Evidence for spin fluctuations in vanadium from a tunneling study of Fermi-liquid effects

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The Fermi-liquid parameter G_0 is found to be close to zero in vanadium, providing new experimental evidence for the importance of spin fluctuations in this material. $Al/Al_2O_3/V$ and $V/Al_2O_3/Fe$ tunnel junctions were used to observe the renormalization caused by Fermi-liquid interactions of the spin splitting of the vanadium's superconducting density of states in a magnetic field. This was done by fitting the theory of Rainer to the measured dynamic tunneling conductance. Excellent agreement was found with this theory, and the results were consistent with critical field measurements made on the same vanadium films. The spin-orbit scattering rate b_{sc} was determined to be 0.07 ± 0.03.

I. INTRODUCTION

The role of spin fluctuations (paramagnons) in limiting the superconducting transition temperature of some transition metals and transition-metal compounds has been investigated by a number of authors. Gladstone *et al.*[1] were the first to point out that because spin fluctuations involve the local (parallel) correlation of electron spins they oppose the Cooper pairing of superconductivity. Some of the best evidence for the importance of spin fluctuations has been the fact that transition-temperature calculations for V, Nb, and VN based on the Eliashberg equations give values which are too large if spin fluctuations are not considered. For example, the T_c calculated for V is ~ 18 K,[2] whereas the measured value is only 5.4 K. On the other hand, it has been shown that including spin fluctuations in the Eliashberg equations could account for the low measured T_c's in V, Nb, and VN.[2,3] At the same time, if the electron-phonon mass enhancements used in these T_c calculations are used to predict the specific heat, the values obtained are somewhat low. Spin fluctuations could also provide the missing mass enhancement. Strong spin fluctuations are also believed to be responsible for the lack of superconductivity in palladium.[1]

Daams, *et al.*[4] have shown that the Coulomb pseudopotential μ^* and the electron-phonon coupling constant $\lambda_{e\text{-ph}}$ will be renormalized by spin fluctuations. Burnell *et al.*[5] have used this fact as evidence for spin fluctuations in vanadium and niobium. They noted that the unusually large values obtained for μ^* from inversion of their $\alpha^2F(\omega)$ data on these elements could be explained by the spin-fluctuation rescaling. This explanation is contingent on the assumption that μ^* should have the same value for transition metals such as vanadium and niobium as it does for the s-p electron superconductors.[6]

Spin fluctuations should also have an effect on the interaction between quasiparticle excitations in a superconductor. Interaction between quasiparticles is mediated by the electron-phonon interaction and by the (spin-fluctuation-enhanced) Coulomb exchange interaction. We will discuss these effects in terms of the Fermi-liquid theory of Landau.[7,8] Two consequences of the Fermi-liquid interaction between superconductor quasiparticles are the renormalization of the Pauli-limited critical field and the quasiparticle density of states. Both of these renormalizations can be used to provide evidence for spin fluctuations in superconductors. Orlando and Beasley[9] have found that the parallel critical field of thin (Pauli-limited) V_3Ga films is lower than expected if only electron-phonon coupling is considered. The electron-phonon interaction tends to increase the Pauli-limited critical field whereas the Coulomb exchange interaction reduces it. The low critical field of V_3Ga may be explained by a paramagnon-enhanced Coulomb interaction.

In the present experiment, the effect of spin fluctuations on the tunneling density of states of superconducting vanadium is examined using $Al/Al_2O_3/V$ and $V/Al_2O_3/Fe$ tunnel junctions. The $l=0$, antisymmetric Fermi-liquid parameter G_0 is determined by observing the quasiparticle density of states as a function of magnetic field. The results are fitted to the theory of Rainer,[10] which incorporates the many-body interactions into the standard theory of high-field superconductivity.[11–13] G_0 has recently been measured in aluminum[10,14] and amorphous gallium[15] in this way. Tunneling experiments are preferable to critical field measurements for determining G_0 because they allow the effects of the many-body renormalization to be unambiguously separated from the effects of spin-orbit scattering. Note also that in these experiments on superconductors the effects of the Fermi-liquid interactions are separated from other renormalization effects, which is not the case for most experiments on normal metals.

The Fermi-liquid parameter G_0 was found to be nearly zero in vanadium. If the electron-phonon interaction were the only important many-body interaction in this element, one would expect $G_0 \simeq \lambda_{e\text{-ph}} \simeq 0.9$.[4,16] As we shall see, the presence of spin-fluctuations tends to lower G_0. Thus, the low observed value for G_0 is strong new evidence for the importance of spin-fluctuations in vanadium.

II. THEORY

Near a second-order phase transition to the normal state, the density of quasiparticles approaches the normal state density of electrons, and interaction between them becomes important. The effect of the neighboring quasiparticles on a given quasiparticle can be described in terms of an additional magnetic field acting on its spin (in addition to the renormalization of its self-energy or effective mass). Since using this effective internal field is equivalent to renormalizing the effective magnetic moment of the quasiparticle, the interaction renormalizes the superconducting properties dependent on this moment, such as the Pauli-limited critical field and the spin splitting of the quasiparticle density of states in a magnetic field. The present study is based on these Fermi-liquid effects.

The theoretical foundation for the application of Fermi-liquid[7,8] theory to isotropic superfluids in the clean limit was laid by Leggett.[17–19] We will use the quasiclassical approach developed by Eilenberger[20] and Larkin and Ovchinikov.[21] This approach has been used by Serene and Rainer[22] to describe ^{3}He. The extension of this theory to high-field superconductivity used here is due to Rainer[10]. It is important to note that in the dirty limit the renormalization of both the quasiparticle density of states and the critical field is characterized by the single parameter G_0. This is the $l=0$, antisymmetric, Fermi-liquid parameter which is sometimes referred to as B_0 in the literature.

Determining G_0 in vanadium is of interest because its value is sensitive to the presence of spin fluctuations. Using the theory of Berk and Schrieffer,[23] Jensen and Andres[24] have shown that the renormalization of the effective mass of the quasiparticles due to the electron-phonon and paramagnon interactions is given by $m^*/m=1+\lambda_{e\text{-ph}}+\lambda_s$. Here $\lambda_{e\text{-ph}}$ is the usual electron-phonon coupling constant

$$\lambda_{e\text{-ph}}=2\int\frac{\alpha^2F(\omega)}{\omega}d\omega\ , \tag{1}$$

where α^2 is the square of the electron-phonon matrix element and $F(\omega)$ is the phonon density of states. Similarly,

$$\lambda_s=2\int\frac{P(\omega)}{\omega}dw \tag{2}$$

is the equivalent mass renormalization due to spin fluctuations with a paramagnon spectral density [the equivalent of $\alpha^2F(\omega)$] given by $P(\omega)$. Berk and Schrieffer's theory can also be used to show that in the static, long-wavelength limit the spin susceptibility is given by,

$$\chi(0,0)=2\mu_B^2N_0/(1-\bar{I})\ , \tag{3}$$

where $(1-\bar{I})^{-1}$ is the Stoner factor. The Stoner factor gives the renormalization of the susceptibility due to electron-electron interactions: $\chi_P^*=\chi_P/(1-\bar{I})$. $\bar{I}$ is the s-wave average over the Fermi surface of the Coulomb exchange interaction. In terms of the Fermi-liquid theory, the spin susceptibility is given by $\chi=2\mu_B^2(m^*/m)N_0/(1+G_0)$ [see, for example, Ref. 25]. Combining these results yields

$$1+G_0=(1+\lambda_{e\text{-ph}}+\lambda_s)(1-\bar{I})\ . \tag{4}$$

Spin-fluctuations act to enhance the electron-electron interaction and, therefore, the Stoner factor.[4] The decrease in G_0 due to a large value for $\bar{I}$ outweighs the increase due to the small mass enhancement λ_s. Thus, we expect spin fluctuations to decrease the observed value for G_0.

It is difficult to determine G_0 from critical field measurements alone. This point has been discussed in detail by Alexander.[26] The problem is that spin-orbit scattering has an effect on the critical field which is very similar to that of the renormalization. The best way to determine G_0 is by fitting the quasiparticle density of states calculated from the theory of Rainer to measured tunnel conductance curves. One of the main features of the renormalization of the superconductor density of states is a decrease in the Zeeman splitting of the quasiparticle energies. The effective additional field due to quasiparticle interaction is given by[19]

$$H_{\text{int}}=H_{\text{ext}}\left[\frac{-G_0Y(t)}{1+G_0Y(t)}\right]\ , \tag{5}$$

where $Y(t)$ is the Yosida function. The Yosida function equals one for $t=T/T_c(H)\geq 1$ and decreases monotonically to zero as t drops to zero. This effective field can either add to or oppose the applied field depending on the sign of G_0. Because of the extra internal field, the Zeeman splitting δ of the quasiparticle excitations is renormalized,

$$\delta\rightarrow 2\mu_BH/[1+G_0Y(t)]\ . \tag{6}$$

If the spin-orbit scattering rate is low,[27] G_0 can be determined by directly measuring the deviation of the splitting from $2\mu_BH$ as a function of field and comparing the result with the theory. This approach has been used by Tedrow *et al.*,[14] on aluminum, which has a very low spin-orbit scattering rate ($b_{\text{so}}=0.05$). They used $Al/Al_2O_3/Fe$ tunnel junctions to resolve the two quasiparticle spin densities of states of the aluminum and by measuring the separation in energy of these densities of states obtained $G_0=0.3$. This spin-resolved tunneling technique has been described in Refs. 28 and 29.

G_0 can also be determined by fitting the full energy dependence of the quasiparticle density of states in a magnetic field to the theory. Alexander *et al.*[10] and Alexander[26] have done this for aluminum and again got a value of $G_0\simeq 0.3$. This method also has been used recently to determine that $G_0\simeq 0.8$ for amorphous gallium.[15] In the present work this technique is used on $Al/Al_2O_3/V$ tunnel junctions to determine G_0 in vanadium. The spin-orbit scattering rate in vanadium was concurrently found to be low, so that it is reasonable to try to determine G_0 directly from measured values of the Zeeman splitting by spin-resolved tunneling. This has been accomplished using $V/Al_2O_3/Fe$ tunnel junctions.

III. PREPARATION AND TESTING OF $Al/Al_2O_3/V$ AND $V/Al_2O_3/Fe$ TUNNEL JUNCTIONS

Tunnel junctions were prepared in a diffusion-pumped vacuum system with a base pressure of less than 1×10^{-7} torr. Successful $Al/Al_2O_3/V$ junctions were readily made. First 5 Å of iron and then 300 Å of aluminum were deposited through a "long-strip" mask onto a glass substrate held at liquid-nitrogen temperature. This was then warmed to room temperature and glow discharged in oxygen for ~ 50 sec. Finally, thin vanadium cross strips were deposited to produce the junctions. These were coated with 50 Å of Al_2O_3 to prevent oxidation. The purpose of the iron was to drive the aluminum normal. This allowed the direct observation of the vanadium quasiparticle density of states at low field, making it easy to determine the zero-field depairing.

To make $V/Al_2O_3/Fe$ junctions we first deposited vanadium cross strips onto a room-temperature glass substrate. The substrate was then cooled to liquid-nitrogen temperature and the cross strips were overcoated with 45–55 Å of Al. The edges of the cross strips were masked with a thick layer of either Al_2O_3 or SiO_2 (~300 Å) to prevent shorting. After warming to room temperature the samples were glow discharged *in situ* in an oxygen plasma for approximately 50 sec to form an Al_2O_3 barrier. Next, 300-Å Fe long strips were evaporated to complete the tunnel junctions. The Al and Fe were evaporated from tungsten boats; the V and Al_2O_3 were deposited using an electron-beam gun. It was difficult to obtain good $V/Al_2O_3/Fe$ junctions; most were either shorted or had an extremely high resistance. However, a few junctions had tunnel resistances between 100 Ω and 10 k Ω and were used in this experiment.

In the first-preparation technique the vanadium must be deposited at room temperature so as not to destroy the barrier. We found that this did not significantly degrade the T_c for a given thickness over that obtained for films deposited at 700 °C on sapphire substrates. For 100-Å films the T_c was about 3.3 K in both cases.[30] The transition temperatures for films made at ~ 80 K, however, were reduced significantly. 100-Å films deposited at this temperature had a T_c of only 2.1 K. Attempts made to produce junctions with the vanadium deposited first onto a substrate held at ~700 °C were unsuccessful, perhaps because of the morphology of the vanadium films.

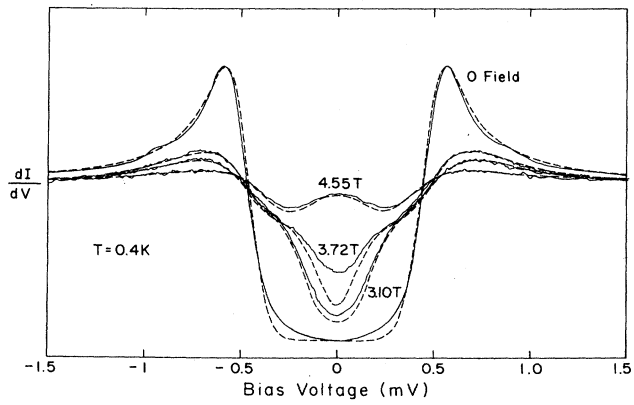

FIG. 1. Dynamic conductance vs bias voltage for an $Al/Al_2O_3/V$ tunnel junction at a number of fields. The dashed curves are a fit to the theory. Here we have used $G_0=0$, $C_F=0.9$, $b_{so}=0.09$, and $P_0=0.1$. The vanadium film is 100 Å thick.

The junctions were mounted on a probe with a tiltable sample holder. This probe was inserted in a ^3He refrigerator which in turn was mounted in an 8-T superconducting magnet. The transition temperatures of the vanadium films were determined resistively while cooling. Critical field data were then taken in both the parallel and perpendicular directions. The dynamic conductance was measured at a number of different fields and temperatures. The amplitude of the modulation used to determine the dynamic conductance was kept at 20 μV (0.23 K) so as to be less than the smearing introduced by the temperature noise.

IV. ANALYSIS OF $Al/Al_2O_3/V$ TUNNELING DATA

We will begin by discussing the determination of G_0 in vanadium using $Al/Al_2O_3/V$ tunnel junctions. This was accomplished by fitting their dynamic conductance versus bias voltage using a program written by Rainer based on his extension of the theory of high-field superconductivity[11–13] to include Fermi-liquid interactions.[10] The input parameters to the theory are the Fermi-liquid parameter G_0, the spin-orbit scattering rate, two depairing parameters, and the measured transition temperature. To describe the spin-orbit scattering rate we will use the parameter $b_{so}=\hbar/3\Delta\tau_{so}$, where $\Delta=1.76kT_c$ is the order parameter and τ_{so} is the spin-orbit scattering time. Theoretically, the orbital depairing for a thin film in a parallel field should be proportional to the square of the field.[12,13] We find that in order to get the best fit to the data we must include a pairbreaking term P_0, which is independent of field. This has also been found to be necessary in fitting tunneling data on aluminum[28] and amorphous gallium.[15] Possible sources for this term are discussed in Ref. 15. To describe the H^2 depairing term we will use Fulde's depairing parameter,[13] $c_F=(De^2d^2\Delta_0/\mu_B^2\hbar c^2)$. Here $D=lv_F/3$ is the diffusion constant with l the transport mean free path and v_F the Fermi velocity. The total pairbreaking is given by

$$P=\left[\frac{k_BT_{c0}}{\Delta_0}\right]c_Fh^2+P_0$$

where P_0 is the zero-field depairing parameter, T_{c0} is the transition temperature in the absence of all pairbreaking, and $h=\mu_bH/k_BT_{c0}$. As defined here, $P-P_0$ is the square of the ratio of the orbital to spin-energy differences between time-reversed states. Typically we found $P_0\sim0.1$ and $c_F\sim0.9$. This small value for P_0 has negligible effect on the value we determine for G_0.

A typical set of conductance curves, at low temperature, is shown in Fig. 1. The dashed curves are a fit to Rainer's theory using $G_0=0$. An interesting feature of these curves is the peak at zero bias which appears at

high field. This zero-bias peak is the result of the overlap of the peaks of the two spin density of states when the Zeeman splitting becomes comparable to the order parameter. Roughly speaking, the zero-bias peak is predicted by the theory only if $\mu_B H/\Delta(T,H) \geq 0.7$ while at the same time the order parameter $\Delta(T,H)$ is not too greatly reduced from its zero-field, zero-temperature value. The second condition is important because a small order parameter reflects the filling of the gap in the quasiparticle density of states and the rounding of its features. The application of a magnetic field produces the central, "overlap" peak only if the peaks in the individual spin densities of states remain large compared to the density of states at the center of their gaps. The condition $\mu_B H/\Delta(H) \geq 0.7$ is approximate. The exact cutoff may be higher. It depends on the shapes of the individual spin densities of states, which are determined by the renormalization, depairing, and spin-orbit scattering. Increasing the spin-orbit scattering rate, for example, makes it more difficult to observe the peak in the sense that one must be closer to the phase boundary. This is illustrated in Fig. 2. In fitting the data on our 100-Å vanadium films we find that the very existence of the zero-bias peak puts an upper limit[31] on b_{so} of about 0.12.

The zero-bias peak is quite useful in determing G_0. We cannot make extremely thin vanadium films that are electrically continuous without depositing them on very cold substrates, which severely degrades the transition temperature. The films described here were deposited at room temperature, are 100 Å thick, and exhibit significant orbital depairing. This orbital depairing rounds out the tunneling conductance curves, making it somewhat more difficult to discern the effects of the renormalization. Despite this, the Zeeman splitting can still be observed at intermediate fields and provides useful information on the renormalization and spin-orbit scattering rate. However, the zero-bias peak which emerges at high field allows us an accurate look at what is going on near the phase boundary, where the effects of the renormalization are greatest.

Figure 3 shows conductance data (solid curves) at fields approaching the critical field. The dashed lines are a fit to Rainer's theory (again using $G_0=0$). The match to the data is quite good. It should be noted that T_{c0} was calculated from the measured (zero-field) transition temperature T_c using the value for P_0 obtained from the zero-field conductance. In the present experiment we find $P_0 \leq 0.1$ so that T_c is close to T_{c0}. The conditions for the observation of the zero-bias peak which were mentioned above are equivalent to the requirement that the superconducting transition be of first order or at least close to first order at the temperature the data were taken. Figure 4 shows a typical phase diagram for a thin film in a parallel magnetic field, for which the transition is of first order below a critical temperature T^*. In order to obtain a first-order transition the spin-orbit scattering, renormalization, and orbital depairing must all be sufficiently low. Increasing any of these quantities changes the susceptibility of the superconductor so as to lower T^*. (T^* can be calculated from the Ginzburg-Landau theory; for a review see Ref. 13.)

Figure 5 can be used to demonstrate the accuracy to which G_0 can be determined by using high-field conductance data such as that in Fig. 3 in conjunction with critical field data (see Fig. 6). If we use the parameters obtained from fitting the curves in Fig. 3 to calculate the order parameter as a function of applied field we get the curve labelled 2 in Fig. 5. Curve 1 is the result of arbi-

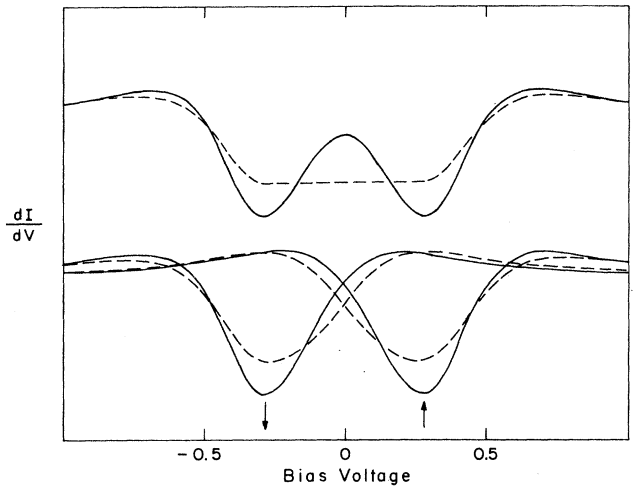

FIG. 2. Theoretical prediction for dynamic conductance (upper curves) and its individual spin components (lower curves) at two different values of b_{so} at $T=0$ K. Solid curves, $b_{so}=0.05$; dashed curves, $b_{so}=0.15$. In the low-b_{so} case the production of the zero-bias peak by the overlap of the peaks in the individual spin densities of states is demonstrated. In both cases the other parameters were typical for 100-Å vanadium films: $G_0=0$, $c_F=0.85$, and $P_0=0.1$. Even though a slightly larger value for $\mu_B H/\Delta(H)$ was used for the dashed curves (0.969) than for the solid ones (0.935) the zero-bias peak disappears for the high-b_{so} (dashed) curves.

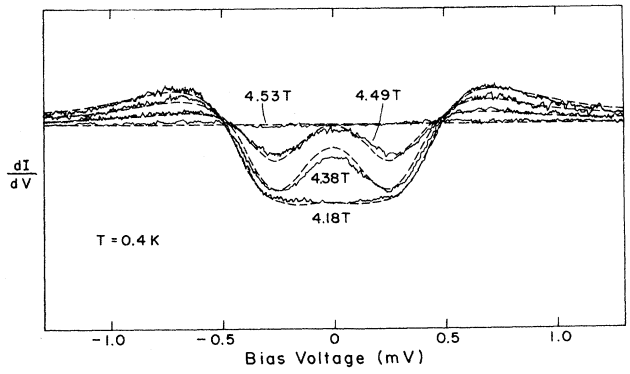

FIG. 3. Dynamic conductance at a number of fields approaching the phase boundary at $T=0.4$ K. The vanadium's order parameter remains large until very close to the transition. Dashed lines are a fit to the theory with G_0, $b_{so}=0.07$, $c_F=0.90$. $T_c=3.3$ K and $P_0=0.1$ so that $T_{c0}=3.62$ K.

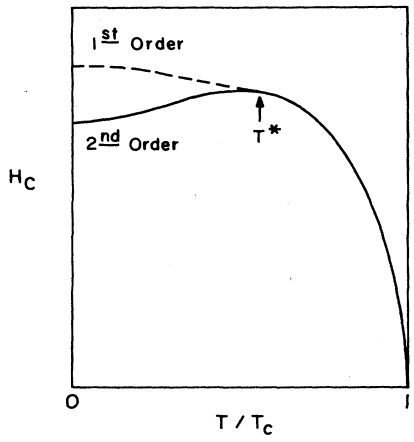

FIG. 4. Phase diagram for a thin superconductor in a parallel magnetic field.

trarily fixing G_0 at -0.167 while varying the other parameters for the best fit of the parallel critical field data of Fig. 6 for the same vanadium film. In this case the best fitted is obtained using $c_F=0.63$, and $b_{so} = 0.11$. The dashed part of the curve is the "unphysical" second solution for the gap in the region between the first- and second-order phase boundaries. Similarly, curve 3 is obtained by fixing G_0 at 0.5. Then the best fit to the critical field data is obtained using $c_F=1.32$ and $b_{so}=0$. All three curves are for $T=0.4$ K. The dashed vertical lines indicate the range of field over which the zero-bias peak was observed at this temperature.

For the parameters which provide the best fit to the conductance data (those of curve 2 in Fig. 5), the calculated value for T^* is 0.28 K. As we decrease G_0 below zero in the theory, T^* rapidly increases. If we arbitrarily fix G_0 at -0.167, and then vary the other parameters so as to best fit the critical field data, we find that the superconducting transition is first order at 0.4 K. The gap is large compared to the splitting even near the transition (see curve 1 in Fig 5) and the zero-bias peak is not produced. We find that the data cannot be fit using values for G_0 less than about -0.05. If G_0 is fixed at a value larger than zero, the resulting gap is too small, as in curve 3 of Fig. 5. The shape of the predicted conduc-

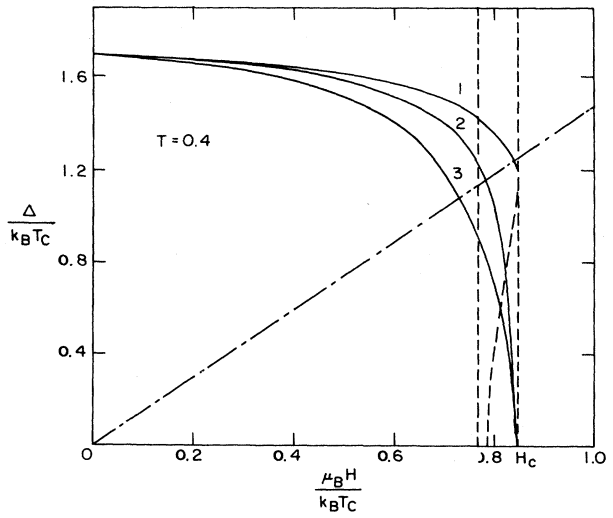

FIG. 5. Gap vs applied field in units of k_BT_c at $T=0.4$ K. Curve 1 is the result of fixing G_0 at -0.167 while varying the other parameters so as to best fit the parallel critical field data for the same vanadium film. Similarly, curve 3 is obtained by fixing G_0 at 0.5. Curve 2 is obtained using the fitting parameters from Fig. 3. The vertical lines indicate the range of field over which the zero-bias peak is observed. Usually, this peak can only be seen for values of Δ and H to the lower right of the dash-dot line.

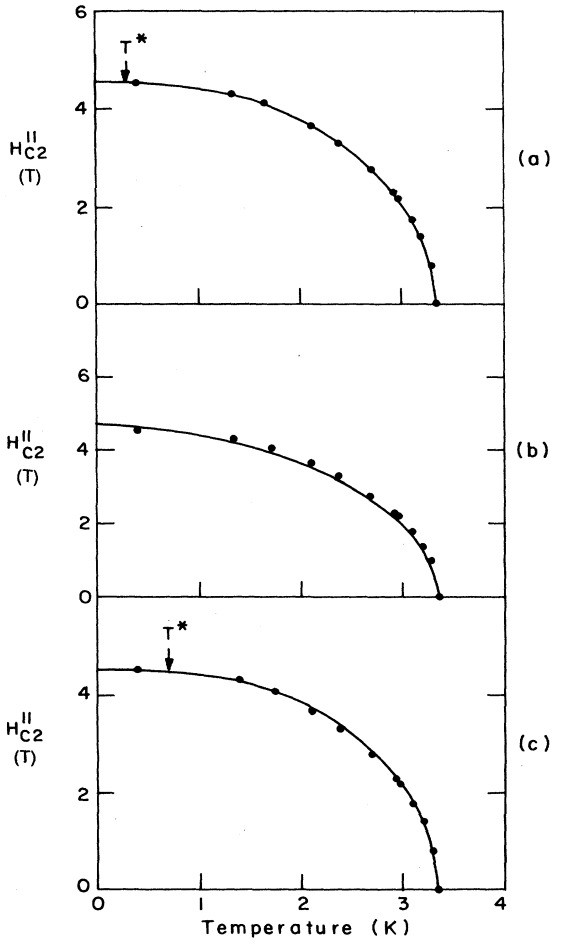

FIG. 6. Points are parallel critical field data for vanadium electrode of Fig. 3 junction. Solid lines are prediction of high-field theory for the second-order phase boundary using (a) $G_0=0$, $c_F=0.90$, and $b_{so}=0.07$; (b) $G_0=0.5$ $c_F=1.32$, and $b_{so}=0$; (c) $G_0=-0.167$, $c_F=0.63$, and $b_{so}=0.11$. In all cases $P_0=0.1$ and $T_{c0}=3.62$ K so that $T_c=3.33$ K. T^* is indicated in the figures. (b) The transition is second order at all temperatures.

tance curves also changes more slowly than the data with increasing field near the phase boundary. In this way we can put an upper bound on G_0 of about 0.2 for our V films.

The value $G_0=0$ fits the curves for all fields and temperatures quite well. This was the case for all four junctions studied, each of which had a 100-Å-thick vanadium electrode. The shape of the conductance curves at fields too low to observe the zero-bias peak, in particular the features associated with the splitting, also indicates that $G_0\simeq 0$ and that $b_{so}=0.07-0.10$.

Note that the parallel critical field data is,of itself, consistent with a value for G_0 of zero. The critical fields of the four 100-Å films studied were very similar. In Fig. 6(a), we see that if G_0 is held at zero, the other parameters can be adjusted so that the variance of the 12 data points from the theory is only 0.11 $[\text{kG}]^2$. If we fix G_0 at 0.5 as in Fig. 6(b), then the theoretical prediction is too high at low temperature, even with $b_{so}=0$ [variance equals 3.49 $(\text{kG})^2$]. Similarly, if we fix G_0 at -0.167 and try to fit the data by varying the other parameters we get the result shown in Fig. 6(c) [variance equals 3.62 $(\text{kG})^2$].

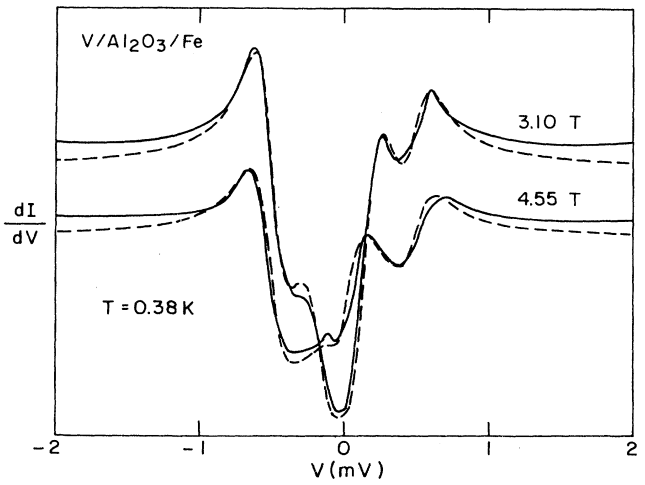

FIG. 7. Dynamic conductance vs bias voltage at two fields for a $V/Al_2O_3/Fe$ tunnel junction. Solid lines are experimental and dashed lines are the prediction of theory for $G_0=0.177$, $c_F=0.20$, $b_{so}=0.03$, $P_0=0.05$, and $T_{c0}=2.8$ K.

V. ANALYSIS OF V/Al_2O_3 /Fe TUNNELING DATA

Our spin-resolved tunneling measurements on $V/Al_2O_3/Fe$ junctions provide supporting evidence for the values obtained for G_0 and b_{so} from the $Al/Al_2O_3/V$ junctions. However, it should be noted that it was necessary to deposit a relatively thick aluminum layer (45–50 Å) on the vanadium to form the tunneling barrier. The transition temperature determined from the gap in the tunneling density of states was somewhat lower (2.8 K) than the resistive transition, which is close to the 3.3 K normally measured for 100-Å vanadium films (see Sec. III). Note that 2.8 K is still significantly higher than the transition temperature of aluminum films of the same thickness as the barrier (≤ 2.2 K). We believe that we are tunneling into a combination of vanadium and partly oxidized aluminum which is proximity-effect coupled to vanadium. We present these results here both for completeness and because the mesured values for G_0 and b_{so} should still be strongly influenced by the properties of vanadium. We will take the value ($G_0\simeq 0$) obtained from the $Al/Al_2O_3/V$ junctions as our result and treat the $V/Al_2O_3/Fe$ data as being consistent with it.

Tunnel-conductance data were taken at a number of fields and temperatures on three $V/Al_2O_3/Fe$ junctions. We present here the data on the tunnel junction with the least leakage current ($\simeq 3\%$) and the highest transition temperature (2.8 K). Figure 7 shows the tunneling conductance for this junction at two representative fields. The characteristic asymmetry obtained with ferromagnetic (spin-polarized) counterelectrodes is observed. The dashed lines are a fit to the theory using $G_0=0.177$ and $b_{so}=0.03$. The increasing discrepancy between theory and experiment with increasing energy is similar to that observed in disordered systems.[15,32–34] However, this vanadium film is polycrystalline and has a low resistivity (12 $\mu\Omega$ cm), so that one would not normally expect to observe correlation effects. This may indicate that the tunneling is into a disordered region at the interface. Note that this background curvature in the density of states was not seen in any of the $Al/Al_2O_3/V$ tunnel junctions.

The curves in Fig. 7 can be readily separated into their individual spin components as described in Refs. 35 and 29. The result of doing this for the 3.10-T curve of Fig. 7 is shown in Fig. 8. The dashed and solid curves represent the up and down spin conductances, respectively. One curve is simply a reflection of the other about $E=0$. The dotted line is the prediction of the theory using the same parameters as in Fig. 7.

The two spin-conductance curves are stored in a com-

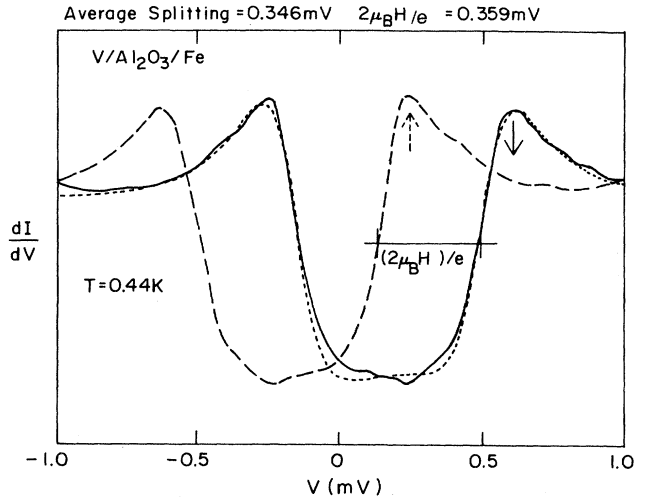

FIG. 8. Individual spin conductances of the 3.10-T curve from Fig. 7. The dotted line is the prediction ofthe theory using the same parameters used to fit the curves in that fiugre. Horizontal bar represents $2\mu_B H/e$ for the applied field.

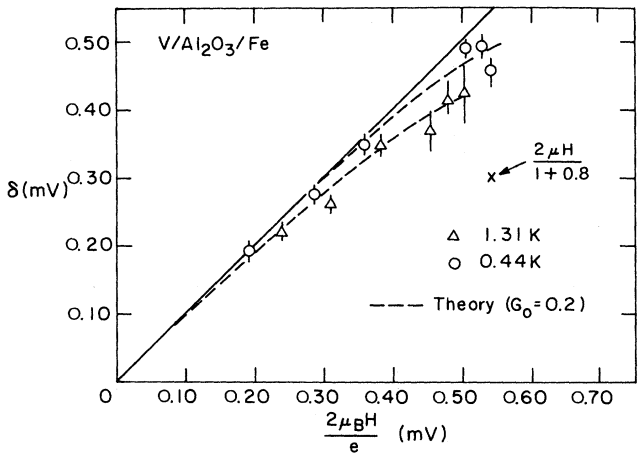

FIG. 9. Apparent splitting δ as a function of field at two temperatures. Solid line represents $\delta=2\mu_B H$, which is expected in the absence of Fermi-liquid effects. Vertical error bars are the variance in the splitting between curves such as those in Fig. 8. Dashed lines are the prediction of the theory for $G_0=0.2$.

puter, and the splitting between them is averaged digitally. The result of doing this at a number of different fields and at two different temperatures is shown in Fig. 9. Here the apparent splitting δ as measured directly from curves such as those in Fig. 8 is plotted as a function of applied field. The last data point for each temperature is just slightly below the critical field at that temperature. The solid line represents $\delta=2\mu_B H$. In the absence of Fermi-liquid effects all the data should fall on this line. The dashed curves are the prediction of the theory for $G_0=0.2$.

The deviation of δ from $2\mu_B H$ is not large. This is also the case for the other two $V/Al_2O_3/Fe$ tunnel junctions. This provides direct evidence that G_0 is small and is consistent with a value of no more than 0.2. It is also consistent with the data taken on $Al/Al_2O_3/V$ tunnel junctions. At the phase boundary δ should approach $2\mu_B H/(1+G_0)$ [see Eq. (6)]. If the electron-phonon interaction were the only important many-body interaction then we would expect from Eq. (6) that $\delta\rightarrow 2\mu_B H/(1+\lambda_{e\text{-ph}})\sim 2\mu_B H/1.8$ at the transition. The $\times$ shown in Fig. 9 indicates this value for the lower temperature data. Clearly, the deviation from $2\mu_B H$ is not nearly this large. The action of spin fluctuations could account for this discrepancy. This point will be discussed further in the next section.

VI. DISCUSSION

We will begin by discussing the applicability of the high-field theory, as described by Rainer, to our vanadium samples. An important consideration is that bulk vanadium is a borderline type-II material. The presence of vortices would cause the effective depairing to vary with position in the vanadium. From the perpendicular critical field of our 100-Å vanadium films we calculate an effective coherence length of 115 Å. Since $d<\xi$ the formation of vortices in a parallel field should be suppressed. Tedrow and Meservey[36] have procured a good fit to the quasiparticle density of states in the high-κ alloy V-Ti. They used the theory of Bruno and Schwartz[37] to fit $Al/Al_2O_3/V$-Ti junctions both parallel and perpendicular to the field. Thus, leaving Fermi-liquid effects aside, the theory can be effective in the presence of vortices. Note also that for 100-Å films the mean free path calculated[38] from the resistivity (10–50 Å) is significantly less than the coherence length. Thus, we are in the dirty limit for which the theory was derived.

The existence of a first-order portion of the phase boundary is not a problem. The theory used here predicts the density of states just as accurately near a first-order transition as it does near one which is second order. However, care must be taken when considering the apparent splitting near a first-order transition. Here the density of quasiparticles is not as high as the normal state density of electrons, and the renormalization of the splitting is less than the factor $(1+G_0)^{-1}$ at the boundary. Thus, for example, in a figure such as Fig. 8 if the temperature is well below T^*, the splitting will not be a strong function of G_0. For the parameters used to fit the data on the $V/Al_2O_3/Fe$ tunnel junction $T^*=1.28$ K and the low-temperature data in Fig. 9 should not be strongly affected by the renormalization. For example, the theory indicates that for $G_0=0.2$, δ should be 0.95 ($2\mu_B H$) for the low-temperature data near the critical field. On the other hand, T^* drops rapidly with increasing G_0. If we keep the other parameters the same and increase G_0 to 0.4, then T^* drops below 0.4 K, and we see the full effect on δ. Thus, the small deviation from $2\mu_B H$ of the low-temperature data in Fig. 9 does indeed indicate that G_0 is small. The higher-temperature data in Fig. 9 is renormalized by the full factor of $(1+G_0)^{-1}$ at the phase boundary and therefore indicates that G_0 is no more than 0.2.

We will now consider the implications of our measured value for G_0 and whether it can be understood in terms of Eq. (4) The electron-phonon coupling constant $\lambda_{e\text{-ph}}$ and the Coulomb pseudopotential μ^* have been determined for vanadium from inversion of the phonon spectrum $\alpha^2F(\omega)$ by Zasadzinski *et al.* They find $\lambda_{e\text{-ph}}=0.82$ and $\mu^*=0.15$. This value for $\lambda_{e\text{-ph}}$ is in reasonable agreement with the value of 1.04 calculated by Rietschel and Winter. Using the paramagnon rescaling theory of Daams *et al.*[4] it has been argued that the proper values for vanadium are $\mu^*\simeq 0.206$, $\lambda_{e\text{-ph}}\simeq 0.88$, and $\lambda_s\simeq 0.2$.[5,39] Jensen and Andres[24] have shown that a crude approximation for the Coulomb exchange potential is that it is three times the Coulomb pseudopotential. Thus, for vanadium we have

$$\bar{I}\sim 3\mu^*\sim 0.6\ .$$

Orlando and Beasley[40] have estimated $\bar{I}$ for vanadium using the T_c equation of Jensen and Andres[24] and obtained 0.4–0.5. We will average the results of these two methods and use $\bar{I}\simeq 0.5$. We can now estimate G_0 using Eq. (4),

$$1+G_0=(1+\lambda_{e\text{-ph}}+\lambda_s)(1-\bar{I})$$
$$=(1+0.88+0.2)(1-0.5)$$
$$=1.04 .$$

This is in good agreement with our experimental result $G_0=0$.

There is some question as to whether Eq. (4) is the proper way to determine the net renormalization when both electron-phonon and paramagnon-enhanced electron-electron interactions are important. Leavens and MacDonald[39] argue that Eq. (4) is only good when the exchange-enhancement factor is large. Rainer[41] has also pointed out that it is not conceptually correct to try to separate the net renormalization into its constituent interactions. However, for amorphous gallium,[15] aluminum[42] and, as we have seen, vanadium, Eq. (4) seems to predict values for G_0 consistent with the data. Thus, it seems possible to predict the overall renormalization by simply summing the contributions from the electron-electron and electron-phonon interactions in this way.

Finally, we can make an estimate for b_{so} in vanadium using the relation proposed by Abrikosov and Gor'kov[43],

$$\tau/\tau_{so}=(\alpha Z)^4 \tag{7}$$

where α is the fine structure constant, τ is the transport scattering time, and Z is the atomic number of the scatterer. If we assume that all the spin-orbit scattering in these thin films occurs at the surface[44] and that every surface atom causes scattering, then $\tau \simeq d/v_F$. Thus,

$$b_{so}=\frac{\hbar v_F(\alpha Z)^4}{(3)(1.76kt_c)d}\simeq 0.05 .$$

This is in reasonable agreemnt with our measured value considering the approximations involved.

VII. SUMMARY

We have found excellent agreement between Rainer's theory, which incorporates Fermi-liquid effects into the high-field theory of superconductivity, and our tunneling and critical field data on vanadium. This demonstrates the accuracy of the theory when a strong electron-electron interaction competes with the electron-phonon interaction.

We found the Fermi-liquid parameter in vanadium to be close to zero. This was determined by fitting the conductance of $Al/Al_2O_3/V$ tunnel junctions to Rainer's theory. This result was corroborated by directly observing the apparent Zeeman splitting of the spin components of the quasiparticle density of states in $V/Al_2O_3/Fe$ tunnel junctions. The low value for G_0 constitutes new evidence for the imporatnce of spin fluctuations in vanadium. It can be seen to be the result of the cancellation of the Fermi-liquid enhancement due to the electron-phonon interaction by an electron-electron interaction enhanced by spin fluctuations.

It was also found that the magnitude of the Fermi-liquid parameter G_0 could be predicted from knowledge of its constituent interactions using the simple relation

$$1+G_0=(1+\lambda_{e\text{-ph}}+\lambda_s)(1-\bar{I}) .$$

Finally, these techniques were found to yield a value for the spin-orbit scattering parameter $b_{so}^V=0.07\pm0.03$, which is in reasonable agreement with the prediction of a simple calculation.

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