Positron Quantum Reflection in Thin Metal Films and Efficient Generation of High Brightness Low Energy Positron Beams at 4.2 K

Finn M. Jacobsen and Kelvin G. Lynn
Department of Physics, Brookhaven National Laboratory, Upton, New York 11973
(Received 8 December 1995)

High energy positrons implanted into a metal having a negative positron affinity, ϕ_+, can be reemitted into vacuum with an energy equal to $-\phi_+$ smeared by the thermal energy. Reduction of the temperature to 4.2 K to increase the brightness of the reemitted positrons is normally offset by a loss of emission efficiency due to the quantum mechanical reflection at the metal-vacuum interface, approaching unity as the temperature is reduced to zero. By using a thin moderator (0.1 μm), the quantum reflection is compensated by multiple encounters with the surface, resulting in an efficient high brightness low energy positron moderator. Our results show that efficient accumulation of positrons at 4.2 K necessary for the formation of antihydrogen can be done if a thin metal film is used to moderate the positrons. [S0031-9007(96)00212-8]

PACS numbers: 79.20.Mb

Negative positron work-function, ϕ_+, (affinity) metal films form the key component in low energy positron beams [1]. When high energy β^+'s are stopped and thermalized in a metal film some of them will diffuse to the metal-vacuum interface within their lifetime, where they may be ejected into vacuum with a kinetic energy of $-\phi_+$ blurred by the thermal motion of the e^+'s. When an e^+ approaches the surface from within the metal several channels are open beside the elastic emission into vacuum. Inelastic (electron-hole excitation) emission may occur, the e^+ may pick up an electron and escape into vacuum in the form of the positronium atom (Ps), or it may experience an inelastic collision causing the e^+ to become trapped in the surface potential. In addition, quantum reflection the e^+ wave function may occur due to the rapid change of the potential energy at the surface, whereby the e^+ is returned to the bulk of the metal film.

Standard text books [2] show that quantum reflection (QR) approaches unity as the temperature of the e^+ goes to zero. Several papers have been devoted to this problem with the main motivation that accurate data on QR may shed further light into the detail of the e^+ surface potential. The understanding of QR is also important for the production of high brightness low energy e^+ beams. It is clear, at least in principle, that the energy spread of the elastically emitted e^+'s can be narrowed considerably by operating the β^+ moderator at 4.2 K as opposed to room temperature.

There exist several measurements of the yield of low energy e^+, f_+, from various metals versus temperature [3–5]. Furthermore, the energy spread, $\Delta\epsilon$, of the emitted e^+'s have been measured as a function of temperature [6,7], showing a significant reduction of $\Delta\epsilon$ as the temperature is lowered. The temperature dependence of f_+ has also attracted much theoretical attention [8,9] as has e^+ thermalization in cold solids [10].

In Ref. [5] it was demonstrated that the reemitted e^+ yield, f_+, and the Ps yield, $f_{\rm ps}$, follow the same temperature dependence, and it was shown that both quantities for Cu(111) and Al(110) reduces by a factor of 2.5–3 when the temperature is lowered from 300 to 20 K. Extrapolation of these results show that f_+ and $f_{\rm ps}$ are extremely small at 4.2 K.

Other experimental data on $f_{\rm ps}$ [3,4] have shown only a weak temperature dependence at temperatures below room temperature. The latter results were obtained by implanting rather low energy e^+'s into the samples under investigation and may therefore contain effects due to epithermal e^+'s. In a recent measurement [11] it was shown that QR at the metal-vacuum interface of Ni equals 0.65 at room temperature.

In this Letter we present values of f_+ in the temperature range from 4.2 to 200 K from a 0.1 μm thin W(100) film when bombarded with β^+ particles obtained from a 100 mCi ^{22}Na source. Although the present method of producing a low energy e^+ beam may not be the most efficient way, our results show that brightness enhancement through remoderation of the e^+ beam [12] should be done with the remoderator held at low temperature.

The measurements of the temperature dependence of f_+ for a 0.1 μm thin W(100) were done using the BNL "intense" e^+ beam equipped with a 100 mCi ^{22}Na source supplying a stable flux of β^+ particles. The W film was prepared as in Ref. [13] in a separate vacuum chamber and then transported through air to the experimental apparatus. The ^{22}Na source and the W film were held onto a 4.2 K cold head with the W film being bombarded with β^+'s from one side and the low energy e^+'s extracted from the opposite side. The e^+'s were accelerated to 30 eV and transported by a 50 G axial magnetic field to a channel plate detector located about 20 m downstream from the ^{22}Na source. During the drift, the e^+'s were deflected twice by two $\mathbf{E} \times \mathbf{B}$ filters in order to separate unmoderated β^+ particles from the low energy positrons.

To enable cleaning of the W surface, a 300 W halogen lamp was mounted inside the 77 K shield. The lamp was

 0031-9007/96/76(22)/4262(3)$10.00

located behind a grounded high transmission copper grid in order to prevent possible charge-up of the lamp by the β^+'s from affecting the transport of the low energy e^+'s. By pulsing the lamp, it was possible to clean off the W surface from condensed gases without heating up the more massive parts of the cold head and the 77 K shield. The halogen lamp was mounted 20 cm away from the W film, and the temperature of the W film during the hearing cycles is only known to be higher than 150 K as it was possible to remove a thick layer of condensed water. During the pulse heating of the W film, the temperature of the cold head stayed below 10–15 K.

Figure 1(a) shows f_+ and Fig. 1(b) shows temperature T versus time, and in Fig. 1(c) is displayed f_+ as a function of T. Before the measurement of each datum point, the W film was flash heated for a few seconds, and, after a delay of 5 min, the e^+ count rate was recorded. This five-minute wait between hearing and measurement was sufficient for the temperature of the W film to come into thermal equilibrium with the cold head. At the lower temperatures the pulse heating of the W film caused the e^+ count rate to increase to a higher level. After the pulse heating was stopped, it took about 1 min for the count rate to stabilize at a constant level.

At about 20 min after the cold head had reached 4.2 K, the cleaning procedure was stopped, and the e^+ intensity deteriorated slowly due to impurity contamination of the surface of the W film. the e^+ intensity decrease corresponds to a half-life of about 36 h. This moderator half-life can certainly be made much longer by improving the vacuum over the present 10^{-8} torr level. After about 100 min without the use of the lamp, we began our standard cleaning procedure and recovered the lost e^+ intensity. The combined source-moderator efficiency in converting β^+ particles into low energy positrons was about 10^{-5}. The reason for this low value is a large distance of 5 mm between the ^{22}Na source and the W film.

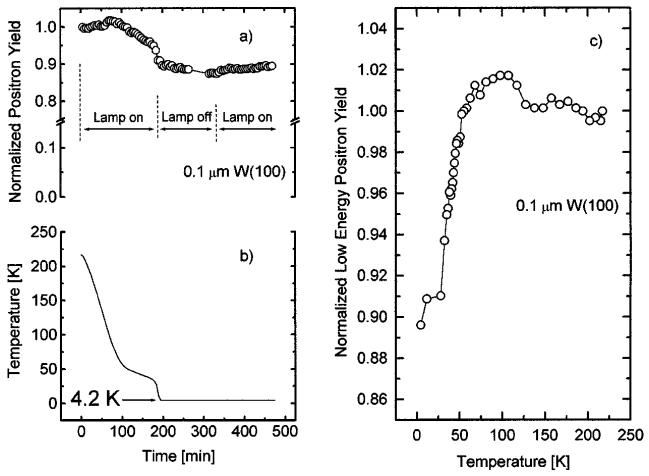

FIG. 1. (a) The normalized low energy positron yield from a 0.1 μm W(100) film during cooling down of the W film from 220 to 4.2 K. (b) The temperature of the W film. (c) The normalized e^+ yield versus temperature. The background (not subtracted) corresponds to less than 0.000 02.

Figure 1 shows that, when the temperature is lowered from 220 to 4.2 K, f_+ reduces about 10%. The value of f_+ at 220 K is slightly higher than the measured value at room temperature. In contrast, simple extrapolation to 4.2 K for thick crystals of Cu and Al [5] shows that f_+ almost vanishes.

It is obvious that, in order to explain the measured results, we must assume that the e^+'s can encounter the metal-vacuum interfaces many times at the lowest temperature. At the highest temperature, it is simple diffusion which drives the e^+ toward the surfaces, and the initial increase of f_+ with decreasing temperature just reflects that the e^+ diffusion coefficient is limited by phonon scattering ($D \propto T^{-1/2}$). At the lowest temperature, our results are consistent with a freely moving e^+ bouncing between the two surfaces with very little scattering in the bulk of the W film until either annihilation or emission into vacuum takes place. At 300 K, D is about 1 cm^2/s [13] corresponding to a mean free path, λ, of 1.6 nm. By assuming $D \propto T^{-1/2}$, λ becomes 0.13 μm at 4.2 K, a distance comparable to the thickness of the W film.

If a step potential with a height equal to $-\phi_+$ (= 3 eV) is used to model the metal-vacuum interface, we can calculate the quantum reflection coefficient to be 0.66 at 300 K and 0.955 at 4.2 K. In order to explain the measured results, we must assume that the e^+ can encounter the metal-vacuum interface about 10 times more frequently at 4.2 K as compared to 300 K.

The thermal velocity of an e^+ at 4.2 K is 10^4 m/sec, and its mean lifetime, τ, is about 100 psec; therefore, a freely moving e^+ in the W film gets about ten chances for emission into vacuum. At 300 K, where the motion of the e^+ is diffusion limited, the diffusion length [defined as $(D\tau)^{1/2}$] is about 0.1 μm, so only a few encounters with the metal-vacuum interfaces will take place before annihilation occurs. These types of estimates are very qualitative but do offer some physical interpretation of our results. It is possible that the extended e^+ wave function at 4.2 K ($\lambda \sim 650$ Å) takes an important role.

Figure 2 summarizes our interpretation of the results of Fig. 1. At 4.2 K the W film forms a quasiquantum well which becomes a true quantum well at 0 K. This quantum well is unusual in that its potential energy is about 3 eV above the free vacuum state, and its formation is caused by quantum reflection of the e^+ wave function at the metal-vacuum interfaces. Note that the e^+ wave packet evolves in time, causing it to bounce between the two surfaces until emission or annihilation takes place. An upper limit for the zero-point energy, E_z, can be obtained by assuming the e^+ wave function to vanish at the two surfaces, whereby we obtain $E_z = (\hbar\pi/L)^2/2m = 0.037$ meV, a quantity which is still small in comparison to $kT = 0.36$ meV, and thus E_z in this film contributes

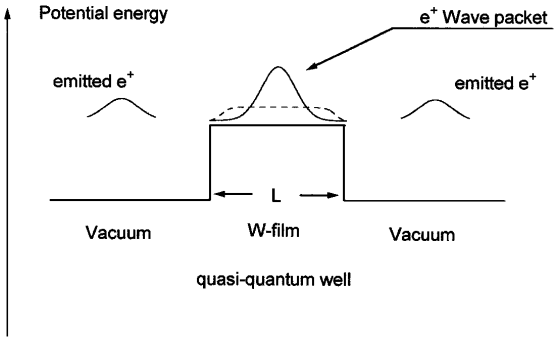

FIG. 2. Our physical interpretation of the results of Fig. 1. The e^+ wave packet, constructed assuming a Maxwellian distribution of momentum at 4.2 K, bounces many times between the two metal-vacuum interfaces forming a quasiquantum well until either emission into vacuum or annihilation takes place. The dashed curve gives the square of the e^+ wave function (probability) using the random phase approximation.

little to the e^+ temperature, and therefore E_z is only a small factor in the e^+ emission probability.

It is possible that some of the e^+'s do not thermalize completely prior to emission into vacuum and that this effect is part of the reason for the high yield at 4.2 K. The important point is, however, that even if complete thermalization takes place, the quantum nature of e^+ emission from a thin metal film at low temperature as pictured in Fig. 2 increases the yield of elastically emitted e^+'s. We mention that e^+ emission from thick crystals is consistent with complete e^+ thermalization at 20 K [5], and, furthermore, a theoretical study [10] suggests that e^+ thermalization may be possible even at 4.2 K. In the latter work, the e^+ was found to slow down to 1.1 T in 35 ps at $T = 10$ K. Theoretical studies of e^+ emission from cold metal films using a proper quantum mechanical description would be welcome.

Our results have practical significance concerning the formation of high brightness micro-e^+ beams, the low energy e^+ microscope [14–16], for exotic experiments such as Bose condensation [17] and Ps liquid studies [16], and for antihydrogen formation [18].

Brightness enhancement of an e^+ beam is done by the remoderation technique [12] in which a $\sim$5 keV e^+ beam is focused onto, e.g., a 1000 Å W film, and about (20–40)% [13,19] of the e^+ beam is reemitted on the opposite side of the film with a diameter equal to the incoming beam but with a kinetic energy of only 3 eV $(= -\phi_+)$. By operating two brightness enhancement stages in reflection mode at room temperature, a gain in brightness of 550 has been obtained [14].

The energy normalized brightness, B, is defined as

$$B = I/\Theta^2 d^2 E\,, \tag{1}$$

where I is the beam current, Θ is the angular divergence, d is the beam diameter, and E is the beam energy. B is a conserved quantity when the e^+ beam is manipulated by conservative fields, but the conservation rule is broken during a remoderation.

For a well annealed defect-free W film, Θ is simply given by $\Theta = [kT/(-\phi_+)]^{1/2}$. Our results have shown that, by operating the brightness enhancement stages at 4.2 K using 1000 Å W films (it will not work with thick films), only a small loss in e^+ intensity occurs due to quantum reflection. Therefore, by cooling two brightness enhancement stages to 4.2 K, an additional factor of brightness gain of at most $75 \times 75 = 5625$ should be possible, assuming e^+ thermalization to 4.2 K and that surface roughness and nonuniformity of the dipole layer are unimportant.

This work was supported by DOE under Contract DE-AC02-76CH00016.

[1] P. J. Schultz and K. G. Lynn, Rev. Mod. Phys. **60**, 701 (1988).
[2] See, e.g., L. D. Laudau and E. M. Lifshitz in *Quantum Mechanics* (Pergamon Press, Oxford, 1977).
[3] K. G. Lynn, P. J. Schultz, and I. K. MacKenzie, Solid State Commun. **38**, 473 (1981).
[4] P. J. Schultz and K. G. Lynn, Phys. Rev. B **26**, 2390 (1982).
[5] D. T. Britton, P. A. Huttunen, J. Mäkinen, E. Soininen, and A. Vehanen, Phys. Rev. Lett. **62**, 2413 (1989).
[6] B. L. Brown, W. S. Crane, and A. P. Mills, Jr., Appl. Phys. Lett. **48**, 739 (1986).
[7] D. A. Fischer, K. G. Lynn, and D. W. Gidley, Phys. Rev. B **33**, 4479 (1986).
[8] R. J. Wilson, Phys. Rev. B **27**, 6074 (1983).
[9] R. M. Nieminen and J. Oliva, Phys. Rev. B **22**, 2226 (1980).
[10] K. O. Jensen and A. B. Walker, J. Phys. Condens Matter **2**, 9757 (1990).
[11] G. R. Brandes, Phys. Rev. B **43**, 10 111 (1991).
[12] A. P. Mills, Jr., Appl. Phys. **23**, 189 (1980).
[13] D. M. Chen, K. G. Lynn, R. Pareja, and B. Nielsen, Phys. Rev. B **34**, 4123 (1985).
[14] G. R. Brandes, K. F. Canter, and A. P. Mills, Jr., Phys. Rev. Lett. **61**, 492 (1988).
[15] J. Van House and A. Rich, Phys. Rev. Lett. **61**, 488 (1988).
[16] A. P. Mills, Jr., Science **218**, 335 (1982).
[17] P. M. Platzman and A. P. Mills, Jr., Phys. Rev. B **49**, 454 (1994).
[18] L. H. Haarsma, K. Abdullah, and G. Gabrielse, Phys. Rev. Lett. **75**, 806 (1995).
[19] F. M. Jacobsen, M. Charlton, J. Chevallier, B. I. Deutch, and M. R. Poulsen, J. Appl. Phys. **67**, 575 (1990).