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Rapid Communications

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Generation of slow positive muons from solid rare-gas moderators

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We observe the emission of slow positive muons (μ^+) from solid neon, argon, krypton, and xenon moderators exposed to a 4.2-MeV incident μ^+ beam. The time-of-flight spectra for all of the targets studied exhibit a narrow distribution with no delayed component. Energy spectra obtained from the time-of-flight data indicate a maximum below ~ 10 eV with a tail extending to higher energies. The data suggest a slowly thermalizing muon emission mechanism, implying a long diffusion length for low-energy μ^+ in these solids. Of the targets measured, argon was observed to produce the highest yield ($\sim 10^{-5}$ slow μ^+ per incident μ^+), providing a useful flux for further experimentation.

It would be very useful to have beams of slow positive muons (μ^+) analogous to the slow positron beams now employed in a variety of solid-state and atomic physics experiments.[1] Thus, we are searching for a way to moderate the energetic (4.2 MeV) μ^+ that are available from stopped pion decay at a number of accelerators.[2] Our first successful moderator[3] is single-crystal LiF which has an efficiency of a few parts in 10^7 for converting fast μ^+ into slow μ^+ and into muonium negative ions ($\mu^+e^-e^-$ or Mu^-). In this Rapid Communication we report that the solid rare gases are more efficient muon moderators (by about 2 orders of magnitude) and could be used to make a practical slow μ^+ beam.

The choice of LiF and the rare-gas solids as possible slow μ^+ moderators was made by drawing guidance from previously reported positron results. A large e^+ emission probability is now attributed to the emission of slowly thermalizing positrons with energies below the ~ 10-eV inelastic thresholds for positronium and electron-hole pair formation.[4-6] Energetic positive muons slow down rapidly in condensed media by ionization until the velocity of the μ^+ becomes comparable to that of the valence electrons.[7] At lower velocities, the cross sections for electronic processes are significantly reduced.[8] Because of this, there should be no analogous sharp thresholds for muonium (μ^+e^- or Mu) and electron-hole pair formation for slow muons in insulators. At ~ 10 eV the energy loss should therefore be dominated by phonon excitation, resulting in a comparatively small energy loss per unit distance dE/dx. Thus, low-energy muons should have a relatively long diffusion length in insulators and should be able to escape with high efficiency. Unlike the alkali halides, rare-gas solids do not support optical phonons (fcc lattice), possibly making dE/dx even smaller in the low-energy thermalization region. The present work is motivated by the positron results mentioned, the interest in understanding better the energy-loss mechanisms involved at near thermal velocities, and the desire to obtain an efficient slow μ^+ moderator.

Energetic (4.2 meV, $\Delta E \approx 20\%$, 350000/s) positive muons for the M20(B) secondary channel at TRIUMF were incident on a cold target assembly. A scintillation counter upstream of the target was used to detect the incident muons. The incident beam momentum was tuned so that the stopping distribution was centered at the downstream surface of the target. An electrostatic immersion lens, immediately downstream from the target, collected and accelerated to 10 keV any low-energy charged particles that emerged from the target. The extracted particles were injected into a magnetic (dipole-quadrupole-quadrupole) spectrometer which momentum selected and focused the 10-keV particles onto a 4-cm-diam channelplate detector. The basic measurement was a time of flight (TOF) between the incident μ^+ counter and the channelplate detector. The gap (≈ 3.5 mm wide) between the target surface and the immersion lens was forward biased at two different voltages: +500 and +9.45 V. The higher value was used in determining the total yield, while the lower one allowed a better determination of the energy spectrum.

Several improvements have been made to the apparatus since the previous work on LiF was reported.[3] In particular, the vacuum has been improved to provide a routine operating range down to 5×10^{-9} T, the quadrupoles were redesigned to give a larger acceptance, and the large diameter (4 cm) channelplate was introduced. Monte Carlo calculations, assuming uniform distributions in energy (50 eV wide), emission angle, and origin position on the target surface, give the acceptance of the beam transport as $\approx 80\%$. Assuming the detection efficiency of the channelplate to be $\approx 50\%$ for 10-keV muons, the experimental efficiency is, thus, estimated to be about 40%. The experimental time resolution, determined in the same manner as previously reported,[3] was found to be about 3.5 ns full width at half maximum (FWHM), with no long-time tails observed.

The cold target consisted of a rectangular stainless-steel helium reservoir having two 0.025-mm-thick stainless steel windows through which the muons pass. The windows are separated by 3 mm and have a usable projected area of 25 by 25 mm^2, approximately 3 times smaller than the incident beam spot. The target was cooled by flowing ^{4}He gas or liquid via a transfer line. The moderating gases were condensed at two different rates: one with 1.5×10^{-5}-mbar partial pressure for 15 s and another at 1.5×10^{-4}-mbar partial pressure for a period of 1.5 s, both corresponding to about 150 atomic layers.[9] To condense argon, krypton, and xenon only the cold helium vapor was required, whereas for neon, it was necessary to have liquid in the helium reservoir.

The TOF data for solid argon and krypton are shown in Fig. 1. The data peaked at early times were taken with the target biased at +500 V with respect to the electrostatic lens, and the data peaked at later times were taken with a +9.45-V bias. A small flat background, determined from the integrated rate over a 100-ns interval between 75 and 175 ns, has been subtracted for all of the spectra reported here. We note that the full width at the base of the 9.45-V bias data is about 60–70 ns, which is equal to the time of flight of a μ^+ of zero initial kinetic energy through the gap region between the target and the lens. Any thermal diffusion process would be signified by a $1/\sqrt{t}$ dependence in the late-time TOF,[3] which was not observed. By integrating the 500-V bias data over the region between 350 and 400 ns, the slow μ^+ yield for solid argon [Fig. 1(a)] was found to be $y=(1.8\pm0.2)\times10^{-6}$ per incident fast μ^+. By taking the experimental efficiencies into account, one obtains a yield $y\sim10^{-5}$ slow μ^+ per incident μ^+. For deposition times on the order of a few minutes the yield was observed to be a factor of ~ 2 smaller, but the shape of the TOF flight spectrum was indistinguishable (within statistics) from Fig. 1(a). The data also suggest a reduction in the yield with time after deposition. The smaller amplitude observed in $N(t)$ for krypton [Fig. 1(b)], at short times, as compared to that

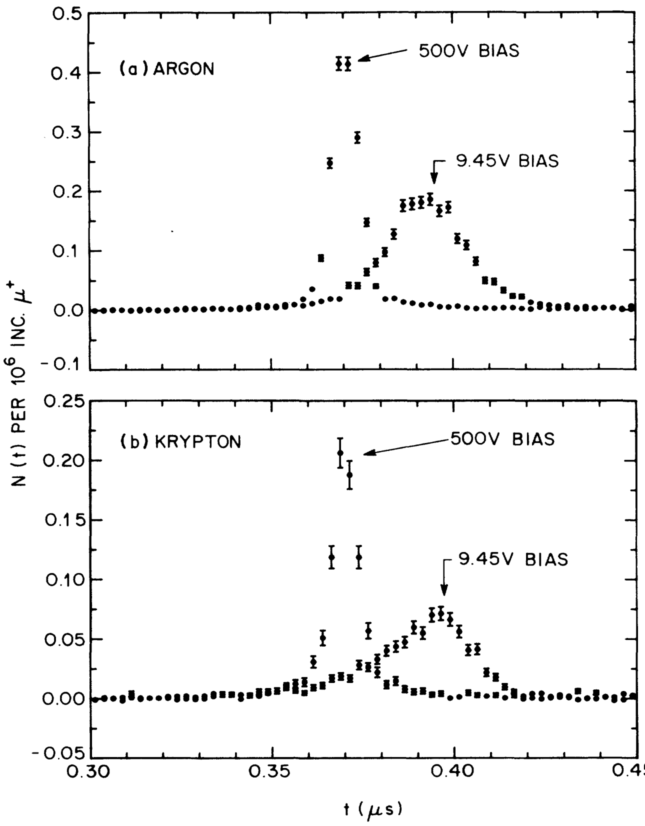

FIG. 1. Slow μ^+ TOF spectra for (a) argon and (b) krypton, with the accelerating bias set at 500 V (data peaked at early times) and 9.45 V (data peaked at late times). The errors shown are purely statistical.

observed for argon, is consistent with a weighting of the krypton energy distribution to lower energies and the larger ionization potential of argon. The yield for solid krypton was found to be $y=(8.9\pm0.4)\times10^{-7}$ per incident fast μ^+.

Solid xenon and neon were also measured and the data were found to be similar in shape to that observed for argon and krypton. In the case of xenon, the yield was found to be $(3.4\pm0.3)\times10^{-7}$ per incident fast μ^+, while the yield for neon was $(1.2\pm0.3)\times10^{-6}$ per incident fast μ^+. The yield for neon might have been substantially reduced by the presence of liquid helium in the reservoir and the associated large variations in stopping density. Indeed, the comparatively large band-gap energy, smaller positron scattering cross section,[10] and the increasing trend in the slow μ^+ yield in going from xenon to argon would lead one to expect neon to have about twice the yield of argon.

Energy distributions corresponding to the TOF spectra were calculated for argon and krypton by applying a Jacobian transformation $N(E_\perp)=-(dE_\perp/dt)^{-1}N(t)$ to the 9.45 V bias data. Here, $E_\perp$ is the energy associated with the perpendicular component of velocity. The resulting distributions indicate a maximum in $N(E_\perp)$ at low energies (~ 5 eV), with a high-energy tail falling off monotonically. Unfortunately, the exact shape of the energy distributions cannot be established at this time, due to the imprecise determination of time zero and the uncertainty in the gap measurement. Our best estimates of the energy spectra (corresponding to a 3.5-mm gap distance) are shown in Fig. 2. Monte Carlo results, assuming this gap dimension and a $\cos^2\theta$ angular emission distribution, also show a maximum in $N(E)$ below 10 eV along with a high-energy tail, in agreement with the Jacobian analysis of the perpendicular component.

As mentioned, the slow μ^+ emission probability for argon was observed to be dependent upon the deposition rate and, possibly, the age of the target. It is likely that contamination by background gases such as H_2 and CO is greater for the longer deposition time, and increases the density of trap sites. As well, a reduction in the yield with time after deposition could be attributed to surface contamination. An improved vacuum and a more stable cryogenic target would therefore be required before the true yield and the energy spectrum could be determined.

An argon yield of $y \approx 2\times 10^{-5}$ corresponds to a hot μ^+ diffusion length of $\lambda = \Delta y \approx 35$ Å in solid argon, where $\Delta R \approx 175$ μm is the μ^+ range width. Using the number density $n = 2.66\times 10^{22}$ cm^{-3} for the argon atoms and our inferred value of λ, we calculate a collision cross section of $\sigma_\mu = (n\lambda)^{-1}(2M_{\rm Ar}/3M_\mu)^{1/2} \approx 2\times 10^{-15}$ cm^2. Here we estimate the number of collisions necessary to lose a significant amount of energy to be $\approx 2M_{\rm Ar}/M_\mu$. Owing to the fact that under ideal conditions y may be larger, and since we are not accounting for Mu formation during thermalization, the σ_μ calculated here is an upper limit. At these low energies, σ_μ should be roughly the same as the zero-energy limit of the e^+ cross section $\sigma_e(0)$. Extrapolating the measurements of Ref. 11 to zero momentum, we find $\sigma_e(0) \approx 1.2\times 10^{-15}$ cm^2, in rough agreement with our estimate for σ_μ. It is interesting that the much smaller zero-energy e^+ cross section for Ne (Ref. 12) would imply a slow muon yield about 5 times larger than the Ar value. Since muons with tens of keV kinetic energy would have a range comparable to the estimated diffusion length, they could be brought to a sharp focus and remoderated[13] to obtain a brighter beam of slow muons with little loss of intensity.

Further possible candidates for efficient slow μ^+ moderators are liquid He and high surface area targets such as ^{4}He-coated silica powder.[14,15] Since the electron affinities of liquid He and solid Ne are negative,[9] the affinity of Mu^- ions could also be negative, and the rare gases might be efficient sources of slow Mu^-. If a moderator were placed near the pion production target, the slow μ^+ rate could be enhanced 100-fold due to the increased efficiency for collecting the fast μ^+. The resulting beam of $\sim 10^3$ slow μ^+/s would have applications including surface diffusion studies,[14,15] electron density measurements near surfaces, microbeam formation,[13] and atomic-physics experiments. Of these, the eventual production of $\mu^+\mu^-$ (Ref. 16) in vacuum is of particular importance since it would provide a unique opportunity for QED studies, owing to the various decay channels available.

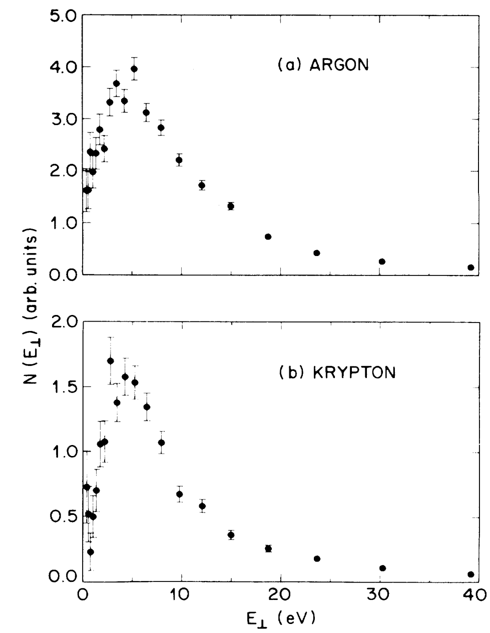

FIG. 2. Energy spectra estimated from the TOF data (9.45-V bias) for (a) argon and (b) krypton. The errors in $N(E_\perp)$ shown are the transformed statistical errors.

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[1]See, for example, *Positron Scattering in Gases,* edited by J. W. Humberston and M. R. C. McDowell (Plenum, New York, 1983).

[2]T. Bowen, Phys. Today **38** (No. 7), 22 (1985).

[3]D. R. Harshman, J. B. Warren, J. L. Beveridge, K. R. Kendall, R. F. Kiefl, C. J. Oram, A. P. Mills, Jr., W. S. Crane, A. S. Rupaal, and J. H. Turner, Phys. Rev. Lett. **56**, 2850 (1986); D. R. Harshman (unpublished).

[4]A. P. Mills, Jr. and W. S. Crane, Phys. Rev. Lett. **53**, 2165 (1984).

[5]E. Gullikson and A. P. Mills, Jr., Phys. Rev. Lett. **57**, 376 (1986).

[6]K. G. Lynn and B. Nielson, Phys. Rev. Lett. **58**, 81 (1987).

[7]J. H. Brewer, K. M. Crowe, F. N. Gygax, and A. Schenck, in *Muon Physics,* edited by V. W. Hughes and C. S. Wu (Academic, New York, 1975), Vol. III.

[8]J. K Berkowitz and J. C. Zorn, Phys. Rev. A **29**, 611 (1974); H. H. Anderson and J. F. Ziegler, *Hydrogen Stopping Powers and Ranges in All Elements* (Pergamon, New York, 1977); S. H. Overbury, P. F. Dittner, S. Datz, and R. S.

Thoe, Radiat. Eff. **41**, 219 (1979); E. Fermi and E. Teller, Phys. Rev. **72**, 399 (1944); P. M. Echenique, R. M. Nieminen, and R. H. Ritchie, Solid State Commun. **37**, 799 (1981).

[9]*Rare Gas Solids,* edited by M. L. Klein and J. A. Venables (Academic, London, 1976), Vol. 1. Rare-gas solids grown from the vapor phase are typically polycrystalline.

[10]W. E. Kauppila and T. S. Stein, in Ref. 1, p. 15.

[11]W. E. Kauppila, T. S. Stein, and G. Jesion, Phys. Rev. Lett. **36**, 580 (1976).

[12]R. P. McEachran, A. G. Ryman, and A. D. Stauffer, J. Phys. B **11**, 551 (1978).

[13]A. P. Mills, Jr., Appl. Phys. **23**, 189 (1980).

[14]D. R. Harshman, Ph.D. thesis, University of British Columbia, 1986 (unpublished) (available from University Microfilms, Ann Arbor, Michigan).

[15]D. R. Harshman, Hyperfine Interact. **32**, 847 (1986).

[16]K. Nagamine (unpublished); A. Ohsaki, T. Wantanabe, K. Nagamine, and K. Iguchi, in *Proceedings of the Ninth International Conference on Atomic Physics, Seattle, Washington, 1984,* edited by R. S. VanDyck, Jr. and E. Norval Fortson (World Scientific, Singapore, 1985); Q. Ma, X. Cheng, Z. Liu, Y. Liu, and T. Wantanabe, in *ibid.*, Abstract A63.