

MEAN-FIELD THEORY

The mean-field Nambu-Gor'kov Hamiltonian is

$$H = \frac{1}{2} \iint d^3\mathbf{r} d^3\mathbf{r}' \hat{\Psi}^\dagger(\mathbf{r}') \begin{pmatrix} \xi(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}')\hat{1} & \hat{\Delta}(\mathbf{r},\mathbf{r}') \\ \hat{\Delta}^\dagger(\mathbf{r},\mathbf{r}') & -\xi(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}')\hat{1} \end{pmatrix} \hat{\Psi}(\mathbf{r}) \quad (1)$$

$$\equiv \frac{1}{2} \iint d^3\mathbf{r} d^3\mathbf{r}' \hat{\Psi}^\dagger(\mathbf{r}') \hat{\tau}_3 \left(\xi(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}') + \hat{\Delta}(\mathbf{r},\mathbf{r}') \right) \hat{\Psi}(\mathbf{r}). \quad (2)$$

where

$$\hat{\Delta}(\mathbf{r},\mathbf{r}') = \begin{pmatrix} 0 & \hat{\Delta}(\mathbf{r},\mathbf{r}') \\ -\hat{\Delta}^\dagger(\mathbf{r},\mathbf{r}') & 0 \end{pmatrix} \quad (3)$$

When the system is homogeneous, the two-point gap function only depends on the relative coordinate, i.e., $\hat{\Delta}(\mathbf{r},\mathbf{r}') = \hat{\Delta}(\mathbf{r}-\mathbf{r}')$. In this case, we can transform to momentum space, and the Hamiltonian becomes

$$H = \frac{1}{2} \sum_{\mathbf{p}} \hat{\Psi}_{\mathbf{p}}^\dagger \hat{\tau}_3 (\xi_{\mathbf{p}} + \hat{\Delta}(\mathbf{p})) \hat{\Psi}_{\mathbf{p}}. \quad (4)$$

where $\hat{\Psi}_{\mathbf{p}}^\dagger = (c_{\mathbf{p}\uparrow}^\dagger, c_{\mathbf{p}\downarrow}^\dagger, c_{-\mathbf{p}\uparrow}, c_{-\mathbf{p}\downarrow})$.

FINITE TEMPERATURE

The imaginary time Green's function is

$$\hat{G}(x, x') = - \left\langle T_\tau \hat{\Psi}(x) \hat{\Psi}^\dagger(x') \right\rangle. \quad (5)$$

where $x = (\mathbf{r}, \tau)$. The unperturbed Matsubara Green's function is

$$\hat{G}_0(\mathbf{p}, i\epsilon_n) = (i\epsilon_n - \hat{\tau}_3 \xi_{\mathbf{p}})^{-1} = - \frac{i\epsilon_n + \hat{\tau}_3 \xi_{\mathbf{p}}}{\epsilon_n^2 + \xi_{\mathbf{p}}^2}. \quad (6)$$

The Gorkov Green's function satisfies

$$\hat{G}^{-1}(\mathbf{p}, i\epsilon_n) = \hat{G}_0^{-1}(\mathbf{p}, i\epsilon_n) - \hat{\tau}_3 \hat{\Delta}(\mathbf{p}) = i\epsilon_n - \hat{\tau}_3 \xi_{\mathbf{p}} - \hat{\tau}_3 \hat{\Delta}(\mathbf{p}). \quad (7)$$

which gives

$$\hat{G}(\mathbf{p}, i\epsilon_n) = - \frac{i\epsilon_n + \hat{\tau}_3 \xi_{\mathbf{p}} + \hat{\tau}_3 \hat{\Delta}(\mathbf{p})}{\epsilon_n^2 + \xi_{\mathbf{p}}^2 + |\Delta|^2} \quad (8)$$

The quasiclassical Green's function is

$$\hat{g}(\mathbf{p}, i\epsilon_n) = \int d\xi_p \hat{G}(\mathbf{p}, i\epsilon_n) \hat{\tau}_3 = -\pi \frac{i\epsilon_n \hat{\tau}_3 - \hat{\Delta}(\mathbf{p})}{\sqrt{|\Delta|^2 + \epsilon_n^2}} = \frac{\pi}{\sqrt{|\Delta|^2 + \epsilon_n^2}} \begin{pmatrix} -i\epsilon_n & \hat{\Delta} \\ -\hat{\Delta}^\dagger & i\epsilon_n \end{pmatrix} \equiv \begin{pmatrix} \hat{g} & \hat{f} \\ -\hat{f}^\dagger & -\hat{g} \end{pmatrix} \quad (9)$$

and it satisfies the normalization condition

$$\hat{g}(\mathbf{p}, i\epsilon_n)^2 = -\pi^2 \hat{1}. \quad (10)$$

The bulk quasiclassical Green's function satisfies

$$\left[i\epsilon_n \hat{\tau}_3 - \hat{\Delta}, \hat{g} \right] = 0 \quad (11)$$

But when near the boundary or impurities, the quasiclassical Green's function $\hat{g}(\mathbf{r}, \mathbf{p}; \epsilon)$ and the gap function $\hat{\Delta}(\mathbf{r}, \mathbf{p})$ are inhomogeneous, and are described by the Eilenberger equation and gap equation.

$$\left[\epsilon \hat{\tau}_3 - \hat{\Delta}(\mathbf{r}, \mathbf{p}), \hat{g}(\mathbf{r}, \mathbf{p}; \epsilon) \right] + i\hbar \mathbf{v}_p \cdot \nabla \hat{g}(\mathbf{r}, \mathbf{p}; \epsilon) = 0 \quad (12)$$

and

$$\hat{\Delta}(\mathbf{r}, \mathbf{p}) = \left\langle v(\mathbf{p}, \mathbf{p}') T \sum_{\epsilon_n = -\omega_c}^{\omega_c} \hat{f}(\mathbf{r}, \mathbf{p}', \epsilon_n) \right\rangle_{p'} \quad (13)$$

³He-A

For ³He-A, the spin structure is $\hat{\mathbf{d}} \cdot (i\vec{\sigma}\hat{\sigma}_y) = \hat{\sigma}_x$, and we have two components of the gap function,

$$\hat{\Delta}(\mathbf{r}, \mathbf{p}) = \hat{\sigma}_x (\Delta_1(\mathbf{r}) p_x + \Delta_2(\mathbf{r}) p_y) \quad (14)$$

In bulk we have $\hat{\Delta}(\mathbf{r}, \mathbf{p}) = \hat{\sigma}_x \Delta(p_x + ip_y)$.

S-WAVE PAIRING

For s-wave pairing, the spin structure is $i\hat{\sigma}_y$, and we have

$$\hat{\Delta}(\mathbf{r}, \mathbf{p}) = i\hat{\sigma}_y \Delta(\mathbf{r}) \quad (15)$$

In bulk we have $\hat{\Delta}(\mathbf{r}, \mathbf{p}) = i\hat{\sigma}_y \Delta$.

EDGE GAP PROFILE

We assume translational invariance along the edge, i.e. the y direction. We also assume the gap to be real(imaginary) along the $p_x(p_y)$ direction.

$$\hat{\Delta}(x, \mathbf{p}) = \hat{\sigma}_x(\Delta_1(x)p_x + i\Delta_2(x)p_y) \quad (16)$$

Here $\Delta_1(x)$ and $\Delta_2(x)$ are real functions, and we have

$$\hat{\Delta}(\mathbf{r}, \mathbf{p}) = \begin{pmatrix} 0 & \hat{\sigma}_x(\Delta_1(x)p_x + i\Delta_2(x)p_y) \\ -\hat{\sigma}_x(\Delta_1(x)p_x - i\Delta_2(x)p_y) & 0 \end{pmatrix} \quad (17)$$

$$= i\hat{\sigma}_x(\Delta_2p_y\hat{\tau}_1 + \Delta_1p_x\hat{\tau}_2) \quad (18)$$

We can also write the anomalous Green's function as

$$\hat{f}(\mathbf{r}, \mathbf{p}, \epsilon_n) = \hat{\sigma}_x \left(f_1(\mathbf{r}, \mathbf{p}, \epsilon_n) + if_2(\mathbf{r}, \mathbf{p}, \epsilon_n) \right) \quad (19)$$

and we have

$$\hat{g}(\mathbf{r}, \mathbf{p}, \epsilon_n) = \hat{g}\hat{\tau}_3 + i\hat{\sigma}_x(f_2\hat{\tau}_1 + f_1\hat{\tau}_2) \quad (20)$$

NUMERICAL SOLUTION

The $(1, 1)$ and $(1, 2)$ elements of the Eilenberger equation are

$$i\epsilon_n\hat{g} + \hat{\Delta}\hat{f}^\dagger + i\hbar\mathbf{v}_p \cdot \nabla\hat{g} = 0 \quad (21)$$

$$i\epsilon_n\hat{f} + \hat{\Delta}\hat{g} + i\hbar\mathbf{v}_p \cdot \nabla\hat{f} = 0 \quad (22)$$

Note that $\hat{\Delta}$ and \hat{f} has the same spin structure, so we can substitute in \hat{g} and \hat{f} , divide by T_c , and we get

$$i(2n+1)\pi tg(\mathbf{r}, \hat{\mathbf{p}}, n) + \delta(\mathbf{r}, \hat{\mathbf{p}})f^*(\mathbf{r}, \hat{\mathbf{p}}, n) + i(\hat{\mathbf{p}}_x\partial_x + \hat{\mathbf{p}}_y\partial_y)g(\mathbf{r}, \hat{\mathbf{p}}, n) = 0 \quad (23)$$

$$i(2n+1)\pi tf(\mathbf{r}, \hat{\mathbf{p}}, n) + \delta(\mathbf{r}, \hat{\mathbf{p}})g(\mathbf{r}, \hat{\mathbf{p}}, n) + i(\hat{\mathbf{p}}_x\partial_x + \hat{\mathbf{p}}_y\partial_y)f(\mathbf{r}, \hat{\mathbf{p}}, n) = 0 \quad (24)$$

where $t = T/T_c$, $\delta = \Delta/T_c$, $\xi = \hbar v_f/T_c$ and $\vec{\partial} = \xi\nabla$.

For the gap equation, we ...

$$\delta = \quad (25)$$

We first assume an initial guess for the gap function $\delta(\mathbf{r}, \hat{\mathbf{p}})$. For each trajectory $\hat{\mathbf{p}}$ along which the quasiparticle propagates, we can solve the Eilenberger equation to get the Green's function $g(\mathbf{r}, \hat{\mathbf{p}}, n)$ and the anomalous Green's function $f(\mathbf{r}, \hat{\mathbf{p}}, n)$. Then we iterate to update the gap function $\delta(\mathbf{r}, \hat{\mathbf{p}})$ by solving the gap equation. Repeat until convergence.