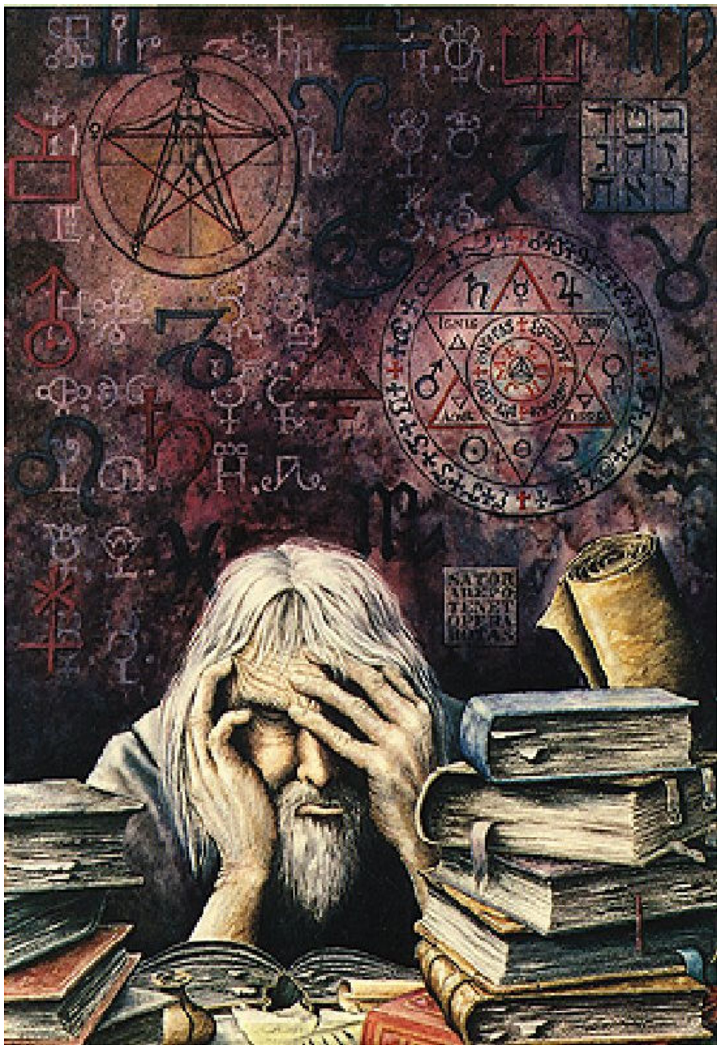
Longer term prospects for double beta decay

Kai Zuber, Technical University Dresden

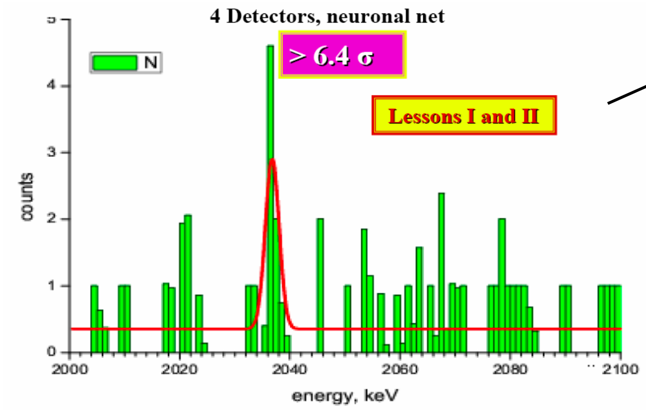
Contents



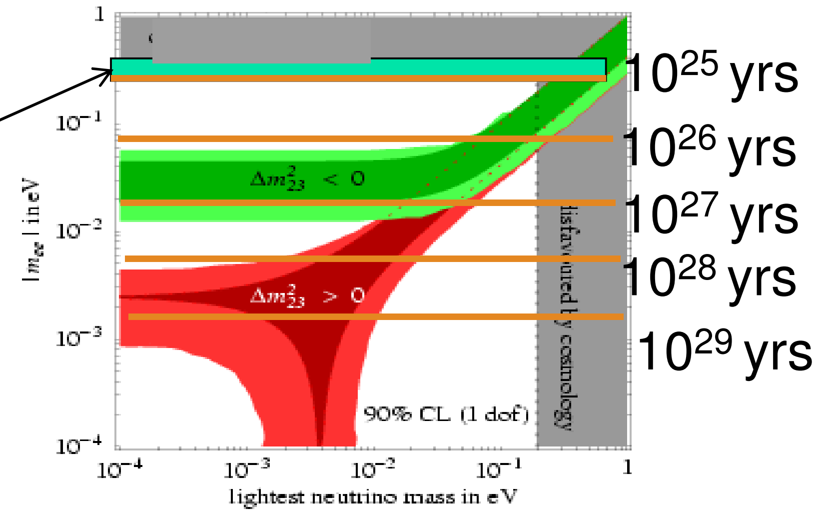
- The „ultimate“ double beta experiment
- Rather general discussion on what the critical ingredients are

The options

claim of evidence



Will be probed by 2014



For an order of magnitude in half-life you get a factor of √10 improvement in neutrino mass

Strategy

★ Is there a peak?
★ If not do a more sensitive experiment
▯ If yes, check with several other isotopes
▯ If not confirmed
★ If confirmed, disentangle physics mechanism

Back of the envelope

This is the 50 meV option, just add 0's to moles and kgs if you want smaller neutrino masses

$T_{1/2} = \ln 2 \cdot a \cdot N_A \cdot M \cdot t / N_{\beta\beta}$ $(\tau >> T)$ (Background free)

For half-life measurements of 10^{26-27} yrs

1 event/yr you need 10^{26-27} source atoms

This is about 1000 moles of isotope, implying 100 kg

Now you only can loose: nat. abundance, efficiency, background, ...

Double beta decay - Basics

- ★ Observable is a half-life (limit), depending on the number of observed (excluded) events in the peak region

$$N_{\beta\beta} = N_0 e^{-\ln 2 t / T_{1/2}}$$

- ★ Experimental sensitivity depends on

$$T_{1/2}^{-1} \propto a\varepsilon \sqrt{\frac{Mt}{\Delta E B}}$$ (BG limited)

$$T_{1/2}^{-1} \propto a\varepsilon M t$$ (BG free)

- ★ Half-life can be converted into effective Majorana neutrino mass

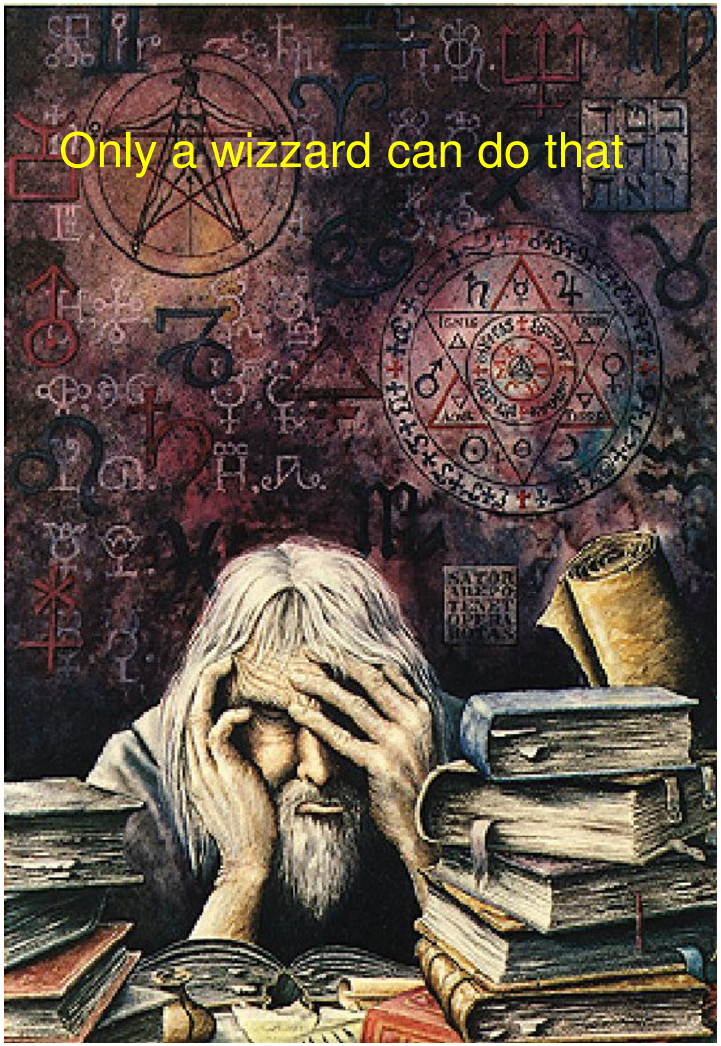
$$T_{1/2}^{-1} = PS^{0\nu} \left| M_{GT}^{0\nu} - M_{F}^{0\nu} \right|^2 \frac{\langle m_\nu \rangle^2}{m_e^2} \longrightarrow m_\nu \propto \sqrt[4]{\frac{\Delta E B}{Mt}}$$

From theory you would maximise this

The ultimate experiment

There are 35 potential double beta emitters, you have to stay with these isotopes

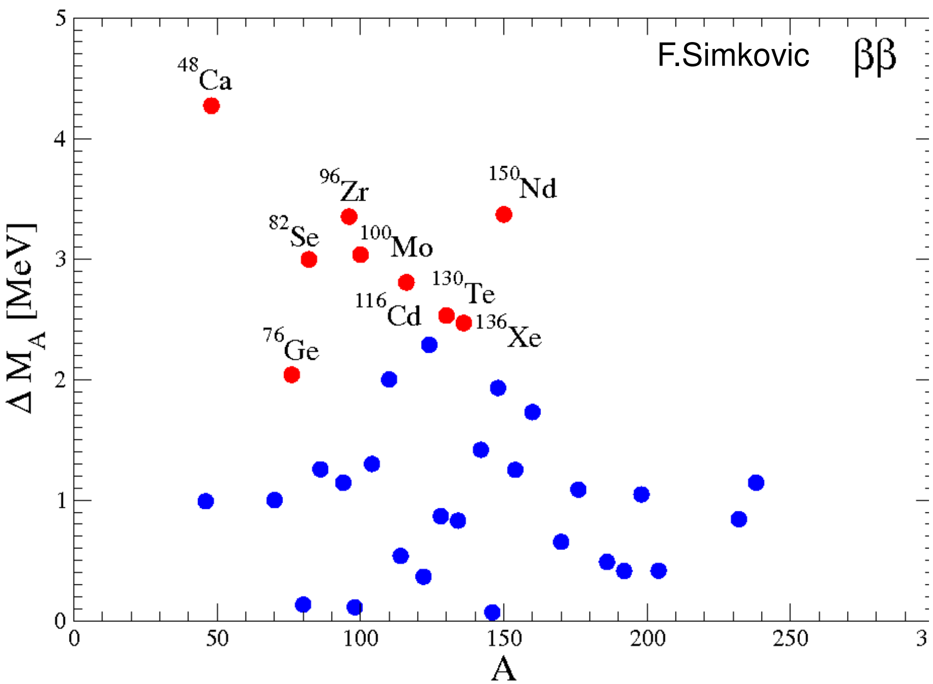
- ★ Number of source atoms : ∞
- ★ Measuring time: ∞ ✓
- ★ Background : 0
- ★ Energy resolution: δ –function
- ★ Efficiency: 100% ✓
- ★ Phase space: as large as possible
- ★ Nuclear matrix elements: precisely known



Phase space

★ Neutrinoless decay rate scales with Q^5

Thus, only Q>2 MeV isotopes are considered



Isotope	Q-Value (keV)	Nat. abund. (%)
Ca 48	4271	0.187
Ge 76	2039	7.8
Se 82	2995	9.2
Zr 96	3350	2.8
Mo 100	3034	9.6
Pd 110	2013	11.8
Cd 116	2809	7.5
Sn 124	2288	5.64
Te 130	2529	34.5
Xe 136	2479	8.9
Nd 150	3367	5.6

Future projects, ideas

K. Zuber, Acta Polonica B 37, 1905 (2006) updated

Experiment	Isotope	Experimental approach
CANDLES	^{48}Ca	Several tons of CaF_2 crystals in Liquid scintillator
COBRA	^{116}Cd, ^{130}Te	420 kg CdZnTe semiconductors
CUORE	^{130}Te	750 kg TeO_2 cryogenic bolometers
DCBA	^{150}Nd	20 kg Nd layers between tracking chambers
EXO	^{136}Xe	1 ton Xe TPC (gas or liquid)
GERDA	^{76}Ge	$\sim$ 40 kg Ge diodes in LN_2, phase 3 with MAJORANA
MAJORANA	^{76}Ge	$\sim$ 180 kg Ge diodes, expand to larger masses
MOON	^{100}Mo	several tons of Mo sheets between scintillator
SNO+	^{150}Nd	1000 t of Nd-loaded liquid scintillator
'LNGS'	^{150}Nd	10 ton Nd-loaded liquid scintillator
SuperNEMO	^{82}Se(?), ^{150}Nd (?)	100-200 kg of Se or Nd foils between TPCs
KamLAND	^{136}Xe	300 kg (2013) , 1 ton (2015?) of Xe in liquid scintillator
XMASS	^{136}Xe	10 t of liquid Xe
NEXT	^{136}Xe	High Pressure Xe TPC

Likely a bit out of date... field is very active in finding new ideas!

The ultimate experiment

- ★ Number of source atoms : ∞
- ★ Measuring time: ∞ ✓
- ★ Background : 0
- ★ Energy resolution: δ –function
- ★ Efficiency: 100% ✓
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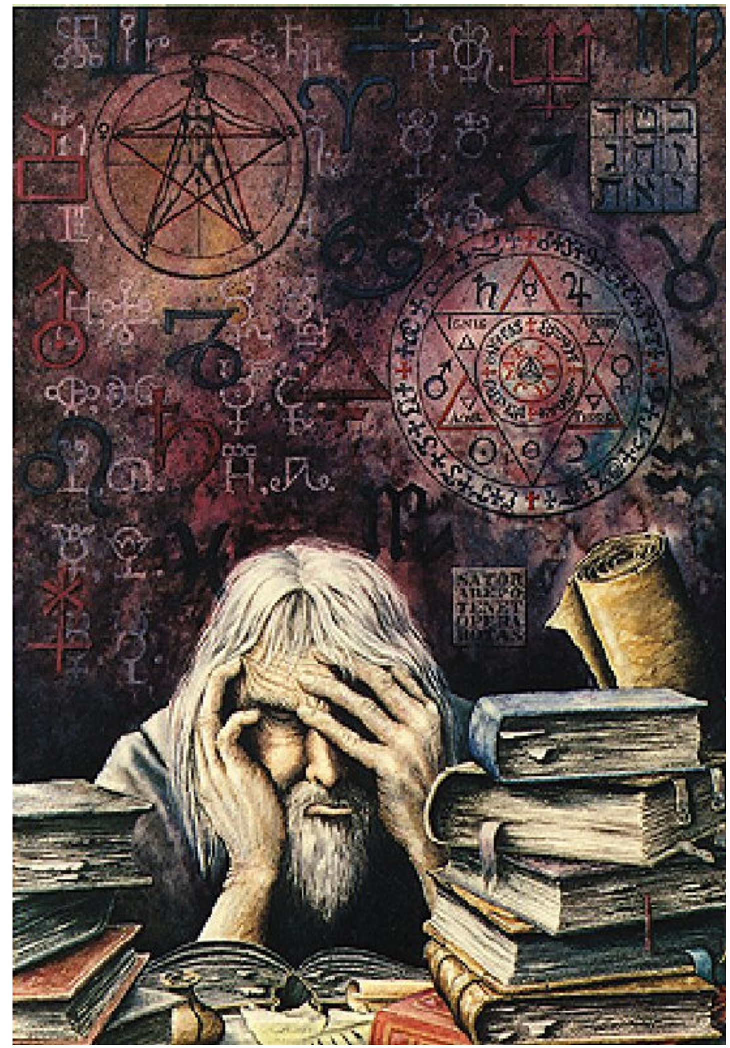


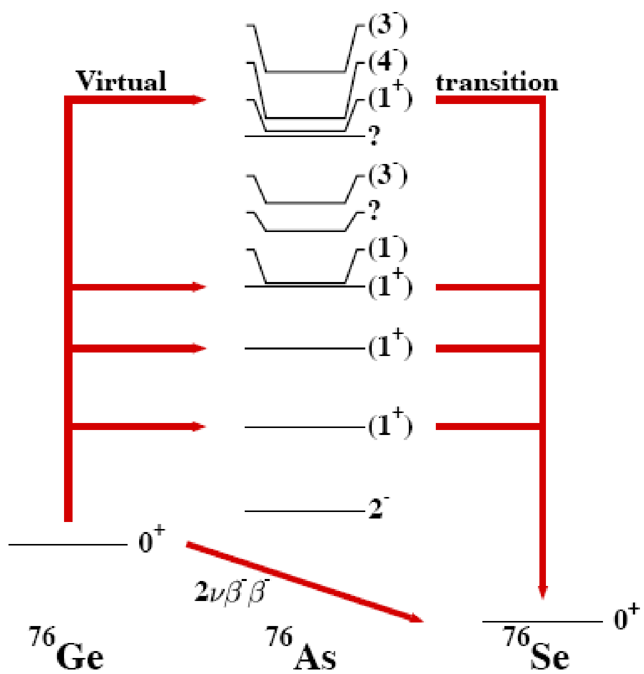
Nuclear matrix elements

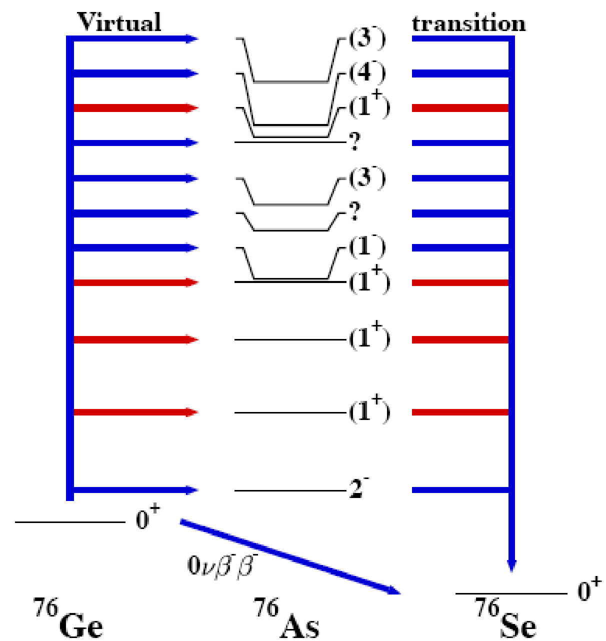
The dark side of double beta decay

Nuclear matrix elements

2νββ: Only intermediate 1⁺ states contribute

Supportive measurements from accelerators

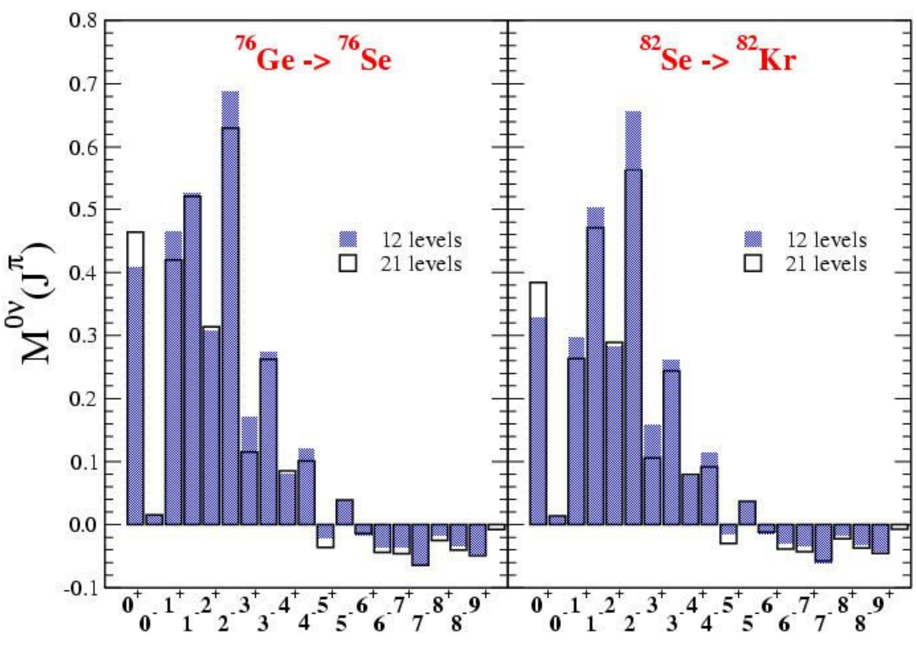




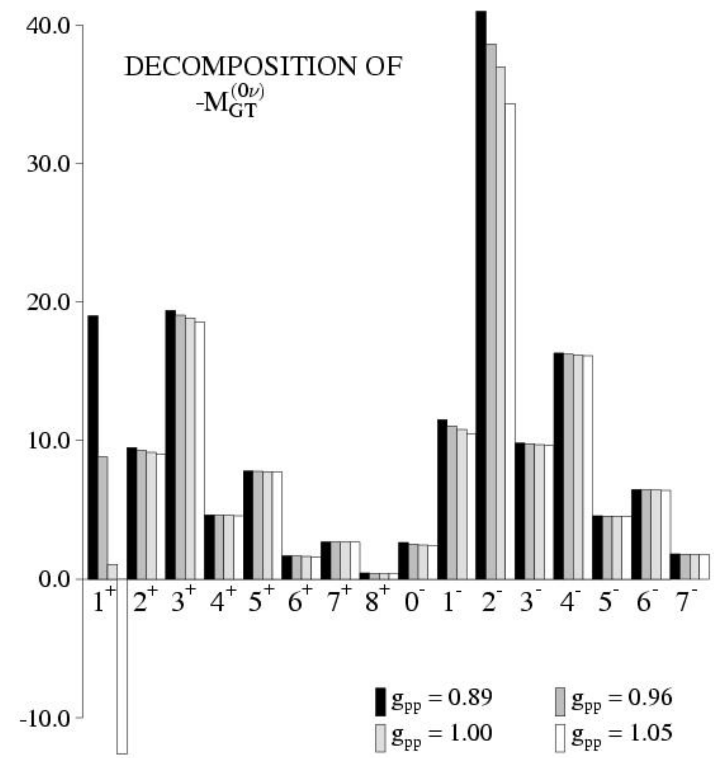
Matrix elements - Decomposition

2ν matrix elements determined by intermediate 1^+ states

0ν matrix elements different



V. Rodin et al.

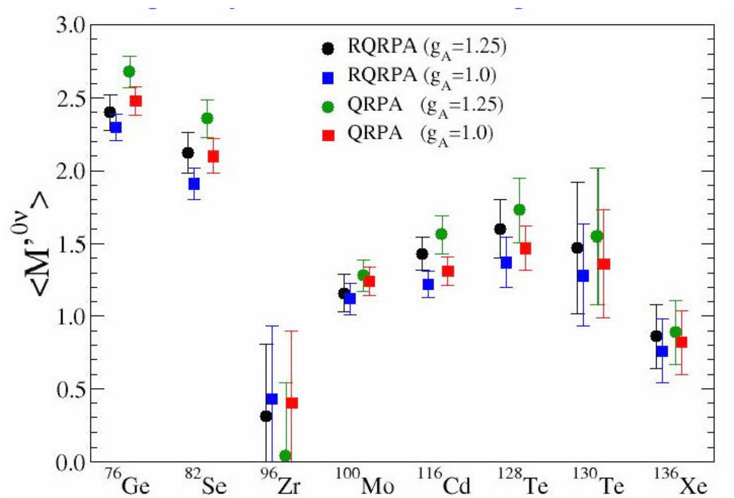


J. Suhonen

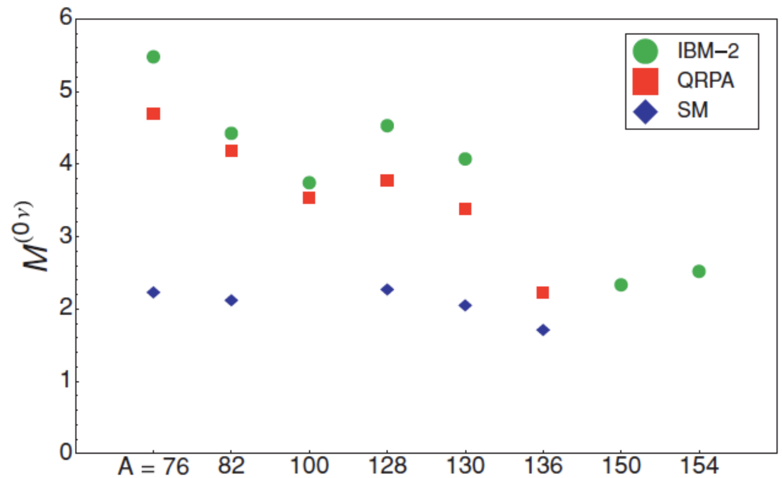
Some calculations

Severe theoretical issue

2005



2009

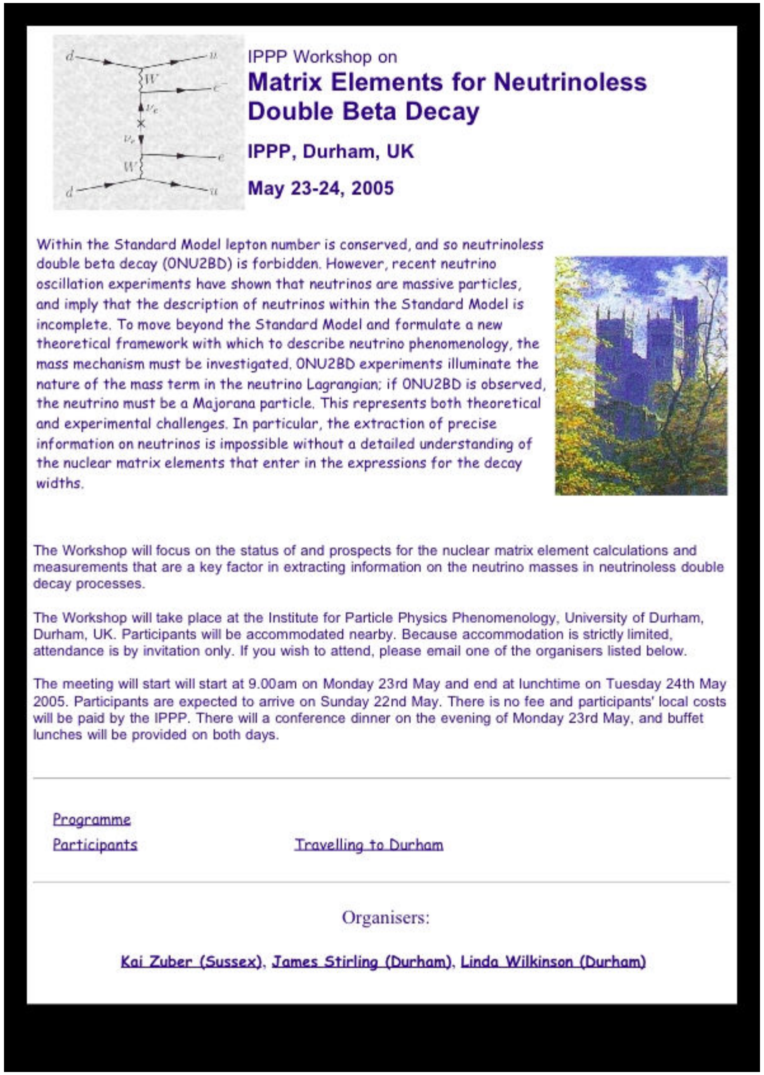


Looks like 1998...

Deformation not taken into account (except for IBM), important for ^{150}Nd

Supportive measurements

Classical nuclear structure physics strikes back



IPPP Workshop on

Matrix Elements for Neutrinoless Double Beta Decay

IPPP, Durham, UK

May 23-24, 2005

Within the Standard Model lepton number is conserved, and so neutrinoless double beta decay (0NU2BD) is forbidden. However, recent neutrino oscillation experiments have shown that neutrinos are massive particles, and imply that the description of neutrinos within the Standard Model is incomplete. To move beyond the Standard Model and formulate a new theoretical framework with which to describe neutrino phenomenology, the mass mechanism must be investigated. 0NU2BD experiments illuminate the nature of the mass term in the neutrino Lagrangian; if 0NU2BD is observed, the neutrino must be a Majorana particle. This represents both theoretical and experimental challenges. In particular, the extraction of precise information on neutrinos is impossible without a detailed understanding of the nuclear matrix elements that enter in the expressions for the decay widths.

The Workshop will focus on the status of and prospects for the nuclear matrix element calculations and measurements that are a key factor in extracting information on the neutrino masses in neutrinoless double decay processes.

The Workshop will take place at the Institute for Particle Physics Phenomenology, University of Durham, Durham, UK. Participants will be accommodated nearby. Because accommodation is strictly limited, attendance is by invitation only. If you wish to attend, please email one of the organisers listed below.

The meeting will start will start at 9.00am on Monday 23rd May and end at lunchtime on Tuesday 24th May 2005. Participants are expected to arrive on Sunday 22nd May. There is no fee and participants' local costs will be paid by the IPPP. There will a conference dinner on the evening of Monday 23rd May, and buffet lunches will be provided on both days.

Programme
Participants
Travelling to Durham

Organisers:

Kai Zuber (Sussex), James Stirling (Durham), Linda Wilkinson (Durham)

Working packages

Charge exchange reactions

Precise Q-value measurements (ISOLTRAP and others)

ft-values

Muon capture

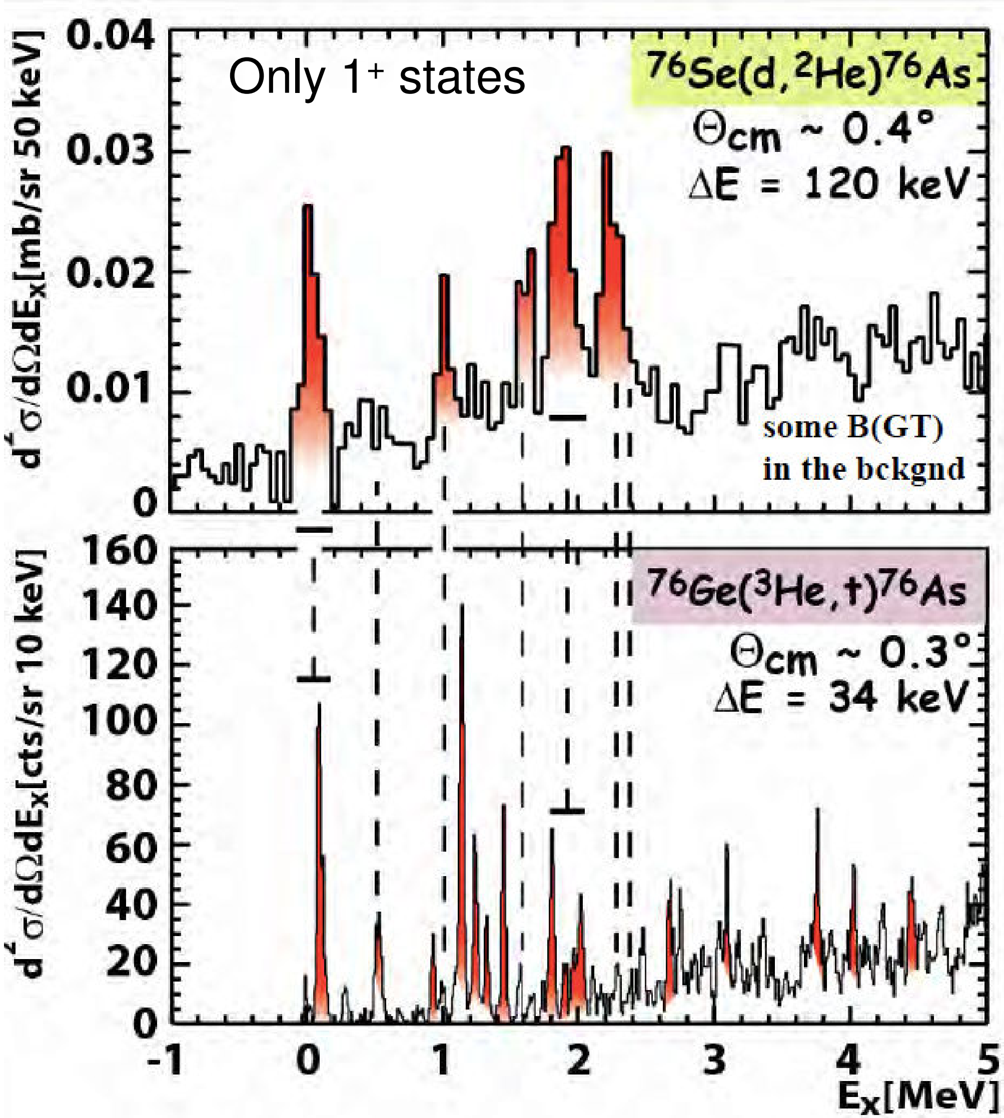
Double electron captures

Neutrino-Nucleus scattering

Nucleon transfer reactions

Consensus Report:
K. Zuber, nucl-ex/0511009

Charge exchange reactions



D. Frekers, Erice 2009

Currently: (d,^{2}He) and (^{3}He,t)

$$B(GT) = \hat{\sigma}(GT)\frac{d\sigma}{d\Omega}(q=0)$$

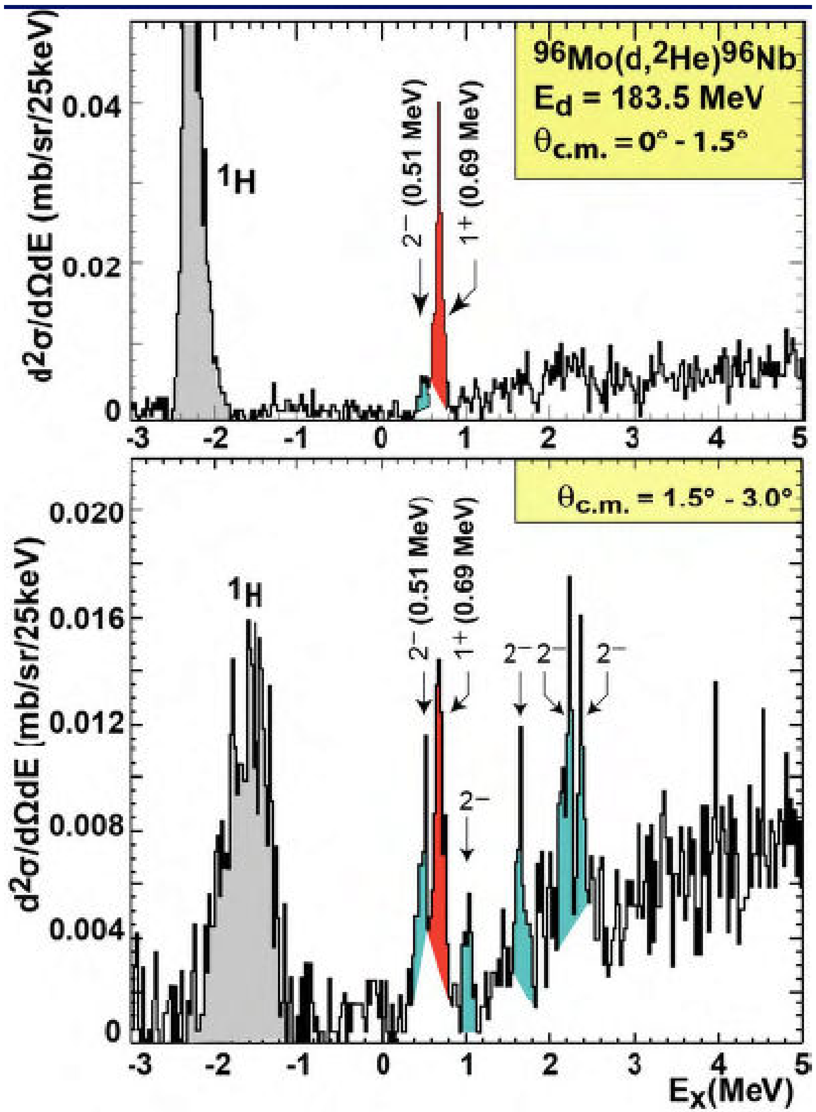
Anticorrelation in strengths (seen in most isotope pairs)

Effect of deformation on 2nu matrix element seems to be a state-to-state mismatch not an overall effect.
What does this imply for 0nu ME?

Important is the difference in shapes between mother and daughter not absolute deformation

^{96}Zr and ^{100}Mo seem to show single state dominance

Charge exchange reactions



Very recently (RCNP Osaka)

Under small angles 2^{-} show up

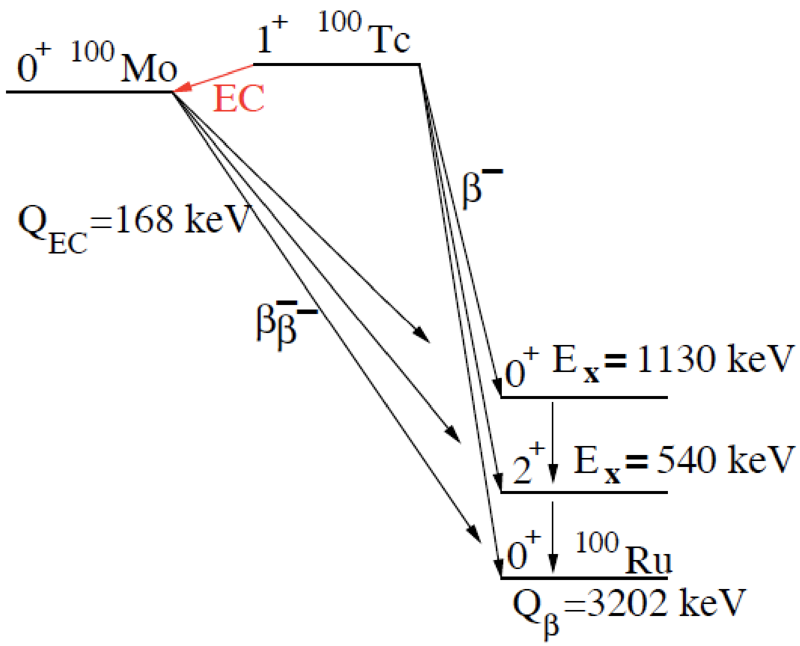
Relation between differential cross section and B(GT) not as easy as in the 1^{+} case

There still is some classic nuclear structure physics to be done!

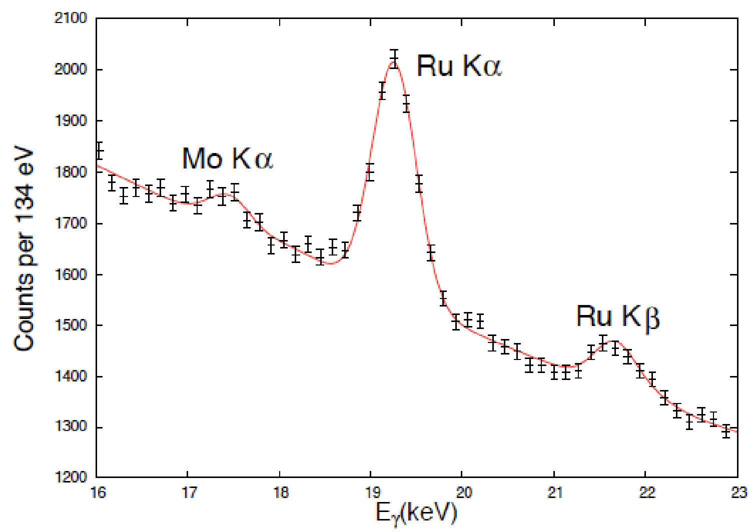
We need for the 11 isotope pairs under consideration as much Information as possible!!!

Ft-values

Ft-values of EC badly known, if at all! These are ground state transitions!



S.K.L. Sjue et al., Phys.Rev.C 78,064317 (2008)



Extracted B(GT) of EC differs by 80% from charge exchange reaction, Disagreement with QRPA calculation (unless you allow fitting of g_A with values smaller than 1, normally 1 and 1.25 are used!)

Measurements with EBIT at TRIUMF in preparation

The ultimate experiment

- ★ Number of source atoms : ∞
- ★ Measuring time: ∞ ✓
- ★ Background : 0
- ★ Energy resolution: δ –function
- ★ Efficiency: 100% ✓
- ★ Phase space: as large as possible ✓
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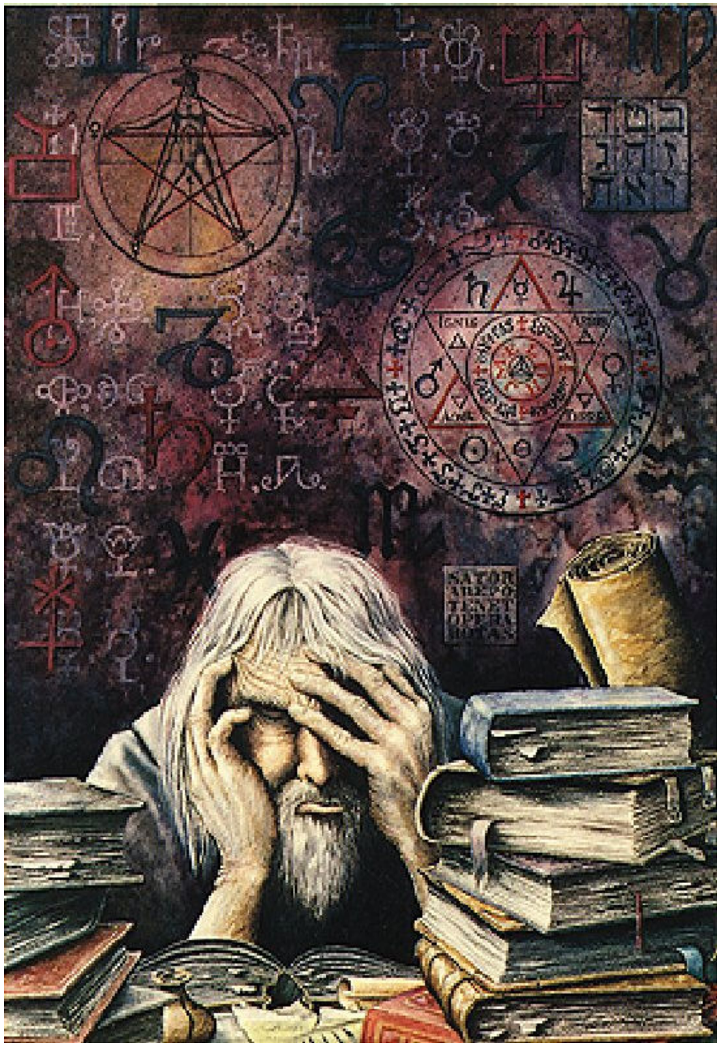
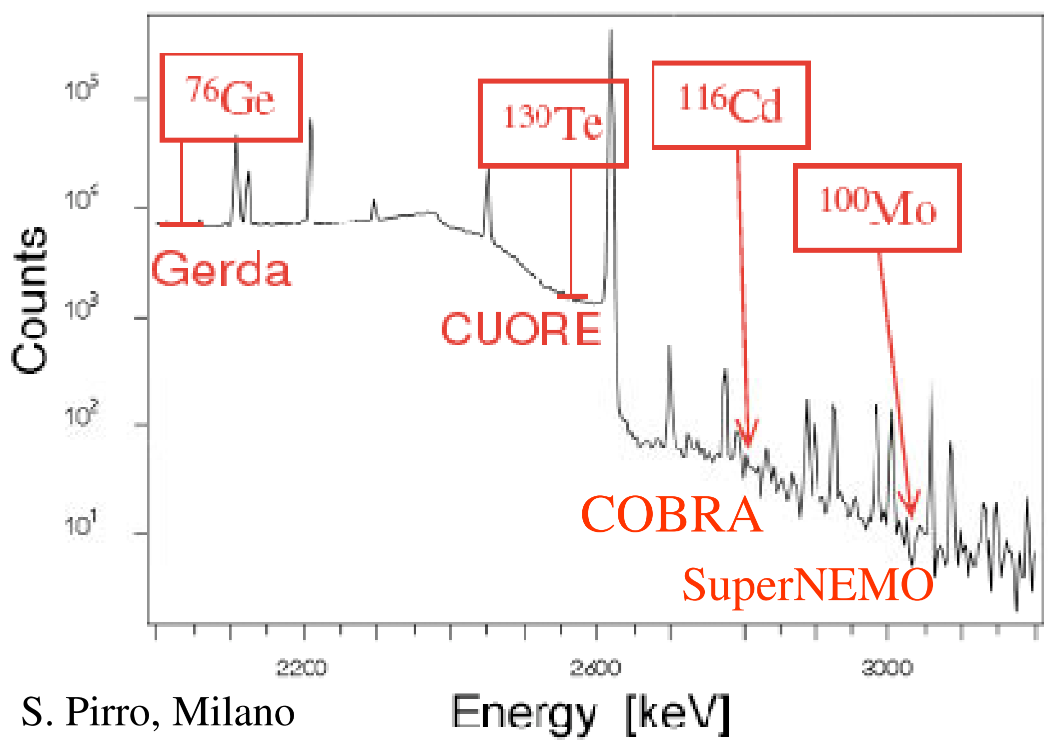


Background

- Natural radioactivity (U,Th,K,Rn) (work very clean)
- Cosmogenic produced isotopes (minimize surface time)
- Neutrons (shielding)
- Muons (veto)
- 2 neutrino double beta decay (energy resolution)



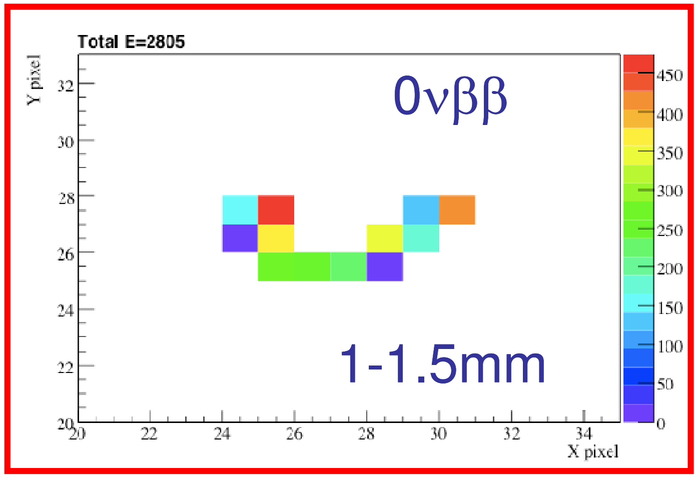
S. Pirro, Milano

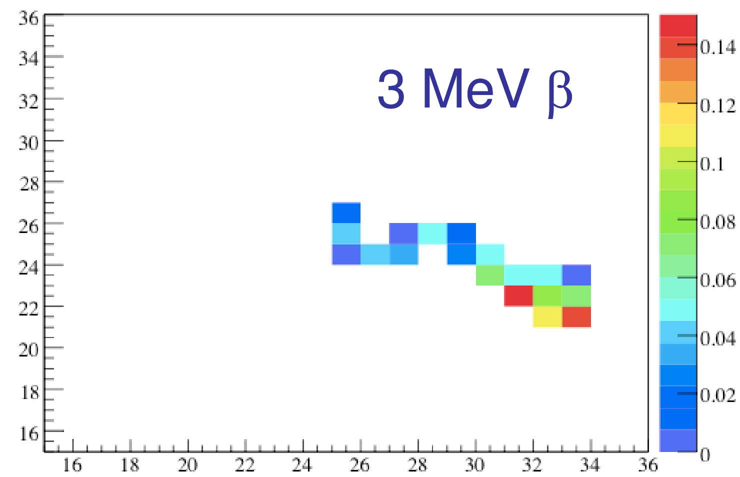
Active BG supression - COBRA

★ Idea: Massive background reduction by particle identification

The Semiconductor Tracker (Solid State TPC)

α= 1 pixel, β and ββ= several connected pixel, γ= some disconnected p.





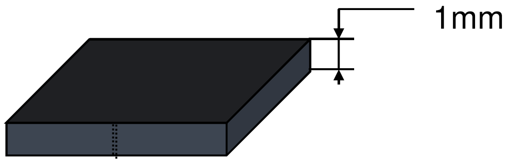
MC: Pixel size 200 μm

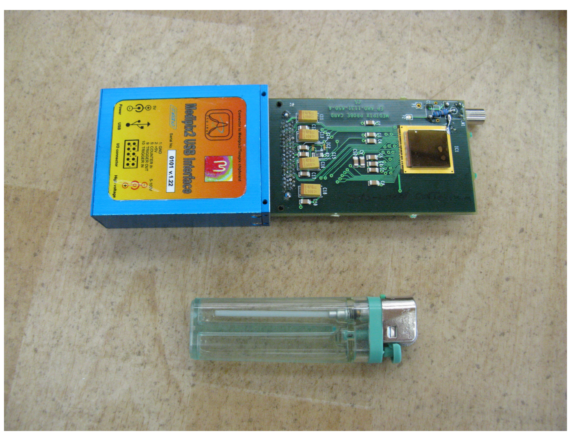
Beta with endpoint 3.3MeV

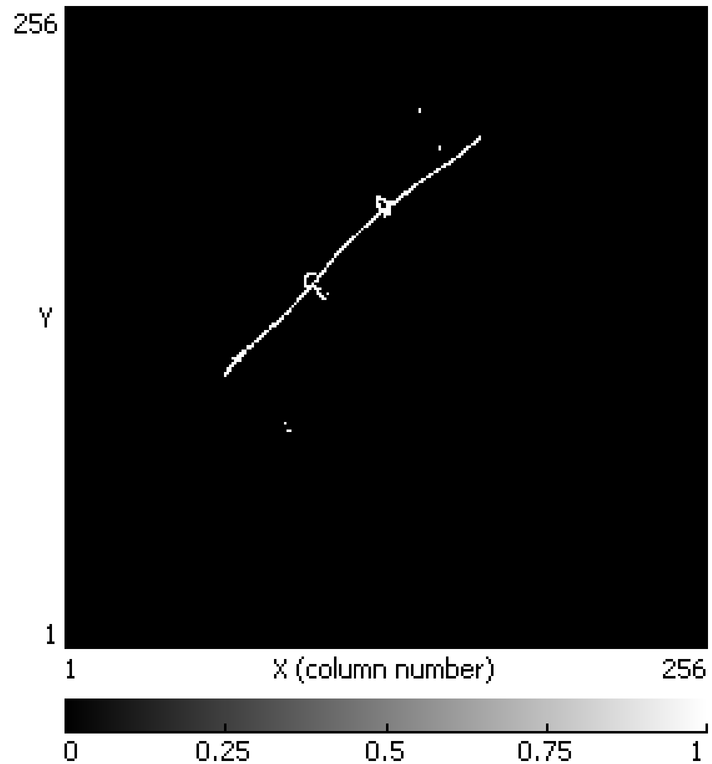
7.7MeV α life-time = 164.3μs

Timepix (Medipix2-coll.)

- ★ TimePix CdTe Detektor
- ★ 1mm Dicke, 256x256 Pixel, 55µm pitch, 1.4x1.4 cm^2



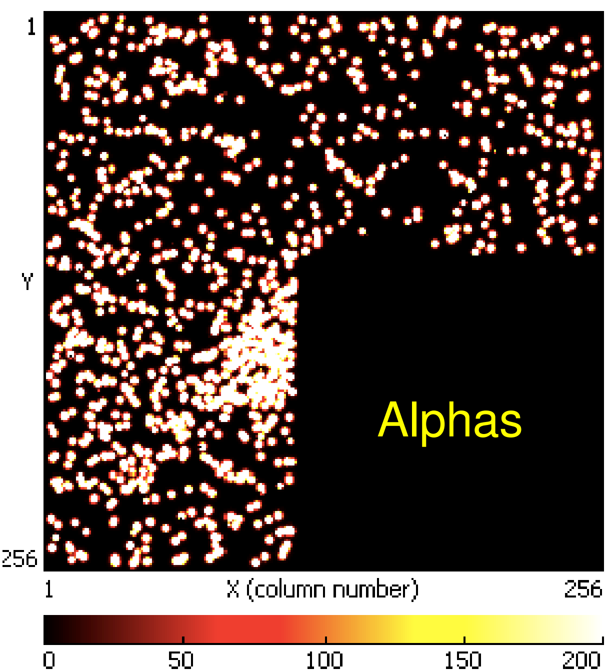


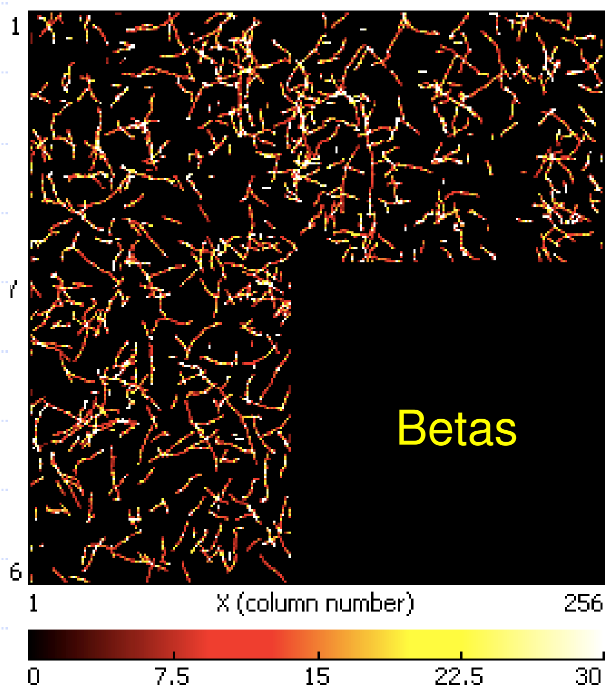


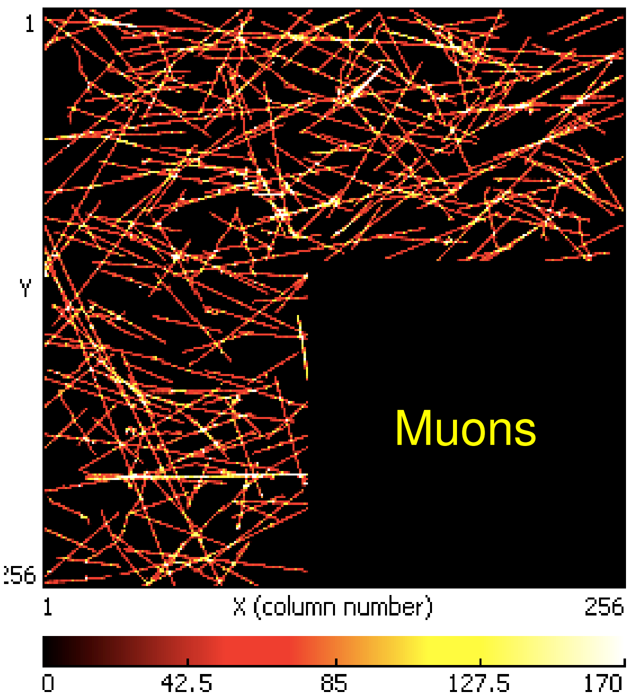
Myon candidate

Particles....

Preselected samples





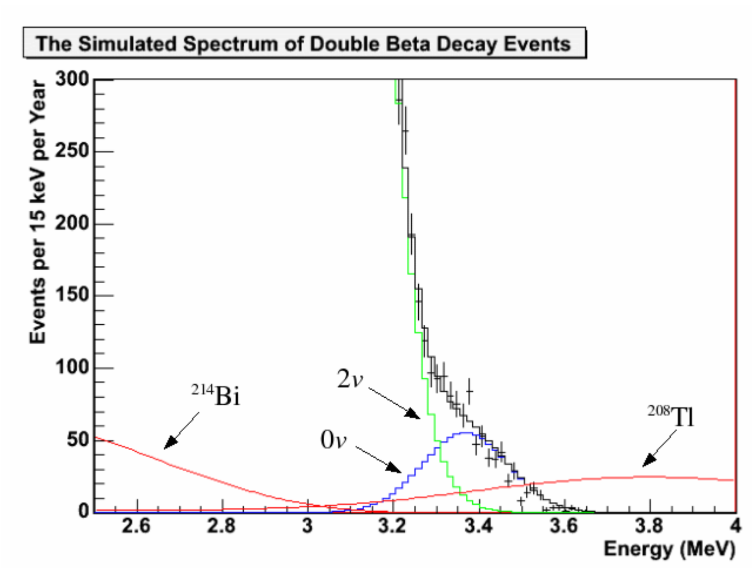


Energy resolution

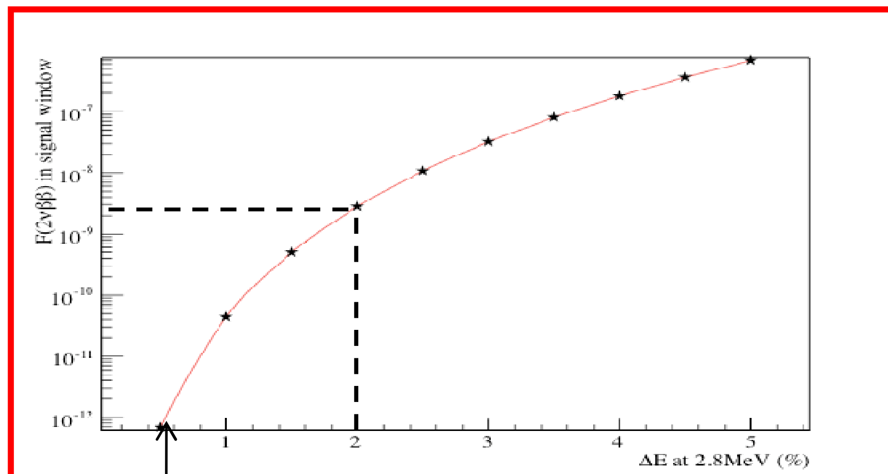
- ★ Irreducible background is 2νββ ➔
- ★ By the end of the day energy resolution is crucial!

  In this respect Ge-semiconductors are the best

Example: SNO+ (LSc+Nd)



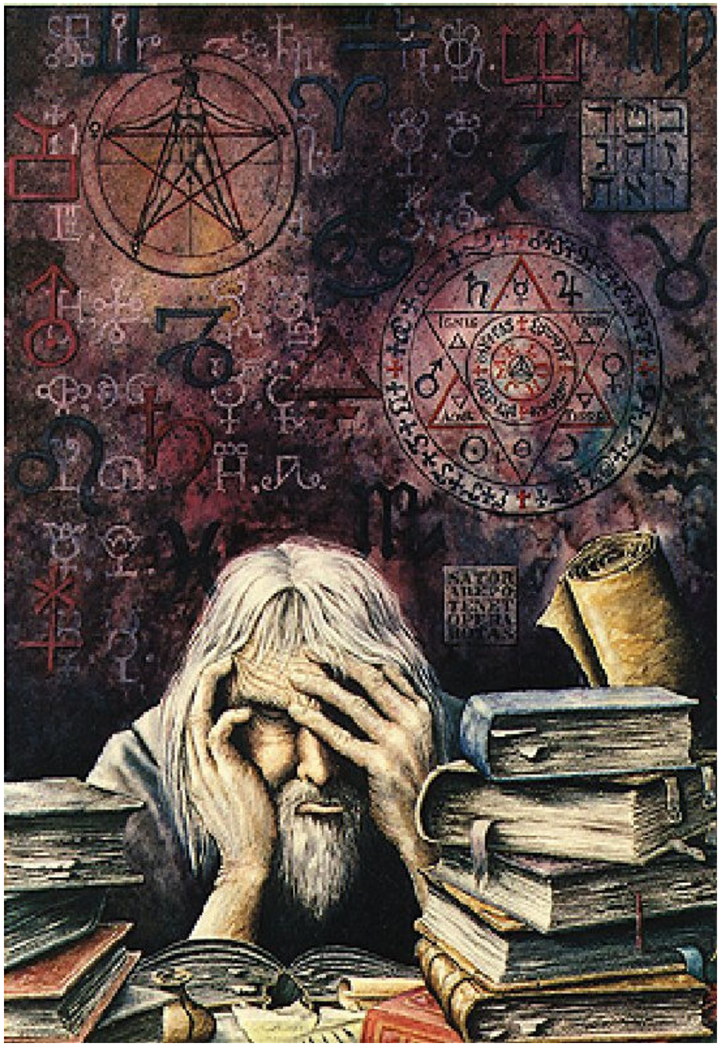
Example: COBRA
(CdZnTe semiconductor)



achieved

The ultimate experiment

- ★ Number of source atoms : ∞
- ★ Measuring time: ∞ ✓
- ★ Background : 0 ✓
- ★ Energy resolution: δ –function ✓
- ★ Efficiency: 100% ✓
- ★ Phase space: as large as possible ✓
- ★ Nuclear matrix elements: precisely known ✓



Number of source atoms

All future experiments will be isotopical enriched!!!

This is the most costly part of the experiments (nobel gases are the cheapest to enrich)

Parent isotope	$\langle F_N \rangle \equiv \langle G^{0\nu} \lvert M^{0\nu} \rvert^2 \rangle \text{year}^{-1}$	$\overline{\eta}$	$\lvert Q_{\beta\beta} \rvert$ (keV)	Enrichment Today	Enrichment Future(?)
^{48}Ca	$(5.4^{+3.0}_{-1.4}) \times 10^{-14}$	0.54	4271		ICR
^{76}Ge	$(7.3 \pm 0.6) \times 10^{-14}$	0.73	2039	Ultracentrifuge	ICR
^{82}Se	$(1.7^{+0.4}_{-0.3}) \times 10^{-13}$	1.70	2995	Ultracentrifuge	ICR
^{100}Mo	$(5.0 \pm 0.3) \times 10^{-13}$	5.0	3034	Ultracentrifuge	ICR
^{116}Cd	$(1.3^{+0.7}_{-0.3}) \times 10^{-13}$	1.30	2802	Ultracentrifuge	ICR
^{130}Te	$(4.2 \pm 0.5) \times 10^{-13}$	4.26	2533	Ultracentrifuge	
^{136}Xe	$(2.8 \pm 0.4) \times 10^{-14}$	0.28	2479	Ultracentrifuge	
^{150}Nd	$(5.7^{+1.0}_{-0.7}) \times 10^{-12}$	57.0	3367		ICR

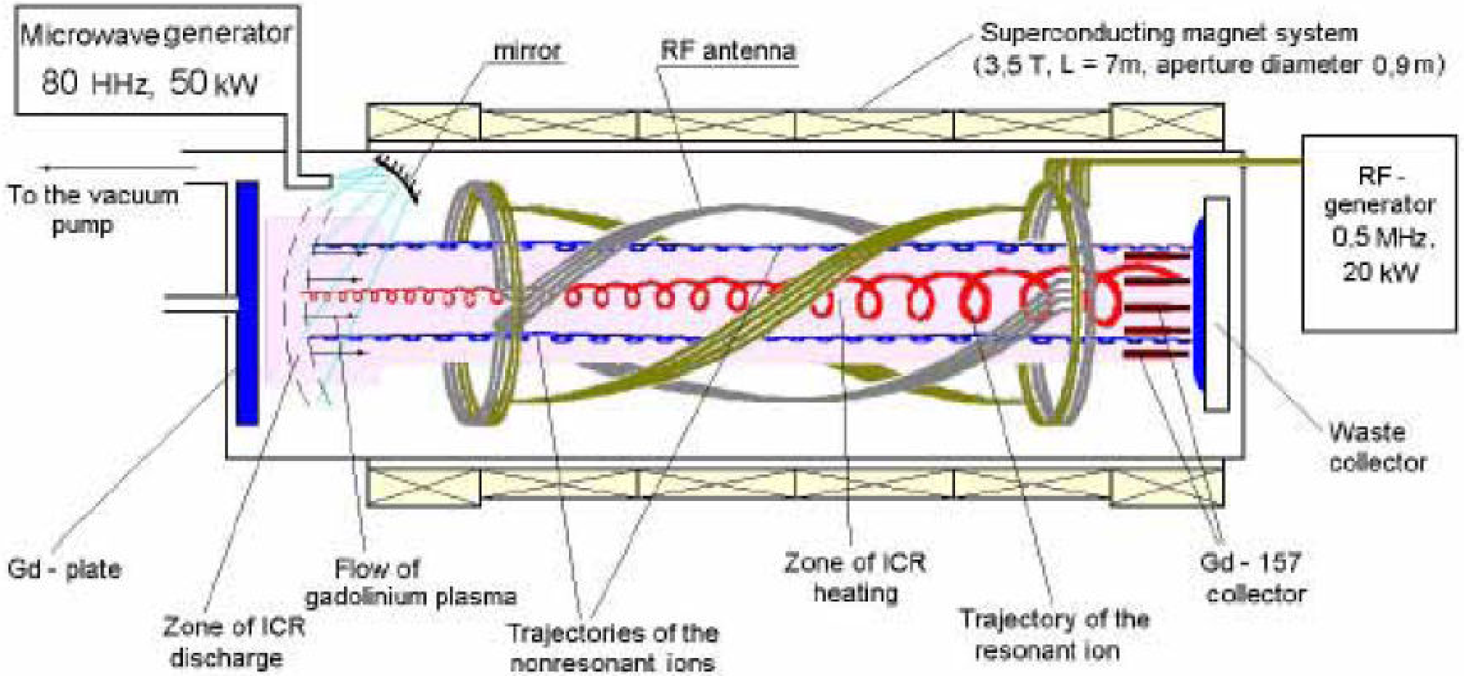
F.T. Avignone II et al., New Journal of Physics **7** (2005) 6

Ion Cyclotron Resonance separation

Big advantage: Flexibility

from: G. Yu. Grigoriev, Kurchatov Institute, Moscow

MCIRI isotope separation system



$Q \approx 10$ kg/day

$I_{eq} \leq 100$A

Zone of homogeneous field

$B = 3{,}5$ T, $\frac{\Delta B}{B} \leq 3 \cdot 10^{-4}$

$l = 5$ m, diameter 0,5 m.

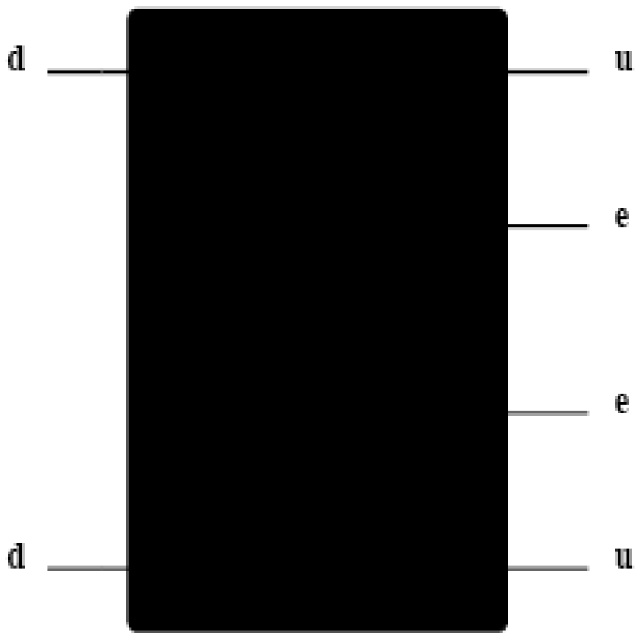
^{157}Gd (80%)	250 g/day
^{102}Pd (40%)	10 g/day
^{150}Nd (80%)	200 g/day
^{48}Ca (20%)	10 g/day

E. Previtali, Joint Annual ILIAS Meeting "Physics of massive neutrinos", Blaubeuren 1-5 July 2007 (FP6)

0νββ

Assume you have a well established signal ...

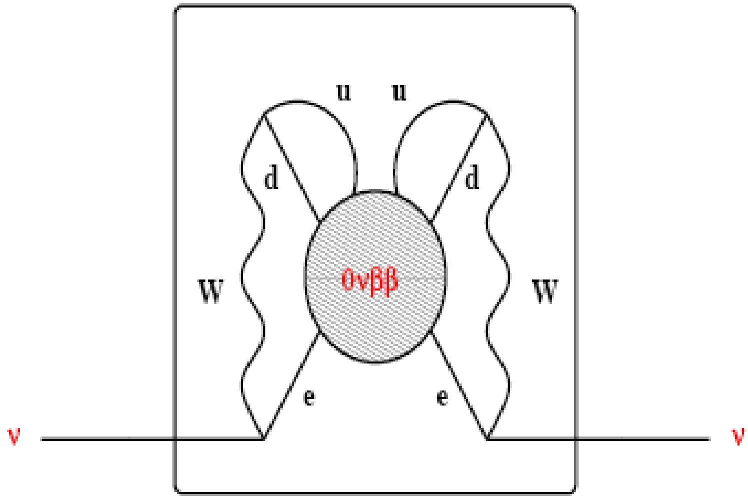
Any ΔL=2 process can contribute to 0νββ



R_p violating SUSY
V+A interactions
Extra dimensions (KK- states)
Leptoquarks
Double charged Higgs bosons
Compositeness
Heavy Majorana neutrino exchange
Light Majorana neutrino exchange
...

$$1 / T_{1/2} = PS * NME^2 * \varepsilon^2$$

But...



Schechter & Valle, 1982

Independent of mechanism of $0\nu\beta\beta$ decay Majorana neutrino mass will appear in higher order!

Thus:

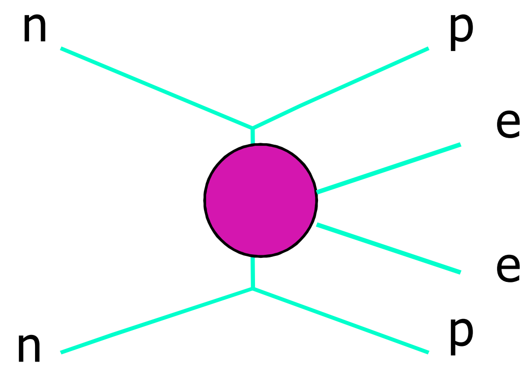
Observe $0\nu\beta\beta$ decay

$\equiv$

Neutrinos are Majorana particles

$\beta^+\beta^+$ - modes

In general:



- $(A,Z) \rightarrow (A,Z-2) + 2\,e^+ \,(+2\nu_e)$ $\beta^+\beta^+$ $Q-4m_ec^2$
- $e^- + (A,Z) \rightarrow (A,Z-2) + e^+ \,(+2\nu_e)$ β^+/EC $Q-2m_ec^2$
- $2\,e^- + (A,Z) \rightarrow (A,Z-2)\,(+2\nu_e)$ EC/EC Q

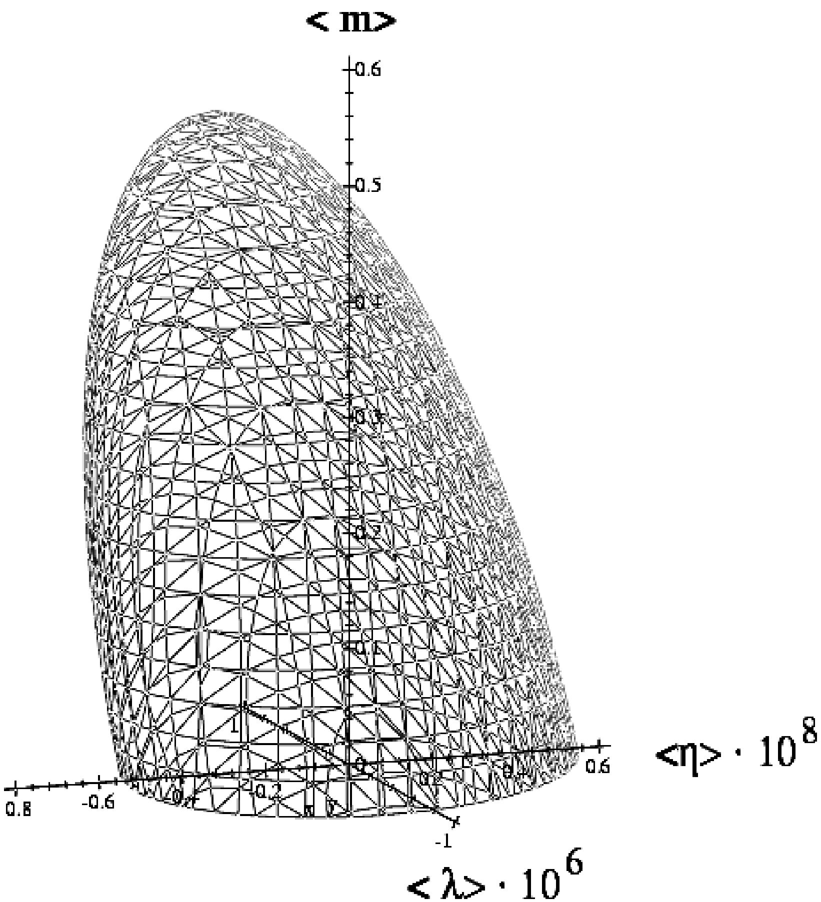
Resonance enhancement in 0 EC/EC if initial and final state are degenerate

ISOLTRAP and other traps are investigating candidates

Neutrino mass vs. right handed currents

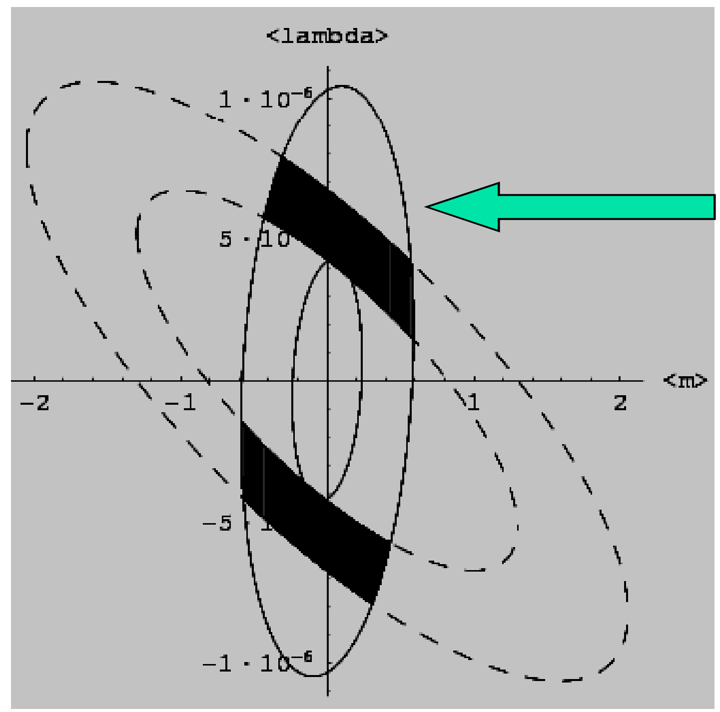
$$H_{\text{int}} \propto j_L J_L^+ + \kappa j_L J_R^+ + \eta j_R J_L^+ + \lambda j_R J_R^+$$

$$\lambda, \eta << 1$$



EC/β+

<λ>



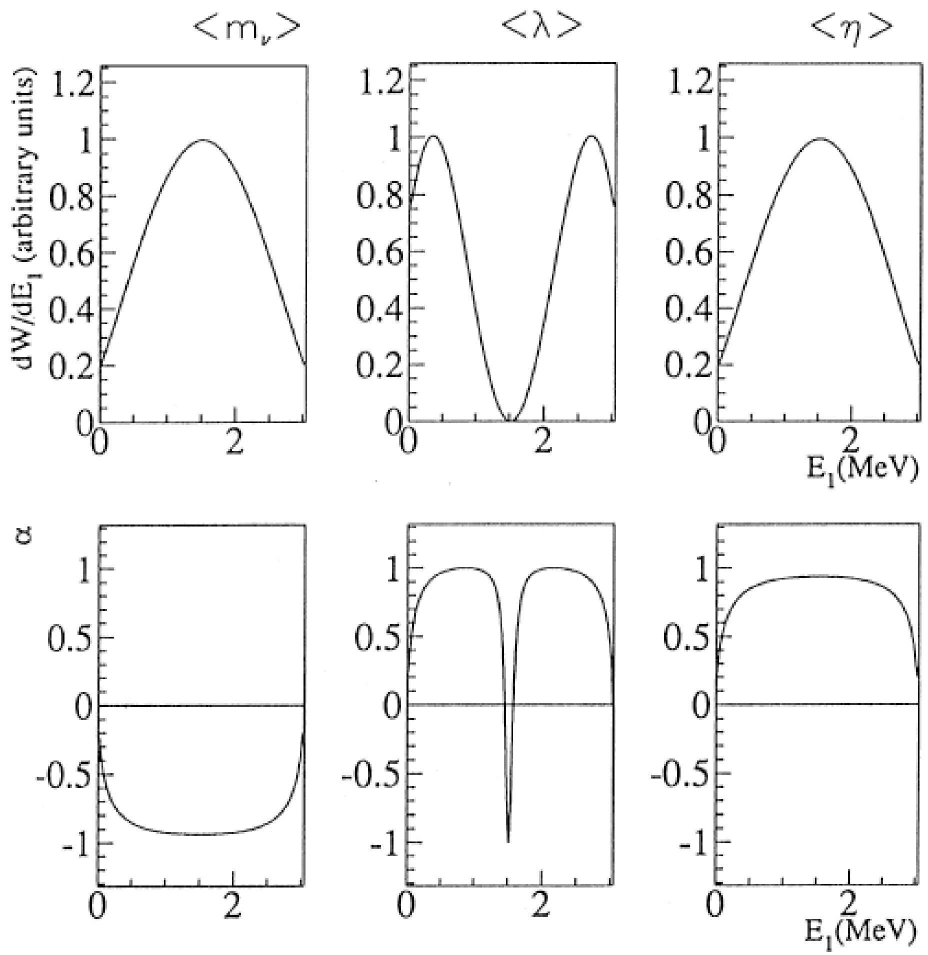
Possible evidence

$<m_\nu>$ **(eV)**

M. Hirsch et al., Z. Phys. A 347,151 (1994)

Sign of V+A

Another option: measure single electron spectra and angular correlation



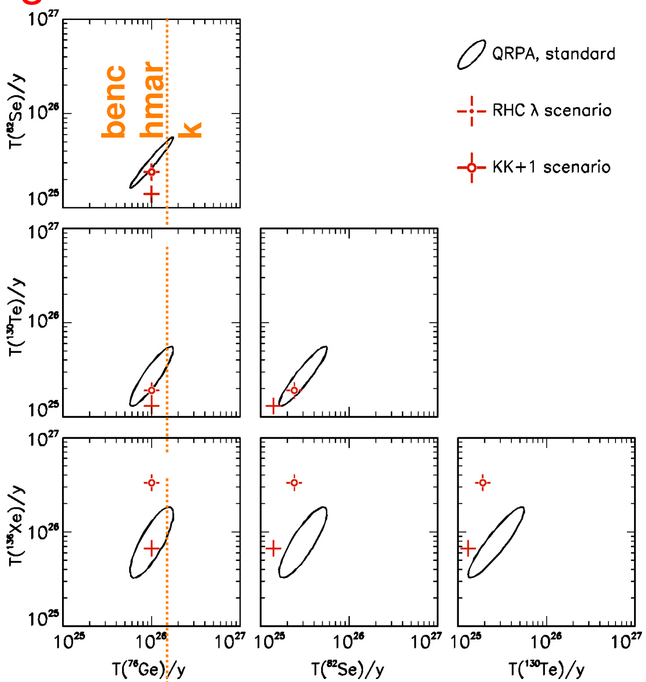
H. Ejiri, Phys. Rep. 2000

Discrimination

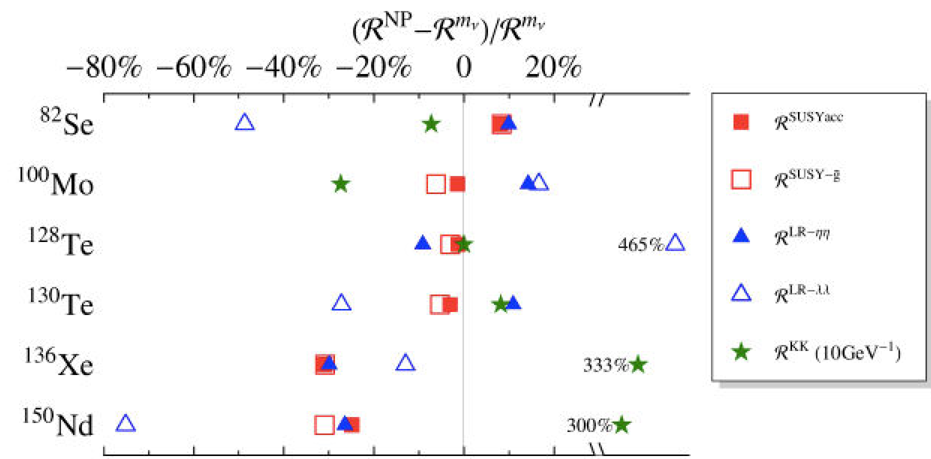
Nuclear matrix element correlations

Theory based

Results: two of the previous mechanisms can be distinguished at >95 % CL



E. Lisi, Erice 2009



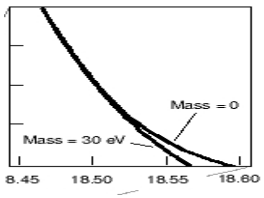
F. Deppisch, H. Paes,
Phys. Rev. Lett. 98,232501 (2007)

Neutrino Physics

Also other neutrino physics matters

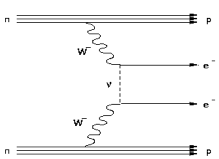
Beta decay:

$$m_\beta = \left[c_{13}^2 c_{12}^2 m_1^2 + c_{13}^2 s_{12}^2 m_2^2 + s_{13}^2 m_3^2\right]^{\frac{1}{2}}$$



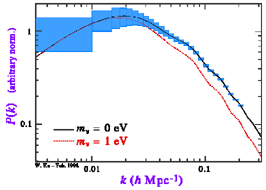
Double beta decay:

$$m_{\beta\beta} = \left|c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 m_2 e^{i\phi_2} + s_{13}^2 m_3 e^{i\phi_3}\right|$$



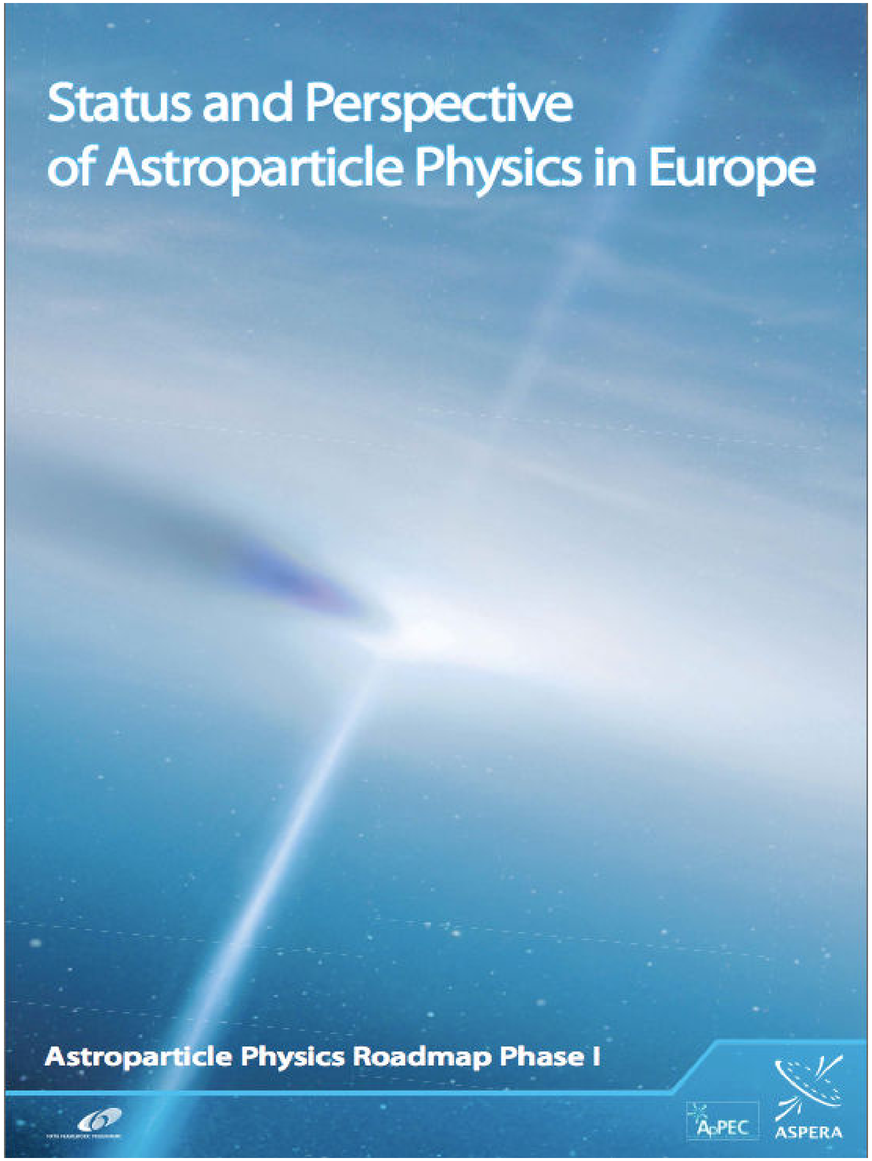
Cosmology:

$$\Sigma = m_1 + m_2 + m_3$$



+ oscillation parameters

Astroparticle - Roadmap



A subgroup of the HM collaboration (Klapdor-Kleingrothaus et al., KKGH in what follows) has claimed a positive effect from a re-analysis of their data, with $T_{1/2} \sim 1.2 \cdot 10^{25}$ y and $m_{\beta\beta} \sim 0.2$ -0.6 eV. Although this claim remains controversial, it provides an additional motivation for experiments with sensitivities in this mass range.

The KKGH claim

The largest running experiments are CUORICINO and NEMO-3. CUORICINO (Gran Sasso Lab) uses ^{130}Te as the double beta parent nucleus. It is an array of cryogenic bolometers of Tellurite crystals with a total mass of 41 kg (33.8% ^{130}Te) and is a first stage for CUORE conceived with a total mass of 740 kg. The main isotopes in NEMO-3 are ^{100}Mo (7kg) and ^{82}Se (1kg). NEMO-3 is a cylindrical detector with a central source foil sandwiched by tracking detectors and surrounded by a calorimeter in a 25 Gauss magnetic field and is located in the Fréjus laboratory. NEMO-3 is a stage on the way to the Super-NEMO detector, currently conceived to contain 100 kg ^{150}Nd or ^{82}Se. The sensitivities of both experiments are in the 0.5 eV range. These experiments could possibly confirm, but not fully disprove the KKGH claim.

Running experiments

The European next-stage detectors are GERDA, CUORE and Super-NEMO. GERDA is being set-up in Gran Sasso and uses Germanium detectors enriched in ^{76}Ge, 18 kg in a first and about 40 kg in a second phase. They will scrutinize the KKGH claim starting in 2008, and will reach a sensitivity $T_{1/2} > 2 \cdot 10^{26}$ y and $m_{\beta\beta} < 0.1$-0.3 eV targeted for 2010. Depending on the physics results, a third phase using 500 to 1000 kg of enriched germanium detectors is planned merging GERDA with the US lead Majorana collaboration. The start of CUORE operation is scheduled for 2011, reaching a final sensitivity of 0.05-0.1 eV. Super-NEMO will finish a phase of design study in 2008 and projects the completion of the full detector in 2012 with 100 kg of ^{150}Nd or ^{82}Se. Its final sensitivity will be in the range 0.05–0.2 eV. All three experiments can prove or disprove the KKGH claim. Their motivation, as well as ultimate goal is to start the exploration of the parameter range predicted by the inverted mass hierarchy. This endeavour will commence at the beginning of the next decade.

Coming soon...

It is not excluded at this point that an innovative European approach, COBRA, will join the competition. COBRA uses dominantly ^{116}Cd and ^{130}Te isotopes. A detector array of 64 CdZnTe semiconductor devices with a mass of about 0.5 kg has been installed in the Gran Sasso laboratory. Work towards a large scale detector is ongoing, and a Conceptual Design Study is expected in 2010.

R&D on Cadmium

At this point, two large experiments located in the USA with similar sensitivity and a fourth innovative European approach have to be mentioned: EXO will use ^{136}Xe isotopes in a Time Projection Chamber filled with liquid enriched Xenon, 200 kg in a first stage. Neuchatel is the one European EXO collaborator. EXO-200 would address a similar mass range as CUORICINO and NEMO-3. For a later one-ton version, a 0.03 eV sensitivity

Outside Europe

Summary

- ★ The current evidence will be probed by GERDA and probably others by 2014
- ★ There is no absolutely preferred isotope
- ★ The uncertainties in the matrix elements and the disentangling of the underlying physics require the measurement of at least 3-4 isotopes.
- ★ For the isotope pairs of interest as much as possible experimenal information should be collected
- ★ The dominating costs for most experiments is enrichment of isotopes. Should Europe build its own enrichment plant (ICR)? Especially if you want to go below 50 meV
- ★ The ASPERA roadmap includes double beta decay in form of GERDA, CUORE, SUPERNEMO and COBRA
- ★ Field is very active and healthy. Some projects are pushed towards large scales now, but people are still open to new ideas.