Solid neon moderator for producing slow positrons

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Slow positrons can be obtained by moderating the energetic β^+ particles from a radioactive source. We find that solid Ne makes a more efficient moderator than any other material known to date. The efficiency ϵ, defined as the number of slow positrons per β^+ emitted by the source, is $(0.30 \pm 0.02)\%$ for a flat layer of Ne covering a ^{22}Na deposit. In a cylindrical geometry, ϵ is $(0.70 \pm 0.02)\%$, more than twice the previous best efficiency obtained with single-crystal tungsten. The energy spectrum for Ne has a full width at half-maximum of 0.58 eV, somewhat broader than the spectrum of positrons from a single-crystal metal. Moderators made from the other solid rare gases have a much lower efficiency and a larger energy spread.

Slow positrons are useful in a wide range of experiments covering atomic collisions, precision spectroscopy, metallurgy, solids, surfaces, plasmas, and astrophysics.[1] Positrons are created with energies comparable to $mc^2 = 511$ keV by pair production and by the β-decay of certain radioactive isotopes. Slow positrons with energies of order 1 eV are obtained by slowing these energetic positrons in a suitable solid and collecting the escaping low-energy positrons to form a beam. Since the first slow positron beam of Cherry[2] there has been a steady increase in the moderation efficiency from the initial value of $\approx 3 \times 10^{-8}$ to the present day levels approaching 1%. In this letter we describe a new moderator that has more than twice the efficiency of any other, a low atomic number that will make it useful for polarized positron experiments,[3] and an ease of fabrication that frees us from the delicate source plating procedures of the past.[4,5] The neon moderator should allow us to produce a ^{64}Cu slow positron source of gigantic proportions.[6]

The physics of positron emission from the rare gas solids has been described recently.[7] Briefly, positrons implanted at high energies will quickly lose energy by ionizing collisions. Because of the wide band gap there is a minimum positron kinetic energy E_{th} below which the only available energy loss mechanism is phonon emission. Figure 1 is a plot of the positron re-emission probability versus positron implantation energy for a thick target of solid Ne frozen onto a cold finger at a temperature of approximately 5 K. The experimental details are given in Ref. 7. The re-emission probability has a dip at very low energies (≈ 1 eV), is nearly unity between 2 and 10 eV, has a precipitous drop at an energy $E_{th} = 16$ eV, and has sudden increases at energies $E_x = 17.5$ eV and $E_g = 21.5$ eV. We identify E_g and E_x with the incident energy above which a positron may escape from the solid, leaving behind an electron-hole pair or an exciton. E_g is thus the band gap of solid Ne and E_x is less than E_g by the exciton binding energy. E_{th}, the inelastic threshold, is the energy above which positronium formation in the solid becomes possible. The gap and threshold energies are related to the positronium binding energy in the solid E_b and the positron affinity or work function, ϕ_+, by $E_b + \phi_+ = E_g - E_{th}$. For energies less than E_{th} an implanted positron is very likely to escape from the solid because the energy loss rate is low, while the diffusion rate is high. At very low energies the positron has some probability of becoming trapped either in the solid or at the surface. Just below E_{th} the re-emission probability is not quite unity because some positronium formation directly into the vacuum is possible.

The energy spectrum of the positrons emitted from a rare gas solid should extend from zero to E_{th} with a distribution that depends on the initial distribution of positron energies just after falling below the inelastic threshold energy E_{th}, on the phonon energy loss rate, and on the positron implantation depth. Figure 2 shows the positron emission spectrum from solid Ne versus the component of energy normal to the surface under three different conditions: positron implantation at 800 eV and 4800 eV, and positrons implanted directly from a ^{22}Na β^+ source. The spectra become narrower at higher implantation energies because a greater implantation depth means the positrons have had more time to lose energy by phonon emission. The remarkably narrow distribution of positron energies from Ne on ^{22}Na would presumably be even narrower if it were not for a trapping

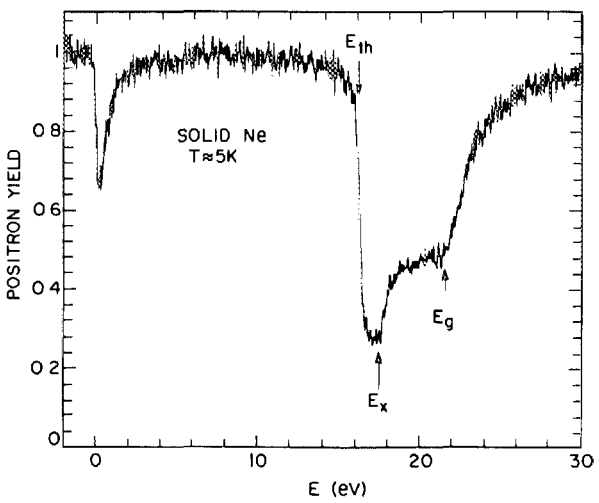

FIG. 1. Slow positron re-emission probability vs implantation energy for a thick sample of neon. The inelastic threshold E_{th}, the exciton threshold E_x, and the band gap E_g are indicated.

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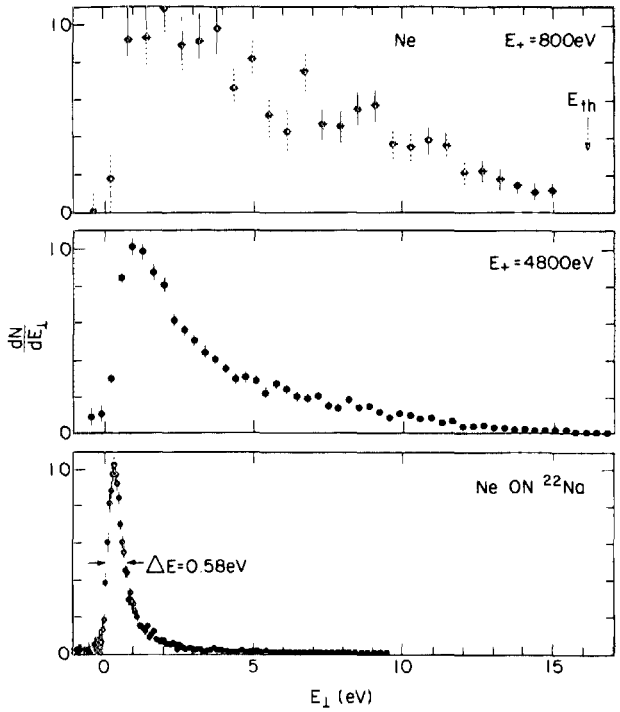

FIG. 2. Energy spectrum of slow positrons re-emitted from solid Ne vs the component of energy normal to the surface. The positrons were implanted into the Ne at (a) 800 eV and (b) 4800 eV. (c) Positrons emitted by a thick layer of Ne covering a 300-μCi ^{22}Na source.

mechanism that inhibits the emission of very low-energy particles. We speculate that this could either be due to positron trapping at the surface or to low-energy positrons not being able to escape from the solid because of the positron affinity being positive.

Some indication of how well the rare gases will function as slow positron moderators is given by the plots in Fig. 3 of the slow positron yield versus positron implantation energy for thick targets of Ne, Ar, Kr, Xe, and Ni. From the figure we determine by linear extrapolation the yield at zero implantation energy y_0 and the energy $E_{1/2}$ at which the yield falls to half of y_0. Solid Ne has the largest values of y_0 and $E_{1/2}$ of any material studied thus far. Tungsten, the best

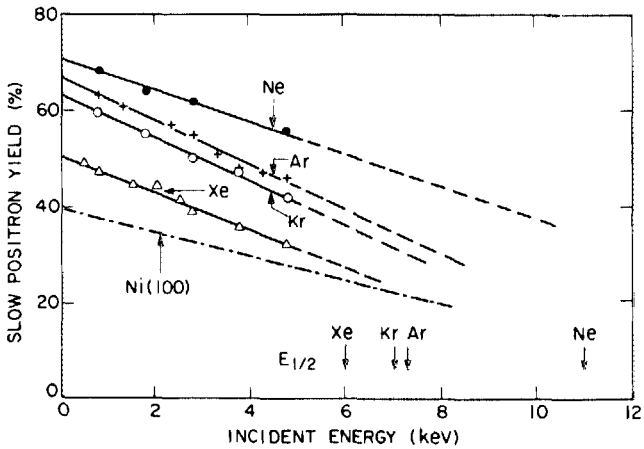

FIG. 3. Positron re-emission probability vs implantation energy for rare gas solids and clean Ni(100). The arrows indicate the implantation energies $E_{1/2}$ at which the yield falls to one-half of its value at $E = 0$.

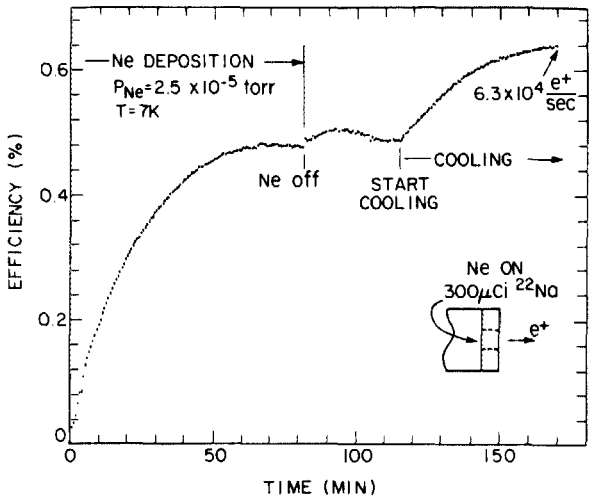

FIG. 4. Efficiency of the ^{22}Na plus solid Ne slow positron source vs time. Neon was condensed onto the ^{22}Na for the first 81 min. The efficiency increased to 0.64% when the source was cooled to $\approx$5 K. The inset shows the source deposit with the efficiency-enhancing cylinder in place.

known single-crystal metallic moderator for producing slow positrons, has an $E_{1/2}$ value comparable to that of Ne, but a y_0 that is much less.

We would thus expect solid Ne to be the best slow positron moderator when judged in terms of efficiency. We deposited a 6-mm-diam 300-μ Ci source of ^{22}Na on the flat face of a 2.5-cm-diam Cu cylinder that could be screwed onto a liquid He transfer refrigerator. The radioactive deposit was coated with a 10-μm-thick layer of "Krylon" plastic spray. The source was installed at one end of our magnetically guided slow positron beam. The slow positrons were detected at the other end with a channel electron multiplier and a NaI(Tl) detector. The ratio of coincidence and singles counting rates was used to determine the detector efficiencies and thus the absolute slow positron counting rates. The background was removed by taking the difference between the counting rates with the source biased at $+20$ and -20 V relative to an analyzer electrode. When the source was covered with a $\approx$50-μm-thick layer of solid Ne we were able to obtain an efficiency, defined as the ratio of the slow positron count rate to the total yield of positrons from the ^{22}Na, of $\epsilon = 0.3\%$.

A solid rare gas can be easily fabricated in unusual geometries. Given the high re-emission probability for energies less than E_{th} exhibited in Fig. 1 and our belief that a backscattering geometry would be preferable to the transmission geometry of our first Ne moderator, we attached a cylindrical Cu extension 8.5 mm i.d. and 7 mm long over the ^{22}Na source as shown in the inset of Fig 4. The moderation efficiency versus time is shown in this figure. Ne was deposited at a pressure of 2.5×10^{-5} Torr and a substrate temperature of $\approx$7 K until the efficiency reached a maximum at 0.48%. The Ne source was then shut off and the pressure in the vacuum system fell to 1.5×10^{-9} Torr. We then found that the efficiency increased to $(0.64 \pm 0.02)\%$ when we cooled the refrigerator to $\approx$6 K by pumping on the exhaust He. We subsequently replaced the cylinder with one that was 16 mm long and obtained an efficiency of $(0.70 \pm 0.02)\%$.

We have probably not attained the best geometry, but

TABLE I. Properties of rare gas solid moderators.

	Ne	Ar	Kr	Xe
Efficiency (%)	0.70(2)	0.13(2)	0.14(2)	0.13(2)
ΔE(eV)	0.58(5)	1.7(2)	1.8(2)	3.2(4)

the cylinder over the source completely eliminated the charging that occurred in the flat source configuration. (The data of Fig 2 were obtained with the cylindrical geometry.) While we were unable to test the stability of the moderator beyond the 3-h capacity of our Dewar and refrigerator, we would expect a decay of the moderation efficiency due to the absorption of contaminants. Given the 10^{-10} Torr base pressure of the vacuum chamber and the use of cryogenic radiation shields, the decay time should be at least a day.

The 0.7% efficiency is more than twice the best value reported before,[8,9] but the 0.58 eV energy width of Fig. 2 is an order of magnitude worse than that obtainable with a cooled single-crystal moderator.[10] Nevertheless, the solid Ne moderator should be a very effective primary moderator, and may be employed to advantage as a secondary moderator for brightness enhancement,[6,11,12] especially if the final stage of remoderation uses a metallic single crystal. The obvious advantages of not having to prepare clean metal surfaces and of being able to deposit the moderator directly on a radioactive source are offset by having to work at near liquid He temperatures. (The vapor pressure of Ne is $\approx 10^{-9}$ Torr at 7 K.) We have tested the other rare gas solids as moderators useful at substrate temperatures up to ≈ 50 K. We found that their efficiencies are comparable to single-crystal W in a backscattering geometry using a ^{58}Co-on-Rh source. In the cup geometry, diameter = 8.5 mm and depth = 16 mm, using ^{22}Na, the efficiencies are about one-fifth as good as solid Ne and the energy widths are worse, as summarized in Table I. It should be mentioned that the efficiencies were found to increase when the films were annealed after being deposited on a ≈ 10 K substrate. The values listed in Table I were the maximum efficiencies we were able to obtain. One possible explanation for the high efficiency and narrow energy distribution of positrons moderated in Ne is that the positron work function of solid Ne is much smaller than the other solid rare gases, perhaps even negative.

As an example of the usefulness of the solid Ne moderator, let us consider what we could do with ^{64}Cu, currently being employed at Brookhaven by Lynn and collaborators.[13] A source of ≈ 40 Ci is evaporated onto a 1 cm^2 substrate to yield 4×10^7 slow positrons/s.[5] The slow positron yield is limited by self-absorption of the β^+ particles in the Cu deposit and by the relatively low efficiency of the Cu as a moderator. If the same source were evaporated onto the inside surface of a 1-cm-diam by 2-cm- long cylinder, the deposit would be ten times thinner.[14] This being the same geometry that gave 0.7% efficiency above, we would expect such a Ne-coated ^{64}Cu source to yield about 2×10^9 slow positrons/s, an improvement of 50 times. Since the Brookhaven facility can handle a source of 10^4 Ci, it would be possible to scale up the dimensions of the source to a 10-cm-diam by 20-cm-long cylinder yielding 10^{11} slow positrons/s. There are numerous possible applications of such an enormous slow positron flux.[9,15,16]

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