Development of negative muonium ion source for muon acceleration

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A negative muonium ion (Mu^-) source using an aluminum foil target (Al target) was developed as a low-energy muon source. Mu^- ions are produced by irradiating the Al target with a 3-MeV positive muon (μ^+) beam and observed using a microchannel plate. An experiment to produce Mu^- ions was conducted to evaluate the performance of this Mu^- ion source. The measured event rate of Mu^- ions was $(1.7 \pm 0.3) \times 10^{-3} \text{ Mu}^-/\text{s}$ when the event rate of the incident μ^+ beam was $1.3 \times 10^6/\text{s}$. The experiment was conducted at the Muon Science Establishment, D-line in the Materials and Life Science Experimental Facility within the Japan Proton Accelerator Research Complex. The formation probability, defined as the ratio of the Mu^- ions to the incident muons on the Al target, was $(1.1 \pm 0.2(\text{stat})_{+0.0}^{-0.1}(\text{syst})) \times 10^{-6}$. This Mu^- ion source was first adopted in the commissioning of the muon accelerator at the D-line, and the event rate of the accelerated Mu^- ions was consistent with the expectation. This Mu^- ion source boosted the development of the muon accelerator, and the practicality of this low-energy muon source obtained using a relatively simple apparatus was demonstrated.

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I. INTRODUCTION

A negative muonium ion ($\text{Mu}^-; \mu^+ e^- e^-$) [1–3] is the bound state of one positive muon (μ^+) and two electrons (e^-) and is known to be produced in a vacuum by irradiating an aluminum foil target (Al target) with a μ^+ beam. Mu^- ion production has primarily been studied in the context of atomic physics, for example, as it pertains to the Lamb shift because Mu^- ions are analogous to negative hydrogen ions. In this experimental study, we focus on the fact that Mu^- ions are emitted with a small kinetic energy of approximately $O(10^{-1})$ keV and propose a new usage of Mu^- ions as a method to cool muon beams.

Typically, muon beams produced with accelerators have been used to research particle physics and in studies

regarding materials and life science, for example, using the muon spin rotation, relaxation, and resonance (μSR) method [4]. However, since muons are produced as tertiary beams via the decay of pions originating from the primary proton beam reacting with the target nuclei, the emittance of muon beams is intrinsically large. A novel muon beam with a small emittance has been long sought-after to achieve a precision measurement of the muon dipole moment in particle physics [5]. Moreover, such a beam has potential use in research regarding the new phenomena around the interface of the sample for materials and life science [6,7].

In the precision measurement of the muon dipole moment project in the Japan Proton Accelerator Research Complex (J-PARC E34), a muon beam with $p_l/p_t < 10^{-5}$, where p_l is the longitudinal momentum, and p_t is the transverse momentum, is required to reduce systematic uncertainties when using a new method. This unique muon beam is obtained by producing ultra-slow muons (USMs) with a mean energy of 0.02 eV from the surface muon beam (which is produced from the pion decay stopped around the surface of the muon production target) and then reaccelerating the

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USMs using a linac. We call this muon beam a reaccelerated thermal muon beam. The laser-resonant ionization of the muonium atom ($\text{Mu}; \mu^+ e^-$) [8–10] was developed to obtain USMs. To obtain slow muons, several methods like so-called moderator method [1,11–13] were often utilized. However, the laser-ionization method is adopted due to the synthesis of the J-PARC pulsed muon beam.

A reaccelerated thermal muon beam requires both the beam cooling, like that caused by an USM source, and a muon accelerator [14–19]. These two important techniques should be developed individually in a timely manner for the early realization. However, to develop a muon accelerator, muons with low energy are required; with exception of USM source, few low-energy muon sources exist. Therefore, in this study, a Mu^- ion source using an Al target is investigated as a pseudo-USM source. For example, since a radio-frequency quadrupole (RFQ) linac, which is applied to the initial accelerator of the muon linac [16,20], requires an input energy of 5.6 keV, the Mu^- ion source, the energy of which is less than 1 keV, is suitable for the RFQ after electrostatic preacceleration. Although the formation probability of the Mu^- ion source is smaller than that of USMs, and its transverse emittance is larger ($O(10^{-3})$ and approximately 1π mm mrad, respectively, for USMs) [5], the Mu^- ion source is highly superior in terms of easy handleability.

To apply the Mu^- ion source to the muon acceleration, the formation probability of the Mu^- ion is quite important to estimate the beam transmission efficiency. The precursor study [2] inspires us to apply the Mu^- ion emission from metal surfaces to the ion source of the accelerator. To realize this in the practical experimental apparatus, the detailed understanding is necessary concerning the Mu^- ion emission rate, the energy, and the emission angle distribution. To conduct the commissioning of the muon accelerator in a realistic period, the emission rate of Mu^- ions was needed to be $O(1)$ Mu^-/s on the rear surface of the Al target. In this study, the event rate of the produced Mu^- ion beam was measured and the result was compared with the Monte-Carlo simulation where the practical condition from the incident muon beam to the detector was reproduced. It is the essential information to evaluate the beam transmission in the commissioning of the muon accelerator using our Mu^- ion source. In this paper, first, the experimental setup is described in Sec. II. Next, the simulation is described in Sec. III, and the experimental results are described in Sec. IV. The measured formation probability of Mu^- ions is discussed in Sec. V, and the conclusion is presented in Sec. VI.

II. EXPERIMENTAL SETUP

The Mu^- ion production experiment was carried out at the muon experimental facility known as the Muon Science Establishment (MUSE), D-line in the J-PARC Materials and Life Science Experimental Facility [7]. The event rate

of the incident μ^+ beam in this experiment was $1.3 \times 10^6/\text{s}$ ($5.2 \times 10^4/\text{pulse}$ with a repetition rate of 25 Hz). The momentum of the incident μ^+ beam was set to 25 MeV/c to maximize the number of the μ^+ 's stopped at the downstream surface of the Al target. The momentum spread of the D-line was 4% in RMS (root-mean-square).

Figures 1 and 2 are schematic drawings; the former shows the experimental apparatus, and the latter shows the Al target and an electrostatic acceleration and focusing system called the Soa lens [21]. The incident μ^+ beam passes through a stainless steel window (SUS window) with a thickness of 50 μm , which separates the vacuum of

FIG. 1. Schematic drawing of an experimental setup of the Mu^- ion production experiment. A detailed description of the diagnostic beamline is given in the text.

FIG. 2. Schematic drawing of the Al target and the Soa lens.

the D-line and experimental apparatus, and a Kapton (Dupont inc.) degrader with a thickness of $150\ \mu\text{m}$ to decelerate the μ^+ 's. Then, the μ^+ 's were injected into the Al target with a purity of 99% and a thickness of $200\ \mu\text{m}$. The Kapton degrader was used for the fine adjustment of the stopping range of the μ^+ 's because the density of the Kapton is smaller than that of the Al target. Both the Kapton degrader and the Al target were rectangular with the dimension of $43 \times 35\ \text{mm}^2$; the degrader was layered on the upstream side of the Al target, and both were mounted on the target holder. To measure the time at which the μ^+ 's entered the Al target, a beam counter composed of three plastic scintillation boards was positioned near the Al target. The dimensions of these boards, beginning with the one nearest to the Al target, were $3 \times 3.5 \times 0.5$, $6 \times 6.5 \times 0.5$, and $6 \times 5.5 \times 1\ \text{mm}^3$, respectively.

The Soa lens consisted of five electrodes: Target, S1, S2, S3, and S4. The Mu^- ions were accelerated to 20 keV to be transported through a diagnostic beamline. For 20-keV acceleration, the applied voltages of the Target, S1, S2, and S3 electrodes were 20.0, 18.9, 18.0, and 16.0 kV, respectively, while the S4 was grounded. The S1 was the mesh electrode, and its open aperture ratio was 85%. The Al target and the Soa lens were the main components of the Mu^- ion source. The RFQ was connected to the downstream of the Soa lens when the Mu^- ions were accelerated with the RFQ.

The Mu^- ions were transported using the diagnostic beamline and detected with a microchannel plate (MCP) located downstream of the diagnostic beamline. The diagnostic beamline consisted of one electrostatic deflector (ED), five electrostatic quadrupoles (EQs), and one bending magnet (BM). The Mu^- ion beam contained μ^+ 's that had penetrated the Al target, decay positrons from the μ^+ 's, and low-energy electrons produced by the field emission around the electrodes. These backgrounds should be distinguished from the Mu^- ions using both kinetic energy and momentum information. They were suppressed by combining the ED and the BM. Voltages of $\pm 5\ \text{kV}$ were applied to each electrode to bend the 20-keV Mu^- ion beam. The magnetic field of the BM was 250 Gauss with an applied current of 16.3 A.

The Mu^- ions were detected with an MCP, Hamamatsu F2225-21P308 [22]. The diameter of the effective area was 40 mm, and the open aperture ratio of the channels was 60%. The MCP has a high sensitivity for low-energy muons [23,24]. The waveform from the MCP was recorded with a waveform digitizer, CAEN V1720 [25]. The hit timing and pulse height were extracted from the waveform. The 25-Hz reference trigger from the J-PARC accelerator was used for the trigger of the digitizer. The incident μ^+ 's reached the Al target approximately $1\ \mu\text{s}$ after the start of the sampling.

The formation probability of the Mu^- ions was determined by the measured event rate of Mu^- ions. The relationship between the event rate of incident μ^+ 's at

the just upstream of the chamber of the Al target, $R_{\text{inc } \mu^+}$, and the event rate of the Mu^- ions measured with the MCP, R_{Mu^-} , is described as

$$R_{\text{Mu}^-} = R_{\text{inc } \mu^+} \times \varepsilon_{\text{form}} \times \varepsilon_{\text{mesh}} \times \varepsilon_{\text{beam}} \times \varepsilon_{\text{MCP}}, \quad (1)$$

where $\varepsilon_{\text{form}}$ is the formation probability of the Mu^- ions, $\varepsilon_{\text{mesh}}$ is the transmission efficiency of the mesh electrode S1 in the Soa lens, $\varepsilon_{\text{beam}}$ is the beam transport efficiency through the Soa lens and the diagnostic beamline including the acceptance of the Al target, and ε_{MCP} is the detection efficiency of the MCP.

III. SIMULATION

A series of simulations were conducted to estimate the characteristics of the diagnostic beamline and the ratio of μ^+ 's irradiated on the Al target to the total number of incident μ^+ 's. First, the D-line was simulated with the G4beamline [26,27]. The initial distribution of the surface muon beam was generated at the downstream surface of the muon production target. The horizontal and vertical positions are defined as x and y , respectively. The initial position distribution was calculated from the size of the primary proton beam injected into the muon production target. The momentum distribution was calculated from the relation of $dN_\mu/dp \propto p^{2.6}$ (See the Appendix) derived from the Bethe-Bloch formula [28], where dN_μ was the number of the muons per momentum p , assuming that the stopping distribution of the pion in the muon production target was uniform. The initial angular distribution was assumed to be isotropic because the surface muon was produced from the decay of the stopped pion. Figure 3 shows the simulated beam-profile distribution of the μ^+ 's transported to the Al target using the G4beamline.

Next, the beam transportation of the diagnostic beamline for the Mu^- ions produced at the Al target was simulated.

FIG. 3. Simulated beam-profile distribution of surface muons at the Al target. The dotted rectangle is a region of the Al target.

First, the initial distribution of the μ^+ 's was generated at the upstream surface of the Kapton degrader. A two-dimensional Gaussian distribution in the two transverse dimensions based on the measured beam size at this position was used. The energy loss and the multiple scattering in the Kapton degrader and the Al target were simulated using *musrSim* [29], a simulation program for μ SR that can easily simulate the transportation of the muon beam. The energy (velocity) and angle distribution of the μ^+ 's at the downstream surface of the Al target, $f_{\mu^+}(v, \theta)$, was obtained, where v and θ are the velocity and the angle of the μ^+ 's, respectively.

Assuming that the process of Mu^- ion production is similar to the charge exchange process of the hydrogen atom [30], the energy and angle distribution of the Mu^- ion, $f_{\text{Mu}^-}(v, \theta)$, is described as

$$f_{\text{Mu}^-}(v, \theta) = f_{\mu^+}(v, \theta) Y_{-/+}(v), \quad (2)$$

FIG. 4. Generated two-dimensional distribution for the Mu^- ions in terms of the kinetic energy and the emission angle. The number of generated events is 10^6 events. The emission angle obtained by the horizontal direction of the momentum vector is drawn. The distribution in the vertical direction is similar.

where $Y_{-/+}(v)$ is an experimental abundance ratio of the H^- with respect to the H^+ from Ref. [30].

Figure 4 shows the two-dimensional distribution of the Mu^- ions in terms of the kinetic energy and the emission angle using Eq. (2). This distribution was transported using *musrSim*. Electromagnetic field distributions of the Soa lens, the ED, the BM, and the EQs were calculated using OPERA [31] and implemented in *musrSim*. The beam transport efficiency of the Mu^- ions through the Soa lens and the diagnostic beamline including the acceptance of the Al target, ϵ_{beam} , was evaluated based on the simulation, that was 2.3×10^{-3} . The decay loss of the Mu^- ion was included in this efficiency. The dominant beam loss occurred around the Soa lens due to the large initial emittance of the Mu^- ion beam. Normalized RMS horizontal and vertical emittance at the Al target were 25π and 21π mm mrad, respectively, as shown in Fig. 5, while those at the exit of the Soa lens were 9.3π and 8.4π mm mrad, respectively. The kinetic-energy acceptance of the diagnostic beamline was evaluated to be 1.4% (RMS).

Misalignment of the beamline components could be the major systematic uncertainty in the transmission efficiency. Thus, the effect of the possible case was examined. Each beamline component was confirmed to be aligned within ± 0.5 mm using the survey system during the assembly. The error of ϵ_{beam} was evaluated using simulations where typical cases of misalignment were reproduced. Compared with the ideal situation, ϵ_{beam} was reduced by 10% in the worst case, where all the components were assumed to be shifted to the same direction in the transverse plane and their effects of misalignment were piled up. Therefore, ϵ_{beam} was evaluated as $(2.3^{+0.0}_{-0.2}(\text{syst})) \times 10^{-3}$.

IV. RESULTS

The Mu^- ion was identified by measuring the time of flight (ToF) and the pulse height using the MCP. The ToF is defined as the time difference between the hit timing of the

FIG. 5. Simulated phase-space distributions of the Mu^- ion beam on the downstream surface of the Al target. The top and the bottom figures show the horizontal and vertical phase spaces, respectively. The number of generated events is 10^6 events. The average kinetic energy of the Mu^- ions was selected: 1 keV ($\beta\gamma = 0.0044$).

MCP and the arrival time of the incident μ^+ 's at the Al target. As described in Sec. II, the arrival time was determined using the beam counter by detecting the positrons from the μ^+ 's decayed at the Al target. Timing calibration between the beam counter and the MCP was conducted using prompt positrons. Many positrons are generated at the muon production target together with the μ^+ 's. Passing through the D-line at the speed of light, these positrons arrive at the experimental area before the μ^+ 's; as such, they are called prompt positrons. Prompt positrons can be used as a time reference for the ToF because they are observed with both the beam counter and the MCP almost simultaneously.

Background events are suppressed using the pulse-height information of the MCP. The particles with opposite charges and different kinetic energies and momenta from the Al target can be suppressed with the ED and the BM. However, a lot of decay positrons from the μ^+ 's remained in the MCP signal because they could directly reach the MCP from anything of the beamline components, penetrating the vacuum chamber wall. By applying the pulse-height cut, Mu^- -like events can be distinguished because the pulse height of the muon is higher than that of the decay positron [23,24].

Figure 6 shows two-dimensional distribution of the ToF and pulse height for the extraction mode of negatively charged particles in the Soa lens and the diagnostic beamline. The signal region was defined as ± 3 standard deviations (300 ns) of the pulse width of the incident μ^+ 's with respect to the expected arrival time of the Mu^- ions at the MCP, while in the sideband region, the background events were dominant. The μ^+ 's decelerated through the Al target could be observed with the MCP in the positive extraction mode. The decelerated μ^+ 's were used to confirm the ToF of the Mu^- ions because the energy of

transported μ^+ 's was identical as that of the Mu^- ions. Although decelerated μ^+ 's had a wide energy distribution, the diagnostic beamline was able to select the intended energy with limited energy acceptance. The mass of the μ^+ 's is nearly identical to that of the Mu^- ions; thus, the ToF of the decelerated μ^+ 's is equal to that of the Mu^- ions. The decelerated μ^+ 's were observed in the same signal region as the Mu^- ions; therefore, the large-pulse-height events in the signal region of Fig. 6 were confirmed to be the Mu^- ion events. Many Mu^- -like events with large pulse heights were observed in the signal region of Fig. 6, while smaller pulse-height events were observed in the sideband region.

The net pulse-height distributions of the decelerated μ^+ 's and the Mu^- ions were derived by subtracting the pulse-height distribution in the sideband region from that in the signal region of the two-dimensional distributions. Figure 7 shows the derived net-pulse-height distributions of the decelerated μ^+ 's and the Mu^- ions. The pulse-height distributions of the Mu^- ions and the decelerated μ^+ 's should be identical. The threshold of the pulse-height cut was set to 100 mV, which was low enough to have no effect on the formation probability of Mu^- ions, as discussed below.

Figure 8 shows the ToF spectra of the slow μ^+ 's and Mu^- ions after the pulse-height cut was applied. Peaks around 300 ns were prompt positrons contaminated in the surface muon beam. The extended log-likelihood method [32] was used to evaluate the number of Mu^- ions, and MINUIT [33] was used as the minimizer of the fitting. Probability density functions of the signal, f_{sig} , and the background, f_{bg} , were assumed to be the Gaussian and the exponential function, respectively, defined as follows:

FIG. 6. Two-dimensional distribution of the ToF and the pulse height of the negative extraction. The number of incident μ^+ 's was 2.7×10^{10} .

FIG. 7. Comparison of subtracted pulse-height distributions for decelerated μ^+ 's and Mu^- ions. The histograms were normalized based on the number of total events. The green arrow indicates the threshold level applied to obtain ToF spectra shown in Fig. 8.

FIG. 8. The ToF spectra for the positive extraction (top) and negative extraction (bottom). The red dotted line in the negative extraction indicates the fitted function, and the green histograms indicate the simulated ToF distributions. Numbers of incident μ^+ 's for positive and negative extractions were 3.4×10^{10} and 2.7×10^{10} , respectively. Peaks around -300 ns were prompt positrons contaminated in the surface muon beam.

$$f_{\text{sig}}(t; p_{\text{sig}}, a, \sigma) = \frac{p_{\text{sig}}}{\sqrt{2\pi}\sigma^2} e^{-\frac{(t-a)^2}{2\sigma^2}}; \quad (3)$$

$$f_{\text{bg}}(t; p_{\text{bg}}) = p_{\text{bg}} C_{\text{bg}} e^{-\frac{t}{\tau}}, \quad (4)$$

where p_{sig} and p_{bg} are the number of signal and background events, respectively; a and σ are the mean and standard deviation of the Gaussian in the signal function, respectively; C_{bg} is the normalization constant in the background function; and τ is the lifetime of the muon. The fitting parameters are p_{sig} , p_{bg} , a , and σ . The fitting results of the Mu^- ions are shown in the bottom of Fig. 8 and indicated by the red dotted lines. The green histogram is the ToF distribution obtained by the simulation described in the previous section. The fitted ToF of the Mu^- ions was 636.9 ± 7.1 ns, and the number of events for the Mu^- ions was 36.6 ± 7.5 . The number of beam pulses of incident μ^+ 's used for the analysis was 5.5×10^5 for the negative extraction. The total data taking time for the measurement was 2.2×10^4 s for the Mu^- ions. Therefore, the measured event rate was $(1.7 \pm 0.3) \times 10^{-3}$ Mu^-/s .

V. DISCUSSION

The formation probability of the Mu^- ion is evaluated using Eq. (1). Table I shows the summary of the evaluation of the Mu^- ion production. As shown in Sec. II, $R_{\text{inc } \mu^+}$ was 1.3×10^6 μ^+/s . Based on the simulation in Sec. III, ϵ_{beam} was $(2.3^{+0.0}_{-0.2}) \times 10^{-3}$. The ϵ_{mesh} was 8.5×10^{-1} , and ϵ_{MCP} was 6.0×10^{-1} from their open aperture ratios. The R_{Mu^-} was $(1.7 \pm 0.3) \times 10^{-3}$ Mu^-/s ; therefore, ϵ_{form} can be evaluated to be $(1.1 \pm 0.2(\text{stat})^{+0.0}_{-0.1}(\text{syst})) \times 10^{-6}$. The evaluated

formation probability satisfied the requirement for the commissioning of the accelerator.

This developed Mu^- ion source was successfully applied in a separate work of the muon acceleration experiment with the RFQ [34]. Applying the method of the evaluation in the total efficiency that was established in the present study, the efficiency in the acceleration experiment was determined to be 2.5×10^{-4} with the beam losses in the Soa lens, RFQ, and the diagnostic beam line for the acceleration experiment but without the formation probability. The beam rate of incident μ^+ 's was 2.5×10^6 μ^+/s in the acceleration experiment; therefore, the expected event rate of accelerated Mu^- ions was $(6.8 \pm 1.2(\text{stat})^{+0.0}_{-0.4}(\text{syst})) \times 10^{-4}$ Mu^-/s , considering the formation probability from this result of the Mu^- ion production experiment. Errors of the expected rate are predominantly originating from that in the formation probability determined by the present study. The measured event rate of the accelerated Mu^- ions was $(5.1 \pm 0.8) \times 10^{-4}$ Mu^-/s , so the measured event rate was consistent with the expected rate within the range of errors.

TABLE I. Summary of the evaluation of the Mu^- ion production.

Term	Symbol	Value
Event rate of Mu^- ion	R_{Mu^-}	$(1.7 \pm 0.3^a) \times 10^{-3}$
Event rate of incident μ^+	$R_{\text{inc } \mu^+}$	1.3×10^6
Form. prob. of Mu^- ion	ϵ_{form}	$(1.1 \pm 0.2^{a-0.0b}_{+0.1}) \times 10^{-6}$
Trans. of mesh electrode	ϵ_{mesh}	8.5×10^{-1}
Trans. of Mu^- ion beam	ϵ_{beam}	$(2.3^{+0.0b}_{-0.2}) \times 10^{-3}$
Detection eff. of MCP	ϵ_{MCP}	6.0×10^{-1}

^astatistical error.

^bsystematic error due to the misalignment.

VI. CONCLUSION

A Mu^- ion source using an Al target was developed as a low-energy muon source. This Mu^- ion source can directly produce a cooled Mu^- ion beam from the surface muon beam using a simple apparatus essentially composed of an Al foil only. The Mu^- ion emission from the metal surface was studied by the precursor study [2], and this phenomenon was first applied to the ion source for the accelerator. In the Mu^- ion production experiment, the measured event rate and the formation probability of the Mu^- ions were $(1.7 \pm 0.3) \times 10^{-3} \text{ Mu}^-/\text{s}$ and $(1.1 \pm 0.2(\text{stat})_{+0.0}^{-0.1}(\text{syst})) \times 10^{-6}$, respectively. Using this Mu^- ion source, the accelerated Mu^- ions were successfully observed in the first demonstration of the muon acceleration with the RFQ [34]. The measured event rate of the accelerated Mu^- ions was consistent with that of the simulation. This Mu^- ion source is an essential and practical device for the development of a muon accelerator, and its reliability was experimentally confirmed by the actual commissioning of the accelerator.

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APPENDIX: CALCULATION OF SURFACE-MUON-MOMENTUM DISTRIBUTION

The surface muons are emitted from pions stopping near the surface of the muon production target, and their momentum distribution is known to be expressed by a power function of the momentum [35]. The cutoff of the muon momentum distribution has a maximum edge of 29.8 MeV/c. The momentum distribution reflects the energy loss of the muon in the muon production target, and thus is approximated by the 2.6th power of the momentum. We derive the momentum distribution of the surface muon from the generic Bethe-Bloch formula [28], which is described as

$$-\frac{dE}{dx} = \frac{G}{\beta^2} \ln\left(\frac{2m_e c^2 \beta^2}{I}\right), \quad (\text{A1})$$

where $G \equiv 4\pi e^4 N Z / m_e c^2$; e is the charge of the muon; m_e is the mass of the electron; N and Z are the density and the atomic number of the absorber, respectively; β is defined as $\beta = v/c$, where v is the velocity of the muon, and c is the speed of light; and $I \approx 10Z$ (eV) is the ionization energy of the absorber. The relation between the energy E and the momentum p of the muon is $E = \sqrt{(m_\mu c^2)^2 + (pc)^2}$, where m_μ is the mass of the muon. Thus, the energy deposit is related to momentum loss:

$$-\frac{dE}{dx} = \frac{pc}{E} \left(\frac{dp}{dx}\right). \quad (\text{A2})$$

Substituting Eq. (A2) into Eq. (A1), dE/dx can be converted to dp/dx as

$$\frac{dp}{dx} = -\frac{G}{\beta^3} \ln\left(\frac{2m_e c^2 \beta^2}{I}\right). \quad (\text{A3})$$

The logarithm function in Eq. (A3) is approximated by the power function. The Maclaurin expansion centered on $\beta = \beta_0$ for $f(\beta) \equiv \ln(2m_e c^2 \beta^2 / I)$ is

$$\begin{aligned} f(\beta) &= \ln\left[\frac{2m_e c^2 \beta_0^2}{I} (1+h)^2\right] \\ &= C + 2\ln(1+h) \\ &= C + 2\left(h - \frac{h^2}{2} + \dots\right) \\ &= C\left(1 + \frac{2}{C}h - \frac{1}{C}h^2 + \dots\right), \end{aligned} \quad (\text{A4})$$

where $h \ll 1$, $\beta = \beta_0(1+h)$ and $C = \ln(2m_e c^2 \beta_0^2 / I)$. When the approximate function of $f(\beta)$ is $g(\beta) \equiv A\beta^\alpha$, where α is the real number and A is an arbitrary constant, the Maclaurin expansion of $g(\beta)$ is

$$\begin{aligned} g(\beta) &= A\beta_0^\alpha (1+h)^\alpha \\ &= A\beta_0^\alpha \left[1 + \alpha h + \frac{\alpha(\alpha-1)}{2!}h^2 + \dots\right]. \end{aligned} \quad (\text{A5})$$

Higher-order terms in Eq. (A4) and (A5) are negligible due to $h \ll 1$. Thus, in case of $f(\beta) \approx g(\beta)$, based on a comparison between coefficients of first-order terms in Eq. (A4) and (A5), α is calculated as

$$\alpha = \frac{2}{C} = 2 \left[\ln\left(\frac{2m_e c^2 \beta_0^2}{I}\right) \right]^{-1}.$$

In case of the surface muon, $\beta \sim 0.25$, α is calculated as $0.3 \sim 0.4$; thus, dp/dx is typically described as

$$\frac{dp}{dx} \propto p^{-2.6}.$$

The number of the surface muons per momentum, $\Delta N/\Delta p$, is $\Delta N/\Delta p = (\Delta N/\Delta x)(\Delta p/\Delta x)^{-1}$, where $\Delta N/\Delta x$ is the number of the muons at a certain region Δx , assuming the stopping distribution of the pion in the muon production target is uniform. Finally, the momentum distribution of the surface muon is calculated as the function of

$$\frac{dN}{dp} \propto p^{2.6}.$$

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