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LOW-ENERGY MUON AND MUONIUM BEAM SOURCE AT FERMILAB*

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Abstract

A high-efficiency source of muonium that can be transported as a beam in vacuum provides opportunities for fundamental muon and precision physics measurements such as sensitive searches for symmetry violation. Although PSI is currently the world leader, the intense 800-MeV PIP-II linac beam at Fermilab could provide world-class low-energy muon and muonium beams, with unparalleled intensity, driving the next generation of precision muon-based physics experiments at the intensity frontier. However, it is critical to initiate the prerequisite R&D now to prepare for the PIP-II era. A low-energy secondary muon line recently installed in an operating facility (the MeV Test Area, which utilizes the intense 400-MeV Fermilab Linac beam) could support the required R&D, and potentially compete for new physics in the immediate term, if approved. This beamline was developed for μ^- and will need to be re-optimized for surface μ^+ production and transport, making it also suitable for muon spin rotation physics—a unique research and industrial application for which no U.S. facility exists, and whose facilities are oversubscribed worldwide.

OVERVIEW

We are performing requisite R&D for a future facility in the PIP-II era at Fermilab aimed at low-energy muon and muonium physics and applications. The research exploits a recently implemented capability using Fermilab's 400 MeV Linac: an ultralow-energy muon production target and secondary beamline recently installed (Fig. 1) in the MeV Test Area (MTA) hall (the former MuCool Test Area). This is an experimental area using the intense primary beam extracted directly from the 400 MeV Linac. This capability was implemented in order to study high-power targetry and efficient capture and transport of low energy muon beams for multiuser applications. (The first MTA experiment going through the approval process is an ARPA-E-funded one fostering cooperation and leveraging resources between different branches of the DOE.) We capitalize on that prior investment in the MTA to perform R&D for high-efficiency production of low-energy muons and their conversion to muonium.

MUONIUM

Muonium is the hydrogen-like bound state of a positive muon and an electron. Chemically it is very similar to hydrogen, except that it has a much lower mass and the muon acting as its nucleus decays with 2.2 μs average lifetime. Much is known about the properties of muonium; in particular, it is an ideal testbed for QED and the search for new forces, because it is a purely leptonic system devoid of the complexities of hadronic interactions. There is great interest in studying muonium in more detail, with higher statistics, and a future muonium facility at PIP-II would be well placed to do so. Such a facility would be a small increment to a future muon facility at PIP-II being studied for other reasons [1].

Figure 1: Low-energy pion/muon beamline recently installed at Fermilab MeV Test Area.

Muonium is readily produced when μ^+ stop in matter, because the muon has a higher affinity for electrons than the surrounding atoms; the challenge is getting it out of the material, solved here via a unique and innovative technical approach. Muonium production generally is aided by use of "surface muon" beams, which are formed when pions at

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[1] Surface muons come from the 2-body decay of a pion stopped at the surface of the production target. Slow pions tend to stop at the surface due to the work function required to leave the surface. This is a 2-body decay of a stopped particle, so the kinetic energy of the muon is sharp, here 4.1 MeV (or, once the muon has exited the target, a bit less due to muon ionization energy loss in the target material). As the pion has spin 0 and the other particle is a neutrino, the muon is 100% polarized. (This applies only to π^+, as stopping π^- are usually captured by a nucleus with which they interact rather than decaying.) Note that "cloud" muons from pion decay-in-flight have a much higher energy (>20 MeV) and wide distribution that cannot be efficiently degraded into the low energy and narrow bandwidth required for efficient muonium beam production.

rest decay near the exit surface of the production target, producing muons with a narrow kinetic energy distribution peaked at 4 MeV[1]. The beam-production technique described below is based on stopping surface muons in superfluid helium (SFHe), which then expels the muonium normal to its surface due to the difference in chemical potential of a hydrogenic atom within and external to the fluid. The resulting muonium beam has a narrow momentum distribution and small transverse emittance, allowing efficient capture and beam transport, thus supporting broad muonium-based applications and basic research. One important feature that must be taken into account in implementing this innovative approach is the 2.2 µs muonium lifetime, which will be carefully considered. A second important feature is that muonium is neutral.

At present there are no “muonium facilities”; muonium is produced from surface muon beams only within dedicated experiments. The leading facility for surface muon beam production is the Paul Scherrer Institute in Switzerland (PSI), with other facilities in Canada, Japan, and the U.K.; there are no low-energy muon beam facilities in the U.S. Using the technique described below, our estimates indicate that in the near term, Fermilab’s MTA surface muon beam and muonium production could be competitive with PSI in terms of muonium production rate. A future PIP-II-based facility would surpass PSI capabilities by at least two orders of magnitude.

MUONIUM PHYSICS AND APPLICATIONS

There is great interest in using muonium to test our fundamental theories of physics:

- QED – as muonium is a purely leptonic system, the complexities and uncertainties from hadronic interactions and finite-size effects are absent. High-precision spectroscopy with increased muonium rates will provide improved tests of QED [2]. Discrepancies could lead to investigation of new physics beyond the Standard Model of particle physics.
- Charged Lepton Flavor Conservation – increased muonium rates will permit a significantly improved search for muonium/anti-muonium oscillation, which in some models is more likely than the $\mu N \rightarrow eN$ process sought by the Mu2E experiment at Fermilab [3]. The current experimental limit on this doubly charged-lepton-flavor violating process is over 24 years old [4]. We know that the three neutrino flavors mix, but that is a negligible contribution here, giving a low-background search for new physics.
- Antimatter gravity – there has never been an experimental measurement of the gravitational attraction between any lepton or antilepton and the Earth. The antimuon constitutes 99.7% of the mass of the muonium atom. While there are theoretical reasons to expect the gravitational behavior of antileptons to be the same as that of matter in general, this is the only feasible gravitational test using leptons or a 2nd-generation particle. Despite the recent observation at the CERN Antiproton Decelerator of antihydrogen gravitational acceleration downwards consistent with 1g [5], antimuon gravity is well worth a direct measurement [6].
- Very Cold Muon Source – ionizing muonium can yield a very low-emittance μ^+ source. That would yield an ultra-slow μ^+ beam, which is of interest for µSR and tests of fundamental physical theories. This is the technique proposed for the J-PARC $g-2$ experiment [7].

The existence of a facility providing a muonium beam with high rates will be a game-changer for these experiments. At present the primary use of surface-muon beams is for the commercial analysis of material surfaces (µSR), and it is quite possible that the existence of such a muonium facility will induce researchers to develop techniques that use muonium as a new type of probe for the analysis of surfaces – potentially giving access to material properties and data beyond those of standard µSR.

TECHNICAL APPROACH

Our approach to producing muonium from surface μ^+ is based on several observations:

- Any μ^+ that stops in liquid helium below ~800 mK has a large probability to bind with an electron and become muonium (see Fig. 2).
- The decay of muonium provides an easily identifiable signature.
- Muonium is chemically indistinguishable from hydrogen, except for its lower mass.
- Hydrogen is immiscible in superfluid helium, and atoms that reach the surface are ejected perpendicular to its surface, due to the difference in chemical potential.

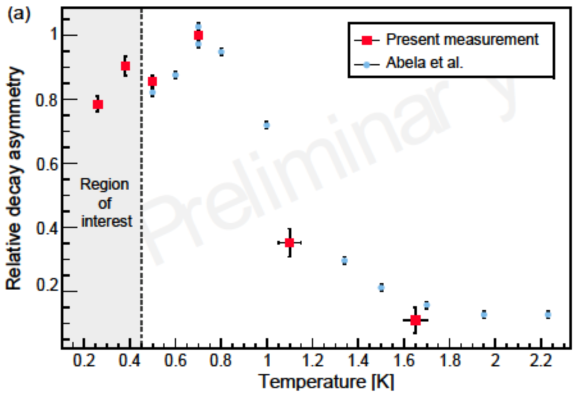


Figure 2: Muonium production vs. temperature in liquid helium (from [8]). The decay asymmetry shown is approximately equal to the fraction of muonium/μ^+.

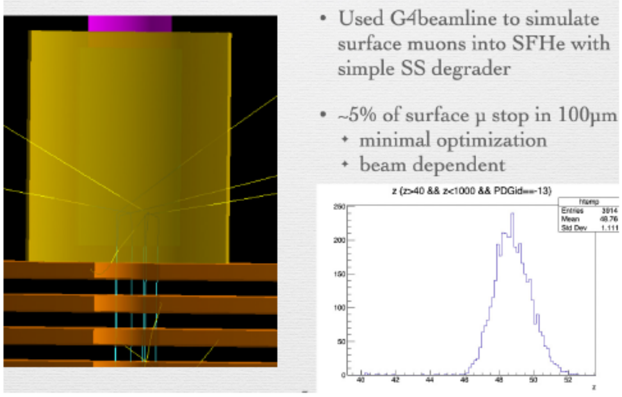
Calculations (experimentally verified for deuterium [9]) of this expulsion yield a narrow velocity distribution centered at 6,300 m/s and reasonably low transverse emittance [10]. Note that the temperature must be less than ~500 mK so that the helium vapor pressure has minimal effect on the muonium beam [8].

- The idea is to arrange it so μ^+ stop at the upper horizontal surface of a film of superfluid helium, where they convert to muonium and are ejected into the vacuum.

- To increase the probability of μ⁺ stopping at the surface, trap electrons at the surface to create an *E* field that propels to the surface any μ⁺ that would have stopped lower down. Maintaining electrons on the surface is an established technique [11].
- That means a superfluid helium bath $>$ 100 microns thick can be used.
- To get many μ⁺ to stop in the superfluid helium bath, start with surface muons, which inherently have a narrow energy spread, and use a carefully designed and optimized degrader to reduce their kinetic energy and maximize the fraction that stop in the SFHe bath (see Fig. 3).

Note these values have had only minimal optimization, to establish that the approach will work. Phase I of the project, in which we will thoroughly optimize the design parameters, is now funded. The key optimization is of the material and thickness of the degrader so that the initial surface muon beam will experience the appropriate ionization energy loss to maximize the fraction of muons that stop in the SFHe.

The overall concept is shown in Fig. 4.



- Used G4beamline to simulate surface muons into SFHe with simple SS degrader
- ~5% of surface μ stop in 100μm
  - minimal optimization
  - beam dependent

Figure 3: G4beamline [12] simulation of a stainless-steel degrader/cryostat beam-entry window preparing surface μ⁺ to stop in a 100-μm-thick superfluid helium bath.

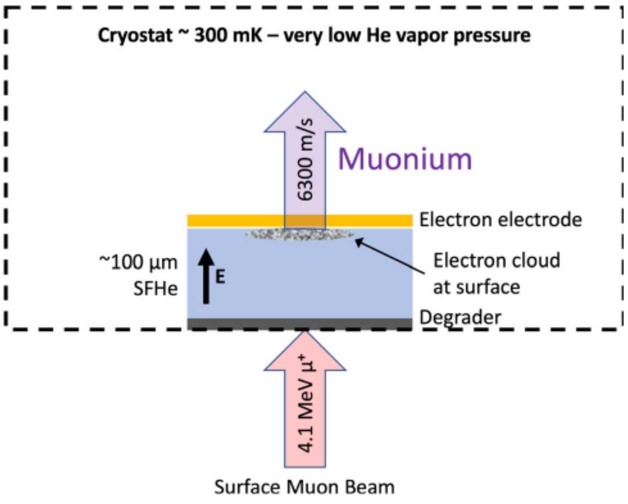


Figure 4: Overall muonium beam production concept starting from a surface muon beam. Muonium formation in the volume of the SFHe is inhibited because the E field keeps the muons moving, so they stop and form muonium at the surface where the muonium atoms can be ejected (the *E* field terminates at the electron cloud at the surface). The degrader must be designed to maximize the number of μ⁺ that stop in the SFHe near the surface (not to scale).

CONCLUSIONS

The availability of a muonium beam facility will be a game changer for muonium experiments. It will be especially valuable in the PIP-II era at Fermilab, with the potential for rates up to two orders of magnitude higher than any surface muon or muonium production at existing facilities. Importantly, the proposed critical R&D at Fermilab's 400 MeV Linac also has the potential to provide production rates comparable to the current highest rates of muonium production in the world.

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