs have to high background for calorimetry
  - for other isotopes Q_{exc} and or $\tau_{1/2}$ have still too large uncertainties
  - approaches other than calorimetry are technically challenging
- the atomic way: RENP
  - fascinating but still to be fully worked out

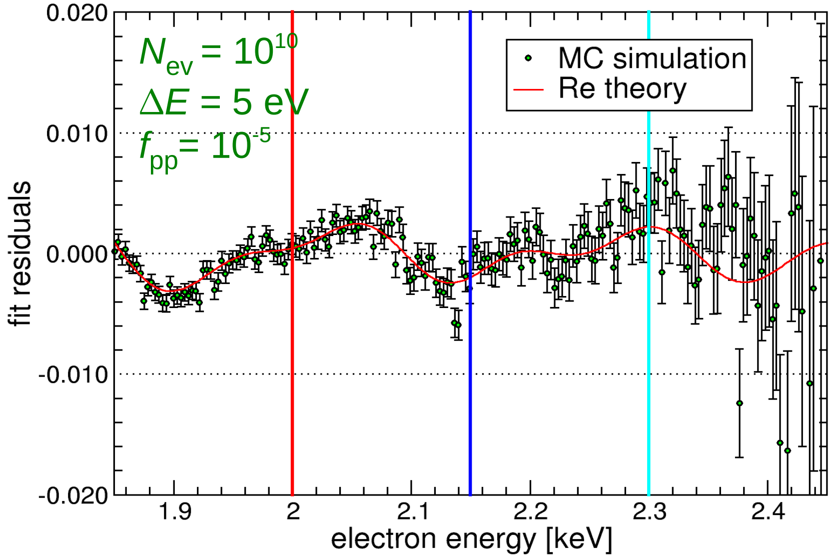
Rhenium-187 systematics: BEFS

Beta Environmental Fine Structure (BEFS)



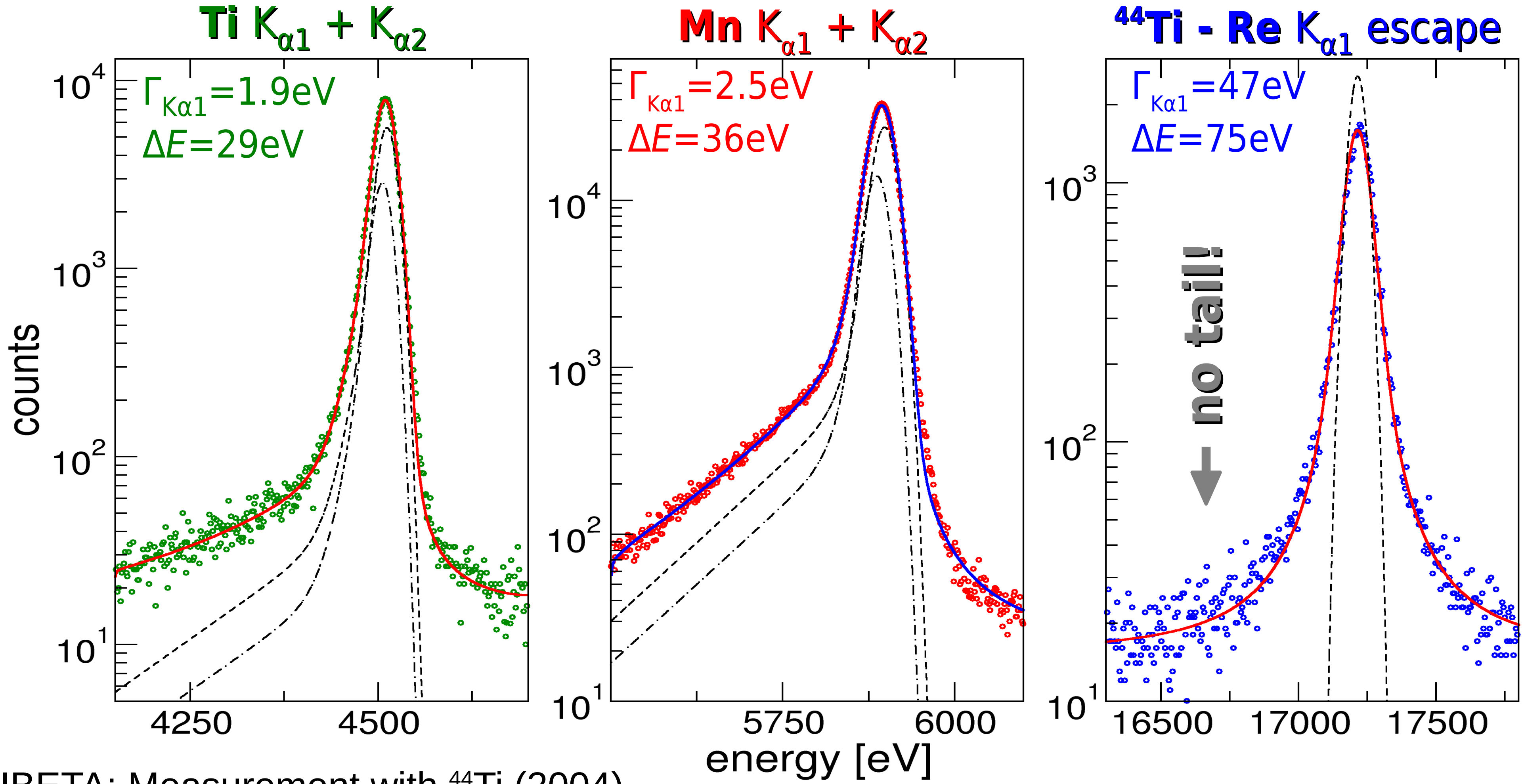


BEFS in ^{187}Re (metallic rhenium)



F. Gatti, et al., Nature, 397, 137 (1999)
C. Arnaboldi et al., Phys. Rev. 96(4) 042503 (2006)
A. Nucciotti et al., Astropart. Phys. 34, 80 (2010)

Rhenium-187 systematics: response function



MIBETA: Measurement with ^{44}Ti (2004)

E. Ferriet al. European Physical Journal A 48.10 (2012)