KSETA topical courses

Neutrino physics III: Neutrino Mass

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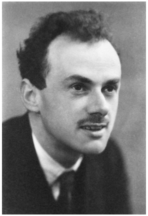
Karlsruhe, 7-8 Oct 2020

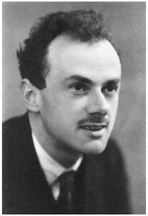
Neutrinos oscillate...



... and have mass $\Rightarrow$ physics beyond the Standard Model

- Lecture I: Neutrino Oscillations
- Lecture II: Neutrinos in Cosmology
- Lecture III: Neutrino mass - Dirac versus Majorana
- Lecture IV: Neutrinos and physics beyond the Standard Model

Neutrinos oscillate...



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Outline

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Absolute neutrino mass

Beta decay – the KATRIN experiment

Neutrinoless double-beta decay

Fermion masses

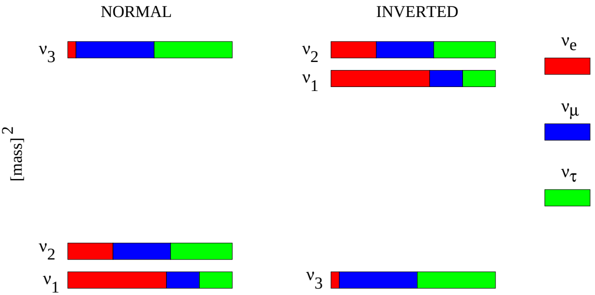
Dirac mass

Majorana mass

Dirac versus Majorana neutrinos in the SM

The Standard Model and neutrino mass

- neutrino oscillations only determine Δm^2_{ij}
- absolute mass scale is not constrained



Absolute neutrino mass

Three ways to measure absolute neutrino mass:

- Cosmology
  (with caveats: cosmological model/data selection)
- Endpoint of beta spectrum: $^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$
  (experimentally challenging $\to$ KATRIN)
- Neutrinoless double beta-decay: $(A, Z) \to (A, Z+2) + 2e^-$
  (with caveats: lepton number violation)

Absolute neutrino mass

Three ways to measure absolute neutrino mass:
sensitive to different quantities

- Cosmology
  (with caveats: cosmological model/data selection)
  $\sum_i m_i$
- Endpoint of beta spectrum: ${}^3\text{H} \to {}^3\text{He} + e^- + \bar{\nu}_e$
  (experimentally challenging $\to$ KATRIN)
  $m_\beta^2 = \sum_i |U_{ei}^2| m_i^2$
- Neutrinoless double beta-decay: $(A, Z) \to (A, Z+2) + 2e^-$
  (with caveats: lepton number violation)
  $m_{ee} = |\sum_i U_{ei}^2 m_i|$

Beta decay

$$N(A,Z) \to N(A,Z+1) + e^- + \bar{\nu}_e$$

$$\frac{d\Gamma}{dE_e} = \frac{G_F^2 m_e^5}{2\pi^2} \cos\theta_c |\mathcal{M}|^2 F(Z,E_e) \underbrace{E_e p_e E_\nu p_\nu}_{\text{phase space}}$$

Tritium decay: ${}^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \bar{\nu}_e$

$$\begin{aligned}
M_{^3\mathrm{H}} &= 2.808\,920\,8205 \times 10^6\,\mathrm{keV} \\
M_{^3\mathrm{He}} &= 2.808\,391\,2193 \times 10^6\,\mathrm{keV} \\
m_e &= 510.9989\,\mathrm{keV} \\
Q &\equiv M_{^3\mathrm{H}} - M_{^3\mathrm{He}} - m_e = 18.6023\,\mathrm{keV} \ll M_{^3\mathrm{H}}, M_{^3\mathrm{He}} \\
\kappa &\equiv M_{^3\mathrm{He}}/M_{^3\mathrm{H}} = 1 - 1.89 \times 10^{-4}
\end{aligned}$$

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Tritium beta decay

use E-momentum conservation, calculate electron kin. energy:

$$T \equiv E_e - m_e = \frac{1}{2M_{^3\mathrm{H}}}\left[(M_{^3\mathrm{H}} - m_e)^2 - M^2_{^3\mathrm{He}} - 2M_{^3\mathrm{He}}E_\nu\right]$$

T has a maximum when E_ν has a minimum:

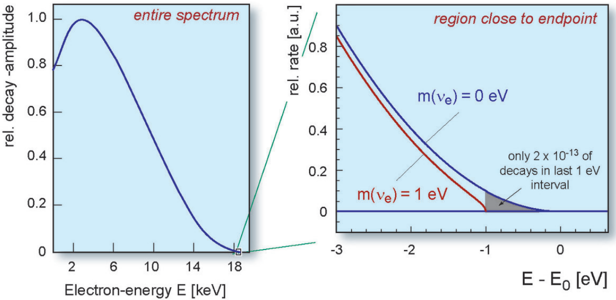
$$\begin{aligned} m_\nu = 0: \quad T_{max,0} &= \tfrac{1}{2M_{^3\mathrm{H}}}\left[(M_{^3\mathrm{H}} - m_e)^2 - M^2_{^3\mathrm{He}}\right] \\ &= Q - \tfrac{(M_{^3\mathrm{H}} - M_{^3\mathrm{He}})^2}{2M_{^3\mathrm{H}}} \approx Q - 3.4\,\mathrm{eV} \\ m_\nu > 0: \quad T_{max} &= T_{max,0} - \kappa m_\nu \end{aligned}$$

$\Rightarrow$ finite neutrino mass leads to a shift in electron spectrum endpoint

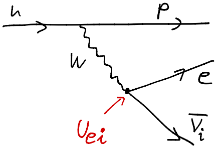
Tritium decay spectrum close to the endpoint

phase space factor: $E_\nu p_\nu = E_\nu \sqrt{E_\nu^2 - m_\nu^2}$, use $E_\nu \approx \frac{M_{^3\mathrm{H}}}{M_{^3\mathrm{He}}}(T_{max,0} - T)$:

$$\frac{d\Gamma}{dT} \propto (T_{max,0} - T)\sqrt{(T_{max,0} - T)^2 - \kappa^2 m_\nu^2}$$



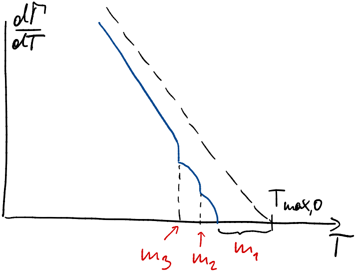
Take into account neutrino mixing



incoherent sum of individual mass states:

$$\frac{d\Gamma}{dT} = \sum_i |U_{ei}|^2 \frac{d\Gamma_i}{dT}$$

$$\propto (T_{max,0} - T) \sum_i |U_{ei}|^2 \sqrt{(T_{max,0} - T)^2 - \kappa^2 m_i^2}$$

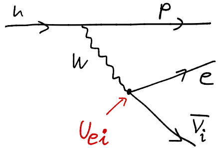


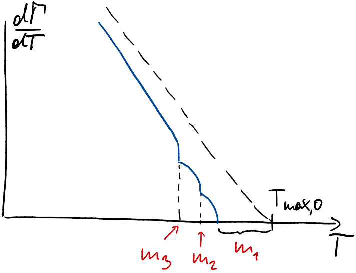
for $T_{max,0} - T \gg \Delta m$:

$$\frac{d\Gamma}{dT} \approx (T_{max,0} - T) \sqrt{(T_{max,0} - T)^2 - \kappa^2 m_\beta^2}$$

$$m_\beta^2 \equiv \sum_i |U_{ei}|^2 m_i^2$$

Take into account neutrino mixing





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$$m_\beta^2 \equiv \sum_i |U_{ei}|^2 m_i^2$$

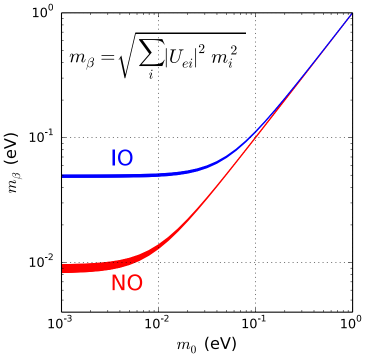
The effective mass

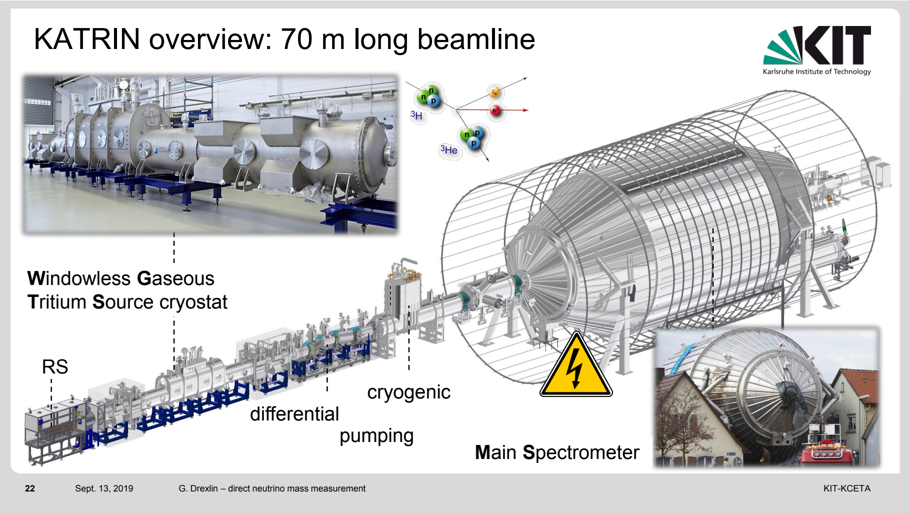
$$m_\beta^2 \equiv \sum_i |U_{ei}|^2 m_i^2 \approx \begin{cases} m_0^2 + |U_{e2}|^2 \Delta m_{21}^2 + |U_{e3}|^2 \Delta m_{31}^2 & \text{(NO)} \\ m_0^2 + (1 - |U_{e3}|^2)|\Delta m_{31}^2| & \text{(IO)} \end{cases}$$

minimum values for $m_0 = 0$:

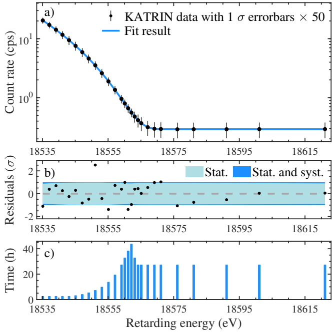
$$m_\beta^{\text{min}} \approx \begin{cases} 9\,\text{meV} & \text{(NO)} \\ 50\,\text{meV} & \text{(IO)} \end{cases}$$

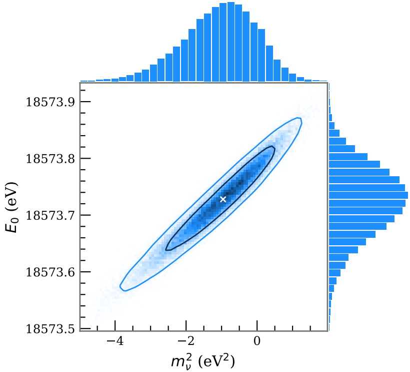
for $m_0 \gg |\Delta m_{31}^2|$: $m_\beta \approx m_0$




KATRIN overview: 70 m long beamline
Karlsruhe Institute of Technology
³H
³He
Windowless Gaseous
Tritium Source cryostat
RS
differential
pumping
cryogenic
Main Spectrometer
22
Sept. 13, 2019
G. Drexlin – direct neutrino mass measurement
KIT-KCETA

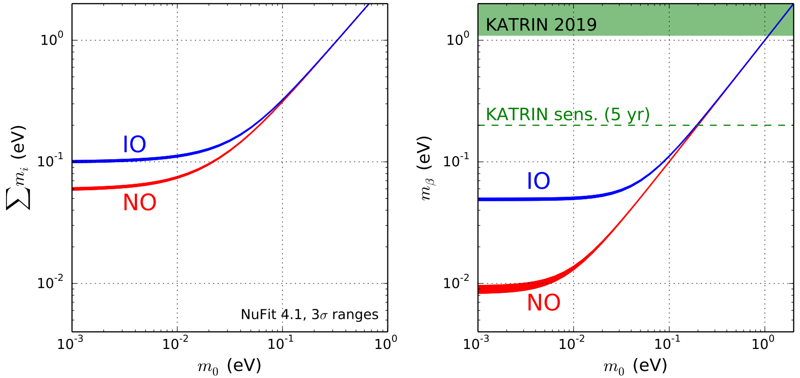
KATRIN 2019 Aker et al., 1909.06048



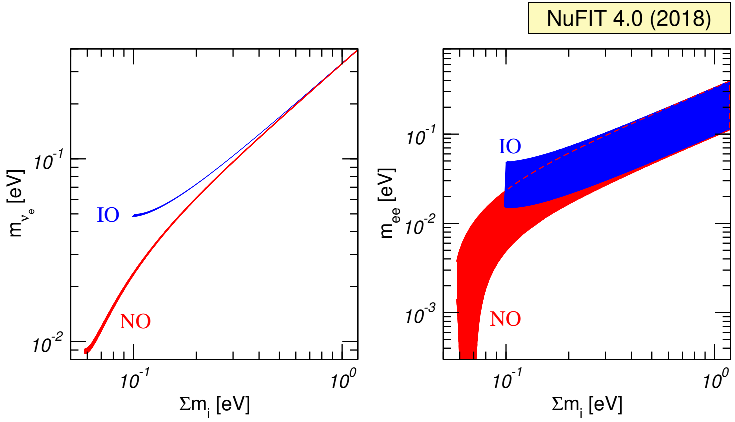


$$m_\beta^2 = -1.0^{+0.9}_{-1.1}\,\mathrm{eV}^2 \qquad m_\beta < 1.1\,\mathrm{eV}\,(90\%\,\mathrm{CL})$$

Cosmology and β decay observables



Absolute neutrino mass



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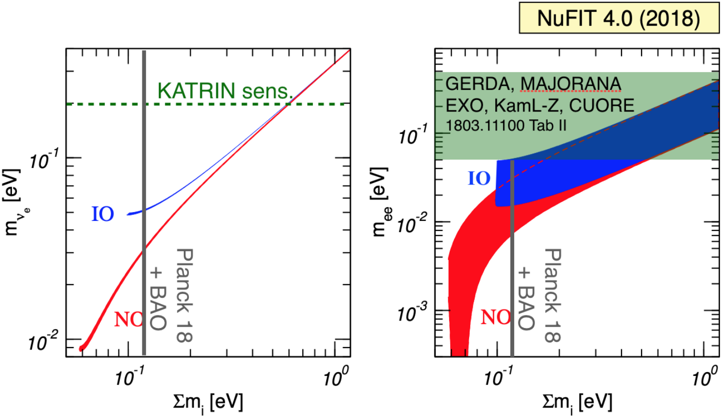

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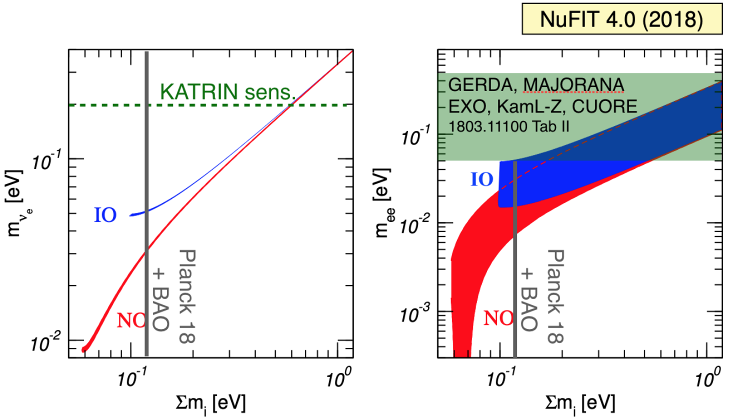


relies on standard three-flavour scenario and standard cosmology

Any inconsistency would indicate new physics beyond 3 flavour neutrino mass!

Relaxing the neutrino mass bound with neutrino decay

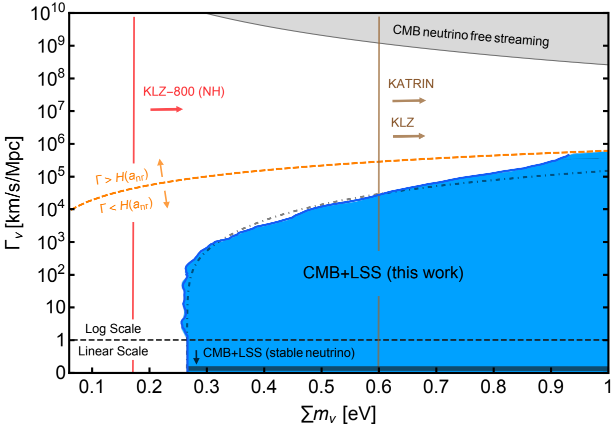
Chacko, Dev, Du, Poulin, Tsai,
1909.05275, 2002.08401

assume neutrino decay:

$$\nu_i \to \nu_4 \phi$$

with $i = 1, 2, 3$ and
$m_4, m_\phi = 0$

decay rate: Γ_ν



see also Escudero,Fairbairn,1907.05425; Escudero,Lopez-Pavon,Rius,Sandner,2007.04994

Neutrinoless double-beta decay

2-neutrino double-beta decay: $(A, Z) \to (A, Z+2) + 2e^- + 2\bar{\nu}_e$

- 2nd order in G_F
- only observable if single beta decay forbidden
- 35 natural isotopes are known (all even-even nuclei)
- $T^{2\nu}_{1/2} \sim 10^{18} - 10^{20}$ yr ($\gg t_{\text{Universe}}$)

neutrinoless double-beta decay: $(A, Z) \to (A, Z+2) + 2e^-$

- no neutrinos emitted
- violation of lepton number by two units
- sum of electron kinetic energies $T = T_1 + T_2 = Q_{2\beta} = M_i - M_f - 2m_e$
- Examples: ${}^{76}\text{Ge} \to {}^{76}\text{Se}$ $\quad Q_{2\beta} = 2.039$ MeV
  ${}^{136}\text{Xe} \to {}^{136}\text{Ba}$ $\quad Q_{2\beta} = 2.468$ MeV

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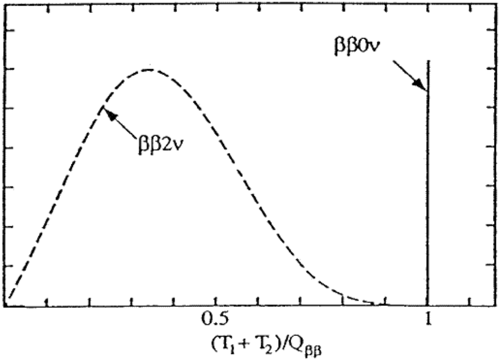


Example ^{76}Ge (GERDA experiment):

$$2\beta 2\nu : \quad T_{1/2} = (1.8 \pm 0.1) \times 10^{21}\,\mathrm{yr}$$
$$2\beta 0\nu : \quad T_{1/2} > 2.1 \times 10^{25}\,\mathrm{yr}$$

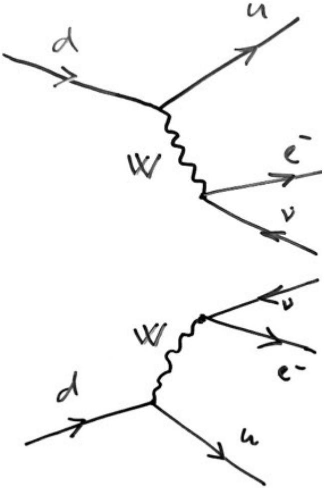
(importance of energy resolution and background suppression)

Neutrinoless double-beta decay

$$(A, Z) \to (A, Z+2) + 2e^-$$

- an observation of this process would prove that lepton number is violated
- proves Majorana nature of neutrinos
- BUT no direct prove of neutrino mass
  (a different mechanism could be responsible)

The neutrino-mass mechanism



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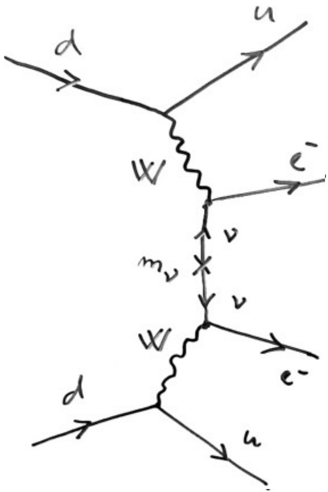

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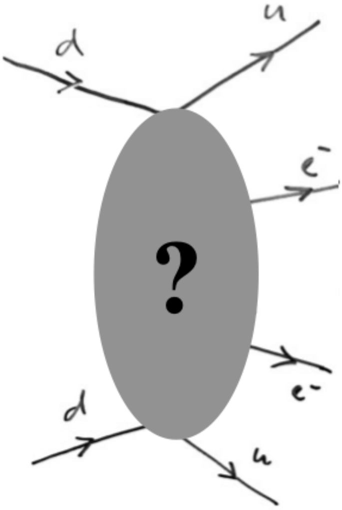


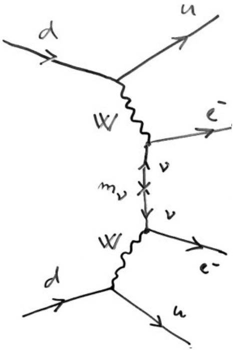
BUT: what we observe is just $\Delta L = 2$

The neutrino-mass mechanism

assuming that light neutrino exchange is responsible for the decay:

$$m_{\beta\beta} = |\mathcal{M}_{ee}| \qquad \text{(in basis where ch. lepton mass matrix is diag.)}$$

$$= \left| \sum_i U_{ei}^2 m_i \right| = \left| c_{13}^2 c_{12}^2 m_1 + c_{13}^2 s_{12}^2 e^{i\alpha_1} m_2 + s_{13}^2 e^{i\alpha_2} m_3 \right|$$



coherent sum of individual neutrino masses

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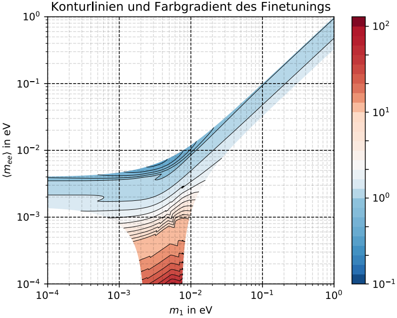
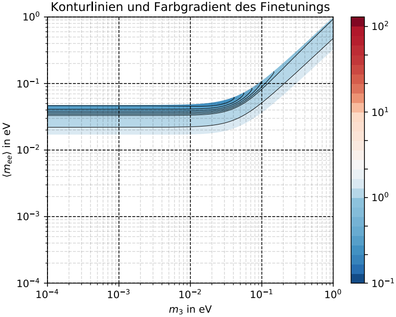
normal ordering

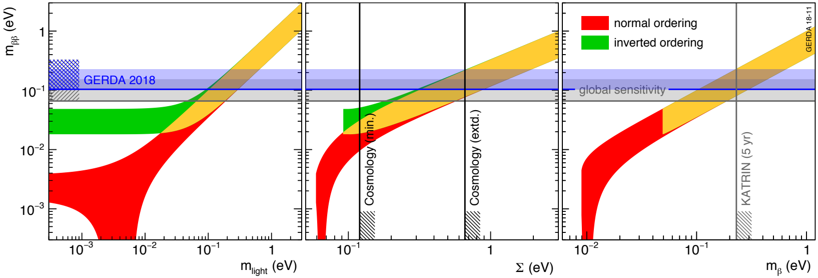


inverted ordering



M. Eichhorn, BSc thesis, KIT 2018

Experiment	Isotope	M_i (kmol)	FWHM (keV)	$\mathcal{L}(T_{1/2})$ (10^{25} yr)	$\mathcal{S}(T_{1/2})$ (10^{25} yr)	$m_{\beta\beta}$ (meV)
GERDA (this work)	^{76}Ge	0.41	3.3	9	11	104 - 228
Majorana [22]	^{76}Ge	0.34	2.5	2.7	4.8	157 - 346
CUPID-0 [23]	^{82}Se	0.063	23	0.24	0.23	394 - 810
CUORE [24]	^{130}Te	1.59	7.4	1.5	0.7	162 - 757
EXO-200 [25]	^{136}Xe	1.04	71	1.8	3.7	93 - 287
KamLAND-Zen [26]	^{136}Xe	2.52	270	10.7	5.6	76 - 234
Combined						66 - 155



GERDA Coll., 1909.02726

Outline

Dirac fermion

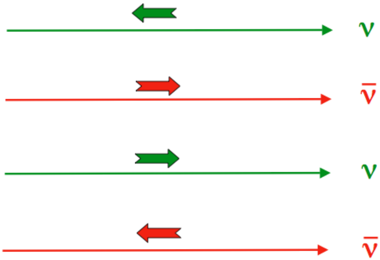
$$\mathcal{L}_D = i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi$$

Dirac equation:

$$(i\gamma^\mu\partial_\mu - m)\psi = 0$$

ψ is a 4-component object: 2 helicity states for particle and anti-particle

4 mass-degenerate states:



Chirality

parity is violated in weak interactions
left and right chiral fields transform differently under SM gauge group

left- and right-chirality projection operators:

$$P_L = \frac{1}{2}(1 - \gamma_5)\,, \qquad P_R = \frac{1}{2}(1 + \gamma_5)$$

left and right chiral flields (irreducible representations of Lorentz group):

$$P_L \psi_L = \psi_L\,, \qquad P_R \psi_R = \psi_R\,, \qquad \psi = \psi_L + \psi_R$$

Dirac Lagrangian:

$$\begin{aligned}\mathcal{L}_D &= i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi \\ &= i\bar{\psi}_L\gamma^\mu\partial_\mu\psi_L + i\bar{\psi}_R\gamma^\mu\partial_\mu\psi_R - m\bar{\psi}_L\psi_R - m\bar{\psi}_R\psi_L\end{aligned}$$

Dirac equation:

$$\begin{aligned}i\gamma^\mu\partial_\mu\psi_L - m\psi_R = 0 \\ i\gamma^\mu\partial_\mu\psi_R - m\psi_L = 0\end{aligned}$$

mass term mixes chiralities

for mass-less fermion the equations of motions for left- and right-chiral fields decouple $\rightarrow$ Weyl equation:

$$\begin{aligned}i\gamma^\mu\partial_\mu\psi_L = 0 \\ i\gamma^\mu\partial_\mu\psi_R = 0\end{aligned}$$

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invariant under a $U(1)$ symmetry

$$\psi_L \to e^{i\alpha}\psi_L\,, \qquad \psi_R \to e^{i\alpha}\psi_R$$

conserved quantum number (charge, lepton number,...)

particle is different from anti-particle

$\Rightarrow$ any charged Fermion has to be a Dirac particle

define particle- antiparticle conjugation $\hat{\mathcal{C}}$:

$$\hat{\mathcal{C}}: \qquad \psi \to \psi^c \equiv C\bar{\psi}^T \equiv C\gamma_0^T\psi^*$$

with

$$C^{-1}\gamma^\mu C = -\gamma^{\mu T}, \qquad C^\dagger = C^{-1} = -C^*$$

note that $\hat{\mathcal{C}}$ changes chirality:

$$\psi_L \to (\psi_L)^c \equiv \psi_L^c \quad \text{with} \quad P_R\psi_L^c = \psi_L^c, \quad P_L\psi_L^c = 0$$

Majorana field: replace ψ_R by ψ_L^c:

$$\psi = \psi_L + \psi_L^c$$

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$$C^{-1}\gamma^\mu C = -\gamma^{\mu T}\,, \qquad C^\dagger = C^{-1} = -C^*$$

note that $\hat{\mathcal{C}}$ changes chirality:

$$\psi_L \to (\psi_L)^c \equiv \psi_L^c \quad \text{with} \quad P_R\psi_L^c = \psi_L^c\,, \quad P_L\psi_L^c = 0$$

Majorana field: replace ψ_R by ψ_L^c:

$$\psi = \psi_L + \psi_L^c$$

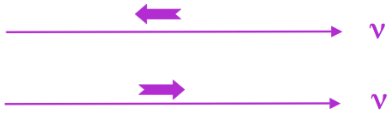
Majorana fermion

the Majorana field $\psi = \psi_L + \psi_L^c$ fulfills the Majorana condition

$$\psi = \psi^c$$

"is its own anti-partice"

only 2 independent
(mass-degenerate) states:



Majorana fermion

Lagrangian for a Majorana fermion

$$\mathcal{L}_M = i\overline{\psi_L}\gamma^\mu\partial_\mu\psi_L + \mathcal{L}_{\rm mass}$$

$$\begin{aligned}\mathcal{L}_{\rm mass} &= -\frac{m}{2}\left[\overline{\psi_L^c}\psi_L + \overline{\psi_L}\psi_L^c\right] \\ &= +\frac{m}{2}\left[\psi_L^T C^{-1}\psi_L - \overline{\psi_L}C\overline{\psi_L}^T\right] = \frac{m}{2}\left[\psi_L^T C^{-1}\psi_L + \mathrm{h.c.}\right]\end{aligned}$$

explicitly built out of only ψ_L (2 dof)

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using $\psi = \psi_L + \psi_L^c$ and dropping a term with a total derivative:

$$\mathcal{L}_M = \frac{i}{2}\bar{\psi}\gamma^\mu \partial_\mu \psi - \frac{m}{2}\bar{\psi}\psi$$

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Majorana equation:

$$i\gamma^\mu \partial_\mu \psi_L - m\psi_L^c = 0$$

this form holds for representations of the γ-matrices where C is real, i.e., where $C^{-1} = -C$, e.g., $C = i\gamma^2\gamma^0$

Majorana fermion

$$\mathcal{L}_M = i\overline{\psi_L}\gamma^\mu\partial_\mu\psi_L + \frac{m}{2}\left[\psi_L^T C^{-1}\psi_L + \mathrm{h.c.}\right]$$

this Lagrangian is not invariant under $\psi_L \to e^{i\alpha}\psi_L$

Majorana mass term breaks all $U(1)$ charges by 2 units

cannot define “particle” and “anti-particle”

any (electrically) charged particle cannot be a Majorana particle

In weak interactions we speak about "neutrinos" and "antineutrinos"

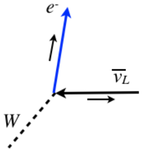
How can the neutrino be a Majorana particle, being its own antiparticle?

In the SM neutrinos are massless and only left-chiral fields participate in weak interactions:

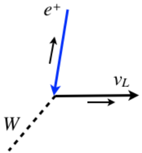
$$\begin{aligned}\mathcal{L}_{\mathrm{CC}} &= -\frac{g}{\sqrt{2}} W^\rho\, \overline{\ell_L} \gamma_\rho\, \nu_L + \mathrm{h.c.} \\ &= -\frac{g}{\sqrt{2}} W^\rho\, \overline{\ell_L} \gamma_\rho\, \nu_L - \frac{g}{\sqrt{2}} W^{\rho\dagger}\, \overline{\nu_L} \gamma_\rho\, \ell_L\end{aligned}$$

- the field ν_L contains two helicity states
- for massless fermions helicity states correspond to chiral states
- the left-handed field ν_L acts as "neutrino"
  the right-handed field $\overline{\nu_L}$ acts as "antineutrino"

$$\mathcal{L}_{\rm CC} = -\frac{g}{\sqrt{2}} W^\rho \, \overline{\ell_L}\gamma_\rho \nu_L - \frac{g}{\sqrt{2}} W^{\rho\dagger} \, \overline{\nu_L}\gamma_\rho \ell_L$$



outgoing "antineutrino" (right-handed field $\overline{\nu_L}$) produced together with negative charged lepton



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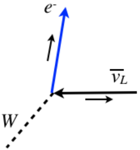

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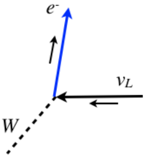

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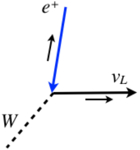

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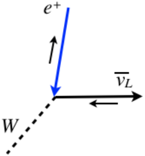

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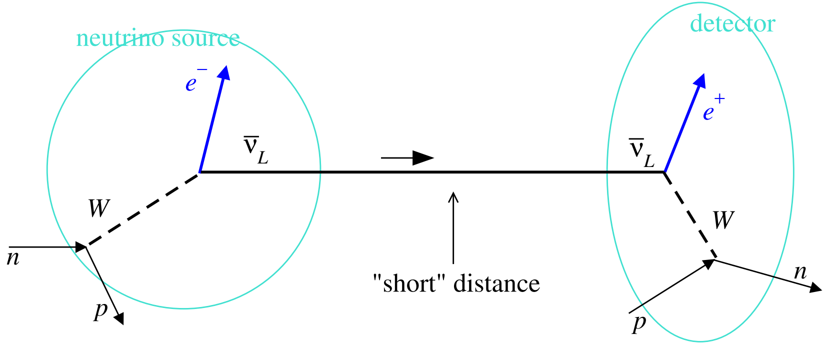
A typical neutrino experiment



- we need a L and a R neutrino state for weak interactions (to describe "neutrino" and "antineutrino")
- we need a L and a R neutrino state to form a mass term

Marjorana:

- those states are identical (there are only two independent states)

Dirac:

- the R state to from the mass term is different than the one acting as "antineutrino" in weak interactions (4 independent states) $\rightarrow$ "right-handed neutrino": does not participate in weak interactions

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Chirality versus helicity

physical states are helicity eigenstates:

$$\frac{\vec{\sigma}\vec{p}}{|\vec{p}|}\psi_\pm = \pm\psi_\pm$$

for massless fermions helicity and chirality coincides:

$$\psi_- = \psi_L\,, \qquad \psi_+ = \psi_R \qquad \text{(massless)}$$

for relativistic massive fermions ($m \ll E$) we have:

$$\psi_- \approx \psi_L + \frac{m}{2E}\psi_R\,, \qquad \psi_+ \approx \psi_R + \frac{m}{2E}\psi_L$$

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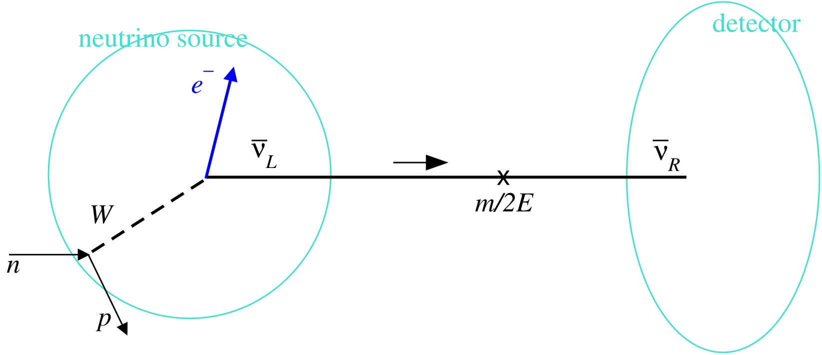
Mass induced chirality flip - Dirac

with a probability suppressed wrt leading diagram by $(m/2E)^2 \lesssim 10^{-12}$



Mass induced chirality flip - Majorana

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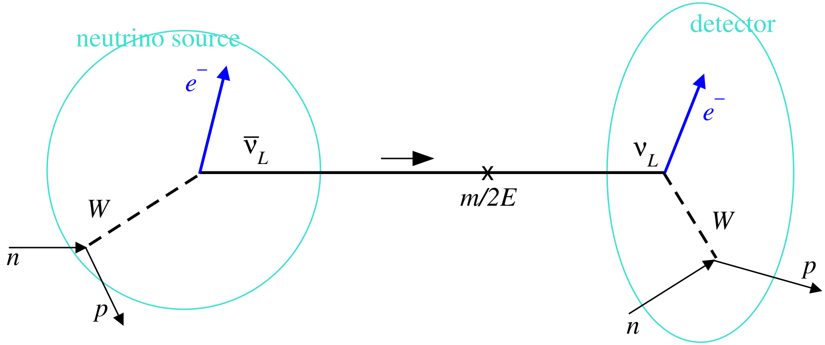
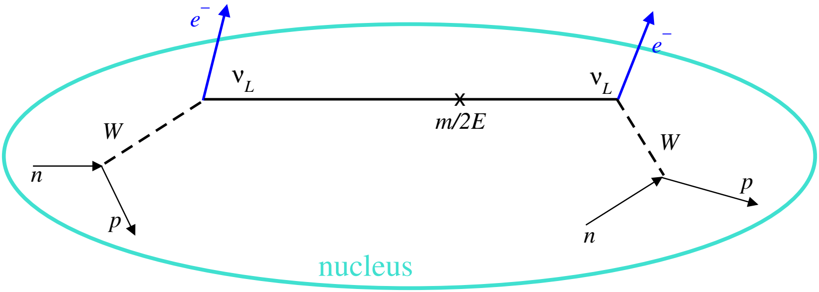


Schechter, Valle, PRD 1981

Mass induced chirality flip - Majorana

Neutrinoless double-beta decay $(A, Z) \to (A, Z+2) + 2e^-$



Outline

Masses in the Standard Model

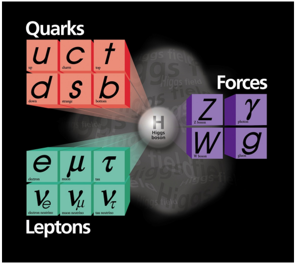
- The Standard Model has only one dimension full parameter: the vacuum expectation value of the Higgs:

$$\langle \phi \rangle \approx 174 \text{ GeV}$$

- All masses in the Standard Model are set by this single scale:

$$m_i = y_i \langle \phi \rangle$$

top quark: $y_t \approx 1$
electron: $y_e \approx 10^{-6}$



Fermion masses in the Standard Model

fermions of one generation:

$$\text{quarks: } Q_L = \begin{pmatrix} u_L \\ d_L \end{pmatrix},\ u_R,\ d_R \qquad \text{leptons: } L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix},\ e_R$$

mass terms from Yukawa coupling to Higgs ϕ

$$\mathcal{L}_Y = -\lambda_d \bar{Q}_L \phi d_R - \lambda_u \bar{Q}_L \tilde{\phi} u_R + \text{h.c.} \qquad -\lambda_e \bar{L}_L \phi e_R + \text{h.c.}$$

$$\text{EWSB} \rightarrow \quad -m_d \bar{d}_L d_R - m_u \bar{u}_L u_R + \text{h.c.} \qquad -m_e \bar{e}_L e_R + \text{h.c.}$$

$$\tilde{\phi} \equiv i\sigma_2 \phi^*,\ m_d = \lambda_d \frac{v}{\sqrt{2}},\ m_u = \lambda_u \frac{v}{\sqrt{2}},\ m_e = \lambda_e \frac{v}{\sqrt{2}},\ \langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

Dirac mass terms for charged fermions

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Dirac mass terms for charged fermions

- “right-handed” neutrinos would be complete gauge singlets in the SM
- no gauge interactions
- left out in the original formulation of the SM
  $\Rightarrow$ no Dirac mass term for neutrinos
- Why is there no Majorana mass term?
- Lepton-number is an accidental symmetry in the SM $\rightarrow$ given the gauge symmetry and the field content of the SM we cannot construct a Majorana mass term for neutrinos (true at any loop order)

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In the SM neutrinos are massless because. . .

1. there are no right-handed neutrinos to form a Dirac mass term
2. because of the field content (scalar sector) and gauge symmetry lepton number[1] is an accidental global symmetry of the SM and therefore no Majorana mass term can be induced.
3. restriction to renormalizable terms in the Lagrangian

[1] B-L at the quantum level

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Neutrino mass implies physics beyond the Standard Model

At least one of the above items needs to be violated

[1] B-L at the quantum level