Measuring neutrino mass with radioactive ions in a storage ring

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

based on arXiv:0904.1809

OUTLINE

THE PROBLEM OF NEUTRINO MASS

Discovery of neutrino oscillations implies neutrinos have mass, but its presence is a very small effect.

Δm^2_{21}	$7.6 \cdot 10^{-5}$ eV^2	SNO, KamLAND
$\lvert\Delta m^2_{23}\rvert$	$2.4 \cdot 10^{-3}$ eV^2	SK, K2K, MINOS
	< 2.3 eV	Mainz, Troitsk
m_ν	0.2 - 2.3 eV ?	KATRIN, MARE-II
	< 0.2 ?	?

- No access to neutrino mass scale from oscillations.
- Cosmology and $0\nu\beta\beta$ are model dependent approaches.
- Need direct searches

T. Schwetz, M. Tortola and J. W. F. Valle, New J. Phys. 10 (2008) 113011

C. Kraus et al., Eur. Phys. J. C 40, 447 (2005); V. M. Lobashev et al., Nucl. Phys. Proc. Suppl. 91 (2001) 280.

A. Osipowicz et al. [KATRIN Coll.], arXiv:hep-ex/0109033

ELECTRON SPECTRUM

The electron spectrum in beta decay is the incoherent sum over the spectra of the mass eigenstates

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

where

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

For poor energy resolution, we may introduce the effective neutrino mass

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

This ‘textbook’ spectrum has been compared with more accurate expressions.

F. Vissani, Nucl. Phys. Proc. Suppl. 100 (2001) 273

S. Gardner, V. Bernard and U. G. Meissner, Phys. Lett. B 598, 188 (2004)

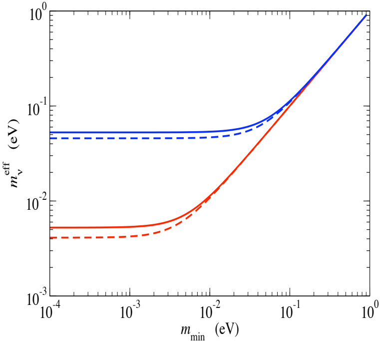
S. S. Masood, S. Nasri, J. Schechter, M. A. Tortola, J. W. F. Valle and C. Weinheimer, Phys. Rev. C 76, 045501 (2007)

EFFECTIVE MASS BEHAVIOUR

The sign of Δm^2_{23} is presently unknown. The ordering of the mass eigenstates impacts the behaviour of the effective mass.

Up to $\mathcal{O}(\sqrt{\Delta m^2_{21}}) \sim 0.01$ eV

$$m_\nu^{\rm eff} \simeq \begin{cases} m_{\rm min} & \text{(NO)} \\ \sqrt{m^2_{\rm min} + |\Delta m^2_{31}|} & \text{(IO)} \end{cases}$$



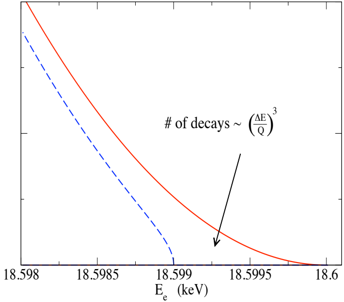
Long term target for end point studies is $m_{\rm eff} < 0.04$ eV and, ultimately, the resolution of individual mass eigenstates.

S. M. Bilenky, M. D. Mateev and S. T. Petcov, Phys. Lett. B 639, 312 (2006)

REQUIREMENTS FOR A DIRECT SEARCH

We are searching for and would like to measure a very small kinematic effect.

Specifically, to achieve a measurable and useful event rate requires



We need

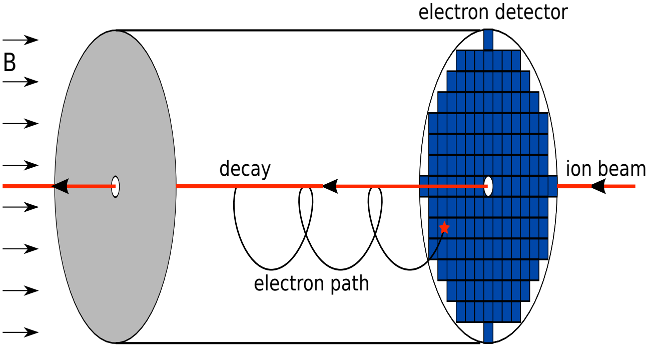
- A high source rate
- Control of backgrounds
- High precision

Innovative technology and/or experimental guile is needed if $m_\nu < 0.2eV$.

THE IDEA

KINEMATICS

Advancements in technology allow for the control of low boost ions with extremely high precision.



- Not many electrons close to the endpoint will travel in the backward direction $\longrightarrow$ we are considering a slice of momentum rather than a sphere.

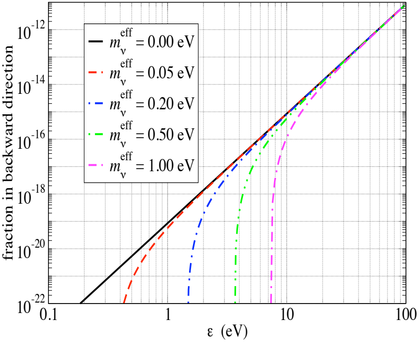
$$N(p_{\min}, p_{\max}) = \frac{1}{2}\iint_{\mathcal{S}} \frac{d\Gamma}{dE}\frac{p_\perp}{pE}dp_\perp dp_\parallel$$

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

$$p_{\max} - \varepsilon < p_\parallel < p_{\max}$$

and

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



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

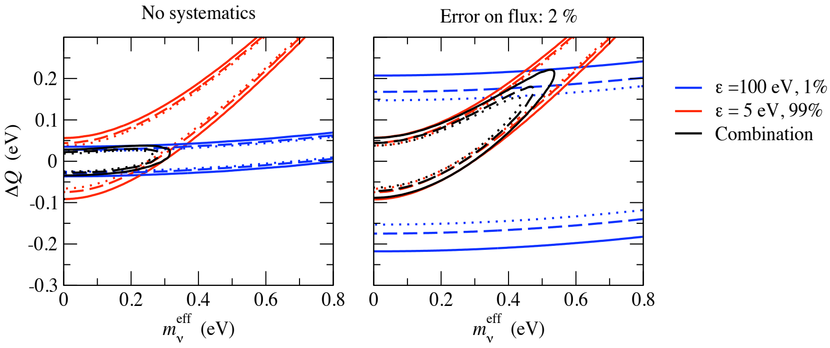
1. Run with a small ε, selecting electrons very close to the endpoint travelling in the backward direction.
2. Run with large ε to constrain the Q-value.

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.

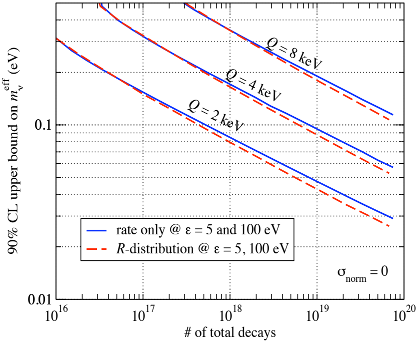
RESULTS

2-PARAMETER FITS

- Q = 5 keV
- Nature 'chosen' $m_\nu = 0.1$ eV
- Useful decays, $N_{\text{dec}} = 10^{18}$

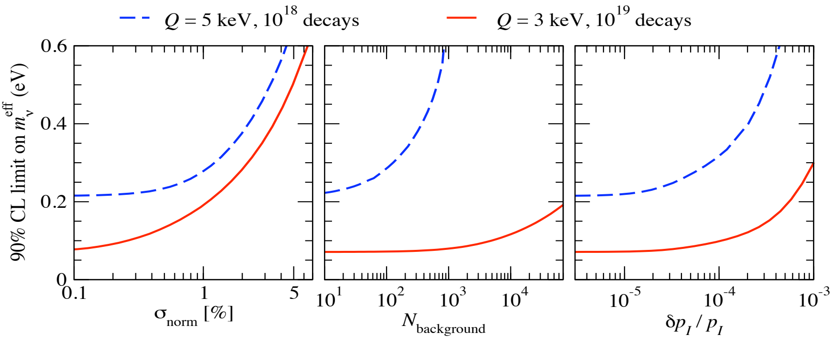


DISCOVERY POTENTIAL



- Spectral information can be obtained through examination of the radial distribution of events.
- There is significant averaging, however
  $\longrightarrow$ very little gain.

SYSTEMATICS AND BACKGROUND



SUMMARY AND OUTLOOK

- Measuring the neutrino mass is hard. Innovative technology and/or experimental guile will be required if below KATRIN limit.
- Technological advances in crystalised ion beams have opened possibility of measuring beta decay kinematics with sub-eV precision*.
- Low Q and a high number of useful decays are necessary to match the KATRIN limit in a counting experiment of this type.
- More complicated and creative strategies are required to exploit low energy radioactive beams in this way.

BACKUP SLIDES

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

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

- $N'_{\varepsilon} = (1+\eta)N_{\varepsilon}$ 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

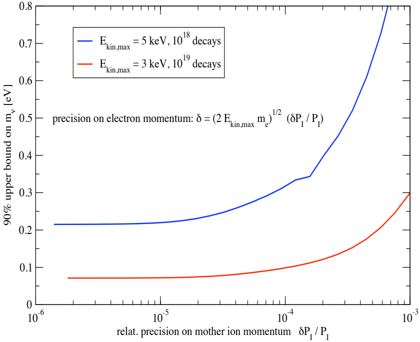
EFFECT OF MOMENTUM UNCERTAINTY

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.



Q-VALUES

For a half-life < 10 yr

- ^{106}Ru Q= 39.4 keV
- ^{228}Ra Q= 45.9 keV

are the smallest Q-values. The total number of decays will need to be increased by 3-4 orders of magnitude to match the sensitivities discussed previously. Tritium with Q =

18.6 keV, is desirable, however electron cooling is necessary rather than laser cooling. Number of ions that can be obtained is orders of magnitude larger as it is naturally occurring and does not need to be produced in an accelerator.

NUMBER OF IONS

This analysis indicates $10^{18} - 10^{20}$ ions will be needed. This is in line with projected EURISOL production rates. However

- Ions will be long lived
- Ions will possibly have large proton number

Storage of ions will be a problem - c.f. beta beams require low Z and half-lives ~ 1 second to source 10^{18} useful neutrinos each year.

In addition, space charge effects are largest at non-relativistic velocities.

J. Cornell, Caen GANIL - (03/12,rec.Mar.04) 1 CD, 622 p.

http://www.eurisol.org; H. L. Ravn et al., Nucl. Instrum. Meth. B 88 (1994) 441.

C. Volpe, J. Phys. G 30 (2004) L1.

COOLING OF BEAMS

If ions with Q-values $\mathcal{O}(1)$ keV are available then classical cooling techniques are available. For larger Q-values, new techniques will be required. For cooled low intensity

ion beams of 5000-10000, a transition to much lower momentum spread has been observed with increasing cooling current at NAP-M in Novosibirsk , ESR at GSI and CRYRING at MSL.

V. V. Parkhomchuk, in Proceedings of ECOOL 1984, edited by H. Poth (KfK 3846, Karlsruhe, 1984), p. 71; N. S. Dikansky and D.V. Pestrikov, ibid., p. 275; M. Steck et al., Phys. Rev. Lett. 77, 3803 (1996); H. Danared, A. Kallberg, K.-G. Rensfelt, and A. Simonsson, Phys. Rev. Lett. 88, 174801 (2002).