Efficient Method for Cold Muonium Negative Ion Production

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Abstract. A new, efficient method to produce cold negative muon ions is proposed. The muonium atom is made up of an antimuon and an electron and is given the chemical symbol Mu. A second electron with binding energy or electron affinity of 0.75 eV makes the Mu- ion, which is in many ways almost identical to the H- ion that is used for charge-exchange injection into most proton particle accelerators. Muonium negative ions were observed in 1987 by interaction of muons with a foil. Using the foil charge-exchange approach, the efficiency of transformation of muons to negative muonium ions has been very low ~10^{-4}. However, by using a hot tungsten or palladium single crystal foil treated by cesium deposition, the production efficiency can be improved up to 50%. The process described here has surface muons focused onto a tungsten or palladium single crystal foil (that can be heated up to 2000 Celsius) and partially covered by a cesium layer up to minimal work function. The negative muon ions can be extracted by a DC electric field and further accelerated by a linac and stripped in a thin foil.

INTRODUCTION

It has been more than 45 years since muon colliders and muon storage rings were proposed [1,2,3]. Interest in muon colliders increased significantly following the development of ionization cooling as a method to rapidly cool muon beams. Several workshops were held in the 1980s and 1990s, and in 1997 the Muon Collider Collaboration was formed, which later became the Neutrino Factory and Muon Collider Collaboration (NFMCC). By the late 1990's muon collider and neutrino factory design efforts were well-established worldwide. In 2007 the International Design Study for a Neutrino Factory (IDS-NF) was initiated. In 2011, muon R&D in the United States was consolidated into a single entity, the Muon Accelerator Program (MAP) [4,5]. In 2014, the P5 Committee lowered the priority for Muon Collider work, terminating further MAP funding [6].

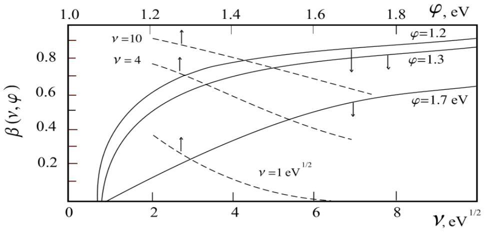
The work described below represents continued interest by the Industrial Community, often supported in the past by SBIR and STTR grants [7], to develop new ideas for intense, cooled muon beams that are useful for colliders, neutrino factories, energy and intensity frontier experiments, as well as commercial applications such as a muon microscopy, muon spin spectroscopy, cargo scanning and tomography.

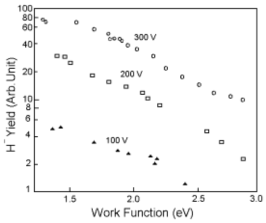
In the following sections we first describe the present technique for Mu+ production. We then our proposed new approach that avoids the use of a complex laser by taking advantage of adding cesium to the foil and offers the prospect of increased production efficiency [8]. Improvement estimates are made with comparisons to H- and positronium negative ion production. Finally, we discuss possible locations and uses for testing the proposed approach.

COLD MUONIUM NEGATIVE ION PRODUCTION

Ultra-slow muons up to now have been generated by resonant ionization of thermal muonium atoms (Mu) generated from the surface of a hot tungsten foil placed at the end of an intense surface muon beam line. In order to efficiently ionize the Mu near the W surface, a resonant ionization scheme via the 1s-2p unbound transition has been used. The low emittance muon beam has been discussed in several scientific reports [9, 10, 11, 12]. A complex laser system has been used to efficiently ionize the Mu near the W surface [10,12]**.**

Cesiation is the addition of a small admixture of cesium to a gas discharge, increasing negative ion emission and decreasing electron emission below that of the negative ions [13,14,15,16,17]. Cesiation decreases the surface work function and increases the probability for back scattered and sputtered particles to escape as negative ions. It is difficult to control the surface work function during the discharge [18].





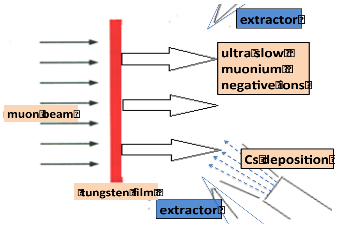


FIGURE 1. Calculated probability of sputtered and reflected particles escaping as H$^-$ as function of work function and as function of speed of escaping [19,20].

FIGURE 2. Dependence of H$^-$ production on the work function of the Mo surface in cesiated hydrogen discharge for different bias voltages [8].

FIGURE 3. Schematic diagram of ultraslow muonium negative ion production.

As shown by Kishinevskii [19,20], when atoms approach the metal surface, the electron affinity level goes down and widens. If the surface work function is not significantly greater than the electron affinity, at some distance from the surface, the electron affinity becomes lower than the Fermi level and an electron can jump from the metal into the electron affinity level. If such a negative ion moves fast enough away from the surface, the additional electron cannot tunnel back with any significant probability. This probability was calculated by Kishinevskii [19,20]. Calculations are presented in [8,20].

Fig. 1 shows the calculated probability of sputtered and reflected particles escaping as H$^-$. For a realistic work function $\varphi > 1.7$ eV, the probability, β^-, of a negative ion forming on the metal surface is proportional to the escape velocity of the ejected ion v (transverse to the surface) and inversely proportional to the surface work function less the affinity, as shown in Fig 1 for low velocities; at larger velocities, it saturates.

$$\beta^- = 0.12\,(v-v_o)/(\varphi-S),$$

where $v_o=(\varphi-S)^{1/2}$ in $(eV)^{1/2}$, $(\varphi-S)$ is in eV. Fig. 2 shows the dependence of the H$^-$ production on the work function of the Mo surface in cesiated hydrogen discharge for different bias voltages (escape velocities) [18], as shown in Fig 1.

To find the total ionization coefficient we must integrate β^- (v) with the distribution function of the ejected particles with respect to the velocity $v(R_0)$. The integration should be carried out over all particles whose kinetic energy exceed φ-S in the perpendicular direction. This is the energy that a negative ion must have in order to overcome the attraction toward the surface by image forces and to depart from the distance R_0 to infinity.

POSITRONIUM NEGATIVE ION PRODUCTION

Reference [21] describes the observed significant increase of positronium negative ion emission after deposition of cesium on a surface of tungsten single crystal. In [22] was proposed to use this effect for control of a surface work function in surface plasma sources.

Positronium negative ions are created when a positronium atom escaping from metal captures an electron from the surface. Regarding H$^-$, the probability of formation of positronium negative ions strongly depends on the surface work function. In publication [21] was observed significant increase of positronium negative ion emission after deposition of cesium on a surface of tungsten single crystal.

NEW MUONIUM PRODUCTION SYSTEM

For production of muonium negative ions, a high energy proton (deuteron) beam is first injected into a primary pion production target made of 20-30 mm thick, disc-shaped, isotropic graphite. Most positive muon beams are generated from pions stopped at the inner surface layer of the primary production target and decaying at rest, hence the common name, surface muons. The muon is emitted isotropically from the pion with momentum 29.8 MeV/c and kinetic energy 4.119 MeV (in the rest frame of the pion).

The intensity of the surface muon beam can be estimated from the number of pions stopped near to the surface. The extraction angle of two beam transport lines is 60 degrees relative to the proton beamline (forward) direction.

The required acceptance of the beam transport line is evaluated to be about 100 msr. The transported muon beam will be focused onto a palladium single crystal foil target to produce muonium negative ions. The transmission efficiency of the beamline is preferred to be as high as possible. The focused beam spot size at the foil is required to be less than 4 cm in diameter. Achieving the smallest beam spot size increases the slow muon beam intensity. A schematic of a system for production of slow muonium negative ions is shown in Fig. 3. The principle component of this system is a single crystal of tungsten or palladium with deposition of cesium and extraction system. The work function can be controlled by photo effect registration.

The target should be able to be flashed up to 2500 C. Enclose should be heated for outgazing. Mu mesons can be converted into muonium negative ions by impact of the muons flux to thick palladium single crystal with deposited part of monolayer cesium. The muonium negative ions escaping the crystal can be accelerated. Muonium negative ions can be accelerated up to 30-50 keV and directed to stripping foil and accelerated again as muons or can be accelerated to injection energy of, for instance, a g-2 experiment.

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