Neutrino mass from accelerated ions?

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New Instruments for Neutrino Relics and Mass,

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Work in collaboration with Mats Lindroos, Bob McElrath and Thomas Schwetz

OUTLINE

1. Motivation
2. The idea
3. Strategy and simulations
4. Summary and outlook

NEUTRINO MASS

Three approaches to determining the neutrino mass scale:

- Direct searches
- Neutrinoless double beta decay
- Cosmology and Astrophysics

Current and projected sensitivities for direct mass measurements

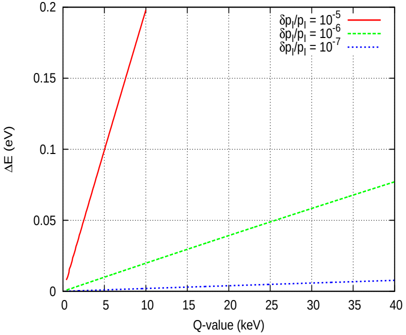
Troitsk and Mainz:	$m_\beta < 2.2\,\mathrm{eV}$
KATRIN:	$m_\beta < 0.2\,\mathrm{eV}$
MARE II:	$m_\beta < 0.2\,\mathrm{eV}$

HIGH PRECISION ION BOOSTS

- Advancements in technology allow for the control of low boost ions with extremely high precision.
- Translates to precision on energies of electrons close to the endpoint $\sim m_\nu$

The $\delta p_I/p_I$ required is dependent on the Q-value.

For $Q < 5$ keV, the uncertainty on the energy is smaller than likely sensitivity, even for modest $\delta p_I/p_I$.



KINEMATICS

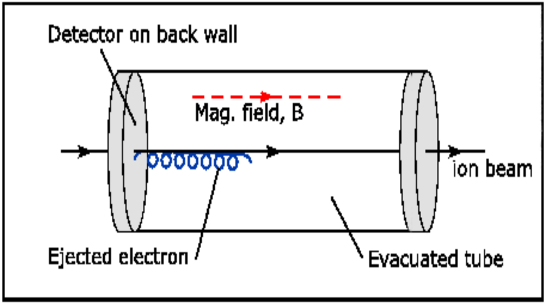
- Relative velocities in Special Relativity:

$$w = \frac{u - v}{1 - uv/c^2}$$

- A cut of the flux can be performed by choosing sufficiently small boosts.

A magnetic field set up parallel to beam to collect the electrons. Trajectories are helical with radius

$$r_g = \frac{p_\perp}{qB}$$



ELECTRON SPECTRUM

The electron spectrum is the incoherent sum over the mass eigenstates

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

where

$$\frac{d\Gamma_i}{dE_\beta} = p_\beta E_\beta (E_0 - E_\beta)\sqrt{(E_0 - E_\beta)^2 - m_i^2}\; F(Z, E_\beta)\, S(E_\beta) \Theta(E_0 - E - m_i)$$

We have no energy resolution so we may introduce the effective neutrino mass

$$m_\beta = \sqrt{\sum_i |U_{ei}|^2\, m_i^2}$$

- We have compared this ‘textbook’ spectrum with the more accurate expressions,

  e.g *Mahood et al.*

COUNT RATES

- Not many electrons close to the endpoint will travel in the backward direction

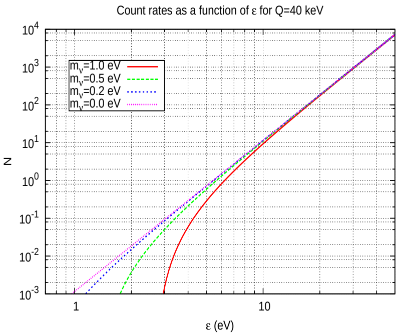
$$N(p_{\rm min}, p_{\rm max}) = \frac{1}{2} \iint_{\mathcal{S}} \frac{d\Gamma}{dE} \frac{p_\perp}{pE} dp_\perp dp_\|$$

where $\mathcal{S}$ is the region:

$$p_{\rm max} - \epsilon < p_\| < p_{\rm max}$$

and

$$0 < p_\perp < \sqrt{p_{\rm max}^2 - p_\|}$$

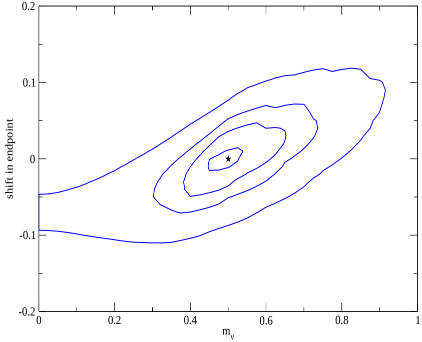


CORRELATION BETWEEN Q AND m_ν

- m_ν is not degenerate with an uncertainty on the endpoint.
- The is a correlation though if only event numbers are considered.

A 'toy-fit', which simulataneously fits m_ν and the endpoint energy. χ^2 contours are shown and can be thought of as equal event numbers.

The rest frame neutrino spectrum has been used.



STRATEGY

Q values are not known very well; for example, ^{106} Ru has $Q = 39.40 \pm 0.21$ keV.

In this work we have employed the following strategy

1. Run with a small ϵ, selecting electrons very close to the endpoint travelling in the backward direction.
2. Run with large ϵ to constrain the Q-value.

To extract the neutrino mass it is necessary to perform, at least, a two-parameter fit to the 'data', unless Q can be determined externally.

- KATRIN varies four parameters independantly - signal, overall background strength, endpoint energy and the square of the effective neutrino mass.

SIMULATIONS

We construct the following χ^2 statistic

$$\chi^2 = \min_{\eta} \left[\chi^2_{\text{near}} + \chi^2_{\text{far}} + \left(\frac{\eta}{\sigma} \right)^2 \right]$$

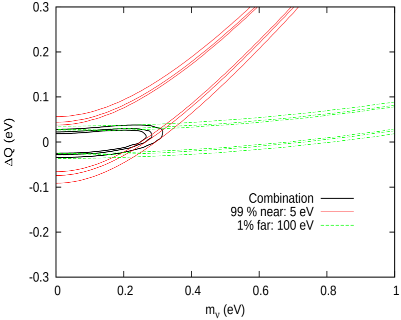
using the poisson form

$$\chi^2_{\epsilon} = 2 \ \left[N'_{\epsilon} - n_{\epsilon} + n_{\epsilon} \ \log \left(\frac{n_{\epsilon}}{N'_{\epsilon}} \right) \right]$$

- $N'_{\epsilon} = (1+\eta) N_{\epsilon}$ is the expected number of events for a particular choice of parameters
- n_{ϵ} is the simulated number of events by varying the parameters freely
- η is the pull parameter
- σ is the normalisation error on the flux

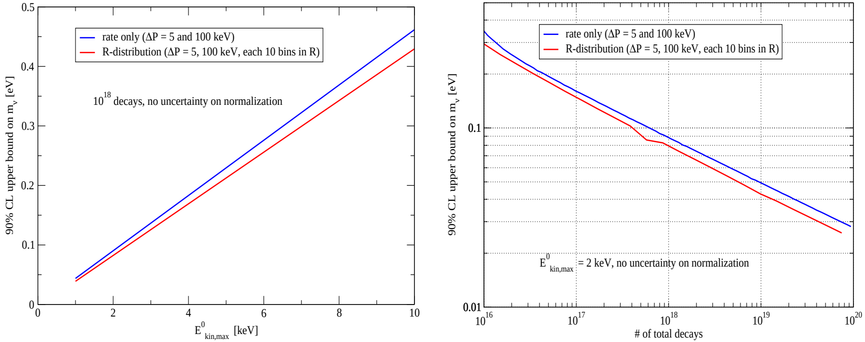
2-PARAMETER FITS

- Consider the combination of small and large ϵ
- Effective at removing the correlation but the senstivity is still poor.

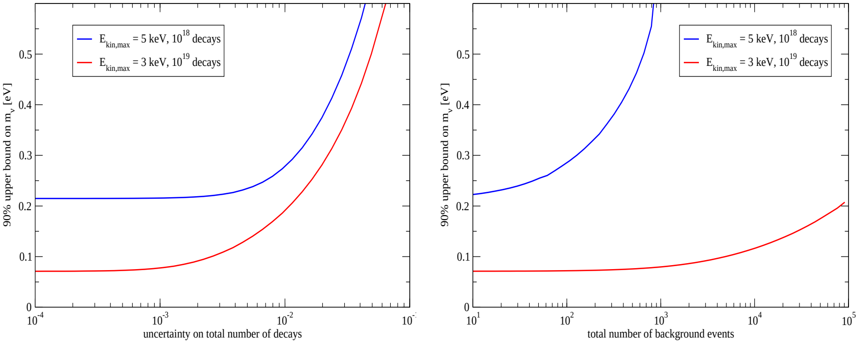


- Q = 5 keV
- Nature ‘chosen’ $m_\nu = 0.1$ eV
- Useful decays, $N_{\text{dec}} = 10^{18}$
- 99 % at $\epsilon = 5$ eV
- 1% at $\epsilon = 100$ eV

DISCOVERY POTENTIAL



SYSTEMATICS AND BACKGROUND



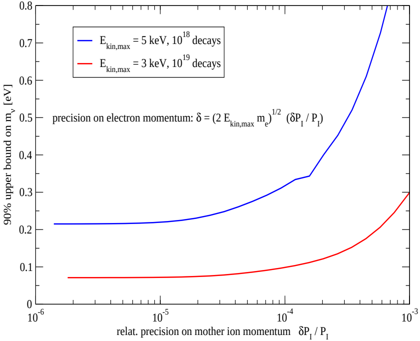
EFFECT OF MOMENTUM UNCERTAINTY

Precision on electron momentum given by

$$\delta p_e \sim \frac{\delta p_I}{p_I} \sqrt{2Qm_e}$$

A third integral is performed assuming a Gaussian momentum distribution.

The lower Q require less accuracy to obtain a given sensitivity.



SUMMARY AND OUTLOOK

- Technological advances in crystalised ion beams have opened possibility of measuring beta decay kinematics close to the endpoint.
- Owing to the lack of spectral information, low Q and a high number of useful decays are necessary reduce the limit post-KATRIN, if only total rates are used.
- We have adopted a strategy that is very light of spectral information to get a few for behaviour. More complicated and creative strategies are required to fully exploit this technology.
- Any ideas ?