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Advancing Thermal Field Theory: NLO Calculations for Finite Size Systems

Understanding the behavior of matter under extreme conditions is one of the key goals of high-energy physics. In particular, the study of the quark-gluon plasma (QGP) offers insights into the early universe and the dynamics of strongly interacting matter. A powerful way to study such systems in thermal equilibrium is through the thermal partition function, which encodes the statistical properties of a quantum field theory at finite temperature. This formalism is often called Thermal Field Theory, and it will be the topic of my talk. Specifically, I would discuss the next-to-leading order finite-size corrections to the partition function in ϕ^4 theory.

In order to compute the partition function from first principles, we begin in the Hamiltonian operator formalism and move toward a path integral representation. A crucial step in this transition involves coherent states, which form a natural basis for extracting information about quantum fields. These states are particularly useful when computing the trace in the partition function, as they allow us to capture the field configurations involved in the system's dynamics. Their algebraic properties, particularly the eigenstate property of the annihilation operators, make them especially effective for deriving the path integral in a controlled way.

$$Z = Tr[e^{-\beta H}] = \int D\phi \, e^{-\frac{1}{2}\int_0^\beta d\tau \int d^n\mathbf{x}\left[\dot{\phi}^2+(\nabla\phi)^2+m^2\phi^2\right]}$$

Working in imaginary time and employing periodic boundary conditions in the temporal direction naturally leads to the Matsubara formalism. This framework allows us to express field configurations as discrete Fourier series in terms of Matsubara frequencies. Once this setup is in place, the path integral can be explicitly computed in the free theory, yielding a compact and elegant form of the partition function from which thermodynamic quantities such as the free energy and the pressure can be extracted.

$$Z = C\frac{T}{m}\prod\nolimits'_m \frac{\omega_\ell^2}{(\omega_\ell^2+E_{\mathbf{pm}}^2)}$$

$$f = \frac{F}{V} = -\frac{T}{V}\ln Z, \qquad P = \frac{\partial(T\ln Z)}{\partial V}.$$

We then consider the extension to interacting theories, where the presence of interaction terms complicates the structure of the path integral and the use of coherent states as a bridge from operators to classical field configurations. The coherent state techniques must be treated with care, especially since time evolution is now governed by the full Hamiltonian and not just the free part. The interaction picture becomes essential, but its use in imaginary time raises subtle issues, particularly in how time ordering and commutators behave in the thermal trace. These complications are closely related to the need for more sophisticated contour prescriptions in the complex time plane. The appropriate prescription is the Schwinger-Keldysh contour, which is necessary when studying real-time dynamics in combination with thermal processes.

Through this careful computation, we have found additional correction terms to the path integral representation of the partition function that do not appear in existing literature. As a preview, we show the current result of the discretized finite path integral interacting partition function including these corrections:

$$Z = \int D\phi \, e^{-\frac{1}{2}\int_0^\beta d\tau \int d^n\mathbf{x}\left[\dot{\phi}^2+(\nabla\phi)^2+(m^2+\frac{\lambda}{4!}\langle 0|\hat{\phi}^2|0\rangle)\phi^2+\frac{\lambda}{4!}\phi^4+\frac{\lambda}{4!}\langle 0|\hat{\phi}^4|0\rangle\right]}$$

The precise interpretation of these corrections is still under investigation, but they may have important implications for how interacting thermal systems are treated beyond the leading order. By the time of the conference, I expect to have resolved the origin of these terms and to have explicitly evaluated the path integral for the fully interacting theory. I may already be able to present preliminary results on the renormalized computation of next-to-leading order finite-size corrections to the pressure.

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