PROCEEDINGS OF SCIENCE

Analysis of multiple Coulomb scattering of muons in the MICE liquid-hydrogen absorber

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Ionization cooling is a new rapid beam-cooling technique, particularly important for muon accelerators due to the short lifetime of the particle. The Muon Ionization Cooling Experiment (MICE) is a multi-national accelerator physics experiment built to demonstrate IC. The amount of cooling achieved depends on two key processes — energy loss due to collisional ionization, and Multiple Coulomb Scattering (MCS) — for which accurate models are crucial in enabling quantitative design studies for future muon accelerators. Experimental measurements of MCS of positive muons with momentum in the range 170–240 MeV/c through liquid-hydrogen are reported in this study.

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1. Introduction

High-brightness muon-beams are attractive candidates for future 'energy frontier' particle physics experiments [1] and may also provide a well-characterised neutrino source, ideal for neutrino oscillation measurements [2]. The primary challenge is the particles' short life-time (2.2 μs at rest) compared to the relatively long cooling periods required by the current techniques to obtain high-brightness beams.

2. Ionization Cooling

A beam-cooling technique that exploits the dissipative forces when passing through an energy-absorbing material was first published in [3] and later proposed for application to muon-beams as ionization cooling (IC) [4]. MICE recently demonstrated this novel cooling technique in a particle-by-particle measurement of emittance [5]. The technique relies on momentum loss of the beam in the transverse and longitudinal directions due to ionization of the absorber material whilst MCS serves to increase the transverse momentum of the beam, reducing the effectiveness of the IC process. To evaluate the performance of future proposed facilities, accurate modelling of both collisional ionization and MCS are needed. Although collisional ionization is believed to be well understood, the MuScat collaboration demonstrated that previous versions of GEANT4 [7] were not compatible with their measurements of MCS [6].

MCS is the phenomenon describing the multiple small-angle scattering a charged particle undergoes when traversing a material. Equation 1 describes the RMS scattering width of the plane projected angle $\theta_{x,y}$ (y–z, x–z plane projection respectively) for a beam with momentum p, velocity $\beta = v/c$ traversing a length, z, of material with atomic number Z and X_0 radiation length [8]:

$$\theta_{RMS} = \frac{13.6\,MeV/c}{\beta p} Z \sqrt{\frac{z}{X_0}} \left(1 + 0.038 \frac{zZ^2}{X_0 \beta^2}\right) \quad (1)$$

3. Method

3.1 The MICE Apparatus

The muons reaching MICE were decay products of pions provided by the ISIS proton beam colliding with a titanium target. The momentum of the captured products was selected by a series of magnets before reaching the MICE channel. The MICE Step IV configuration was used for this analysis comprising the upstream scintillating fibre tracker (US Sci-Fi), the absorber focus coil (AFC) module, which housed the liquid-hydrogen absorber vessel, and a further scintillating fibre tracker (DS Sci-Fi). Preceding the US Sci-Fi tracker an adjustable diffuser with a 100 cm aperture was used to control the emittance of the incoming muon beam. Three time-of-flight detectors were used to provide velocity measurements (TOF0, 1 & 2). The absorber maintained 21 litres of liquid-hydrogen at a temperature of 20.51±0.07 K, providing a mean length of liquid-hydrogen in the beam path of 33 cm.

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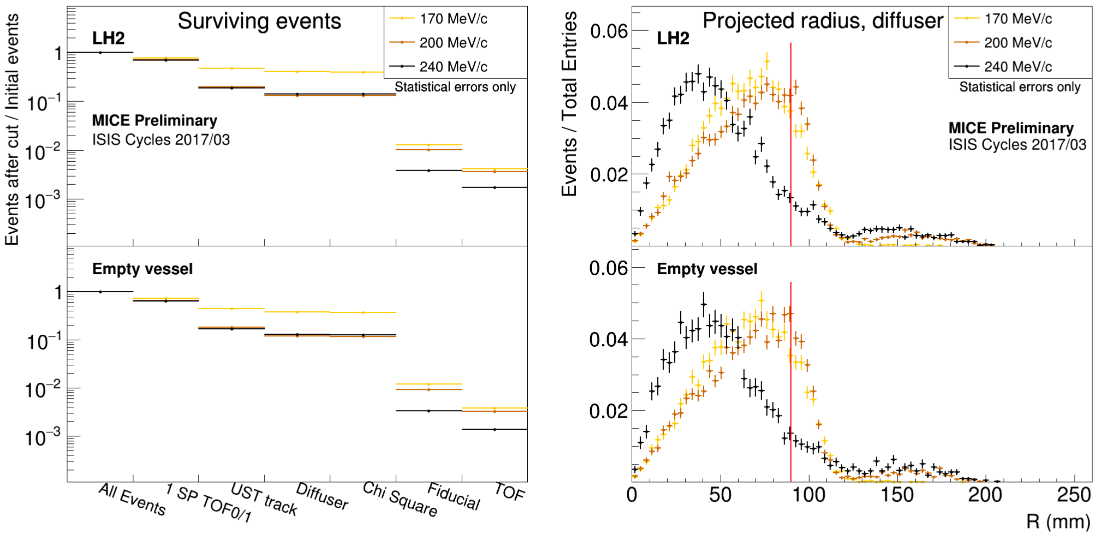

(a) Ratio of events surviving each cut to total number of events (first bin)

(b) Distribution of the particles' projected distance ($R = \sqrt{x^2 + y^2}$) from the experimental axis at the diffuser. The red line shows the maximum accepted limit at 90 mm.

Figure 1: Selection criteria for the MICE MCS event selection

3.2 Event Selection

MICE has gathered data with beamline settings configured to provide beams with 170, 200 and 240 MeV/c nominal muon momenta at the absorber. The cooling channel solenoid magnets were not powered during this study so that particle trajectories followed straight lines between interactions with materials. For each nominal momentum setting two different configurations are used: with the absorber empty — but in place — and filled with liquid-hydrogen. Events that pass the following selection criteria (with the survival rate shown in Figure 1a) are included in this analysis:

- Single TOF0 and TOF1 space-point (SP).
- A single reconstructed track in the US Sci-Fi tracker.
- An US track that, when extrapolated to the diffuser aperture, deviates by less than 90 mm from the experimental axis (z) (Fig. 1b).
- A good fit to the signal clusters formed in the US Sci-Fi tracker ($\chi^2/NDF < 4$).
- An US track that, when extrapolated to the downstream tracker, deviates by less than 100 mm from the z-axis (Fig. 2a).
- A transit time between TOF0 and TOF1 that is within a selected range (Fig. 2b).

The time-of-flight of each particle is assessed between TOF0 and TOF1. Electrons muons and pions in the MICE channel are well separated in that metric, therefore this provides momentum selection and muon-beam purity >99%. The quoted momenta for the beams analysed here correspond to the expectations at the absorber from the beamline settings. Explicit momentum calculations will be included in future publications. Figures 1b, 2a, 2b show the distributions of particles that have passed all other cuts except the one illustrated.

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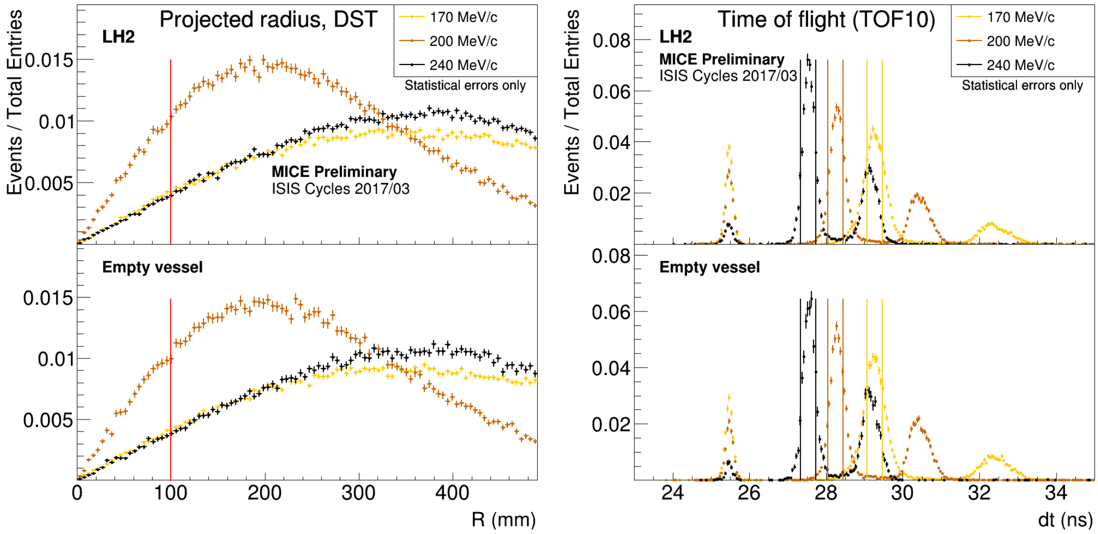

(a) Distribution of the particles' projected distance ($R = \sqrt{x^2 + y^2}$) from the experimental axis at the DS Sci-Fi tracker. The red line shows the maximum accepted limit at 100 mm.

(b) Time-of-flight distribution with selection intervals (170 MeV/c: 29.07–29.47 ns, 200 MeV/c: 28.05–28.45 ns and 240 MeV/c: 27.33–27.73 ns)

Figure 2: Fiducial radius and time-of-flight selections for MCS measurement.

4. Results

The resulting scattering distributions (Fig. 3) are expressed as the difference of angles between the US and DS momentum vectors ($\vec{P}_{US}$, $\vec{P}_{DS}$) when projected into corresponding orthogonal planes. The first plane is defined as the plane containing the US vector and the y experimental axis, and the second plane is defined as its orthogonal. This means that the two planes required for the projected angle calculations are defined on a particle-by-particle basis. This definition would be equal to using the y–z and x–z planes (from the experimental coordinates) if all particles moved parallel to the experimental z-axis. Because this is not the case the following definitions are established:

$$\theta_y = \arctan\left(\frac{\vec{P}_{DS}\cdot(\hat{Y}\times\vec{P}_{US})}{|\hat{Y}\times\vec{P}_{US}||\vec{P}_{DS}|}\right), \qquad \theta_x = \arctan\left(\frac{\vec{P}_{DS}\cdot(\vec{P}_{US}\times(\hat{Y}\times\vec{P}_{US}))}{|\vec{P}_{US}\times(\hat{Y}\times\vec{P}_{US})||\vec{P}_{DS}|}\right) \tag{2}$$

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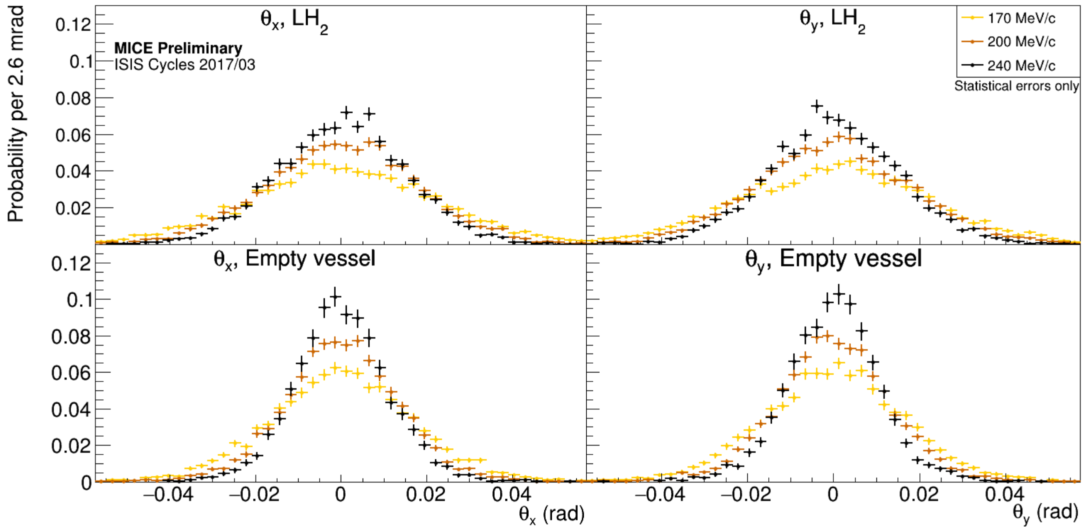

Figure 3: Distribution of θ_x (left) and θ_y (right) for the three momentum settings for vessel full (top) and empty (bottom) configurations.

5. Conclusions

This paper presents experimental measurements of MCS of muons in liquid-hydrogen using data taken by the MICE experiment at the ISIS facility at the Rutherford Appleton Laboratory. These data can be used to understand IC of muon beams in liquid-hydrogen absorbers with greater precision, which can be used to design future accelerator facilities, such as a muon collider or a neutrino factory.

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