and also for his continuous encouragement during the last several years. We also thank Dr. R. A. Ruehrwein of Monsanto Chemical Company for supplying the InAs crystal.

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MOTION OF POSITRONS*

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This Letter presents the results of an experiment[1] which was designed to observe directly whether or not positrons in a metal were thermalized. The results were surprising to us. They led to the conclusion that the positron is thermalized but has an effective mass in sodium metal approximately twice the rest mass.

Lee-Whiting[2] and Adler[3] have calculated that a positron in a metal thermalizes, by scattering with the conduction electrons, at a rate much faster than the annihilation rate. In fact, they estimate that a positron should have an energy of order $k_B T$ in about 10^{-12} sec whereas the mean life of a positron in a metal is about 10^{-10} sec. Ever since the early results of Stewart[4] showed a sharp cutoff at the Fermi momentum in the momentum distribution of annihilation photons, it has been known that the positron average energy at annihilation was much less than an electron volt. With our present higher resolution apparatus, it was decided to attempt to observe directly the positron motion.

First of all we must estimate the size of the thermal broadening Δk of the Fermi surface. It is given by

$$(\hbar^2/2m)(k_F \pm \Delta k)^2 = E_F \pm k_B T,$$

from which

$$\frac{\Delta k}{k_F} = \frac{k_B T}{2E_F} \approx \frac{1}{200}$$

for $T = 600°K$. This thermal broadening is one order of magnitude beyond present detectability. However, the usual experiment measures $k_z = (\vec{k}_- + \vec{k}_+)_z$, the sum of both electron and positron momentum. The positron momentum k_+, being its total momentum, is given by

$$(\hbar^2/2m)k_+^2 = \tfrac{3}{2}k_B T,$$

whence

$$\frac{k_+}{k_F} = \left(\frac{3k_B T}{2E_F}\right)^{1/2} \approx \frac{1}{10}$$

for $T = 600°K$. This is just observable at present. The effect of temperature upon positron motion should therefore be detectable. Because of the positron's random motion, the effect should be equivalent to a worsening of apparatus resolution.

Sodium was chosen as the material in which to attempt to measure positron motion for two reasons: The Fermi surface is known to be spherical and the higher momentum components therefore probably small, and secondly, even at high temperature the mean free path of electrons is large. There is, therefore, little smearing of the Fermi surface due to electron scattering.

Sodium specimens maintained at 110, 300, 400, and 600°K were bombarded with positrons and the annihilation photons detected in the usual long slit detector arrangement. The slits subtended an angle of 0.2×10^{-3} rad at the specimen. For sodium the "Fermi angle," θ_F, is 3.5×10^{-3} rad and thus the optical resolution of the apparatus is 6% of k_F. The optical res-

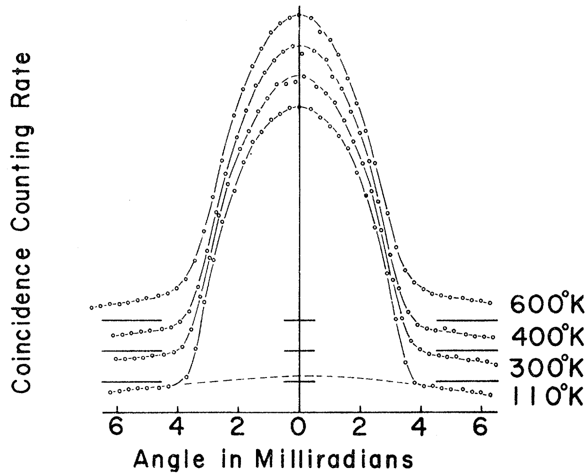

FIG. 1. The angular correlation of photons from positrons annihilating in sodium at the four temperatures indicated. Note that as the temperature is raised, the junction between the broad distribution and the parabolic section becomes more smeared.

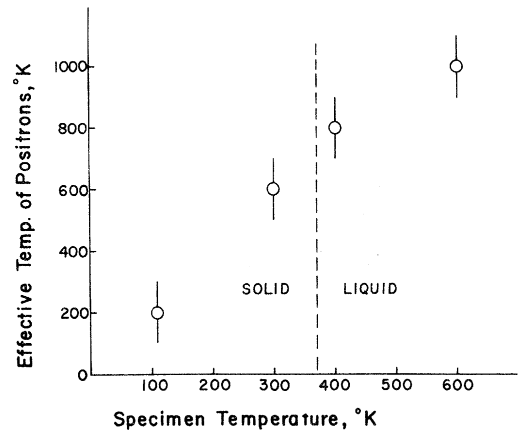

FIG. 2. The "effective temperature" of the positrons obtained from the data of Fig. 1.

olution and the positron motion (at 100°K) are thus expected to contribute about equal apparent smearing of the observed electron momentum distribution.

The measured angular correlation of photons from positrons annihilating in sodium at four different temperatures is shown in Fig. 1. These data have been fitted—in the "slope" representation—by a convolution of a free-electron-theory momentum distribution with a Gaussian function for instrument resolution. The instrument resolution has been considered as consisting of two parts, an optical part determined only by apparatus geometry and a part due to positron motion, the distribution $\exp(-\hbar^2 k_+^2/2mk_B T)$. Using an effective temperature of the positrons as a disposable parameter, we have obtained reasonable fits to the data. The resultant effective temperatures are shown in Fig. 2. Note that the effective temperature is approximately linear with specimen temperature. The slope is 1.9 ± 0.4.

Since thermalization is highly likely, it would probably be better to describe these results in terms of an effective mass

$$m_+^* = (1.9 \pm 0.4) m_0.$$

If, as one supposes, the band mass of the positron is close to unity, this result is then a measure of the many-body mass of a positron in an electron sea.[5,6]

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[5]After this work was done, two papers on this subject were published by Majumdar [C. K. Majumdar, Phys. Rev. 140, A227 (1965), and especially Phys. Rev. 140, A237 (1965)]. For minor practical reasons we prefer the analysis used to the one he proposes. For example, in our analysis k_F remains a disposable parameter and does not affect the effective-mass results, thus avoiding the questions of thermal expansion and lattice parameter and the accuracy of free-electron theory for sodium. At this time we are also most pleased to acknowledge the interesting and profitable discussions of this subject with Dr. Majumdar.

[6]C. K. Majumdar, in Proceedings of the International Conference on Positron Annihilation, Wayne State University, July 1965 (to be published), gave a preliminary estimate of the positron effective mass due to interaction with a sea of electrons of density equivalent to sodium. His result was $m_+^* = 1.3$ m.