Improvement of rare-gas solid moderators by using conical geometry

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A slow positron beam with narrow energy spread can be obtained by moderating the β^+ decay of a radioactive source. We report here the improvement in the efficiency of the rare-gas solid positron moderators by using a different geometry. The efficiency for slow positrons, ϵ, was measured for the cylindrical and the cone configurations of the moderator with the latter yielding ϵ of $(4.6\pm0.2)\times10^{-3}$ for solid neon deposited on an encapsulated radioactive ^{22}Na source deposited on a 5 μm Cu_{98}/Be_2 window. No corrections were applied for the attenuation caused by the window. The ϵ for the conical configuration is (2.7 ± 0.2) times higher than that for the cylindrical configuration. Other rare-gas solids (e.g., Ar, Xe, Kr) yielded lower ϵ as compared to that for the solid neon in agreement with the earlier measured efficiencies of Mills and Gullikson [Appl. Phys. Lett. **49**, 1121 (1986)].

Since the first slow positron beam of Cherry[1] using moderation of high-energy positrons from a radioactive nuclide, there has been a steady increase in the application of slow positron beams for research in various fields. Generally in order to make moderated positrons the ≈200 keV, positrons from a radioactive source are stopped by a solid sample where they lose energy rapidly by ionization, electron-hole excitation, and finally by positron-phonon scattering. Within a few tens of picoseconds, positrons reach thermal equilibrium with the lattice and some of these thermalized positrons subsequently diffuse to the solid surface, where a fraction of them are emitted with energies of the order of the negative e^+ work function. Slow positrons are useful in a wide range of experiments covering atomic collisions, precision spectroscopy, metallurgy, defects in solids, structure of surfaces, interfaces, charged plasmas, positronium reflection from solid surfaces, and astrophysics.[2,3] Such a vast range of application makes it important to continue the search for more efficient positron moderators. A widely quoted figure of merit for a source and moderator is the efficiency, ϵ, which is defined as the ratio of the low-energy positrons extracted from the moderator to the total number of positrons e^+ being emitted by the radionuclide. The source and moderator efficiency involves source details such as the self absorption of the e^+ in the source material, and the source and moderator geometry as well as the intrinsic properties of the moderator that include moderator material, impurities, defects, and surface cleanliness. The extraction field and transport efficiency also affect the overall performance of a slow positron source.

In this letter we report the improvement in the ϵ of the solid neon moderator when used in the conical geometrical configuration. Previously, moderated positrons were obtained using a chromium-plated mica, smoked MgO, polycrystalline or single crystals, and films as the moderators in the transmission or backscattering mode.[4] However at present, mostly the thin-film positron moderators (e.g., W, Ni) in the transmission mode are used with a ^{22}Na source, which commonly yield ϵ in the range of 10^{-4}.[5] These thin-film single-crystal moderators demand a high quality fabrication with low defect (10^{-6} atomic fraction) and low impurity concentration (e.g., carbon). To achieve such a high ϵ requires great care in cleaning and annealing procedures. Recently ϵ as high as 1.5×10^{-3} has been reported with a single-crystal W cone used in the forward reemission mode with a sealed ^{22}Na source.[6] The inherent problem with all of these moderators is in their preparation and handling complexities. However, the energy spectrum of the emitted e^+ does have a narrow full width at half maximum (FWHM) of $\approx$ 75 meV at room temperature.[7] With the use of rare-gas solids, particularly neon, it has been possible to achieve a better positron efficiency but with a much broader energy spectrum with a FWHM of 0.58 eV.[8] So far, the highest positron ϵ of 7×10^{-3} was reported by Mills and Gullikson for the solid neon moderator, used in the cylindrical configuration[8] with the Ne directly deposited on a ^{22}Na positron source coated with ~2 μm of Krylon. We note that in most instances, ^{22}Na sources have been sealed with a few micron (≈5 μm) titanium windows that absorb more than 40% of the forward emitted positrons from this isotope.[6]

The details of positron emission from rare-gas solids are described elsewhere.[9] In brief, the positrons implanted at high energies will quickly lose energy by ionizing collisions. The wide band gap in insulators imposes a limit on

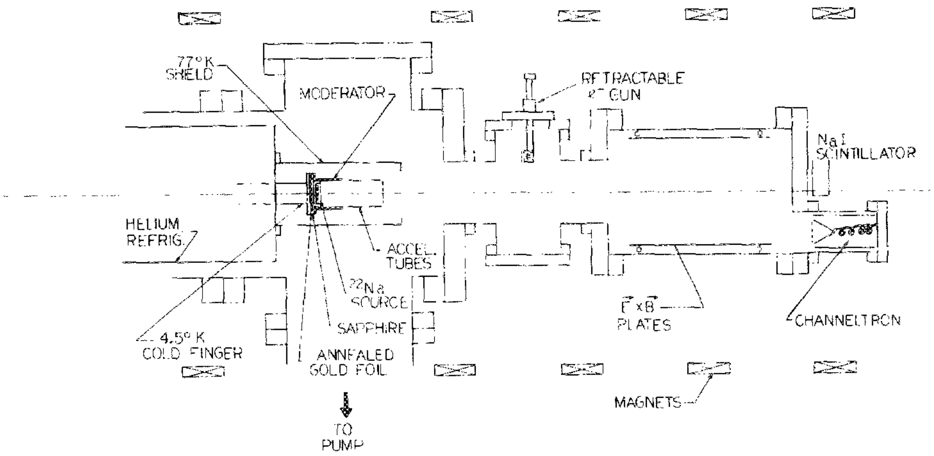

FIG. 1. Magnetically guided e^+ beam. $\mathbf{E} \times \mathbf{B}$ plates are used for selecting energy of the moderated e^-.

the minimum positron kinetic energy below which phonon emission is the only available energy loss mechanism. For energies less than this minimum energy, an implanted positron is very likely to escape from the solid, as the energy loss rate is low while the diffusion rate is high.

We have tested a neon moderated beam at Brookhaven National Lab using a 35O μ Ci ^{22}Na sealed source deposited on a 5 μm Cu_{98}/Be_2 window. A schematic of the experimental setup is shown in Fig. 1. The ^{22}Na positron source (0.25 in. diameter on a Cu_{98}/Be_2 window) was in thermal contact and electrically isolated from the cooling system. It was mounted at one end of the magnetically guided beam line. A sapphire plate with an annealed gold gasket was found ideal to provide both thermal contact and electrical isolation from the third stage of the cooling system. A helium refrigerator was used to cool down the source and the moderator assembly to 5–7 K. The axial magnetic field transported the moderated positrons from the source to the detector end. The beam line was maintained in a ultrahigh vacuum (UHV) environment, with a pressure of $\approx 2 \times 10^{-9}$ Torr. The Ne vapor pressure at 7 K is $\approx 10^{-9}$ Torr. In order to avoid contamination of the rare gases and hence of the moderator, the gas injection line was made UHV compatible and was maintained in the same pressure range as the beam line. The Ne gas (as well as the other rare gases) was deposited at the source/moderator assembly and the moderated positrons were extracted from the moderator using a combination of accelerating tubes and a grid assembly (90% transmission). The moderated positrons were extracted with an electric field of $E \approx 100$ V/cm and transported at an energy of 100 eV. An $\mathbf{E} \times \mathbf{B}$ energy filter was used to filter out higher energy e^+. The transport of the beam was optimized by adjusting the magnetic field and the $\mathbf{E} \times \mathbf{B}$ filter. The slow positrons were counted using a channel electron multiplier (CEM) and a 3 in. × 3 in. NaI(Tl) detector in coincidence. The ratios of coincidences and the single counting rates of CEM and NaI(Tl) were used to measure the detector efficiencies and thus the absolute slow positron counting rate. The background contribution from the coincidence and the single rates was removed by taking the difference between the counting rates with the beam on and the beam off.

As it is very easy to fabricate solid rare-gas solids in unusual geometries (e.g., perforated plane, cylindrical, conical, parabolic, venetian blind, cylindrical rings etc.), a number of cylindrical moderators in backscattering geometry with different aspect ratios (defined as the ratio of length to the diameter), a combination of cylindrical geometry with a venetian blind of annealed polycrystalline Cu foils (thickness ≈ 7 μm) and the truncated conical configuration moderator made of oxygen-free high-conductivity (OFHC) copper were investigated. Here OFHC copper was used especially for its good thermal conductivity and its future use with a ^{64}Cu radioactive source.[8] However this can be substituted with any other material with high atomic number (Z) and good thermal conductivity (e.g., Au, Pt etc.). The cross section together with dimensions for these moderators are shown in Fig. 2. The thickness of the solid neon is one of the parameters that influences ϵ of the Ne moderator (shown in Fig. 3.). Measurements for a cylindrical surface with an aspect ratio of 2 indicated that the ϵ for moderation increases as a function of the thickness of the solid Ne and was observed

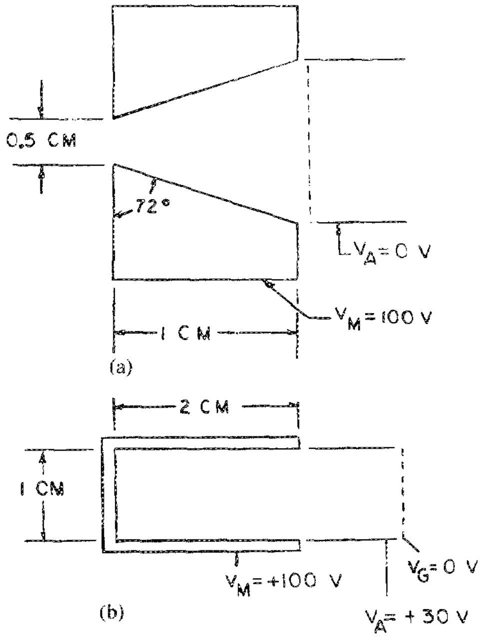

FIG. 2. Cross-sectional view of conical and cylindrical moderator.

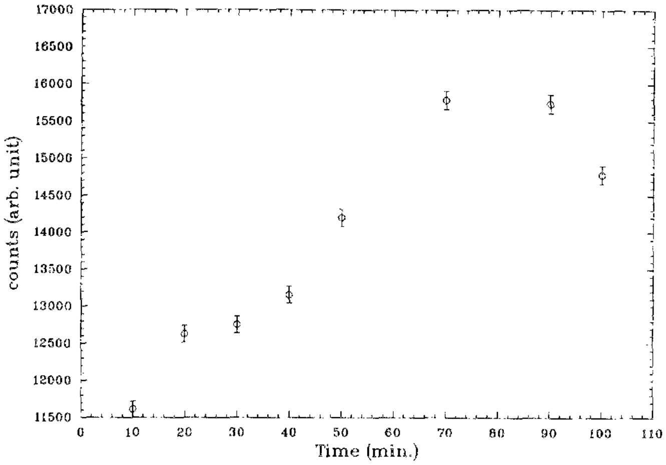

FIG. 3. Slow moderated e^+ counts vs time as neon was deposited onto ^{22}Na@3.2×10^{-4} Torr.

to rise steadily to a maximum value, in agreement with the observations of Mills and Gullikson.[8] To attain this, high-purity (99.9995% from Matheson Gas Products) Ne gas was injected in to the vacuum system at a rate of 3.2×10^{-4} Torr for about ≈ 80 min. The conical OFHC copper cup ϵ with Ne was measured to be $(4.6\pm 0.1)\times 10^{-3}$, while for the cylindrical cup[8] with an aspect ratio of 2 was $(1.7\pm 0.1)\times 10^{-3}$. It should be stressed here again that these quoted ϵ were measured for a cylindrical moderator with a sealed ^{22}Na source (sealed with 5 micron Cu_{98}/Be_2 window) as compared to the $\epsilon \approx 7\times 10^{-3}$ for a bare ^{22}Na source coated with a thin layer of Krylon. Comparison between the ϵ for cylindrical and conical geometrical configurations with the same aspect ratio of 2 and extraction voltage of 100 eV indicated that the conical moderator performed better by a factor of (2.7 ± 0.2) than the cylindrical moderator. One of the reasons for this improved performance for conical moderator might be that slow positrons were extracted[6] more efficiently in this particular geometrical configuration. It was also observed that the other rare-gas solids (e.g., Ar, Xe, Kr) were $\sim 1/6$ as efficient as solid Ne in the cylindrical configuration moderator with the same aspect ratio, in agreement with the results of Mills and Gullikson.[8] We were unable to observe any enhancement in the ϵ of the neon moderator when a venetian blind foil configuration was inserted into the cylindrical moderator. One of the reasons for this might have been that we were unable to deposit enough Ne layers on the surface of the foils.

One of the motivations for this project was also to further investigate the feasibility of the neon moderator for use with an intense ^{64}Cu radioactive source to obtain a high flux beam of moderated positrons. The use of ^{64}Cu would involve vacuum depositing the ^{64}Cu on the conical/cylindrical surface and condensing neon gas (or other rare gases) on it to act as a moderator. Therefore, it is important to know the efficiency ϵ for a bare source such as ^{22}Na for these particular geometrical configurations. We find that with conservative error estimates the ϵ for the encapsulated ^{22}Na source was underestimated by a factor of $\approx(3.1\pm 0.5)$ as compared to that for the bare ^{22}Na source. Thus the corrected ϵ for a Ne moderator in the conical configuration with a bare ^{22}Na source will be $(1.4\pm 0.2)\times 10^{-2}$. For example, the cylindrical moderator corrected to bare ^{22}Na gives $(0.53\ \pm 0.09)\%$ which is in reasonable comparison with the results of Mills and Gullikson.[8]

In conclusion, this study has shown that for a bare source with a conical solid Ne moderator, it should be possible to achieve ϵ as high as $(1.4\pm 0.2)\%$. It is apparent that with improved field extraction techniques (e.g., concentric cylindrical rings connected together with a resistive chain), the cylindrical and other geometrical configurations can provide even better ϵ, although with a much larger ΔE. At present, the Ne moderator in the conical configuration is being used with a 110 m Ci ^{22}Na source to perform low-energy positron-stimulated Auger electron emission spectroscopy (PAES).[10] So far there has been no indication of either radiation damage or charging effects and the moderator has been found to be stable for at least three to four days without regenerating the solid Ne. Using the conical configuration and a linear scaling to the high-flux-beam reactor (HFBR) generated ^{64}Cu source, we estimate that it will be possible to obtain a moderated positron flux[8,11] as high as 10^9–10^{10} e^+/s.

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