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Summer School on Particle Physics

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Neutrino at Collider - I

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"Parity restored at TeV scale?"

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Summer School on Particle Physics

ICTP — April 2011

Are we satisfied with the SM?

Gravity? [Dvali]

Dark Matter? [Weiner]

The Higgs? Hierarchy? [Dvali]

SM aestetically *incomplete* [Bajc]

Accidental symmetries, $\not B$, $\not L$? [Bajc]

Can we have new physics at collider? [Tarantino]

Neutrino masses are new physics [Marciano]

Dirac or Majorana?

Low scale?

- Key questions: which symmetry? at which scale?

Outline

New physics - SM already needs extension

- Neutrino mass
  Majorana - Dirac - generic
- Consequences
  $0\nu\beta\beta$
  versus Cosmology?
  New physics at TeV?

Beyond SM

- Further hints from Quantum Numbers
- Let's restore Parity, Left-Right at TeV scale
- Constraints
- Back to $0\nu\beta\beta$
  typeII example
- LNV @ Collider
  Signals
- Outlook

Neutrino have mass

[see lectures by Marciano]

From oscillations we know their mass differences

$$m_2^2 - m_1^2 = 7.6\times10^{-5}\,\text{eV}^2$$

$$|m_3^2 - m_2^2| = 2.4\times10^{-3}\,\text{eV}^2$$

and mixing angles, $\theta_{12} = 35^\circ \pm 4^\circ$, $\theta_{23} = 45^\circ \pm 8^\circ$, $\theta_{13} < 13^\circ$.

From oscillations we don't know:

- The absolute neutrino mass scale
  (direct searches, cosmology: $m_{1,2,3} < 1\,eV$)
- The mass hierarchy
  (normal $m_1 < m_2 < m_3$ or inverted $m_3 < m_1 < m_2$?)
- Dirac or Majorana
  ($\nu \not\equiv \nu^c$ or $\nu \equiv \nu^c$ [Majorana '37])

Theory?

What about theory?

In the SM:

- Lepton Number conserved. (also *family* L_e, L_μ, L_τ separately!)
- Only left neutrinos, there is no renormalizable mass term.
- Effective theory: a $D = 5$ nonrenormalizable operator?

BSM:

- Or new states.
- Question: is it low or high scale physics?
- Physical consequences.

Neutrino masses

- Dirac mass ($\Delta L = 0$) – need Right-Handed neutrino ν_R

$$M_D \overline{\nu_R} \nu_L + h.c. \equiv M_D \nu_R^{ct} C \nu_L \to M_D \nu^*_{R\,\dot\alpha} \nu_{L\,\beta}\, \delta^{\dot\alpha\beta} + h.c.\,.$$

M_D generic complex.

Generated with familiar Yukawa term, $y_D\, H\, \bar\ell_L \nu_R$.

- Majorana mass ($\Delta L = 2$)

$$M_L \overline{(\nu_L^c)} \nu_L + h.c. \equiv M_L \nu_L^t C \nu_L \to M_L \nu_{L\,\alpha} \nu_{L\,\beta}\, \epsilon^{\alpha\beta} + h.c.\,.$$

M_L symmetric!

Breaks total lepton number L. (as *family* ones, L_e, L_μ, L_τ.)

Generated only as effective operator, $\frac{\lambda}{M}(\ell H)(H\ell)$.

[Mohapatra, Pal, "Massive neutrinos in physics and astrophysics"]

[Denner et al, "Compact Feynman rules for Majorana fermions", PLB291]

[Dreiner, Haber, Martin, "Feynman Rules using two-component spinor notation"]

Seesaw (type-I)

Once present, the singlet ν_R can have renormalizable Majorana mass. So,

$$\begin{pmatrix}\nu_L & \nu_R^c\end{pmatrix}\begin{pmatrix}0 & M_D^t \\ M_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L \\ \nu_R^c\end{pmatrix}.$$

- Seesaw: if $M_R \gg M_D$, the mass matrix is $\begin{pmatrix}M_\nu & 0 \\ 0 & M_N\end{pmatrix}$,

$$M_\nu \simeq -M_D^t M_R^{-1} M_D\,, \qquad M_\nu \simeq M_R\,,$$

M_R large $\Rightarrow M_\nu$ small.

(eigenstates: light Majorana and heavy Majorana)

[Minkowski '77, Mohapatra Senjanović '79, GRS '79, Glashow '79; Yanagida '79]

But what can M_D and M_R be?

Seesaw (type-I) - at which scale?

Scales m_D, m_R quite free... (yukawa perturbativity, $M_D < 500\text{GeV}$)

Some scenarios using $m_\nu = m_D^2/m_R \lesssim 1\, eV$ ignoring mixings

- $m_D \sim 100\,\text{GeV}$ – (like heavy quarks?)

  $$m_D^2/m_\nu = m_R \gtrsim 10^{13\div 15}\,\text{GeV}\,, \qquad \text{High scale physics}$$

  Fits with GUT scenario, releted to $\not{B}$?, ... [Bajc lectures]

- $m_D \lesssim \text{MeV}$ – Now one can have much lower m_R:

  $$m_D^2/m_\nu = m_R \lesssim \text{TeV}\,, \qquad \text{Collider scale}$$

  More interesting:

  m_R associated to physical states: observable (see later)

Seesaw-I not the only possibility...

Seesaw (type-II)

- In a $SU(2)\times U(1)_Y$ theory, the lepton doublet ℓ can couple also with a triplet scalar field $\Delta_L \in (\mathbf{3}, 1)$:

$$\mathcal{L}_{y_\Delta} = Y_\Delta \ell_L^t \tau_2 \Delta_L \ell_L$$

with symmetric Y_Δ. In components

$$\Delta_L = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

- If it has a (neutral!) VEV $\langle \delta^0 \rangle = v_L$, it generates a neutrino Majorana mass $M_L \nu_L^t \nu_L$, with

$$M_L = Y_\Delta v_L \,.$$

- The triplet couples to Higgs, $m_\Delta^2 \Delta^2 + m_\Delta H \Delta H$. $\qquad (m_\Delta \gg v)$
So it has a naturally small VEV, $v_L \sim v^2/m_\Delta$.

$$M_\nu \sim Y_\Delta v^2/m_\Delta$$

Again, large $m_\Delta \to$ small M_L. [Magg, Wetterich, PLB '80]

Masses, general

Seesaw type-I plus type-II lead to the general scenario:

$$\begin{pmatrix}\nu_L & \nu_R^c\end{pmatrix}\begin{pmatrix}M_L & M_D^t \\ M_D & M_R\end{pmatrix}\begin{pmatrix}\nu_L \\ \nu_R^c\end{pmatrix}.$$

with M_L, $M_D \ll M_R$.

- Eliminating the M_D mixing, one gets $\begin{pmatrix}M_\nu & 0 \\ 0 & M_N\end{pmatrix}$, with

$$M_\nu \simeq M_L - M_D^t \frac{1}{M_R} M_D\,, \qquad M_N \simeq M_R\,.$$

- Note, now that there can be cancelations to get light M_ν.

  And there can be cancelations also inside $M_D^t M_R^{-1} M_D$.

  (see Casas-Ibarra parametrization of M_D)

Masses, diagonalization

Now, as for quarks, mass eigenstates are not flavour ones.
Charged leptons-neutrino mismatch enters Left charged current.

$$\begin{aligned} M_e &= V_{eL}\, m_e V_{eR}^\dagger \\ M_\nu &= V_{\nu L}\, m_\nu V_{\nu R}^\dagger \end{aligned} \quad , \quad U_{PMNS} = V_{eL}^\dagger V_{\nu L} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} =$$

$$= \begin{bmatrix} e^{i\alpha_e} & 0 & 0 \\ 0 & e^{i\alpha_\mu} & 0 \\ 0 & 0 & e^{i\alpha_\tau} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{bmatrix}$$

- Dirac mass, generic complex $\quad V_{\nu L} \neq V_{\nu R}$
  so 5 external phases irrelevant.
  (Kinetic, current and masses respect $U(1)_{L_x}$!)
  Only $\not{C}P$ from the 'Dirac' phase, as in CKM (U_{e3} suppressed).

- Majorana mass, complex symmetric $\quad V_{\nu R} \equiv V_{\nu L}^*$
  Now the two phases α_1 and α_2 can not be removed!
  (i.e. Majorana mass breaks lepton numbers!)
  These phases however appear only in LNV processes.

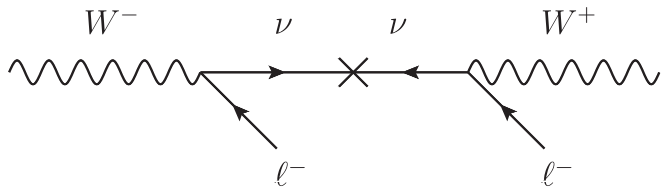
Neutrino - up to now

What we saw:

- Neutrino have masses (Dirac or Majorana)
- Need extension of the SM.
- Add heavy ν_R $\longrightarrow$ seesaw-I.
- Add heavy Δ_L $\longrightarrow$ seesaw-II.
- Majorana violates Lepton number by two units
- Two extra 'Majorana' CP phases in the mixing matrix U_{PMNS}.

let's look at consequences. . .

Lepton number violation, consequences

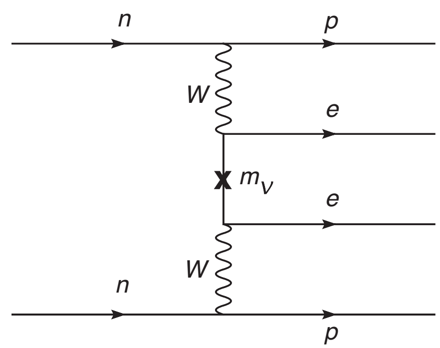


- Nuclear neutrinoless double beta decay:

  $${}^A_Z X \to {}_{Z+2}{}^A X + 2e^-$$

  $\ldots \tau_{0\nu\beta\beta} \gtrsim 10^{24} y$, but testable!

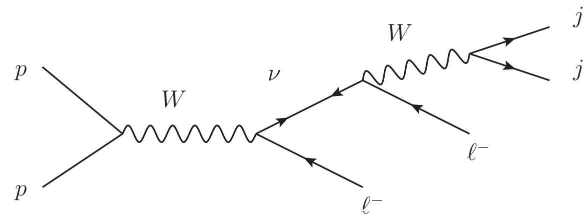
  (and double electron nuclear capture,
  ${}^A_Z X + 2e^- \to {}_{Z-2}{}^A X$, etc.)



[Racah, Nuovo Cim. '37]

- Collider: same sign dileptons:

  Very small for standard W...



[Keung Senjanović '83]

- Meson neutrinoless double beta decay, e.g. $K^+ \to \pi^- \ell^+ \ell^+$
  $BR < 10^{-20}$, much less than current limits, $BR \lesssim 10^{-10}$

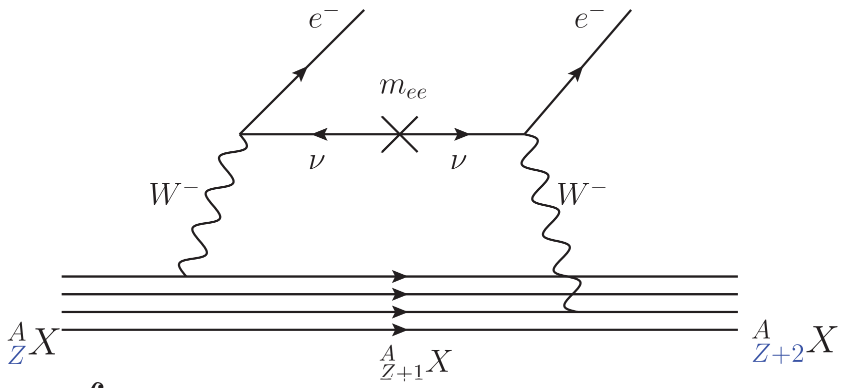
[Littenberg Schrok, '92]

$0\nu\beta\beta$

Neutrinoless double beta decay $0\nu\beta\beta$

- Actually a loop process:
  Neutrino $p \sim 100\,\text{MeV}$
  Released $Q \sim 3\,\text{MeV}$.

  Decay width:
  $\Gamma_{0\nu} = G(Q)\,|\mathcal{M}|^2$
  [phase space] [amplitude]



- The amplitude is $\mathcal{M} = 8 G_F^2 \int d^4x d^4y J^\mu_{had}(x) J^\nu_{had}(y)\, L_{\mu\nu}(x,y)$
  where the leptonic tensor is (in momentum space)

$$L_{\mu\nu} = \bar{e}\,\gamma_\mu L \left[\frac{\not p + M_\nu}{p^2 - M_\nu^2}\right]_{ee} \gamma_\nu R\, e^c$$

- LNV explicitly related to Majorana neutrino masses.
  Light neutrinos ($M_\nu \ll p \sim 100\,\text{MeV}$) give

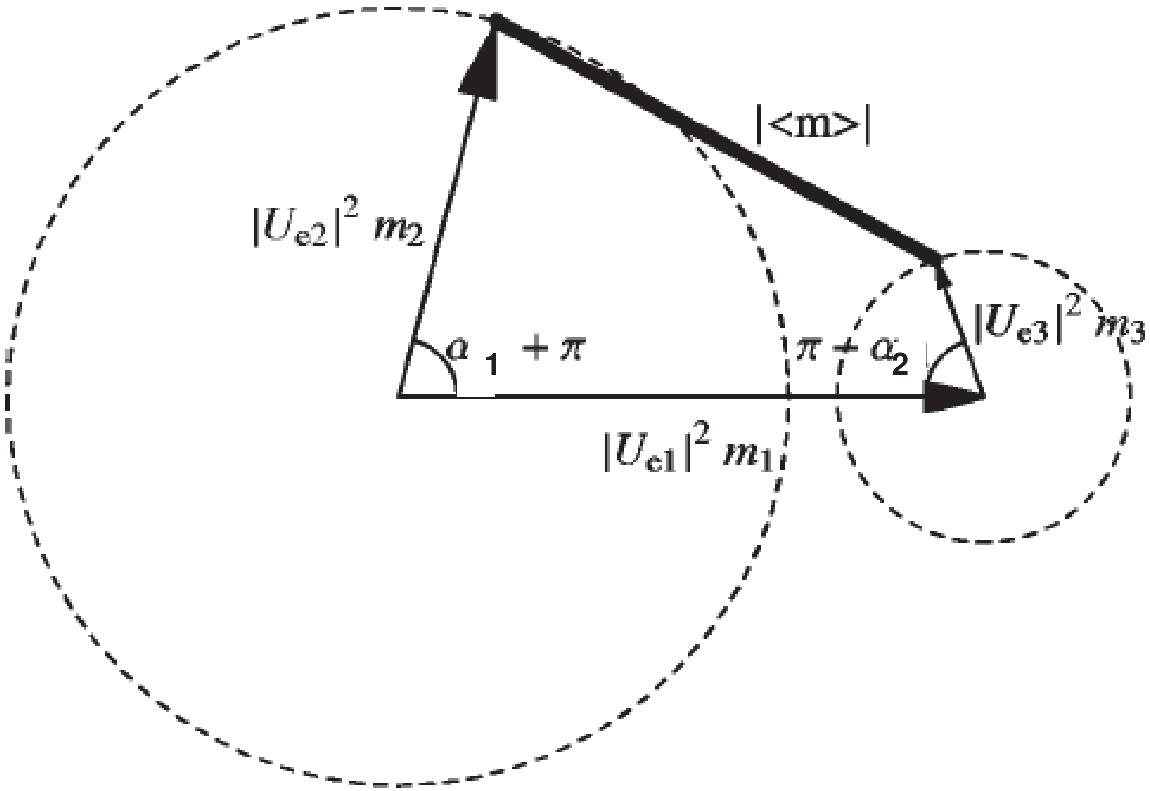
$$L_{\mu\nu} \propto M_\nu^{ee} \frac{1}{p^2}$$

$0\nu\beta\beta$ cont'd

Strenght of LNV in $0\nu\beta\beta$, from standard light neutrinos:

$$M_\nu^{ee} = \sum U_{ei}^2 m_i = m_1|U_{e1}^2| + m_2|U_{e2}^2|e^{i\alpha_1} + m_3|U_{e3}^2|e^{i\alpha_2}$$

- So, from oscillations, $|U_{e1}^2| \sim 0.6$, $|U_{e2}^2| \sim 0.25$, $|U_{e3}^2| < 0.04$, ... Majorana phases important and there can be a cancelation!



$0\nu\beta\beta$ cont'd

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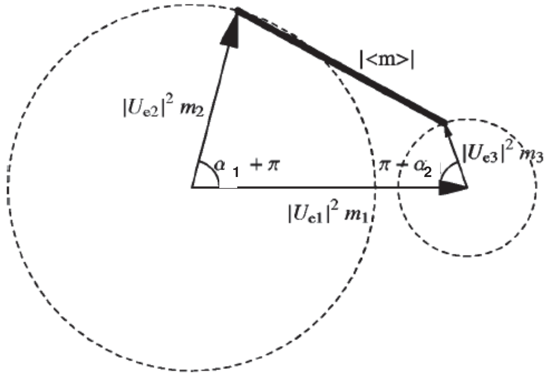
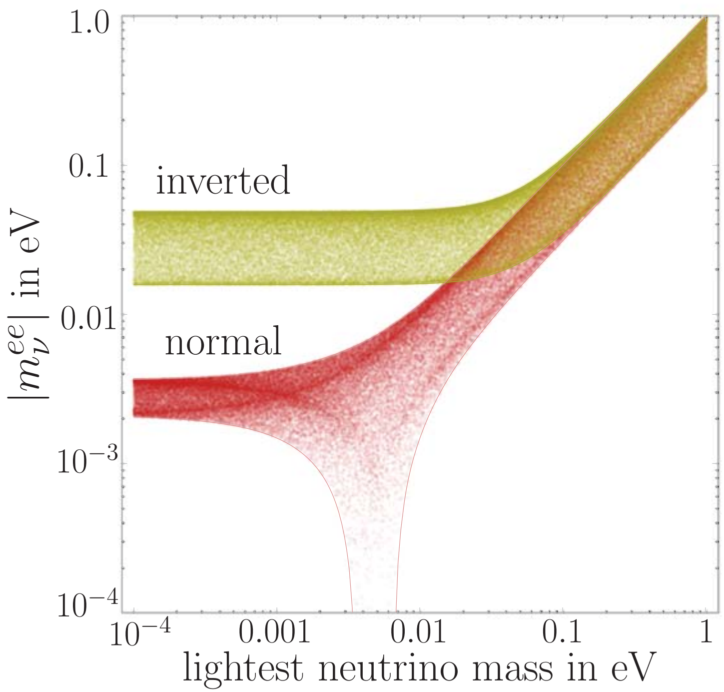




- Possible $0\nu\beta\beta$, as a function of lightest neutrino mass:

[Vissani '02]

Can distinguish the hierarchy. And the absolute mass.

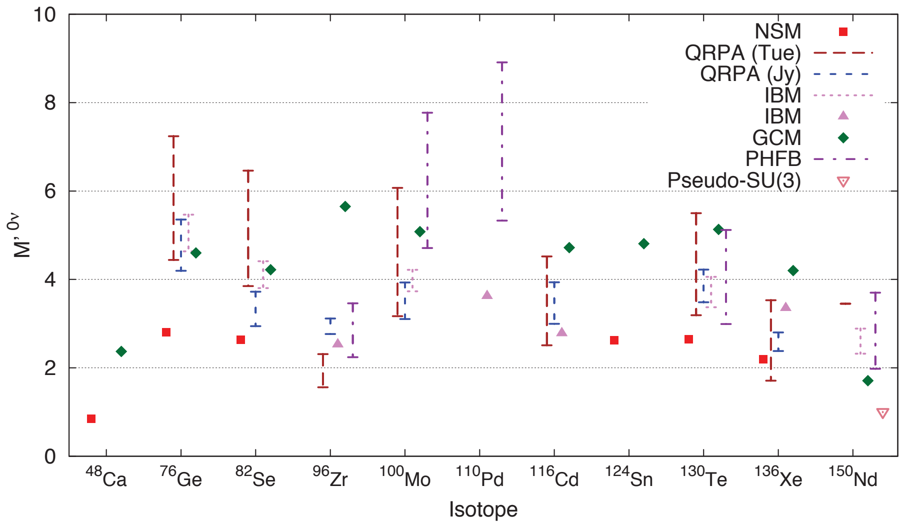
$0\nu\beta\beta$, matrix elements

Neutrino propagator, i.e. $1/r$ for light e^{-mr}/r for heavy neutrino.

- Well approximated by its typical momentum $p \sim 100 \div 200\,\text{MeV}$. Both for light or heavy neutrino exchange (no core suppression)

$$\left\langle \frac{m_\nu}{p^2} \right\rangle_{nuc} \simeq \frac{m_\nu}{p^2}, \qquad \left\langle \frac{1}{m_N} \right\rangle_{nuc} \sim \frac{1}{m_N}$$

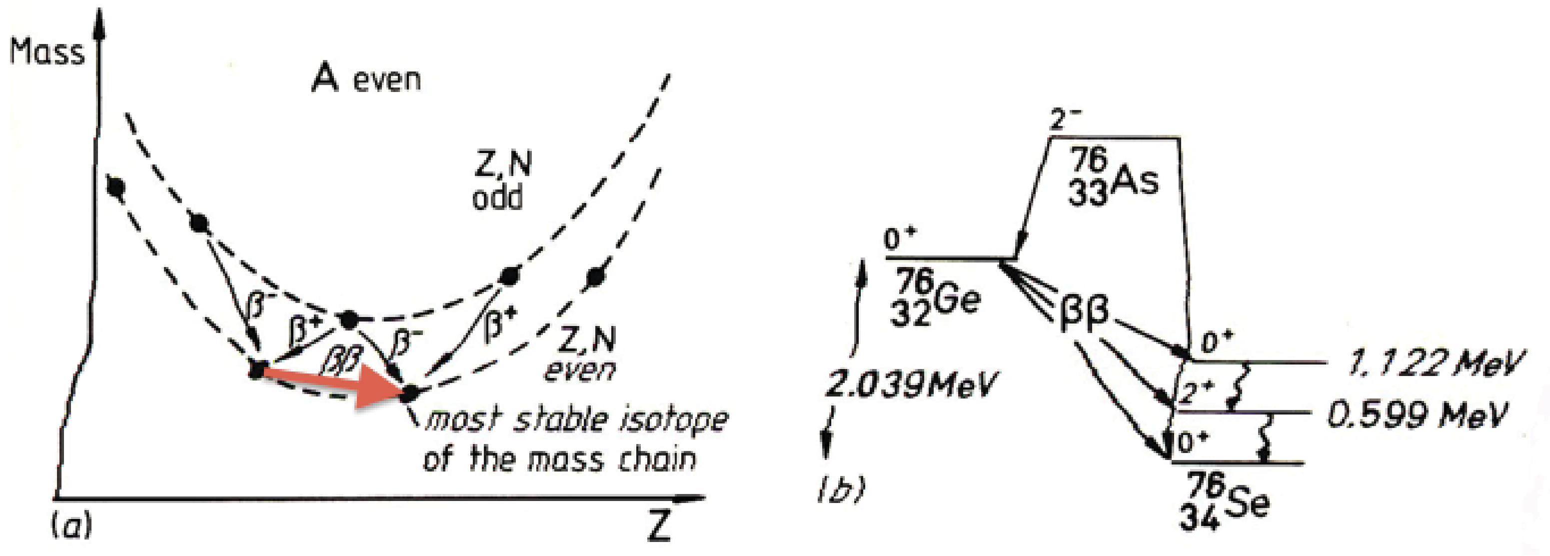
- Real calculation, w/ nuclear models, uncertain by a factor of 20–100–200%



Neutrinoless double beta decay, cont'd

Need to avoid the much more favored single beta decay.

- In some nuclei β-decay is forbidden! [Bethe-Weizsäcker formula]

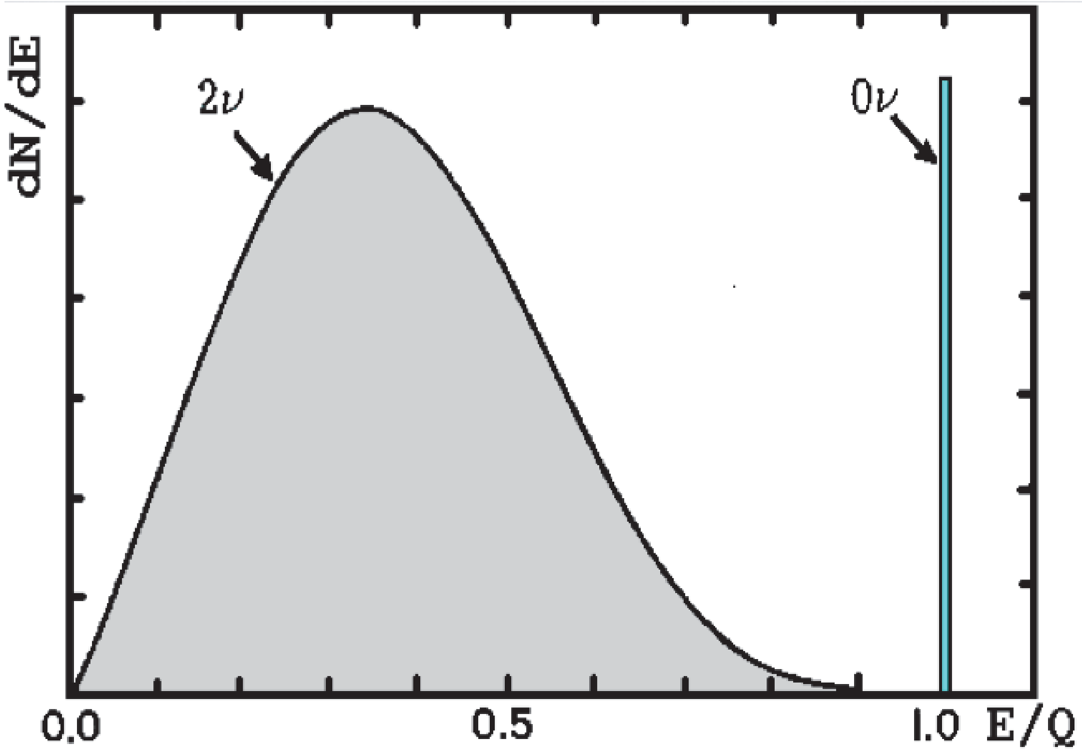


- Now, $\beta\beta$ can proceed through both $2\nu\beta\beta$, or $0\nu\beta\beta$..

How to distinguish them? – We don't detect neutrinos.

Neutrinoless double beta decay, cont'd

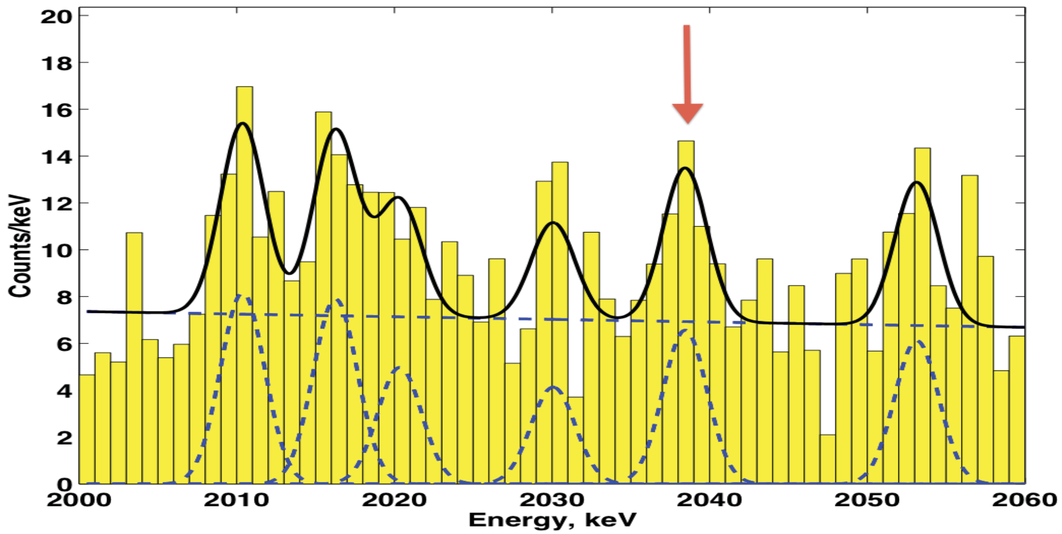
- Recognized by the spectrum of electrons



- In real life, the line is not *so* definite. . .

Neutrinoless double beta decay, evidence

- Heidelberg-Moscow experiment...



...claim of observation (!)[Klapdor-Kleingrothaus+, PLB '04, MPL '06, '10]

$$\tau_{0\nu} \sim 2.2\times 10^{25} y \qquad (6\sigma\ldots)$$

- This is conservatively translated into

$$m_\nu^{ee} \simeq (0.4 \pm 0.2)\,\text{eV}$$

If true, evidence of Majorana...

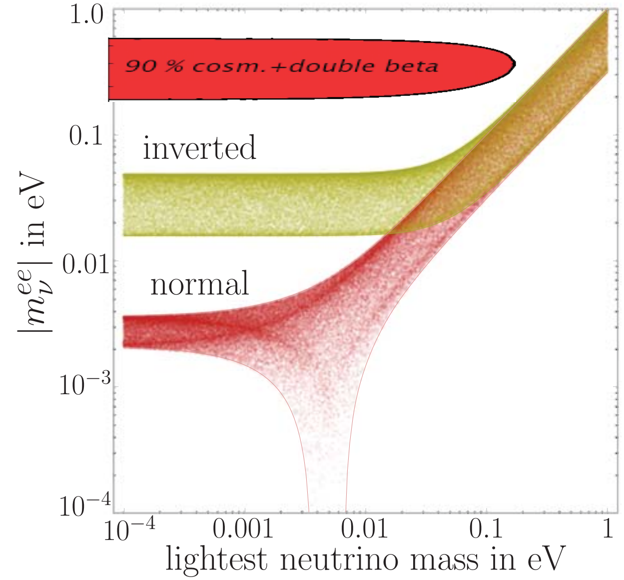
Experiments ongoing!

Experiment	Isotope	Mass of Isotope [kg]	Sensitivity $T^{0\nu}_{1/2}$ [yrs]	Sensitivity $\langle m_\nu \rangle$, meV	Status	Start
GERDA	^{76}Ge	18	3×10^{25}	$\sim$ 200	running!	2011
		40	2×10^{26}	$\sim$ 70	in progress	$\sim$ 2012
		1000	6×10^{27}	10-40	R&D	$\sim$ 2015
CUORE	^{130}Te	200	$(6.5 \div 2.1) \times 10^{26}$	20-90	in progress	$\sim$ 2013
MAJORANA	^{76}Ge	30-60	$(1 \div 2) \times 10^{26}$	70-200	in progress	$\sim$ 2013
		1000	6×10^{27}	10-40	R&D	$\sim$ 2015
EXO	^{136}Xe	200	6.4×10^{25}	100-200	in progress	$\sim$ 2011
		1000	8×10^{26}	30-60	R&D	$\sim$ 2015
SuperNEMO	^{82}Se	100-200	$(1 - 2) \times 10^{26}$	40-100	R&D	$\sim$ 2013-2015
KamLAND-Zen	^{136}Xe	400	4×10^{26}	40-80	in progress	$\sim$ 2011
		1000	10^{27}	25-50	R&D	$\sim$ 2013-2015
SNO+	^{150}Nd	56	4.5×10^{24}	100-300	in progress	$\sim$ 2012
		500	3×10^{25}	40-120	R&D	$\sim$ 2015

For a recent review [Rodejohann, arXiv:1106.1334]

Stay tuned

Future clash with cosmology?



- Cosmology, limits on absolute scale (WMAP-7, SDSS, HST)

  $\sum m_\nu \lesssim 0.4 \div 1\,\text{eV}$ [WMAP 95% C.L.]

  $\sum m_\nu \lesssim 0.17\,\text{eV}$ [Seljak, Slosar, Mcdonald 06]

  $\sum m_\nu \lesssim 0.44 \div 1\,\text{eV}$ [Hannestad+ '08, Hamann+ '10]

...shrinking toward incompatibility with evidences of $0\nu\beta\beta$...

...in this case, need new physics beyond light neutrinos!

New Physics - where? when?

If m_ν^{ee} excluded by cosmology, can new Physics do the job?

Try to guess at the level of effective operators...

- The 'New Physics' operator is dimension 9

$$O_{NP} = \lambda \frac{nnppee}{\Lambda^5}$$

- Require new physics amplitude to saturate $m_\nu^{ee} \sim eV$

$$A_{0\nu}^{NP} = \frac{\lambda}{\Lambda^5} \qquad \leftrightarrow \qquad A_{0\nu}^{m_\nu} = G_F^2 \frac{m_\nu}{p^2}$$

Result, the amplitudes are comparable for (say $\lambda \sim G_F^2 M_W^4$)

$$\Lambda \sim TeV.$$

...something would be expected at collider.

Neutrino, recap

- Neutrino have mass
- Majorana? ($\not{L}$, and possible $0\nu\beta\beta$).
- Possibly an effective operator: (not telling us the origin)

$$\frac{\lambda}{M}(\ell H)^t(H\ell)\,,$$

[Weinberg '79]

- Realizations, e.g. type-I seesaw: (y and M quite free)

$$y\,\bar{\ell}H\nu_R + M\nu_R^t\nu_R$$

- $0\nu\beta\beta$ probes, may require new physics beyond neutrino, at TeV.
- So. . . maybe TeV M hints to something? New interactions?
  . . . e.g.: M breaks lepton number, $B-L$, ...
- Maybe we can test a low M and new forces at LHC?
  (Yes, because of $\not{L}$ at collider.)

Hints from quantum numbers. . .
Tomorrow.