LATTICE ATOM DISPLACEMENTS PRODUCED NEAR THE END OF IMPLANTED μ^+ TRACKS ☆

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Spin rotation experiments with implanted μ^+ projectiles are a convenient method for extending studies of the isotope effect for hydrogen diffusion in metals to very light mass. In the present letter information is presented which allows a determination of the mean free path for vacancy production by μ^+ particles slowing down in C (graphite), Al, V, Fe, Ni, Cu, Nb, Pd, and Ta targets. Also given is the excess distance traveled by the μ^+ after its energy is reduced below the threshold necessary for vacancy production in these materials.

Spin rotation experiments with implanted μ^+ particles (μ^+ SR) have provided a method for extending the study of hydrogenic impurities in metals to lower mass, since the positive muon can be considered as an isotope of hydrogen with one-ninth the proton mass [1].

One of the questions of importance in interpreting such experiments concerns the effect on the muon motion of damage introduced into the target by the muon implant itself. That is, after the muon becomes thermalized in the target what are the relative locations of the muon and the damage it has introduced? In this letter the results of calculations which give information pertinent to this question will be presented. Two types of information will be presented here. These are (1) the additional distance the muon travels into the target after its energy is reduced sufficiently low that it can no longer produce lattice displacements, and (2) the rate at which the muon produces damage at each energy as it is slowing to a stop in the target. Information will be presented for the specific targets C (graphite), Al, V, Fe, Ni, Cu, Nb, Pd, and Ta. All these materials are of interest for μ^+ SR experiments: Fe, Ni, and Pd for magnetism studies; A, V, Cu, Nb, and Ta for μ^+ diffusion. These elements all have gyromagnetic ratios and nuclear spins such that an effect can easily be observed except for C ($I = 0$) which is used for calibration purposes.

The muon decays into a positron and two neutrinos with a characteristic lifetime τ of 2.2×10^{-6} s, with the positron emitted preferentially along the spin axis of the muon. The decay time of the muon provides a quite useful time scale in such experiments since: (1) implanted muons of 50 to 150 MeV initial energy become thermalized in the target in a time much shorter than τ, (2) the characteristic periods of lattice vibrations are much shorter than τ, (3) relatively small magnetic field ($\gtrsim$100 G) are required to obtain a significant number of Larmor rotations of the magnetic moment of the muon during the time period τ, and (4) experimental apparatus for detecting and measuring the emitted positron intensity with nanosecond response time is readily available.

The basic procedure in a spin rotation experiment is to implant a polarized beam of muons, one at a time, into a target material located in a magnetic field. The initial polarization direction is along the incident beam direction, with polarization efficiencies of up to 95% being typical [2]. The intensity of the positron emission at some fixed angle with respect to the incident beam and the magnetic field is then measured as a function of time. In the absence of the magnetic field the intensity simply shows an exponential decay with characteristic decay time τ. The magnetic field causes the spin axis of the muon to precess, however, and thus superimposed on the exponential decay is a sinusoidal variation in the intensity with characteristic

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frequency equal to the muon Larmor precession frequency. The variation with time of the amplitude of the sinusoidal component of the intensity function carries information concerning the motion of the muon through the lattice during its decay.

The model used in the present calculations assumes a sharp threshold energy, E_d, for the permanent displacement of a lattice atom from its regular site in the target material, i.e., a struck target atom is assumed to be displaced if it receives a kinetic energy greater than E_d. For this model the muon is no longer able to produce displacements after its energy drops below T_d, where $T_d = E_d/\gamma$ with $\gamma = 4M_1M_2/(M_1+M_2)^2$. In these expressions M_1 is the muon mass, and M_2 is the target atom mass.

The excess projected range, $R_p(T_d)$, is defined as the average range of a muon of energy T_d, projected onto its initial direction of motion. The transport equations governing the evolution of R_p are readily solved [3], and in fig. 1 R_p is plotted as a function of E_d, for the nine specific targets mentioned above. The Thomas–Fermi elastic scattering cross section as developed by Lindhard et al. [4] was used in these calculations. The electronic contribution to the stopping power was assumed to be that of a hydrogen atom having the same velocity as the muon and it was described by a three-parameter formula in order to extrapolate to low energies [5]. The tabulated stopping power data of Janni [6] were used for this purpose.

The average distance between the stopped muon and the last displacement produced depends on R_p, but it also depends on the mean free path for displacement production by the muon during its deceleration to T_d. This mean free path, $R_D(E)$, is defined as the inverse of $dN_D/dR(E)$, the displacement production rate for a muon of energy E. A Kinchin–Pease (KP) mode [7] of the displacement process (or a modified KP model [8]) allows one to relate dN_D/dR to dE_D/dR, the rate at which energy is given to displaced atoms by the muon, through

$$2E_d dN_D/dR = \beta dE_D/dR\,, \tag{1}$$

where β is the displacement production efficiency. The value of β depends somewhat on the model used for the displacement process, but for reasonable models lies between 0.5 and 1 [7,8]. Oen [9] gives an expression for dE_D/dR based on the Thomas–Fermi

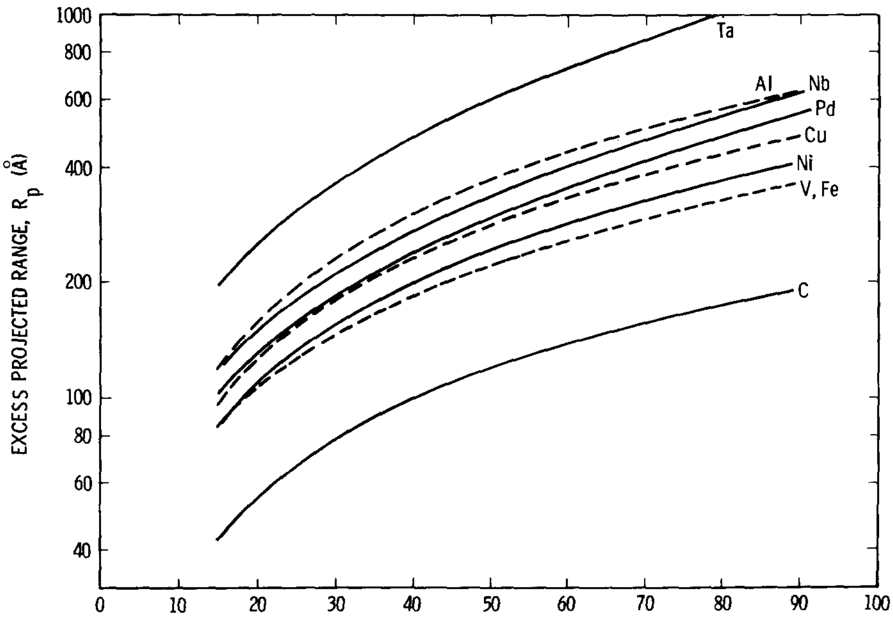

Fig. 1. Excess projected range as a function of displacement threshold energy for μ^+ projectiles incident on C (graphite), Al, V, Fe, Ni, Cu, Nb, Pd, and Ta.

elastic scattering cross section. In order to present the calculated curves on a single plot it is convenient to give dE_D/dR in reduced units, $d\epsilon_D/d\rho$, where $\epsilon_D = E_D/E_L$ and $\rho = R/R_L$. E_L and R_L are an energy and a length which are characteristic of the projectile–target combination [4].

Fig. 2 shows $d\epsilon_D/d\rho$ for muons incident on Ta and C as a function of ϵ (= E/E_L) for three different values of E_d, 15, 30, and 60 eV. The curves for the other targets considered in this paper can be found by interpolating between the curves shown in the figure. This is best done by evaluating ϵ for $E = T_d$ and taking this as the intersection of the desired curve with the abscissa of fig. 2. Table 1 gives values of E_L and R_L to aid in using the information presented in fig. 2, and to make the interpolation more convenient.

As an example of the use of the information in fig. 2, consider a Ta target, and assume a displacement threshold energy E_d = 30 eV. From fig. 2, one finds that the maximum value of $d\epsilon_D/d\rho$ is 0.05. This value, along with the values of E_L and R_L in table 1 yields dE_D/dR = 0.00252 eV/Å, which substituted into eq. (1) with $\beta = 1$, gives $dN_D/dR = 4.19 \times 10^{-5}$ Å^{-1}, or R_D = 23840 Å. Fig. 1 shows R_p to be 360 Å for this case. Thus the average distance between the implanted muon and the last produced vacancy is ~24000 Å. Similarly for the graphite case (again using E_d = 30 eV and $\beta = 1$) R_D = 7255 Å while R_p = 78 Å, and thus in all cases the muon on the average

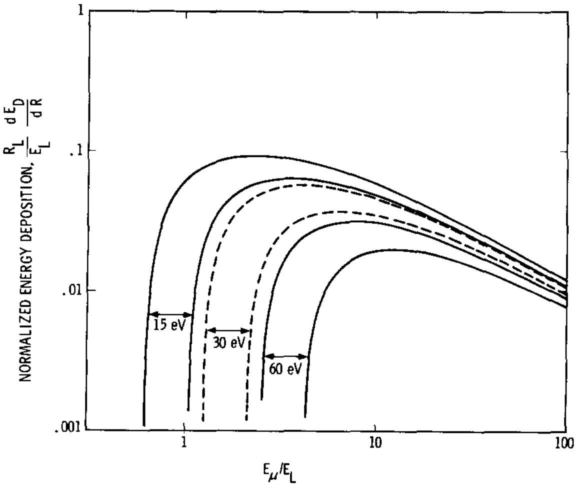

Fig. 2. Reduced rate of energy deposition into displacements for C and Ta targets as a function of reduced μ^+ energy for E_d = 15 eV, 30 eV, and 60 eV. The upper curve in each set corresponds to the Ta target.

Table 1
Values of E_L and R_L for muons incident on various targets.

Target	E_L (eV)	R_L (Å)
C (graphite)	386	1477
Al	1025	9339
V	2135	20600
Fe	2502	20420
Ni	2755	20920
Cu	2883	24940
Nb	4527	68070
Pd	5262	68630
Ta	9643	191600

stops quite far from the last vacancy produced.

To continue the example of the previous paragraph, the diffusion coefficient D for H in Ta at room temperature [10] is about 2×10^{-6} cm^2/s which with the lifetime, τ, of the muon gives a diffusion length of about 200 Å. Since the value of D for the muon is expected to be about a factor of 3 or so larger than the H value, the diffusion length for the muon is probably ~350 Å, so essentially no interaction between the muon and those vacancies produced during its implantation would be expected. For the other target materials for which diffusion data are available the room temperature value of D is sufficiently low that such interaction is completely negligible.

In conclusion, the mean distance between the stopped μ^+ projectile and the nearest vacancy produced by its implantation is determined primarily by the mean free path for vacancy production, R_D. For realistic values of E_d and β, R_D is greater than or of the order of several thousand Ångstroms for the materials considered here. Thus, vacancies produced by the implantation will have no significant effect on the room temperature muon diffusion rate over its lifetime.

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