Far Infrared Absorption in Superconducting Lead Alloys*

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Measurements have been made at 1.3°K of the absorption of far infrared radiation in the surface of bulk samples of superconducting alloys composed of lead with various amounts of thallium, bismuth, or tin. The data provide the first direct experimental evidence for a sharp gap edge in superconducting alloys. The width of the energy gap decreased as thallium or tin is added to lead, and increases as bismuth is added. For concentrations up to 7.7 at. % thallium the fractional decrease in the gap width is approximately proportional to the fractional decrease in the critical temperature, but is significantly greater than the latter for 10.0 at. % thallium. The steepness of the absorption edge is roughly the same in all of the samples, and is greater than might have been expected from theoretical calculations, although these have been performed only in the extreme anomalous limit, which none of our samples strictly satisfy. The structure which was previously observed on the absorption curves of pure lead and mercury is also present in all of our alloys, indicating that it is probably not a result of anisotropy. This work has been described in detail elsewhere.[1]

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[1] D. M. Ginsberg and J. D. Leslie, Phys. Rev. (to be published).

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BLATT: I don't really have a question, I just have a theoretical comment. Namely, I'm not terribly surprised if the theory does not agree well with those particular data because the theory itself has certain problems. Matthias and Bardeen calculate on the basis of an infinite medium with essentially a sine wave field perturbing it. A susceptibility or a response function is obtained which does not take into account mathematically the presence of the surface; you then have to do certain special things such as diffusion or specular reflection at the surface. I don't think that one can talk about either specular or diffuse reflection of something as big as one of those superelectrons. It is not at all surprising that it is only in the high temperature region that you get good agreement between that kind of theoretical approach and the experiments.

GOODMAN: In connection with your suggestion that the states inside the gap are not due to anisotropy, I wonder if you've seen the recent work of Caroli, Matricon, and de Gennes. They have done a calculation which enables one to estimate the reduction in the anisotropy as a function of ξ/l, the mean free path. To give you an idea of how slowly the anisotropy decreases, we have recently measured the specific heat of pure and impure aluminum at very low temperatures and find that with the mean free path of only 5% of ξ_0, the reduction of the anisotropy is only $\frac{1}{3}$. I would estimate that your mean free path is relatively speaking larger and that the reduction anisotropy is quite small in your alloys.

D. GINSBERG, *University of Illinois:* Some of our mean free paths are shorter than the coherence length of the pure material, and there seems to be no large effect of alloying on the shape of the absorption edge.

TINKHAM: Have you any ideas on what this precursor absorption is caused by if you feel that you've annihilated the two standard explanations?

GINSBERG: I have no idea.

P. L. RICHARDS, *Bell Telephone Laboratories:* I've measured similar absorption edges in very pure, very carefully prepared, single crystal lead samples and in lead samples with 1% bismuth giving a mean free path about equal to the coherent length. In this range a very strong change of the slope of the absorption edge with impurity is observed which I interpret as the disappearance of anisotropy. This is in disagreement with what Dr. Goodman finds in aluminum.

D. J. SCALAPINO, *University of Pennsylvania:* I wonder if perhaps the sharp rise in the absorption above the gap might be explained by taking into account the damping of the excitations. I also wonder if it's possible (this is similar to Dr. Blatt's suggestion) to explain the precursor in terms of collective excitations if the presence of the surface is taken into account. The absorption varies as the square of the momentum transfer and inversely as the slope of the collective excitation energy versus momentum transfer at the momentum transferred. In bulk material the collective excitations pass into the single-particle continuum for momentum transfers greater than about the inverse coherence length, so that the larger momentum transfers available in the anomalous case, of order the inverse penetration depth, are not effective. When the surface is taken into account the collective excitations may exist below the continuum for these larger momentum transfers and the absorption rate should be correspondingly enhanced.

GINSBERG: I will pass this question to Professor Bardeen.

J. BARDEEN, *University of Illinois:* I can answer the first question. One of my students (S. B. Nam) has looked at the problem of damping, and the effect is not great enough. It's in the right direction but not nearly large enough to account for the discrepancy.

L. N. COOPER, *Brown University:* I think, in line with Dr. Goodman's suggestion, it would be interesting, if it were possible, to measure the specific heat of these samples to see whether in fact it was characteristic of a single energy

gap or of an anisotropic energy gap, before one concluded that anisotropy were not a possible explanation of the precursor absorption.

GINSBERG: If one does this one will have to do it at a very low temperature because of the low Debye temperature of lead.

COOPER: I said if it were possible.

KEESOM: We measured that and our data could be explained with an anisotropic energy gap something like $\frac{1}{5}$. If we put about 6% indium into it, it looks like it disappears. I don't know if that answers Dr. Cooper's question.

COOPER: Well, if you've measured it and it disappears, it disappears.

PIPPARD: I would like to add to this. It seems to me that Dr. Ginsberg and Dr. Garfunkel ought to get together and measure the same material, one of them using his technique with microwaves on a flat surface and the other pushing the same frequencies into a cavity. If they got the same answer, then one might begin to worry very seriously about explaining some of the details. But I must say I would be happy to see some sort of tie-up between the two very different techniques, just in case there are unsuspected experimental snags.

GINSBERG: Dr. Garfunkel will need microwaves with a wavelength of about a half a millimeter and this is not quite impossible, but almost.

PIPPARD: We'll wait a year then.

GINSBERG: Yes.

TUNNELING

CHAIRMEN: *E. Burstein, I. Giaever*

Tunneling between Superconductors

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Using the tunneling technique, studies have been made of both the density of states variation in superconductors and the magnetic field dependence of the Josephson current.

The density of states variation with energy in a superconductor is measured as the plot of first derivative (dI/dV) of the tunnel current against voltage (V) for a metal–insulator–superconductor (M–I–S) junction. This variation at energies greater than the gap (Δ) follows, in general, the BCS dependence[1] but deviations from this behavior are easily observed in the case of lead and are of considerable significance.[2,3]

The experimentally observed density of states versus energy variation in lead has two pronounced drops centered at energies of 4.4 and 8.5 mV. These are associated with the transverse and longitudinal peaks in the phonon spectrum. A detailed solution of the gap equation[4] using an approximate spectrum with peaks at these positions yields a theoretical density of states plot in good agreement with experiment over the whole energy range. At higher energies, structure at sum and harmonic positions of the fundamental peaks is observed.

Fine structure in the density of states variation is resolved by plotting d^2I/dV^2 versus V for M–I–S junctions, or, more strikingly, for S–I–S junctions. In addition to structure due to the main peaks in the phonon spectrum, we resolve structures which are attributed to the Van Hove critical points in the spectrum. For example, the end of the spectrum is resolved as a square root singularity, in agreement with recent theory.[5] This locates the end of the phonon spectrum in lead as 8.85 $\pm$ 0.1 mV and in tin as 17.7 $\pm$ 0.2 mV. Structure at 1.8 and 1.35 mV from the gap in lead and tin, respectively, is at energies which are surprisingly low for critical points and is as yet unexplained.

[1] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **108**, 1175 (1957).

[2] I. Giaever, H. R. Hart, Jr., and K. Megerle, Phys. Rev. **126**, 941 (1962).

[3] J. M. Rowell, P. W. Anderson, and D. E. Thomas, Phys. Rev. Letters **10**, 334 (1963).

[4] J. R. Schrieffer, D. J. Scalapino, and J. W. Wilkins, Phys. Rev. Letters **10**, 336 (1963).

[5] D. J. Scalapino and P. W. Anderson (to be published); D. J. Scalapino, Rev. Mod. Phys. **36**, 205 (1964).