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Covariant gaussian approximation in Ginzburg–Landau model

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HIGHLIGHTS

- A symmetry conserving approximation based on Dyson–Schwinger equations is proposed.
- The approximation keeps all the Ward Identities in a theory with continuous symmetry.
- The approximation is more accurate than other mean-field type approximations.
- The penetration depth of Ginzburg–Landau model shows a downward cusp near T_c.

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ABSTRACT

Condensed matter systems undergoing second order transition away from the critical fluctuation region are usually described sufficiently well by the mean field approximation. The critical fluctuation region, determined by the Ginzburg criterion, $|T/T_c - 1| \ll Gi$, is narrow even in high T_c superconductors and has universal features well captured by the renormalization group method. However recent experiments on magnetization, conductivity and Nernst effect suggest that fluctuations effects are large in a wider region both above and below T_c. In particular some "pseudogap" phenomena and strong renormalization of the mean field critical temperature T_{mf} can be interpreted as strong fluctuations effects that are nonperturbative (cannot be accounted for by "gaussian fluctuations"). The physics in a broader region therefore requires more accurate approach. Self consistent methods are generally "non-conserving" in the sense that the Ward identities are not obeyed. This is especially detrimental in the symmetry

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broken phase where, for example, Goldstone bosons become massive. Covariant gaussian approximation remedies these problems. The Green's functions obey all the Ward identities and describe the fluctuations much better. The results for the order parameter correlator and magnetic penetration depth of the Ginzburg–Landau model of superconductivity are compared with both Monte Carlo simulations and experiments in high T_c cuprates.
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1. Introduction

Many-body systems at nonzero temperature exhibit a host of physical phenomena triggered by strong thermal fluctuations [1]. Most remarkable are of course phase transitions, in which the ground state rearranges. In addition, crossovers and qualitatively recognizable phenomena, such as metastability or possibly the "pseudogap" physics in high T_c cuprates, also attract intensive interest. It was noticed by Landau that for temperatures close to critical point of a second order transition, symmetry and energetics considerations suggest that the system can be described by a rather simple universal Ginzburg–Landau (GL) model. The model expressed in terms of an appropriate order parameter field ϕ contains a very small number of phenomenological parameters, since one retains only terms up to fourth power of ϕ in the GL free energy (on the condition that it is well separated from the tricritical point where the sixth order of ϕ cannot be neglected).

The universality was established in the critical fluctuation region, where physics is determined by several critical exponents well captured by the renormalization group approach to the GL ϕ^4 theory [2]. However the critical region is usually very narrow even in the most fluctuating materials like the high temperature superconductors. In fact, the width of critical region for an anisotropic 3D superconductor can be evaluated by the following Ginzburg criterion [3,4],

$$|T/T_c - 1| \ll Gi \equiv 2\left(\frac{4\pi^2 T_c \kappa^2 \xi \gamma}{\Phi_0^2}\right)^2, \tag{1}$$

where $\kappa = \lambda/\xi$ is the ratio of magnetic penetration depth (see details in Section 5.1) over the superconducting coherence length, and the anisotropy parameter $\gamma = \xi/\xi_c$ is the ratio between coherence length in the ab-plane and along the c-axis. $\Phi_0 = hc/e^*$ is the unit of magnetic flux. The dimensionless Ginzburg number Gi is of order 10^{-6} or smaller in low T_c superconductors. Though much larger in high T_c materials, it is still typically less than 0.1. Away from the critical fluctuation region, the universality might not hold. One thus traditionally resorts to a variety of mean field or self-consistent models. These models focus on different degrees of freedom, and so a statistical system is often represented in several different ways depending on the choice of the quantity that is considered self-consistently. Examples of self-consistent approaches range from the Bragg–Williams approximation for spin systems to the BCS approximation of conventional superconductors and the Hartree–Fock approximation in the electron gas or liquid. Thus the mean field approach is essentially different from the economic GL description in terms of the order parameter field ϕ defined solely by the symmetry properties of the system. A question arises whether the GL model can nevertheless be reliable away from its intended range of applicability near the criticality.

The GL approach in terms of the order parameter however is in fact widely and successfully used for description of the fluctuations outside the critical region [4]. There are several arguments why actually one can use the universal model beyond its original range of applicability [1,3,5]. Very often the fluctuations are accounted for by the gaussian fluctuations approximation to the GL model [6]. This completely neglects the ϕ^4 coupling of the order parameter that sometimes is included perturbatively [3]. Various approximations beyond perturbation theory were developed.

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