HOW TO TELL DIFFERENCE OF MAJORANA/DIRAC NEUTRINOS

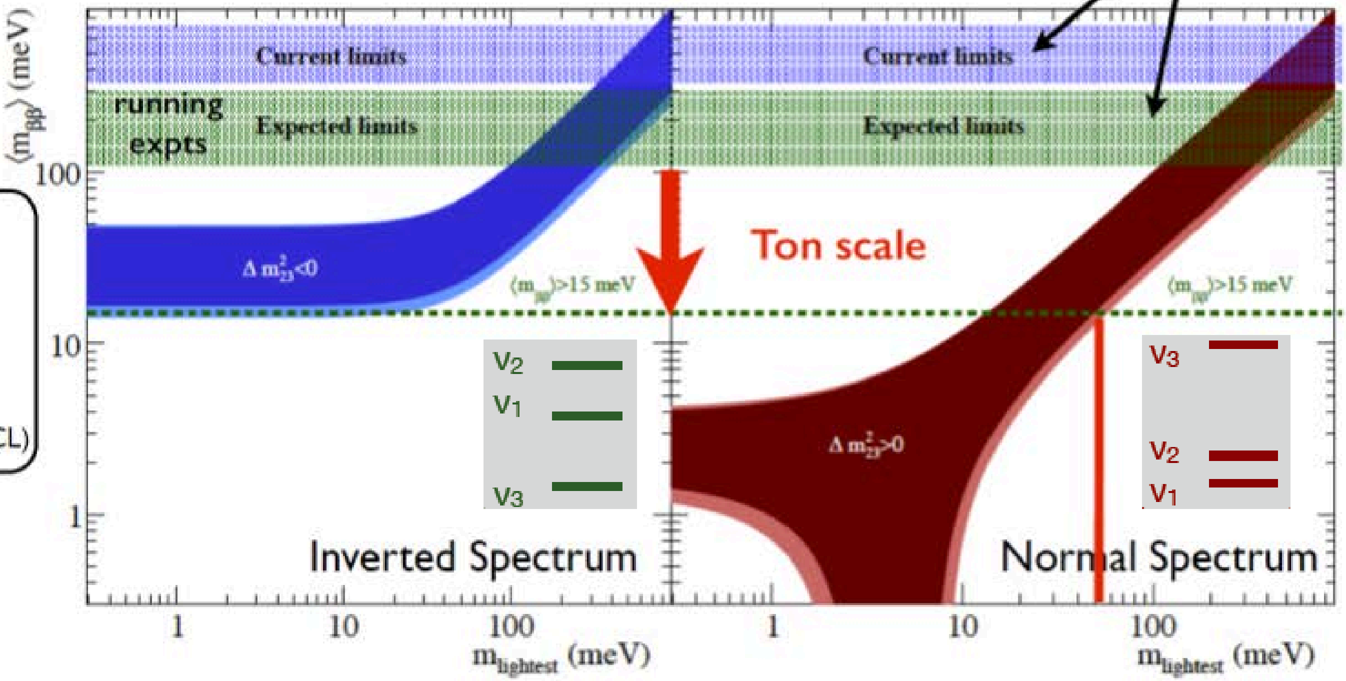
- Why not rely on 0ν2β decay experiments ? NEXT SLIDE
- Why not rely on published literature, that gives almost no hope for other experimental approaches?
- TENTATIVE ANSWER: because literature (almost) only considers neutral current reactions, where M/D difference in cross sections scales like $(m_\nu/E_\nu)^2$, and -> 0 for m_ν -> 0
- Federico and I have an idea to search for M/D difference in CHARGED current reactions.
- (why no one else had our idea?)

- Benchmark sensitivity for standard mechanism

Assume most "pessimistic" values for nuclear matrix elements

Dark bands: unknown phases

Light bands: uncertainty from oscillation parameters(90% CL)



From Xiangdong Ji's talk on PANDAX-III experiment

- Ton-scale experiment will make a discovery if spectrum has
  1. inverted ordering *or*
  2. $m_{lightest}$ > 50 meV (irrespective of ordering)

LESS OPTIMISTICALLY: IF NORMAL HIERARCHY, MAY NEVER DETECT $0\nu2\beta$ decays NOR DISCOVER THAT NEUTRINOS ARE MAJORANA PARTICLES!

THE IDEA

- Recall that a Majorana neutrino coincides with its antiparticle, and has two helicities:
    - negative (like SM neutrinos)
    - positive (like SM anti-neutrinos)
- with massive neutrinos, it is possible to flip helicities by a Lorentz boost
- Flipped – helicity neutrinos or antineutrinos will have different reactions depending on their Majorana vs. Dirac nature
- Example: for a helicity-flipped Dirac neutrino,

  $\nu + {}^{Z}N \rightarrow e^- + {}^{Z+1}N'$ is suppressed, and

  $\nu + {}^{Z}N \rightarrow e^+ + {}^{Z-1}N'$ is forbidden by lepton number conservation
- but if neutrinos are Majorana particles the second reaction would be allowed!
    - because Majorana neutrinos have zero lepton number
- detecting positive leptons in a neutrino beam (*modulo* background, etc) would prove the Majorana nature of neutrinos!

THE IMPLEMENTATION

- Need Lorentz – boosted neutrinos or antineutrinos from decays in flight of **muons** produced at a “suitable accelerator” (e.g., NUSTORM ring)
- Why muons, rather than more copiously produced pions? Because muon 3-body decays provides lower-energy neutrinos, which may be more effectively flipped in the lab system
- The FIRST challenge: CALCULATE the M-to-D difference in this favored phase-space region and for a realistic experiment
  - I am afraid we need a theorist to do the calculations…
- The SECOND challenge: a suitable accelerator, obviously
  - but it would be lovely to show that the idea works!
- but before that, there are ZERO-th order challenges:

1. is the idea correct?
2. convince ourselves that THE HELICITY FLIP IS SIZABLE
   - My progress on this calculation is very slow. No numbers yet.
3. Convince a theorist to do cross-section calculations
   - no success yet…. Maybe need formulas and back-of-envelope numbers

THE POINT I AM AT

- Re-learned spinor formalism, at a very elementary level. Now I know the following:

1. solving the Dirac eq. in the standard Dirac-Pauli representation gives helicity eigenstates
2. Helicity eigenstates can be decomposed into two orthogonal chirality eigenstates
   - Chirality eigenstas are not solutions of the Dirac eq.!
3. HELICITY is not Lorentz-invariant: can be flipped by a L-boost. But it is *conserved* for free particles
4. CHIRALITY is intimately related to “weak charge”
   It is LORENTZ-invariant, and IS NOT CONSERVED
   - **L-invariance**: indeed, in SM a neutrino cannot be L-boosted to have anti-neutrino interactions
   - **Non-conservation**: formally, the γ^5 (chirality) operator does not commute with the Dirac Hamiltonian. Also, “vacuum (the Higgs) eats weak charge” (R. Klauber, and M. Mangano)
5. All this suggests that helicity-flipped Majorana neutrinos ought to interact like anti-neutrinos, and produce “wrong-charge” reactions, not allowed by SM!

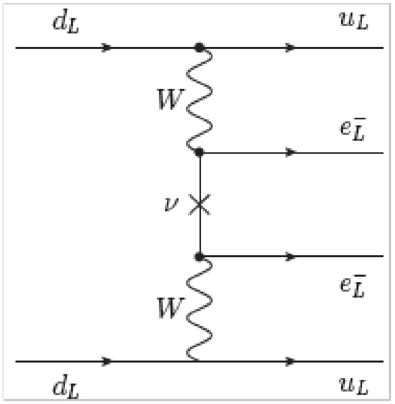
WHAT NEXT

- Calculations, zero level: I would like to show to myself that a L-boost flips the helicity of a spinor. Not as simple as it seemed to me.
- Analogously, would like to show that L-boost does not change chirality of a Dirac spinor
- WHAT DOES A L-BOOST DO TO A MAJORANA SPINOR?
  I am afraid that this needs field theory…. Not one of my strengths
  Also, we need to prove – or to persuade a theorist - that a boosted Majorana spinor does what we hope it does!
- What about the literature?
  Several papers give detailed calculations – even cross-sections – for D and M neutrinos, but only for neutral current reactions! WHY?
  - A beautiful paper (Kayser – Shrock,1982) has lots of results, but only for NC

- Federico suggested an IFAE mini-workshop of theorists (Quirós?) with us.
  I am almost ready for it. Maybe, after summer vacations?
- But perhaps we alreadycould have a little chat with Mariano

EXTRA

Physics of 0νββ process



$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ m^2_{\beta\beta}$$

$$\langle m_{\beta\beta}\rangle = |\sum_i |U_{ei}|^2 m_{\nu_i} e^{i\alpha_i}|$$

COHERENT sum includes unknown Majorana phases that “diffuse” unknown $m_{\beta\beta}$

- Observation would require and involve:
  - Majorana neutrinos: ν = anti-ν
  - Lepton number violation
  - Massive neutrinos
- Most important issue in neutrino physics, with CP violation?
  - Baryogenesis via leptogenesis
  - Non-Higgs mechanism for mass generation
  - New avenue to BSM physics?

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & \nu_1 \\ e^{i\alpha_2/2} & \nu_2 \\ & \nu_3 \end{pmatrix}$$

Neutrino masses: WHAT IS MEASURED

- Endpoint of β decays measures or sets limits on

$$m_{\nu_e} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

- From observational cosmology: DESI future sensitivity

$$\Sigma m_{\nu_i} < 0.017 \text{ eV}$$

- If detect 0νββ, will measure the mass combination:

$$\langle m_{\beta\beta} \rangle = |\sum_i |U_{ei}|^2 m_{\nu_i} e^{i\alpha_i}|$$

- Combining with the Δm^2 and Uij from oscillation experiments, in few years we should should have exciting results on neutrino masses.

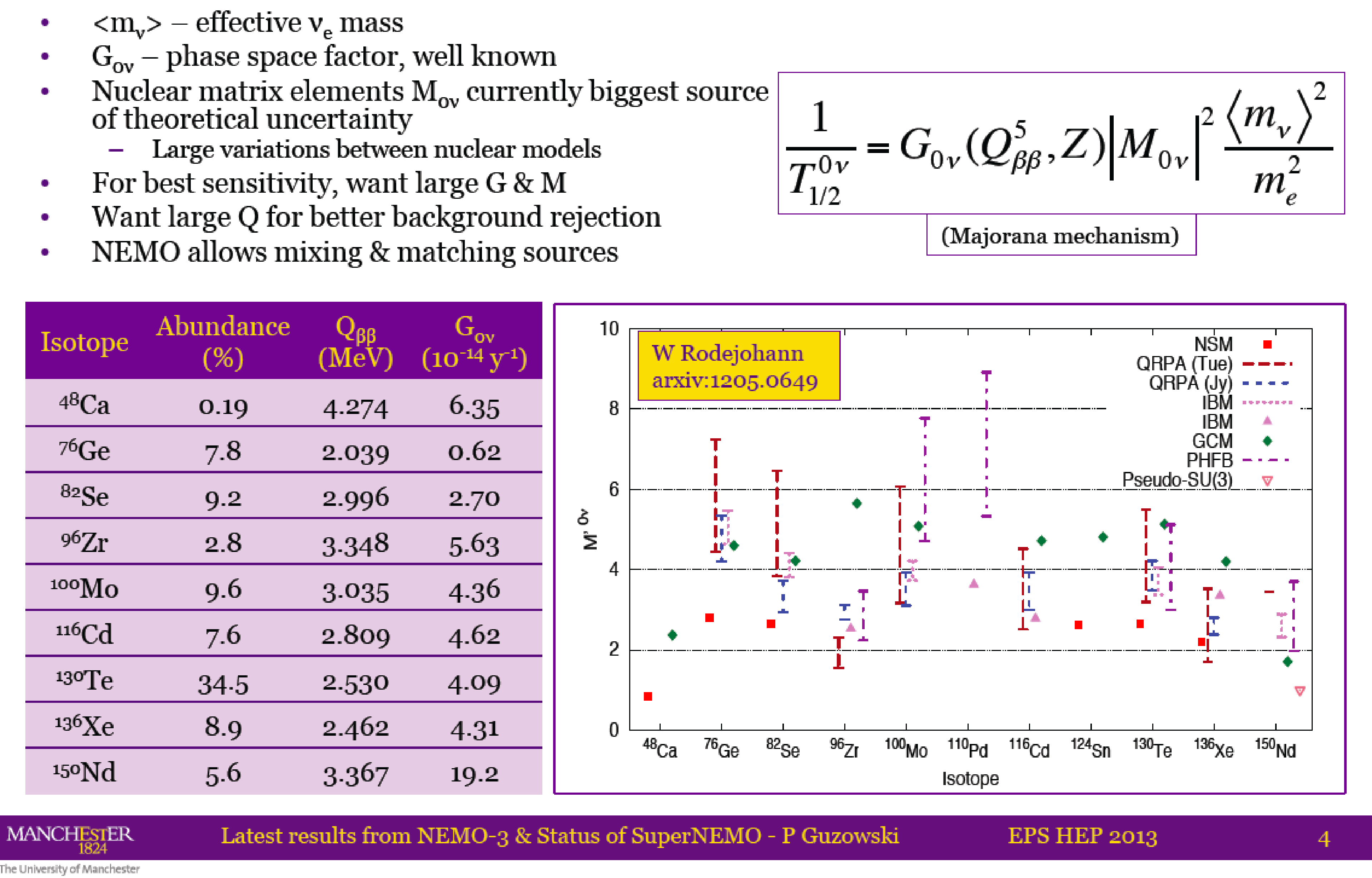
DETECTING 0νββ DECAYS

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\ |M^{0\nu}|^2\ m^2_{\beta\beta}$$

The huge lifetime of this decay (only upper limits, presently) sets experimental requirements:

1. Background-free, large Q (2-electron energy) isotope
2. Large, scalable mass of (not too expensive) purified isotope
3. Large fiducial volume (efficiency)
4. (Realistically) long running time
5. LOW BACKGROUND COUNTS (in counts/kg/keV/time)
6. HIGH ENERGY RESOLUTION (i.e., narrow energy interval for background counts)

NOTE that lowering measured $m_{\beta\beta}$ requires quadratically lowering measured lifetime! ("there is no free lunch")



- $\langle m_\nu \rangle$ – effective ν_e mass
- $G_{0\nu}$ – phase space factor, well known
- Nuclear matrix elements $M_{0\nu}$ currently biggest source of theoretical uncertainty
  - Large variations between nuclear models
- For best sensitivity, want large G & M
- Want large Q for better background rejection
- NEMO allows mixing & matching sources

$$\frac{1}{T^{0\nu}_{1/2}} = G_{0\nu}(Q^5_{\beta\beta}, Z)\left|M_{0\nu}\right|^2 \frac{\langle m_\nu \rangle^2}{m_e^2}$$

(Majorana mechanism)

Isotope	Abundance (%)	$Q_{\beta\beta}$ (MeV)	$G_{0\nu}$ (10^{-14} y^{-1})
^{48}Ca	0.19	4.274	6.35
^{76}Ge	7.8	2.039	0.62
^{82}Se	9.2	2.996	2.70
^{96}Zr	2.8	3.348	5.63
^{100}Mo	9.6	3.035	4.36
^{116}Cd	7.6	2.809	4.62
^{130}Te	34.5	2.530	4.09
^{136}Xe	8.9	2.462	4.31
^{150}Nd	5.6	3.367	19.2

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