[1]M. J. Freiser, F. Holtzberg, S. Methfessel, G. D. Pettit, M. W. Shafer, and J. C. Suits, Helv. Physica Acta. 41, 832 (1968).

[2]A comprehensive review on these materials was given by S. Methfessel and D. C. Mattis, in Handbuch der Physik, edited by S. Flügge (Springer-Verlag, Berlin, Germany, 1968), Vol. 18, Pt.1, pp. 389-562.

[3]L. G. DeShazer and G. H. Dieke, J. Chem. Phys. 38, 2190 (1962).

[4]A. H. Piksis, G. H. Dieke, and H. M. Crosswhite, J. Chem. Phys. 47, 5083 (1967).

[5]G. Busch, P. Junod, and P. Wachter, Phys. Letters 12, 11 (1964).

[6]B. E. Argyle, J. C. Suits, and M. J. Freiser, Phys. Rev. Letters 15, 822 (1965).

[7]T. Kasuya and A. Yanese, Rev. Mod. Phys. 40, 684 (1968).

[8]G. Busch and P. Wachter, Phys. Letters 20, 617 (1966).

[9]J. Feinleib, W. J. Scouler, J. O. Dimmock, J. Hanus, T. B. Read, and C. R. Pidgeon, Phys. Rev. Letters 22, 1385 (1969); J. O. Dimmock, in Proceedings of Symposium on Magnetic Semiconductors, Yorktown Heights, New York, 13-14 November 1969 (to be published); C. R. Pidgeon, J. Feinleib, and W. J. Scouler, ibid.

[10]S. J. Cho, Phys. Rev. 157, 632 (1967).

TRAPPING OF POSITRONS BY DISLOCATIONS IN ALUMINUM

P. Hautojärvi, A. Tamminen, and P. Jauho
Department of Technical Physics, Technical University of Helsinki, Otaniemi, Finland
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Positron lifetime measurements have been performed in plastically deformed aluminum single crystals. Evidence of a second nonspurious lifetime component has been observed. The results are interpreted as the trapping of positrons by dislocations. The lifetimes are found to be 172 psec in the perfect crystal and 228 psec in a dislocation. The escape probability of trapped positrons is estimated to be zero.

Recently, attention has been paid to positron annihilation in deformed metals. The experimental results, which indicate the narrowing of the 2γ angular correlation[1] and the increase of the positron mean lifetime,[2,3] can be understood by assuming an attractive interaction between positrons and defects. This Letter describes positron lifetime measurements in plastically deformed aluminum. The results are discussed in terms of a trapping model, which has previously been applied successfully to vacancies in alkali halides[4] and metals.[5]

It is assumed in the trapping model that positrons, after having slowed down, annihilate in the perfect crystal with a rate λ_c. They are trapped by defects at a rate κ which is assumed to be proportional to the defect density. Denoting the annihilation rate of trapped positrons in defects by λ_d and the escape probability from a defect by δ, then, with the condition that no positrons are initially trapped, the number of positrons left at time t is given by[4,6]

$$\frac{n(t)}{n(0)}=\frac{\lambda_c-\Lambda_2}{\Lambda_1-\Lambda_2}e^{-\Lambda_1 t}+\frac{\Lambda_1-\lambda_c}{\Lambda_1-\Lambda_2}e^{-\Lambda_2 t}. \tag{1}$$

The decay constants Λ_1 and Λ_2 are obtained as the roots of the equation

$$\Lambda^2-(\lambda_c+\lambda_d+\kappa+\delta)\Lambda+(\lambda_c+\kappa)(\lambda_d+\delta)-\kappa\delta=0. \tag{2}$$

The special case with no escape ($\delta=0$) gives

$$\Lambda_1=\lambda_c+\kappa,\quad \Lambda_2=\lambda_d. \tag{3}$$

In a perfect crystal there is only the first component. When the defect density increases, the intensity and lifetime of the first component decrease until the second component dominates.

The aluminum samples were spark-cut from one large single crystal of 99.999% purity. They were electrolytically polished, annealed for 10 h at 600°C in an argon atmosphere, deformed, and polished again just before the lifetime measurements. The crystals were deformed by compression until the desired thickness reduction was achieved. The ^{22}Na source was prepared by sealing 3 μCi of evaporated $^{22}NaHCO_3$ solution in a gold-covered Al foil of 1.5 mg/cm^2 thickness. The source was sandwiched between two identically deformed crystals. The lifetime measurements were performed with a fast-slow coincidence system with 1-in. $\times$ 1-in. Naton 136 scintillators and XP 1021 photomultipliers. The time resolution in positron measurements was 290 psec (full width at half-maximum). Each sample was counted for 2×20 h and about 7×10^5 coincidences were accumulated during this time.

The experimental lifetime spectra were first analyzed conventionally by using a two-exponential fit with a constant chance-coincidence background. The results are shown on the left in Table I, in which the deformation is expressed as the percentage thickness reduction of the sample. The effect of deformation saturates, as is expected from the trapping model, and positrons annihilate mainly with one exponential decay both in the undeformed sample (0 %) and in the two strongly deformed samples (30 %, 58 %). The weak second lifetime component in these three samples has been interpreted as an artifact caused by the common positron source. The results in the middle region of deformation are not valid, because the two nonspurious components assumed in Eq. (1) are mixed into the source component.

The one-exponential fit shown in the middle of Table I was performed after the source component of 1.8 % and 500 psec had been subtracted. The variance of the fitted values [$=\chi^2$/(No. of degrees of freedom)] is consistent with the assumption of one lifetime component in only the undeformed and strongly deformed samples.

The two lifetimes in Eq. (1) are expected to appear in the middle region of deformation. Because they are short and near to each other, it was not possible to resolve them reliably with a fitting procedure having two lifetimes and their intensity ratio as variable parameters. But if the trapping model is correct, the only sample-dependent parameter is the trapping rate κ. Therefore the number of adjustable parameters was reduced by using Eqs. (1) and (2) to determine the lifetimes and intensities from fixed values of the annihilation rates λ_c and λ_d; λ_c was set equal to the annihilation rate in the perfect crystal, and λ_d was set equal to the annihilation rate in the most strongly deformed samples, in which practically all positrons annihilate while trapped in defects.

The differentiation of Eq. (1) with respect to time gives the annihilation rate. It was folded with the Gaussian instrumental resolution function and then fitted to the exponential part of the experimental lifetime spectra in order to get estimates for the trapping rate κ. The results in the case $\delta = 0$ (no escape) are presented on the right in Table I. If $\delta \gg \lambda_d$, only a short-lived compound state would be possible and positrons would annihilate with a single exponential decay. By comparing the χ^2 values of the one-exponential fit with those of the trapping model with no escape it can be seen that the latter gives much better agreement with the data.

Trapping-model fits with various values of δ gave no better fit than the one with $\delta = 0$ and with 95% confidence level we can say that $\delta < 0.1\lambda_d$. No differences were found when the sample temperature was lowered from 300 to 77°K. This means that escape due to the thermal motion is negligible at 300°K and thus the binding between positrons and defects is greater than 0.025 eV.

The values of κ presented in Table I increase monotonically with the sample deformation, as is expected from the proportionality assumed between the trapping rate and defect density. The individual χ^2 values of the trapping model are systematically slightly higher than the corresponding values of the two-exponential fit. This may be due to uncertainties in the zero-time determination and in the form of the instrumental resolution function, as the variance of the fit with two exponentials is independent of these parameters.

The deformation was plastic and thus the principal defects are various types of dislocations. The vacancies are believed to be in thermal equilibrium and their contribution to the positron lifetime at 300°K is negligible.[7] Electron micrographs showed that the dislocation density was about 10^6 cm^{-2} in the undeformed sample. It increased with the thickness reduction in the de-

Table I. Results from different analyses of positron lifetime spectra in deformed aluminium. The indicated errors are statistical standard deviations. The accuracy in the time calibration is 1 %.

	2-exponential fit				1-exp fit		Trapping model	
Deformation (%)	τ_1 (psec)	τ_2 (psec)	I_2 (%)	χ^2/df ($df=43$)	τ_1 (psec)	χ^2/df ($df=45$)	κ (10^9 sec^{-1})	χ^2/df ($df=46$)
0	172 ±1	500 ±30	1.8 ±0.3	1.30	172 ±1	1.27	0.00	1.27
2.4	176 ±3	340 ±20	10 ±3	1.19	193 ±1	2.94	1.11 ±0.04	1.67
4.8	179 ±5	320 ±20	16 ±5	1.24	204 ±1	3.50	2.02 ±0.07	1.54
8.2	192 ±7	320 ±20	20 ±9	1.41	214 ±1	2.62	3.98 ±0.16	1.74
12.4	207 ±7	330 ±30	18 ±11	1.35	226 ±1	1.93	9.60 ±1.3	1.58
30	226 ±3	520 ±90	2.0 ±1	1.24	228 ±1	1.25	18.6 ±2.3	1.37
58	227 ±3	460 ±80	2.9 ±2	1.19	230 ±1	1.18	20.2 ±2.6	1.59

formed samples, in which the dislocation density unfortunately could not be determined owing to a cell structure and the proportionality between the trapping rate κ and the defect density could not be verified.

If we assume that positrons see a dislocation as a row of vacancies on adjacent atomic sites, we can take advantage of the behavior of the positron mean lifetime at elevated temperatures.[7] By following Connors and West[5] we have estimated that the cross section for the trapping of positrons by a vacancy is 34×10^{-15} cm^2 in aluminum. Thus a trapping rate of 10^9 sec^{-1} would be produced by a dislocation density of 7×10^7 cm^{-2} and the dislocation densities of the deformed samples would vary from 8×10^7 cm^{-2} to 2×10^9 cm^{-2}. These values are consistent with the electron micrographs.

In view of these measurements, the trapping of positrons by dislocations in addition to vacancies[5,7] is possible in metals. When studying defects this circumstance can be utilized, but only in a limited defect density region. In experiments concerning positron annihilation in perfect crystals great care should be paid to avoid this phenomenon. Also the observed decrease of the core contribution of 2γ angular correlation curves in several deformed metals[8] can be understood by the aid of trapped positrons in defects, where the overlapping of core electrons with the localized positron wave function is expected to be smaller than the overlapping with a freely moving positron.

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[1]S. Berko and J. C. Erskine, Phys. Rev. Letters 19, 307 (1967).

[2]B. T. A. McKee, H. M. B. Bird, and I. K. MacKenzie, Bull. Am. Phys. Soc. 12, 687 (1967).

[3]J. C. Grosskreutz and W. E. Millett, Phys. Letters, 28A, 621 (1969).

[4]W. Brandt, in Positron Annihilation, edited by A. T. Stewart and L. O. Roellig (Academic, New York, 1967), p. 178.

[5]D. C. Connors and R. N. West, Phys. Letters 30A, 24 (1969).

[6]W. Brandt, private communication.

[7]I. K. MacKenzie, T. L. Khoo, A. B. McDonald, and B. T. A. McKee, Phys. Rev. Letters 19, 946 (1967).

[8]I. K. MacKenzie, Phys. Letters 30A, 115 (1969).

ANOMALOUS THERMAL CONDUCTIVITY IN SUPERCONDUCTING NIOBIUM†

J. R. Carlson* and C. B. Satterthwaite
Department of Physics and Materials Research Laboratory, University of Illinois, Urbana, Illinois 61801
(Received 17 October 1969)

Anomalously high thermal conductivity of superconducting Nb between 0.3 and 0.6°K is interpreted as evidence for a small second energy gap. The temperature dependence of the excess thermal conductivity is consistent with a BCS-like gap about 1/25 of the dominant gap in both magnitude and transition temperature. The magnitude of the excess conductivity appears to justify identifying the small gap with the hole sheet of the Fermi surface centered about symmetry point Γ. Less readily explained on the basis of a two-gap model are the high phonon conductivity observed in this and other experiments and the very high Q_s observed for Nb microwave cavities at low temperatures.

It has been predicted that superconductors in which there are overlapping bands of electrons at the Fermi surface would exhibit two distinct energy gaps if the matrix elements for interband processes were very small relative to those for intraband processes.[1] Anomalies in the specific heat of superconducting Nb[2,3] and V[4] at very low reduced temperatures have been analyzed in terms of a second energy gap, an order of magnitude smaller than the predominant gap. However, until very recently no direct evidence had been found for such a gap.[5] We present results of thermal-conductivity measurements on superconducting Nb which are generally in agreement with a two-gap model.

The specimen used in this experiment was a single crystal 0.475 cm in diam and 10-cm long. It was prepared by electron-beam zone melting in a vacuum of 10^{-10} Torr from starting material obtained from the Wah Chang Corp. The major impurities were metallic Ta and W. Its transition temperature was 9.25°K.

The measurements in the temperature range of interest are shown in Fig. 1. The maximum in the superconducting-state data at about 2°K has been observed by other authors[6,7] and has been