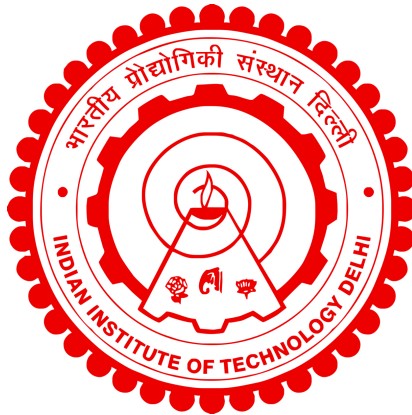


SPECTRAL FUNCTIONS OF HADRONS IN HOT AND DENSE MATTER

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DEPARTMENT OF PHYSICS

INDIAN INSTITUTE OF TECHNOLOGY DELHI

APRIL 2024

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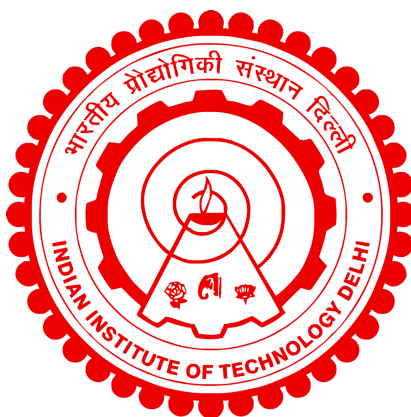
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Submitted

in fulfillment of the requirements of the degree of Doctor of Philosophy

to the



Indian Institute of Technology Delhi

April 2024

Dedicated to my Mother, Brother, Mama and my Family

Certificate

This is to certify that the thesis entitled “**Spectral Functions of Hadrons in Hot and Dense Matter**”, submitted by **Pallabi Parui** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in Physics, is a record of the original, bona fide research work carried out by her under my supervision and guidance. The thesis has reached the standards fulfilling the requirements of the regulations related to the award of the degree.

The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma to the best of my knowledge.

Prof. Amruta Mishra

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Date:

Acknowledgements

I want to sincerely acknowledge the motivation and guidance from my supervisor, Prof. Amruta Mishra, towards my entire Ph.D. journey. My first direct exposure to the fields started through her taught courses at IIT Delhi during my master's program. The endeavor towards this whole five-and-a-half-year process contributes significantly to how I perceive and observe things both in and out of the field. This has made me say that the chapter I started at this Institute seven years back is completed now in terms of maturity, the ability to work in an academic environment, the improved way of learning, and perceiving things that matter to my subject as well as life.

I am grateful to all of my SRC members: Prof. Santanu Ghosh, Prof. V. Ravishankar and Prof. Anima Nagar for their important suggestions and comments on improving the learning process I have gone through during my Ph.D. The group discussions I participated in with my lab mates, Amal Jahan C.S., Sourodeep De, Ankit Kumar, Arpita Mondal, and Manju Soni, during this period certainly opened up new directions of thoughts in pursuing the work. Most importantly, my friends inside and outside the campus provide me with that free space to cater to my emotions, feelings, and perception towards a better self, and I am genuinely grateful for that. This campus, its environment, and the freedom I have to cultivate and nurture my habits and thoughts will always be an integral part of me; occasionally, this place boosts me up when needed. I would sincerely acknowledge the financial support I received from IIT Delhi to participate in various national and International conferences during my Ph.D., and the assistance of academic and non-academic staffs throughout the journey.

In the end, like a pillar, it is my family with many names to write down, stay beside me, support me in every possible way, and most importantly, build me up. There is a constant source of inspiration from my teachers, starting from my Primary school days till my bachelor's, who led me to pave my path in a dedicated, hard-working manner, which constantly strives me to build a personality that prioritizes the well-being of natural health and humanity above all.

Pallabi Parui

Abstract

The spectral properties of hadrons (mesons) are studied in the nuclear matter environment, at finite magnetic field for both zero and non-zero temperatures. The quantities like spectral functions, production cross-sections of the meson states can be modified due to their mass, decay widths in the produced medium. This may have important observable impacts, such as in the production and propagation of particles in the high energy heavy ion collisions. These quantities are studied for the neutral ρ and A_1 mesons in such a medium, considering the effects of inverse magnetic catalysis (IMC) and magnetic catalysis (MC). The effects of Dirac sea at finite magnetic field are emphasized on the spectral properties of the spin-one vector ρ , ω , and axial-vector A_1 mesons. Their masses are computed using the Borel transform of Quantum chromodynamics sum rules (QCDSR) followed by the finite energy sum rules. The strong hadronic decay widths are calculated using an effective interaction vertex of the initial and final state particles. The medium effects are incorporated through the QCD light quark and scalar gluon condensates, which appear in the operator product expansion side of QCDSR. For light mesons, the contributions up to dimension six scalar four-quark condensates are considered. The condensates are connected to the scalar fields in chiral $SU(3)$ model. At finite magnetic field, the contributions of protons' Landau quantization, anomalous magnetic moments (AMMs) of the nucleons, and the magnetized Dirac sea are incorporated into the scalar densities of the nucleons. The effects of temperature is incorporated via Fermi distribution functions into the scalar and number densities of the nucleons. There are observed to be important spectral modifications of peak shifting and width broadening of the neutral mesons spectral functions due to the phenomena of IMC and MC. The vectorial spectral function has direct experimental connection to the dilepton invariant mass spectrum in heavy ion collisions. The heavy quarkonia ($\bar{Q}Q$; $Q = c, b$) produce at the early stages of heavy-ion collisions, during which the strength of the produced magnetic field can still be large in the case of peripheral collisions. The masses of $1S$ - and $1P$ - wave states of charmonia ($1S$: vector J/ψ , pseudoscalar η_c ; $1P$: scalar χ_{c0} and axial-vector χ_{c1}) and bottomonia ($1S$: vector $\Upsilon(1S)$, pseudoscalar η_b ; $1P$: scalar χ_{b0} and axial-vector χ_{b1}) are studied in nuclear matter at finite magnetic field, incorporating the effects of IMC and MC. Their masses are computed using the moment sum rule method. Medium

effects are incorporated through that of the gluon condensates of dimension four which are further connected to the scalar fields of chiral model. The magnetized Dirac sea contribution is derived through the nucleonic one-loop self energy functions in the weak-field expansion of fermion propagator, corresponding to the scalar mesons-nucleon interactions within the effective model Lagrangian. The effects of density, isospin asymmetry, and magnetic field of an external medium are incorporated through the scalar and number densities of the nucleons into the scalar fields' equations of motion for the isoscalars non-strange σ , strange ζ , the isovector δ and the dilaton field χ . The scalar fields are treated to be classical in solving their coupled equations of motion. The nucleons are treated to be quantum in the Dirac sea calculation. The Dirac sea contribution leads to the considerable modifications in the scalar light quark condensates with the magnetic field. The (decrement) increment of their magnitudes with increasing magnetic field is called (inverse) magnetic catalysis. The effects of (inverse) magnetic catalysis on the masses of the heavy quarkonia are seen to be prominent as compared to the case when this effect is not taken into account. The Pseudoscalar vector mesons (PV) mixing is studied for the $1S$ -wave states of $\bar{Q}Q$; $Q = c, b$. The effect is obtained between the pseudoscalar (P) and (longitudinal) part of the vector ($V^{\parallel}$) mesons. It is studied for charmonia ($\eta_c - J/\psi^{\parallel}$) using an effective Lagrangian formalism. A spin-magnetic field interaction Hamiltonian is used for the mixing of ($\eta_b - \Upsilon^{\parallel}(1S)$). The effects of IMC and MC are considered in addition to this mixing effect. There occurs an energy level splitting due to the mixing phenomena, resulting in an increment (decrement) to the mass of $V^{\parallel}(P)$ with increasing magnetic field.

सार

परमाणु पदार्थ पर्यावरण में हैड्रोन (मेसॉन) के वर्णक्रमीय गुणों का अध्ययन किया जाता है, शून्य और गैर-शून्य दोनों तापमानों के लिए सीमित चुंबकीय क्षेत्र पर। वर्णक्रमीय कार्यों, मेसन राज्यों के उत्पादन क्रॉस-सेक्शन जैसी मात्राएँ हो सकती हैं उत्पादित माध्यम में उनके द्रव्यमान, क्षय चौड़ाई के कारण संशोधित किया जा सकता है। शायद यह महत्वपूर्ण अवलोकनीय प्रभाव हैं, जैसे कि उत्पादन और प्रसार में उच्च ऊर्जा वाले भारी आयन टकराव में कण। इन मात्राओं का अध्ययन किया जाता है ऐसे माध्यम में तटस्थ ρ और A_1 मेसॉन, व्युत्क्रम के प्रभावों पर विचार करते हुए चुंबकीय कटैलिसीस (आईएमसी) और चुंबकीय कटैलिसीस (एमसी)। डिराक सागर का प्रभाव परिमित चुंबकीय क्षेत्र में स्पिन-वन के वर्णक्रमीय गुणों पर जोर दिया जाता है वेक्टर ρ , ω , और अक्षीय-वेक्टर A_1 मेसॉन। उनके द्रव्यमान की गणना का उपयोग करके की जाती है क्वांटम क्रोमोडायनामिक्स सम रूल्स (क्यूसीडीएसआर) का बोरेल ट्रांसफॉर्मेशन इसके बाद किया गया परिमित ऊर्जा योग नियम। मजबूत हैड्रोनिक क्षय चौड़ाई की गणना एक का उपयोग करके की जाती है प्रारंभिक और अंतिम अवस्था के कणों का प्रभावी अंतःक्रिया शीर्ष। मध्यम प्रभाव क्यूसीडी प्रकाश कर्क और स्केलर ग्लूऑन कंडेनसेट के माध्यम से शामिल किया गया है, जो QCDSR के ऑपरेटर उत्पाद विस्तार पक्ष में दिखाई देते हैं। हल्के मेसन के लिए, आयाम छह स्केलर चार-कर्क कंडेनसेट तक के योगदान पर विचार किया जाता है। कंडेनसेट चिरल एसयू(3) मॉडल में अदिश क्षेत्रों से जुड़े होते हैं। परिमित पर चुंबकीय क्षेत्र, प्रोटॉन के लैंडौ परिमाणीकरण का योगदान, विसंगतिपूर्ण न्यूक्लियंस के चुंबकीय क्षण (एएमएम), और चुंबकीय डायराक सागर शामिल हैं न्यूक्लियंस के अदिश घनत्व में। तापमान का प्रभाव है फर्मी वितरण कार्यों के माध्यम से अदिश और संख्या घनत्व में शामिल किया गया न्यूक्लियंस का। शिखर के महत्वपूर्ण वर्णक्रमीय संशोधन देखे गए हैं तटस्थ मेसॉन वर्णक्रमीय कार्यों के स्थानांतरण और चौड़ाई के विस्तार के कारण आईएमसी और एमसी की घटनाएं। वेक्टरियल वर्णक्रमीय फ़ंक्शन का प्रत्यक्ष प्रयोगात्मक है भारी आयन टकरावों में डिलेएन अपरिवर्तनीय द्रव्यमान स्पेक्ट्रम से संबंध। भारी कार्कोनिया ($\bar{Q}Q; Q = c, b$) भारी-आयन टकराव के प्रारंभिक चरण में उत्पन्न होता है, जिसके दौरान उत्पन्न चुंबकीय क्षेत्र की ताकत अभी भी बड़ी हो सकती है परिधीय टकराव का मामला। चार्मोनिया की 1S- और 1P- तरंग अवस्थाओं का द्रव्यमान (1S: वेक्टर J/ψ , स्फ़ूडोस्केलर η_c ; 1P: स्केलर χ_{c0} और अक्षीय-वेक्टर χ_{c1}) और बॉटमोनिया (1S: वेक्टर $\Upsilon(1S)$, स्फ़ूडोस्केलर η_b ; 1P: स्केलर χ_{b0} और अक्षीय-वेक्टर χ_{b1}) हैं आईएमसी के प्रभावों को शामिल करते हुए, सीमित चुंबकीय क्षेत्र में परमाणु पदार्थ का अध्ययन किया गया और एम.सी. उनके द्रव्यमान की गणना आधुनिक योग नियम विधि का उपयोग करके की जाती है। मध्यम प्रभाव आयाम चार के ग्लूऑन संघनन के माध्यम से शामिल किए जाते हैं जो आगे चिरल मॉडल के अदिश क्षेत्रों से जुड़े हुए हैं। चुम्बकित डिराक सागर का योगदान न्यूक्लियोनिक वन-लूप स्व-ऊर्जा कार्यों के माध्यम से प्राप्त होता है स्केलर के अनुरूप फर्मियन प्रोपेगेटर के कमजोर-क्षेत्र विस्तार में प्रभावी मॉडल लैंग्रैजियन के भीतर मेसॉन-न्यूक्लियॉन इंटरैक्शन। इसके प्रभाव घनत्व, आइसोस्पिन विषमता और बाहरी माध्यम का चुंबकीय क्षेत्र शामिल हैं अदिश क्षेत्र में न्यूक्लियॉन के अदिश और संख्या घनत्व के माध्यम से ' आइसोस्केलर गैर-अजीब σ , अजीब τ , आइसोवेक्टर δ और के लिए गति के समीकरण डिलाटन फ़ील्ड χ । अदिश क्षेत्रों को उनके युग्म को हल करने में शास्त्रीय माना जाता है गति के समीकरण। डिराक सागर में न्यूक्लियॉन को क्वांटम माना जाता है गणना। डिराक सागर के योगदान से इसमें महत्वपूर्ण संशोधन हुए अदिश प्रकाश कर्क चुंबकीय क्षेत्र के साथ संघनित होता है। (कमी) वृद्धि बढ़ते चुंबकीय क्षेत्र के साथ उनके परिमाण को (उलटा) चुंबकीय कहा जाता है उत्प्रेरण। भारी द्रव्यमान पर (उलटा) चुंबकीय उत्प्रेरण का प्रभाव कार्कोनिया उस मामले की तुलना में प्रमुख रूप से देखा जाता है जब यह प्रभाव नहीं होता है ध्यान में रखा। स्फ़ूडोस्केलर वेक्टर मेसॉन (पीवी) मिश्रण का अध्ययन किया जाता है $\bar{Q}Q; Q = c, b$ की 1S-तरंग अवस्थाएँ। प्रभाव स्फ़ूडोस्केलर के बीच प्राप्त होता है (पी) और (अनुदैर्घ्य) वेक्टर का हिस्सा (वी $\parallel$) मेसॉन। इसका अध्ययन चार्मोनिया के लिए किया जाता है $(\eta_c - J/\psi)$ एक प्रभावी लैंग्रैजियन औपचारिकता का उपयोग करते हुए। एक स्पिन-चुंबकीय क्षेत्र इंटरैक्शन हैमिल्टनियन का उपयोग $(\eta_b - \Upsilon(1S))$ के मिश्रण के लिए किया जाता है। आईएमसी के प्रभाव और इस मिश्रण प्रभाव के अतिरिक्त एमसी पर भी विचार किया जाता है। वहां एक ऊर्जा स्तर उत्पन्न होता है मिश्रण घटना के कारण विभाजन, जिसके परिणामस्वरूप वृद्धि (कमी) होती है बढ़ते चुंबकीय क्षेत्र के साथ $\Upsilon(1P)$ का द्रव्यमान।

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Abbreviations

AMM	A nomalous M agnetic M oment
BE	B inding E nergy
BT	B orel T ransform
CEM	C hiral E ffective M odel
CPT	C hiral P erturbation T heory
COM	C enter O f M ass
DOF	D egrees O f F reedom
DR	D imensional R egularization
DS	D irac S ea
ECSB	E xplicit C hiral S ymmetry B reaking
EMT	E nergy M omentum T ensor
EOM	E quations O f M otion
ESB	E xplicit S ymmetry B reaking
FESR	F inite E nergy S um R ule
FS	F ermi S ea
FST	F ield S trength T ensor
GB	G oldstone B oson
GOR	G ell- M ann O akes R enner
GT	G oldberger T reiman
HIC	H eavy I on C ollision
HQ	H eavy Q uarkonia
IMC	I nverse M agnetic C atalysis
KG	K lein G ordon
KE	K inetic E nergy
LEL	L andau E nergy L evel
LO	L eading O der

L and R	L eft and R ight
LHS	L eft H and S ide
LSM	L inear S igma M odel
MC	M agnetic C atalysis
MFA	M ean F ield A pproximation
MFT	M ean F ield T heory
MSR	M oment S um R ule
NG	N ambu G oldstone
NLSM	N on- L inear S igma M odel
NLO	N ext-to- L eading O der
OPE	O perator P roduct E xpansion
PCAC	P artially C onserved A xial C urrent
PVM	P seudoscalar V ector M ixing
QCD	Q uantum C hromodynamics
QFT	Q uantum F ield T heory
QCDSR	Q CD S um R ule
RHA	R elativistic H artree A pproximation
RHS	R ight H and S ide
SBCS	S pontaneously B roken C hiral S ymmetry
SGC	S calar G luon C ondensate
SIB	S cale I nvariance B reaking
SM	S tandard M odel
SSB	S pontaneous S ymmetry B reaking
UR	U ltra- R elativistic
UV	U ltra V iolet
VEV	V acuum E xpectation V alue
WFE	W eak F ield E xpansion
WM	W alecka M odel
WRT	W ith R espect T o

Symbols

$(t, \vec{x})$	space-time coordinate
$\mathbf{B}$	magnetic field
$\mathbf{E}$	electric field
μ	chemical potential
p and n	proton and neutron
T	Temperature
q and $\bar{q}$	quark and antiquark
ρ_B	baryon density
ρ_0	nuclear matter saturation density
η	isospin asymmetry parameter
$ eB $	magnetic field strength in natural unit
N	nucleon
Σ	self-energy
$\vec{\mu}$	magnetic moment