How to improve the sensitivity of future neutrino mass experiments with thermal calorimeters

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Abstract

In this paper we discuss the perspectives for a new generation of neutrino mass experiments using thermal detectors to reach interesting sensitivities before and after the KATRIN experiment. By scaling the performance of the present Milano neutrino mass experiment with Monte Carlo simulations, we show how a new experiment can validate the present limit of few eV set by spectrometers before the KATRIN experiment starts. We also show how such a result can be used to design a very large thermal detector experiment to reach sensitivities beyond the KATRIN expected one.

1. Introduction

While the existence of a non-vanishing neutrino mass is definitely proved by the evidence for neutrino flavor oscillations, the absolute value of this mass is still unknown. Experiments using electrostatic spectrometers have set a limit on the electron anti-neutrino mass of about 2 eV \cite{1}, while experiments using thermal microcalorimeters have reached sensitivities of about 10 eV \cite{2}. A new experiment to measure the neutrino mass with a sensitivity of about 0.25 eV using a large electrostatic retarding spectrometer (KATRIN) is planned to start taking data in 2007 \cite{3}. To study the requirements for a new calorimetric experiment using \textsuperscript{187}Re to reach the spectrometer sensitivities, both present and future, we have scaled the performance of our neutrino mass search with thermal microcalorimeters \cite{2} by means of Monte Carlo simulations.

2. Monte Carlo simulation

We have developed a Monte Carlo code to estimate the statistical sensitivity of a neutrino mass experiment performed with thermal calorimeters.
The approach is to simulate the $\beta$ spectra that would be measured by a large number of experiments carried out in a given configuration: the spectra are then fit as the real ones [2] and the statistical sensitivity is deduced from the distribution of the obtained $m^2_\nu$ parameters. The Monte Carlo parameters describing the experimental configuration are the total statistics $N_{ev}$, the FWHM of the Gaussian energy resolution $\Delta E$, the fraction of unresolved pile-up events $f_{pup}$ and the constant background level $b$. These input parameters can be derived from the ones actually characterizing a real experiment: $N_{ev} = N_{det} \times A_\beta \times t_M$ and $f_{pup} \approx A_\beta \times \Delta t$, where $N_{det}$ is the number of detectors, $A_\beta$ is the $\beta$ decay activity of a single detector, $t_M$ is the measuring time and $\Delta t$ is the pile-up resolving time—of the order of the detector rise time.

As a first step the function $S(E)$ describing the expected experimental outcome is numerically evaluated: $S(E) = (N_{ev}(N_\beta(E) + f_{pup}N_\beta(E) \otimes N_\beta(E) + b) \otimes g(E)$, where $N_\beta(E)$ is the $^{187}$Re $\beta$ spectrum normalized to unity (usually for $m_\nu = 0$) and $g(E)$ is the Gaussian detector energy response function.

The large number of simulated spectra (usually 1000) are then generated by introducing Poisson distributed statistical fluctuations in the spectrum bins according to their content. The $90\%$ CL $m_\nu$ statistical sensitivity $\Sigma_{90}(m_\nu)$ of the simulated experimental configuration is given by $\Sigma_{90}(m_\nu) = (1.64s)^{1/2}$, where $s$ is the standard deviation of the distribution of the $m^2_\nu$ found by fitting the spectra.

Figs. 1 and 2 show the results obtained for experiments with sensitivities around 3 eV in the absence of background. The simulation results are compared with the prediction (dotted lines) of the formula $\Sigma_{90}(m_\nu) = 1.06(E_0^3\Delta E/N_{ev})^{1/4}$ which can be obtained from statistical considerations for the $^{187}$Re $\beta$ spectrum—with end-point $E_0$—neglecting the effect of pile-up and background. It is apparent how the Monte Carlo results can be usefully scaled with the help of this formula to give further interesting predictions.

We have also run a simulation of the present experimental situation of the Milano neutrino mass search [2] obtaining $\Sigma_{90}(m_\nu) = 16 \pm 1$ eV: the good agreement with the result quoted in Ref. [2] show the reliability of the approach. We plan to extend the use of this approach to estimate also the effect of the various sources of systematic uncertainties [2].

3. A new Milano neutrino mass search

On the basis of the achieved encouraging results we are planning a new experiment with thermal
calorimeters: the aim is to attain a sensitivity $\Sigma_{90}(m_\nu)$ below about 3 eV in order to validate the results recently obtained by the Mainz and Troitsk experiment [1]. We believe this would be an interesting achievement, but it must be fulfilled before the new experiment KATRIN will set improved limits on $m_\nu$.

With the help of the Monte Carlo simulations we have devised an experimental arrangement which could allow to meet these requirements. A limit $\Sigma_{90}(m_\nu) \approx 2.5$ eV should be attained running for 3 years 200 thermal microcalorimeters with an individual $^{187}$Re $\beta$ activity of 0.25 Bq. The detectors must have an energy resolution of about 10–15 eV and a pile-up resolving time of about 100–200 $\mu$s. The required activity is that of an AgReO$_4$ crystal of about 450 $\mu$g mass. The background on the single detector must be lower than about 100 counts/keV/year—the present Milano experiment background scaled for the larger detector mass [2]. As it can be seen by comparison with the performance of the detectors of the present Milano experiment [2], to meet these technical specifications can be quite demanding: we will soon start an R&D phase to verify the feasibility of a new experiment. Our experience makes us confident about the possibility of success. To be conservative, we plan to stick to techniques we have a long and valuable practice with: therefore we will restrict our tests to large micromachined arrays of NTD Ge or Si implanted thermistors.

4. A next generation neutrino mass experiment

Using our Monte Carlo code we have explored the possibility to realize an experiment with thermal detectors competitive with the proposed KATRIN experiment (Fig. 3): the measurement of the neutrino mass is a major commitment of today’s particle physics and this cannot rely on a single difficult experiment. The simulations show that such an experiment is indeed too challenging for presently available techniques. As an example, a limit of about 0.3 eV would require to accumulate a statistics $N_{ev}$ of about $3 \times 10^{13}$ decays with an energy resolution $\Delta E$ of 5 eV and a unresolved pile-up fraction $f_{pup}$ of the order of $10^{-4}$; in practice, this means to run 1000 thermal detectors for 10 years, each detector having an activity of about 100 Bq—a metallic rhenium mass of about 100 mg—and a rise time of the order of 1 $\mu$s. Of course, one must also assume that no unexpected source of systematics would impair the calorimetric approach with the use of $^{187}$Re. Although presently unrealistic, in the future the realization of such a sensitive experiment can turn out to be possible thanks to new developments in the thermal detector field.

References