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RESEARCH ARTICLE

INVESTIGATION OF UPPER CRITICAL MAGNETIC FIELD IN MULTI-BAND IRON-BASED SUPERCONDUCTOR $B_{1-x}K_xF_2A_2$

***Teklie Lissanu Tegegne**

Department of Physics, Assosa University, P.O Box 18, Assosa, Ethiopia

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ABSTRACT

This work focuses on the theoretical investigation of the upper critical magnetic field(H_{c2}), Ginzburg-Landau coherence length $(\xi_G\ (T))$and Ginzburg-Landau(GL) penetration depth $(\lambda_G\ (T))$ by using the Ginzburg-Landau(GL)phenomenological equation for the two-band iron-based superconductor $Ba_{1-x}K_xFe_2As_2$. At zero external magnetic field, $Ba_{1-x}K_xFe_2As_2$ was found to undergo a transition from the normal state to the superconducting state at $T_c = 38$ K.By using the phenomenological Ginzburg-Landau(GL) equation for the two-band coupled superconducting $Ba_{1-x}K_xFe_2As_2$, we obtained expressions for the upper critical magnetic field(H_{c2}), Ginzburg-Landau(GL) coherence length,$\xi_G\ (T)$ and Ginzburg-Landau(GL) penetration depth,$\lambda_G\ (T)$ as a function of temperature and the angular dependency of upper critical magnetic field. By using the experimental values in the obtained expressions, the phase diagrams of the upper critical magnetic field parallel $(H_{c2}^{\parallel c})$ and perpendicular $(H_{c2}^{\perp c})$to the symmetry axis versus temperature are plotted. We also obtained the phase diagrams of the Ginzburg-Landau upper criticalmagnetic field $(H_{c2}(\theta))$ versus the angle θ. Similarly, the phase diagrams of the Ginzburg-Landau (GL) coherence length $\xi_G\ (T)$and Ginzburg-Landau(GL) penetration depth $\lambda_G\ (T)$parallel and perpendicular to the symmetry axis versus temperature are plotted for the superconductor $Ba_{1-x}K_xFe_2As_2$. Our findings are in agreement with experimental observations.

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INTRODUCTION

Since the discovery of superconductivity at 26 K in the Fe-As-based superconductor LaFeAsO1−xFx, great interest has been stimulated in the community of condensed-matter physics and material sciences (1).This welcome surprise brought to an end monopoly of cuprates as the only high temperature superconductors. Under intensive study, the superconducting transition temperature Tc was quickly promoted to 55 K by replacing La with Sm making the iron-based superconductors to be non-copper based materials with *Tc* exceeding 50 K (2). Superconductivity was also obtained in the 122-family iron based multiband superconductors and great efforts were made to raise T_C to temperatures higher than 38K as detected in$(Ba_{0.6}K_{0.4})Fe_2FeAs_2$(3) and beside the high critical temperature, the upper critical field was found to be very high in the iron-based superconductors (4–8). Many theoretical models have been proposed to give explanations for the mechanism of superconductivity, such as non-phonon pairing mechanisms (9).Fortunately, the $Ba_{1-x}K_xFe_2As_2$ single crystals can be grown by metal or by the self-flux method. With this success, more accurate measurements have become possible in this iron-based superconducting system. One of the basic parameters, the superconducting anisotropy $(\gamma = \frac{H_{c2}^{a}(0)}{H_{c2}^{c}(0)})$ which is crucial for both understanding the superconducting mechanism and the potential applications, where $H_{c2}^{a}(0)a$ $H_{c2}^{c}(0)$ are the upper critical fields when the magnetic field is applied within the *ab* plane and *c* axis, respectively. Basically, one can estimate the zero temperature *Hc*2(0) with the classical Werthamer–Helfand–Hohenberg (WHH) expression(10)and then calculate the coherence length ξ_G with the Ginzburg–Landau relations in layered superconductors (11). In conventional superconductors, the electron pairing is mediated by an electron-phonon interaction and can be well understood within the microscopic-model developed by Bardeen, Cooper & Schrieffer (BCS) in the theory superconductivity (5).

****Corresponding author:*** **Teklie Lissanu Tegegne,**
Department of Physics, Assosa University, P.O Box 18, Assosa, Ethiopia

The electron-phonon coupling mechanism is not sufficient to explain the superconductivity in iron-based superconductors and their role is replaced by spin-fluctuation coupling mechanism (where pairs are bound because of magnetic interactions between the electrons spins). The iron-based superconductors exhibit a huge upper critical field (H_{c2}) beyond 100 T, deduced from high magnetic field data **(5,6, 12-13).** The theory of upper critical magnetic field in superconductors was essentially developed right after Abrikosov proposed the type-II superconductors**(14).** It is well known that, the Ginzburg-Landau theory remains a powerful instrument for the study of magnetic phase diagram of superconductors **(15).** The free energy functional of two band superconductors can be expressed by the power series of order parameters in the vicinity of the critical temperature and minimization of the free energy function gives the GL equations that can describe the field distribution in superconductors. The main specialty of iron-based superconductors is their multi-band nature. In the multi-band model of superconductivity, several intra-band and inter-band interaction terms are present. The importance of inter-band pairing in multiband models has been emphasized by Menezes **(16).** The Fermi surface of the optimally doped iron based superconductor $Ba_{1-x}K_xFe_2As_2$ consists of multiple Fermi surface sheets. The density functional theory (DFT) calculations showed that there are three concentric hole cylinders in the center of the Brillouin zone (Γ point) and two electron pockets at the zone corner (M point) **(17)**. Due to the similar shape of the barrels, the hole and electron bands are connected via the interband interaction potential. The Fermi surface (FS), which has contributions from all five possible Fe 3d orbitals **(18)** is very similar to the different iron-based compounds and all the 5 Fe 3d orbitals pass through Fermi surface. The first-principle calculations have shown that, the energy bands near the Fermi surface are mainly contributed by the Fe 3d mainly d_{xz} and d_{yz} orbitals **(19).** One of the main feature of two-band superconductors is the presence of two energy gaps Δ_1 and Δ_2 which vanishes at the same temperature T_c. According to microscopic theory presence of the two gaps is explained by the fact that in each band i an own intra-band coupling constant V_{ii} and the interband coupling constant V_{ij}exists which on the one hand enhances pairing of electrons on the other hand leads to the single critical temperature T_c.

THEORETICAL FORMULATIONS

Calculation of upper critical magnetic field in B $_{1-x}$K$_x$F $_2$A $_2$

In the presence of two-order parameters in a bulk isotropic s-wave superconductor, the phenomenological Ginzburg-Landau free energy density functional for two-band coupled superconducting order parameters Ψ_1 and Ψ_2 can be writtenas (20-25),

$$F_{sc} = F_1 + F_2 + F_{12} + \frac{H^2}{8\pi} \tag{1}$$

where

$$F_1 = -\frac{\hbar^2}{2m_1}\left|\left(\nabla - \frac{2ieA}{\hbar c}\right)\Psi_1\right|^2 - \alpha_1|\Psi_1|^2 + \frac{\beta_1}{2}|\Psi_1|^4 \tag{2}$$

$$F_2 = -\frac{\hbar^2}{2m_2}\left|\left(\nabla - \frac{2ieA}{\hbar c}\right)\Psi_2\right|^2 - \alpha_2|\Psi_2|^2 + \frac{\beta_2}{2}|\Psi_2|^4 \tag{3}$$

$$F_{12} = \epsilon(\Psi_1\Psi_2^* + \Psi_2\Psi_1^*) + \epsilon_1\left(\left[\left(\nabla + \frac{2ieA}{\hbar c}\right)^*\Psi_1^*\left(\nabla - \frac{2ieA}{\hbar c}\right)\Psi_2\right] + \left[\left(\nabla + \frac{2ieA}{\hbar c}\right)^*\Psi_2^*\left(\nabla - \frac{2ieA}{\hbar c}\right)\Psi_1\right]\right) \tag{4}$$

whereF_1 and F_2 are the free energies for each band. $F_{12}$is the interaction free energy term between the two bands. $\frac{H^2}{8\pi}$ is the energy stored in the local magnetic fields. Ψ_1 and Ψ_2 are superconducting order parameters. The coefficients ϵ and ϵ_1 describe the interband interaction of the two order parameters (proximity effect) and the interband mixing of gradients of two order parameters (drag effect) (20) respectively. m_1 and m_2 denote the effective mass of carriers for each band.$\alpha$is the temperature-dependent parameter andβ_i is temperature-independent parameter. $H = \nabla \times A$is the external magnetic field and A is the vector potential.
Now, substituting eqs (2-4) into eq.(1), we get,

$$F_{sc} = -\frac{\hbar^2}{2m_1}\left|\left(\nabla - \frac{2ieA}{\hbar c}\right)\Psi_1\right|^2 - \alpha_1|\Psi_1|^2 + \frac{\beta_1}{2}|\Psi_1|^4 - \frac{\hbar^2}{2m_2}\left|\left(\nabla - \frac{2ieA}{\hbar c}\right)\Psi_2\right|^2 - \alpha_2|\Psi_2|^2 + \frac{\beta_2}{2}|\Psi_2|^4 + \epsilon(\Psi_1\Psi_2^* + \Psi_2\Psi_1^*) + \epsilon_1\left(\left[\left(\nabla + \frac{2ieA}{\hbar c}\right)^*\Psi_1^*\left(\nabla - \frac{2ieA}{\hbar c}\right)\Psi_2\right] + \left[\left(\nabla + \frac{2ieA}{\hbar c}\right)^*\Psi_2^*\left(\nabla - \frac{2ieA}{\hbar c}\right)\Psi_1\right]\right) + \frac{H^2}{8\pi} \tag{5}$$

To derive the Ginzburg-Landau equations for the two-gap superconductor, we minimize the free energy function given in eq.(5) with respect to variations in the complex conjugate of the order parametersΨ_1^*, Ψ_2^*, such that,

$$\frac{\partial F_{sc}}{\partial \Psi_1^*} = 0 \quad \text{and} \quad \frac{\partial F_{sc}}{\partial \Psi_2^*} = 0 \tag{6}$$

Near the critical temperature,T_c we have $\Psi^3_{1,2} \longrightarrow 0$.Thus, using eq.(5) ineq.(6) the first Ginzburg-Landau equations for the two bands can obtain as,

$$-\frac{\hbar^2}{2m_1}\left(\nabla - \frac{2ieA}{\hbar c}\right)^2\Psi_1 - \alpha_1\Psi_1 + \epsilon\Psi_2 + \epsilon_1\left(\nabla - \frac{2ieA}{\hbar c}\right)^2\Psi_2 = 0 \tag{7}$$

And

$$-\frac{\hbar^2}{2m_2}\left(\square-\frac{2ieA}{\hbar c}\right)^2\Psi_2-\alpha_2\Psi_2+\epsilon\Psi_1+\epsilon_1\left(\square-\frac{2ieA}{\hbar c}\right)^2\Psi_1=0 \tag{8}$$

Eqs.(7) and (8) can be expressed in terms of matrix product form as;

$$\begin{pmatrix}H_{11} & H_{12}\\ H_{21} & H_{22}\end{pmatrix}\begin{pmatrix}\Psi_1\\ \Psi_2\end{pmatrix}=\begin{pmatrix}-\frac{\hbar^2}{2m_1}\left(\square-\frac{2ieA}{\hbar c}\right)^2-\alpha_1 & \epsilon+\epsilon_1\left(\square-\frac{2ieA}{\hbar c}\right)^2\\ \epsilon+\epsilon_1\left(\square-\frac{2ieA}{\hbar c}\right)^2 & -\frac{\hbar^2}{2m_2}\left(\square-\frac{2ieA}{\hbar c}\right)^2-\alpha_2\end{pmatrix}\begin{pmatrix}\Psi_1\\ \Psi_2\end{pmatrix}=0 \tag{9}$$

We can compare the equations in eq.(9) to the free-particle time independent Schr ö dinger equation with particle of mass m_i and charge of $e^{\square}$ moving in a magnetic field and is the same as eigenvalues of the harmonic oscillator. For the field in the direction of the c-axis, we can linearize the GL equations as follows;

$H_{11}\Psi_1=-\frac{\hbar^2}{2m_1}\left(\square-\frac{2ieA}{\hbar c}\right)^2\Psi_1=E_{11}\Psi_1andH_{22}\Psi_2=-\frac{\hbar^2}{2m_2}\left(\square-\frac{2ieA}{\hbar c}\right)^2\Psi_2=E_{22}\Psi_2$Hence, eq.(9) becomes,

$$\begin{pmatrix}E_{11}-\alpha_1 & \epsilon+\epsilon_1\left(\square-\frac{2ieA}{\hbar c}\right)^2\\ \epsilon+\epsilon_1\left(\square-\frac{2ieA}{\hbar c}\right)^2 & E_{22}-\alpha_2\end{pmatrix}\begin{pmatrix}\Psi_1\\ \Psi_2\end{pmatrix}=0 \tag{10}$$

The energy eigenvalues of the quantum harmonic oscillator is given by,$E_n=\left(n+\frac{1}{2}\right)$.In order to determine H_{c2}, we must choose n = 0 which gives the upper critical magnetic field. The energy of the two bands for the n = 0 state becomes $E_{11}=\frac{1}{2}\hbar\omega_1$ and $E_{22}=\frac{1}{2}\hbar\omega_2$ where the frequency of the oscillator is given by $\omega_i=\frac{2eH_{c2}}{m_i c}$. For a displacement x in one direction, the vector potential is given by $A = H_{c2}x$.

Then eq. (10) can be reduced into,

$$\begin{pmatrix}\frac{\hbar eH_{c2}}{m_1 c}-\alpha_1 & \epsilon-\epsilon_1\frac{2eH_{c2}}{\hbar c}\\ \epsilon-\epsilon_1\frac{2eH_{c2}}{\hbar c} & \frac{\hbar eH_{c2}}{m_2 c}-\alpha_2\end{pmatrix}\begin{pmatrix}\Psi_1\\ \Psi_2\end{pmatrix}=0 \tag{11}$$

By considering $m_1=m_2=m$, the upper critical magnetic field $H_{c2}$is obtained by setting the determinant of the matrix in eq.(11) to zero, i.e.,

$$\begin{vmatrix}\frac{\hbar eH_{c2}}{m}-\alpha_1 & \epsilon-\epsilon_1\frac{2eH_{c2}}{\hbar c}\\ \epsilon-\epsilon_1\frac{2eH_{c2}}{\hbar c} & \frac{\hbar eH_{c2}}{m}-\alpha_2\end{vmatrix}=0 \tag{12}$$

From which we get,

$$\left[\left(\frac{e\hbar}{m}\right)^2-\frac{4e^2\epsilon_1^2}{\hbar^2c^2}\right]{H_{c2}}^2-\left[\frac{e\hbar}{m}(\alpha_1+\alpha_2)-\frac{4e\epsilon\epsilon_1}{\hbar c}\right]H_{c2}+\alpha_1\alpha_2-\epsilon^2=0 \tag{13}$$

Finally, the solution of the quadratic equation becomes,

$$H_{c2}=\frac{\frac{e\hbar}{m}(\alpha_1+\alpha_2)-\frac{4e\epsilon\epsilon_1}{\hbar c}\pm\sqrt{\frac{e^2\hbar^2}{m^2c^2}[\alpha_1^2+\alpha_2^2]-\frac{2e^2\hbar^2}{m^2c^2}\alpha_1\alpha_2-\frac{8e^2\epsilon\epsilon_1}{mc^2}[\alpha_1+\alpha_2]+\frac{1\ e^2\epsilon_1^2}{\hbar^2c^2}\alpha_1\alpha_2+\frac{4e^2\hbar^2\epsilon^2}{m^2c^2}}}{2\left[\left(\frac{e\hbar}{m}\right)^2-\frac{4e^2\epsilon_1^2}{\hbar^2c^2}\right]} \tag{14}$$

Now let,$\alpha_1=\frac{\hbar^2}{2m\xi_1^2}$, $\alpha_2=\frac{\hbar^2}{2m\xi_2^2}$, $\epsilon=\frac{\hbar^2}{2m\xi_1^2}$where ξ_1, ξ_2, and ξ_1 are the first band, second band and interband effective coherence lengths, respectively,$\epsilon_1=\frac{\kappa\hbar^2}{2m}$where κ is the gradients of interband mixing oftwo order parameters in energy unit and $\Phi_0=\frac{2\pi\hbar}{e}$ and is the quantum flux.

Thus, eq.(14) becomes,

$$H_{c2} = \frac{\Phi_0}{2\pi(1-\kappa^2)}\left(\frac{1}{2\xi_1^2} + \frac{1}{2\xi_2^2} - \frac{\kappa}{\xi_1^2}\right) \pm \frac{\Phi_0}{2\pi(1-\kappa^2)}\left[\left(\frac{1}{2\xi_1^2} + \frac{1}{2\xi_2^2} - \frac{\kappa}{\xi_1^2}\right)^2 - (1-\kappa^2)\left(\frac{1}{\xi_1^2\xi_2^2} - \frac{1}{\xi_1^4}\right)\right]^{\frac{1}{2}} \tag{15}$$

Now, let us consider cases such that,

Case I: $\left(\frac{1}{2\xi_1^2} + \frac{1}{2\xi_2^2} - \frac{\kappa}{\xi_1^2}\right)^2$ □ $(1-\kappa^2)\left(\frac{1}{\xi_1^2\xi_2^2} - \frac{1}{\xi_1^4}\right)$, in this case the term in the square root in eq. (15) becomes complex. Therefore, we can conclude that the first case is not valid sincemagnetic field is a real quantity.

Case II: $\left(\frac{1}{2\xi_1^2} + \frac{1}{2\xi_2^2} - \frac{\kappa}{\xi_1^2}\right)^2$ □ $(1-\kappa^2)\left(\frac{1}{\xi_1^2\xi_2^2} - \frac{1}{\xi_1^4}\right)$

Using the Taylor's binomial series expansions, for the negative value of the square root in eq.(15) we get,

$$H_{c2}^{-} = \frac{\Phi_0}{2\pi}\frac{1}{2}\frac{\left(\frac{1}{\xi_1^2\xi_2^2} - \frac{1}{\xi_1^4}\right)}{\left(\frac{1}{2\xi_1^2} + \frac{1}{2\xi_2^2} - \frac{\kappa}{\xi_1^2}\right)} - \frac{1}{8}\frac{\Phi_0}{2\pi}\left(\frac{(1-\kappa^2)\left(\frac{1}{\xi_1^2\xi_2^2} - \frac{1}{\xi_1^4}\right)^2}{\left(\frac{1}{2\xi_1^2} + \frac{1}{2\xi_2^2} - \frac{\kappa}{\xi_1^2}\right)^3}\right) \tag{16}$$

For the positive value of the square root in eq.(15) we get,.

$$H_{c2}^{+} = \frac{\Phi_0}{2\pi(1-\kappa^2)}\left(\frac{1}{2\xi_1^2} + \frac{1}{2\xi_2^2} - \frac{\kappa}{\xi_1^2}\right) - \frac{\Phi_0}{2\pi}\frac{1}{2}\frac{\left(\frac{1}{\xi_1^2\xi_2^2} - \frac{1}{\xi_1^4}\right)}{\left(\frac{1}{2\xi_1^2} + \frac{1}{2\xi_2^2} - \frac{\kappa}{\xi_1^2}\right)} + \frac{1}{8}\frac{\Phi_0}{2\pi}\left(\frac{(1-\kappa^2)\left(\frac{1}{\xi_1^2\xi_2^2} - \frac{1}{\xi_1^4}\right)^2}{\left(\frac{1}{2\xi_1^2} + \frac{1}{2\xi_2^2} - \frac{\kappa}{\xi_1^2}\right)^3}\right) \tag{17}$$

Due to the drag effect, the GL theory for a two-band superconductor can be reduced to the GL theory for an effective single-band superconductor. Two band model can be reduced to one band model if we set $\alpha_2 = \epsilon = \epsilon_1 = 0$. We observe that eq.(16) cannot be reduced into one bandmodel so does not have a physical meaning. But eq.(17) can be reduced into one band model and is the analytical equation of upper critical magnetic field and thus we have,

$$H_{c2} = \frac{\Phi_0}{2\pi\xi_1^2}\left(\frac{\xi_1^2}{\xi_1^2} + \frac{\xi_1^2}{\xi_2^2} - 2\kappa\right)\left[\frac{1}{1-\kappa^2} - \frac{\frac{\xi_1^2}{\xi_1^2\xi_2^2} - 1}{\left(\frac{\xi_1^2}{\xi_1^2} + \frac{\xi_1^2}{\xi_2^2} - 2\kappa\right)^2} + \frac{(1-\kappa^2)\left(\frac{\xi_1^4}{\xi_1^2\xi_2^2} - 1\right)^2}{\left(\frac{\xi_1^2}{\xi_1^2} + \frac{\xi_1^2}{\xi_2^2} - 2\kappa\right)^4}\right] \tag{18}$$

The effect of anisotropy mass tensor on the upper critical magnetic field is included by replacing ξ in eq.(18) with coherence length tensor $\{\xi\}$.
Finally we have,

$$H_{c2} = \frac{\Phi_0}{2\pi\xi_1^2\sqrt{\sin^2\theta + \gamma^2\cos^2\theta}}\left(\frac{\xi_1^2}{\xi_1^2} + \frac{\xi_1^2}{\xi_2^2} - 2\kappa\right)\left[\frac{1}{1-\kappa^2} - \frac{\frac{\xi_1^2}{\xi_1^2\xi_2^2} - 1}{\left(\frac{\xi_1^2}{\xi_1^2} + \frac{\xi_1^2}{\xi_2^2} - 2\kappa\right)^2} + \frac{(1-\kappa^2)\left(\frac{\xi_1^4}{\xi_1^2\xi_2^2} - 1\right)^2}{\left(\frac{\xi_1^2}{\xi_1^2} + \frac{\xi_1^2}{\xi_2^2} - 2\kappa\right)^4}\right] \tag{19}$$

The inter-band mixing of gradients of two order parameters in anisotropic bulk two-band superconductor plays important role. The two-band superconductor is characterized with a single GL coherence length,ξ_{GL}, single magnetic penetrations depth,λ_{GL}, single upper critical magnetic fields,H_{c2} and a singleGL characteristic parameter,κ.

The effective coherence length,ξ_{eff} can be expressed as,

$$\frac{1}{\xi_e^2} = \frac{1}{\xi_1^2}\left(\frac{\xi_1^2}{\xi_1^2} + \frac{\xi_1^2}{\xi_2^2} - 2\kappa\right)\left[\frac{1}{1-\kappa^2} - \frac{\frac{\xi_1^2}{\xi_1^2\xi_2^2} - 1}{\left(\frac{\xi_1^2}{\xi_1^2} + \frac{\xi_1^2}{\xi_2^2} - 2\kappa\right)^2} + \frac{(1-\kappa^2)\left(\frac{\xi_1^4}{\xi_1^2\xi_2^2} - 1\right)^2}{\left(\frac{\xi_1^2}{\xi_1^2} + \frac{\xi_1^2}{\xi_2^2} - 2\kappa\right)^4}\right] \tag{20}$$

Thus, eq.(19) becomes,

$$H_{c2}(T) = \frac{\Phi_0}{2\pi\xi_e^2(T)\sqrt{\sin^2\theta + \gamma^2\cos^2\theta}} \tag{21}$$

From eq. (21) the angular dependence of the upper critical magnetic field due to an isotropic effective masses at an angle θbetween the c-axis and applied magnetic field at low temperature can be expressed as,

$$H_{c2}(\theta) = \frac{\Phi_0}{2\pi\xi_e^2(0)\sqrt{\sin^2\theta+\gamma^2\cos^2\theta}} \tag{22}$$

The anisotropy parameter for $Ba_{1-x}K_xFe_2As_2$ at T=0K is obtained to be $\gamma = \frac{H_{c2}^{\perp c}(0)}{H_{c2}^{\parallel c}(0)} = 2.07$. The experimental values of the zero temperature coherence length for $Ba_{1-x}K_xFe_2As_2$ are $\xi_a(0) = 1.92\text{nm}$ and $\xi_c(0) = 0.92\text{nm}$ (26,27).For $\Phi_0 = 2.0678 \times 10^{-1}\ \text{Tm}^2$ eq. (21) becomes,

$$H_{c2}(\theta) = \frac{8}{\sqrt{\sin^2\theta+4.2\ \cos^2\theta}} \tag{23}$$

It has been shown that, a single band anisotropic model can properly describe the angular dependence of $H_{c2}(\theta)$ in a multi-band system at temperatures near,T_c(28,29)

If the direction of the applied magnetic field is parallel to the c-axis, then the expression for the upper critical magnetic field $H_{c2}^{\parallel c}$ as function of temperature in eq. (21) is given by,

$$H_{c2}^{\parallel c}(T) = \frac{\Phi_0}{2\pi\xi_a^2(0)}\left[1-\left(\frac{T}{T_c}\right)^2\right] \tag{24}$$

where$\xi_{ab}(T) = \xi_{ab}(0)\left[1-\left(\frac{T}{T_c}\right)^2\right]^{-\frac{1}{2}}and\xi_{ab}(0)$ is the zero temperature coherence lengths in the ab-plane. The mathematical expressions of the temperature dependence of the upper critical magnetic field parallel to the symmetry axis (in the c-direction) in superconductor $Ba_{1-x}K_xFe_2As_2$ becomes,

$$H_{c2}^{\parallel c}(T) = 89\text{Tesla}\left[1-\left(\frac{T}{T_c}\right)^2\right] \tag{25}$$

If the direction of the applied magnetic field is perpendicular to the c-axis, then the expression for the upper critical magnetic field $H_{c2}^{\perp c}(T)$ in eq.(21) is given by,

$$H_{c2}^{\perp c}(T) = \frac{\Phi_0}{2\pi\xi_{ab}(0)\xi_c(0)}\left[1-\left(\frac{T}{T_c}\right)^2\right] \tag{26}$$

Thus,the mathematical expressions of the temperature dependence of the upper critical magnetic field perpendicular to the symmetry axis in superconductor$Ba_{1-x}K_xFe_2As_2$ becomes,

$$H_{c2}^{\perp c}(T) = 185\text{Tesla}\left[1-\left(\frac{T}{T_c}\right)^2\right] \tag{27}$$

2.2.Calculation of Ginzburg-Landau coherence length and penetration depth in $Ba_{1-x}K_xFe_2As_2$

There are two important temperature dependent material parameters which arise from the GL model that characterize the phenomenological properties of a superconductor. The coherence length ξ_G is defined as,

$$\xi_G(T) = \left(\frac{\hbar^2}{2m^*|\alpha(T)|}\right)^{\frac{1}{2}} \tag{28}$$

This parameter specifies the spatial width of the transition layer of the order parameter,Ψ in the neighborhood of the boundary between a normal region and a superconducting region. For $T < T_c$, the temperature-dependent,αcan be written as a function of temperature in the vicinity of the critical temperature,T_c as $\alpha_i(T) = \alpha_0\left[1-\left(\frac{T}{T_c}\right)^2\right]$. Here,$\alpha_0$ is the temperature-independent positive constant. Hence, the expression for the temperature dependent GL coherence length,$\xi_G(T)$ becomes, $\xi_G(T) =$

$$\xi_G(0)\left[1-\left(\frac{T}{T_c}\right)^2\right]^{-\frac{1}{2}} \tag{29}$$

where ξ_G (0) is the zero temperature coherence length.By talking the experimental values of ξ_G^a (0) and ξ_G^c (0), the coherence length in the ab-plane (ξ_G^a) and along the c-axis (ξ_G^c) for $Ba_{1-x}K_xFe_2As_2$ becomes,

$$\xi_G^a\ (T) = 1.92x10^{-9}m\left[1-\left(\frac{T}{T_c}\right)^2\right]^{-\frac{1}{2}} \quad (30)$$

$$\xi_G^c\ (T) = 0.92x10^{-9}m\left[1-\left(\frac{T}{T_c}\right)^2\right]^{-\frac{1}{2}} \quad (31)$$

According to the Meissner-Ochsenfeld effect an external magnetic field is expelled completely from the interior of a superconductor. But there was experimental evidence that magnetic fields penetrates a superconductor and a surface current flows in a very thin layer of thickness which is called the Ginzburg-Landau penetration depth (λ_G) and can be expressed in terms of the superconducting electron density n_s as;

$$\lambda_G\ (T) = \left(\frac{mc^2}{1\ \pi e^2 n_s}\right)^{\frac{1}{2}} \quad (32)$$

For $T \longrightarrow 0, n_s \longrightarrow n$ (total electron density), thus, we have,

$$\lambda_G\ (0) = \left(\frac{mc^2}{1\ \pi e^2 n}\right)^{\frac{1}{2}} \quad (33)$$

In the two-fluid theory of Gorter and Casimir**(30)** we can have,

$$\frac{n_s}{n} = \left[1-\left(\frac{T}{T_c}\right)^4\right] \quad (34)$$

Now, combining eqs. (34),(33) and (32) we have,

$$\lambda_G\ (T) = \lambda_G\ (0)\left[1-\left(\frac{T}{T_c}\right)^4\right]^{-\frac{1}{2}} \quad (35)$$

Using the experimental values for $Ba_{1-x}K_xFe_2As_2$,the expression for the temperature dependent penetration depth in the ab-plane (λ_G^a) and along the c-axis (λ_G^c) becomes,

$$\lambda_G^a\ (T) = 120x\ 10^{-9}m\left[1-\left(\frac{T}{T_c}\right)^4\right]^{-\frac{1}{2}} \quad (36)$$

$$\lambda_G^c\ (T) = 312x\ 10^{-9}m\left[1-\left(\frac{T}{T_c}\right)^4\right]^{-\frac{1}{2}} \quad (37)$$

Using the experimental values for $Ba_{1-x}K_xFe_2As_2$, the GL characteristic parameter κ becomes,

$$\kappa_c = \frac{\lambda_G{}^a\ (0)}{\xi_G{}^a\ (0)} = \frac{1\quad n}{1.2n} = 100 \text{and} \kappa_a = \frac{\lambda_G{}^c(0)}{\xi_G{}^a\ (0)} = \frac{3\quad n}{1.2n} = 260 \quad (38)$$

It is a well-known fact that, Abrikosov 10(14) proved that, the exact break-down point between type-I and type-II superconductors lies at Ginzburg-Landau characteristic parameter such that, $\kappa = \frac{1}{\sqrt{2}}$. If the value of $\kappa < \frac{1}{\sqrt{2}}$, then the superconductor is said to be type-I and type-II for $\kappa > \frac{1}{\sqrt{2}}$.Therefore, from eq.(38), we conclude that the iron-based superconductor $Ba_{1-x}K_xFe_2As_2$ is an example of type-II superconductors.

RESULTS AND DISCUSSION

In this study we obtained expressions for the angular dependence of upper critical magnetic field, temperature dependence of the upper critical magnetic field parallel and perpendicular to the symmetry axis, the temperature dependence of GL coherence length and GL penetration depth parallel and perpendicular to the symmetry axis by using Ginzburg- Landau approach in two-band iron-based superconductor $Ba_{1-x}K_xFe_2As_2$. Firstly, usingeq.(23) the phase diagram of$H_{c2}(\theta)$versus θ is drawn as shown in

Fig. 1. As can be seen in Fig. 1 the upper critical magnetic field increases nonlinearly from $\theta = 0^0$to $\theta = 90^0$ for the iron-based superconductor$Ba_{1-x}K_xFe_2As_2$. Secondly, using eqs.(25) and (27) and by taking some available experimental data, the phase diagrams of $H_{c2}^{\parallel c}$ and $H_{c2}^{\perp c}$versus temperature are plotted as shown in Fig. 2. As can be seen from Fig. 2, the upper critical magnetic field decrease with increasing temperature and have nonlinear dependence for the superconductor$Ba_{1-x}K_xFe_2As_2$. Thirdly, the expression for the temperature(K) dependent Ginzburg-Landau coherence length ξ_G^a and ξ_G^c are given in eqs.(30) and (31) respectively. Using eqs.(30) and (31) and by taking some available experimental data, the phase diagrams of ξ_G^a and ξ_G^c versus temperature are plotted as shown in Fig. 3. As can be seen from the figure, GL coherence length increases with temperature which subsequently diverges at the critical temperature $\xi(T \longrightarrow T_c) \longrightarrow \infty$ for the superconductor $Ba_{1-x}K_xFe_2As_2$. Finally, using eqs.(36) and (37) and taking the experimental values, we plotted the phase diagrams of λ_G^a and λ_G^c versus temperature as shown in Fig. 4. As can be seen from the figure, Ginzburg-Landau penetration depth increases with temperature which diverges at the critical temperature$\lambda(T \longrightarrow T_c) \longrightarrow \infty$ for the superconductor $Ba_{1-x}K_xFe_2As_2$.

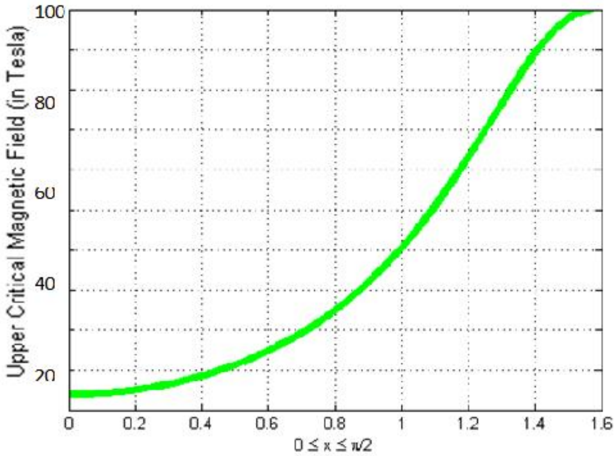

Fig. 1. Variation of upper critical magnetic field H_c (θ)with the angleθ in B $_{1-x}K_xF$ $_2A$ $_2$

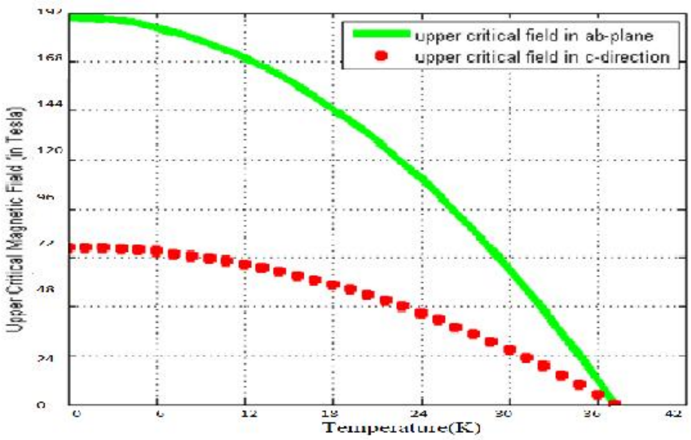

Fig. 2 Upper critical magnetic field parallel and perpendicular to thesymmetry axis versus temperature in$Ba_{1-x}K_xF$ $_2A$ $_2$

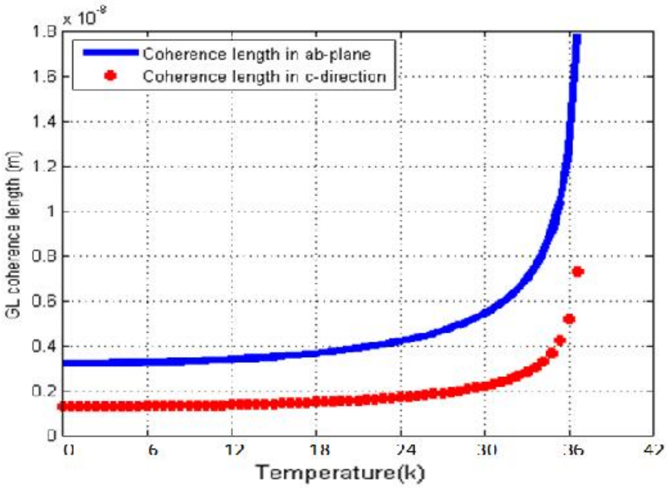

Fig. 3Ginzburg-Landau coherence length ξ_G (T) versus temperature inB $_{1-x}K_xF$ $_2A$ $_2$

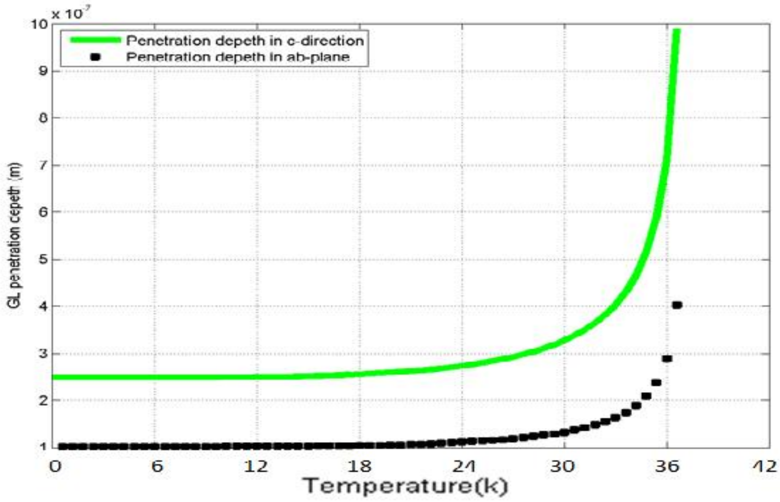

Fig. 4 Ginzburg-Landau penetration depth λ_G (T) versus temperaturein $B_{1-x}K_xF_2A_2$

Conclusion

In this study, we used two-band Ginzburg-Landau approach in order to determine the upper critical magnetic field,Ginzburg-Landau coherence length and Ginzburg-Landau penetration depth for the two-band iron-based optimally doped superconductor $Ba_{1-x}K_xFe_2As_2$. According to the mathematical computation, the coherence length is strongly temperature dependent, so that it can cause temperature dependency and anisotropy nature on the upper critical magnetic field of $Ba_{1-x}K_xFe_2As_2$ .This indicates that, the upper critical magnetic field along ab-plane $(H_{c2}^{\perp c})$ is quite different from c-axis $(H_{c2}^{\parallel c})$. We plotted upper critical field versus temperature graph and the critical magnetic field decays with increasing temperature as shown in Fig.2. We also plotted GL coherence length and GL penetration depth versus temperature and we found the characteristic lengths increases with temperature which diverges to infinite at the critical temperature as shown in Fig.3 and Fig.4. Finally we plotted the angular dependence of the upper critical field as shown in Fig.1 showing a good agreement with the result obtained in Fig.2. Our findings in this work are in broad agreement with experimental findings (31).

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