Reply to comment on ‘Using cold atoms to measure neutrino mass’

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\textbf{Abstract.} We discuss questions raised concerning the proposal of kinematically reconstructing the neutrino mass using an ultracold source of tritium atoms (Otten E W 2011 New J. Phys. 13 078001). We provide further details about our two-dimensional fit and emphasize the importance of simultaneously utilizing information from both the neutrino mass squared peak and the $\beta$-spectrum. We also explain how the simulation evolved over various drafts of the paper, and we comment on future directions for additional simulation work, including more detailed simulations of spectrometers and electromagnetic field variations.

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1. Introduction

We would like to thank Dr Otten both for taking an interest in our paper and for giving us the opportunity to address several interesting questions [1]. While kinematic reconstruction of the neutrino mass would certainly be difficult, we suggest in our paper that as atomic trapping and cooling techniques continue to advance, reconstruction might present a viable, direct, model-free determination of the neutrino mass, even if it is Dirac. Our paper attempts to outline the detector resolutions necessary for such an experiment, as well as the statistics required to make a measurement of interest to the neutrino community. Dr Otten raises questions concerning the accuracy of the $\beta$ spectrometer and the need to control electromagnetic potentials to a sufficient level. He also expresses concerns over the calculation of the error bars on our neutrino mass fit. We will discuss our fit in more detail in order to explain why our errors are smaller than Dr Otten’s estimates would suggest, and we will also discuss the technological challenges posed by the spectrometer and electromagnetic potential requirements.

2. Statistical questions

In his response to our paper, Dr Otten performs a relatively simple estimation of the uncertainty achievable from our two-dimensional (2D) fit. In the early development of our simulation, we also made the same (rather discouraging) calculation. When we actually performed the 2D fit, however, we were surprised. The simple error estimation focuses on the information obtained from the shape of the neutrino mass squared peak; it does not take into account the information obtained from the correlation between the shape of the $\beta$-spectrum and the shape of the neutrino mass squared peak. That correlation is not amenable to an easy analytic expression. One way to observe the power of this correlation is to perform the 2D fit not over our full 18.1–18.6 keV $\beta$-spectrum range, but over smaller energy slices. Table 1 shows the fit results when the fit is limited to 150 eV slices of the $\beta$-spectrum, and the error bars on the results are not dramatically larger than when the full energy slice is utilized. These results indicate that meaningful information is contained in the relationship between the $\beta$-spectrum and the neutrino mass squared peak, which highlights one of the interesting and unique features of probing neutrino mass via kinematic reconstruction. The result of the full 2D fit is noticeably better than the result of fitting the peak and the $\beta$-spectrum separately. We do not believe we have conclusively established 18.1 keV as the lowest point from which useful information can be obtained, and one potentially interesting avenue of further study would be to expand the energy range under examination.

Some additional details concerning the fit are that the Minuit fit result does not depend on the starting value chosen or on the allowed range for $m_\nu$. The negative log-likelihood spaces for the Minuit fits are parabolic and do not appear to contain false minima. The fit result is stable across a variety of different binning choices. We also employed two different techniques to interpolate on the surface of our probability-density functions, and the fit results were independent of the interpolation technique.

In his comments Dr Otten mentions an earlier draft of our paper in which we utilized a much larger micro-channel plate (MCP) and yet quoted similar sensitivity to the neutrino mass. He understandably suggests that perhaps our new simulations are still incorporating statistics acquired from the earlier larger MCP. In actuality, however, the early draft utilized an unnecessarily large MCP. In order to explain why the large MCP was not contributing additional
Table 1. Minuit fit results and Minos errors for simulated data runs.

| Assumed $m_{\nu}$ | Energy slice (keV) | Fit $m_{\nu}$ | (+) error | (−) error |
|------------------|------------------|--------------|-----------|-----------|
| 0.2              | 18.1–18.25       | 0.180        | 0.239     | 0.170     |
| 0.2              | 18.25–18.4       | 0.359        | 0.314     | 0.252     |
| 0.2              | 18.4–18.55       | 7.7E-6       | 0.227     | 0.227     |
| 0.2              | 18.1–18.55       | 0.239        | 0.174     | 0.153     |
| 1.0              | 18.1–18.25       | 0.482        | 0.302     | 0.256     |
| 1.0              | 18.25–18.4       | 1.131        | 0.326     | 0.298     |
| 1.0              | 18.4–18.55       | 0.433        | 0.656     | 0.0       |
| 1.0              | 18.1–18.55       | 0.813        | 0.246     | 0.207     |

information, we must examine the development of the Rydberg atom technique for measuring the $\beta$-momentum.

Given our approach to detector modeling, which was to assume the best conceivable detector resolutions and acceptances, we began our simulations with a 1 m$^2$ MCP. We performed a series of initial simplistic simulations to determine if the technique of kinematic reconstruction was interesting enough to pursue with more detailed simulations, and we used a 1 m$^2$ MCP for these simplistic simulations. We found that the technique had potential, but we were lacking a feasible way to measure the $\beta$-momentum, which led us into another phase of simulations in which we developed the idea of utilizing Rydberg atoms as detection devices. Once we chose a size for the optical lattices filled with Rydberg atoms and positioned those lattices at a fixed distance from the source, that automatically limited the geometrical acceptance of the experiment. The opening angle between the $\beta$ and the ion is almost 180$^\circ$, meaning that for decays in which the $\beta$ misses the optical lattices, we do not care if the ion hits the MCP. Although the simulation we used when we wrote our first draft of the paper had a 1 m$^2$ MCP in the code, most of that area was completely unutilized because the optical lattices were 10 cm$^2$. In subsequent simulations, we simply reduced the size of the MCP to match the geometrical acceptance predetermined by the size of the optical lattices, so the smaller MCP did not greatly affect the statistics collected.

3. Technological questions

In attempting to simulate an experiment to kinematically reconstruct the neutrino mass, we faced many technological questions. We wanted to explore the viability of the overall concept without becoming overly dependent on the details of one particular technology, but we also did not want to drift too far from what was technologically feasible. Our intention was to explore what could be learned given optimum detector resolutions, while simultaneously assessing the detector resolutions that would be necessary to make such an experiment interesting. In our conversations with $\beta$-spectrometer engineers, they expressed the same sentiment echoed by Dr Otten, which is that a spectrometer like the one we describe would need to be custom designed, but would not pose a fundamentally insurmountable challenge. One fair conclusion to draw from our simulation results is that an experiment to kinematically reconstruct the neutrino mass in the manner we describe would require a spectrometer with a resolution in the 5–10 meV range.

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Dr Otten also raises the excellent question of how we would control spurious electromagnetic fields. This is a type of smearing that we did not include in our simulation results because the effect of such a smearing would depend sensitively on the precise details of the types of detectors employed, and we wanted to evaluate the merits of kinematic reconstruction quasi-independently of specific detectors. One of the next steps necessary to develop this type of experiment would be to simulate realistic electromagnetic variations and estimate the additional smearing that would result in both the energy and momentum measurements. We considered that step to be beyond the scope of our initial concept paper, although it would obviously be an essential correction to add in later iterations of development.

4. Conclusions

Recent advances in the slowing and cooling of atoms may have interesting applications in neutrino studies. The goal of the work presented in our paper is to suggest the possibility of integrating research developments in these two fields. Our hope is to stimulate discussion by presenting an innovative approach to the difficult problem of measuring the neutrino mass, and we are grateful to Dr Otten for his interest in our work and for his comments regarding future challenges. We do not share his concerns regarding the error bars on our fit, although we acknowledge both here and in our original paper that trapping and cooling $10^{13}$ tritium atoms would pose a significant challenge. We agree with Dr Otten that before a definitive statement could be made about the precise statistics and run times required, a more detailed simulation that includes smearing due to electromagnetic variations would be required. While much work would remain before a proposal could be written for the kinematic reconstruction of the neutrino mass, we believe our paper indicates the benefits of simultaneously utilizing information from the $\beta$-spectrum and a neutrino mass squared peak, and it also establishes basic detector requirements that would be necessary in order to make kinematic reconstruction sensitive enough to be interesting.

References

[1] Otten E W 2011 *New J. Phys.* **13** 078001