Preliminary Design of a CsI(Tl) Calorimeter for Muonium-to-Antimuonium Conversion Experiment

Siyuan Chen [1] Shihan Zhao [1] Weizhi Xiong [2] Jian Tang [1] *

[1]School of Physics, Sun Yat-sen University, Guangzhou 510275, China
[2]Institute of Frontier and Interdisciplinary Science, Shandong University, Qingdao 266237, China

Abstarct

The Muonium-to-Antimuonium Conversion Experiment (MACE) is proposed to search for this charged lepton flavour violating process and obtain a two orders of magnitude higher sensitivity than the MACS experiment at PSI in 1996, taking advantage of recent technique developments. One clear signature of the conversion is given by positron produced by antimuonium decay. This paper introduce a parameterized near-4π-coverage calorimeter for probing e^+e^- annihilation in MACE, the energy resolution of which reaches 8% at 511 keV. Detailed Monte-Carlo simulation with Geant4 toolkit and MACE offline software is presented for geometry optimization, coincidence system design, background estimation, and benchmark detector validation.

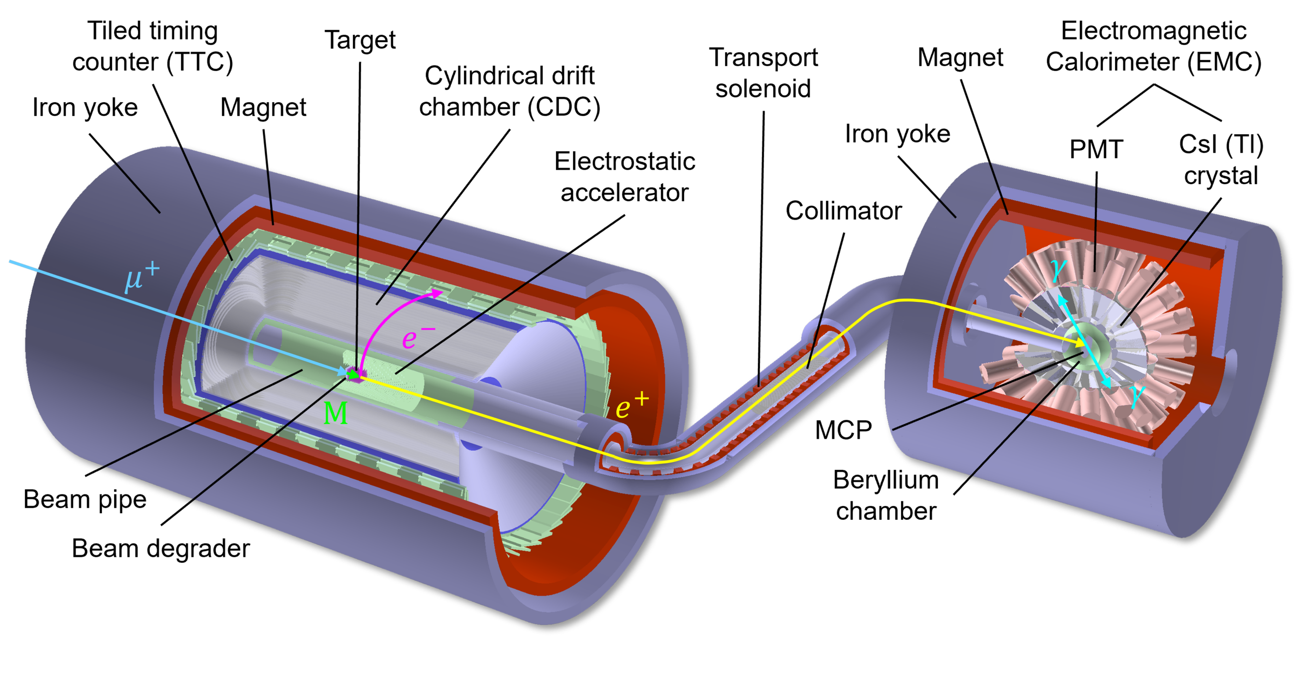

Fig. 1. MACE detectors

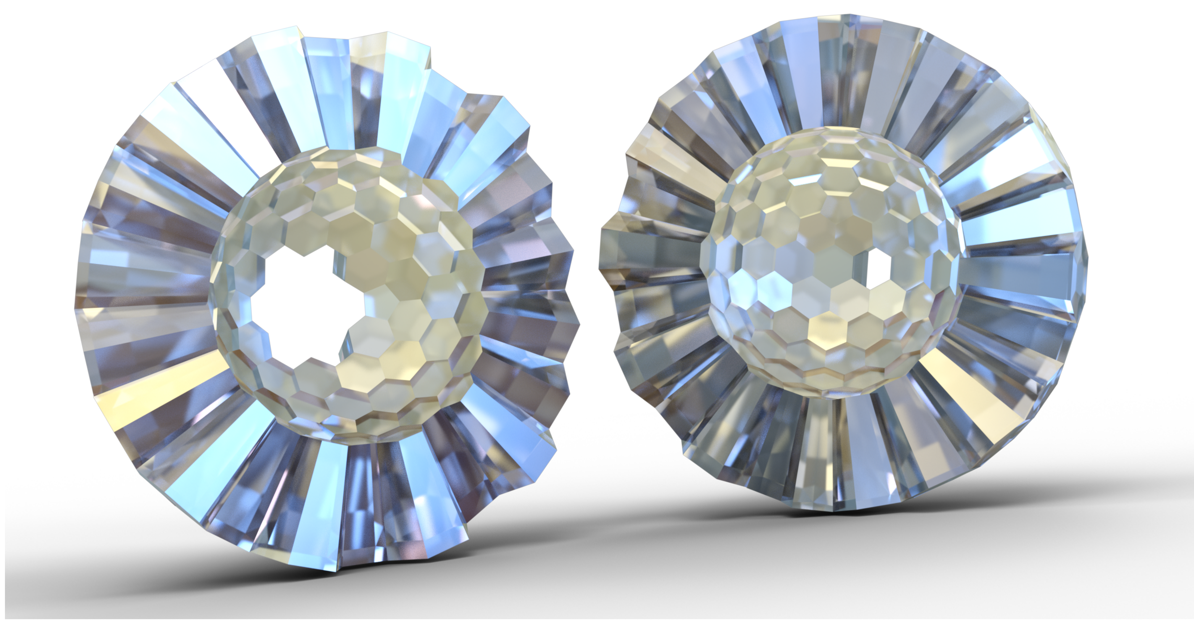

Fig. 2. Schematic diagram of calorimeter crystals.

Highlight

- **Geometry**:
  4π-coverage of 97.5%.
- **Energy resolution**:
  8.4% at 0.511 MeV, 6% at 1.022 MeV.
- **Signal efficiency**:
  68.1% for double γ events with coincidence.

Motivation

- Requirements of MACE calorimeter for sensitivity enhancement:
  - Energy resolution for signal & background discrimination.
  - Hermeticity and spatial resolution for annihilation event reconstruction.
- We adopt a 4π sphere geometry design for MACE calorimeter with following advantages:
  - Large solid angle coverage.
  - Good symmetry for precise reconstruction.
  - Self-supporting modules.

Design Scheme

A conceptual design is proposed and served as a baseline in detailed simulation works using Geant4 toolkit[1] and MACE offline software[2].

- **Geometry**
  - Class I $GP(4, 0)$ Goldberg polyhedron (Fig. 2).
  - 154 modules (3 types as shown in Fig. 3).
  - Inner diameter of 30 cm and crystal length of 15 cm after optimization.
- **Sensitive material**
  - **CsI(Tl)** scintillator: high light yield (~50000 pho/MeV).
- **Photosensors**
  - **PMT**: lower cost, lager sensitive area.
- **Simulation results**
  - Energy resolution achieves 8.4% at 0.511 MeV, 6% at 1.022 MeV.
  - Better than the pure CsI calorimeter in MACS[3].
- **Future upgrade**
  - Inner tracker for spatial resolution and charged particle track identification.
  - SiPM or MPPC could also potentially enhance the performance of MACE calorimeter.
  - LYSO crystal may be introduced to balance energy and time resolution.

Fig. 3. Schematic diagram of the Type-PEN, Type-HEX01, and Type-HEX02 crystals.

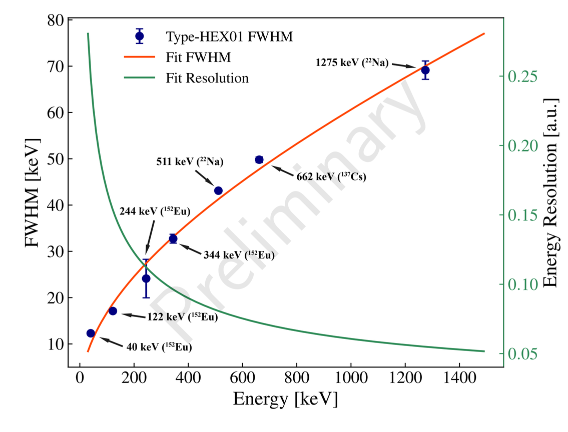

Fig. 4. Energy resolution of Type-HEX01.

M-to-$\bar{\text{M}}$ Conversion Signal

$\bar{\text{M}}$ decays into a Michel electron and an atomic-shell positron. The positron is transported into the calorimeter chamber, then detected by the MCP, and annihilates into a pair of γ-rays. Expected signal will be identified by a coincidence of MCP and calorimeter.

Signal efficiency

A beam of 10^7 μ^+ events of 28 MeV/c entering the MACE detector has been simulated using Geant4. Some of the γ-rays scatter to adjacent modules, forming a Compton continuum (Fig. 5). By adding the energy of all response in each event, the total energy can be reconstructed.

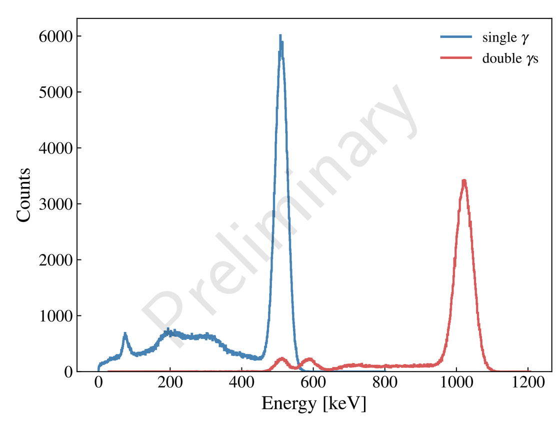

Fig. 5. Spectra of single and double 511 keV γ signals.

The signal efficiency of double γ events is 72.2% in 3σ interval.

Background Level

The surface muon beam usually contains positrons of the same momentum. It is considered as an accidental coincidence (Fig. 6). A parallel simulation of 10^{10} e^+ events has been conducted comparing with the signal.

Beam e^+ background

It is shown that the beam e^+ background and the conversion signal exhibit a clear sequence (Fig. 7). A timing cut of $>$ 2300 ns is determined based on FOM optimization.

- Signal efficiency slightly drop to 68.1%.
- Upper limit of beam e^+ counts is 0.07/year.

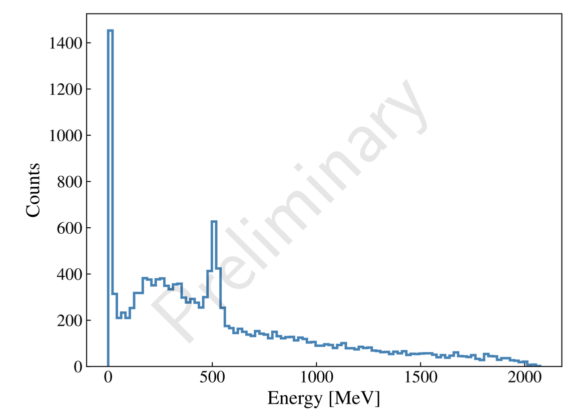

Fig. 6. Spectrum of beam e^+ background.

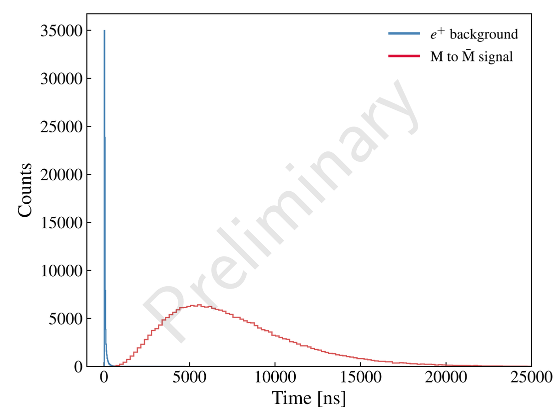

Fig. 7. Signal and background TOF.

Cosmic-ray muon background

The cosmic-ray muon background level is simulated using EcoMug generator[4]. Giving 129 Hz event rates, the background level is about 15/year.

It is expected that the cosmic-ray background can be suppressed to 0 with a veto detector system.

Conclusion and Prospective

With the preliminary design of calorimeter, MACE is anticipated to suppress the recent upper limit of $\mathcal{BR}(\mu^+e^- \to \mu^-e^+)$ by two orders of magnitude. Further works are in progress to achieve more physics goal, *e.g.* muonium decay ($\mu^+e^- \to e^+e^-$), muonium annihilation ($\mu^+e^- \to \gamma\gamma$), etc.. Prototype will be constructed in the future.

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