

HEAVY QUARKONIA UNDER EXTREME CONDITIONS

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INDIAN INSTITUTE OF TECHNOLOGY DELHI

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CONDITIONS**

by

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Department of Physics

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INDIAN INSTITUTE OF TECHNOLOGY DELHI

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To my Family and Friends

Certificate

This is to certify that the thesis entitled “**Heavy Quarkonia Under Extreme Conditions**”, submitted by **Ankit Kumar** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a record of the original, bonafide research work carried out by him 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.

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Abstract

The present thesis primarily focuses on the investigation of in-medium properties of various light and heavy flavor mesons (HFMs) in the extreme environments of baryon density and/or strong magnetic fields. In low-energy regime of quantum chromodynamics (QCD), the strong coupling constant is large and perturbative approaches are not valid. An effective field theory (EFT) approach is employed, which is inspired from the symmetries and symmetries breaking effects of low energy QCD, to describe the strongly interacting matter. An effective chiral Lagrangian is constructed based on the principles of chiral symmetry and scale symmetry along with their symmetry breaking effects. The scalar (σ , ζ , and δ) fields are introduced within the context of chiral $SU(3)$ model to imitate the scalar quark condensates which arise in the QCD vacuum due to spontaneous breaking of chiral symmetry. The effects of scale symmetry breaking, which leads to trace anomaly of QCD, are considered through a scalar dilaton (χ) field. We use a mean field approximation of the chiral Lagrangian and derive the equations of motion for scalar fields. The effects of baryon density (ρ_B), isospin asymmetry (η), and magnetic field are incorporated through number (ρ_i) and scalar densities (ρ_i^s) of the i th baryons. The medium modifications of the QCD condensates (scalar quark and gluon condensates) are thus calculated.

We further introduce the QCD sum rule (QCDSR) approach to relate the parameters of high energy regime of QCD (in terms of quark and gluon degrees of freedom) with the low-energy QCD quantities (in terms of hadronic parameters). The correlator functions are the quantities, in QCDSR approach, which can be calculated reliably in both high energy perturbative regime of QCD as well as in hadronic framework. The finite energy sum rules (FESRs) are solved to find in-medium masses of light vector mesons (ρ , ω , and ϕ) from medium modified QCD condensates. These light vector mesons can lead to e^+e^- production in heavy ion collision (HIC) experiments, and hence the dilepton pairs can serve as good experimental probes to observe their mass variations. The in-medium characteristics of vector mesons can affect dilepton creation in the invariant mass range of these LVMS.

We also discuss the open strange mesons (vector K^* and axial vector K_1) in (magnetized) isospin asymmetric hadronic matter. The in-medium masses are calculated

within the QCDSR approach and the effects of baryon density and isospin asymmetry are studied. The effects of strong magnetic field, like Landau quantization and PV mixing, are also investigated on the masses of vector K^* mesons. The in-medium $K^* \rightarrow K\pi$ and $K_1 \rightarrow K^*\pi$ decay widths are studied from the mass variations of K_1 , K^* and K mesons, using the 3P_0 model. The decay width for the K^* and K_1 meson is also determined using a phenomenological Lagrangian approach. This present analysis of open strange particles might find relevance in HIC experiments in the Relativistic Heavy Ion Collider (RHIC) low-energy scan programme and the High Acceptance DiElectron Spectrometer (HADES) Collaboration at GSI, Darmstadt.

We also investigate the in-medium masses of charmonium and bottomonium states in isospin asymmetric nuclear matter in presence of an external magnetic field within a chiral effective model. These mass modifications are obtained from the medium modified dilaton field. The values of the dilaton field (χ) along with the scalar (σ , ζ , and δ) fields are solved within the chiral $SU(3)$ model by accounting for the effects of Dirac sea (DS) as well as anomalous magnetic moments (AMMs) of nucleons. When AMMs are neglected, both at zero density and at nuclear matter saturation density, ρ_0 , the Dirac sea contributions are found to result in enhancement of the quark condensates (through σ and ζ fields) with increase in magnetic field, an effect called the ‘magnetic catalysis (MC)’. However, the inclusion of AMMs is observed to lead to the opposite trend of ‘inverse magnetic catalysis (IMC)’ for $\rho_B = \rho_0$. Further, the magnetic field leads to PV mixing and these effects are quite notable for larger magnetic field. This might have observable consequences on the creation of the heavy quarkonia and open HFMs, resulting from ultra-relativistic peripheral HIC experiments, where the created magnetic field can be huge.

We further study the production cross-sections of heavy quarkonium states (HQS), such as $\psi(3770)$ and $\Upsilon(4S)$, from the scattering of $\bar{D}D$ and $\bar{B}B$, respectively, in magnetized nuclear medium. These are studied from the medium modifications of the masses and partial decay widths to open charm (bottom) mesons of these HFMs. The contributions of PV mixing, Dirac sea (DS), and the AMMs of nucleons are also considered. The radiative decay widths of vector (V) HQS to pseudoscalar (P) mesons ($J/\psi \rightarrow \eta_c(1S)\gamma$, $\psi(2S) \rightarrow \eta_c(2S)\gamma$ and $\psi(1D) \rightarrow \eta_c(2S)\gamma$ for the charmonium sector and $\Upsilon(NS) \rightarrow \eta_b(NS)\gamma$, $N = 1, 2, 3, 4$, for the bottomonium sector) are also investigated, from the medium modified masses of involved mesons. The

PV mixing induces a mass difference in the transverse and longitudinal component of vector meson, which is seen as a double peak structure in the invariant mass spectrum of the production cross-section of $\psi(3770)$. The modifications of the production cross-sections as well as the radiative decay widths of HQS, in magnetized nuclear matter, might have observable consequences on the creation of these HFMs resulting from ultra-relativistic peripheral HIC experiments.

सार

यह वर्तमान थीसिस मुख्य रूप से अत्यधिक बेरीयनिक घनत्व और/या मजबूत चुंबकीय क्षेत्रों की परिस्थितियों में विभिन्न हल्के और भारी फ्लेवर मेसॉनों के गुणों के अध्ययन पर केंद्रित है। क्वांटम क्रोमोडायनामिक्स (QCD) के निम्न ऊर्जा प्रभाग में मजबूत युग्मन स्थिरांक की संख्या ज्यादा होती है और विक्षुब्ध तकनीकें मान्य नहीं होती हैं। एक प्रभावी क्षेत्र सिद्धांत का अनुप्रयोग किया जाता है, जो कि निम्न ऊर्जा QCD के सिद्धांतों और सिद्धांत तोड़ने के प्रभावों से प्रेरित है, ताकि मजबूत प्रभाव करने वाले पदार्थ को वर्णित किया जा सके। एक प्रभावी कायरल लैंग्रैजियन को निर्मित किया गया है, जो कि कायरल समरूपता, पैमाना समरूपता और साथ ही उनके सिद्धांत तोड़ने के प्रभावों के सिद्धांतों पर आधारित है। अदिश कायरल फ़ील्ड्स (σ , ζ , और δ) को कायरल SU(3) मॉडल के संदर्भ में शामिल किया जाता है ताकि कायरल समरूपता के स्वतःस्फूर्त टूटने के कारण QCD वैक्यूम में उत्पन्न होने वाले अदिश क्वार्क-एंटीक्वार्क कंडेंसटस के प्रभाव को नकल किया जा सके। पैमाना समरूपता टूटने, जो कि QCD में ट्रेस विसंगति को जन्म देता है, के प्रभाव को कायरल मॉडल में एक प्रभावी अदिश डिलेटोन फ़ील्ड (χ) के माध्यम से शामिल किया जाता है। हम कायरल लैंग्रैजियन डेन्सिटी के माध्य फ़ील्ड सन्निकटन का उपयोग करते हैं और कायरल फ़ील्ड्स (σ , ζ , δ , और χ) के लिए गतिसूत्र निकाले जाते हैं। बेरीयन घनत्व (ρ_B), आइसोपिन असम्योति (η), और चुंबकीय क्षेत्र के प्रभाव को संख्या घनत्व (ρ_i) और अदिश घनत्व (ρ_i^s) के माध्यम से सम्मिलित किया गया है। चुंबकीय क्षेत्र के प्रभाव को संख्या घनत्व और अदिश घनत्व में चार्जित बेरीयनों के लांडाउ स्तरीय परिमाणीकरण के माध्यम से और बेरीयनों के असामान्य चुंबकीय मोमेंट्स (AMMs) के माध्यम से शामिल किया जाता है। इस प्रकार QCD के कंडेंसटस (अदिश क्वार्क-एंटीक्वार्क कंडेंसटस और ग्लुऑन कंडेंसटस) का माध्यमिक संशोधन निर्धारित किया जाता है।

हम QCDSR (क्वांटम क्रोमोडायनामिक्स सम नियम) दृष्टिकोण को पेश करते हैं जो QCD के उच्च ऊर्जा प्रभाग (क्वार्क और ग्लुऑन के माध्यम से) के पैरामीटरों को निम्न-ऊर्जा QCD मात्राओं (हैड्रोनिक पैरामीटरों के माध्यम से) से संबंधित करने के लिए प्रयुक्त होता है। कोरलेटर फ़ंक्शन QCDSR दृष्टिकोण में मापे जा सकने वाली वो चीज़ है जो कि उच्च ऊर्जा QCD के विक्षुब्ध क्षेत्र और साथ ही हैड्रोनिक ढांचे की गणना करने में विश्वसनीय हैं। सीमित ऊर्जा सम नियमों (FESRs) को हल किया जाता है ताकि माध्यम में संशोधित

क्वार्क कंडेंसटस और ग्लुऑन कंडेंसटस मूल्यों के द्वारा वेक्टर मेसॉनों के माध्यमिक द्रव्यमान का पता लगाया जा सके। हम QCDSR दृष्टिकोण के अंदर आइसोस्पिन असममित चुंबकीय परमाणु पदार्थ के बीच में हल्के वेक्टर मेसॉनों (ω , ρ , और ϕ) के माध्यमिक द्रव्यमान का अध्ययन करते हैं। भारी-आयन संकषण प्रयोगों में हल्के वेक्टर मेसॉन (ω , ρ , और ϕ) द्वारा सीधे e^+e^- को उत्पन्न किया जा सकता है, इसलिए द्विलेप्टन जोड़ों को इन हल्के वेक्टर मेसॉनों की द्रव्यमान परिवर्तन की गणना करने के लिए अच्छे प्रयोगशाली प्रमाणों के रूप में उपयोग किया जा सकता है। हम इन मेसॉनों के द्रव्यमान परिवर्तन की वजह से अचल द्रव्यमान सीमा में एक बढ़ी हुई द्विलेप्टन उत्पादन की उम्मीद कर सकते हैं।

हम खुले अजीब मेसॉनों (वेक्टर K^* और K_1 एक्सियल वेक्टर) के गुणों का (चुंबकीय) आइसोपिन विषमित हेड्रॉनिक पदार्थ में भी मेलबद्ध अध्ययन करते हैं। इन माध्यमिक द्रव्यमानों की QCDSR दृष्टिकोण के भीतर गणना की जाती है और बेरीयन घनत्व और आइसोपिन विषमता के प्रभाव का अध्ययन किया जाता है। वेक्टर K^* मेसॉनों के माध्यमिक द्रव्यमानों पर मजबूत चुंबकीय क्षेत्र के प्रभावों की भी जांच की जाती है। विद्युतीय आपूर्ति के साथ चार्जित K^* मेसॉन का लांडाउ परिमाणीकरण के कारण द्रव्यमान का अतिरिक्त परिवर्तन होता है और इसके अलावा, एक बाह्य चुंबकीय क्षेत्र की मौजूदगी में सूडोस्केलर कैओन (K) और वेक्टर (K^*) मेसॉन की लंबवत सहितीयता स्टेट्स के बीच स्पिन-मिश्रण होता है। इसके अलावा, एक हल्के क्वार्क-एंटीक्वार्क जोड़ी निर्माण मॉडल अर्थात् 3P_0 मॉडल का उपयोग करके, K_1 , K^* , और K मेसॉनों के माध्यमिक द्रव्यमानों के माध्यम से $K_1 \rightarrow K^*\pi$ और $K^* \rightarrow K\pi$ अपघटन मार्गों की माध्यमिक अपघटन चौड़ाई का अध्ययन किया जाता है। खुले अजीब कणों की माध्यमिक गुणों का यह वर्तमान विश्लेषण भारी-आयन संकषण प्रयोगों, जैसे कि RHIC के कम-ऊर्जा स्कैन कार्यक्रम और GSI, Darmstadt की HADES सहयोगी संगठन, में महत्वपूर्ण हो सकता है।

हम चारमोनियम और बॉटोमोनियम स्टेट्स के माध्यमिक द्रव्यमानों का भी अध्ययन करते हैं, जो आइसोपिन विषमित नाभिकीय पदार्थ में एक बाह्य चुंबकीय क्षेत्र की मौजूदगी में कायरल SU(3) मॉडल के भीतर जांचे जाते हैं। ये द्रव्यमान परिवर्तन एक अदिश डिलेटोन फ़ील्ड, χ , के कायरल SU(3) मॉडल में माध्यमिक मूल्यों से प्राप्त किए जाते हैं। यहां पर डिरेक सागर (DS) के प्रभाव और न्यूक्लियों के असामान्य चुंबकीय मोमेंट्स (AMM) के प्रभाव को ध्यान में रखकर कायरल SU(3) मॉडल की जुड़ी हुई गतिसूत्रों को हल किया जाता है। AMM को अनदेखा करने पर, वैक्यूम घनत्व और न्यूक्लियर पदार्थ की परिपूर्णता

घनत्व, ρ_0 , पर डिरेक सागर के योगदानों का परीक्षण किया गया है, जहां क्वार्क कंडेंसटस का चुंबकीय फ्रील्ड के साथ विकास होता है, एक प्रभाव जिसे चुंबकीय प्राक्रिया (MC) कहा जाता है। हालांकि, AMM के सम्मिलन से $\rho_B = \rho_0$ के लिए उल्टी चुंबकीय प्राक्रिया (IMC) की विपरीत प्रवृत्ति देखी गई है। इसके अलावा, चुंबकीय फ्रील्ड सूडोस्केलर और वेक्टर स्टेट्स के बीच में मिश्रण भी पैदा करती है जोकि उच्च चुंबकीय फ्रील्ड क्षेत्रों में महत्वपूर्ण हो सकता है। यह सब अत्याधिक ऊर्जा वाले उच्च-प्रतिवेगी भारी आयन संकषण प्रयोगों में पैदा होने वाले भारी क्वार्कोनिया और खुले भारी प्लेवर मेसॉनों के उत्पादन पर भी प्रभाव डाल सकते हैं, जहां बना हुआ चुंबकीय क्षेत्र बहुत बड़ा हो सकता है।

हम चुंबकीय न्यूक्लियर माध्यम में $\bar{D}D$ और $\bar{B}B$ के संघटन से होने वाले भारी क्वार्कोनियम अवस्थाओं, जैसे कि $\psi(3770)$ और $\Upsilon(4S)$, के उत्पादन संक्षेपण को भी अध्ययन करते हैं। यह अध्ययन इनके माध्यमिक द्रव्यमानों और खुले चार्म (बॉटम) मेसों में अपघटन चौड़ाई की माध्यमिक संशोधनों से करते हैं। PV मिक्सिंग, डिरेक सागर (DS) और न्यूक्लियन्स की अद्वितीय चुंबकीय मोमेंट्स (AMM) के योगदान को भी इस अध्ययन में ध्यान में लिया गया है। वेक्टर (V) भारी क्वार्कोनियम अवस्थाओं की सूडोस्केलर (P) मेसों में रेडिएटिव अपघटन चौड़ाई (चार्मोनियम क्षेत्र में $J/\psi \rightarrow \eta_c(1S)\gamma, \psi(2S) \rightarrow \eta_c(2S)\gamma$, और $\psi(1D) \rightarrow \eta_c(2S)\gamma$, और बॉटमोनियम क्षेत्र में $\Upsilon(NS) \rightarrow \eta_b(NS)\gamma, N = 1,2,3,4$) के माध्यमिक संशोधनों का भी इस काम में अध्ययन किया गया है। PV मिक्सिंग वेक्टर मेसोन के पर्पेंडिकुलर और लॉन्गिट्यूडिनल कॉम्पोनेंट के बीच में द्रव्यमानों का अंतर कर देता है, जिसे $\psi(3770)$ के उत्पादन संक्षेपण के अचल द्रव्यमान स्पेक्ट्रम में एक डबल पीक संरचना के रूप में देखा जाता है। चुंबकीय न्यूक्लियर माध्यम में हवी क्वार्कोनियम के उत्पादन संक्षेपणों और रेडिएटिव अपघटन चौड़ाई की संशोधनों का इन भारी स्वाद मेसों के उत्पादन पर भी दृश्यमान परिणाम होने चाहिए, खासकर उच्च ऊर्जा रेलेटिविस्टिक परिफेरल हैवी आयन संघटन प्रयोगों में, जहां बनाया गया चुंबकीय क्षेत्र बहुत बड़ा हो सकता है।

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