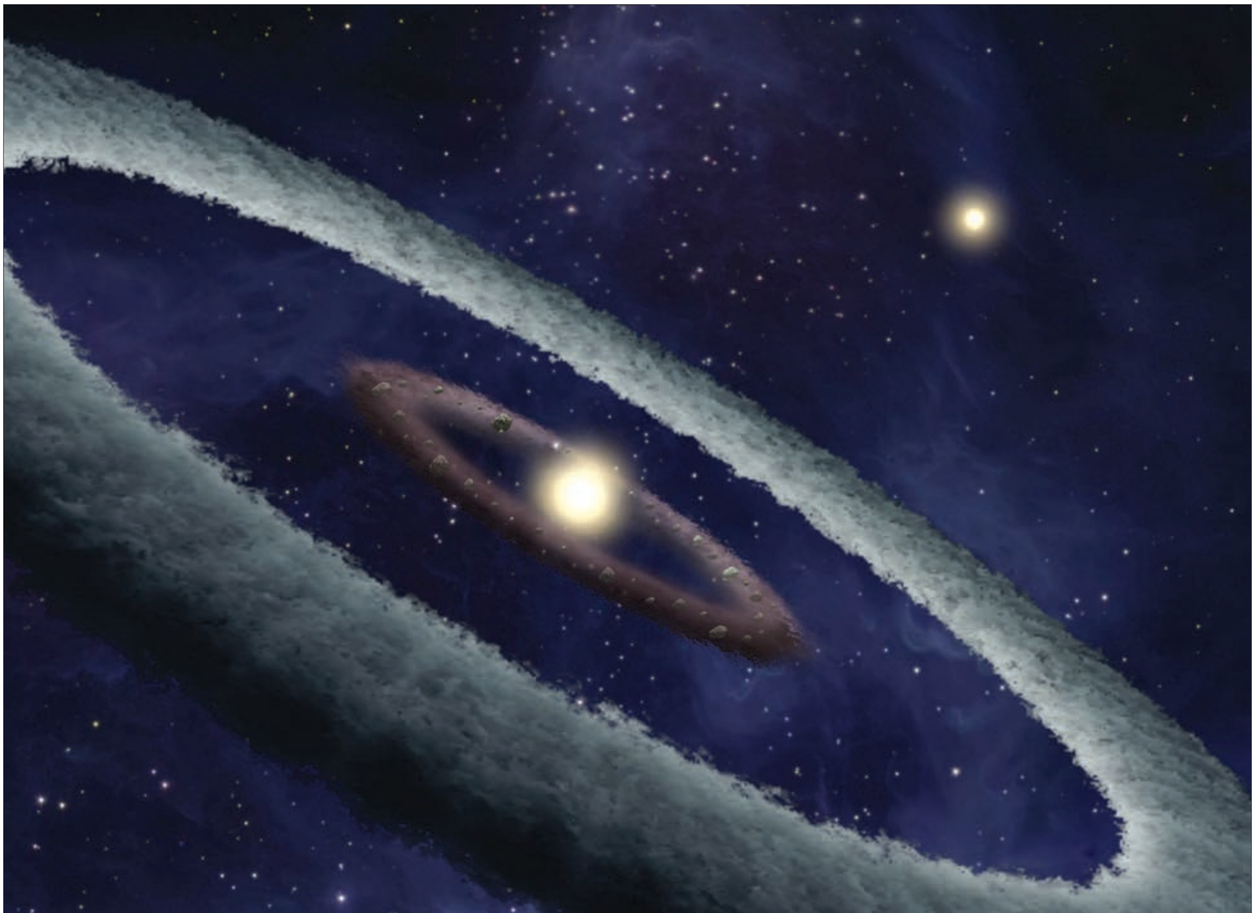

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Phenomenological Two Branches Electronic Specific Heat Method to Explore the Properties of MgB_2 at Superconducting State

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Abstract: The normalized electronic specific heat of superconductors with two gaps can be described by two branches that appear the anomalous gap at low temperature and considered the critical field has two branches; one can also get on the upper critical field curve, upper critical anisotropy and deviation function. The values of them at any temperature within superconducting state are approximately close to the experiment results.

Key words: Entropy, upper critical magnetic field, anisotropy, deviation function

INTRODUCTION

An intermetalic MgB_2 superconductor (Nagamatsu *et al*., 2001) is a two-gap superconductor and the electronic specific heat curve which deviates from the BCS curve as reported from experiment results. The anomaly occurred at low temperatu re more smaller than critical temperature and the behavior is exponentially that fitted variation of the electronic specific heat normalized to normal state with small gap ratio as mention in (Bouquet *et al*., 2001). Many different analysis study for this behavior of electronic specific heat but for an apparent contradiction so that the phenomenological two-gap model come to resolve this contradiction and showed values of parameters were agree with that determined based on independent experiment. The two gap model proposed each band is characterized by a partial Sommerfeld constant and total of them eqnal that for normal state. In this study we will use two branches electronics specific heat at superconducting state as phenomenological method to represent the electronic specific heat and calculate the specific heat jump, then employed this method thermodynamically to show the curves of entropy and critical magnetic field, upper critical magnetic field anisotropy with their values finally also effort to treat the problem of deviation function.

ELECTRONIC SPECIFIC HEAT

The low temperature asymptotic formula can obtained it from the entropy of superconducting state:

$$S_{es} = -2K_B \sum_k [(1-f_k)\ln(1-f_k) + f_k \ln f_k], \quad f_k = 1/e^{\beta E_k} + 1$$

Electronic specific heat:

$$C_{es} = 2\beta^2 K_\beta \sum_k (-\frac{\partial f}{\partial E_k})(E_k^2 + \frac{1}{2}\beta \frac{d\Delta^2(T)}{d\beta})$$

At low temperature $T<<T_c$ that lied to $\Delta(T) \approx \Delta(0)$, the second term becomes zero, $\partial f / \partial E_k \approx \beta^2 e^{-\beta\epsilon}$ and therefore, the final asymptotic formula is:

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$$C_{es} \approx 0.8\gamma T(\alpha T_C/2T)^{5/2} e^{-\alpha/2T}$$

This method proposed that the electronic specific heat has two branches and the specific heat in every branch behaves as exponentially with temperature, also there is extra term resemble to the fluid model but arise to the power 3/2 .

The normalized electronic specific heat (ratio of electronic specific heat at superconductivity state to at normal state) is:

$$C_{es}/\gamma_n T = \sum_{i=1}^{2} \frac{x_i}{2}\left((3(t)^{3/2} + 1.6(\alpha_i/2t)^{5/2} \exp(-\alpha_i/2t)\right) \quad (1)$$

where, $\alpha_1 = 2\Delta(0)_i/K_B T_c$, $t = T/T_C$ and $x_i = \gamma_i/\gamma_n$. The first branch contains the large gap and the second contains the small gap. In this method, the Sommerfeld constant at normal state $\gamma_n = \gamma_1 + \gamma_2$, $\gamma_i = 1/2\ \gamma_n$. The two fit gaps ratio 1.4, 4.2 selected on the basis that the ratio $\Delta_1/\Delta_2 = 3$.

Specific Heat Jump

$$(C_{es} - C_n)/C_n = (C_{es}/\gamma_n T) - 1 \quad (2)$$

Entropy of superconducting state:

$$S_{ec} = \int_{T\geq 0}^{T_c} (C_{es}/T)dT \quad (3)$$

The Upper Critical Field Anisotropy

Corresponding this Phenomenological method and as result of two branches electronic specific heat at superconductivity state also proposed there are two critical magnetic field, one $H_c^{ab}(T)$ related to the second branch with small gap that reflects the behavior of upper critical field in a-b plane and the second $H_c^c(T)$, related to the first branch with large gap in direction C. the equations of $H_c^{ab}(T)$, $H_c^c(T)$ are obtained by applying the thermodynamic critical magnetic field on every branch. Thermodynamic critical magnetic field:

$$-\mu_0 H_c^2/8\pi = \Delta U - T\Delta S$$

Where:

$$\Delta U(T) = \int_T^{T_c} [C_{es}(T) - C_n(T)dT\ , \quad \Delta S(T) = \int_T^{T_c} ([C_{es}(T) - C_n(T)]/T)dT$$

There are GL parameters κ_{ab} , κ_c coherence lengths ξ_{ab}, ξ_c and penetration depths λ_{ab} , λ_c in a-b plan and in the c direction, respectively, the values of parameters at zero temperature can be calculated using the fowling relations:

$$\begin{aligned} H_{C2}^{c}(0) &= (H_c^c(0))\sqrt{2}\kappa_c = r\Phi/2\Pi\xi_{ab}^2 \\ H_{C2}^{ab}(0) &= \Upsilon(H_c^{ab}(0))\sqrt{2}\kappa_{ab} = \Phi/2r\Pi\xi_c^2 \\ H_c^{ab}(0)/\sqrt{2}\kappa_c &= \Phi/4r\Pi\lambda_{ab}^2 \\ H_c^c(0)/\Upsilon\sqrt{2}\kappa_{ab} &= r\Phi/4\Pi\lambda_c^2 \end{aligned} \quad (4)$$

Upper critical field anisotropy:

$$\Upsilon(T) = H_{c2}^{ab}(T)/H_{C2}^{C}(T) \tag{5}$$

$(r = H_c^c(0)/H_c^{ab}(0))$, Υ is upper critical field anisotropy and Φ is the flux quantum. At T = 0K:

$$\kappa_{ab}/\kappa_c = \xi_{ab}/\xi_c = \lambda_c/\lambda_{ab} = \Upsilon r \tag{6}$$

Coherence length in a-b plane:

$$\xi_{ab} = \hbar \upsilon_F^{ab}/\pi\Delta_2 \tag{7}$$

Fermi velocity in a-b plane:

$$\upsilon_F^{ab} = \sqrt{0.02T_c^2(1+\lambda)^{2.4}/H_{c2}^{ab}(0)} \times 10^5 (\mathrm{m\ \ sec^{-1}}) = (r\Delta_2(0)/\hbar)\sqrt{\pi \Upsilon(0)\Phi/2H_{c2}^{c}(0)} \tag{8}$$

T_c =39K, $2\Delta_2$ =1.4K_BT_c, $\Phi_0 = 2.07\times10^{-7}$G cm^2 and the isnteraction coupling between electron and phonon $\lambda = 0.59$.

Total deviation function:

$$D(t) = \alpha_1(0)D^c(t) - \alpha_2(0)D^{ab}(t) \tag{9}$$

RESULTS AND DISCUSSION

The curve of normalized electronic specific heat (Eq. 1) at superconductivity state is shown in Fig. 1, specific heat jump is 0.88 and the small hump is appeared at $0.25T_c$. This jump was 0.83 (Wang *et al*., 2001), 1.09 (Yang *et al*., 2001) and 0.8 (Machida *et al*., 2003). The contribution of specific heat with weak interaction and small gap in low temperature ($T \leq 10$K) seems from the second branch and the electronic specific heat follows an exponential behavior at this region.

Figure 2 shows the entropy's curve at superconducting state compare with entropy of normal state, where it's derived from Eq. 3 under the condition that the entropy of superconducting state

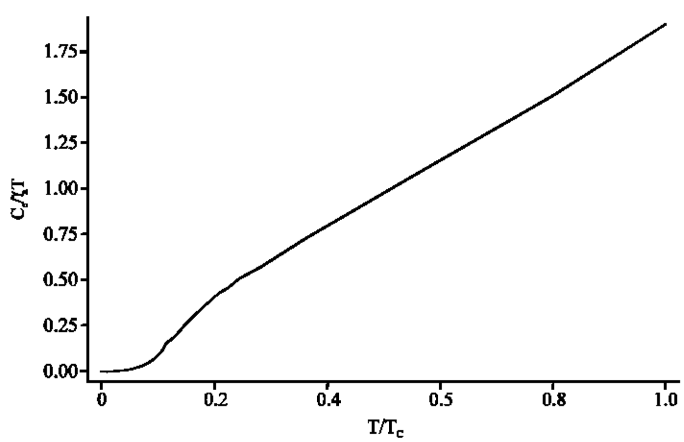

Fig. 1: Normalized electronic specific heat as a function of reduced temperature

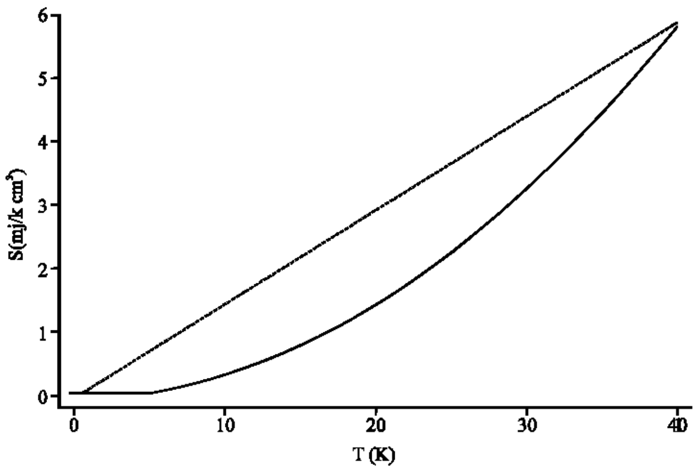

Fig. 2: Entropy of superconducting state as a function of temperature at zero magnetic filed

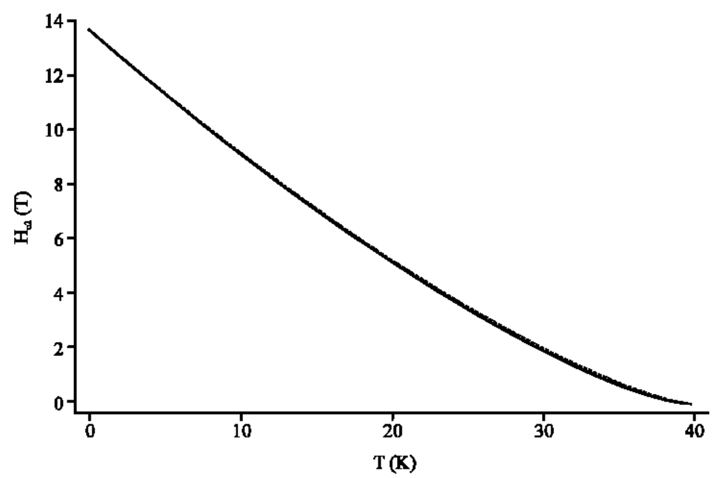

Fig. 3: Upper critical magnetic field with temperature H_{c2} (0) = $(1\text{-}T/T_c)^{1+a}$ (dashed line) with a = 0.36 and this method (thick line)

and normal state should be equal at T_c, i.e., $S_{es}(T_c) = S_n(T_c)$. The fit value of Sommerfeled constant $\gamma = 2.55$ mJ $k^{-2}mol^{-1} = 0.85$ mJ $k^{-2}gat^{-1}$, (1 mol of MgB_2 = 3 gat). As such the behavior of upper critical magnetic which was noticed by many experiments, that the H_2 (T) is not proportional to temperature near critical temperature but at other temperature, it's proportional to temperature. The curve of upper critical field is shown in Fig. 3 with the comparison between this method and the equation (Müller *et al*., 2001).

$$H_c(T) = H(0)\,(1\text{-}T/T_c)^{1+a},$$

The two curves are identical when a = 0.36.

The upper critical field anisotropy has been studied experimentally (Machida *et al*., 2003; Zehetmayer *et al*., 2002) this method can also used it to give a clear image of H_{c2}^{ab}, H_{c2}^{c} curves and their values that will be achieved with consideration of the two critical magnetic field $H_c^{ab}(T)$, $H_c^{c}(T)$

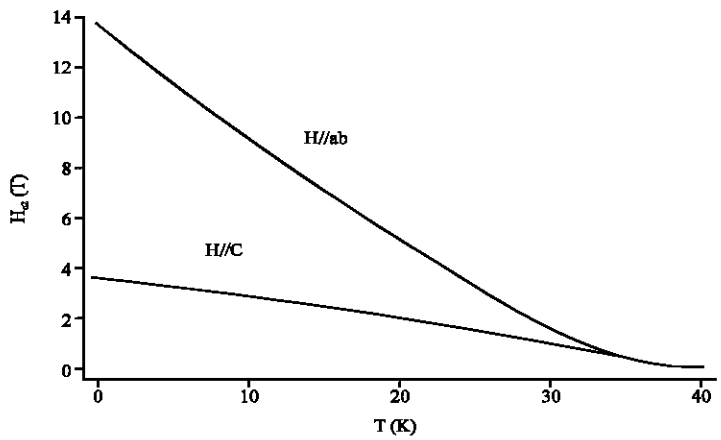

Fig. 4: Upper critical field for H//ab, H//C

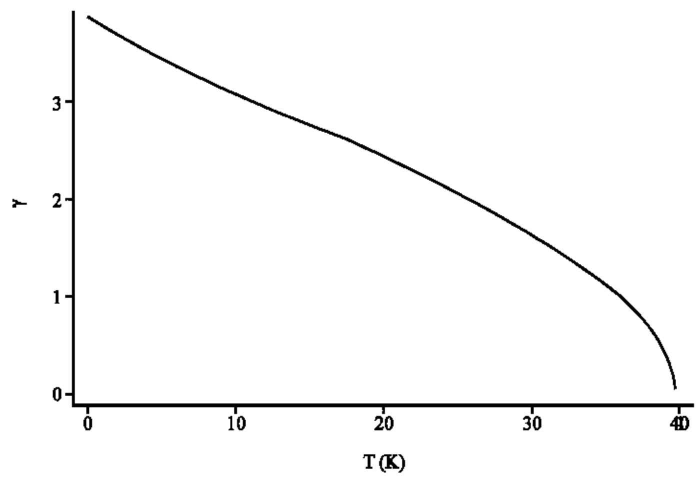

Fig. 5: The upper critical field anistropy $H_{c2}^{ab} = \gamma H_{c2}^{c}$

and the calculation of them by thermodynamic critical field with taken account $C_{s1}/\gamma_n T = 1/2 + (\alpha_2(0)/\alpha_1(0))$ because that behavior of $H_c^{ab}(T)$ did not appear only when $0.33 \le (\alpha_2(0)/\alpha_1(0)) \le 0.45$ in this direction. Therefore, to remove confusion, the second critical field $H_c^c(T)$ obtained only with the only remaining part of the normal electronic specific heat.

Phenomenologically; this process has used only to appear the behavior of upper critical field in a-b plane and c direction as in experiment results of single crystal of MgB_2. Figure 4 shows the upper critical fields, with temperature. The Fermi velocity which played important role to determine all parameters , its obtained (left hand side of Eq. 8) by Shnlga *et al*. (2001) to calculated the upper critical field; in this study belonged to a-b plane. The critical field anisotropy's curve($\Upsilon = H_{c2}^{ab}/H_{c2}^{c}$) is showing in Fig. 5 as a function of temperature and it equals 3.86 at zero Kelvin , then the upper critical fields in c direction and in the a-b plane are $H_{c2}^{c}(0) = 3.6T$, $H_{c2}^{ab}(0) = 13.8T$, respectively. Furthermore, it's too easy to obtain κ_{ab} = 38, ξ_c =2.24 nm, λ_{ab} = 76.8 nm and λc =365 nm from Eq. 4, 6 the results are shown in Table 1. Comparison with experiment resnlts of single crystals and Machida *et al*. (2003) and Zehetmayer *et al*. (2002) with notice that the critical field $\mu_0 H_c(0)$ = 0.287 Tesla of this compound

Table 1: Comparsion of parameters calculated by this method with experment results of single crystals (Zehetmayer *et al.*, 2002; Machida *et al.*, 2003)

Parameters	This method	Zehetamayer *et al.* (2002)	Machida *et al.* (2003)
$\mu_0 H^{ab}_{c2}$ (0)	13.8T	14.5T	13.6T
$\mu_0 H^{c}_{c2}$ (0)	3.6T	3.18T	3.4T
$\mu_0 H_c$ (0)	0.287T	0.28T	
γ (T)	1.3 (33K)-3.86(0K)	1(T_c)-4.6(0K)	1(T_c)-4(22K)
κ_{ab} (0)	38	37.1	
κ_c (0)	8	8.1	
ξ_{ab} (0)	10.6 nm	10.2 nm	
ξ_C (0)	2.24 nm	2.3 nm	
λ_{ab} (0)	76.8 nm	82 nm	
λ_c (0)	365 nm	370 nm	

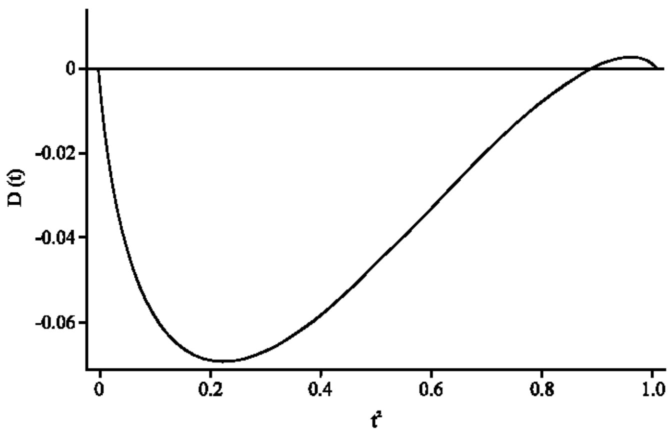

Fig. 6: Total deviation function of critical magnetic field

was calculated from the average of $H_c^{ab}(T)$ and $H_c^c(T)$ at T = 0K. The curve H_c^{ab} shows linear temperature dependence at lower temperature and rise rapidly but near critical temperature is non –linear, H_{c2}^c increase linearly with decreasing temperature.

Deviation Function

Deviation function describing the deviation of $H_c(t)$ from the parabolic behavior and indicating the coupling strength in a conventional superconductor where they evaluated the maximum from -0.3 to -0.9% lies in between the weak-coupling (≈ -3.5%) and the strong-coupling result (≈ 2.5% for Pb) (Zehetmayer *et al*., 2002) the results indicate a clear deviation from the weak-coupling model where it is more negative than BCS curve at lower temperature and it exchange to positive at near critical temperature (Machida *et al*., 2003), it is negative and BCS- like (Bouquet *et al*., 2001). In this study, the suggestion is: considering the thermodynamic critical field has two branches as described before, and there are two deviation function $D^{ab}(t)$ of critical field in a-b plane and the deviation function D^c (t) in C direction, then the total deviation function Eq. 9, Fig. 6 shows the curve of D (t). The effect of the electron phonon coupling and the anisotropy cause opposite effect in deviation function where at lower temperature the anisotropy effect is larger and the coupling is weak so the deviation function is more negative, but when coupling become strong the deviation function shifts from BCS to positive direction. As a result of the anisotropy and weak coupling effects for large rang of temperatures are responsible on a small specific heat jump. In spite of this method is a phenomenological method, but it appeared similar behavior of electronic specific heat, upper critical field, upper critical field anisotropy.

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