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Absence of energy loss in positron emission from metal surfaces

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We have measured the energy distribution of positrons reemitted after implantation into W(110) and Ni(100) surfaces at room temperature. The previously reported broad distribution of the perpendicular component of the energy is now found to be due to a wide angular distribution of essentially monoenergetic positrons. The implied elasticity of the positron-emission process (e.g., less than 25 meV energy loss for 97% of the 1-eV positrons emitted from Ni) is in serious disagreement with present theories that require the emission of energetic electron-hole pairs for positron reemission from metals.

It might be expected that electron-hole pair excitation would play an important role in positron emission from metals. A thermal positron diffusing to the surface of a metal will, with roughly equal probabilities, be emitted as a free positron or as positronium (Ps) or lose energy through some mechanism and be trapped in a surface state.[1] Theoretical estimates[2,3] suggest that the amplitudes for Ps emission and positron emission accompanied by the excitation of an electron-hole pair would be comparable. It has been shown experimentally that Ps emission leaves the metal in a one-hole excited state.[4] Similarly, electron-hole formation might be an important energy-loss mechanism in positron surface-state trapping.[5] The persistence of positron emission to low temperature[6] and the small positron reflection coefficient[7] at incident energies below the barrier due to the negative work function (ϕ_+) also might imply that strong inelastic processes occur at the metal surface.[8]

In spite of these indications of the prevalence of inelasticity, the first high-resolution positron-emission experiments by Fischer, Lynn, and Frieze[9] showed that positrons are emitted essentially elastically with an energy given by $-\phi_+$ and the thermal smearing. The interpretation of these results regarding elasticity was somewhat ambiguous since the positron energy spectrum was only measured in a small solid angle relative to the surface normal, and the data were in apparent disagreement with our 2π solid-angle experiments.[7,10] The latter measurements showed that the normal component of the positron-emission spectrum has a low-energy tail which was thought to result from energy loss at the surface. Our new experiments show that this "loss" tail is, in fact, due to a wide angular distribution of elastically scattered positrons, thus resolving the apparent discrepancy. We find that the actual energy-loss tail is much smaller than is expected from the theories of Neilson, Nieminen, and Szymanski[2] and Pendry.[3]

Our experiments were performed using a magnetically guided positron beam to implant 4-keV positrons into a sample surface in an ultrahigh vacuum chamber at a pressure of 5×10^{-10} Torr. The samples were prepared by Ar-ion bombardment followed by annealing. The surface characteristics of the samples were determined by low-energy electron diffraction (LEED) and Auger electron spectroscopy. The Ni surface was contaminated by less than 0.2 monolayers (ML) of C, 0.05 ML of P, 0.02 ML of S, and <0.005 ML of O, and showed sharp LEED spots. The W surface was covered by a monolayer of C and 0.01 ML of O and the LEED pattern showed a high order of reconstruction. Positrons reemitted from the sample passed through a retarding field analyzer and were deflected into a channeltron detector by a pair of $E\times B$ plates. Since the data were obtained using the retarding field analyzer in the magnetic field of our slow positron beam, only the component of positron energy along the magnetic field was measured. Thus, a single spectrum contains an ambiguous combination of the angular and total energy distributions.

In order to obtain the total energy distribution of reemitted positrons one may place the sample in high magnetic field B_1 and the analyzer in a low field B_0.[11] Since $E(\sin^2\theta)/B$ is an adiabatic invariant of the motion of a particle in a varying magnetic field, where θ is the angle of the positrons velocity to the magnetic field and E is the positrons' energy, $\sin^2\theta$ will be reduced by B_0/B_1 at the analyzer. We used a $SmCo_5$ permanent magnet behind the sample to obtain a field ratio $B_0/B_1=0.1$. Integral energy spectra of the positrons reemitted from Ni and W surfaces with and without the $SmCo_5$ magnet are shown in Fig. 1. It is immediately evident that the low-energy tail that is especially prominent for the W(110) sample is not due to large energy losses of the reemitted positrons.

The differential total energy spectrum for Ni(100) (i.e., with the permanent magnet behind the samples) is shown in Fig. 2 along a fit using a beam Maxwell-Boltzmann distribution[12] $dN/dE=(E+\phi_+)\exp[-(E+\phi_+)/kT^*]$. The fit to the data yields an effective temperature $kT^*=32$ meV, somewhat larger than the 25 meV expected at room temperature. This could be due to the finite resolution of our analyzer and puts an upper limit of 20 meV on the resolution. However, the positrons reemitted from Ni after being

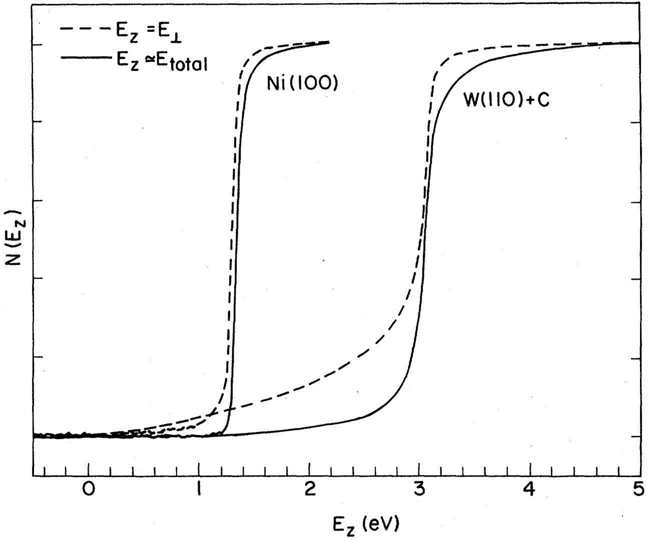

FIG. 1. Integral distributions of positrons reemitted from Ni(100) and W(110) + C vs energy normal to the surface (dashed) and total energy (solid). The low-energy tail of the normal energy distribution is substantially reduced in the total energy distribution and therefore must be due to positrons emitted at large angles to the surface normal and not energy loss as was previously interpreted.

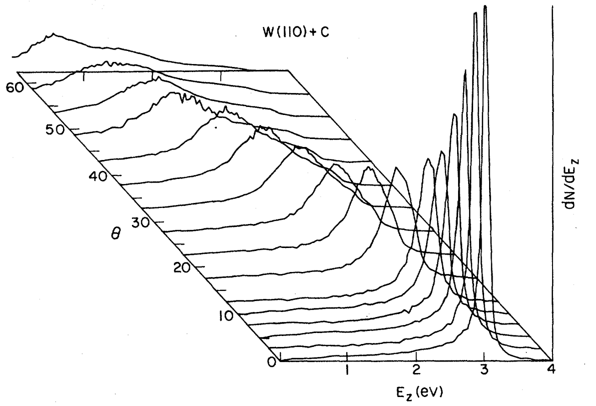

FIG. 3. Differential energy distributions of positrons reemitted from a W(110) + C surface, after implantation at 3950 eV. The distributions were measured vs the component of energy along the direction of the magnetic field. The field is applied at an angle θ to the surface normal.

implanted with an energy of 4 keV have only spent about 12 psec in the sample,[13] a time comparable to the positron thermalization time[14] at 300 K, $t_0 = 10$ psec. Woll and Carbotte[14] find that after a time $t = 1.2t_0$ the positron momentum distribution should be Maxwellian with an effective temperature $T^* = 1.4$ T.[15] Our measured T^* agrees with this estimate. Furthermore, we find that T^* increases as the energy of the incident positrons is decreased as expected for nonthermalization. In addition to the nearly thermal positrons there is an approximately $\frac{3}{2}$-power-law tail of high-energy positrons that we attribute to the escape of hot positrons from the sample. The poor fit at energies less than ϕ_+ is attributed primarily to the finite value of B_0/B_1. Energy losses due to excitation of phonons[16] and vibrational modes of surface contaminants[9] would also be expected to be on the order of 50 meV. We are presently extending our measurements to lower temperatures and smaller B_0/B_1 to investigate these small losses in more detail.

Since Fig. 1 shows that the reemitted positrons must have a spread in angle, we have checked this by measuring the

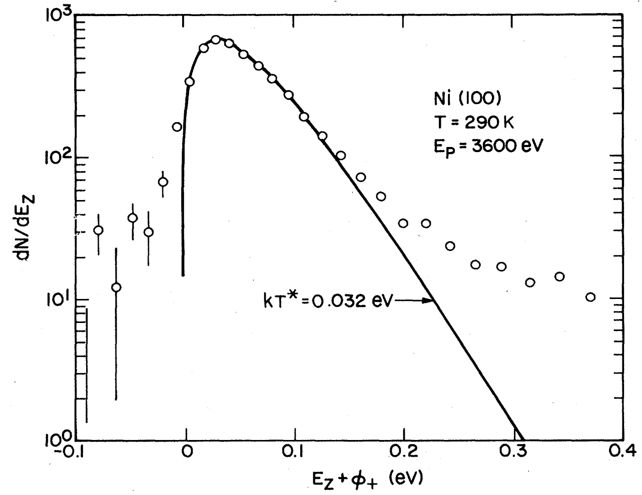

FIG. 2. Differential total energy distribution of positrons reemitted from a Ni(100) surface vs energy measured from the positron work function (ϕ_+). The positrons were implanted with energy $E_p = 3600$ eV. The solid line is a fitted beam Maxwell-Boltzmann distribution with a temperature $kT^* = 32$ meV.

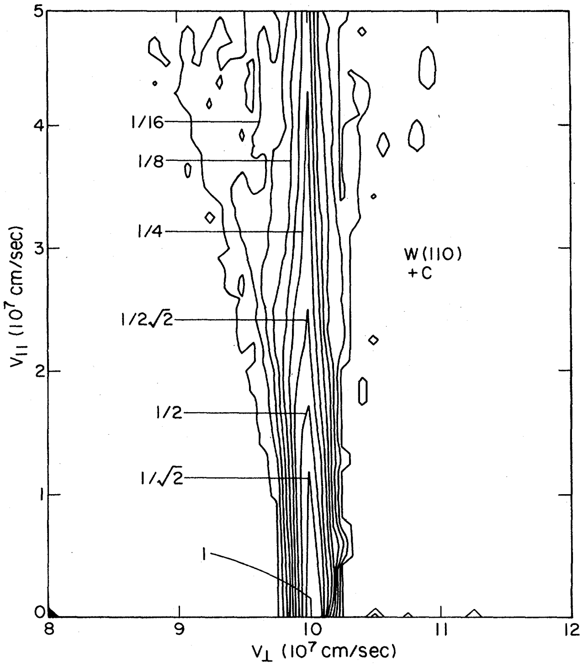

FIG. 4. Contour plot of the velocity distribution of positrons reemitted from W(110) + C obtained by backprojecting the data of Fig. 3.

positron angular distribution. Figure 3 shows our measurements of the axial component of the positron energy distribution for the W(110) sample obtained for several different orientations of the sample normal relative to the magnetic field axis. The angular dependence of the peak energy is fit very well by $E_0 = -\phi_+ \cos^2\theta$, where $\phi_+ = -2.95 \pm 0.10$ eV. The full width at half maximum ΔE has a minimum at $\theta = 0°$ of 90 meV, and for $5° < \theta < 40°$ we find $\Delta E = \alpha\theta$, where $\alpha = 29$ meV/deg. Assuming azimuthal symmetry we have backprojected[17,18] this data to obtain the angular distribution of the emitted positrons shown in Fig. 4. This figure displays a section through velocity space, with logarithmic contours. The half-width of the parallel velocity distribution, 1.7×10^7 cm/sec, is somewhat larger than the value expected from thermal spread, 9.4×10^6 cm/sec. At large values of parallel velocity the distribution fans out toward lower $v_\perp$ due to the positrons elastically emitted at large angles.

Examination of the low-energy tail in the perpendicular energy distribution on a log-log plot[19] shows that the positron angular distribution is roughly proportional to $1/\theta^2$. The wide angular distribution could be due to surface roughness but the roughness would have to be on a scale less than 5000 Å since light scattering indicates roughness of only about a degree. Also there appears to be no relationship between the width of the angular distribution of reemitted positrons and the quality of the LEED pattern. It is also possible that the positrons could be elastically scattering off adsorbates on the metal surface. However, we have also observed a wider angular distribution in Ni than that shown in Fig. 1 and there appears to be no correlation with the level of surface contamination. It appears that under the right conditions Ni(100) can have a very narrow angular spread in the reemitted positron distribution which makes it useful as a remoderator.

In conclusion, we have demonstrated that most of the positrons reemitted from Ni and W are emitted elastically without the large energy losses due to electron-hole excitations predicted by Neilson *et al.*[2] and Pendry.[3] In retrospect one could argue that the positron emission may be adiabatic since $|\phi_+| << \hbar\omega_p/\sqrt{2}$ implies that the screening cloud can respond rapidly enough to avoid shakeup as the positron emerges from the surface.

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[17] The largest angle, $\psi = 62°$, is somewhat smaller than the limit at which normally emitted positrons may, during their first cyclotron period, reenter the sample surface. This condition is given by $\psi = a \tan(\sqrt{3\pi/2}) = 65°$. One should note that it is only because the e^+ emission is primarily surface normal that we may obtain reliable measurements for large ψ and neglect the effect of reincident positrons that will always be present for some emission angles when ψ is nonzero.

[18] The velocity spectrum of Fig. 4 was obtained [*Image Reconstruction from Projections,* edited by G. T. Herman (Springer-Verlag, Berlin, 1979)] by convolving the *z*-component data with a Hamming filter and then backprojecting it.

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