Functional Bosonization of Interacting Fermions in Arbitrary Dimensions

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We bosonize the long-wavelength excitations of interacting fermions in arbitrary dimension by directly applying a suitable Hubbard-Stratonovich transformation to the Grassmannian generating functional of the fermionic correlation functions. With this technique we derive a surprisingly simple expression for the single-particle Greens-function, which is valid for arbitrary interaction strength and can describe Fermi- as well as Luttinger liquids. Our approach sheds further light on the relation between bosonization and the random-phase approximation, and enables us to study screening in a nonperturbative way.

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Several groups [1–4] have recently constructed bosonization rules for interacting fermions in dimensions $d > 1$. The strategy adopted in these works follows closely the usual bosonization of one-dimensional systems [5], and is based on the observation that suitably defined local density operators approximately obey bosonic commutation relations in the Hilbert space of states with wave-vectors close to the Fermi surface. An alternative method to bosonize interacting fermions without calculating commutators is based on functional integration [6,7]. In this letter we shall further develop this approach, and show that it is in many respects more powerful than the usual operator bosonization.

Consider a system of interacting fermions on a d-dimensional hypercube with volume $\mathcal{V}$. The hamiltonian is given by $\hat{H} = \hat{H}_0 + \hat{H}_{int}$, with $\hat{H}_0 = \sum_{\mathbf{k}} \epsilon_{\mathbf{k}} \hat{c}_{\mathbf{k}}^\dagger \hat{c}_{\mathbf{k}}$ and $\hat{H}_{int} = \frac{1}{2\mathcal{V}} \sum_{\mathbf{q} \mathbf{k} \mathbf{k}'} f_{\mathbf{q}}^{\mathbf{k}\mathbf{k}'} \hat{c}_{\mathbf{k}+\mathbf{q}}^\dagger \hat{c}_{\mathbf{k}'-\mathbf{q}}^\dagger \hat{c}_{\mathbf{k}'} \hat{c}_{\mathbf{k}}$, where $\hat{c}_{\mathbf{k}}$ annihilates an electron with wave-vector $\mathbf{k}$, and $\epsilon_{\mathbf{k}}$ is some arbitrary energy dispersion [8]. We assume that the degrees of freedom far away from the Fermi surface have been integrated out, so that $\mathbf{k}$ and $\mathbf{k}'$ are restricted to a shell around the Fermi surface, with radial thickness small compared with the Fermi wave-vector k_F. Thus, $f_{\mathbf{q}}^{\mathbf{k}\mathbf{k}'}$ and $\epsilon_{\mathbf{k}}$ differ from the bare parameters by finite renormalizations. Following Refs. [1–4], we partition the Fermi surface into disjoint patches of volume Λ^{d-1}. The precise shape of the patches is irrelevant as long as we are interested in fluctuations with wave-vectors $|\mathbf{q}| \ll \Lambda$, and the interaction $f_{\mathbf{q}}^{\mathbf{k}\mathbf{k}'}$ is dominated by momentum transfers $|\mathbf{q}| \ll k_F$. Throughout this work we shall assume that these restrictions are satisfied. Let us introduce a label α to enumerate the patches in some arbitrary ordering, and denote by K^α the set of $\mathbf{k}$-points in patch α. For each α we define local density operators

$\hat{\rho}_{\mathbf{q}}^\alpha = \sum_{\mathbf{k}} \Theta^\alpha(\mathbf{k}) \hat{c}_{\mathbf{k}}^\dagger \hat{c}_{\mathbf{k}+\mathbf{q}}$, where $\Theta^\alpha(\mathbf{k}) = 1$ if $\mathbf{k} \in K^\alpha$, and zero otherwise. Assuming that the variations of $f_{\mathbf{q}}^{\mathbf{k}\mathbf{k}'}$ are negligible if $\mathbf{k}$ and $\mathbf{k}'$ are restricted to given patches, we may introduce the coarse-grained interaction function $f_{\mathbf{q}}^{\alpha\alpha'} = \ll \Theta^\alpha(\mathbf{k}) \Theta^{\alpha'}(\mathbf{k}') f_{\mathbf{q}}^{\mathbf{k}\mathbf{k}'} \gg$ where $\ll \ldots \gg$ denotes averaging with respect to $\mathbf{k}$ and $\mathbf{k}'$.

To bosonize $\hat{H}$, we consider the imaginary-time correlation function

$$\Pi_{\mathbf{q}}^{\alpha\alpha'} = \frac{1}{\mathcal{V}} \int_0^\beta d\tau e^{-i\omega_m \tau} < \hat{\rho}_{\mathbf{q}}^\alpha(\tau) \hat{\rho}_{-\mathbf{q}}^{\alpha'}(0) > \quad , \tag{1}$$

where $\beta = 1/T$ is the inverse temperature and $q = [\mathbf{q}, i\omega_m]$ denotes wave-vector $\mathbf{q}$ and bosonic Matsubara frequency $\omega_m = 2\pi m T$. Below it will become evident that bosonization of $\hat{H}$ is equivalent to the calculation of a functional $S_{eff}\{\rho\}$ of a complex field $\rho_{\mathbf{q}}^\alpha$, such that Eq.1 can be written as a bosonic functional integral

$$\Pi_{\mathbf{q}}^{\alpha\alpha'} = \frac{\beta}{\mathcal{V}} \frac{\int \mathcal{D}\{\rho\} \rho_{\mathbf{q}}^\alpha \rho_{-\mathbf{q}}^{\alpha'} e^{-S_{eff}\{\rho\}}}{\int \mathcal{D}\{\rho\} e^{-S_{eff}\{\rho\}}} \quad . \tag{2}$$

We now derive $S_{eff}\{\rho\}$ in arbitrary dimension. Starting point is the representation of $\Pi_{\mathbf{q}}^{\alpha\alpha'}$ as a functional integral over Grassmann fields $c_{\mathbf{k}}$ [9]

$$\Pi_{\mathbf{q}}^{\alpha\alpha'} = \frac{\beta}{\mathcal{V}} \frac{\int \mathcal{D}\{c\} R_{\mathbf{q}}^\alpha R_{-\mathbf{q}}^{\alpha'} e^{-S_1\{c\} - S_4\{c\}}}{\int \mathcal{D}\{c\} e^{-S_1\{c\} - S_4\{c\}}} \quad . \tag{3}$$

with $S_1\{c\} = \beta \sum_{\mathbf{k}} [-i\tilde{\omega}_n + \xi_{\mathbf{k}}] c_{\mathbf{k}}^\dagger c_{\mathbf{k}}$, and $S_4\{c\} = \frac{\beta}{2\mathcal{V}} \sum_{\mathbf{q}} \sum_{\alpha\alpha'} R_{-\mathbf{q}}^\alpha f_{\mathbf{q}}^{\alpha\alpha'} R_{\mathbf{q}}^{\alpha'}$. Here $\tilde{\omega}_n = \pi(2n+1)T$ are fermionic Matsubara frequencies, $\xi_{\mathbf{k}} = \epsilon_{\mathbf{k}} - \mu$ is the energy measured relative to the chemical potential μ of the interacting system, and $R_{\mathbf{q}}^\alpha = \sum_{\mathbf{k}} \Theta^\alpha(\mathbf{k}) c_{\mathbf{k}}^\dagger c_{\mathbf{k}+\mathbf{q}}$. We now decouple $S_4\{c\}$ by means of a Hubbard-Stratonovich transformation that involves two auxiliary fields $\phi_{\mathbf{q}}^\alpha$ and $\rho_{\mathbf{q}}^\alpha$ [7]. Completing squares and using the invariance of the integration measure with respect to shifts [9], it is not difficult to show that

$$e^{-S_4\{c\}} = \int \mathcal{D}\{\rho\} \mathcal{D}\{\phi\} e^{-S_2\{c,\phi\} - S_3\{\phi,\rho\} - S_{int}\{\rho\}} , \tag{4}$$

$$S_2\{c,\phi\} = \sum_{\mathbf{k}\mathbf{k}'} c_{\mathbf{k}}^\dagger V_{\mathbf{k}\mathbf{k}'} c_{\mathbf{k}'} \quad , \quad V_{\mathbf{k}\mathbf{k}'} = i \sum_\alpha \Theta^\alpha(\mathbf{k}) \phi_{\mathbf{k}-\mathbf{k}'}^\alpha \tag{5}$$

$$S_3\{\phi,\rho\} = -i \sum_{\mathbf{q}} \sum_\alpha \phi_{-\mathbf{q}}^\alpha \rho_{\mathbf{q}}^\alpha \tag{6}$$

$$S_{int}\{\rho\} = \frac{1}{2} \sum_{\mathbf{q}} \sum_{\alpha\alpha'} \rho_{-\mathbf{q}}^\alpha f_{\mathbf{q}}^{\alpha\alpha'} \rho_{\mathbf{q}}^{\alpha'} \quad , \quad f_{\mathbf{q}}^{\alpha\alpha'} = \frac{\beta}{\mathcal{V}} f_{\mathbf{q}}^{\alpha\alpha'} \quad . \tag{7}$$

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