Superconductivity in the ferromagnet URhGe under uniaxial pressure

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Uniaxial pressure applied in the b crystallographic direction perpendicular to spontaneous magnetization in the heavy fermion ferromagnet URhGe strongly stimulates superconductivity in this compound. The phenomenological approach allows us to point out two mechanisms of the increase in the superconducting temperature. They originate from stimulation by the uniaxial stress of both the intraband and interband amplitudes of triplet Cooper pairing. The phenomenon of reentrant superconductivity under a magnetic field along the b axis is also strongly sensitive to uniaxial stress in the same direction. Uniaxial stress accelerates suppression of the Curie temperature by the transversal magnetic field. The emergence of a first-order transition to the paramagnetic state occurs at a much lower field than in the absence of uniaxial stress.

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I. INTRODUCTION

The coexistence of superconductivity and ferromagnetism is the hallmark of heavy fermion uranium compounds UGe_2, URhGe, and UCoGe (see the recent experimental [1] and theoretical [2] reviews and references therein). The emergence of the superconducting state at temperatures far below the Curie temperature and the very high upper critical field strongly indicate on the spin-triplet Cooper pairing in these materials. One of the most peculiar observations is the phenomenon of reentrant superconductivity in URhGe [3], which is an orthorhombic ferromagnet with spontaneous magnetization along the c axis. At low enough temperature a magnetic field of about 1.3 T directed along the b axis suppresses the superconducting state [4], but at a much higher field of about 10 T, the superconductivity is recreated and exists until the field is about 13 T [3]. The maximum of the superconducting critical temperature in this field interval is ≈0.4 K. In the same field interval the material transfers from the ferromagnetic to the paramagnetic state by means of a first-order type transition. The superconducting state exists not only inside of the ferromagnetic state but also in the paramagnetic state, which is separated from the ferromagnetic state by a first-order phase transition. The theoretical treatment of this phenomenon has been proposed in Ref. [5].

It has been shown experimentally that a hydrostatic pressure applied to URhGe crystals stimulates ferromagnetism, causing an increase of the Curie temperature $T_c(P)$ and, at the same time, suppresses the superconducting state, decreasing the critical temperature of the superconducting phase transition $T_{sc}(P)$ [6], as well as the maximum of the superconducting critical temperature of the reentrant superconducting state [7]. The latter is also shifted to a bit higher field interval. Quite the opposite behavior has been registered recently [8] under uniaxial stress P_y in the b direction. In what follows, we shall use the x,y,z coordinate axes pinned correspondingly to the a,b,c crystallographic directions. Namely, the uniaxial stress suppresses the ferromagnetism decreasing the Curie temperature $T_c(P_y)$ and stimulates the superconducting state such that the temperature of the superconducting transition increases so strongly that it leads to the coalescence of the superconducting and reentrant superconducting regions in the (H_y,T) phase diagram already at quite moderate uniaxial stress values. A comparison of (H_y,T) phase diagrams at ambient pressure and at some uniaxial stress is presented in Fig. 1.

Here, I show that the stimulation of the superconducting state originates from two mechanisms: the Curie temperature suppression stimulating intraband pairing, and the increase of the magnetic susceptibility along the b direction stimulating interband pairing. Then, making use of the phenomenological approach developed in Ref. [5], I consider the (H_y,T) phase diagram modification caused by uniaxial stress along the b direction. It is demonstrated that uniaxial stress strongly accelerates the process of Curie temperature suppression by a magnetic field along the b direction. Also the field-induced transformation of the second- to the first-order ferro-para phase transition occurs at much lower field $H_y^{cr}(P_y)$ values than in the absence of stress. This leads to the coalescence of the superconducting and reentrant superconducting states.

II. FREE ENERGY

The Landau free-energy density of an orthorhombic ferromagnet in a magnetic field $\mathbf{H}(\mathbf{r}) = H_y\hat{y}$ under an external pressure consists of magnetic, elastic, and magnetoelastic parts,

$$F = F_M + F_{el} + F_{Mel}, \tag{1}$$

where in the magnetic part [2]

$$F_M = \alpha_z M_z^2 + \beta_z M_z^4 + \delta_z M_z^6 + \left(\alpha_y + \beta_{yz} M_z^2 + \delta_{yz} M_z^4\right) M_y^2 - M_y H_y, \tag{2}$$

we bear in mind the orthorhombic anisotropy and also the terms up to sixth order in powers of M_z and in the product of the M_z and M_y components of magnetization. Here, x, y, and z are the coordinates pinned to the a, b, and c crystallographic directions, correspondingly,

$$\alpha_z = \alpha_{z0}(T - T_{c0}), \quad \alpha_y > 0. \tag{3}$$

The elastic part of free energy in an orthorhombic crystal is [9]

$$F_{el} = \tfrac{1}{2}\lambda_x u_{xx}^2 + \tfrac{1}{2}\lambda_y u_{yy}^2 + \tfrac{1}{2}\lambda_z u_{zz}^2 + \lambda_{xy} u_{xx} u_{yy} + \lambda_{xz} u_{xx} u_{zz} + \lambda_{yz} u_{yy} u_{zz} + \tfrac{1}{2}\mu_{xy} u_{xy}^2 + \tfrac{1}{2}\mu_{xz} u_{xz}^2 + \tfrac{1}{2}\mu_{yz} u_{yz}^2, \tag{4}$$

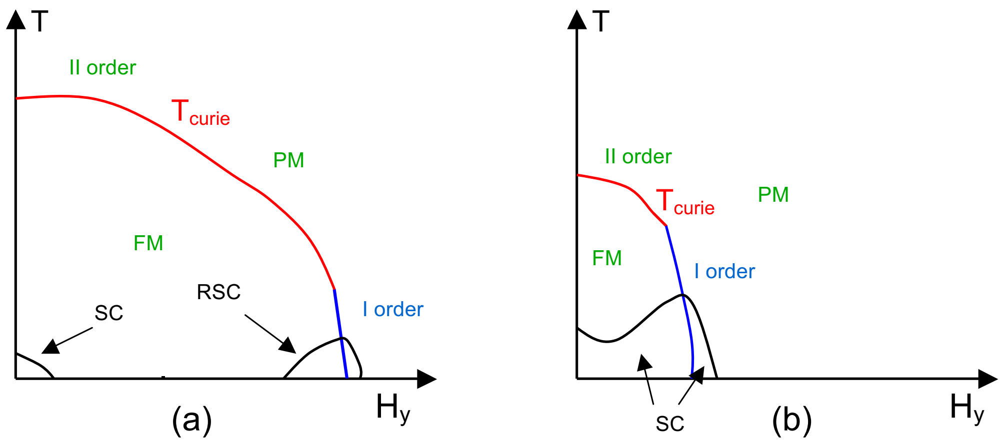

FIG. 1. Schematic phase diagrams of URhGe in a magnetic field along the b axis perpendicular to the spontaneous magnetization direction: (a) at ambient pressure and (b) at strong enough uniaxial stress along the b direction. PM and FM denote paramagnetic and ferromagnetic states. SC and RSC are the superconducting and reentrant superconducting states, correspondingly. The red line is the Curie temperature. The blue line is the line of the first-order transition.

where u_{xx}, u_{yy}, u_{zz}, u_{xy}, u_{xz}, and u_{yz} are the components of deformation tensor.

The magnetoelastic part is

$$F_{Mel} = (p_x u_{xx} + p_y u_{yy} + p_z u_{zz})M_z^2 + (q_x u_{xx} + q_y u_{yy} + q_z u_{zz})M_y^2 + r u_{yz} M_y M_z. \quad (5)$$

To find the deformation arising under the influence of uniaxial stress P_y applied along the b axis, one must solve the linear equations

$$\frac{\partial(F_{el}+F_{Mel})}{\partial u_{xx}} = 0, \quad \frac{\partial(F_{el}+F_{Mel})}{\partial u_{zz}} = 0,$$
$$\frac{\partial(F_{el}+F_{Mel})}{\partial u_{yz}} = 0, \quad \frac{\partial(F_{el}+F_{Mel})}{\partial u_{yy}} = -P_y, \quad (6)$$

with respect to the components of the deformation tensor. Whereas, in the case of hydrostatic pressure P, the corresponding system of equations is

$$\frac{\partial(F_{el}+F_{Mel})}{\partial u_{xx}} = -P, \quad \frac{\partial(F_{el}+F_{Mel})}{\partial u_{zz}} = -P,$$
$$\frac{\partial(F_{el}+F_{Mel})}{\partial u_{yz}} = 0, \quad \frac{\partial(F_{el}+F_{Mel})}{\partial u_{yy}} = -P. \quad (7)$$

Solving Eqs. (6) and substituting the solution back to the sum $F_{el} + F_{Mel}$ given by Eqs. (4) and (5), we obtain the magnetic field H_y and the uniaxial pressure P_y dependent magnetic part of the free-energy density,

$$F_M = (\alpha_z + A_z P_y)M_z^2 + \beta_z M_z^4 + \delta_z M_z^6 + (\alpha_y + A_y P_y)M_y^2 + \beta_{yz} M_z^2 M_y^2 + \delta_{yz} M_z^4 M_y^2 - M_y H_y. \quad (8)$$

The coefficients β_z, β_{yz}, and δ_{yz} in this expression differ from the corresponding coefficients in Eq. (2). However, this difference is pressure independent as long as the magnetoelastic coupling has the simple form given by Eq. (5). Hence, in what follows, we keep for these coefficients the same notations as in Eq. (2).

The coefficient at M_z^2 is now

$$\alpha_z(P) = \alpha_{z0}(T - T_{c0}) + A_z P_y, \quad (9)$$

and in the absence of a field, the Curie temperature acquires the pressure dependence

$$T_{c0}(P_y) = T_{c0} - \frac{A_z P_y}{\alpha_{z0}}. \quad (10)$$

The expression of coefficients A_z and A_y through elastic and magnetoelastic moduli (see the Appendix) not to give up any hope to perform a theoretical estimation of their value. But in fact this is not necessary. As we shall see, an important role is played by their sign, which is determined experimentally. The Curie temperature decreases with uniaxial pressure, [8] which corresponds to a positive A_z coefficient.

The coefficient at M_y^2 also acquires the pressure dependence

$$\alpha_y(P_y) = \alpha_y + A_y P_y. \quad (11)$$

The equilibrium magnetization projection along the y direction is obtained by the minimization of free energy in Eq. (8) with respect to M_y,

$$M_y = \frac{H_y}{2[\alpha_y(P_y) + \beta_{yz} M_z^2 + \delta_{yz} M_z^4]}. \quad (12)$$

The measurements [8] show that the susceptibility along the y direction $\chi_y(P_y) = \frac{M_y}{H_y}$ increases with an increase in pressure. This is owing to both $T_{c0}(P_y)$ and a much stronger $\alpha(P_y)$ decrease with uniaxial pressure. So, the coefficient A_y is proved to be negative, thus

$$\alpha_y(P_y) = \alpha_y - |A_y| P_y. \quad (13)$$

We shall see in the next section that both dependencies (10) and (13) cause an increase in the superconducting critical temperature. Then I will demonstrate that y-direction uniaxial pressure makes it easier to suppress the ferromagnetic state by a magnetic field in the y direction and stimulates the emergence of the reentrant superconducting state.

Hydrostatic pressure creates the dependencies of the coefficients of the same form,

$$\alpha_z(P) = \alpha_{z0}(T - T_{c0}) + A_z^h P, \tag{14}$$

$$\alpha_y(P) = \alpha_y + A_y^h P. \tag{15}$$

In this case, however,

$$A_z^h < 0, \quad A_y^h > 0 \tag{16}$$

which corresponds to the stimulation of ferromagnetism and, as we shall see, to the suppression of superconductivity reported in Refs. [6,7].

III. SUPERCONDUCTING CRITICAL TEMPERATURE IN ZERO FIELD

The superconducting state in a two-band (spin-up and spin-down) orthorhombic ferromagnet is described in its simplest form in terms of two complex order parameter amplitudes [2,10]

$$\Delta^{\uparrow}(\mathbf{k},\mathbf{r}) = \hat{k}_x \eta_{\uparrow}(\mathbf{r}),$$
$$\Delta^{\downarrow}(\mathbf{k},\mathbf{r}) = \hat{k}_x \eta_{\downarrow}(\mathbf{r}) \tag{17}$$

depending on the Cooper pair center of gravity coordinate $\mathbf{r}$ and the momentum $\mathbf{k}$ of the pairing electrons. This particular order parameter structure allows us to explain the specific temperature dependence of the upper critical field anisotropy in URhGe [2,4].

The corresponding critical temperature of transition to the superconducting state is determined by the BCS-type formula

$$T = \varepsilon \exp\left(-\frac{1}{g}\right), \tag{18}$$

where the constant of interaction

$$g = \frac{g_{1x}^{\uparrow} + g_{1x}^{\downarrow}}{2} + \sqrt{\frac{(g_{1x}^{\uparrow} - g_{1x}^{\downarrow})^2}{4} + g_{2x}^{\uparrow} g_{2x}^{\downarrow}} \tag{19}$$

is expressed through the constants of intraband pairing $g_{1x}^{\uparrow}, g_{1x}^{\downarrow}$ and the constants of interband pairing $g_{2x}^{\uparrow}, g_{2x}^{\downarrow}$. They are functions of temperature, pressure, and magnetic field. Thereby formula (18) is, in fact, an equation for the determination of the critical temperature of the transition to the superconducting state.

The constants of intraband pairing interaction for spin-up and spin-down bands are proportional to the average over the Fermi surface density of states and the odd part of susceptibility along the direction of spontaneous magnetization [see Ref. [2], Eq. (103)],

$$g_{1x}^{\uparrow} \propto \frac{\langle \hat{k}_x^2 N_0^{\uparrow} \rangle}{(2\beta_z M_z^2 + \gamma^z k_F^2)^2}, \tag{20}$$

$$g_{1x}^{\downarrow} \propto \frac{\langle \hat{k}_x^2 N_0^{\downarrow} \rangle}{(2\beta_z M_z^2 + \gamma^z k_F^2)^2}. \tag{21}$$

In the absence of the magnetic field, the magnetization below the Curie temperature is given by

$$2\beta_z M_z^2 = \alpha_{z0}[T_{c0}(P_y) - T]. \tag{22}$$

Assuming that at temperatures far below $T_{c0}(P_y)$ this formula is still qualitatively valid, we obtain, using Eq. (10),

$$2\beta_z M_z^2 \approx \alpha_{z0}(T_{c0} - A_z P_y). \tag{23}$$

Thus, the magnetization decreases with uniaxial pressure, which causes in its turn the increase of a superconducting interaction constant.

On the other hand, the constants of the interband pairing interaction are determined by the difference of the odd part of the susceptibilities in the x and y directions [see Ref. [2], Eq. (104)]. Keeping in mind the smallness of susceptibility along the x direction with respect to susceptibility along the y axis [11] we obtain

$$g_{2x}^{\uparrow} \propto -\frac{\gamma_{yy}^x \langle \hat{k}_x^2 N_0^{\uparrow} \rangle}{[\alpha_y(P) + \beta_{yz} M_z^2 + 2\gamma^y k_F^2]^2}, \tag{24}$$

$$g_{2x}^{\downarrow} \propto -\frac{\gamma_{yy}^x \langle \hat{k}_x^2 N_0^{\downarrow} \rangle}{[\alpha_y(P) + \beta_{yz} M_z^2 + 2\gamma^y k_F^2]^2}, \tag{25}$$

where we have neglected by the small fourth-order terms $\sim M_z^4$ which appear in the denominators in Eq. (12). According to Eqs. (13) and (23), the denominators in these expressions are decreasing functions of pressure. Thus, the absolute values of the constant of interband pairing increase with uniaxial pressure.

Thus, all the terms in Eq. (19) increase with an increase in uniaxial pressure, which results in the increasing temperature of the superconducting transition shown in Fig. 1. Conversely, according to Eqs. (14)–(16) a hydrostatic pressure suppresses the superconducting state.

IV. PHASE TRANSITION IN MAGNETIC FIELD PERPENDICULAR TO EASY MAGNETIZATION AXIS

The reentrant superconducting state in URhGe arises in a high magnetic field along the b axis in the vicinity of the first-order transition from the ferromagnetic to the paramagnetic state. The change of the phase transition type from the second to the first order has been described phenomenologically in Ref. [5]. With the aim of establishing the uniaxial pressure dependence of the transition transformation we reproduce this derivation.

The equilibrium magnetization projection along the y direction is given by Eq. (12). Substituting this formula in Eq. (8) we obtain

$$F_M = \alpha_z(P_y) M_z^2 + \beta_z M_z^4 + \delta_z M_z^6 - \frac{1}{4} \frac{H_y^2}{\alpha_y(P_y) + \beta_{yz} M_z^2 + \delta_{yz} M_z^4}, \tag{26}$$

which gives after expansion of the denominator in the last term,

$$F_M = -\frac{H_y^2}{4\alpha_y(P_y)} + \tilde{\alpha}_z M_z^2 + \tilde{\beta}_z M_z^4 + \tilde{\delta}_z M_z^6 + \cdots, \tag{27}$$

where

$$\tilde{\alpha}_z = \alpha_{z0}[T - T_{c0}(P_y)] + \frac{\beta_{yz}H_y^2}{4[\alpha_y(P_y)]^2}, \quad (28)$$

$$\tilde{\beta}_z = \beta_z - \frac{\beta_{yz}^2 - \delta_{yz}\alpha_y(P_y)}{\alpha_y(P_y)}\frac{H_y^2}{4[\alpha_y(P_y)]^2}, \quad (29)$$

$$\tilde{\delta}_z = \delta_z + \frac{\beta_{yz}^2}{\alpha_y(P)^2}\frac{\beta_{yz}H_y^2}{4[\alpha_y(P_y)]^2}. \quad (30)$$

We see that under a magnetic field perpendicular to the direction of spontaneous magnetization, the Curie temperature decreases as

$$T_c = T_c(P_y,H_y) = T_{c0}(P_y) - \frac{\beta_{yz}H_y^2}{4\alpha_{z0}[\alpha_y(P_y)]^2}$$
$$= T_{c0} - \frac{A_zP_y}{\alpha_{z0}} - \frac{\beta_{yz}H_y^2}{4\alpha_{z0}(\alpha_y - |A_y|P_y)^2}. \quad (31)$$

Thus, at a finite field H_y the suppression of Curie temperature by uniaxial pressure occurs much faster than in the absence of field.

In assumption $\beta_{yz}^2 - \delta_{yz}\alpha_y(P_y) > 0$, the coefficient $\tilde{\beta}_z$ also decreases with H_y and reaches zero at

$$H_y^{cr}(P_y) = \frac{2[\alpha_y(P_y)]^{3/2}\beta_z^{1/2}}{B(P_y)}, \quad (32)$$

where

$$B(P_y) = \sqrt{\beta_{yz}^2 - \delta_{yz}\alpha_y(P_y)}.$$

At this field under fulfillment, the condition

$$\frac{\alpha_{z0}[B(P_y)]^2T_{c0}(P_y)}{\alpha_y(P_y)\beta_z\beta_{yz}} > 1, \quad (33)$$

the Curie temperature in Eq. (31) is still positive, and at

$$H_y > H_y^{cr}(P_y)$$

the phase transition from a paramagnetic to a ferromagnetic state becomes a first-order transition (see Fig. 9 in Ref. [2]). The point $[H_y^{cr},T_c(H_y^{cr})]$ on the paramagnet-ferromagnet phase transition line is a tricritical point. The pressure dependence

$$H_y^{cr}(P_y) \propto \frac{\left(1 - \frac{|A_y|}{\alpha_y}P_y\right)^{3/2}}{B(P_y)} \quad (34)$$

roughly corresponds to the observed experimental [8] pressure dependence $H_R(P_y)$. A uniaxial pressure enhancement decreases the field of the first-order phase transition from a ferromagnetic to a paramagnetic state.

The minimization of the free energy in Eq. (27) gives the value of the order parameter in the ferromagnetic state,

$$M_z^2 = \frac{1}{3\tilde{\delta}_z}\left[-\tilde{\beta}_z + \sqrt{\tilde{\beta}_z^2 - 3\tilde{\alpha}_z\tilde{\delta}_z}\right]. \quad (35)$$

The minimization of free energy in the paramagnetic state,

$$F_{\text{para}} = \alpha_y(P_y)M_y^2 - H_yM_y, \quad (36)$$

with respect to M_y gives the equilibrium value of magnetization projection on the y axis in the paramagnetic state,

$$M_y = \frac{H_y}{2\alpha_y(P_y)}. \quad (37)$$

Substitution back into Eq. (36) yields the equilibrium value of free energy in the paramagnetic state,

$$F_{\text{para}} = -\frac{H_y^2}{4\alpha_y(P_y)}. \quad (38)$$

On the first-order phase transition line from the paramagnetic to ferromagnetic state determined by the equations [12]

$$F_M = F_{\text{para}}, \quad \frac{\partial F_M}{\partial M_z} = 0, \quad (39)$$

the order parameter M_z jumps (see Fig. 10 in the Ref. [2]) from

$$M_z^{\star 2} = -\frac{\tilde{\beta}_z}{2\tilde{\delta}_z} \quad (40)$$

in the ferromagnetic state to zero in the paramagnetic state. Its substitution back into the equation $F_M = F_{\text{para}}$ gives the equation of the first-order transition line,

$$4\tilde{\alpha}_z\tilde{\delta}_z = \tilde{\beta}_z^2, \quad (41)$$

that is,

$$T^\star = T^\star(H_y) = T_{c0} - \frac{\beta_{yz}H_y^2}{4\alpha_{z0}[\alpha_y(P_y)]^2} + \frac{\tilde{\beta}_z^2}{4\alpha_{z0}\tilde{\delta}_z}. \quad (42)$$

The corresponding jump of M_y (see Fig. 10 in Ref. [1]) is given by

$$M_y^\star = M_y^{\text{ferro}} - M_y^{\text{para}}$$
$$= \frac{H_y}{2\left[\alpha_y(P_y) + \beta_{yz}M_z^{\star 2} + +\delta_{yz}M_z^{\star 4}\right]} - \frac{H_y}{2\alpha_y(P_y)}. \quad (43)$$

V. CONCLUDING REMARKS

We have shown that both the Curie and the superconducting critical temperature are changed when pressure is applied to a URhGe specimen. The functional pressure dependencies can be established from general phenomenological considerations. However, the direction of the changes must be chosen by comparison with the experimental findings according to which uniaxial in the b direction and hydrostatic pressure act in the opposite sense: The first suppresses ferromagnetism and enhances superconductivity, and the second stimulates ferromagnetism and suppresses the superconducting state. The phenomenological approach allows us to point out two mechanisms of the increase in the superconducting temperature. They originate from stimulation by the uniaxial stress of both the intraband and interband amplitudes of triplet Cooper pairing.

The magnetic field in the b direction decreases the Curie temperature and leads to the transformation of the ferro-para phase transition from the second to the first order. The pairing interaction in the vicinity of the first-order transition from the ferromagnetic to paramagnetic state caused by field H_y is strongly increased in comparison to its zero-field value. This effect proves to be stronger than the orbital suppression of superconductivity by a magnetic field and leads to the reappearance of the superconducting state at a field of the order 10 T. Here, we have demonstrated that in the presence of a uniaxial pressure along the b axis, the process of the suppression of ferromagnetism by a magnetic field occurs much faster. The field-induced transformation of the second- to the first-order ferro-para phase transition occurs at much lower field $H_y^{cr}(P_y)$ values. The effect is so strong that even small uniaxial stress causes the coalescence [8] of superconducting and the reentrantant superconducting area in the (H_y,T) phase diagram shown in Fig. 1.

The shape of the superconducting region drawn in Fig. 1(b) looks similar to the upper critical field temperature dependence $H_{c2}^b(T)$ in the other ferromagnetic superconductor UCoGe. Unlike URhGe, the hydrostatic pressure applied to UCoGe suppresses ferromagnetism and stimulates superconductivity [1]. This allows us to speculate that in the case of UCoGe a uniaxial pressure applied along the b axis can transform the S−shaped $H_{c2}^b(T)$ curve in two separate superconducting and reentrant superconducting regions as it is in URhGe in the absence of uniaxial pressure.

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APPENDIX

The explicit expressions for A_z and A_y coefficients through the elastic and magnetoelastic moduli are

$$A_z = p_x(b_1 + B_1) + p_y(b_2 + B_2) + p_z(b_3 + B_3), \tag{A1}$$

$$A_y = q_x(b_1 + B_1) + q_y(b_2 + B_2) + q_z(b_3 + B_3), \tag{A2}$$

$$\begin{aligned} B_1 &= \lambda_x a_1 b_1 + \lambda_y a_2 b_2 + \lambda_z a_3 b_3 + \lambda_{xy}(a_1 b_2 + a_2 b_1) + \lambda_{xz}(a_1 b_3 + a_3 b_1) + \lambda_{yz}(a_2 b_3 + a_3 b_2),\\ B_2 &= \lambda_x b_1^2 + \lambda_y b_2^2 + \lambda_z b_3^2 + 2\lambda_{xy} b_1 b_2 + 2\lambda_{xz} b_1 b_3 + 2\lambda_{yz} b_2 b_3,\\ B_3 &= \lambda_x b_1 c_1 + \lambda_y b_2 c_2 + \lambda_z b_3 c_3 + \lambda_{xy}(b_1 c_2 + b_2 c_1) + \lambda_{xz}(b_1 c_3 + b_3 c_1) + \lambda_{yz}(b_2 c_3 + b_3 c_2), \end{aligned} \tag{A3}$$

and

$$\begin{aligned} a_1 &= D^{-1}\left(\lambda_{yz}^2 - \lambda_y\lambda_z\right), \quad a_2 = D^{-1}(\lambda_{xy}\lambda_z - \lambda_{xz}\lambda_{yz}), \quad a_3 = D^{-1}(\lambda_y\lambda_{xz} - \lambda_{xy}\lambda_{yz}),\\ b_1 &= D^{-1}(\lambda_{xy}\lambda_z - \lambda_{yz}\lambda_{xz}), \quad b_2 = D^{-1}\left(\lambda_{xz}^2 - \lambda_x\lambda_z\right), \quad b_3 = D^{-1}(\lambda_x\lambda_{yz} - \lambda_{xz}\lambda_{xy}), \end{aligned} \tag{A4}$$

$$\begin{aligned} c_1 &= D^{-1}(\lambda_y\lambda_{xz} - \lambda_{xy}\lambda_{yz}), \quad c_2 = D^{-1}(\lambda_x\lambda_{yz} - \lambda_{xy}\lambda_{xz}), \quad c_3 = D^{-1}\left(\lambda_{xy}^2 - \lambda_x\lambda_y\right),\\ D &= \lambda_x\lambda_y\lambda_z + 2\lambda_{xz}\lambda_{xy}\lambda_{yz} - \lambda_{xz}^2\lambda_y - \lambda_{yz}^2\lambda_x - \lambda_{xy}^2\lambda_z. \end{aligned} \tag{A5}$$

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