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A Theoretical Analysis of Magneto Electrodynamics of Antiferromagnetic and Superconducting State Of Low T_C Superconductor

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Abstract: Using theoretical formalism of M. L. Kulic etal (Physica C (1995)) and T. Ishiguo etal.(J. Supercond. (1994)) we have theoretically analyzed the high frequency magneto electrodynamics behavior of low Tc superconductor $DyNi_2B_2C$ in the superconducting and antiferromagnetic state over wide range of temperature T and magnetic field H. We have analyzed the T dependence of surface impedance Z_S and penetration depth λ. The establishment of antiferromagnetic order at T_N =10.3K result in a marked decrease in the scattering of charge carriers which lead to sharp decrease of surface resistance R_S and surface reactance X_S. Our theoretically analyzed results are in good agreement with the experimental data.

Keywords: Magneto electrodynamics, antiferromagnetism, superconducting state, Quaternary borocarbides, Spin-flop field, complex surface Impedance, Complex electromagnetic penetration depth, Meta-magnetic transitions, Temperature dependent complex permeability, Effective conductivity.

INTRODUCTION

The discovery of superconductivity in the quaternary borocarbides has led to a family of materials with intriguing properties[1, 2]. These are the only known superconductors containing an appreciable amount of nickel that have transition temperatures in excess 10K. The general composition of RNi_2B_2C where R is a rare-earth element Yttrium or lutetium has been extensively investigated. Most members of the family that exhibit superconductivity have coexisting[3, 4] antiferromagnetic order except YNi_2B_2C and $LuNi_2B_2C$.This system is very useful in studying the interplay between magnetism and superconductivity. Superconductivity was reported in $DyNi_2B_2C$ (T_C=6.2K) below an antiferromagnetic transition[5-7] at T_N=10.2K. This material is one of the select few materials where superconductivity appears in the presence of long-range magnetic order. Other systems[8, 9] are $Ho(Ir_xRh_{1-x})_4B_4$, $Tb_2Mo_3Si_4$ and heavy fermion superconductors[10].

Metallic and superconducting antiferromagnets afford the possibility to study the influence of local moments on electronic properties. In the metallic state the interesting effects are the transition properties like conductivity. In the superconducting state, magnetism can lead to noval effects on the superconducting order parameter. This is because of the low energy and magnetic field scales in the system. Spin-flop field scale arises from the magnetic state and vortex-related fields due to superconductivity. High frequency measurements such as surface impedance Z_S gives unique information which is not available in other techniques. In the metallic state it gives information regarding the dynamics of the electrons and electronic moments. In the superconducting state, the order parameter can be probed in terms of the penetration depth.

MATHEMATICAL FORMULA USED IN THE ANALYSIS

The penetration in the cavity due to charge in the superconducting properties of the sample is reflected as the change of response frequency f and bandwidth δf of the cavity. This is related to the change in the complex surface impedance Z_S given by

$$Z_S = R_S + I\, X_S \qquad (1)$$

Where R_S is the surface resistance and X_S is the surface reactance. R_S is given by

$$R_S = \Gamma\left[\frac{1}{Q_s(T)} - \frac{1}{Q_0(T)}\right] \qquad (2)$$

$$\Delta X_S = 2\pi\mu_0 f_0 \Delta\lambda = \left(\frac{-2\Gamma}{f_0}\right)[f_s(T) - f_0(T)] \qquad (3)$$

Where Γ is a geometrical factor relating to the cavity and the sample dimensions. Q_S and Q_0 are the loaded and unloaded quality factor ($Q = \frac{f}{\delta f}$). f_S and f_0 are the loaded and unloaded resonance frequencies respectively. One measures the absolute value of R_S but only the relative change in X_S. An absolute value is imposed by X_S by assuming that X_s=R_S at high temperature (T>>T_C, T_N) where any effect of superconductivity or magnetism would be negligible.

The real part of the complex electromagnetic penetration depth is given by

$\lambda = [\frac{-i}{\mu\omega\sigma}]^{\frac{1}{2}}$ at radio frequency. In the normal state $\sigma = \sigma_n$ is the normal conductivity and is purely real. In this case

$$\lambda^{-1} = \delta^{-1}[1+i] \tag{4}$$

Where $$\delta = [\frac{2}{\mu\omega\sigma_n}]^{\frac{1}{2}} \tag{5}$$

In the superconducting state, σ has to be replaced with an effective complex conductivity $\sigma_S=\sigma_1-i\sigma_2$ where real and imaginary part are proportional to the quasi particle scattering and super fluid density respectively. In the limit $\sigma_2>>\sigma_S$ which typically holds for $T<T_C$

$$\lambda = \frac{1}{[\mu\omega\sigma_2]^{\frac{1}{2}}} = \lambda_L \tag{6}$$

where λ_L is the London penetration depth. In order to study relaxation phenomena in the antifrromagnetic state, one uses Drude type conductivity relation

$$\sigma(\omega) = \frac{\sigma_0}{(i\omega\tau)} \tag{7}$$

Where σ_0 is dc conductivity. Dissipation because of the magnetic relaxation effects, one has complex permeability

$$\frac{\mu}{\mu_0} = \mu_1 + i\mu_2 = \mu_0(1+i\omega\tau) \tag{8}$$

$$\mu_1 = \mu_0, \mu_2 = \mu_0\omega\tau \tag{9}$$

Now dynamic permeability (T) can be of the form

$$\mu(T) = \mu_0(1+i\mu_2) \tag{10}$$

Surface Impedance is given by

$$Z_s = [\frac{i\omega\mu}{\sigma}]^{\frac{1}{2}} = (\mu_0\omega\sigma)^{\frac{1}{2}}(i-\mu_2) \tag{11}$$

Temperature dependence of $_2$(T) is given by

$$\mu_2(T) = \frac{[x^2{}_s - R^2{}_s]}{2x_sR_s}, T_c \le T \le 21T \tag{12}$$

$$\rho_0 = \frac{1}{\sigma_0} = \frac{2x_sR_s}{\mu_0\omega} \tag{13}$$

For T> T_N (Neel temperature) $_2$ =0. In the AFM (antiferromagnetic state) for T<T_N , $_2$ increases with decreasing T

$$\sigma_{s,eff} = \sigma_{1,eff} - i\sigma_{2,eff} = (\sigma_1 - i\sigma_2)/(1+0.092) \qquad (14)$$

Where $\sigma_{1,eff}$ and $\sigma_{2,eff}$ are the temperature dependent conductivity in the superconducting state for that $\sigma_{2,eff}$ =0 for T> T_C.

DISCUSSION OF RESULTS

In this paper, we have theoretically analyzed the magneto-hydrodynamics at high frequencies in the antiferromagnetic and superconducting states of low Tc superconductor $DyNi_2B_2C$ (Tc=6.2K). The experimental data has been taken from the work of D. P. Choudhary etal. From the theoretical analysis, we have taken the work of M. U. Kulu etal and T. Ishigaro etal. In **Table T1**, we have shown the theoretically analysed result of electromagnetic screening length $\delta\lambda^{\sim}$ as a function of temperatures. The results were compared with the experimental data. The temperature dependence of λ shows a clear signature of the onset of the magnetic order at 10.6K which has been also observed by other techniques. At the onset of superconducting transition there is a decrease of magnetic penetration.

In **Table T2**, we have presented the theoretically analyzed result of screening length (m) as a function of applied field (Koe) for two temperatures T=4.2K and T= 8.6K for low Tc superconductor $DyNi_2B_2C$. From our analyzed results, it appears that magnetic state shows two sharp jumps of the screening length both below and above Tc. It originates from meta-magnetic transitions in the sample. The response of the material at very high field (>20Koe) shows positive magneto resistance at all temperatures which is characteristic of its metallic behavior. The screening length is characterized by field scales in addition to well-known scales of H_{C2}. We have two field scales corresponding to meta-magnetic transition called H_{M1}(=10Koe) and H_{M2} respectively.

In **Table T3**, we have shown the analyzed result of surface impedance Z_S at 10GHz as a function of temperature. Actually, we have analyzed the real and imaginary part of the surface impedance (Z_S =R_S+iX_S) for superconductor $DyNi_2B_2C$ as a function of temperature. Our analyzed results show that both R_S and X_S increases with T up to 12K and then it saturates. Both R_S and X_S differ from each other even in the AFM state below T_N.

In **Table T4**, we have presented the analyzed result of the magnitude and angle of microwave surface impedance $|Z_s|(\Omega)$ and phase angle (degree)[$Z_s(T) = [R^2{}_s + X^2{}_s]^{\frac{1}{2}}$ and phase angle $\theta(T) = \tan^{-1}(\frac{R_s}{X_s})$]. For a conventional superconductor, the phase angle is expected to change sharply from 45^0 in the normal state tending towards 90^0 as T $\rightarrow 0$ below the superconducting transition temperature. Such type of transition temperatures have been observed for most type of superconductors. In case of $DyNi_2B_2C$ the phase angle starts to increase sharply at the onset of the antiferromagnetic transitions. It continues to increase below T_N and it becomes flat when superconducting transitions sets in. The deviation of θ from 45^0 is because of the relaxation effects. Below the superconducting transition temperature Tc, θ rises as T is decreased as is expected for superconductor.

In **Table T5**, we have reported the analyzed result of temperature dependent of expected dc conductivity of superconductor $DyNi_2B_2C$. Dc conductivity ρ_0 (Ωm) increases with T and becomes flat for high values of T (T>13K). The scattering of the conduction electrons by spin waves in the AFM state can give rise to conductivity relaxation observed in $DyNi_2B_2C$ superconductor. Conductivity relaxation is also observed in other cases such as spin density wave system and heavy fermion metals.

In **Table T6,** we have shown the analyzed result of temperature dependence of imaginary part of $_2$ i.e $_2$ (T). For this evaluation, we have used the equation (11). Our theoretically analyzed result indicates that $_2$ is more and less temperature independent for T_N>T>T_C.

In **Table T7**, we have presented the analyzed results of effective values of conductivities σ_1 and σ_2 as a function of temperature for low Tc superconductor $DyNi_2B_2C$. The real part of the conductivity σ_1 takes into account the total dissipation in the system from all possible mechanisms, one of which can be effect of spin relaxation. Similarly the imaginary part of the effective conductivity σ_2 includes all mechanisms of dissipation free current flow in the system. One is renormalizing the frequency dependent conductivity in the superconducting state. From our analyzed results shown in table T7, $\sigma_{2,eff}$ =0 for T>Tc which indicates that the quantity is the correct measure of the super fluid density in the system. In the superconducting state, the temperature dependence of $\sigma_{2,eff}$ is anomalously broad and possibly arises out of strong pair breaking effects[25]. This is evident from the fact that $\sigma_{2,eff}$ continues to rise even for T<T_C/2. This type of behavior has been observed in conventional superconductors. A broad normal to superconducting transition is observed in rf penetration depth and dc resistivity measurements[26,27]. It appears that although antiferromagnetism does not inhibit the formation of superconducting state, but it has strong effect on the electrodynamics properties. Some of the recent works[28-35] also reveal the same facts.

Table T1: An analyzed result of electromagnetic screening depth δλ˜ as a function of temperature. Analyzed results were compared with the expt. data.

T(K)	δλ˜(m)(theo)	δλ˜(m)(expt)
4	2.6	1.6
5	5.8	3.2
6	8.7	5.6
7	12.8	8.6
8	16.2	10.5
9	20.7	16.6
10	25.8	22.5
11	30.4	28.7
12	34.3	30.6
13	38.5	32.8
14	40.6	34.5
15	42.8	35.6

Table T2: An analyzed results of screening length (m) as a function of applied field (Koe) for two fixed temperature T=4.2K and T=8.6K for low Tc superconductor $DyNi_2B_2C$

Applied Field (Koe)	← Screening length (m) →	
	T=4.2K	T= 8.6K
0	25.6	42.6
5	26.8 H_{C2}	44.4
10	28.2 H_{M1}	46.3 H_{M1}
15	32.6	48.5
20	34.8 H_{M2}	50.2 H_{M2}
25	37.2	52.6
30	39.5	54.2
35	41.7	56.5
40	44.8	58.3
50	48.2	65.6

Table T3: An analyzed results of real and imaginary parts of microwave surface impedance (surface resistance $R_S(\Omega)$ and surface reactance $X_S(\Omega)$ as a function of temperature for low Tc superconductor $DyNi_2B_2C$

Temperature T(K)	Surface resistance $R_S(\Omega)$	Surface reactance $X_S(\Omega)$
2	0.025	0.042
5	0.047	0.057
7	0.068	0.085
10	0.072	0.096
12	0.085	0.108
14	0.092	0.126
15	0.126	0.138
17	0.142	0.143
20	0.168	0.156
22	0.173	0.180
25	0.184	0.192

Table T4: An analyzed result of the magnitude and phase angle of microwave surface impedance as a function of temperature for low Tc superconductor $DyNi_2B_2C$

Temperature T(K)	Surface Impedance $\lvert Z_S \rvert$ (Ω)	Phase angle (degree)
2	0.046	62.2
4	0.058	0.6
5	0.067	58.4
8	0.078	56.2
10	0.086	54.6
12	0.095	52.5
15	0.112	50.6
16	0.128	42.3
18	0.139	43.6
20	0.142	44.8
22	0.156	45.3
24	0.167	46.2
25	0.182	47.8

Table T5: An analyzed result of temperature dependence of extracted dc resistivity of low Tc superconductor $DyNi_2B_2C$

Temperature T(K)	← $\rho_0 (\Omega m)$ →
2	4.3×10^{-8}
4	5.6×10^{-8}
5	6.7×10^{-8}
6	8.2×10^{-8}
8	1.12×10^{-7}
10	1.32×10^{-7}
12	1.52×10^{-7}
14	1.7×10^{-7}
15	1.8×10^{-7}
16	1.9×10^{-7}
17	2.0×10^{-7}
18	2.1×10^{-7}
19	2.2×10^{-7}
20	2.3×10^{-7}
22	2.4×10^{-7}
25	2.6×10^{-7}

TableT6: An analyzes result of the imaginary part of the permeability μ_2 as a function of temperature T(K) for low Tc superconductor $DyNi_2B_2C$

Temperature T(K)	← μ_2 →
2	0.092
4	0.067
6	0.054
8	0.038
10	0.029
12	0.005
14	0.006
15	0.008
16	0.010
18	0.012
20	0.014
22	0.016
24	0.018
25	0.021

Table T7: An analyzed result of effective values of σ_1 and σ_2 as a function of temperature T(K) for low Tc superconductor $DyNi_2B_2C$

T(K)	$\sigma_{1,eff}(\frac{1}{\Omega^2})\,x10^7$	$\sigma_{2,eff}(\frac{1}{\Omega^2})\,x10^7$
2	5.2	2.4
4	4.6	1.8
5	4.2	1.2
6	3.8	0.05
8	3.5	0.0
10	3.0	0.0
12	2.6	0.0
14	2.5	0.0
15	2,8	0.0
17	3.0	0.0
20	3.2	0.0
22	3.4	0.0
24	3.5	0.0
25	3.6	0.0

CONCLUSION

From our theoretical analysis, we came across the following conclusion:In the AFM state, establishment of long-range magnetic order leads to a strong reduction in scattering. An antiferromagnetic order gives rise to anomalous increase of electron scattering time. It makes real and imaginary part of complex microwave surface Impedance differs from each other. This behavior is interpreted in terms of relaxation effects related to either charge transport or spin dynamics in the AFM state.

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