Neutrinoless double beta-decay: theory and experimen

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Mass scale of $m_\nu \sim \sqrt{\Delta m^2 \sim}$ 0.05 eV have been established by the atmospheric neutrino oscillation experiments. Can experiments on neutrinoless $\beta\beta$ decay reach in foreseeable future the sensitivity to that mass scale, and help to fix the absolute value of the neutrino mass?

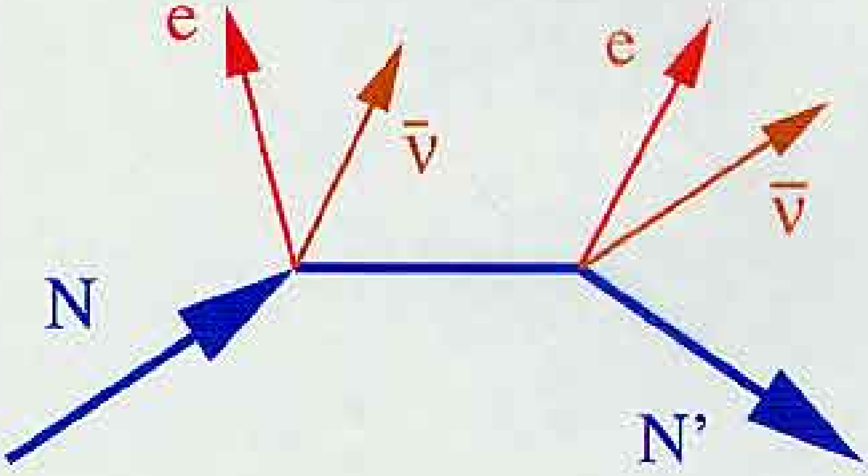
To answer this question, I will review the present status of the $\beta\beta(0\nu)$ search and describe the many proposals and ideas how to increase the sensitivity of the experiments.

Also, the relations between the neutrino rest masses m_i, the effective mass $\langle m_\nu \rangle$, and the rate of the $\beta\beta(0\nu)$ decay will be discussed. The uncertainties inherent in these relations, stemming from both nuclear (nuclear matrix elements) and particle physics (Majorana phases in the mixing matrix) will be estimated.

Addendum: The very recently claimed 'evidence' for the observation of the $0\nu\beta\beta$ decay will be briefly discussed.

Most sensitive neutrino mass measurements can be obtained from double-beta decay

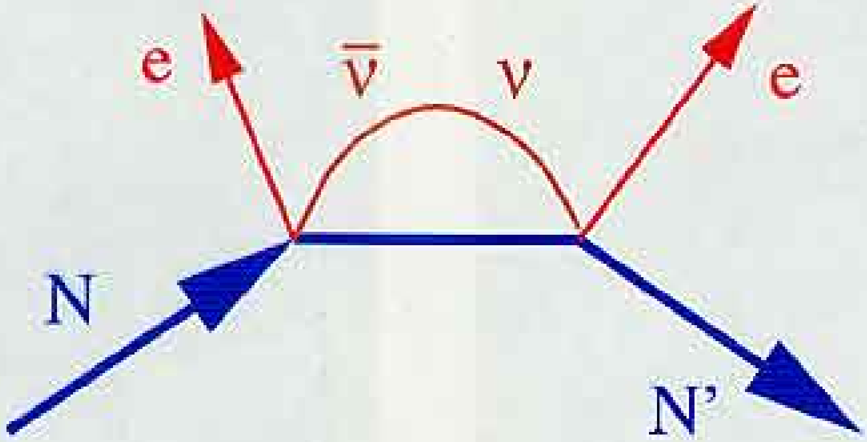
$2\nu\ \beta\beta$ decay: a standard process in nuclear physics



$0\nu\ \beta\beta$ decay: a hypothetical process

→ $m_\nu \neq 0$ since helicity has to "flip"

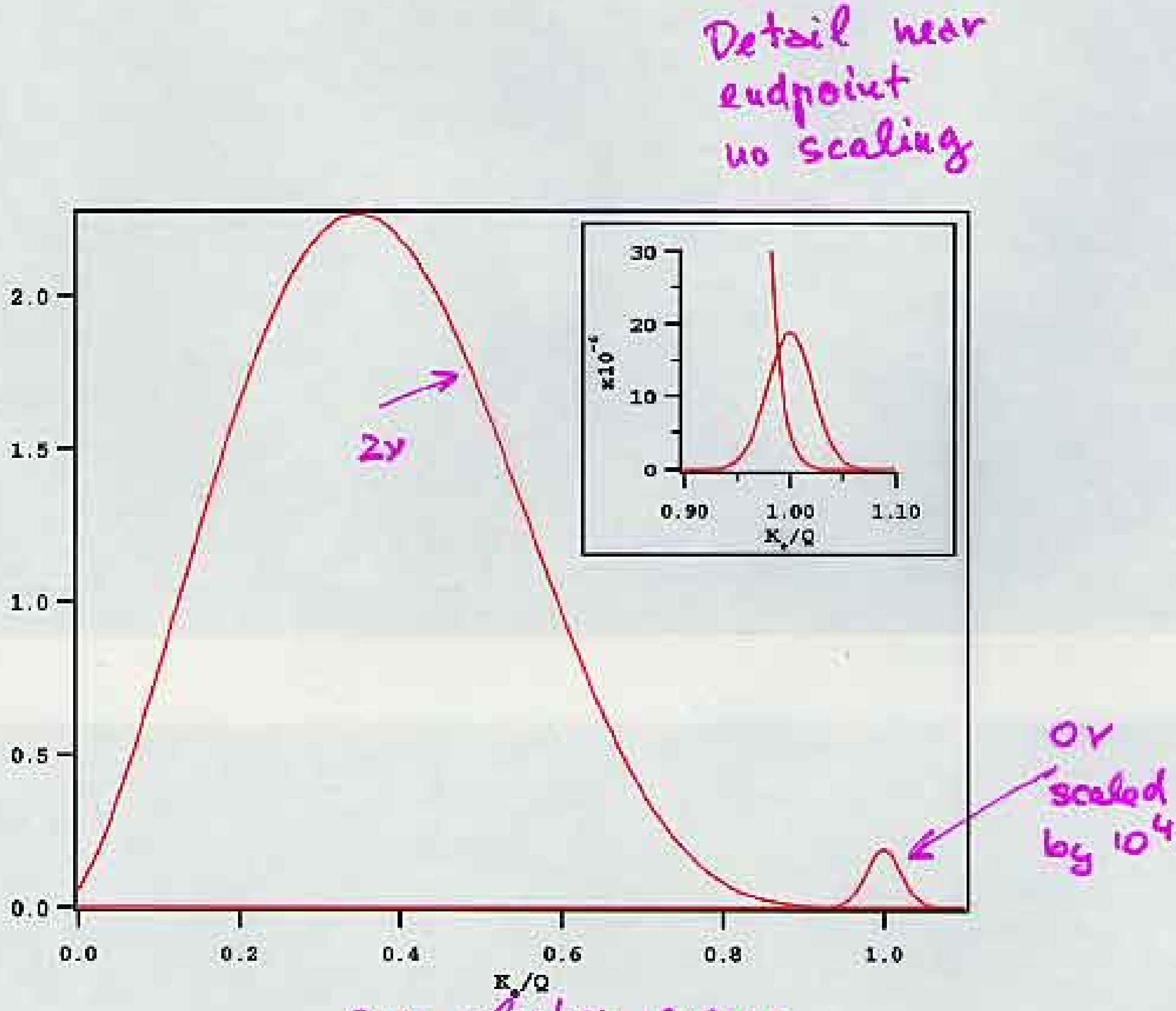
→ $\bar{\nu} = \nu$



Separating 2ν and 0ν $\beta\beta$ decay modes

Assume: $T_{1/2}^{0\nu} / T_{1/2}^{2\nu} = 10^6$

resolution = 5%



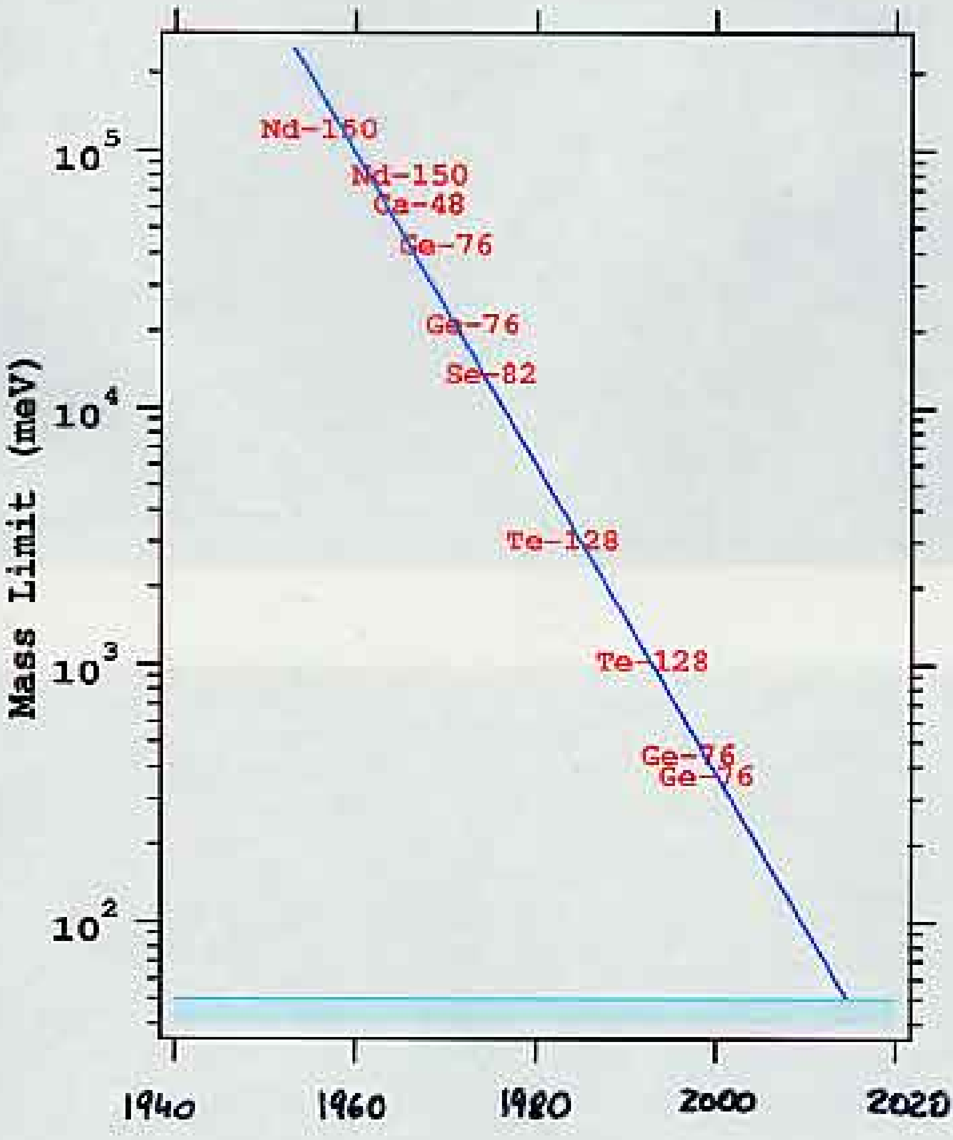
(thanks to S. Elliott)

Summary of experimental $2\nu\beta\beta$ halflives and matrix elements (except for ^{136}Xe where a limit is quoted). For each parent nucleus the results of most recent experiments are weighted averages (averaging the asymmetric error bars first, and adding the systematic errors in quadrature for each measurement). The symbol † is used for inconsistent results; the error bars then reflects their spread. The nuclear matrix elements were deduced using the phase-space factors of Boehm & Vogel (1992).

Isotope	$T^{2\nu}_{1/2}$ (y)	$M^{2\nu}_{GT}$ (MeV^{-1})
^{48}Ca	$(4.25 \pm 1.6) \times 10^{19}$	0.05
^{76}Ge	$(1.38 \pm 0.14) \times 10^{21}$	0.15
^{82}Se	$(8.9 \pm 1.0) \times 10^{19}$	0.10
^{96}Zr†	$(1.43^{+3.4}_{-0.8}) \times 10^{19}$	0.12
^{100}Mo	$(8.2 \pm 0.6) \times 10^{18}$	0.22
^{116}Cd	$(3.2 \pm 0.3) \times 10^{19}$	0.12
^{128}Te$^{(1)}$	$(7.2 \pm 0.3) \times 10^{24}$	0.025
^{130}Te$^{(2)}$	$(2.7 \pm 0.1) \times 10^{21}$	0.017
^{136}Xe	$> 8.1 \times 10^{20}$	<0.03
^{150}Nd†	$7.0^{+12.0}_{-1.0} \times 10^{18}$	0.07
^{238}U$^{(3)}$	$(2.0 \pm 0.6) \times 10^{21}$	0.05

(1) deduced from the geochemically determined half-life ratio ^{128}Te/^{130}Te
(2) geochemical result includes all decay modes; other geochemical determinations are sometimes inconsistent
(3) radiochemical result again for all decay modes

Moore's law for $0\nu\beta\beta$ decay



(thanks to S. Elliott

In **neutrinoless** $\beta\beta$ **decay** ($0\nu\beta\beta$) two neutrons bound in a nucleus are simultaneously transformed into two protons, **two electrons and nothing else**, like e.g.,

$$_{32}\mathrm{Ge}^{76} \rightarrow {}_{34}\mathrm{Se}^{76} + 2e^- \quad \text{or} \quad {}_{54}\mathrm{Xe}^{136} \rightarrow {}_{56}\mathrm{Ba}^{136} + 2e^-$$

$0\nu\beta\beta$ decay violates the total lepton number conservation. Its existence implies that the electron neutrino have a **massive Majorana** component. The rate of the $0\nu\beta\beta$ decay is determined by

$$1/T^{0\nu}_{1/2} = G(E_{tot}, Z)\mathcal{M}^2\mathcal{X}^2,$$

where $G(E_{tot}, Z)$ is a calculable phase space factor,

$\mathcal{M}$ is a nuclear matrix element, calculable with difficulties,

and $\mathcal{X}$ is an unknown fundamental parameter (e.g. effective neutrino Majorana mass).

Various processes could contribute to $\mathcal{X}$ (light or very heavy Majorana neutrinos, right-handed current weak interactions, various supersymmetric particles, etc.). All of them imply **"physics beyond the Standard Model"**. Since we **believe now** that massive (and light) neutrinos exist (even though we cannot be sure that they are Majorana particles), we will consider **only** this possibility further.

In $0\nu\beta\beta$ decay with the exchange of a light Majorana neutrino

$$\boxed{\mathcal{X} \;=\; < m^{\nu}_{eff} >= \Sigma_i \, |U_{e,i}|^2 m_i e^{2\delta_{e,i}}}$$

where $\delta_{e,i}$ is the **phase** of the mixing matrix element $U_{e,i}$. That phase is peculiar to Majorana neutrinos and cannot be determined in oscillation experiments. If CP is conserved, this phase becomes just a sign $e^{\delta_{e,i}} = \epsilon_i = \pm 1$.

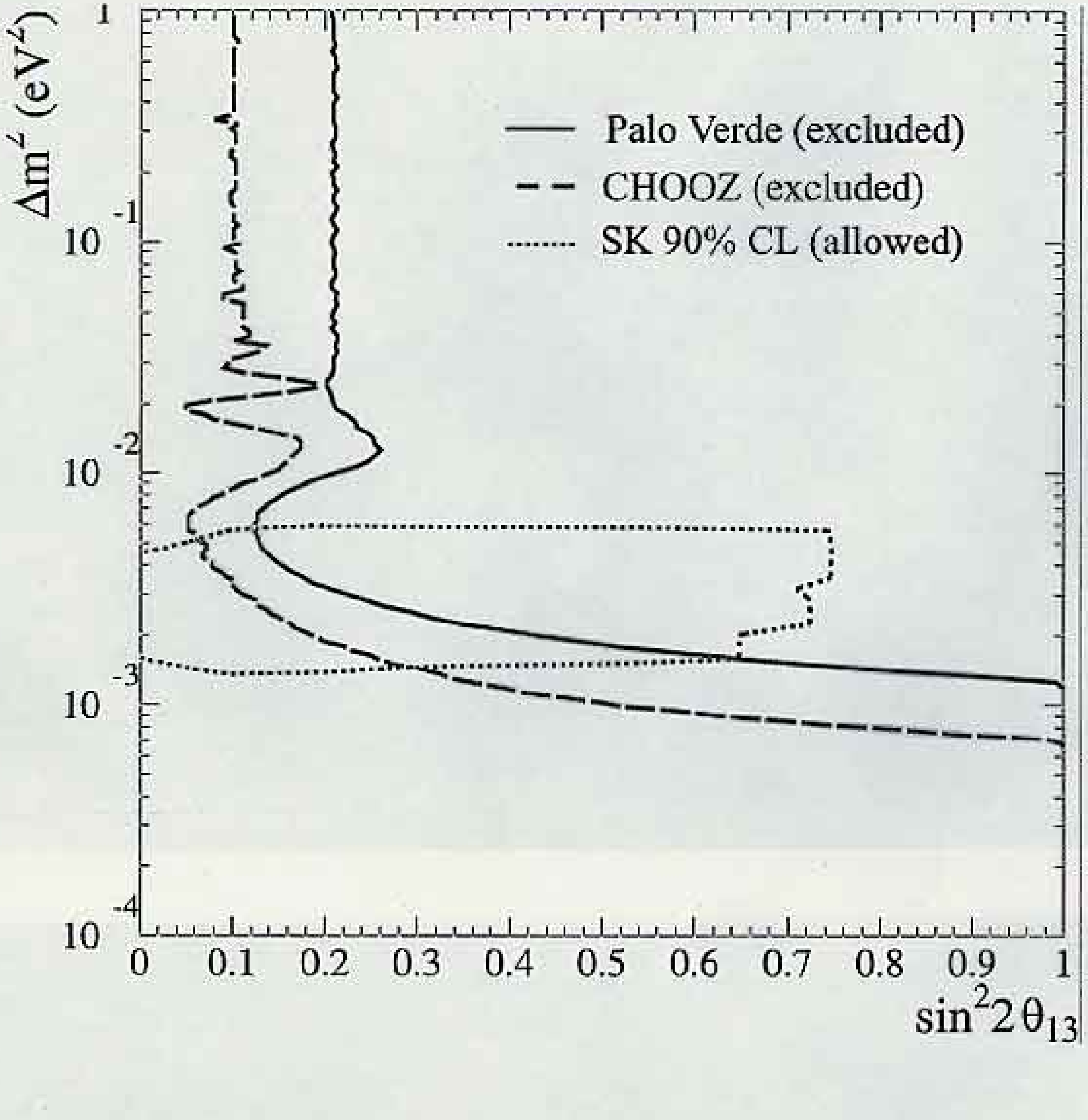
No matter what the Majorana phases $\delta_{e,i}$ the effective mass is contrained to be between the limits (Vissani)

$$\boxed{\max 2|U_{e,i}|^2 m_i - \Sigma_i \, |U_{e,i}|^2 m_i \;\le\; < m^{\nu}_{eff} > \;\le\; \Sigma_i \, |U_{e,i}|^2 m_i}$$

$<m_\nu>_{min}$ $<m_\nu>_{max}$

So, suppose we know from the oscillation experiments the mixing probabilities $|U_{e,i}|^2$, and we determine **experimentally** the value of $< m^{\nu}_{eff} >$. We can then find the interval of values where the lightest neutrino mass m_{min} must be. Once we have m_{min}, we can use the quatities $\Delta m_{i,j}$ from the oscillation experiments and **we know everything**.

⑨


Δm^2 (eV^2)
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$\sin^2 2\theta_{13}$
Palo Verde (excluded)
CHOOZ (excluded)
SK 90% CL (allowed)

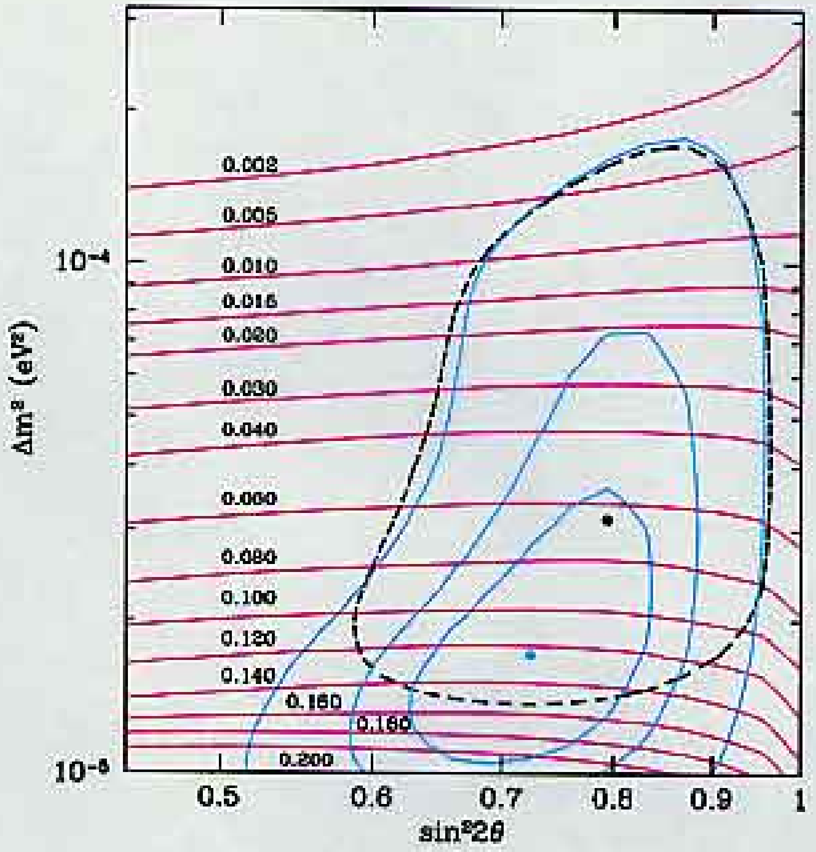
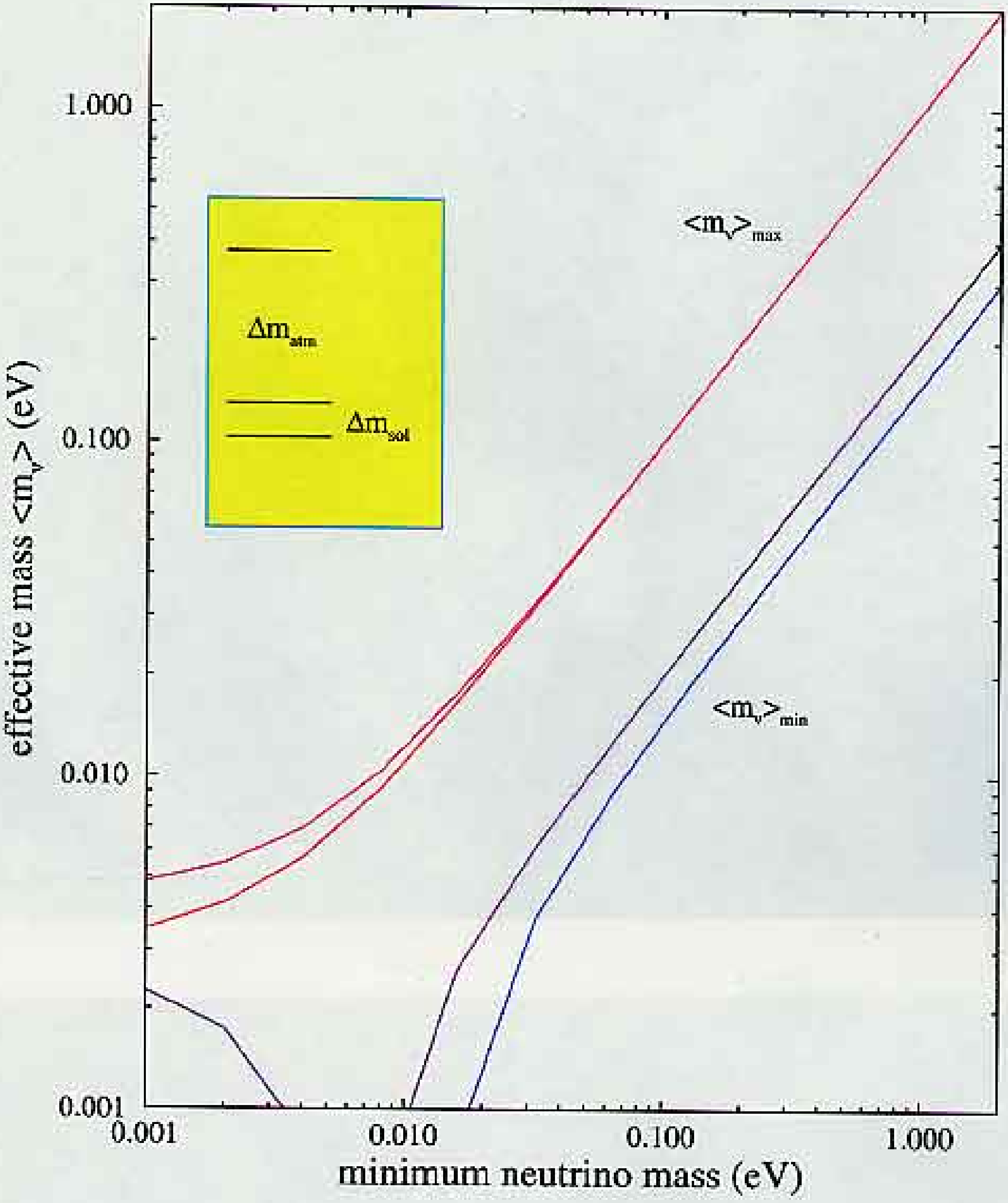


FIG. 1. The allowed region of the LMA MSW parameter space. When only the rates in the chlorine, SuperKamiokande, SAGE, and GALLEX experiments are considered, the vertical continuous lines are part of the allowed contours at 90%, 95%, and 99% C.L. The dashed contour corresponds to the allowed region at 99% C.L. when both the total rates and the Night-Day asymmetry are included. The best fit parameters, indicated by a dot in the figure, are for the rates-only fit: $\sin^2(2\theta) = 0.72$ and $\Delta m^2 = 1.7 \times 10^{-5}\mathrm{eV}^2$. The best-fit parameters for the combined fit are $\sin^2(2\theta) = 0.76$ and $\Delta m^2 = 2.7 \times 10^{-5}\mathrm{eV}^2$. The approximately horizontal lines show the contours for different Night-Day asymmetries (numerical values indicated); see Ref. [30] for an illuminating discussion of the Night-Day asymmetry. The data are from Refs. [1,3,4,9].

Effective neutrino mass in 0ν ββ decay

normal hierarchy, LMA solution

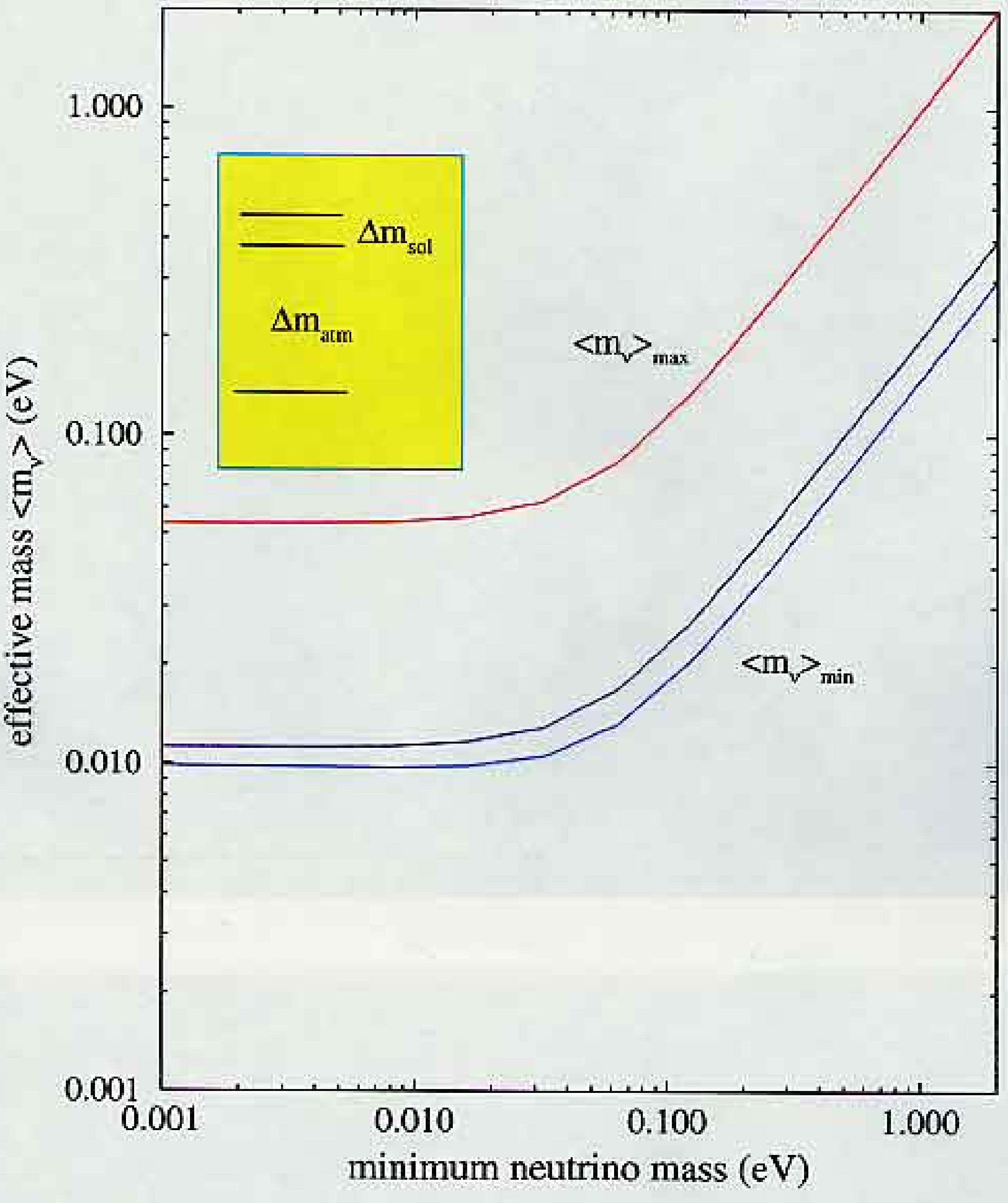


$U_{e2}^2 = 0.4$ U_{e3}^2 .. 0 - 0.025

$\Theta \sim 40°$

Effective neutrino mass in $0\nu\ \beta\beta$ decay

inverse hierarchy, LMA solution



Calculated $\beta\beta0\nu$ half-lives in units of 10^{26} years corresponding to $\langle m_\nu \rangle = 100$ meV for nuclear matrix elements evaluated in the indicated references.

(1) Haxton & Stephenson, 1984, truncated shell model
(2) Caurier *et al.*, 1999, shell model
(3) Engel, Vogel & Zirnbauer, 1988, QRPA schematic int.
(4) Staudt, Muto & Klapdor-Kleingrothaus, 1990, QRPA realistic int.
(5) Toivanen & Suhonen, 1995, renormalized QRPA realist int.
(6) Pantis *et al.*, 1996, QRPA with $p - n$ pairing

Nucleus	ref.: (1)	(2)	(3)	(4)	(5)	(6)
^{76}Ge	1.7	17.7	14.0	2.3	3.2	3.6(18.4)
^{82}Se	0.6	2.4	5.6	0.6	0.8	1.5(2.8)
^{100}Mo	-	-	1.0	1.3	0.3	3.9(3600)
^{130}Te	0.2	5.8	0.7	0.5	0.9	0.9(2.1)
^{136}Xe	-	12.1	3.3	2.2	5.3	1.8(2.8)

Experimentally best cases involve materials that can be used a detection medium

candidate	$T_{1/2}^{0\nu\beta\beta}$		kg yr	$\langle m \rangle$ (eV)	
				QRPA	NSM
^{48}Ca	$> 9.5 \times 10^{21}$ (76% CL)				
^{76}Ge*	$> 1.9 \times 10^{25}$ (90% CL)	Ge diode calorimeter	29	< 0.4	< 1.1
^{82}Se	$> 2.7 \times 10^{22}$ (68% CL)				
^{100}Mo	$> 5.2 \times 10^{22}$ (68% CL)				
^{116}Cd	$> 2.9 \times 10^{22}$ (90% CL)				
^{130}Te*	$> 1.4 \times 10^{23}$ (90% CL)	TeO_2 cryo calorimeter	0.85	< 1.9	
^{136}Xe*	$> 4.4 \times 10^{23}$ (90% CL)	Xe TPC	8	< 2.2	< 5.2
^{150}Nd	$> 1.2 \times 10^{21}$ (90% CL)				

Best reported limits on $T^{0\nu}_{1/2}$

Isotope	$T^{0\nu}_{1/2}$ (y)	Reference
^{48}Ca	$> 9.5 \times 10^{21}$	You *et al.* 91
^{76}Ge	$> 1.9 \times 10^{25}$	Klapdor-Kleingrothaus *et al.* 01
	$> 1.6 \times 10^{25}$	Aaalseth *et al.* 99
^{82}Se	$> 2.7 \times 10^{22}$	Elliott *et al.* 92
^{100}Mo	$> 4.5 \times 10^{22}$	Ejiri *et al.* 96
^{116}Cd	$> 7 \times 10^{22}$	Danevich *et al.* 00
^{128,130}Te	$\frac{T_{1/2}(130)}{T_{1/2}(128)} = (3.52 \pm 0.11) \times 10^{-4}$ (geochemical)	Bernatovicz *et al.* 93
^{128}Te	$> 7.7 \times 10^{24}$	Bernatovicz *et al.* 93
^{130}Te	$> 1.4 \times 10^{23}$	Alessadrello *et al* 00
^{136}Xe	$> 4.4 \times 10^{23}$	Luescher *et al* 98
^{150}Nd	$> 1.2 \times 10^{21}$	De Silva *et al* 97

What is needed to reach the interesting region of 10 - 100 meV ?

① Very large fiducial mass (*tons*)

- **Unprecedented isotopic enrichment program**

② New ways to reduce backgrounds

- **Present experiments already dominated by background**

- Ge: 0.3 events/kg yr FWHM → 8.7 events
- Te: 7.7 events/kg yr FWHM → 1.2 events
- Xe: 2.5 events/kg yr FWHM → 20 events

$$\boxed{\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/\sqrt{Nt}.}$$

If *no* background

$$\boxed{\langle m_\nu \rangle \propto 1/\sqrt{T_{1/2}^{0\nu\beta\beta}} \propto 1/(Nt)^{1/4}.}$$

If background scales with *Nt*

① is essential

① without ② is a waste !

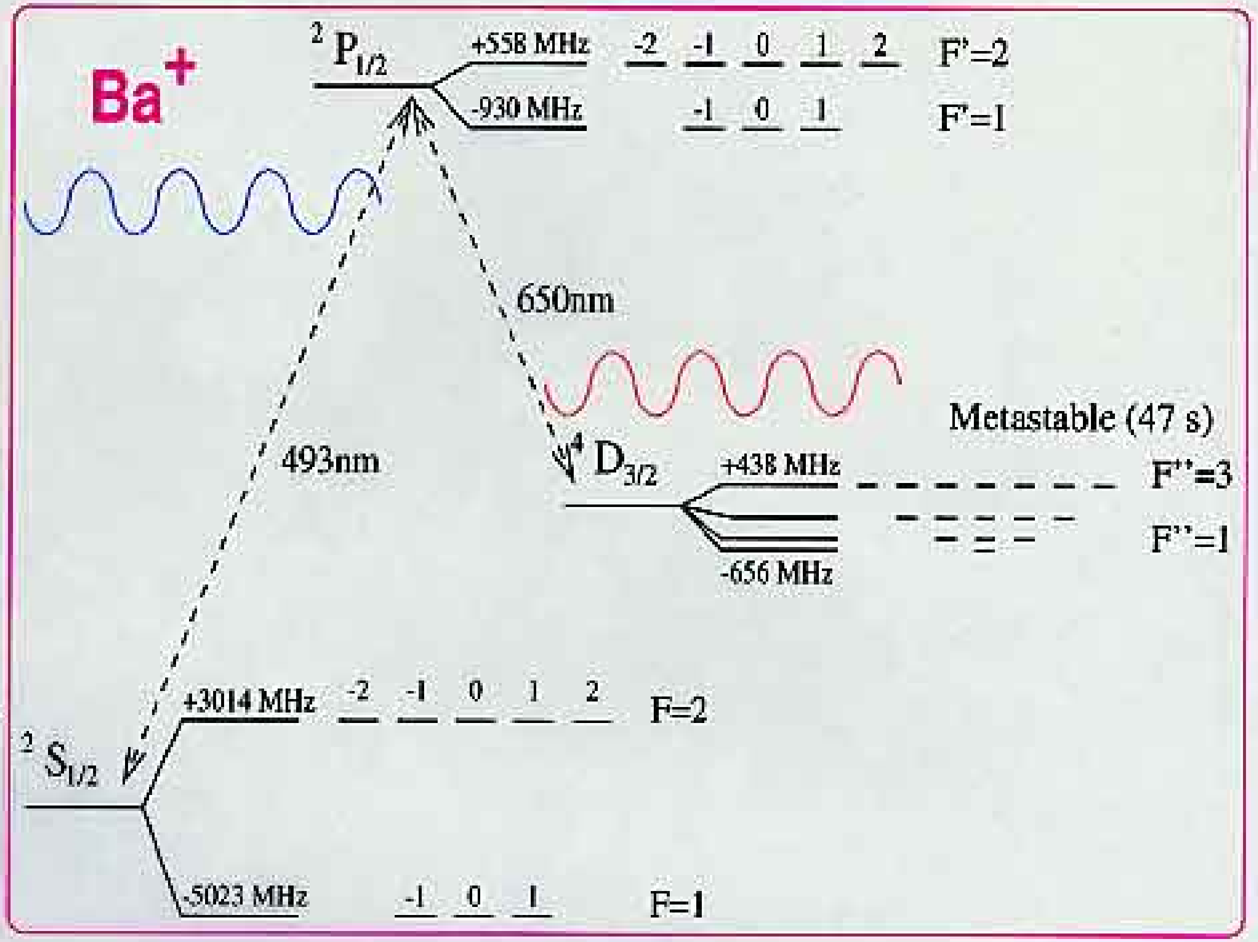
Proposed ton–size experiments

Common features:

1) Need for large amount of the source material. Typically enriched, hence costly.
2) Innovative background suppression. Hence some R&D required.
3) Plan to proceed through intermediate steps, perhaps ~100 kg. This by itself can lead to 100 – 500 meV sensitivity.
4) The ultimate goal is to reach 20–50 meV sensitivity.

Xe allows for a qualitative new tool against background

$^{136}Xe \rightarrow {}^{136}Ba^{++} e^- e^-$ final state can be identified using optical spectroscopy (M.Moe PRC44 (1991) 931)



- Important additional constraint
- Huge background reduction

Ba^+ system best studied
(Neuhauser, Hohenstatt, Toshek, Delmelt 1980)

Very specific signature "shelving"

Proposed or suggested future $0\nu\beta\beta$ experiments. The $T^{0\nu}_{1/2}$ limits are those estimated by the collaborators but scaled for 5 years of data taking. These anticipated limits should be used with caution since background assumptions are made for experiments that do not yet exist.

Experiment	Source	Detector Style	Sensitivity to $T^{0\nu}_{1/2}$ (y)
COBRA	^{130}Te	10 kg CdTe semiconductors	1×10^{24}
DCBA	^{150}Nd	20 kg ^{enr}Nd layers between tracking chambers	2×10^{25}
NEMO 3	^{100}Mo	10 kg of $\beta\beta(0\nu)$ isotope (7 kg Mo) with tracking	4×10^{24}
CAMEO	^{116}Cd	1 t $CdWO_4$ crystals in liq. scint.	$> 10^{26}$
CANDLES	^{48}Ca	several tons of CaF_2 crystals in liq. scint.	1×10^{26}
CUORE	^{130}Te	750 kg TeO_2 bolometers	2×10^{26}
EXO	^{136}Xe	1 t ^{enr}Xe TPC (gas or liquid)	8×10^{26}
GEM	^{76}Ge	1 t ^{enr}Ge diodes in liq. nitrogen	7×10^{27}
GENIUS	^{76}Ge	1 t 86% ^{enr}Ge diodes in liq. nitrogen	1×10^{28}
GSO	^{160}Gd	2 t Gd_2SiO_5:Ce crystal scint. in liq. scint.	2×10^{26}
Majorana	^{76}Ge	0.5 t 86% segmented ^{enr}Ge diodes	3×10^{27}
MOON	^{100}Mo	34 t ^{nat}Mo sheets between plastic scint.	4×10^{26}

Conclusions

- There is a good possibility that the neutrinoless $\beta\beta$ decay corresponding to $< m^{\nu}_{eff} >\sim 10$ meV really exists.
- To prove that it indeed does exist, i.e. to observe it, is of extreme physics interest.
- This can be achieved only with much larger and thus more challenging and costly experiments than those presently running.
- There is a wealth of proposals how to do it, which have to be carefully scrutinized and, if found feasible, the community should wholeheartedly support them (or at least the best of them). Many of these proposals involve old practitioners; however some are 'open' i.e. involve people with new ideas. This is going to be an international effort, very likely open to enthusiastic outsiders.

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EVIDENCE FOR NEUTRINOLESS DOUBLE BETA DECAY

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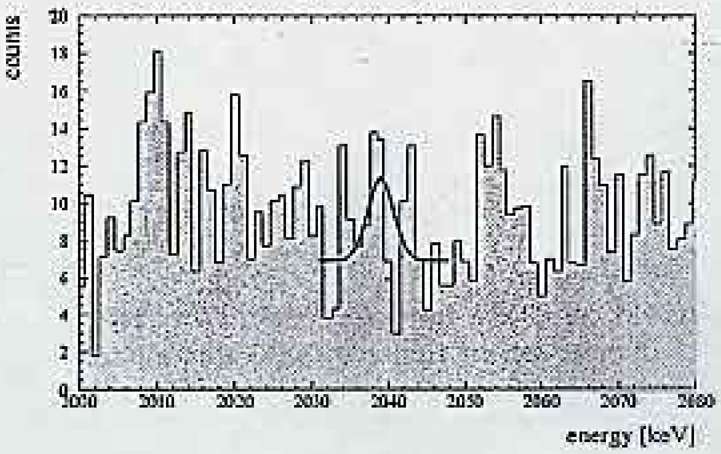
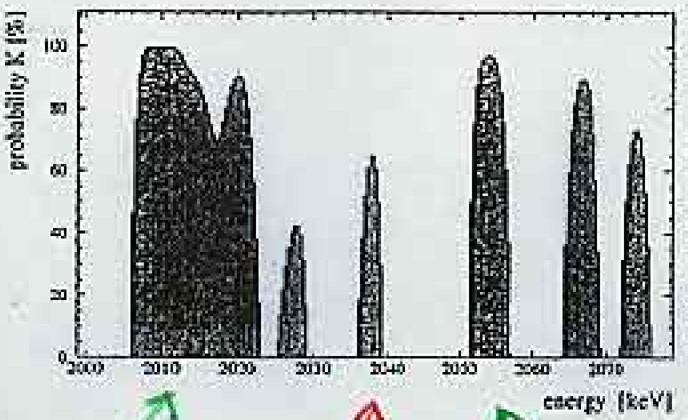
The data of the Heidelberg–Moscow double beta decay experiment for the measuring period August 1990–May 2000 (54.9813 kg y or 723.44 molyears), published recently, are analyzed using the potential of the Bayesian method for low counting rates. First evidence for neutrinoless double beta decay is observed giving first evidence for lepton number violation. The evidence for this decay mode is 97% (2.2σ) with the Bayesian method, and 99.8% c.l. (3.1σ) with the method recommended by the Particle Data Group. The half-life of the process is found with the Bayesian method to be $T_{1/2}^{0\nu} = (0.8\text{–}18.3) \times 10^{25}$ y (95% c.l.) with a best value of 1.5×10^{25} y. The deduced value of the effective neutrino mass is, with the nuclear matrix elements from Ref. 1, $\langle m \rangle = (0.11\text{–}0.56)$ eV (95% c.l.), with a best value of 0.39 eV. Uncertainties in the nuclear matrix elements may widen the range given for the effective neutrino mass by at most a factor 2. Our observation which at the same time means evidence that the neutrino is a Majorana particle, will be of fundamental importance for neutrino physics.

Keywords: Neutrino mass and mixing; weak-interaction and lepton (including neutrino) aspects; beta decay; double beta decay; electron and muon capture.

PACS Nos.: 14.60.Pq, 23.40.Bw, 23.40.-s

All data till 5/2000   55 kg y



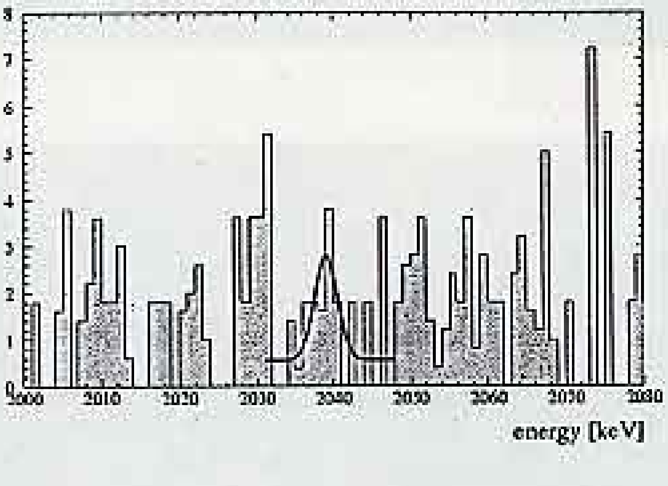


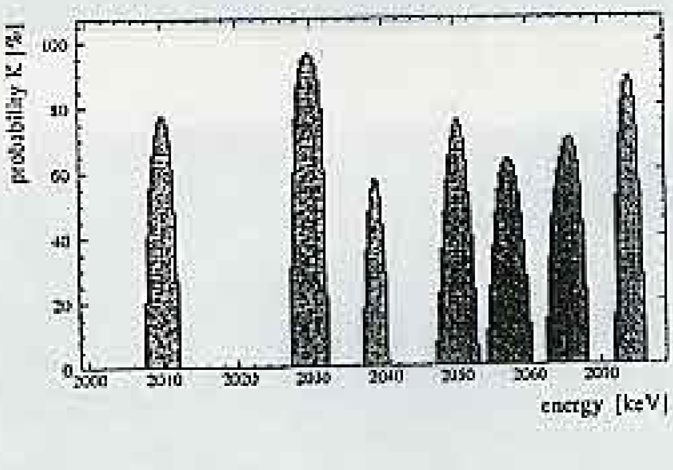
^{214}Bi
3 lines γ

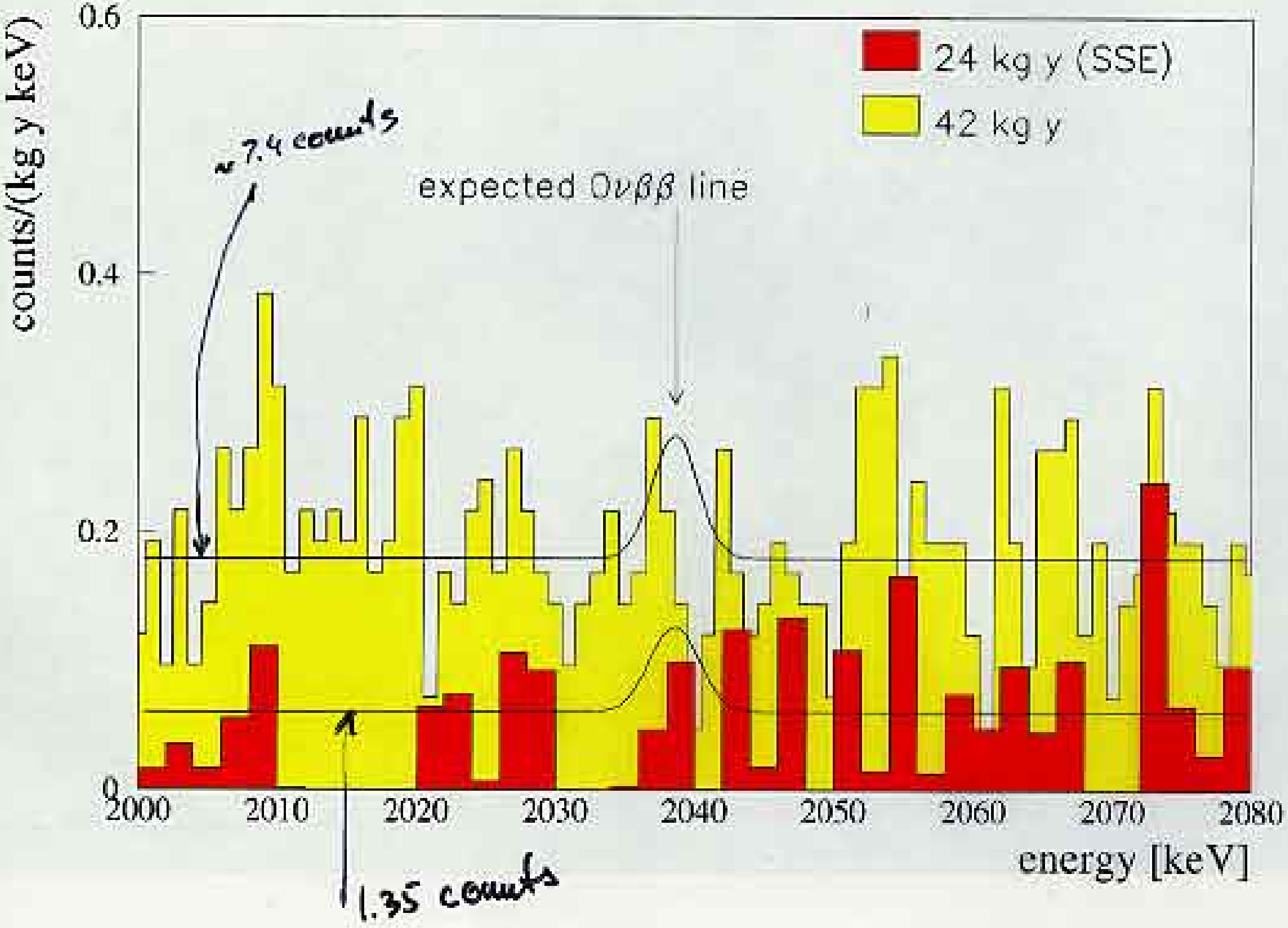
0νββ

^{214}Bi
1 line γ

Background suppressed subset   28 kg y







^{76}Ge, Heidelberg-Moscow coll.
Gran-Sasso, $T_{1/2} \geq 1.3 \times 10^{25}$ y (yellow) 90% CL
$\geq 1.6 \times 10^{25}$ y (red) 90% CL
analysis using bkg deficit $\geq 6.7 \times 10^{25}$ y