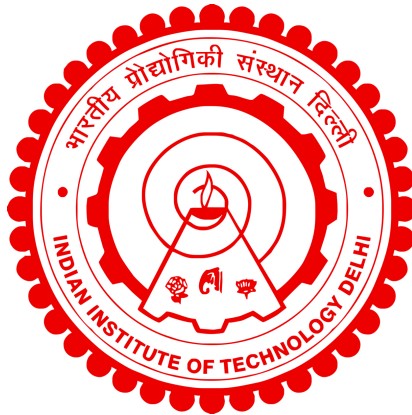


HEAVY FLAVOUR MESONS IN HADRONIC MEDIUM

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DEPARTMENT OF PHYSICS

INDIAN INSTITUTE OF TECHNOLOGY DELHI

JUNE 2023

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by

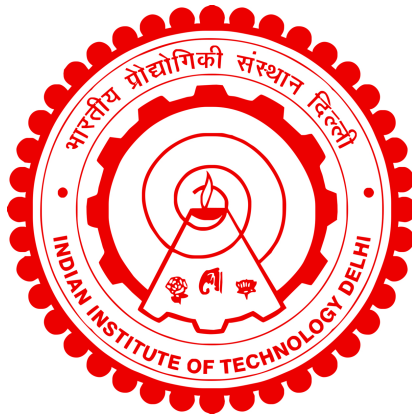
AMAL JAHAN. C.S

Department of Physics

Submitted

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

to the



INDIAN INSTITUTE OF TECHNOLOGY
DELHI

JUNE 2023

Dedicated to my family and friends

Certificate

This is to certify that the thesis entitled “**Heavy flavour mesons in hadronic medium**”, submitted by **Amal Jahan. C.S** to the Department of Physics, Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy**, is a record of the original, bona fide research work carried out by him under my supervision and guidance. He has fulfilled the requirements for submission of the thesis, which, to the best of my knowledge, has reached the required standard.

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. I certify that he has pursued the prescribed course of research.

Prof. Amruta Mishra
Department of Physics,
Indian Institute of Technology
Delhi

Date:
Place:

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Amal Jahan. C.S

Abstract

This thesis attempts to understand the properties of various heavy flavor mesons such as open charm mesons, open bottom mesons, charmonium states, and upilon states in the nuclear and strange hadronic medium at finite baryon densities and/or temperature in the presence of strong magnetic fields. In Heavy-Ion Collision experiments where such extreme conditions are created, this study is necessary as these medium modifications can affect the experimental observables. To study the in-medium properties of these mesons, we shall follow a chiral effective Lagrangian approach based on the non-linear realization of chiral symmetry and the broken scale invariance of QCD. In the chiral effective model, the scalar fields (the non-strange field σ , strange field ζ , isovector field δ) mimic the chiral condensates and the dilaton field χ mimics the gluon condensates of QCD. From the mean-field Lagrangian density, the coupled equations of motion of scalar fields are obtained, which are expressed in terms of scalar densities of the baryons. In the presence of the magnetic field, the number density and scalar density of charged baryons will have contributions from Landau energy levels. The effects of the anomalous magnetic moments of the baryons are also incorporated. At finite temperatures, the number density and scalar density of baryons also contain thermal distribution functions. The equations of motion of these scalar fields are solved to obtain their values at different baryon densities, isospin asymmetry, magnetic field, strangeness fraction, and temperature, using which we calculate the mass modifications of heavy flavor mesons in the magnetized hadronic medium.

Initially, we investigate the effective masses of pseudoscalar open charm mesons ($D(D^0, D^+)$, $\bar{D}(\bar{D}^0, D^-)$, $D_s(D_s^+, D_s^-)$) as well as pseudoscalar open bottom mesons ($B(B^+, B^0)$, $\bar{B}(B^-, \bar{B}^0)$, $B_s(B_s^0, \bar{B}_s^0)$) in the magnetized hadronic medium. The chiral $SU(3)$ model has been generalized to chiral $SU(4)$ in the case of open charm mesons and chiral $SU(5)$ in the case of open bottom mesons to incorporate their interactions with the light hadronic sector. The masses of these open heavy flavor mesons get modified through their interactions with the baryons and the scalar mesons (σ , ζ , and δ), which undergo modifications in the magnetized medium. The charged open heavy flavor mesons have additional positive mass shifts due to Landau quantization in the presence of the magnetic field. We also investigate the

mass shifts of heavy quarkonium states such as charmonium states (J/ψ , $\psi(3686)$, $\psi(3770)$, χ_{c0} , χ_{c2}) and upsilon states ($\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\Upsilon(4S)$, and $\Upsilon(1D)$) in the magnetized hadronic medium using the chiral effective model. The mass shifts of these heavy quarkonium states originate from the modification of the gluon condensates in the magnetized medium simulated by the variation of the dilaton field (χ). The effect of masses of light quarks on the modification of gluon condensates and subsequently on these mass shifts are also considered in the present work. From the obtained in-medium masses of charmonia and open charm mesons, we also calculate the partial decay widths of various charmonium states to $D\bar{D}$ in the magnetized nuclear medium, using a light quark pair creation model, namely the 3P_0 model. Finally, we investigate the effects of magnetically induced spin mixing between the pseudoscalar and the corresponding vector open charm mesons, as well as the pseudoscalar and vector charmonium states on their in-medium properties. The effects of spin mixing are incorporated through a phenomenological effective Lagrangian interaction.

The heavy flavor mesons experience a mass drop in the magnetized medium with an increase in baryon density. At high densities, the effects of the isospin asymmetry and the anomalous magnetic moments of the baryons on the meson masses are also quite prominent. The effective masses of open heavy flavor mesons decrease more in the strange hadronic medium than in the nuclear medium. The masses of these mesons initially increase with a rise in temperature, and beyond a high-temperature value, their masses are observed to drop. Due to Landau quantization, the charged mesons have substantial mass modifications in the presence of the magnetic field. An increase in the magnetic field is observed to result in larger in-medium masses of these heavy flavor mesons when the temperature is moderate. However, at higher temperatures, the in-medium masses of all mesons become smaller with an increase in the magnetic field. The decay widths of the charmonium state to D^+D^- are observed to be suppressed in the magnetic field at low baryon densities. When the spin mixing effect is incorporated, the mass of the longitudinal component of the neutral vector meson increases, and the mass of the pseudoscalar neutral mesons decreases with the magnetic field. For charged mesons, the effect of Landau quantization is observed to be dominant compared to the effect of spin mixing. These in-medium modifications can have experimental consequences, such as the production and propagation of these mesons in various asymmetric heavy-ion collision experiments.

सार

यह थीसिस मजबूत चुम्बकी क्षेत्र की उपस्थिति में सीमित बेरिऑन डेंसिटी और/या तापमान पर न्यूक्लियर और स्ट्रेंज हेड्रोणिक माध्यम में विभिन्न हेवी फ्लेवर मेसॉण सजैसे ओपन चार्म मेसॉण, ओपन बॉटम मेसॉण, चारमोणियम स्टेट्स और उपसिलोन स्टेट्स के गुणों को समझने का प्रयास करते हैं। हेवी-अयॉन कॉलिशन प्रयोग में जहां ऐसी चरम स्थितियां बनती हैं, यह अन्वेषण आवश्यक है क्योंकि ये माध्यम संशोधनों प्रायोगिक अवलोकनों को प्रभावित कर सकते हैं। माध्यम में इन मेसॉण के गुणों का अन्वेषण करने के लिए, हम कैरल इफेक्टिव लैंग्रैन्जियन मॉडल का उपयोग करते हैं। कैरल इफेक्टिव मॉडल में, स्केलर क्षेत्र (नॉन स्ट्रेंज क्षेत्र σ , स्ट्रेंज क्षेत्र ζ , ऐसोवेटर क्षेत्र δ) कैरल कंडेनसेट्स का अनुकरण करते हैं और क्षेत्र χ क्वांटम क्रोमोडायनामिक्स के ग्लून कंडेनसेट्स की अनुकरण करते हैं। मीन-फील्ड लैंग्रैन्जियन डेंसिटी से, स्केलर क्षेत्र की गति के युग्मित समीकरण प्राप्त होते हैं, जो कि बेरिऑन के स्केलर डेंसिटी के रूप में व्यक्त किए जाते हैं। चुंबकीय क्षेत्र की उपस्थिति में, विद्युत आवेशित बेरिऑन के संख्या डेंसिटी और स्केलर डेंसिटी में लेन्डौ ऊर्जा स्तरों से योगदान होगा। परिमित तापमान पर, बेरिऑन की संख्या डेंसिटी और स्केलर डेंसिटी में तापमान वितरण-फंक्शन भी होते हैं। इन अदिश क्षेत्रों की गति के समीकरणों को विभिन्न बेरिऑन डेंसिटी, आइसोस्पिन असममितता, चुंबकीय क्षेत्र, स्ट्रेंजनेस अंश और तापमान पर उनके मूल्यों को प्राप्त करने के लिए हल किया जाता है, जिसके उपयोग से हम चुंबकीय हेड्रोणिक माध्यम में हेवी फ्लेवर मेसॉण के संशोधनों की गणना करते हैं।

प्रारंभ में, चुम्बकीय हेड्रोणिक माध्यम में, स्यूडोस्केलर ओपन चार्म मेसॉण (D (D^+, D^0), $\bar{D}$ ($D^-, \bar{D}^0$), D_s (D_s^+, D_s^-)) और साथ ही स्यूडोस्केलर ओपन बॉटम मेसॉण (B (B^+, B^0), $\bar{B}$ ($B^-, \bar{B}^0$), B_s ($B_s^0, \bar{B}_s^0$)) के प्रभावी द्रव्यमान की जांच करते हैं। कैरल एसयू (3) मॉडल को ओपन चार्म मेसॉण के मामले में कैरल एसयू (4) और ओपन बॉटम मेसॉण के मामले में कैरल एसयू (5) के लिए सामान्यीकृत किया गया है ताकि लैट हेड्रोणिक सेक्टर के साथ उनकी इंटरैक्शन को शामिल किया जा सके। बेरिऑन और स्केलर मेसॉण (σ , ζ और δ) के साथ इंटरैक्शन के माध्यम से, ओपन चार्म मेसॉण और ओपन बॉटम मेसॉण के द्रव्यमान संशोधित हो जाते हैं। चुम्बके क्षेत्र की उपस्थिति में लेन्डौ क्वांटाइजेशन के कारण विद्युत आवेशित ओपन चार्म और

ओपण बॉटम मेसौण में अतिरिक्त सकारात्मक द्रव्यमान परिवर्तन होता है। हम चुंबकीय हैड्रोनिक माध्यम में चारमोनियम और उपसिलोन स्टेट्स के द्रव्यमान के संशोधनों की भी जांच करते हैं। इन हेवी क्वार्कॉनियम स्टेट्स के द्रव्यमान का संशोधन ग्लूऑन कंडेनसेट्स के संशोधन से उत्पन्न होता है जो कि चुंबकीय माध्यम में क्षेत्र χ के संशोधन द्वारा सिम्युलेटेड होता है। चारमोनिया और ओपन चार्म मेसॉण के प्राप्त द्रव्यमान से, हम 3P_0 मॉडल का उपयोग करके चुंबकित न्यूक्लियर माध्यम में विभिन्न चारमोनियम स्टेट्स की आंशिक क्षय-चौड़ाई की गणना भी करते हैं। अंत में, हम स्यूडोस्केलर और संबंधित वेक्टर ओपण चार्म मेसॉण के साथ-साथ स्यूडोस्केलर और वेक्टर चारमोनियम स्टेट्स के बीच चुंबकीय रूप से प्रेरित स्पिन मिश्रण के प्रभावों की जांच करते हैं। स्पिन मिश्रण के प्रभावों को एक फेनोमेनोलॉजिकल प्रभावी लैंग्रैंगियन इंटरैक्शन के माध्यम से शामिल किया गया है। इन-मध्यम संशोधनों के प्रायोगिक परिणाम हो सकते हैं, जैसे विभिन्न असममित हेवी-अयॉण कॉलिशन प्रयोग में इन मेसॉण का उत्पादन और प्रसार।

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