Further improvements in the efficiency of low-energy positron moderators

Allen P. Mills, Jr.
Bell Laboratories, Murray Hill, New Jersey 07974

(Received 13 June 1980; accepted for publication 8 July 1980)

Low-energy positrons are emitted by negative-positron-affinity moderator surfaces irradiated by the β^+ spectrum of a radioactive source. The slow-positron conversion efficiency ϵ (flux of slow positrons/total β^+ activity) of a Cu (111) single-crystal moderator increases 30% when the positron affinity is made more negative by exposure of the Cu to H_2S *in situ*. Upon cooling the moderator crystal to 100 K, ϵ increases an additional 50% to $\epsilon = (1.5 \pm 0.3) \times 10^{-3}$ using a low-self-absorption β^+ source in a backscattering geometry.

PACS numbers: 25.30.Cg

Beams of slow positrons are making possible a number of new experiments yielding information about the properties of clean surfaces,[1–7] positron-atom scattering cross sections,[8] and the atomic physics of positronium.[9,10] There is, consequently, great interest in obtaining positron beams of high intensity. The low-energy positrons for such beams are presently obtained by moderating the $\sim 10^6$-eV end-point energy β^+ spectrum of a suitable radioactive source using a solid surface. Recent advances in our understanding of how low-energy positrons interact with a solid surface have defined clearly the necessary elements of a high-efficiency slow-positron moderator, the result being that one can now extract one part in 10^3 of the energetic β^+ particles in a <0.5-eV-wide slow-positron beam.[11] This note presents some of the details of the slow-positron source used in Ref. 11 with new procedures which result in a further twofold improvement in the slow-positron yield.

The primary requirement of a slow-positron moderator is that the surface have a negative positron work function.[2,12] It is also necessary for the material to have a large diffusion coefficient for positrons so that some of the implanted β^+ particles can diffuse back to the surface after reaching near-thermal energies.[1] It is preferable to use a high-density material for the moderator to minimize the β^+ implantation depth.[13,14] We now know that of the positrons reaching a surface, the fraction y emitted as slow positrons increases as the positron work function ϕ_+ becomes more negative[15]:

$$y = \exp[-(E_0/\phi_+)^{1/2}], \qquad (1)$$

with $E_0 \approx 0.27$ eV. The positrons not emitted as slow positrons either form positronium or are trapped in their "image" potential well at the surface.[3] Furthermore, the positrons tend to be emitted with velocity perpendicular to the surface plane[16] as one would expect if the emission process were to be described by a one-dimensional potential. A good slow-positron moderator should therefore be a flat, high-density single crystal with a large negative positron work function. It is also best to use a low-self-absorption radioactive source configuration to maximize the number of particles available at the low-energy end of the β^+ spectrum.[11]

Figure 1 shows the arrangement of the radioactive source ^{58}Co, the Cu (111) single-crystal moderator, the W shielding, and the slow-positron extraction electrode. The entire assembly can be cooled to near 77 °K by thermal contact with a stainless-steel tube through which liquid nitrogen flows. The Cu moderator is held onto the end of a Mo plug by Ta tabs. The plug can be removed from behind the radioactive source by means of a vacuum manipulator mounted on a flexible bellows. The plug can then be positioned in front of an ion gun for cleaning by Ar^+ bombardment or inserted into a small furnace capable of heating the Cu crystal to ~ 900 °C. The Cu crystal can be exposed to H_2S gas by positioning it in front of a 3-mm stainless-steel pipe leading to a leak valve and H_2S tank. High-energy positrons and γ rays are removed from the positron beam by the $E \times B$ velocity selector shown in Fig. 2.

The Cu crystal was etched as described in Ref. 11. The moderator plug was heated in the furnace to a bright orange temperature (~ 900 °C) for 10 min and removed from the furnace. The pressure in the vacuum system rose to 5×10^{-9} Torr while the Cu was hot and fell below 10^{-9} Torr after ~ 30 min. This heating procedure has been found to remove O and C contamination from the Cu surface while allowing S impurities to migrate to the surface where a partial monolayer of S is observed to form.[11] After cooling for 40 min, the Cu surface was exposed for 10 sec to H_2S gas to make the positron work function of the Cu (111) surface more negative than is possible to achieve using bulk impurities alone. The Cu crystal face was 2 cm in front of the 3-mm-diam pipe, and the

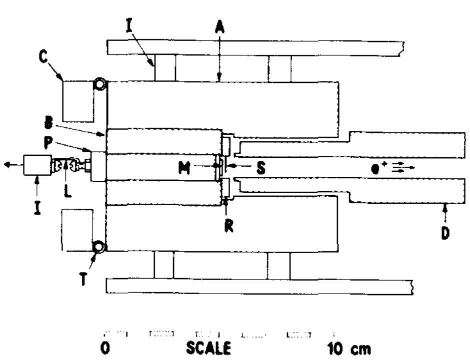

FIG. 1. Slow-positron gun. A is the 90% W γ-ray shield; B is the 90% W removable source holder plug; P is the Mo moderator plug; S is the ^{58}Co source on 1 mm $\times$ 0.1 mm W foil; R is the Au source mounting ring; D is the e^+ drift tube; I are the ceramic insulators; L is the flexible link; F is to the linear motion feedthrough; M is the 99.999% Cu (111) moderator crystal; C is the clamp ring to hold the liquid nitrogen tube T.

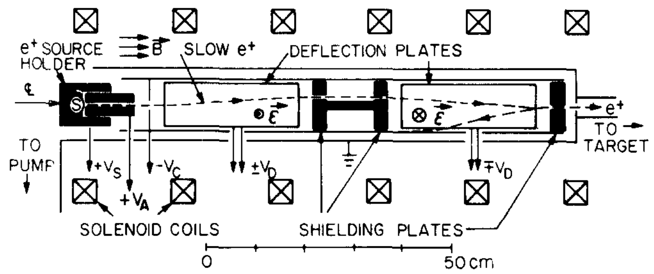

FIG. 2. Slow-positron gun and E×B velocity selector.

system pressure rose to $\sim 10^{-8}$ Torr during the exposure. Using the system pumping speed of ~ 500 l sec^{-1}, one can estimate that $\sim 5\times 10^{-5}$ Torr l of H_2S passed through the 3-mm orifice. Assuming all the molecules were directed at the 0.5-cm^2 surface yields an upper limit on the H_2S exposure of $\sim 2\times 10^{15}$ molecules. The Cu converter was then put in place behind the ^{58}Co source as shown in Fig. 1. The biases on the electrodes shown in Fig. 2 were $V_c = -1.6$ V, $V_{D+} = -75$ V, $V_{D-} = -150$ V, and $V_A = -50$ V all with respect to V_S. The total count rate of a 3×3-in. NaI(Tl) detector 100 mm from a glass target biased at -1.5 kV was 3.37×10^4 sec^{-1}, approximately 30% greater than the count rate obtained before exposing the Cu to H_2S.

Dividing by twice the efficiency for detecting 511-keV γ rays, and correcting for 10% attenuation in the 5-mm-thick glass implies a total positron flux of $(8\pm 2)\times 10^5$ e^+ sec^{-1}. The total β^+ flux from the 160-mCi ^{58}Co source is 0.80×10^9 e^+ sec^{-1}, so the efficiency[17] of the moderator is $\epsilon = (1.0\pm 0.2)\times 10^{-3}$ not including losses due to the passage of the positron beam through two 97%-transmitting grids. The positron beam energy was $V_s \approx 25$ eV for this measurement. The 10–90% integral energy width was $\Delta E \approx 0.60$ eV, and the positron work function of the moderator was measured to be (2.0 ± 0.2) eV by examining the shape of the energy spectrum.[18] The energy width could be reduced to $\Delta E = 0.25$ eV with a small loss in intensity by adjusting the accelerating voltages. The efficiency is observed to change by less than 10% over a period of 58 days.

The above moderator efficiency is slightly greater than that obtained previously.[11] The improvement is attributed primarily to the increased slow-positron yield associated with a larger positron negative work function of the sulfur-saturated Cu (111) surface. A better slow-positron yield will also result if the diffusion length $(D\tau)^{1/2}$ of the positrons can be increased.[19] Accordingly, liquid nitrogen was passed through the cooling tube shown in Fig. 1. The slow-positron flux increased to a saturation value of 1.5 times higher than the room temperature flux after about 6 h of cooling. Assuming an emmissivity of 1, the radiative heat load of the cold W shield in Fig. 1 would be about 15 W. Conduction through the four 1-cm^2 cross section stainless-steel support straps ~ 30 cm long would amount to an additional ~ 5 W heat load. The 0.75-mm wall liquid-nitrogen pipe is estimated to be in contact with the W shield over about 1 cm^2. This leads to an estimated 1-°K/W thermal impedance connecting the W shield to the 77-°K heat sink. Consequently, the W shield and also the Cu (111) moderator should be about 20 °K warmer than the liquid nitrogen. The increase in ϵ seems to be greater than one would predict from the $T^{-1/4}$ dependence of $(D\tau)^{1/2}$ to be expected if D were limited by positron scattering from thermal phonons only. ΔE was not observed to decrease, presumably because the beam optics is the limiting factor in the beam energy resolution. At low temperature, the positron beam energy increased by ~ 0.1 eV, presumably because of the change in the contact potential of the moderator.

In a sufficiently perfect crystal, the positron diffusion should only be limited by the bulk annihilation lifetime τ at very low temperatures. The maximum diffusion length and therefore maximum ϵ occurs when $(D\tau)^{1/2} \approx (kT/m)^{1/2}\tau$. If D varies with temperature as $D = D_0(T/300)^{-n}$, the maximum diffusion length

$$\lambda_{\max} \approx \lambda_0 (10^4/D_0)^{n/(2+2n)}$$

occurs at the temperature

$$T/300 \approx (D_0/10^4)^{1/(1+n)},$$

where λ_0 and D_0 are room-temperature (300 °K) values. Assuming[1] $D_0 \approx 1$ cm^2 sec^{-1}, the diffusion length would be $\approx 5\lambda_0$ $(10\lambda_0)$ at 0.6 °K (3 °K) for $n = \frac{1}{2}$ (1). It is evident that the slow-positron conversion efficiency can probably be improved even more by operating the single-crystal moderators at liquid He temperatures

The author is pleased to thank C. A. Murray for useful discussions.

[1] A. P. Mills, Jr., Phys. Rev. Lett. **41**, 1828 (1978).
[2] A. P. Mills, Jr., P. M. Platzman, and B. L. Brown, Phys. Rev. Lett. **41**, 1076 (1978).
[3] A. P. Mills, Jr., Solid State Commun. **31**, 623 (1979).
[4] K. G. Lynn, Phys. Rev. Lett. **43**, 391 (1979); **43** 803(E) (1979).
[5] A. P. Mills, Jr. and L. N. Pfeiffer, Phys. Rev. Lett. **43**, 1961 (1979).
[6] K. G. Lynn, Phys. Rev. Lett. **44**, 1330 (1980).
[7] I. J. Rosenberg, A. H. Weiss, and K. F. Canter, Phys. Rev. Lett. **44**, 1139 (1980).
[8] T. S. Stein, W. E. Kauppilla, V. Pol, J. H. Smart, and G. Jesion, Phys. Rev. A **17**, 1600 (1978) and references therein.
[9] K. F. Canter, A. P. Mills, Jr., and S. Berko, Phys. Rev. Lett. **33**, 7 (1974); **34**, 177 (1975); **34**, 1541 (1975).
[10] P. W. Zitzewitz, J. C. Van House, A. Rich, and D. W. Gidley, Phys. Rev. Lett. **43**, 1281 (1979) and references therein.
[11] A. P. Mills, Jr., Appl. Phys. Lett. **35**, 427 (1979).
[12] L. Madanski and F. Rasetti, Phys. Rev. **79**, 397 (1950); W. H. Cherry, PhD. dissertation (Princeton University, 1958), available from University Microfilms, Inc., Ann Arbor, Mich.; D. G. Costello, D. E. Groce, D. F. Herring, and J. W. McGowan, Phys. Rev. B **5**, 1433 (1972).
[13] R. D. Evans, *The Atomic Nucleus* (McGraw-Hill, New York, 1955), p. 628.
[14] W. Brandt and R. Paulin, Phys. Rev. B **15**, 2511 (1977).
[15] C. A. Murray and A. P. Mills, Jr., Bull. Am. Phys. Soc. **25** 392 (1980).
[16] C. A. Murray and A. P. Mills, Jr., Solid State Commun. **32**, 789 (1980).
[17] It is important to note that this definition of the efficiency is the ratio of the slow-positron yield to the total flux of positrons from the radioactive source.
[18] C. A. Murray, A. P. Mills, Jr., and J. E. Rowe, Surf. Sci. (to be published).
[19] A. P. Mills, Jr. and C. A. Murray, Appl. Phys. **21**, 323 (1980).