Measuring neutrino mass with radioactive ions in a storage ring

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Abstract. We propose a method to measure the neutrino mass kinematically using beams of ions which undergo beta decay. The idea is to tune the ion beam momentum so that in most decays, the electron is forward moving with respect to the beam, and only in decays near the endpoint is the electron moving backwards. Then, by counting the backward moving electrons one can observe the effect of neutrino mass on the beta spectrum close to the endpoint. In order to reach sensitivities for $m_\nu < 0.2$ eV, it is necessary to control the ion momentum with a precision better than $\delta p/p < 10^{-5}$, identify suitable nuclei with low $Q$-values (in the few to ten keV range), and one must be able to observe at least $O(10^{18})$ decays.

1. Introduction

The present bound on the neutrino mass from kinematic studies of beta decay endpoints was obtained from the Mainz and Troitsk Tritium beta decay experiments \cite{1, 2, 3}:

$$m_{\nu}^\text{eff} < 2.3 \text{ eV},$$

where $m_{\nu}^\text{eff}$ is the effective neutrino mass in beta decay. The next iteration of the Tritium and beta decay technologies \cite{4} and Rhenium calorimeters \cite{5} should be able to place a limit $m_{\nu}^\text{eff} < 0.2$ eV; however it is unlikely that these approaches will scale to lower neutrino masses. Thus, new experimental technologies are required to reach the level of hierarchical masses. In this talk we present an idea to measure the neutrino mass by measuring the kinematics of the electrons ejected in a beta decay using a beam of ions in a storage ring.

2. The concept

A low boost radioactive ion beam is sent through an evacuated chamber with a weak magnetic field parallel to the beam line. A detector is set up on the back wall of the chamber to record the number of electrons still traveling backwards after the boost (see Fig. 1). The purpose of the boost is to perform a cut on the electron momenta, only selecting electrons very close to the beta spectrum endpoint where the effect of the neutrino mass manifests itself. In our proposal we cut on the momentum component parallel to the beam. Hence, we use only a slice of the momentum sphere (for small $\epsilon$): $p_{\text{max}} - \epsilon < p_{\parallel} < p_{\text{max}}$. However, this approach has the disadvantage that many electrons close to the endpoint are lost.
Figure 1. Diagram of the proposed experiment. The ion beam enters an evacuated cavity whose back wall holds an electron detector. Each ejected electron follows a helical trajectory. Electrons moving in the backward direction in the laboratory frame are counted by the detector.

Figure 2. Sensitivity to the neutrino mass at 90% confidence level as a function of useful decays for $Q = 2, 4, 8$ keV. We show the total rate analyses with two ion boosts corresponding $\epsilon = 5$ and 100 eV (solid) and an analysis with using also the radial distribution with 20 bins of equal width in $R$ (dashed).

3. Results
In the simulations carried out in this study, we combine two experimental runs: one with small $\epsilon$ close to the endpoint and one with large $\epsilon$. At large $\epsilon$ the total count rate is several orders of magnitude larger than the change invoked by a non-zero neutrino mass. Hence, a 2-parameter fit for the neutrino mass and $Q$-value at large $\epsilon$ will be largely independent of the neutrino mass, i.e. one effectively makes a measurement of the $Q$-value. For small $\epsilon$, however, the total count rate becomes comparable to the reduction for non-zero neutrino mass. There is a strong neutrino mass dependence in this case which, when combined with the $Q$-value measurement from the run with large $\epsilon$, constrains the neutrino mass.

In Fig. 2, we present the upper bound on $m_{\nu}^{\text{eff}}$ at 90% confidence level, which can be obtained if the true value is $m_{\nu}^{\text{true}} = 0$, as a function of useful decays for $Q$-values of 2, 4 and 8 keV. Runs of $\epsilon = 5$ eV and $\epsilon = 100$ eV are considered in the ratio 99:1 such that the total useful number of decays sum up to the value shown on the horizontal axis. No backgrounds or systematics have been included, and we neglect the momentum spread of the ions. We also show in Fig. 2 an analysis that takes into account the radial distribution of the backward moving electrons (see [6] for details).
Figure 3. Sensitivity to $m_{\nu}^{\text{eff}}$ at 90% confidence level for $Q = 5$ keV and $10^{18}$ useful decays (dashed/blue) and $Q = 3$ keV and $10^{19}$ useful decays (solid/red). In the left panel, the effect of the normalization uncertainty on the flux is considered; background levels are varied in the center panel; whilst the effect of the momentum spread of the initial ion is taken into account in the right panel.

In Fig. 3 we examine the behavior of neutrino mass sensitivity with systematics, backgrounds and the ion beam momentum spread. We consider the cases $Q = 3$ keV with $10^{19}$ useful decays (“high sensitivity”) and $Q = 5$ keV with $10^{18}$ useful decays (“low sensitivity”), and, as before, in both cases we run at $\epsilon = 5$ and 100 eV with a ratio of 99:1. We include each one of the three above mentioned effects separately, in order to investigate at which level the sensitivity starts to deviate from the nominal sensitivities.

4. Conclusions
The talk discussed the possibility to use radioactive ion beams to study the kinematic effects of a non-zero neutrino mass close to the endpoint of the beta decay spectrum. The crucial questions are whether it will be possible to accelerate enough ions within reasonable time such that of order $10^{18} - 10^{19}$ decays can be observed; the identification of a suitable ion with a low enough $Q$-value and a small enough half life.

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