Holland Publishing Company, Amsterdam, 1961), Vol. III, p. 267.

[3]V. L. Ginzburg, Doklady Akad. Nauk S.S.S.R. 118, 464 (1958) [translation: Soviet Phys.–Doklady 3, 102 (1958)].

[4]J. Bardeen, Phys. Rev. Letters 7, 162 (1961).

[5]N. I. Ginzburg and A. I. Shal'nikov, J. Exptl. Theoret. Phys. (U.S.S.R.) 37, 399 (1959) [translation: Soviet Phys.–JETP 10, 285 (1960)].

[6]M. Tinkham, Phys. Rev. 110, 26 (1958).

[7]R. H. Pry, A. L. Lathrop, and W. V. Houston, Phys. Rev. 86, 905 (1952).

QUANTUM INTERACTION OF MICROWAVE RADIATION WITH TUNNELING BETWEEN SUPERCONDUCTORS

A. H. Dayem and R. J. Martin
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received February 2, 1962)

Electron tunneling has been used[1-4] to determine the width of the energy gap in the quasi-particle excitation spectrum of superconductors. The experiment is usually carried out using two metal films separated by a thin oxide layer. A good quantitative agreement between theory and experiment was obtained[1-4] by assuming that the matrix element of the transition of an electron from one side of the barrier to the other can be treated as a constant over the energy range of interest. A discussion of tunneling from a many-particle point of view was given by Bardeen[5] to show the plausibility of this assumption. Bardeen[5] further shows that coherence factors in superconductivity do not influence the tunneling process, since the matrix element depends only on the tail of the electron wave function in the barrier region where it is essentially the same as in the normal state. Thus the only relevant factor is the density of states in energy and the net tunneling current may be expressed by an integral over the energy E of the form[2,3]

$$I(V) = \text{const} \times \int \rho_1(E)\rho_2(E+eV)[f(E)-f(E+eV)]dE, \quad (1)$$

where ρ is the density of states, f the Fermi function, and V the applied voltage.

Tien[6] suggested the use of optical excitation of electrons across the energy gap of the superconductor to modify the negative-resistance region in the I-V curve. Burstein et al.[7] discussed the use of tunneling between two superconducting films for the quantum detection of microwave and submillimeter wave radiation. If the microwave frequency ν is such that $h\nu > 2\epsilon_1$, an electron in metal 1 may be excited across the gap and subsequently tunnel through the barrier into an empty state in metal 2. This is shown schematically in Fig. 1(a). If this were the only possible interaction with the electromagnetic field, no change in the tunneling current would be observed for $h\nu < 2\epsilon_1$. We have noticed experimentally, however, that considerable interaction with the microwave field occurs for $h\nu < 2\epsilon_1$. The experimental results suggest that with a bias voltage which brings the top of the filled band on one side of the barrier to a level lower by an amount $h\nu$ from the bottom of the empty band on the other side, an electron may absorb a photon and tunnel from one side to the other as shown in Fig. 1(b). This process seems consistent with tunneling from a many-particle point of view. Absorption by a tunneling electron of more than one photon has also been observed.

We carried out the experiments at different microwave frequencies on samples of Al-Al_2O_3-Pb, In, or Sn. The sample was placed in a resonant cavity with appropriate current and voltage leads connected to the metal films. The results presented consist of oscilloscope traces obtained by

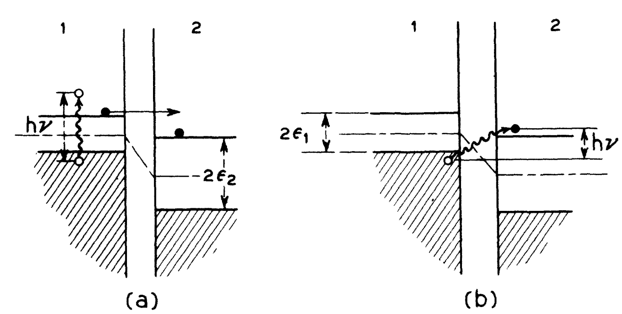

FIG. 1(a). Optical excitation across the gap of metal 1 followed by tunneling through the barrier to metal 2; $h\nu > 2\epsilon_1$. (b) Photon absorption by a tunneling electron; $h\nu < \epsilon_1$.

sweeping the applied bias at 60 cps and square-wave modulating the microwave power input at about 2000 cps. This gives a composite trace showing simultaneously the $I-V$ curves in the presence and absence of the microwave field.

We discuss first the expected $I-V$ curve in the presence of an electromagnetic field if the proposed mechanism of interaction is permissible. For simplicity we limit the discussion to $T=0$ where no thermally excited electrons exist in the upper band and assume that only one photon can be absorbed or emitted by a tunneling electron. As the bias voltage is increased from zero, the current remains zero up to $|eV|=\epsilon_1+\epsilon_2-h\nu$ where a sharp rise in current takes place due to electrons near the top of the filled band[8] which can now absorb a photon and tunnel into the empty states near the bottom of the empty band. The sharp rise is due to the fact that the density of states is very large (theoretically infinite) at the gap edges. For higher voltages the current will continue to rise, obviously at a lower rate, up to $|eV|=\epsilon_1+\epsilon_2$. For $|eV|>\epsilon_1+\epsilon_2$ one may expect the tunneling current to be less than its corresponding value in the absence of the rf field. Here a tunneling electron which absorbs a photon will make a transition to a higher energy level where the density of states is smaller than that near the bottom of the band. However, when $|eV|>\epsilon_1+\epsilon_2+h\nu$, emission as well as absorption of a photon is possible. The current rises sharply near $|eV|=\epsilon_1+\epsilon_2+h\nu$ because an electron near the top of the filled band can tunnel into a state near the bottom of the empty band after the emission of a photon. The experimental results are shown in the oscilloscope traces in Fig. 2, where the voltages at which the sharp rise in current occurs substantiates the above discussion. Notice also evidence of multiple photon absorption occurring at $|eV|=\epsilon_1+\epsilon_2-nh\nu$, $n=1, 2, \cdots$.

The number and magnitude of measurable steps in the $I-V$ curve increase with the intensity of the microwave field. A measured $dI/dV-V$ characteristic is shown in Fig. 3. This derivative was graphically determined from a large scale $I-V$ curve obtained from a series of photographs (~20) of overlapping portions of the $I-V$ oscilloscope trace. We notice that the peaks for $|eV|<\epsilon_1+\epsilon_2$ are equally spaced with exactly 0.16 mv between successive peaks corresponding to the applied microwave frequency of 38.83 kMc/sec. However, for $|eV|>\epsilon_1+\epsilon_2$, the measured peaks are displaced from the expected positions shown by the dashed curve. These displacements might have arisen from errors in plotting the $I-V$ curve from a large number of photographs or they are otherwise inherent in the interaction with the field. Using a single small-scale picture one may conclude that, within the experimental error, these peaks should occur at the expected values of the voltage. It may

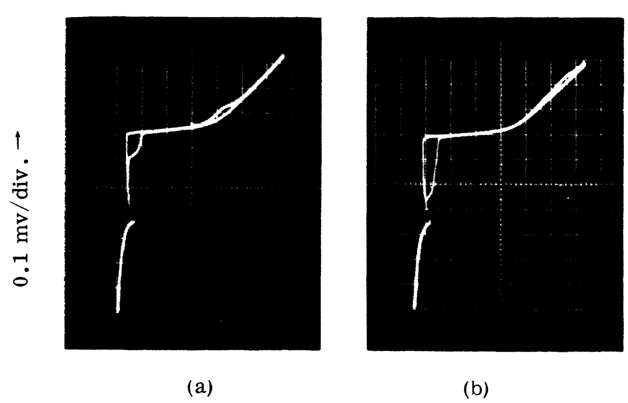

FIG. 2. $I-V$ curves with and without microwave field at two different frequencies for an Al - Al_2O_3 - In sample. Input power level is -12 dbm. (a) 24.82 kMc/sec in TE_{11} mode; (b) 63.02 kMc/sec in TE_{01} mode.

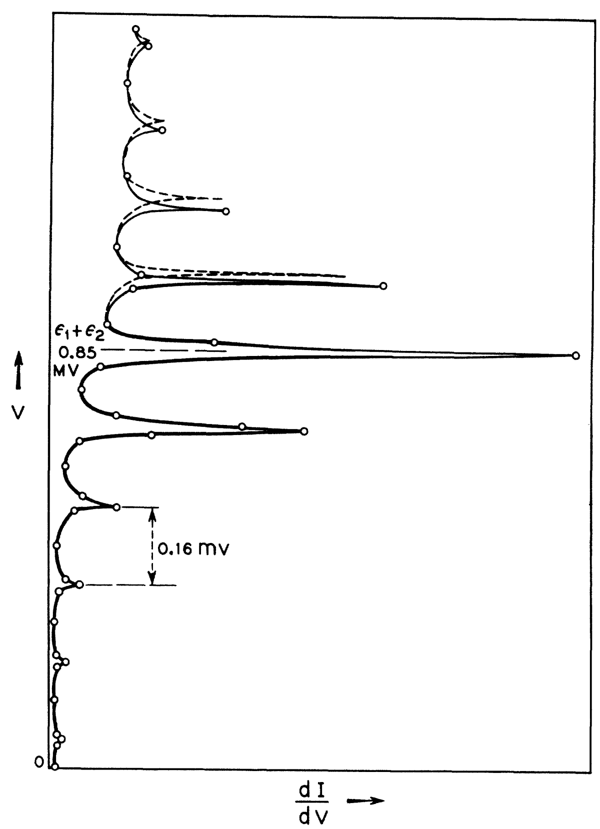

FIG. 3. o -Measured points. $\nu=38.83$ kMc/sec; $h\nu=0.16\times10^{-3}$ ev.

be helpful to consider the $|dI/dV|$-V curve shown in Fig. 3, as representing an "equivalent density of states" of the combined structure of two superconductors in the presence of a microwave field.

Further characteristics of the interaction will be covered in a future publication.

The authors are indebted to Dr. J. P. Gordon, Dr. P. K. Tien, and other members of the Electronics Research Department for many valuable discussions.

[1] I. Giaever, Phys. Rev. Letters 5, 147, 464 (1960).

[2] J. Nicol, S. Shapiro, and P. H. Smith, Phys. Rev. Letters 5, 461 (1960).

[3] I. Giaever and K. Megerle, Phys. Rev. 122, 1101 (1961).

[4] N. V. Zavaritzkii, Zhur. Eksp. i Teoret Fiz. 41, 657 (1961) [translation: Soviet Phys—JETP 14, 470 (1962)].

[5] J. Bardeen, Phys. Rev. Letters 6, 57 (1961), see also W. A. Harrison, Phys. Rev. 123, 85 (1961).

[6] P. K. Tien (unpublished work).

[7] E. Burstein, D. N. Langenberg, and B. N. Taylor, Phys. Rev. Letters 6, 92 (1961).

[8] Notice that the filled band is on one side of the barrier while the empty band is on the other side.

NUCLEAR MAGNETIC RESONANCE IN CHROMIUM METAL*

R. G. Barnes and T. P. Graham
Institute for Atomic Research and Department of Physics, Iowa State University, Ames, Iowa
(Received February 16, 1962)

The nuclear magnetic resonance of naturally abundant (9.5 %) Cr^{53} has been observed in pure (crystal-bar) chromium metal at temperatures above the antiferromagnetic ordering temperature T_N of 40°C, and the Knight shift of the resonance has been measured. We have also observed the Cr^{53} resonance in chromium containing up to 3 at. % (nominal) vanadium, and have measured the Knight shift of the V^{51} resonance in these and other vanadium-chromium alloys.

These two metals form a complete solid solution system of body-centered cubic alloys, showing no evidence for the formation of intermetallic compounds.[1] Alloy specimens were prepared by arc-melting crystal-bar vanadium and chromium. Homogenizing anneals of the arc-melted buttons were made in some cases, but this does not appear to affect the Knight shift significantly. Samples suitable for nuclear resonance were obtained from filings of the alloy buttons.

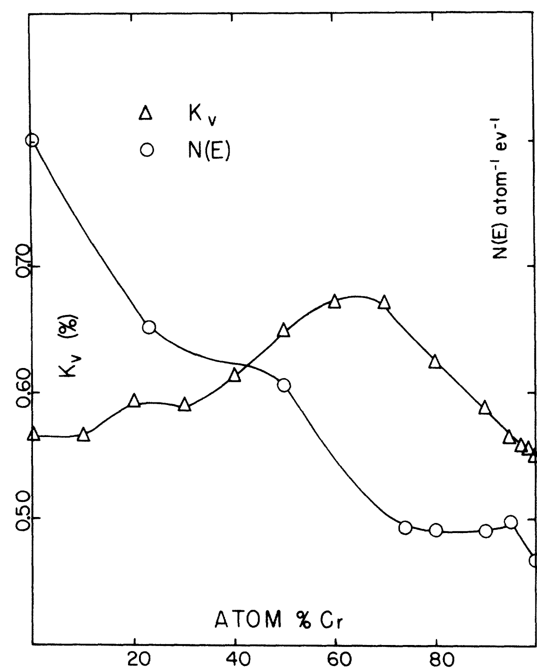

FIG. 1. Knight shift k_V of the V^{51} resonance in the V-Cr alloy system. The density of states at the Fermi level $N(E)$ calculated from the specific heat data of reference 3 is also shown. The 4s contribution to $N(E)$ [taken as equal to $N(E)$ for copper] has not been subtracted from the observed γ values, as was done in reference 3.

Figure 1 shows the Knight shift k_V at room temperature for V^{51} at composition intervals of 10 at. % (nominal) across the entire V-Cr system. Measurements of k_V were also made at vanadium concentrations of 0.25, 0.50, 1.5, 3.0, and 5.0 at. %. These latter results are included in Fig. 1 and are shown on an expanded scale in the lower portion of Fig. 2. Measurements of k_V were also made at 77°K in all alloys except those containing 3 at. % or less vanadium. In these latter alloys the V^{51} resonance was not detectable at 77°K. The shift at 77°K is always slightly smaller (by 0.01-0.03 %) than that at room temperature. The Knight shift k_{Cr} of the Cr^{53} resonance was measured in the range 0-3 at. % vanadium concentration, and these values are shown in the upper portion of

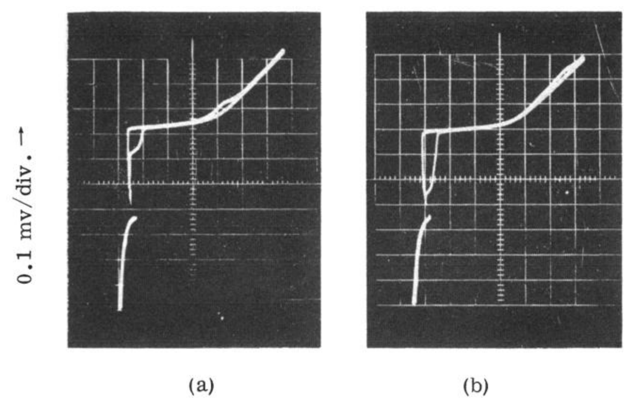

FIG. 2. *I - V* curves with and without microwave field at two different frequencies for an Al - Al_2O_3 - In sample. Input power level is -12 dbm. (a) 24.82 kMc/sec in TE_{11} mode; (b) 63.02 kMc/sec in TE_{01} mode.