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Using cold atoms to measure neutrino mass

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Abstract. We propose a β-decay experiment based on a sample of ultracold atomic tritium. These initial conditions enable detection of the helium ion in coincidence with the β. We construct a two-dimensional fit incorporating both the shape of the β-spectrum and the direct reconstruction of the neutrino mass peak. We present simulation results of the feasible limits on the neutrino mass achievable in this new type of tritium β-decay experiment.

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1. Introduction

The past decade has transformed our understanding of the neutrino; nevertheless, the absolute scale of the neutrino mass remains unknown. The best neutrino mass limits from direct measurements come from the tritium endpoint experiments Mainz and Troitsk [1, 2], both

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of which place $m_\nu < 2.2\,\text{eV}$. Measurements of the cosmic microwave background, coupled with cosmological models, have led to somewhat better (but model-dependent) constraints of $m_\nu < 1\,\text{eV}$ [3].

The next generation of tritium endpoint measurement is now being pursued by the KATRIN experiment [4]. They expect to push the limit on the neutrino mass as low as $m_\nu < 0.2\,\text{eV}$. An independent avenue of research is neutrinoless double β-decay, which could test the Majorana nature of the neutrino and possibly determine its mass [5].

We propose here a new approach, fundamentally different from both KATRIN and neutrinoless double β-decay. Our work is motivated by the recent development of general methods for trapping and cooling of atoms, which enable the creation of a sample of ultracold atomic tritium. We first describe the atomic trapping and cooling methods and then outline a prototype of a neutrino mass experiment. We present detailed simulation results and the detector requirements necessary to reach sub-eV sensitivity for the neutrino mass.

2. Slowing and cooling methods

Cooling of atomic translational motion has been the topic of intense research for the past 30 years. The standard approach to date is laser cooling [6], which has been applied to cooling and trapping of radioactive alkali atoms in order to probe the weak interaction [7]–[10]. Despite the enormous success of this method, it has been limited to a small set of atoms due to the requirement of a cycling transition that is accessible with lasers. In particular, hydrogenic atoms have not been amenable to laser cooling. Trapping and cooling of hydrogen atoms was accomplished in a dilution refrigerator, followed by evaporative cooling, but these methods have not been extended to other isotopes of hydrogen [11].

Over the past few years, a more general method has been demonstrated in a series of experiments. The starting point is the supersonic molecular nozzle, which creates a very monochromatic but fast beam [12]. Paramagnetic atoms or molecules are seeded into the beam in a region of high density and decouple from the carrier gas downstream. These atoms are stopped with a series of pulsed electromagnetic coils, an 'atomic coilgun'. Such a device has been used to stop a beam of metastable neon, molecular oxygen and atomic hydrogen [13]–[18]. Once the atoms are magnetically trapped, they can be further cooled using a method of single-photon cooling, which is based on a one-way barrier [19, 20]. Together, the atomic coilgun and single-photon cooling provide a general two-step solution to the trapping and cooling of paramagnetic atoms or molecules. In particular, these methods will work well on atomic tritium, which has a suitable 12.3 year half-life.

3. Prototype experiment

We consider an experiment to observe the β decay of ultracold atomic tritium. The decay produces an outgoing $^3\text{He}^+$ ion and a β, both of which can be detected. We need a spectrometer to measure the energy of the β, along with a non-invasive technique for measuring two components of its momentum. By utilizing the coincidence between the β and the $^3\text{He}^+$ ion, we can determine the ion's three-momentum components from its time-of-flight. Measurement of the four-momenta of the ion ($\tilde{p}_{\text{He}}$) and the β ($\tilde{p}_\beta$) yields the neutrino mass squared:

$$m_\nu^2 = \tilde{p}_\nu \cdot \tilde{p}_\nu = (\tilde{p}_{^3H} - \tilde{p}_{He^3} - \tilde{p}_\beta) \cdot (\tilde{p}_{^3H} - \tilde{p}_{He^3} - \tilde{p}_\beta). \tag{1}$$

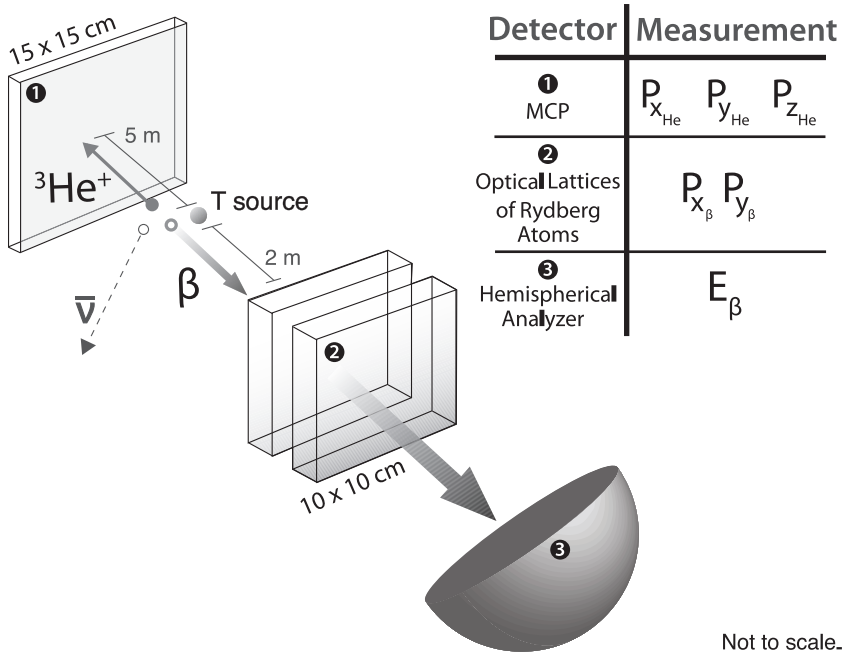

Figure 1. Experimental setup of the three detectors proposed for kinematic reconstruction of the neutrino mass: an MCP, optical lattices of rubidium Rydberg atoms and a spectrometer.

The advantages of this approach include: an extremely thin source that results in low scattering; an atomic tritium source with simple final state effects; a coincidence measurement with the β to reduce background; a direct neutrino mass peak reconstruction; and the utilization of at least 500 eV of the β energy spectrum. Nevertheless, this approach faces several experimental challenges, particularly regarding the measurement of the β momentum to sufficient precision and trapping enough tritium atoms to obtain sufficient statistics.

We address these challenges with a proposed experimental setup that would consist of three detectors shown in figure 1: a microchannel plate (MCP) to detect the helium ion, a spectrometer to measure the β's energy, and an optical lattice of rubidium Rydberg atoms capable of measuring two of the β's three-momentum components.

We can place the β-spectrometer close to the source, with the MCP for the $^3He^+$ ion detection several meters away from the source. Using the β event detected by the spectrometer as the initial time, we can determine the time-of-flight of the ion to the MCP. Combining the time-of-flight with the MCP hit position yields the three-momentum components of the helium ion. For example,

$$p_x = \gamma m v \sin\theta \cos\phi, \tag{2}$$

where $v = z/(\mathrm{TOF})\cos\theta$ and θ and ϕ are reconstructed from the MCP hit position assuming that the tritium decay came from the center of the source. Here z is the distance from the MCP to the source.

The background event rate from the MCP would be <1 event cm^{-2} s^{-1} [21], where cosmic ray events are eliminated either by deploying the detector in an underground laboratory or by implementing an efficient veto. Although the coincidence in the β-spectrometer would be helpful, for any given β event of the correct energy there will be a 7% chance of seeing a

background MCP hit, given that the coincidence time between the β and the ion will be of the order of 0.3 ms. In order to evaluate our ability to discriminate true events from backgrounds, we simulated data in which the MCP hit position was randomized, and we studied how our reconstruction algorithm evaluated the neutrino mass squared for such random events. Such events typically reconstruct to be more negative than $-10^6\,\mathrm{eV}^2$ and would be clearly separated from true helium ion hits. Our simulations indicate it is possible to reduce backgrounds to 1.0×10^{-5}, not including the rejection due to the coincidence requirement, simply by cutting any events that reconstruct the neutrino mass squared to be more negative than $-5000\,\mathrm{eV}^2$. This cut introduces negligible bias into the neutrino mass-squared peak.

In order to measure the momentum of the β without significantly altering its energy, we propose exploiting the effect of a passing electron on Rydberg atoms [22, 23]. In the β's flight path before it reaches the spectrometer, we create an optical lattice filled with rubidium atoms in the ground state [24, 25]. Using laser excitation, we can excite the atoms to a high Rydberg state [26, 27], such as 53s. When the β passes one of these atoms, it can excite the atom from a 53s state to a 53p state, and the atom will remain trapped in its optical lattice position. We propose slowing the electrons with a controlled voltage soon after they leave the source so that by the time they reach the optical lattice, they have a maximum energy of 900 eV, which increases their cross section for exciting a Rydberg atom to $0.36 \times 10^{-9}\,\mathrm{cm}^2$.[5] When a β signal is detected downstream in the spectrometer, the 53 s atoms are optically de-excited using stimulated Raman adiabatic passage (STIRAP) [27], and an electric field of $100\,\mathrm{V\,cm}^{-1}$ is ramped within $\sim$130 ns to ionize any Rydberg atoms in a 53p state. Once the atoms are ionized, they will be detected by a multi-hit position-sensitive MCP. Based on realistic density limits, the β will excite several Rydberg atoms as it passes through the optical lattice, so we will be able to obtain the projection of a track from the passing β.

In order to obtain the two β momentum components necessary for reconstruction, we need to have a second optical lattice to project the momentum component in a direction orthogonal to the first. By combining the track projections from these two MCPs with the energy measurement from the spectrometer, we can reconstruct the momentum of the β that traversed the optical lattices using equation (2) and the reconstructed velocity:

$$v = c(1 - 1/(T/m + 1)^2)^{1/2}, \tag{3}$$

where T is the kinetic energy of the β as measured in the spectrometer and θ and ϕ are obtained from the β tracks in the optical lattices. Using Rydberg atoms with a principal quantum number $n = 53$ would result in a negligible change in the β's four-momentum as it passes. We estimate that we can obtain a density of $10^{11}\,\mathrm{atoms\,cm}^{-3}$ in the optical lattice [6], and we expect the passing β to excite an atom within 5 μm, leading to a high spatial resolution.

The two major sources of backgrounds that must be eliminated for this Rydberg technique are collisions and black body excitations. Holding the Rydberg atoms in an optical lattice eliminates collisions that could cause spurious transitions to the 53p state [24]. By surrounding the optical lattice with a wire mesh, we can eliminate most of the black body radiation that could

[5] We calculated this transition cross section using the first-order Born approximation, which is applicable because the electron energy is more than 10^7 times larger than the transition energy, and the transition is dipole allowed. We numerically computed the radial part of the transition matrix element by using a Numerov algorithm to compute the radial orbitals on a square root mesh in r. We numerically integrated the radial orbitals times the Bessel function, $j_1(qr)$, for the transition operator using fourth-order integration. To obtain the total cross section, we numerically integrated over the momentum transfer q from $q_{\min} = k - \sqrt{k^2 - 2\Delta E}$ to a $q_{\max} = 0.25/n$ using equally spaced points in q with a $\Delta q = 0.01/n^2$.

excite atoms from the 53s to the 53p state. The spacing of the mesh would be small compared to the microwave wavelength, suppressing black body emission of the mesh itself. Additionally, the rubidium atoms can be periodically cycled back to the ground state and then up to the Rydberg 53s state [26, 27], which will prevent background 53p events from accumulating, while still allowing the atoms to spend most of their time in the 53s state. This non-invasive method may find other applications in the detection of low-energy electrons.

4. Simulation results

Our current experimental simulation makes several assumptions about detector precision in order to determine the required equipment. We assume an MCP of 15 cm × 15 cm with a timing resolution of 20 ps and a high spatial resolution of 2 μm [28]–[30]. It is placed 5 m from the tritium source and has a 44% efficiency for detecting an ion when it is hit. The tritium source is modeled as a 100 μm sphere at a temperature of 1 μK. Given that the density of the source cannot exceed 10^{15} atoms cm^{-3} and that the radius of the source is 50 μm, the column density of the source is less than 10^{13} atoms cm^{-2}. We therefore estimate multiple scattering within the source to be small and do not include it in the simulation. The β-spectrometer is a hemispherical analyzer with an energy resolution of 5 meV, which is reasonable given current devices [31]. Simulations indicate that the Rydberg atom method of measuring the β momentum results in a resolution that varies from 40 to 2.8 meV c^{-1} depending on the β's four-momentum. We assume a large Rydberg atom optical lattice with dimensions 10 cm × 10 cm × 1 cm placed 2 m from the source, which optimizes the detector's resolution and solid-angle acceptance.

Our simulated β spectrum includes first-order final state corrections. In tritium β-decay, the helium ion is formed in the ground state in 70% of the decays, and our simulation simplifies the true spectrum of final states by assuming that the helium ion goes into the first excited state for the remaining 30% of the decays. For more than 99.9% of the events, the magnitude of the reconstructed neutrino mass is larger when the wrong state is assumed for the helium ion, which provides us with a simple method of determining the true state of the helium ion. This method does not bias the neutrino mass fit in any significant way.

Both the neutrino's reconstructed mass peak and the shape of its β-spectrum contain information about its mass. In order to utilize all of this information, we perform a maximum-likelihood fit using two-dimensional (2D) probability density function (pdf). We create a series of 2D pdfs using much higher statistics than we use for our simulated data. Each of the six pdfs we create has a different assumed neutrino mass, and the assumed mass values are 4.0 eV apart. Figure 2 shows the 2D pdf for the case of zero neutrino mass. By interpolating between the pdfs, we find the most likely value for the neutrino mass for a particular data set.

Unlike previous tritium β-decay experiments that utilize information only a few eV away from the endpoint, our fit extends back to 18.1 keV, a full 500 eV from the endpoint. The statistics gained by moving away from the endpoint substantially improve the precision on the neutrino mass even as the spread in reconstructed mass gets broader. Figure 3 shows how individual detector and reconstruction uncertainties contribute to broadening the reconstructed neutrino mass squared peak, especially the β momentum measurement and the initial ^{3}H temperature. These smearings create large uncertainties for each reconstructed event, but the uncertainty in the mean of the peak decreases with added statistics. Combining this neutrino mass peak information with the information from the beta spectrum fit allows for a sub-eV determination of the neutrino mass. Clearly, systematic shifts in the mean of the reconstructed

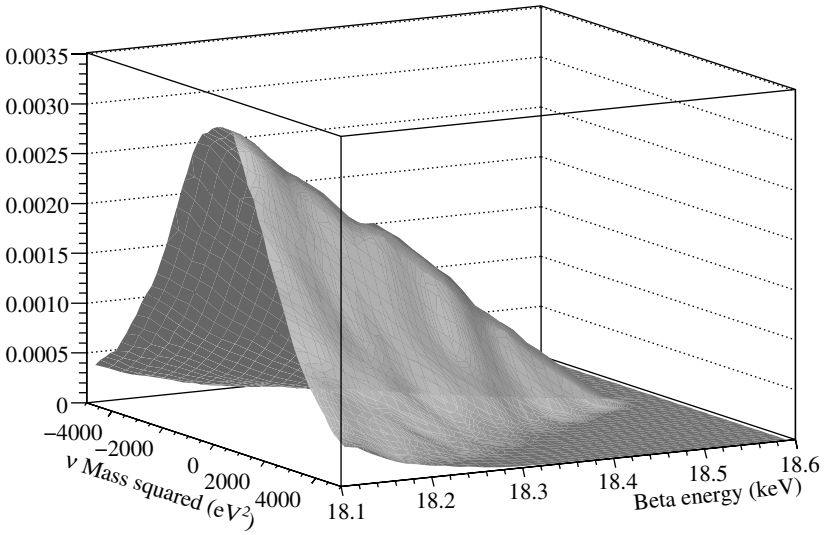

Figure 2. One of the six 2D pdfs used in the fitting process. This sheet corresponds to a neutrino mass of 0.0 eV, and the data set was fitted by interpolating between pdfs of different assumed neutrino masses.

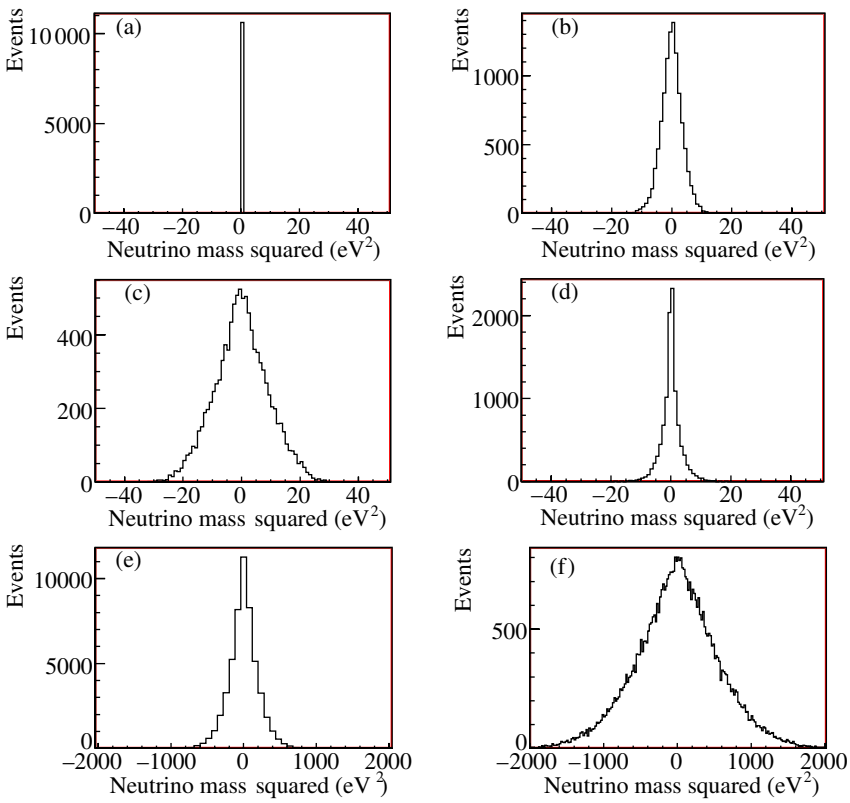

Figure 3. Reconstructed neutrino mass squared peak broadenings caused by various uncertainties and detector resolutions. (a) All smearings turned off. (b) β energy resolution. (c) ^{3}He ion's MCP binning resolution. (d) ^{3}He ion's MCP timing resolution. (e) β momentum resolution. (f) ^{3}H 1 μK initial temperature.

Table 1. MINUIT fit results and MINOS errors for simulated data runs, which had different assumed neutrino masses.

Assumed m_ν	Fit m_ν	(+) error	(−) error
0.2	0.239	0.174	0.153
0.4	0.354	0.166	0.150
0.6	0.690	0.270	0.203
0.8	0.794	0.247	0.215
1.0	0.813	0.246	0.207
5.0	5.188	0.402	0.378

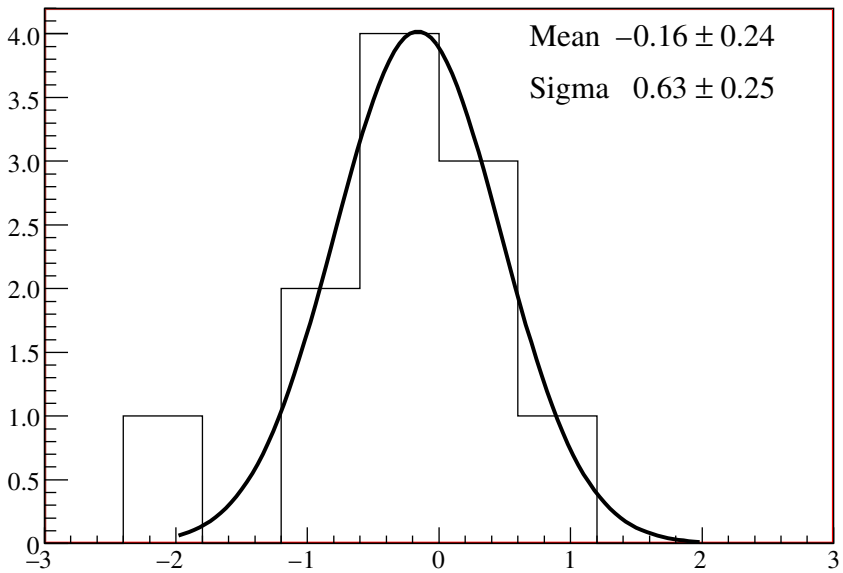

Figure 4. Pull distribution comparing the fit results shown in table 1 to the neutrino mass that was assumed in the various simulation trials.

mass spectrum would have to be controlled at a very high level, but calibrations of the spectrometer using the conversion electron from ^{83m}Kr as well as information from the energy spectrum itself should allow us to mitigate these effects.

In order to reach an m_ν limit comparable to KATRIN's, of the order of 10^{12} tritium decays would have to occur, which corresponds to trapping 2×10^{13} tritium atoms as a source if the experimental live runtime is 75% of one year. That many atoms cannot be contained in a single 100 μm diameter trap, which cannot have a density exceeding 10^{15} atoms cm^{-3} without contributing significant scattering in the source. Any feasible experiment, therefore, will require an array of tritium traps spaced far enough apart to allow the fit reconstruction to accurately determine the decay origin. A third optical lattice filled with Rydberg atoms could also be used to detect a track from the beta as it leaves the source, aiding in the reconstruction of where the decay occurred in the extended source. Tritium sources can be stacked by repeated launching and trapping. The primary limitation to the number that can be stacked is the trap lifetime. This trap lifetime can be of the order of 5–10 min using appropriate cryogenic cold fingers and careful

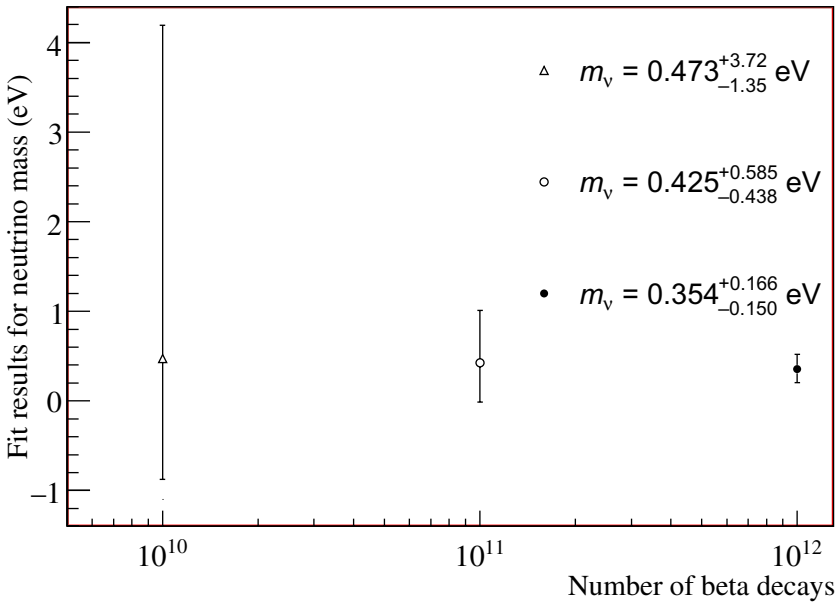

Figure 5. MINUIT fit results and MINOS errors from simulated data runs in which the neutrino mass was 0.4 eV.

bake-out of the chamber. We estimate that the necessary 10^{13} tritium atoms can be accumulated in this fashion.

Table 1 shows the results of the fit assuming 10^{12} tritium decays for six different assumed neutrino masses. Figure 4 shows the pull distribution of the fit results shown in table 1, and its shape is consistent with a normal Gaussian. Figure 5 indicates how the size of the fit uncertainties increases as the number of tritium decays decreases.

5. Conclusions

Our method of investigating tritium β-decay has the potential to establish an interesting limit on the neutrino mass. Although several engineering challenges remain, such an experiment provides an independent and complementary method of measuring the neutrino mass.

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