# COLD MUONIUM NEGATIVE ION PRODUCTION

Vadim Dudnikov*, Mary Anne Clare Cummings, Rolland Paul Johnson, Muons, Inc, IL, USA
Andrei Dudnikov, BINP, Novosibirsk, Russia

*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 [1,2] 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 [3,4,5]. 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) [6,7]. In 2014, the P5 Committee lowered the priority for Muon Collider work, terminating further MAP funding [8].

The work described below represents continued interest by the Industrial Community, often supported in the past by SBIR and STTR grants [9], 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 present 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. Improvement estimates are made with comparisons to H- and positronium negative ion production. We describe conceptually how the system would work. 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 [10,11,12,13]. A complex laser system has been used to efficiently ionize the Mu near the W surface [10,11].

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 [14,15,16,17,18]. 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 [19]. We will be using photoemission measurements to regulate cesium deposition.

### *Positronium Negative Ion Production*

Reference [20] describes the observed significant increase of positronium negative ion emission after deposition of cesium on a surface of tungsten single crystal. In [21] was proposed to use this effect for control of a surface work function in surface plasma sources.

A positronium negative ion, Ps-, is a bound system consisting of a positron and two electrons. The binding energy of positronium is I= 6.9 eV. The binding energy of the additional electron in a positronium negative ion, the affinity, is S=0.32 eV [22].

Positronium negative ions are created when a positronium atom escaping from metal captures an electron from the surface. In regard to $H^-$, the probability of formation of positronium negative ions strongly depends on the surface work function. When corrections beyond the third level were included for the first time, the $Ps^-$ decay rate was found to be 2.087963(12) $ns^{-1}$.

* vadim@muonsinc.com

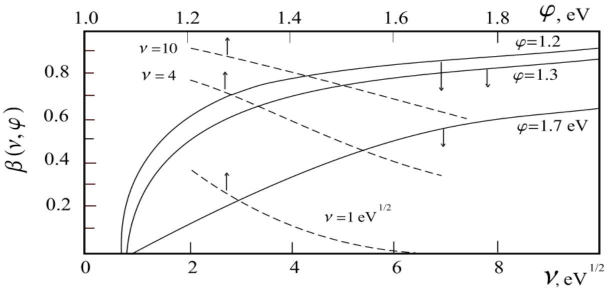


Figure 1: Calculated probability of sputtered and reflected particles escaping as $H^-$ as function of work function and as function of speed of escaping.

As shown by Kishinevskii [23,24], 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 [21,22].

The probability of negative ion neutralization at a distance R from the surface is (in atomic units):

$$W(R) = B^2\gamma\Gamma^2(1-\lambda)e^{-\frac{1}{2\gamma}}(\frac{R}{2\lambda})^{2\lambda}e^{-2\gamma R}$$

where $\gamma = 0.236$, $(\gamma^2/2)= S$ is an electron affinity in atomic units, $\lambda = 1/(4\sqrt{2\varphi})$, φ is the work function, $B = 1.68$ is the coefficient in the wave function of the electron in a hydrogen negative ion far away from the surface $\Psi \approx \left(\frac{B\sqrt{2\gamma}}{\sqrt{4\pi}}\right)(\frac{e^{\gamma r}}{r})$, and Γ is the gamma function.

The ionization coefficient is

$$\beta^- = exp - \int_{R0}^{\propto} W(R)\frac{dR}{v_\perp(R)} =$$

$$exp - \frac{B^2\Gamma^2(1-\lambda)}{2v_\perp R_0}\sqrt{\frac{\varphi}{U_0}}e^{-\frac{1}{2\gamma}}(\frac{R_0}{2\lambda})^{2\lambda}e^{-2\gamma R_0}$$

where $R_0 = \frac{1}{4(\varphi-S)}$, $U_0$ is the depth of the potential well in the metal, $v_\perp(R)$ is the speed of the negative ion escaping from the surface at a point of $R_0$. For Mu- the ionization coefficient should be higher than for H- because its speed is higher for the same escaping energy.

Fig. 1 shows the calculated probability of sputtered and reflected particles escaping as $H^-$. For a realistic work function φ > 1.7 eV, the probability, $\beta^-$, 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 $(eV)^{1/2}$, (φ-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) [19], as shown in Fig 1.

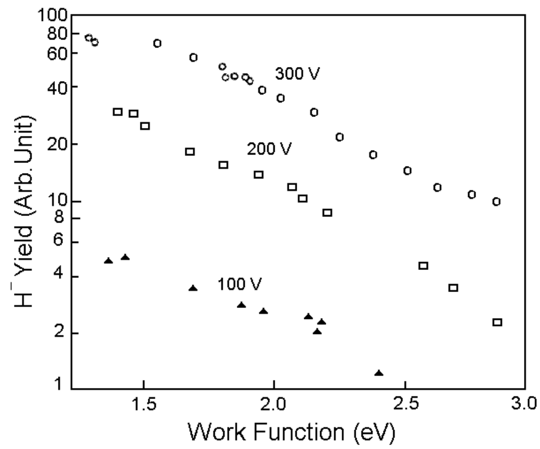


Figure 2: Dependence of $H^-$ production on the work function of the Mo surface in cesiated hydrogen discharge for different bias voltages [19].

To find the total ionization coefficient we must integrate $\beta^-$ (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.

### *Muonium Negative Ion Production*

For production of muonium negative ions, a proton (deuteron) beam is first injected into a primary pion production target made of 20-30 mm thick, disc-shaped, isotropic graphite. About 5% of the proton beam is consumed in the target. 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 isotopically 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, taking into account the extraction angle for an effective surface-muon-emission rate of 15,000 muons/s. 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.


ISBN 978-3-95450-182-3

## NEW MUONIUM PRODUCTION SYSTEM

A schematic of our proposed 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 using photoelectric emission to regulate the cesium deposition.

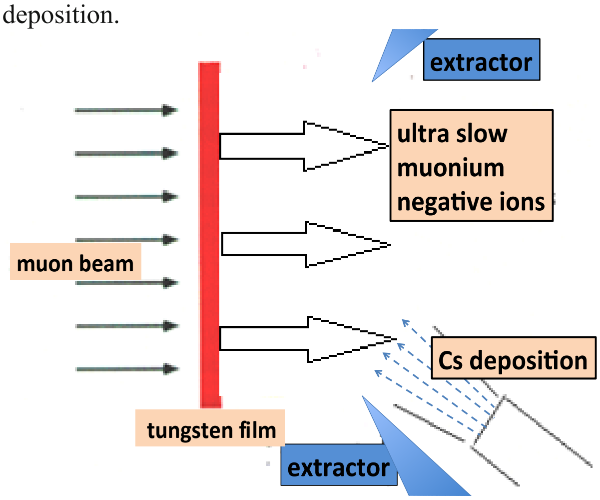


Figure 3: Schematic diagram of ultraslow muonium negative ion production.

The target should be able to be flashed up to 2500 C. The enclosure should be heated for degassing. Mu mesons can be converted into muonium negative ions by the 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 up to 30-50 keV and directed to the stripping foil and accelerated again as a bright muon source, or can be accelerated to the injection energy of, for instance, a g-2 experiment.

A proposed location for this system is at J-PARC, in the so called U-Line, which consists of a large acceptance solenoid made of mineral insulation cables (MIC), a superconducting curved transport solenoid magnet and a superconducting axial focusing magnet system [10,11]. There, it is possible to collect surface muons with a large acceptance of 400 mSr. Compared to the conventional beamlines such as D-Line, the large acceptance of the front-end solenoid will allow for the capture of more than 10 times intensity pulsed muons [10]. With a muon capture of $5 \times 10^8$/s surface muons, can be collected $2 \times 10^8$/s surface muons on the W target in the Mu chamber, with an approximate transport efficiency of 40%.

The 29.8 MeV/c muon beam will be focused onto the palladium target. The muonium negative ions are formed by electron capture of μ+ near the surface of the hot palladium foil with cesium. Then the muonium negative ions can be evaporated to the vacuum with thermal velocity. By producing muonium, the μ+ beam will be effectively stopped, yet maintains its polarization. The electrons are then stripped from the muonium negative ions using thin foil. The ultra-cold muons produced this way will be fully polarized, with small transverse momentum.



## REFERENCES

[1] Y. Kuang, K.-P. Arnold, F. Chmely, et al., “First observation of the negative muonium ion produced by electron capture in a beam-foil experiment”, Physical Rreview A, Volume 35, 3172 (1987).
[2] Y. Kuang, K.-P. Arnold, and F. Chmely, et al., “Formation of the negative muonium ion and charge-exchange processes for positive muons passing through thin metal foils”, Phys. Rev. A, general physics, Third Series, Volume 39, 6109 (1989).
[3] G. I. Budker, —Accelerators and colliding beams, 7th International Conference on High-Energy Accelerators, Yerevan, USSR, 27 Aug - 2 Sep 1969, p. 33, extracts in AIP Conf. Proc. 352 (1996) 4; G. I. Budker, —Research work on the colliding beams of the Novosibirsk Institute of Nuclear Physics (present state of experiments and perspectives), 15th International Conference on High Energy Physics, 26 Aug - 4 Sep 1970, Kiev, USSR, p. 1017, extracts in AIP Conf. Proc. 352 (1996) 5.
[4] A E. A. Perevedentsev and A. N. Skrinsky, Proc. 12th Int. Conf. High Energy Accelerators (1983).
[5] D. Cline and D. Neuffer, “A Muon Storage Ring for ν Oscillations Expts,” AIP Conf. Proc. 68 (1980).
[6] http://map.fnal.gov
[7] Issue Editor: M. A. Palmer, Editor in Chief: W. Chou ICFA Beam Dynamics Newsletter, No.55, 2011.
[8] http://science.energy.gov/~/media/hep/hepap/pdf/May-2014/FINAL_P5_Report_Interactive_060214.pdf.
[9] R.P.Johnson, “Industry Role for Advanced Accelerator R&D,” IPAC2016, Busan, Korea, http://accelconf.web.cern.ch/AccelConf/ipac2016/papers/weib06.pdf
[10] M. Yoshida , F. Naito, S. Artikova, Y. Kondo, Hayashizaki, , Y. Iwashita, K. Torikai, , ”Re-acceleration of Ultra Cold Muonin J-Parc MLF”, WEPWA018 Proceedings of IPAC2015, Richmond, VA, USA, (2015).
[11] Y. Miyake · Y. Ikedo · K. Shimomura · P. Strasser · N. Kawamura · K. Nishiyama, A. Koda · H. Fujimori · S. Makimura · J. Nakamura · T. Nagatomo · R. Kadono, E. Torikai · M. Iwasaki · S. Wada· N. Saito · K. Okamura · K. Yokoyama · T. Ito, W. Higemoto, Hyperfine Interact, 216, p.79, 2013.
[12] M. Bogomilov et al, The MICE Collaboration, JINST 7, P05009, 2012 Proceedings of IPAC2016, Busan, Korea TUPMY002 03.
[13] Sayyora Artikova, Fujio Naito, Mitsuhiro Yoshida, PASJ2013 Proc. (Nagoya, Japan, 2013), SAP045
[14] V. Dudnikov, SU Author Certificate, C1.H01 3/04, No. 411542, 10 March,1972, http://www.fips.ru/cdfi/reestr_rupat.htm; patent number 411542.
[15] Yu.I. Belchenko, G.I. Dimov and V.G. Dudnikov, A powerful injector of neutrals with a surface-plasma source of negative ions, *Nucl. Fusion,* 14, 113 (1974).
[16] V.Dudnikov, Forty years of surface plasma source development, Rev. Sci. Instrum. 83, 02A708 (2012).
[17] V. Dudnikov, P. Chapovsky, and A. Dudnikov, Cesium control and diagnostics in surface plasma negative ion sources, Rev. Sci. Instrum. 81, 02A714 (2010).

[18] V. Dudnikov and R. P. Johnson, "Cesiation in highly efficient surface plasma sources", Physical Review Special Topics - Accelerators and Beams 14, 054801 (2011)
[19] M. Wada, K. H. Berkner, R. V. Pyle, and J. W. Stearns, Photoelectric work function measurement of a cesiated metal surface and its correlation with the surface produced H− ion flux, J. Vac. Sci. Technol. A 1, 981 (1983).
[20] Y. Nagashima, T. Hakodate, A. Miyamoto and K. Michishio, Efficient emission of positronium negative ions from Cs deposited W(100) surfaces, *New Journal of Physics* 10 (2008) 123029 (7pp) (2008); http://www.njp.org/
[21] V. Dudnikov and A. Dudnikov, "Positronium Negative Ions For Monitoring Work Functions of Surface Plasma Source", NIBS 2016, Oxford, UK, 2016.
[22] Drake G W F and Grigorescu M 2005 *J. Phys. B: At. Mol. Opt. Phys.* 38 3377
[23] M.E. Kishinevskii, Zh. Tekh. Fiz. 45, 1281 (1975); translated in Sov. Phys. - Tech. Phys. 20, 799 (1975).
[24] M. E. Kishinevskii, Sov. Phys. Tech. Phys. 23, 458 (1978).




ISBN 978-3-95450-182-3