UNIVERSITI PUTRA MALAYSIA

REAL-TIME THERMAL FIELD THEORY AND ITS APPLICATIONS

MOHAMMED ABDULMALEK ABDULRAHEEM AHMED

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia,
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DEDICATIONS

I would like to dedicate this thesis
...to the soul of my beloved mother who had dreamed about this day
&
...to my beloved father, my wonderful wife,
my daughter Lojain and my son Abdulmalek
with my love

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment
of the requirement for the degree of Doctor of Philosophy

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MOHAMMED ABDULMALEK ABDULRAHEEM AHMED

June 2022

Chairman: Hishamuddin Bin Zainuddin, PhD
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The many-body physics in physics require the use of Thermal Field Theory (TFT) or statistical field theory methods. TFT can describe a large ensemble of interacting particles in a thermodynamic environment. However, it will involve the use of path integral techniques, the ability to calculate for abelian interactions like quantum electrodynamics (QED) and non-abelian interactions like quantum chromodynamics (QCD). The first success of TFT was an understanding and quantitative study of phase transitions (or phase changes) of the matter within quantum field theory (QFT). There are two formalisms of TFT or QFT at finite temperature in Real Time. Real Time Formalism (RTF) is fully consistent with some suitable changes in the structure of the Bogoliubov transformation (BT). In the complex t plane, there is a one-parameter family of paths within RTF. This parameter is σ, which manifests in the Feynman rules for two popular choices of propagators, and they are $\sigma = 0, 1/2$. The first choice for the path is a closed contour when $\sigma = 0$, which explains why the associated formalism is known as closed-time path (CTP) formalism. The second choice for path parameter σ reproduces the Feynman rules of an operatorial approach to quantum thermal field theory known as ThermoField Dynamics (TFD) in which this parameter equals to $1/2$. The propagator was given in the momentum space, but it is also appropriate to work in the mixed coordinates where the Green's functions are defined as functions of the time coordinate and the spatial momentum. The propagator in mixed space showed that there is an unexpected simple relation between any temperature dependent $T \neq 0$ graph and its temperature independent $T = 0$ counterpart, through a multiplicative scalar operator which carried the entire temperature dependence. In RTF, we usually use Boltzmann-Gibbs (BG) statistics to study the condensed matter phenomena like QED plasma and QCD plasmas, the early universe including other many-body physics phenomena. In this thesis, we have shown systematically that an operator description for a theory defined in RTF with an arbitrary σ does indeed exist. Therefore, some works gathering those formalisms are given through two popular choices for contour parameter σ, i.e. $\sigma = 0$ and $1/2$ for both CTP and TFD, respectively. By analogy, the viewpoint suggests modifying Transformation Matrix by adding a new parameter λ and use the new transformation in the definition of the thermal propagator, which leads to the fermion field propagator as well to the scalar field propagator, for specific values of λ. Then, we compute the scalar propagator, and tadpole self-energies within scalar QED. However, we want to treat them in a systematic and comprehensive way when one considers these components of propagator in different bases. Thereafter, we use those components to compute the tadpole self-energies in momentum space and the mixed space (momentum-time) within RTF. Hence, we have studied explicitly the photon-photon interaction within RTF (for any value of the arbitrary parameter σ), which allows for a path integral description. Indeed, the photon interaction has an application with the cosmic microwave background (CMB) radiation. Note that the photon self-energy is the same for both approaches in RTF, in which one considers the relevant effective $2n$-photon vertex in a thermal photon gas where $n \geq 2$ at low energy within QED in both spaces. In addition, we constructed the propagator in TFD with Tsallis statistics. Next we consider two applications: the thermal photon-photon interaction within QED at low energy for scalar Tsallis thermal propagator, and the phase of e^+e^- annihilation into hadrons is considered through a single photon exchange within QCD at high temperature for fermion Tsallis thermal propagator. In addition, we have observed that a non-extensive MIT bag equation of state obtained with the help of the Tsallis distributions given. Our study is relevant to the Deconfinement Phase Transition from a Hadronic Gas (HG) to a Quark-Gluon Plasma (QGP) or Partonic Plasma (PP). We investigate the behavior of some thermodynamic quantities of the system, such as the energy density, the pressure, the interaction measure and entropy.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai
memenuhi keperluan untuk ijazah Doktor Falsafah

TEORI-MEDAN TERIMA MASA NYATA DAN APLIKASINYA

Oleh

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Masalah berbilang-jasad dalam fizik memerlukan penggunaan Teori Medan Terma (TMT) atau kaedah teori medan statistik. TMT dapat memerihal suatu ensembel besar zarah-zarah bersaling tindak dalam persekitaran termodinamik. Namun, ini melibatkan penggunaan teknik kamiran lintasan dan kebolehan untuk mengira saling tindakan abelan seperti teori elektrodinamik kuantum (EDK) dan saling tindakan tak-abelan seperti kromodinamik kuantum (KDK). Kejayaan pertama TMT adalah kefahaman dan kajian kuantitatif peralihan fasa (atau perubahan fasa) bagi jirim dalam teori medan kuantum (TMK). Terdapat dua formalisme TMT atau TMK pada suhu terhingga bagi masa nyata. Formalisme Masa Nyata (FMN) adalah konsisten sepenuhnya dengan beberapa perubahan dalam struktur matriks transformasi Bogoliubov (BT) yang dibuat. Dalam satah t kompleks, terdapat famili lintasan satu parameter dalam FMN. Parameter ini adalah σ yang tampak dalam petua Feynman bagi dua pilihan popular dalam perambat iaitu $\sigma = 0, 1/2$. Pilihan pertama lintasan adalah kontur tertutup apabila $\sigma = 0$, yang menjelaskan kenapa formalisme berkaitan dipanggil formalisme lintasan masa-tertutup (LMT). Pilihan kedua bagi parameter lintasan σ menerbit semula petua Feynman bagi pendekatan operator kepada teori medan terma yang dikenali sebagai Dinamik MedanTermo (DMT), apabila parameter bersamaan dengan $1/2$. Perambat ini diberi dalam ruang momentum, sementara itu ia turut berlaku dalam koordinat campuran apabila fungsi Green ditakrif sebagai fungsi koordinat masa dan momentum spatial. Perambat dalam ruang campuran ini menunjukkan bahawa terdapat hubungan mudah antara graf bersandar keada suhu $T \neq 0$ dengan padanan $T = 0$ yang tak bersandar kepada suhu, melalui suatu operator scalar pendaraban yang membawa keseluruhan persandaran suhunya. Dalam FMN, lazimnya kita menggunakan statistik Boltzmann-Gibbs (BG) untuk mengkaji fenomena jirim terkondensasi seperti plasma EDQ dan plasma KDK, alam semesta awal serta pelbagai fizik berbilang jasad. Dakan tesis ini, kita dapat tunjukkan secara sistematik bahawa perihalan operator bagi teori tertakrif dalam FMN dengan

sebarangan σ turut wujud. Dengan itu, beberapa kajian mengumpulkan formalisme-formalisme tersebut melalui dua pilihan popular parameter kontur σ, iaitu $\sigma = 0$ dan $1/2$ bagi masing-masing LMT dan DMT dibuat. Secara analogi, pandnagan yang disarankan adalah untuk mengubah Matriks Transformasi dengan menambah suatu parameter baharu λ dan menggunakan transformasi baharu ini dalam takrifan perambat terma yang membawa kepada perambat medan fermion dan juga perambat medan skalar bagi beberapa nilai tentu λ. Kemudian, kami kirakan perambat skalar, dan swa-tenaga gelung tunggal dalam EDK scalar, namun, kta berkehendakkan suatu pengolagan yang sistematik dan komprehensif apabila mempertimbangkan komponen-komponen kuantiti tersebut dalam asa berlainan. Sejurus itu, kita gunakan komponen tersebut untuk mengira swa-tenaga gelung tunggal dalam ruang momentum dan ruang campuran (momentum-masa) dalam FMN. Dengan itu, kita kaji secara eksplisit, saling tindakan foton-foton dalam RTF (bagi setiap nilai parameter sebarangan σ) yang membolehkan perihalan kamiran lintasan. Malahan, saling tindakan foton dalam sinaran mikrogelombang latarbelakang (SML) telah diambil sebagai suatu aplikasi. Perhatikan bahawa swa-tenaga foton adalah sama dalam kedua-dua pendekatan dalam RTF, yang mana verteks $2n$-foton relevan dalam gas foton pada tenaga rendah dalam EDK bagi kedua-dua ruang. Sebagai tambahan, kita bangunkan perambat dalam FMN bagi statistik TG. Kemudian, kita pertimbang dua aplikasi: saling tindakan foton-foton terma dalam EDK pada tenaga rendah bagi perambat terma Tsallis skalar, dan pertimbangan fasa pemusnahan e^+e^- ke hadron melalui tukar-ganti foton tunggal dalam KDK pada suhu tinggi bagi perambat terma fermion Tsallis. Sebagai tambahan, kita turut menjumpai persamaan keadaan beg MIT tak-ekstensif, diperolehi dengan bantuan taburan Tsallis. Kajian kita adalah relevan kepada Peralihan Fasa Nyahkurungan dari gas hadronic (HG) ke Plasma Quark-Gluon (PQG) atau Plasma Parton (PP). Kita turut kaji perlakuan beberapa kuantiti termodinamik sistem, seperti ketumpatan tenaga, tekanan, ukuran saling tindakan dan entropi.

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Finally, I'd want to thank everyone who contributed to the successful completion of this thesis, and I apologize for not mentioning everyone individually.

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Brief Introduction to thermal field theory

In Quantum Field Theory (QFT) at zero temperature is often assumed to ignore its computations in this level of energy. This is because, under typical conditions, thermal energy is too small to excite virtual particles; for example, at ambient temperature, $T = 273K$, thermal energy is just 25×10^{-3} eV, despite the fact that an electron's rest energy is 511 keV. However, given the incredibly high temperatures that dominate the early cosmos, their contributions cannot be ignored. This will be critical for the mechanism of particle creation. Thermal field theory will be used to investigate these contributions. To describe a Thermal Field Theory (TFT), there are two commonly used real time formalisms (RTF). The first is the Schwinger-Keldysh formalism (also known as the closed time path formalism (CTP)). Secondly, an operator formalism, called ThermoField Dynamics (TFD), was suggested by Takahashi and Umezawa. Both approaches are tailor-made for calculating Green functions (Schwinger (1961); Keldysh (1965); Takahashi and Umezawa (1996)). While the complete theory can be reconstructed from Green functions in principle, for practical and theoretical reasons, an operator formulation of *TFT* may be useful. In particular, it could illustrate why it is important to double the degrees of freedom for the real time formalism, and the standard Green's function is replaced by four Green's functions with arguments on two different parts of the corresponding integration contour represented by 2×2 matrix in both formalisms CTP and TFD. However, in contrast to TFD, there are no mutually commuting representations of the basic operator algebra. The RTF represents the propagators of fermionic and scalar bosonic fields in matrix form. So, a close comparison between the CTP and TFD can be made. We find that TFD and CTP are in many ways the same in form; in particular, the two approaches are identical in stationary situations. However, TFD and CTP are quite different in time-dependent out of equilibrium situations. The main source of this difference is that the time evolution of the density matrix itself is ignored in CTP while in TFD it is replaced by a time-dependent Bogoliubov transformation (BT). The BT constructed which connects the doubling of field degrees of freedom in the RTF of the non thermal vacuum state to the thermal vacuum in this case, leads to Green's function at finite temperature "propagator" as an expectation value in the thermal vacuum. The RTF can be applied to describe the systems in thermal equilibrium, and also on an extension to describe nonequilibrium situations. As well in RTF, the number of independent fields doubles as mentioned earlier. Instead of a single scalar field ϕ, we encounter two scalar fields, ϕ_1 and ϕ_2, called type-1 and type-2 fields, respectively. In other words, we have two types of vertex now, where each type has only fields that emerge from it and has its usual value, e.g. the four-particle vertex, fields of type-2 are not mixed with fields of type-1. Because of the anti-time ordering, the vertex involving fields of type-2 has a relative minus sign. The propagator at finite temperature is given in many works for the momentum space. In

TFT, we can use Fourier transformed to represent the propagator in the mixed space at finite temperature. Fourier transforming these elements of the propagator in the energy variable, this transformation leads to obtaining the propagator for the general contour, in the mixed space. The transformed propagator is a function of time and the spatial component of momentum. Such a (mixed space) representation is quite helpful to study some graphs at finite temperature.

In RTF, the elements of the propagator matrix are usually given in the momentum space. It is simple to check that the basic finite temperature propagator factorizes again by Fourier transforming this to mixed space. What is more impressive is that although the propagator is a matrix, each element of the matrix can be factorised by the same thermal operator (Das (2006); Das et al. (2018)). In this regard, the first element of the propagator consists of the sum of two parts; the first one is a non-thermal part, and the second is the thermal part, and the integration is taken over a real, continuous, energy p_0 with the presence of the delta function. The finite temperature contribution is trivial to obtain, thus suggesting the possibility of a "real time" perturbation theory (Kapusta and Gale (2006)). It is interesting that perturbation theory at finite temperature can be formulated directly in both RTF and ITF. The RTF will be adopted in this thesis. In RTF, we usually use the Boltzmann-Gibbs (BG) statistics to study condensed matter phenomena like hot and dense plasmas, then early universe, many-body physics and so on. As we know, the Gaussian distribution is signature of the BG statistical mechanics (Tsallis (1988)). There are, however, quasi-stationary states related to the $\mathfrak{q}$-Gaussian distributions (Tsallis (2009)). Analogous to Gaussian distribution optimize BG-equilibrium states, $\mathfrak{q}$-Gaussians can play roughly the same role in Tsallis statistics. Moreover, we can obtain BG statistics from Tsallis statistics, when the parameter $\mathfrak{q}$ goes to the unity, so we can say BG statistics is a particular instance of Tsallis statistics.

1.2 Problem Statement

One of the main issues of real time thermal field theory is the many-body physics. The problem here is to determine the thermal propagator of the system. There are various approaches to study the thermal effect. Some researchers compute the one-loop in scalar QED for the photon in the momentum space and the $1/2$ basis. On the other side, it is not easy to study the scalar propagator and the fermion propagator at finite temperature for Tsallis statistics. This motivates us to find a generalization of the thermal matrix, study the photon self-energy in the mixed space in a new basis, and construct ThermoField Dynamic with Tsallis statistics and introduce some applications. In many-body physics, the TFT has been used to describe response functions, namely the mean value of physical observables such as energy, free energy, entropy, and so on, which will be completely parallel to the TFT at zero temperature. This necessitates the development of a method for calculating physical mean values. As a result, we should employ propagators at finite temperature in RTF. In the Real Time Thermal Field Theory, there is a one-parameter family of paths in the complex

t. This parameter σ has two popular choices appearing in the Feynman rules for the elements of the propagator in momentum space (Schwinger (1961); Keldysh (1965); Takahashi and Umezawa (1996); Gozzi and Penco (2011); Das and Kalauni (2016)). To construct the thermal propagator in the mixed space we use Fourier transformed to represent the thermal propagator in the mixed Das (2006); Das et al. (2018), which is of our interest here. In our research, we are interested in the transformations matrix at finite temperature for the general path (Xu (1996)). We introduce a very convenient representation, which is constructed from linear combinations of the components of the RTF, for both scalar and fermion fields. The results are represented the propagators with the chemical potential in both spaces momentum and mixed (Lundberg and Pasechnik (2021)). We next construct the thermal scalar propagator and a tadpole self-energy in two different bases in the momentum space (Chou et al. (1985); Landsman and van Weert (1987); Smilga (1997); Ghiglieria et al. (2020)) as well as the mixed space (Das (2006); Das et al. (2018)). Then, we proceed to study the photon self-energies for effective photon vertex, e.g. the tadpole diagram of photons for the four-photon vertex within QED in one basis. In addition, there are some research has emerged that studied the TFT of the Tsallis statistics (Rahaman et al. (2021)) in real time. This is our technique to investigate the thermodynamic variables of a hot and dense system in TFD with Tsallis statistics, for which we will construct the propagator in TFD with Tsallis statistics to study the thermal photon-photon interaction within QED. We will also study the phase of e^+e^- annihilation into hadrons within QCD (Thoma (2000b); Chekerker et al. (2011)). This is relevant to the Deconfinement Phase Transition from a hadronic matter to a QGP (Bhattacharyya and Mukherjee (2020)).

1.3 Objectives of Research

This work aims to understand better the thermal effect in many-body physics governed by quantum electrodynamics and quantum chromodynamics. The real time thermal field theory is used to calculate some physical quantities describing these systems at a finite temperature, unifying in equilibrium and out of equilibrium processes due to the doubling of the degrees of freedom. This method allows us to study the interactions of scalar and fermion fields in the momentum space as well as the mixed space. Overall, the objectives of this research are as follows:

1. To generalize the thermal matrix transformation in RTF.
2. To study the thermal self energies in the momentum space as well as the mixed space for two different bases in RTF.
3. To compute the thermal self-energy of photons in the momentum space as well as the mixed space in the new basis.
4. To construct the propagator in TFD with Tsallis statistics.
5. To use TFD with TS to study the phase of e^+e^- annihilation into hadrons in QCD, and Deconfinement Phase Transition from a HG to a QGP.

1.4 Thesis Organization

The thesis comprises of nine chapters, and we briefly mention the layout of this thesis as follows.

Chapter 1 gives a brief introduction, the problem statement, and the objectives of the current research.

Chapter 2 includes an overview of relevant literature

Chapter 3 contains some definitions and relevant background information related to the research conducted and the method applied.

Chapter 4 gives transformations matrix at finite-temperature in RTF with an arbitrary parameter σ. The thermal propagator is presented for both scalar and fermion fields with the chemical potential in both momentum and mixed spaces.

Chapter 5 introduces a systematic study for studying the scalar propagator and tadpole self-energy by considering an arbitrary parameter σ that allows for a path integral description in RTF. Next, the scalar propagator and a tadpole self-energy are constructed in two different bases in the momentum space and the mixed space.

Chapter 6 we used the effective Lagrangian at a low temperature to study photon-photon interaction in RTF with an arbitrary path σ within the new basis. The thermal scalar propagator in the mixed space without chemical potential is introduced. We then calculate some electromagnetic properties, such as dielectric tensor and velocity of light from photon self-energy in the mixed space.

Chapter 7 presents the thermal propagator in ThermoField Dynamic with Tsallis statistics for scalar field and fermion field. We then study two applications: the first one in QED at low temperature and the second in QCD at high temperature.

Chapter 8 we give the distribution of particle in ThermoField Dynamic of the Tsallis statistics for scalar field and fermion field to study the Deconfinement Phase Transition from a HG to a QGP. We investigate the behaviour of some thermodynamic quantities of the system, such as the energy density, the pressure and the interaction measure, etc.

Chapter 9 provides the conclusion of this work. We also make a few suggestions here for future works.

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