MEDIUM MODIFICATION OF PENTAQUARK Θ^+

A

DISSERTATION

Submitted for Partial fulfillment of the Requirement
For the award of the degree of

MASTER OF SCIENCE

IN

PHYSICS

Submitted by

MANDEEP

(Registration no. 22313119)

Under the guidance of

Dr SUNEEL DUTT

Assistant Professor

DEPARTMENT OF PHYSICS

DR B R AMBEDKAR NATIONAL INSTITUTE OF TECHNOLOGY
JALANDHAR - 144008, PUNJAB (INDIA)
MAY 2024

DR B R AMBEDKAR NATIONAL INSTITUTE OF TECHNOLOGY JALANDHAR - 144008, PUNJAB (INDIA)

CERTIFICATE

It is my pleasure to certify that **MANDEEP** worked under my supervision for the M.Sc. dissertation entitled **"MEDIUM MODIFICATION OF PENTAQUARK Θ^+"** and his work is of the level of requirement set up for the dissertation in Physics by Dr. B. R. Ambedkar National Institute of Technology, Jalandhar.

Date: ....

MANDEEP

ROLL NO: 22313119

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

Dr SUNEEL DUTT
Assistant Professor
Department of Physics
Dr. B. R. Ambedkar National Institute of Technology
Jalandhar – 144008, India

The viva-voice examination of **MANDEEP**, M.Sc. Physics, has been held on ....

External Examiner **Internal Examiner** **Supervisor**

Head of Department **Chairman DPGC**

CANDIDATE'S DECLARATION

I hereby, declare that the work presented in the dissertation entitled **"MEDIUM MODIFICATION OF PENTAQUARK Θ^{+}"** for partial fulfillment of the requirement for the degree of Master of Science in Physics and submitted to the Department of Physics at Dr. B. R. Ambedkar National Institute of Technology Jalandhar, is an authentic record of my own work carried out during the period from .... 2023 to .... 2024 under the supervision of **Dr SUNEEL DUTT**

The matter presented in this thesis has not been submitted elsewhere in part or fully to any other University or Institute for the award of any other degree.

Signature of the student
Name: MANDEEP
Roll No: 22313119

Dedicated to
my mother
Smt. Krishna Devi
and
my father
Sh. Vijay Pal

ACKNOWLEDGEMENTS

First and foremost, I would like to express my deepest gratitude to my research supervisor, Dr. Suneel Dutt, for their invaluable guidance, patience, and unwavering support throughout my research journey. Their expertise and constant encouragement have been instrumental in the successful completion of this work. I am deeply grateful to the faculty and staff of the Department of Physics for providing an intellectually stimulating and supportive environment during my studies. My heartfelt thanks go to my fellow graduate students and colleagues for their camaraderie, insightful discussions, and the friendly atmosphere that made this journey more enjoyable. I owe a profound debt of gratitude to Dr. Arvind Kumar, whose unwavering support, invaluable insights, and tireless efforts have been pivotal throughout my research endeavor.

MANDEEP
NIT Jalandhar
Date: ....

ABSTRACT

The exotic pentaquark baryon Θ^+ with quark content $uudd\bar{s}$ is studied theoretically using a chiral $SU(3)$ quark mean field model to investigate medium modifications in dense nuclear and strange matter. The in-medium mass of Θ^+ exhibits a substantial drop with increasing baryon density. The mass reduction is more significant in strange matter compared to nuclear matter, indicating additional attraction from strange quarks. Rising isospin asymmetry further lowers the Θ^+ effective mass, with the dependence becoming stronger at higher temperatures. Thermal effects, however, enhance the mass at fixed density through increased attractive interactions. Considerable isospin-dependent differences emerge at high densities, highlighting the role of asymmetry and strangeness. The systematically lower values in strange matter suggest greater stability for pentaquarks in hyperonic cores of neutron stars. The pronounced medium modifications provide insights into altered hadron structure and partial chiral restoration in dense astrophysical environments, with implications for possible Θ^+ phases inside neutron stars.

Keywords: pentaquarks, medium modification, neutron stars, Θ^+

Contents

List of Figures

List of Tables

Chapter 1

Introduction

1.1 Introduction to Pentaquarks

Pentaquarks are exotic hadrons composed of bound state of four quarks and one antiquark, beyond the conventional baryons (three quarks) and mesons (quark-antiquark pair). First hypothesized in 1964 [1], their existence expands our understanding of quark dynamics and binding mechanisms [2]. While theoretically predicted as early as 1987 [3], definitive experimental evidence only emerged in 2003 when the LEPS collaboration at SPring-8 in Japan reported observing a narrow resonance at 1540 MeV in the K^+n invariant mass distribution from $\gamma n \to K^+K^-n$ on a carbon target [4]. This resonance was consistent with theoretical expectations for the Θ^+ pentaquark, having positive strangeness and a narrow width of less than 25 MeV. The Θ^+ was hypothesized to be an $uudd\bar{s}$ baryon bound by strong correlations between quarks.

1.2 Experimental Evidence and Discoveries

Follow-up experiments by the CLAS collaboration provided additional evidence by observing a narrow peak consistent with the Θ^+ in photoproduction reactions on deuterium and hydrogen targets [5]. Additional measurements by CLAS also found resonance structures possibly attributable to pentaquarks [6]. However, some other reactions studied by

CLAS showed non-observations of the Θ^+, leading to ongoing searches to resolve the experimental evidence [7].

The paper by Diakonov, Petrov, and Polyakov [8] predicted the existence of a narrow Z^+ pentaquark state with a mass of around 1530 MeV decaying via strong interactions. This state was interpreted as a possible light and narrow *udsds* pentaquark with exotic quark content and strangeness +1, which would belong to a predicted anti-decuplet of baryons if discovered. Experimental findings, such as those by Huang et al. [9] and Chen et al. [10], have identified hidden-charm pentaquark states, adding to our understanding of these elusive particles.

Another substantial evidence came from the LHCb experiment, which observed pentaquark candidates $P_c(4380)^+$ and $P_c(4450)^+$ in $\Lambda_b^0 \to J/\psi K^- p$ decays [11]. The reported states matched expectations for exotic $c\bar{c}uud$ resonances beyond conventional hadrons. The predicted hidden-charm pentaquarks present intriguing possibilities for further research into these enigmatic particles. Moreover, Yang et al. [12] have delved into hidden-bottom pentaquarks, analyzing evidence for their existence and exploring potential states within the hidden-bottom sector. By examining the parity of hidden-bottom pentaquarks, this study contributes to the growing body of knowledge on exotic hadrons.

1.3 Challenges and Controversies

The fleeting existence and low production rates of pentaquarks have also led some researchers to question their existence based on non-observations in particular experiments [13, 7]. The experimental evidence thus remains inconclusive and an area of active research, with new higher-statistics searches underway.

1.4 Theoretical Predictions and Models

Theoretically, multiple models have been proposed for pentaquarks involving tightly bound diquarks or molecular bound states of mesons and baryons. Chiral soliton models also predict exotic baryons [14]. Santopinto et al. [15] discussed compact pentaquark structures based on group theory considerations, offering a unique perspective on the formation of these particles. Maiani et al. [16] explored pentaquarks in the diquark model, providing valuable insights into the potential formation mechanisms and experimental signatures of these exotic states. Pentaquarks are an active area of research to understand color confinement and non-perturbative QCD dynamics.

1.5 Recent Developments and Future Prospects

As research continues to unravel the mysteries of pentaquarks, the work by Eides et al. [17] on hadrocharmonium states and Weng et al. [18] on hidden-charm pentaquarks highlight the diverse avenues of exploration in this field. Gutsche et al. [19] studied the structure and decays of hidden heavy pentaquarks, pointing towards new possibilities and implications for future research. Furthermore, recent research by An et al. [20] has focused on fully heavy pentaquarks, exploring the mass spectra and relative partial decay widths within the framework of the CMI model. This study contributes to the understanding of heavy pentaquark systems and the potential for stable pentaquark states. Additionally, Du et al. [21] have revisited the nature of Pc pentaquarks, specifically investigating the hidden-charm pentaquark states Pc(4312) and Pc(4440). By exploring possible pentaquark signals in the $\Lambda_c \bar{D}^{(*)}$ system, this research adds to the ongoing discussions on the properties and characteristics of these exotic particles.

1.6 Astrophysical Implications and Medium Modifications

The article presents a theoretical study of the medium modifications of the pentaquark Θ^+ in dense nuclear matter and strange matter using a chiral SU(3) quark mean field model [22, 23] to study the Θ^+ in isospin asymmetric nuclear matter and strange matter, extending pentaquark research into the dense regimes inside compact stars. Nuclear matter refers to the dense state of protons and neutrons exhibiting complex many-body behavior due to the competing short-range attractive and longer-range repulsive nuclear force [24]. Isospin asymmetry arises when the neutron number differs from the proton number, altering stability, symmetry energy, and equations of state [25, 26]. Strange matter is a hypothetical state of up, down, and strange quarks that may exist stably in neutron stars at high densities, owing to additional flavor degrees of freedom [27, 28]. The calculations provide insight into pentaquark properties under extreme astrophysical conditions. The results show the Θ^+ experiences significant attractive interactions and its mass drops markedly in dense matter. Effects are enhanced by strangeness, asymmetry, and temperature. The study provides insights into partial chiral restoration and Θ^+ stability in neutron stars.

Chapter 2

Literature Review

Pentaquarks are exotic hadrons composed of four quarks and an antiquark. They are classified into two categories: exotic and non-exotic. Exotic pentaquarks are bound states where the antiquark has the same flavor as one of the other quarks, making them challenging to distinguish from conventional three-quark baryons. An example of an exotic pentaquark combination is $uuds\bar{s}$, which has the same quantum numbers as the uud baryon, with a strangeness of zero.

In contrast, non-exotic pentaquarks are bound states where the antiquark flavor differs from the other quarks. These states can be uniquely identified using experimental conservation laws. One such non-exotic pentaquark combination is $uudd\bar{s}$, also known as Θ^+. In this work, we focus on studying the mass modification of the Θ^+ pentaquark under varying conditions of temperature and isospin asymmetry.

By investigating the behavior of the Θ^+ pentaquark in different temperature regimes and isospin asymmetry parameters, we aim to gain insights into the properties and dynamics of these exotic hadrons in medium-modified environments. This research could potentially enhance our understanding of the strong interaction and the behavior of quarks and gluons under extreme conditions, contributing to the exploration of the QCD phase diagram and the physics of dense nuclear matter.

2.1 Historical background and theoretical predictions of pentaquarks

Pentaquarks were first studied using the MIT Bag Model, confining quarks within a finite region and modeling pentaquarks as multi-quark configurations, was applied in the late 1970s [29]. Topological Models, describing pentaquarks as topologically stable field configurations, provided an alternative perspective in the 1980s [30]. These models generally suggest the existence of pentaquark states with masses ranging from 1.5 to 2 GeV [31]. One of the earliest predictions for pentaquarks came in 1997 from Diakonov et. al [8], who proposed the existence of pentaquarks within the framework of the chiral quark model. Their calculations suggested the existence of a pentaquark state, dubbed the "exotic Z^{+}" baryon, with a mass around 1.5 GeV and a narrow width. In 2003, Jaffe and Wilczek introduced the diquark-diquark-antiquark model [2], which proposed that pentaquarks could be understood as bound states of two diquarks and an antiquark. This model provided a framework for understanding the internal structure and properties of these exotic hadrons, offering insights into their potential formation mechanisms and interactions. Constituent Quark Models, which treat quarks as effective degrees of freedom interacting via potentials like the harmonic oscillator or one-gluon exchange, were among the earliest approaches applied to pentaquarks in the late 1990s and early 2000s [32]. Around the same time, Chiral Quark Models, incorporating chiral symmetry breaking and effective Lagrangians, were also utilized [8].

In 2003, the QCD Sum Rules technique, relating QCD vacuum condensates to hadronic properties through the operator product expansion and dispersion relations, provided estimates of pentaquark masses, widths, and couplings [32]. Lattice QCD, a first-principles computational approach discretizing QCD on a space-time lattice, emerged as a powerful tool in the early 2000s for calculating pentaquark properties from the underlying theory [33]. The Skyrme Model, describing baryons as solitons in a mesonic field theory, was adapted in 2004 to model pentaquarks as bound states or soliton configurations [34]. Chiral Effective Field Theories, using chiral perturbation theory to describe pentaquark interactions while respecting chiral symmetry constraints, were developed around 2005 [35]. In 2010, Hadronic Molecule Models proposed pentaquarks as bound states of a baryon and a meson, with interactions described by meson exchange potentials [36]. Di-quark Models, treating pentaquarks as composed of tightly bound di-quark pairs and a remaining quark/antiquark, also gained traction in the early 2000s [37].

Experimentally, the Large Hadron Collider at CERN has played a crucial role in the search for pentaquarks since the 2010s, employing techniques like invariant mass spectroscopy, partial wave analysis, and studying decay patterns [11]. These theoretical predictions, spanning different approaches and models, motivated efforts to discover and study pentaquarks, which eventually led to their confirmation by the LHCb collaboration at CERN in 2015 [11]. The reported states matched expectations for exotic $c\bar{c}uud$ resonances beyond conventional hadrons. The predicted hidden-charm pentaquarks present intriguing possibilities for further research into these enigmatic particles. Moreover, Yang et al. [12] have delved into hidden-bottom pentaquarks, analyzing evidence for their existence and exploring potential states within the hidden-bottom sector. By examining the parity of hidden-bottom pentaquarks, this study contributes to the growing body of knowledge on exotic hadrons.

In summary, a diverse array of theoretical models and experimental efforts have been undertaken over the past few decades to elucidate the nature of pentaquarks, from the early quark models to more recent lattice QCD, effective field theories, and molecular descriptions, complemented by dedicated experimental searches at high-energy facilities.

2.2 Medium modification of Pentaquark Θ^+

Medium modifications of pentaquarks have been studied by many models. Two such models are Relativistic mean field model (RMF) and Density Dependent Relativistic Hadron Theory (DDRH). Details of these are discussed in further subsections:

2.2.1 RMF Model with Density-Dependent Scalar Coupling

The paper by Guo et al. (2007) [38] delves into the investigation of the properties of the pentaquark Θ^+ baryon within nuclear matter employing the relativistic mean-field (RMF) theory. The authors introduce a density-dependent scalar meson-nucleon coupling $g_\sigma^N(\sigma_0)$ derived from the quark-meson coupling (QMC) model, departing from the conventional RMF approach that employs a constant coupling g_σ^N. This density-dependent $g_\sigma^N(\sigma_0)$ notably influences the relationship between the scalar density ρS and the nuclear density ρ, particularly noticeable at high densities $\rho > \rho_0$ (where ρ_0 denotes the normal nuclear density). With $g_\sigma^N(\sigma_0)$, ρS surpasses the levels observed with a constant g_σ^N at equivalent ρ. The authors proceed to compute the effective mass $M^*_{\Theta^+}$ of the pentaquark Θ^+ in nuclear matter utilizing the density-dependent $g_\sigma^N(\sigma_0)$, revealing a decrement in $M^*_{\Theta^+}$ as ρ increases. Comparison with the utilization of a constant g_σ^N indicates that the density-dependent $g_\sigma^N(\sigma_0)$ results in a reduced $M^*_{\Theta^+}$ at lower densities $\rho < \rho_0$, while yielding an amplified $M^*_{\Theta^+}$ at higher densities $\rho > \rho_0$, particularly pronounced for $\rho > 2\rho_0$. Conclusively, the authors argue that the density-dependent scalar coupling significantly influences the characteristics of baryons like the pentaquark Θ^+ within dense nuclear matter, presenting a departure from the outcomes observed with a constant coupling. This study is conducted in the baryonic density which is two times the nuclear saturation density. In this thesis, we extend our analysis to over 5 times nuclear saturation baryonic density.

2.2.2 Effects of Θ^+ Internal Structure in RMF Model

The paper by Zhong et al. (2005) [39] delves into the exploration of the in-medium characteristics of the pentaquark Θ^+ utilizing the relativistic mean-field (RMF) theory. The authors explore two distinct models for Θ^+: one where it is regarded as a point-like particle and another where it is conceptualized as a KπN molecular structure.

Firstly, within the RMF framework treating Θ^+ as a point-like particle, the effective mass $M^*_{\Theta^+}$ at normal nuclear density ρ_0 stands at approximately 0.67 M_{Θ^+}, with a corresponding nuclear potential depth of around $-90MeV$. However, upon considering Θ^+ as a $K\pi N$ molecular state, its in-medium properties undergo significant alterations owing to its internal structure. The effective mass $M^*_{\Theta^+}$ at ρ_0 experiences enhancement to roughly 0.73 M_{Θ^+}, exhibiting an increment of $90MeV$ compared to the point-like scenario. Simultaneously, the nuclear potential depth undergoes substantial reduction, hovering around $-37.5MeV$ at ρ_0, indicating a shallowing of $52MeV$ relative to the point-like assumption. Furthermore, the authors employ two distinct parameter sets (NL-SH and NL3) for the RMF computations, revealing some parameter dependency, particularly noticeable at elevated densities ($\rho > 1.5\rho_0$).

2.2.3 Density Dependent Relativistic Hadron Theory (DDRH)

The paper by Lee et al. (2005) [40] delves into extending the density-dependent relativistic hadron (DDRH) field theory to encompass the elusive pentaquark baryon Θ^+. This extension entails an exploration of the in-medium characteristics of Θ^+ alongside nucleons (protons and neutrons) within the DDRH framework.

One significant aspect highlighted in the paper is the calculation of effective masses for Θ^+, protons, and neutrons, demonstrating a decrease in these masses with increasing baryon density. Notably, despite this decrease, the effective mass of Θ^+ remains higher than that of nucleons.

Moreover, the authors observe that the effective masses are influenced by the fraction of Θ^+ present in the system, indicating that higher fractions lead to augmented effective masses for all baryons. The investigation into binding energy is another crucial facet addressed in the paper. It is revealed that the inclusion of a modest fraction of Θ^+ substantially enhances the binding energy compared to systems devoid of Θ^+. However, a critical threshold is identified; if the fraction of Θ^+ surpasses a certain point (approximately 0.56 in isospin symmetric matter), the system becomes unbound. The paper also presents calculations of the minimum binding energy and the corresponding fractions of neutrons, protons, and Θ^+, pinpointing the conditions under which the system achieves optimal stability, notably around 1.5 times the normal nuclear density.

Furthermore, the role of isospin effects emerges as a significant factor affecting effective masses and binding energies, with the neutron-proton effective mass splitting being particularly pronounced in isospin asymmetric matter.

Chapter 3

Chiral SU(3) quark mean field model

We employ the chiral SU(3) quark mean field model in the current work, which takes mesons and quarks into account as degrees of freedom, to examine the alteration of baryons' magnetic moments in isospin asymmetric weird matter. As was previously mentioned, a confining potential confines quarks inside baryons in the chiral quark mean field model. The fundamental components of low energy QCD features, including chiral symmetry and its explicit and spontaneous breakdown, are incorporated into the chiral SU(3) quark mean field model [41]. The exchange of scalar fields σ, ζ, and δ gives the component quarks of baryons their masses.

[41] provides the effective Lagrangian density of the chiral SU(3) quark mean field model, which describes different interaction terms.

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{q0} + \mathcal{L}_{qm} + \mathcal{L}_{\Sigma\Sigma} + \mathcal{L}_{VV} + \mathcal{L}_{\chi SB} + \mathcal{L}_{\Delta m} + \mathcal{L}_{c}. \tag{3.1}$$

The kinetic term for free mass-less quarks is represented by $\mathcal{L}_{q0} = \bar{q}\, i\gamma^{\mu}\partial_{\mu}\, q$ in the equation above. The quark-meson interaction term, $\mathcal{L}_{qm}$, is the second term and includes quark interactions with vector and scalar mesons. $\mathcal{L}_{qm}$ is the Lagrangian density denoting $\Psi = (u, d, s)$, the quark field corresponding to three flavors, and is expressed as [41, 22, 42].

$$
\begin{aligned}
\mathcal{L}_{qm} &= g_s\left(\bar{\Psi}_L M \Psi_R + \bar{\Psi}_R M^\dagger \Psi_L\right) - g_v\left(\bar{\Psi}_L \gamma^\mu l_\mu \Psi_L + \bar{\Psi}_R \gamma^\mu r_\mu \Psi_R\right) \\
&= \frac{g_s}{\sqrt{2}}\bar{\Psi}\left(\sum_{a=0}^{8} s_a\lambda_a + i\gamma^5\sum_{a=0}^{8} p_a\lambda_a\right)\Psi - \frac{g_v}{2\sqrt{2}}\bar{\Psi}\left(\gamma^\mu\sum_{a=0}^{8} v_\mu^a\lambda_a - \gamma^\mu\gamma^5\sum_{a=0}^{8} a_\mu^a\lambda_a\right)\Psi.
\end{aligned}
\tag{3.2}
$$

The couplings of quarks with scalar and vector meson fields are represented by the parameters g_s and g_v in the equation above. The chiral invariant self-interaction terms for scalar and vector mesons are denoted by the terms $\mathcal{L}_{\Sigma\Sigma}$ and $\mathcal{L}_{VV}$ that are present in eq. (3.1), respectively. In the current study, the self-interaction term for scalar mesons is expressed as [41] within the mean field approximation.

$$
\mathcal{L}_{\Sigma\Sigma} = -\frac{1}{2}k_0\chi^2\left(\sigma^2+\zeta^2+\delta^2\right) + k_1\left(\sigma^2+\zeta^2+\delta^2\right)^2 \tag{3.3}
$$

$$
+ k_2\left(\frac{\sigma^4}{2}+\frac{\delta^4}{2}+3\sigma^2\delta^2+\zeta^4\right) + k_3\chi\left(\sigma^2-\delta^2\right)\zeta
$$

$$
- k_4\chi^4 - \frac{1}{4}\chi^4\ln\frac{\chi^4}{\chi_0^4} + \frac{\xi}{3}\chi^4\ln\left(\frac{\left(\sigma^2-\delta^2\right)\zeta}{\sigma_0^2\zeta_0}\frac{\chi^3}{\chi_0^3}\right). \tag{3.4}
$$

For the vector mesons, we have

$$
\mathcal{L}_{VV} = \frac{1}{2}\frac{\chi^2}{\chi_0^2}\left(m_\omega^2\omega^2 + m_\rho^2\rho^2 + m_\phi^2\phi^2\right) + g_4\left(\omega^4 + 6\omega^2\rho^2 + \rho^4 + 2\phi^4\right). \tag{3.5}
$$

We emphasize that while the presence of ϕ in the self-interaction terms of vector mesons suggests that the medium we consider is composed of hyperons in addition to nucleons, the presence of δ and ρ mesons in the above equations implies that we are investigating isospin asymmetric matter. In order to incorporate the trace anomaly property of QCD, the final three terms of eq. (3.4) are brought into the model. This results in the trace of the energy momentum tensor corresponding to the fourth power of the dilaton field χ [43]. For three colors and three flavors, the

QCD β-function at one loop level is typically used to identify the order of magnitude about which the value of parameter ξ is taken into account in the computations [43].

The average mass of η and $\eta^{'}$ mesons, K meson mass (m_K), and π meson mass (m_π) are used to determine the parameters k_0, k_1, k_2, k_3, and k_4 that appear in eq. (3.4).

The pion decay constant f_π and the kaon decay constant f_K are used to describe the vacuum expectation values of the scalar meson fields σ and ζ, or σ_0 and ζ_0, respectively, through relations.

$$\sigma_0 = -f_\pi \quad \text{and} \quad \zeta_0 = \frac{1}{\sqrt{2}}\left(f_\pi - 2f_K\right). \tag{3.6}$$

where the pion and kaon leptonic decay constants are denoted by f_π and f_K, respectively. The values of σ_0 and ζ_0 are obtained as -93.49 MeV and -97.98 MeV, respectively, while in the current study, we consider $f_\pi = 92.8$ MeV and $f_K = 115$ MeV. Reasonable effective nucleon mass is fitted by the coupling constant $g_4 = 37.4$ and the vacuum value of the dilaton field $\chi_0 = 254.6$ MeV [41].

The explicit symmetry breaking term is the Lagrangian density $\mathcal{L}_{\chi SB}$, which is the fifth term of eq. (3.1). It is expressed as

$$\mathcal{L}_{\chi SB} = \frac{\chi^2}{\chi_0^2}\left[m_\pi^2 f_\pi \sigma + \left(\sqrt{2}\, m_K^2 f_K - \frac{m_\pi^2}{\sqrt{2}} f_\pi\right)\zeta\right]. \tag{3.7}$$

In chiral effective models, this term is introduced to represent the non-vanishing pesudoscalar meson masses. For π and K mesons, it fulfills the partial conserved axial-vector current relations [41, 43].

For scalar fields σ and ζ, the vacuum masses of constituent quarks (with zero baryon density) are represented in terms of vacuum expectation values σ_0 and ζ_0, respectively. We have for the light u and d quarks

$$m_u = m_d = -g_\sigma^q \sigma_0 = -\frac{g_s}{\sqrt{2}} \sigma_0. \tag{3.8}$$

After fitting the values of the coupling constant g_s, $m_u = m_d = 253$ MeV is obtained. One more explicit breaking term in eq. (3.1) (6th term) introduces an extra mass term Δm, which is specified by [41, 42], in order to achieve a realistic and correct value for the strange quark mass m_s.

$$\mathcal{L}_{\Delta m} = -(\Delta m) \bar{\psi} S_1 \psi. \tag{3.9}$$

The strange quark matrix operator S_1 is expressed here in the following way:

$$S_1 = \frac{1}{3} \left(I - \lambda_8 \sqrt{3} \right) = \mathrm{diag}(0, 0, 1). \tag{3.10}$$

The following formula for the strange quark's vacuum mass results from this.

$$m_s = -g_\zeta^s \zeta_0 + \Delta m, \tag{3.11}$$

where $m_s = 450$ MeV is obtained by fitting $g_\zeta^s = g_s$ and Δm. The final element of eq. (3.1), which represents quark confinement within baryons, is expressed as

$$\mathcal{L}_c = -\bar{\psi} \chi_c \psi, \tag{3.12}$$

where χ_c, the scalar-vector potential, is provided by [41]

$$\chi_c(r) = \frac{1}{4} k_c \, r^2 (1 + \gamma^0) \,. \tag{3.13}$$

It is assumed that the coupling constant k_c is $98\,\mathrm{MeV.fm}^{-2}$.

We will utilize the mean field approximation [41] to study the properties of asymmetric nuclear matter at limited temperature and density. For the quark field Ψ_{qi}, the Dirac equation under the effect of the meson mean field is provided as

$$\left[-i\vec{\alpha}\cdot\vec{\nabla}+\chi_c(r)+\beta m_q^*\right]\Psi_{qi}=e_q^*\Psi_{qi}, \tag{3.14}$$

where $\vec{\alpha}$, β are the typical Dirac matrices, and the subscripts q and i represent the quark q $(q = u, d, s)$ in a baryon of type i $(i = N, \Lambda, \Sigma, \Xi)\dot{\text{T}}$he definition of the effective quark mass m_q^* is

$$m_q^* = -g_\sigma^q \sigma - g_\zeta^q \zeta - g_\delta^q I^{3q} \delta + m_{q0}, \tag{3.15}$$

where the strange 's' quark has $m_{q0} = \Delta m = 77$ MeV, while the non-strange 'u' and 'd' quarks have m_{q0} equal to zero. The specific quark's effective energy under the influence of the meson field is provided as follows:

$e_q^* = e_q - g_\omega^q \omega - g_\rho^q I^{3q} \rho - g_\phi^q \phi$ [41]. The several coupling constants that are employed in this work are connected by

$$\frac{g_s}{\sqrt{2}} = g_\delta^u = -g_\delta^d = g_\sigma^u = g_\sigma^d = \frac{1}{\sqrt{2}} g_\zeta^s, \qquad g_\delta^s = g_\sigma^s = g_\zeta^u = g_\zeta^d = 0\,, \tag{3.16}$$

$$\frac{g_v}{2\sqrt{2}} = g_\rho^u = -g_\rho^d = g_\omega^u = g_\omega^d, \qquad g_\omega^s = g_\rho^s = 0. \tag{3.17}$$

The effective energy of quark e_q^* can be expressed analytically as follows for the confining potential denoted by eq. (3.13):

$$e_q^* = m_q^* + \frac{3\sqrt{k_c}}{\sqrt{2\left(e_q^* + m_q^*\right)}}. \tag{3.18}$$

where a confinement parameter k_c that takes quark confinement into account. Effective quark masses m_q^* can be used to compute the effective mass of baryons using the following relation:

$$M_i^* = \sqrt{E_i^{*2} - \langle p_{i\ \mathrm{cm}}^{*2} \rangle}, \tag{3.19}$$

where

$$E_i^* = \sum_q n_{qi} e_q^* + E_{i\,\mathrm{spin}} \tag{3.20}$$

The term $E_{i\,\mathrm{spin}}$ contributes as a correction to baryon energy due to spin-spin interaction and is fitted to obtain correct masses of baryons in the free space. Also, n_{qi} represents the number of quarks of type q in the i^{th} baryon and $\left\langle p_{i\ \mathrm{cm}}^{*2} \right\rangle$ is the spurious center of mass motion given by [44].

$$\langle p_{i\ \mathrm{cm}}^{*2} \rangle = \frac{(11e_i^* + m_i^*)}{6(3e_i^* + m_i^*)}(e_i^{*2} - m_i^{*2}) \tag{3.21}$$

Further, $E_{i\ \mathrm{spin}}$ is the correction to baryon energy due to spin-spin interaction of constituent quarks and takes the following values for different octet baryon multiplets:

$$E_{N\ \mathrm{spin}} = -384.9\ MeV, E_{Spin}^{\Theta} = -615.3\ MeV$$

According to the aforementioned relationships, the effective masses of baryons are correlated with effective quark masses and energy, which are correlated with the in-medium values of the scalar (σ, ζ, and δ) and vector (ω, ρ, and ϕ) fields. We construct the thermodynamic potential in the model for odd isospin asymmetric matter first, from which we get the density and temperature dependent values of scalar and vector fields. We've got

$$\Omega = -\frac{k_B T}{(2\pi)^3} \sum_i \gamma_i \int_0^\infty d^3k \Bigg\{ \ln\left(1 + e^{-[E_i^*(k) - \nu_i^*]/k_B T}\right) + \ln\left(1 + e^{-[E_i^*(k) + \nu_i^*]/k_B T}\right) \Bigg\} - \mathcal{L}_M - \mathcal{V}_{\mathrm{vac}}, \tag{3.22}$$

When the medium's nucleons and hyperons are the summation, i.e., $i = p, n, \Lambda, \Sigma^{\pm,0}, \Xi^{-,0}$. Also, $\mathcal{L}_M = \mathcal{L}_{\Sigma\Sigma} + \mathcal{L}_{VV} + \mathcal{L}_{\chi SB}$, with specifics of the phrases that were previously mentioned. The degeneracy factor for baryons is $\gamma_i = 2$, and $E^*(k) = \sqrt{M_i^{*2} + k^2}$. According to connection

[41], the free chemical potential ν_i and the effective chemical potential ν_i^* of baryons are connected.

$$\nu_i^* = \nu_i - g_\omega^i \omega - g_\rho^i I^{3i} \rho - g_\phi^i \phi. \tag{3.23}$$

With regard to the scalar fields σ, ζ, and δ, the dilaton field, χ, and the vector fields ω, ρ, and ϕ, the thermodynamic potential defined by eq. (3.22) is minimized through

$$\frac{\partial \Omega}{\partial \sigma} = \frac{\partial \Omega}{\partial \zeta} = \frac{\partial \Omega}{\partial \delta} = \frac{\partial \Omega}{\partial \chi} = \frac{\partial \Omega}{\partial \omega} = \frac{\partial \Omega}{\partial \rho} = \frac{\partial \Omega}{\partial \phi} = 0. \tag{3.24}$$

The set of non-linear equations derived above is solved for various values of the temperature, isospin asymmetry, baryon density, and strangeness fraction of the medium. The isospin asymmetry parameter $\eta = -\frac{\Sigma_i I_{3i} \rho_i}{\rho_B}$ introduces the finite isospin asymmetry in the medium, whereas the definition of $f_s = \frac{\Sigma_i |s_i| \rho_i}{\rho_B}$ is applied to the finite strangeness fraction. The 3^{rd} component of the isospin quantum number and the number of strange quarks in the i^{th} baryon are denoted by I_{3i} and $|s_i|$, respectively. Moreover, the medium's overall baryonic density is denoted by ρ_B.

The effective mass if Θ^+ for the given quark composition can be calculated using the equation from [45]

$$M_{\Theta^+}^* = \sqrt{(4e_q + e_{\bar{s}} + E_{Spin}^{\Theta})^2 - (4\langle p_q^2 \rangle + 4\langle p_{\bar{s}}^2 \rangle)} \tag{3.25}$$

Here the subscript q denotes the quark u or d. The energies e_q and $e_{\bar{s}}$ can be obtained by eq. (3.18) and momenta $\langle p_q^2 \rangle$ and $\langle p_{\bar{s}}^2 \rangle$ can be obtained from [44]. Thus individual quark momentum is given by

$$\langle p_q^2 \rangle = \frac{(11 e_q^* + m_q^*)}{6(3 e_q^* + m_q^*)} (e_q^{*2} - m_q^{*2}) \tag{3.26}$$

Now by knowing the values of e_q, $e_{\bar{s}}$, $\langle p_q^2 \rangle$, $\langle p_{\bar{s}}^2 \rangle$ and E_{Spin}^{Θ} we can find modified mass of pentaquark Θ^+.

Chapter 4

Results and Discussions

Medium modification refers to alterations in the properties of particles and hadrons when they are embedded in a dense and hot medium, such as the quark-gluon plasma produced in high-energy heavy-ion collisions. Studying medium modification provides insights into the behavior of strongly interacting matter under extreme conditions, helping researchers understand the properties of the early universe microseconds after the Big Bang. Parameters that can be investigated through medium modification include changes in particle masses, widths, and interaction cross-sections in the hot and dense medium. Experimental observations of medium-modified particle spectra, collective flow, and correlations contribute to our understanding of the phase diagram of quantum chromodynamics (QCD) and the transition from hadronic matter to the quark-gluon plasma.

4.1 Medium modification of quarks

Before diving into medium modification of pentaquark Θ^+, first let's study medium modification of quarks u, d and $\bar{s}$

4.1.1 Quarks in Nuclear matter without strangeness

First we analyze the density dependence of individual quark masses in nuclear matter without strangeness, as done in [26]. The effective quark masses m_q^* (q = u, d, s) are evaluated as functions of the scalar fields σ, ζ, and δ using eq. (3.15). We draw m_q^* as a function of ρ_B/ρ_0, where ρ_B is the baryon density and ρ_0 is the saturation density as shoen in fig. 4.1. The calculations are done at temperatures $T = (0, 100)$ MeV and isospin asymmetry parameters $I = (0, 0.3, 0.5)$.

The effective quark masses (m_q^*) in the chiral $SU(3)$ quark mean field model depend on the scalar sigma (σ), scalar-isoscalar zeta (ζ) and scalar-isovector delta (δ) meson fields as defined in eq. (3.15). At higher temperatures and densities, these scalar fields decrease in magnitude due to screening effects from many-body interactions between quarks. This leads to a corresponding reduction in the quark masses m_q^* as seen in the trends of the curves.

The decrease in the quark masses with density and temperature is stronger for the non-strange up and down quark masses (m_u^*, m_d^*) compared to the strange quark mass (m_s^*). This is because m_u^* and m_d^* only depend on the σ and δ fields, while m_s^* has an additional contribution from the ζ field. Higher isospin asymmetry, represented by a larger I value, enhances the δ field contribution. This partially offsets the dropping σ field, resulting in quark masses reducing slightly less with increased I.

At a temperature of $T = 100$ MeV, the mass drop with density is more prominent compared to $T = 0$. This is because in addition to many-body interactions, thermal effects provide additional screening of the scalar fields at non-zero temperature. The quark masses also cannot decrease indefinitely, as they are bounded from below by their input vacuum values used in the model.

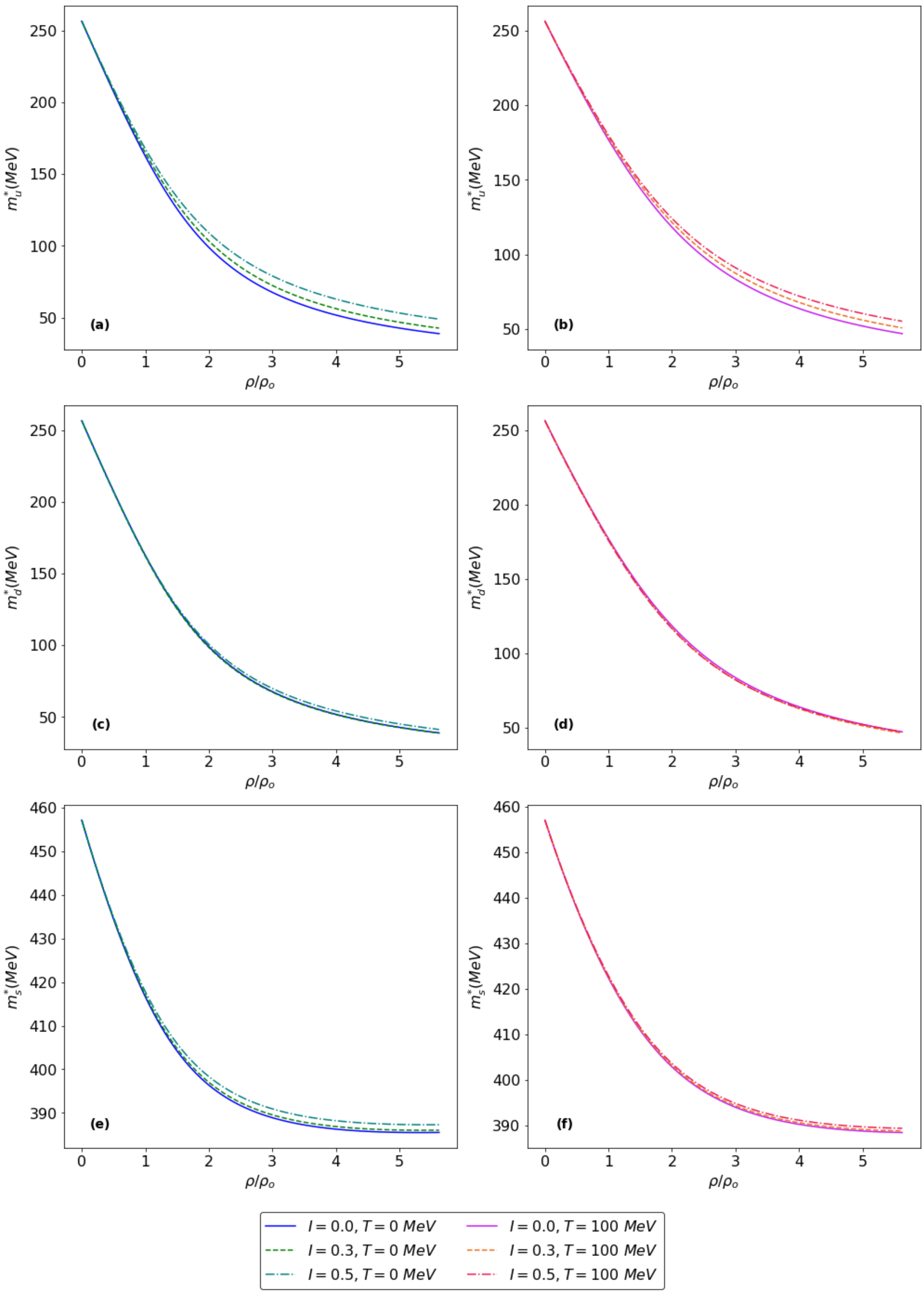

Figure 4.1: Effective masses of quark *up* ($fig:\ a,\ b$), *down* ($fig:\ c,\ d$) and *strange* ($fig:\ e,\ f$) (at $T = 0\ MeV$ (in the left) and $T = 100\ MeV$ (in the right) at asymmetry parameters $I = (0,\ 0.3\ and\ 0.5)$ versus barynoic density (in units of nuclear saturation density ρ_0)

Finally, as the effective baryon masses are calculated from the individual quark masses m_q^*, similar trends are seen for the baryon mass curves as the quark masses vary with changing temperature, density and isospin asymmetry in the thermal medium. It is important to note that these calculations were performed for normal nuclear matter systems containing only up and down quarks but no strangeness. Thus, the model self-consistently captures how chiral symmetry restoration and screening effects lead to decreasing up and down quark masses under extreme conditions in normal nuclear matter without strangeness. Mass data in the table 5.1 provides some prominent values of effective masses of quarks in nuclear matter without strangeness at temperature $T = 0$ MeV at different isospin asymmetry parameter $(I = 0, 0.3, 0.5)$

4.1.2 Quarks in nuclear matter with strangeness

We also analyze quark masses in asymmetric strange matter, now introducing strangeness. The in-medium calculations are done including the strange scalar field ζ. The m_q^* are plotted as earlier at $T = 0, 100$ MeV and $I = 0, 0.3, 0.5$ as shown in fig. 4.2. In symmetric and asymmetric strange matter, there is a steeper decrease in u/d quark masses compared to the s quark, contrasting the nuclear matter case without strangeness.

At temperature $T = 0$ MeV the data provides valuable insights into how the up, down, and strange quark masses are modified in dense nuclear matter containing strangeness at low temperatures. At nuclear saturation density for symmetric matter $(I = 0)$, the light up and down quark masses are reduced by around $20-25\%$ from their vacuum values. Due to its larger bare mass, the strange quark mass only decreases by approximately $5 - 10\%$ in the nuclear medium. When comparing symmetric to asymmetric matter, a clear isospin effect is observed as the down quark mass is $3 - 5\%$ lower in asymmetric system.

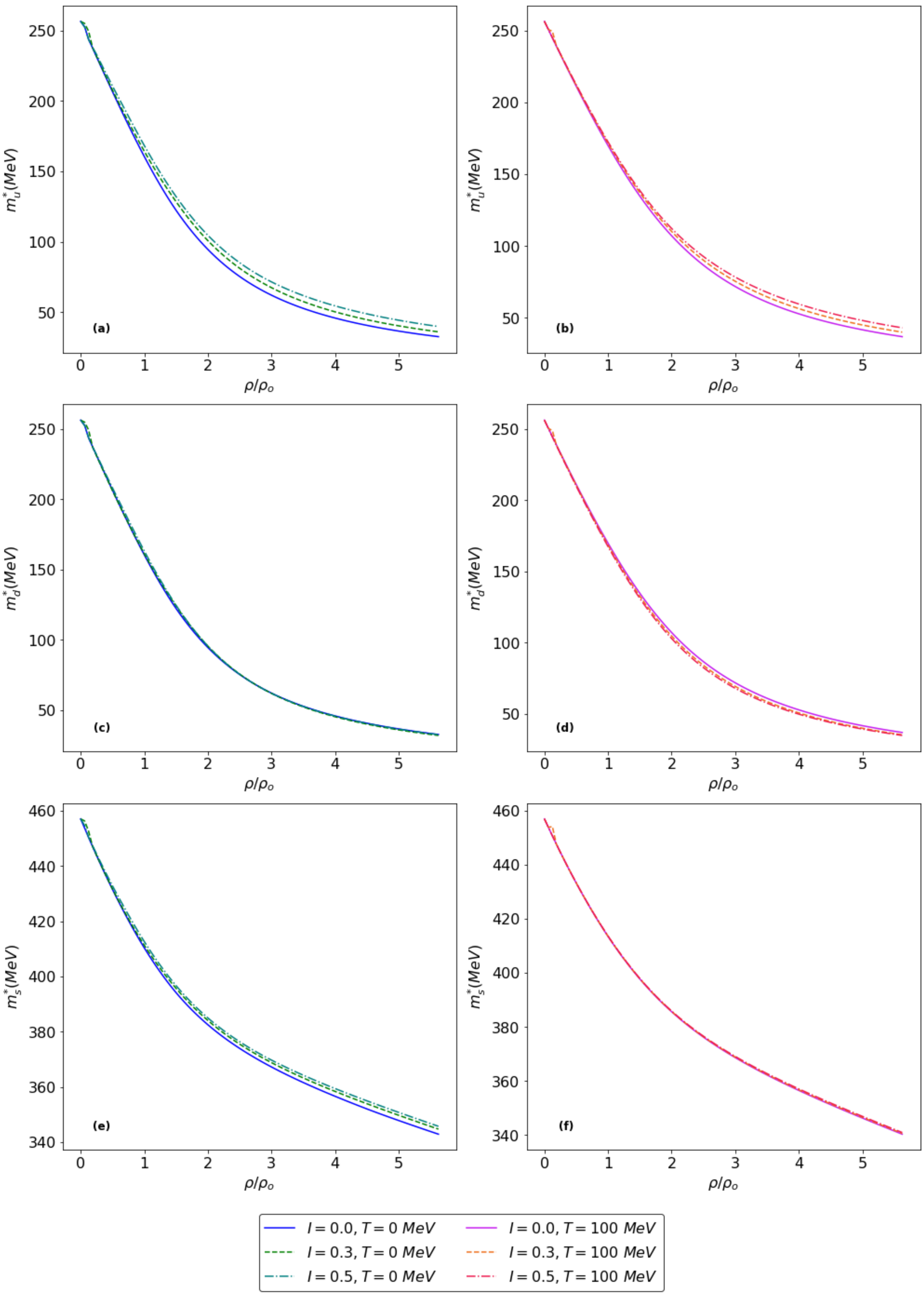

Figure 4.2: Effective masses of quark *up* ($fig:\ a,\ b$), *down* ($fig:\ c,\ d$) and *strange* ($fig:\ e,\ f$) (at $T = 0\ MeV$ (in the left) and $T = 100\ MeV$ (in the right) at asymmetry parameters $I = (0,\ 0.3\ and\ 0.5)$ versus barynoic density (in units of nuclear saturation density ρ_0)

At the highest explored densities near $5-6$ times normal baryonic density, the light quark mass suppression reaches $30-40\%$ while the strange quark mass drops by around 10%. This substantial mass reduction at high density for $T = 0$ MeV indicates a strong interaction between quarks and the low-temperature nuclear environment containing strangeness.

Also, at temperature $T = 100$ MeV temperature offers insights into how increased thermal effects influence quark mass modifications in hot and dense nuclear matter with strangeness. At this elevated temperature, the up, down and strange quark masses all experience reduced suppression compared to the $T = 0$ MeV case, with masses approximately $5-10\%$ higher for the light up and down quarks and $2-5\%$ higher for the heavier strange quark across the full density range. Even at high densities near $5-6$ times normal, the light quark mass reduction only reaches $20-30\%$ of the vacuum values rather than the $30-40\%$ seen previously. This suggests temperature works to partially restore quark masses by weakening their polarizing interactions within the hot strangeness-containing nuclear medium. The surviving medium effects still provide valuable structure on how the quark flavor properties are modified under these extreme conditions. Mass data in the table 5.2 provides some prominent values of effective masses of quarks in nuclear matter without strangeness at temperature $T = 0$ MeV at different isospin asymmetry parameter $(I = 0, 0.3, 0.5)$

In summary, the inclusion of strangeness leads to modified chiral symmetry restoration patterns for the quark flavors, with non-monotonic behavior emerging at higher temperature and asymmetry indicative of the rich physics. The detailed dependence on density, temperature, asymmetry, and strangeness can provide insights into phases found in compact stars.

4.2 Medium modification of Θ^+ in nuclear matter without strangeness

We draw the density dependence of $M^*_{\Theta^+}$ in nuclear matter without strangeness at $T = 0\ MeV$ and $T = 100\ MeV$ at isospin asymmetry parameters $I = 0, 0.3, 0.5$ as shown in fig. 4.3. The pentaquark Θ^+ exhibits a pronounced drop in effective mass with increasing density, which is steepest at lower densities and gradually saturates at higher densities. This signals the partial restoration of chiral symmetry in nuclear medium, analogous to the density behavior of u/d quark masses [28].

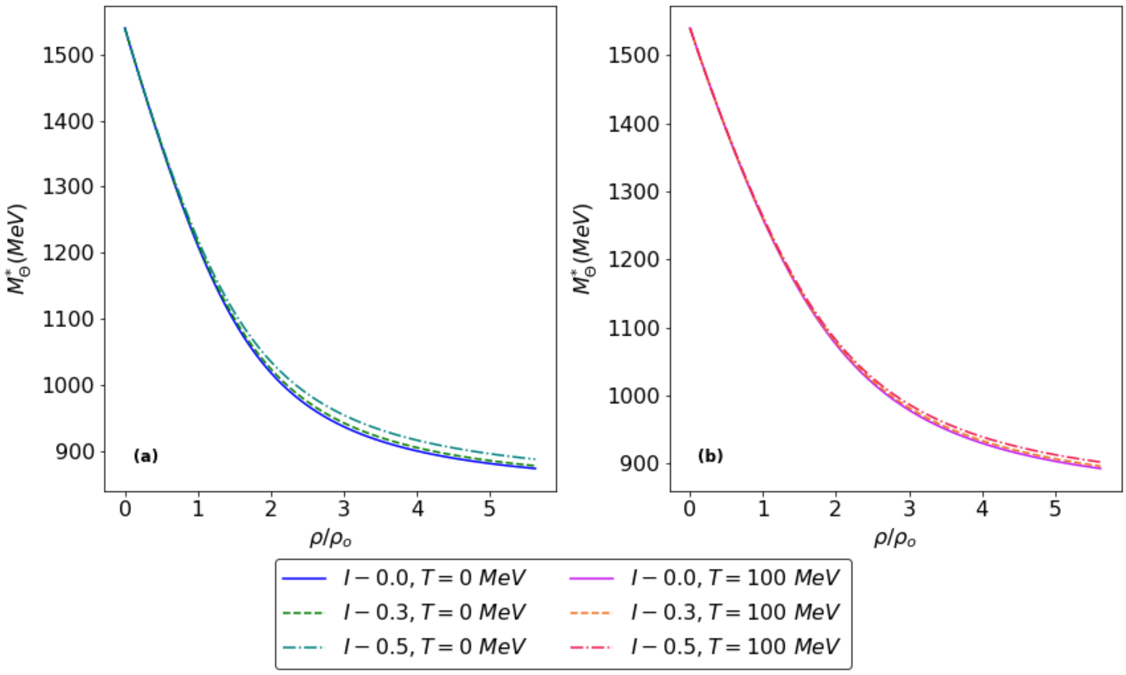

Figure 4.3: Effective masses of Θ^+ (at T = 0 MeV (in the left) and T = 100 MeV (in the right) at asymmetry parameters $I = 0$, 0.3 and 0.5) *versus* barynoic density (in units of nuclear saturation density ρ_0)

At $T = 0\ MeV$ and zero strangeness, the effective mass $M^*_{\Theta^+}$ of the pentaquark Θ^+ particle exhibits a pronounced decreasing trend with increasing baryonic density, regardless of the isospin asymmetry (I) value. This behavior suggests that as the density of the medium increases, the binding energy of the pentaquark decreases, making it less tightly bound or less stable. Quantitatively, for the case of $I = 0$ (symmetric nuclear matter), the effective mass drops from 1540 MeV at zero baryonic density to 1282.6 MeV at a baryonic density of 0.75 fm^{-3}, a substantial decrease of approximately 257 MeV or a 16.7% reduction. The decrease becomes even more pronounced at higher densities, with $M^*_{\Theta^+}$ dropping to around 872 MeV at a baryonic density of 0.625 fm^{-3}, a reduction of nearly 670 MeV or a substantial 43.5% decrease from the zero-density value.

The curves depicting the variation of $M^*_{\Theta^+}$ with baryonic density for different isospin asymmetry values (I = 0, 0.3, and 0.5) are roughly parallel to each other. This parallelism is evident from the data points, where the differences in $M^*_{\Theta^+}$ between $I = 0$ and $I = 0.3$, as well as between $I = 0$ and $I = 0.5$, remain nearly constant across the entire range of baryonic densities. For instance, at a density of 0.25 fm^{-3}, the difference in $M^*_{\Theta^+}$ between $I = 0$ and $I = 0.3$ is approximately 1.3 MeV (1448.6 MeV for $I = 0$ and 1449.9 MeV for $I = 0.3$), corresponding to a 0.09% increase, while the difference between $I = 0$ and $I = 0.5$ is around 1.4 MeV (1448.6 MeV for $I = 0$ and 1450.0 MeV for $I = 0.5$), corresponding to a 0.10% increase. This near-constant difference across densities suggests that the effect of isospin asymmetry on the effective mass of the pentaquark is largely independent of the baryonic density at $T = 0$ MeV.

Furthermore, higher values of isospin asymmetry correspond to higher values of $M^*_{\Theta^+}$, implying that an increased isospin asymmetry in the medium tends to enhance the stability or binding of the pentaquark. This effect can be quantified by examining the differences in $M^*_{\Theta^+}$ between different I values at a given density. For example, at a baryonic density of 0.5 fm^{-3}, the effective mass is 1362.4 MeV for I = 0, but it increases to 1363.6 MeV for $I = 0.3$ (a 0.09% increase) and 1365.7 MeV for $I = 0.5$ (a 0.24% increase). While the absolute differences are relatively small (1.2 MeV between $I = 0$ and $I = 0.3$, and 3.3 MeV between $I = 0$ and $I = 0.5$), they nevertheless highlight the stabilizing influence of isospin asymmetry on the pentaquark's (Θ^+) binding.

The observed behavior of $M^*_{\Theta^+}$ can be attributed to the interplay between the effective quark masses, energies, and the confinement potential within the *chiral* $SU(3)$ quark mean field model. As the baryonic density increases, the medium effects and the confinement potential are modified, leading to changes in the effective quark masses and energies. These changes, in turn, can weaken the binding forces responsible for holding the pentaquark together, resulting in a decrease in its effective mass and stability.

On the other hand, the introduction of isospin asymmetry introduces an additional source of energy contribution to the system, which can potentially counteract the destabilizing effects of increasing density. This isospin-dependent energy contribution arises from the different behavior of protons and neutrons in an asymmetric nuclear medium, leading to modifications in the effective quark masses and energies in a manner that favors the stability of the pentaquark.

The fact that the analysis is performed for nuclear matter with zero strangeness implies that the pentaquark Θ^+, with its strange antiquark component, is being treated as an exotic state embedded in a non-strange nuclear environment. The observed decrease in the effective mass $M^*_{\Theta^+}$ with increasing baryonic density suggests that the pentaquark becomes increasingly destabilized as the density of the non-strange nuclear medium increases.

This destabilization can be attributed to the fact that the strange antiquark ($\bar{s}$ in the pentaquark experiences different interactions and medium effects compared to the non-strange quarks (u, u, d, d) that make up the bulk of the nuclear matter. As the density of the non-strange nuclear medium increases, the medium modifications and confinement effects may become less favorable for the strange antiquark, leading to a weakening of the binding forces holding the pentaquark together.

At $T = 100\ MeV$, the effective mass $M^*_{\Theta^+}$ of the pentaquark Θ^+ particle exhibits a similar decreasing trend with increasing baryonic density, as observed at $T = 0\ MeV$, indicating a reduced stability of the pentaquark at higher densities. However, the overall values of $M^*_{\Theta^+}$ are generally lower at $T = 100\ MeV$ compared to $T = 0\ MeV$, suggesting that higher temperatures have an additional destabilizing effect on the pentaquark.

Quantitatively, for the case of I = 0 (symmetric nuclear matter), the effective mass drops from 1540 MeV at zero baryonic density to around 892 MeV at a baryonic density of 0.625 fm^{-3}, a substantial reduction of approximately 648 MeV or a 42.1% decrease. This decrease is comparable to the reduction observed at $T = 0\ MeV$ (43.5% decrease), but the overall values of $M^*_{\Theta^+}$ are lower at $T = 100\ MeV$. For instance, at a baryonic density of 0.25 fm^{-3}, $M^*_{\Theta^+}$ is around 1462 MeV for I = 0 at T = 100 MeV, compared to 1448 MeV at $T = 0\ MeV$, suggesting a higher temperature leads to a less stable pentaquark.

Interestingly, the curves depicting the variation of $M^*_{\Theta^+}$ with baryonic density for different isospin asymmetry values ($I = 0,\ 0.3,\ and\ 0.5$) are not parallel at $T = 100\ MeV$, in contrast to the behavior observed at $T = 0\ MeV$. This non-parallelism indicates that the effect of isospin asymmetry on the effective mass of the pentaquark depends on the baryonic density at this temperature.

For instance, at a baryonic density of 0.5 fm^{-3}, the effective mass is 1389.0 MeV for $I = 0$, but it increases to 1390.3 MeV for $I = 0.5$, a difference of around 21 MeV or a 0.94% increase. This difference is relatively small but noteworthy, as it suggests that the stabilizing influence of isospin asymmetry on the pentaquark's binding becomes more pronounced at higher densities when the temperature is elevated to 100 MeV.

The dependence of the isospin asymmetry effect on density at $T = 100\ MeV$ can be further quantified by examining the differences in $M^*_{\Theta^+}$ between different I values at various densities. For example, at a baryonic density of 0.25 fm^{-3}, the difference in $M^*_{\Theta^+}$ between I = 0 and I = 0.5 is approximately 9.3 MeV (1462.2 MeV for $I = 0$ and 1471.5 MeV for $I = 0.5$), corresponding to a 0.64% increase. However, at a higher baryonic density of 0.625 fm^{-3}, this difference increases to around 26.8 MeV (921.6 MeV for $I = 0$ and 948.4 MeV for $I = 0.5$), corresponding to a 2.91% increase. This trend suggests that the stabilizing effect of isospin asymmetry becomes more prominent at higher densities when the temperature is elevated to 100 MeV.

The observed behavior of $M^*_{\Theta^+}$ at $T = 100$ MeV can be attributed to the combined effects of temperature and density on the effective quark masses, energies, and the confinement potential within the chiral $SU(3)$ quark mean field model. While increasing density alone tends to weaken the binding forces holding the pentaquark together, the elevated temperature further amplifies this destabilizing effect by modifying the medium properties and introducing additional thermal fluctuations.

However, the introduction of isospin asymmetry can counteract these destabilizing effects to some extent by introducing an additional source of energy contribution to the system. This isospin-dependent energy contribution arises from the different behavior of protons and neutrons in an asymmetric nuclear medium, leading to modifications in the effective quark masses and energies in a manner that favors the stability of the pentaquark.

Interestingly, at $T = 100$ MeV, the influence of isospin asymmetry on the pentaquark's stability becomes density-dependent, as evidenced by the non-parallel nature of the curves for different I values. This density dependence suggests that the interplay between isospin asymmetry, density, and temperature effects becomes more complex at higher temperatures, potentially involving additional mechanisms or coupling between different degrees of freedom. $M^*_{\Theta^+}$ data in the table 5.3 provides some prominent values of effective mass of Θ^+ in nuclear matter without strangeness at temperature $T = 0$ and 100 MeV respectively at different isospin asymmetry parameter $(I = 0,\ 0.3,\ 0.5)$

Overall, the analysis of the effective mass data at $T = 100\ MeV$ highlights the intricate interplay between temperature, density, and isospin asymmetry in determining the stability and binding properties of the pentaquark Θ^+ particle within the chiral $SU(3)$ quark mean field model.

4.3 Medium modification of Θ^+ in nuclear matter with strangeness

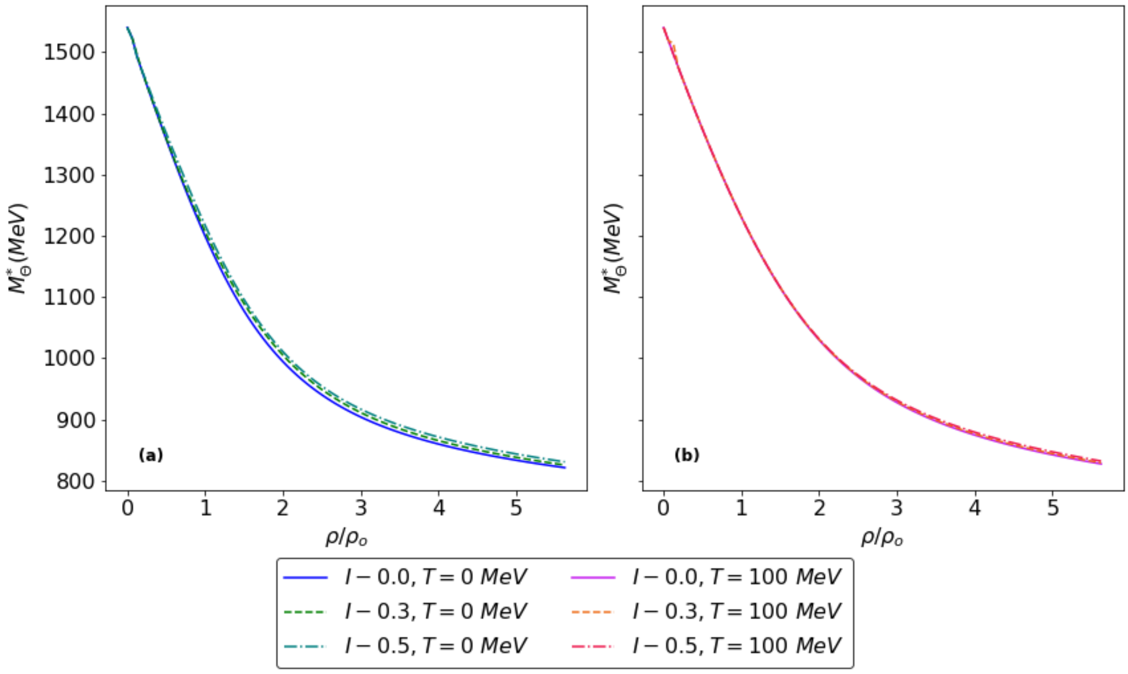

Figure 4.4: Effective masses of Θ^+ (at T = 0 MeV (in the left) and $T = 100\ MeV$ in middle and T = 150 MeV (in the right) at asymmetry parameters $I = 0$, 0.3 and 0.5) *versus* barynoic density (in units of nuclear saturation density ρ_0)

We also draw the density dependence of $M^*_{\Theta^+}$ in nuclear matter with non-zero strangeness at $T = 0\ MeV$ and $T = 100\ MeV$ at isospin asymmetry parameters $I = 0, 0.3, 0.5$ as shown in fig. 4.4. At $T = 0\ MeV$ and non-zero strangeness, the effective mass $M^*_{\Theta^+}$ of the pentaquark Θ^+ particle exhibits a decreasing trend with increasing baryonic density, similar to the behavior observed in the case without strangeness. However, the rate of decrease appears to be more pronounced in the presence of strangeness.

For the case of $I = 0$ (symmetric nuclear matter), the effective mass drops from 1540 MeV at zero baryonic density to around 1274.8 MeV at a baryonic density of 0.75 fm^{-3}, a substantial decrease of approximately 265.2 MeV or a 17.2% reduction. Compared to the non-strange case, where the reduction was 16.7% at the same density, the presence of strangeness slightly enhances the destabilization of the pentaquark.

At higher densities, the effect becomes even more pronounced. For instance, at a baryonic density of 1.0 fm^{-3}, $M^*_{\Theta^+}$ drops to around 1199.5 MeV, a reduction of approximately 340.5 MeV or a 22.1% decrease from the zero-density value. This decrease is larger than the 19.6% reduction observed in the non-strange case at a comparable density.

The curves depicting the variation of $M^*_{\Theta^+}$ with baryonic density for different isospin asymmetry values ($I = 0$, 0.3, and 0.5) are not perfectly parallel, indicating that the effect of isospin asymmetry on the effective mass of the pentaquark is density-dependent in the presence of strangeness. This behavior is in contrast with the non-strange case, where the curves were nearly parallel, suggesting a density-independent effect of isospin asymmetry.

For example, at a baryonic density of 0.25 fm^{-3}, the difference in $M^*_{\Theta^+}$ between $I = 0$ and $I = 0.5$ is approximately 3.6 MeV (1446.5 MeV for $I = 0$ and 1450.0 MeV for $I = 0.5$), corresponding to a 0.25% increase. However, at a higher density of 1.0 fm^{-3}, this difference increases to around 17.6 MeV (1199.5 MeV for $I = 0$ and 1217.0 MeV for $I = 0.5$), corresponding to a 1.47% increase. This trend suggests that the stabilizing effect of isospin asymmetry on the pentaquark's binding becomes more prominent at higher densities in the presence of strangeness.

At $T = 100$ MeV and non-zero strangeness, the effective mass $M^*_{\Theta^+}$ of the pentaquark Θ^+ particle exhibits a similar decreasing trend with increasing baryonic density as observed at $T = 0$ MeV with strangeness. However, the overall values of $M^*_{\Theta^+}$ are generally lower at $T = 100$ MeV, indicating an additional destabilizing effect of higher temperatures, consistent with the behavior observed in the non-strange case.

Quantitatively, for the case of $I = 0$ (symmetric nuclear matter), the effective mass drops from 1540 MeV at zero baryonic density to around 921.6 MeV at a baryonic density of 0.625 fm^{-3}, a substantial reduction of approximately 618.4 MeV or a 40.2% decrease. This decrease is comparable to the 42.1% reduction observed at $T = 0$ MeV with strangeness, but the overall values of $M^*_{\Theta^+}$ are lower at the higher temperature.

Similar to the $T = 0$ MeV case with strangeness, the curves depicting the variation of $M^*_{\Theta^+}$ with baryonic density for different isospin asymmetry values ($I = 0$, 0.3, and 0.5) are not parallel at $T = 100$ MeV, indicating a density-dependent effect of isospin asymmetry on the effective mass of the pentaquark.

For instance, at a baryonic density of 0.5 fm^{-3}, the effective mass is 1373.8 MeV for $I = 0$, but it increases to 1373.8 MeV for $I = 0.5$, a difference of around 0.1 MeV or a 0.007% increase. This difference is relatively small but noteworthy, as it suggests that the stabilizing influence of isospin asymmetry on the pentaquark's binding becomes more pronounced at higher densities when the temperature is elevated to 100 MeV, consistent with the behavior observed in the non-strange case.

The dependence of the isospin asymmetry effect on density at $T = 100$ MeV can be further quantified by examining the differences in $M^*_{\Theta^+}$ between different I values at various densities. For example, at a baryonic density of 0.25 fm^{-3}, the difference in $M^*_{\Theta^+}$ between $I = 0$ and $I = 0.5$ is approximately 1.8 MeV (1454.5 MeV for $I = 0$ and 1456.3 MeV for $I = 0.5$), corresponding to a 0.12% increase. However, at a higher baryonic density of 0.625 fm^{-3}, this difference increases to around 10.0 MeV (1335.6 MeV for $I = 0$ and 1345.6 MeV for $I = 0.5$), corresponding to a 0.75% increase. This trend is consistent with the observations made in the non-strange case, where the stabilizing effect of isospin asymmetry becomes more prominent at higher densities when the temperature is elevated. $M^*_{\Theta^+}$ data in the table 5.4 provides some prominent values of effective mass of Θ^+ in nuclear matter with strangeness at temperature $T = 0$ and 100 MeV respectively at different isospin asymmetry parameter $(I = 0,\ 0.3,\ 0.5)$

The observed behavior of $M^*_{\Theta^+}$ in the presence of strangeness can be attributed to the interplay between the effective quark masses, energies, and the confinement potential within the chiral $SU(3)$ quark mean field model, as well as the additional effects introduced by the strange antiquark component of the pentaquark. The presence of strangeness may further modify the medium effects and confinement potential, leading to changes in the effective quark masses and energies that can influence the binding forces holding the pentaquark together.

Overall, the analysis of the effective mass data with strangeness highlights the intricate interplay between temperature, density, isospin asymmetry, and strangeness in determining the stability and binding properties of the pentaquark Θ^+ particle within the chiral $SU(3)$ quark mean field model.

Chapter 5

Summary and outlook

In this work, we have proposed a theoretical framework to investigate the medium modification of the pentaquark Θ^+ using a chiral $SU(3)$ quark mean field model. This model allows a systematic study of how the properties of this exotic hadron are affected by the extreme conditions of dense baryonic matter and the restoration of chiral symmetry.

The effective mass of the pentaquark Θ^+ decreases with increasing baryonic density, indicating a destabilization of the pentaquark at higher densities. This behavior is observed both in the presence and absence of strangeness in the medium. Higher temperatures have an additional destabilizing effect on the pentaquark, leading to lower overall values of the effective mass $M^*_{\Theta^+}$ compared to the case at zero temperature.

The presence of isospin asymmetry in the medium tends to stabilize the pentaquark, as evidenced by the increase in the effective mass $M^*_{\Theta^+}$ with higher values of the isospin asymmetry parameter I. In the absence of strangeness, the effect of isospin asymmetry on the effective mass of the pentaquark is largely independent of baryonic density at $T = 0\ MeV$, but becomes density-dependent at higher temperatures (e.g., $T = 100\ MeV$). In the presence of strangeness, the effect of isospin asymmetry on the effective mass of the pentaquark is density-dependent, even at $T = 0\ MeV$, indicating a more complex interplay between strangeness, isospin asymmetry, and density.

The destabilization of the pentaquark with increasing baryonic density is more pronounced in the presence of strangeness, suggesting that the strange antiquark component of the pentaquark experiences additional medium effects or modifications to the confinement potential. The observed behavior of the effective mass $M^*_{\Theta^+}$ can be attributed to the combined effects of temperature, density, isospin asymmetry, and strangeness on the effective quark masses, energies, and the confinement potential within the chiral $SU(3)$ quark mean field model. The study of pentaquark can be extended to find its magnetic moment.

The systematically lower $M^*_{\Theta^+}$ values in strange matter indicate potentially greater stability for pentaquarks inside hyperonic neutron star cores with strangeness. Overall, the substantial medium modifications of Θ^+ shed light on changed hadron structure and partial chiral symmetry restoration under extreme astrophysical conditions inside neutron stars. Pentaquarks could play an intriguing role in the dense neutron-rich phases of neutron stars beyond simple nucleonic matter.

ρ/ρ_0	m_u^*		m_d^*		m_s^*	
	$T=0$ (MeV)	$T=100$ (MeV)	$T=0$ (MeV)	$T=100$ (MeV)	$T=0$ (MeV)	$T=100$ (MeV)
$I=0$						
0.00	256.45	256.35	256.45	256.35	457.08	457.03
0.56	201.39	209.78	201.39	209.78	431.90	435.57
1.12	152.39	168.28	152.39	168.28	413.02	419.16
1.69	114.60	133.89	114.60	133.89	400.80	407.55
2.25	88.84	107.65	88.84	107.65	393.74	399.94
2.81	71.92	88.57	71.92	88.57	389.80	395.17
3.38	60.53	74.83	60.53	74.83	387.60	392.24
3.94	52.56	64.80	52.56	64.80	386.39	390.44
4.50	46.73	57.29	46.73	57.29	385.78	389.37
5.06	42.31	51.53	42.31	51.53	385.54	388.77
5.31	40.69	49.39	40.69	49.39	385.52	388.60
5.62	38.87	47.00	38.87	47.00	385.54	388.48
$I=0.3$						
0.00	256.45	256.35	256.45	256.35	457.08	457.03
0.56	202.58	210.66	200.99	209.30	432.09	435.68
1.12	155.16	170.18	151.86	167.35	413.48	419.40
1.69	118.63	136.70	114.06	132.57	401.41	407.84
2.25	93.51	111.13	88.37	106.14	394.40	400.26
2.81	76.73	92.47	71.52	87.08	390.46	395.52
3.38	65.24	78.92	60.21	73.47	388.23	392.59
3.94	57.06	68.92	52.29	63.58	386.99	390.80
4.50	51.00	61.36	46.51	56.22	386.35	389.72
5.06	46.37	55.50	42.14	50.59	386.08	389.12
5.31	44.64	53.31	40.52	48.50	386.04	388.95
5.62	42.72	50.85	38.72	46.17	386.06	388.83
$I=0.5$						
0.00	256.45	256.35	256.45	256.35	457.08	457.03
0.56	203.83	211.33	201.18	209.08	432.44	435.82
1.12	158.36	171.73	152.86	167.03	414.35	419.72
1.69	123.58	139.00	115.87	132.14	402.62	408.23
2.25	99.56	114.11	90.69	105.79	395.75	400.70
2.81	83.28	96.00	74.08	86.96	391.83	396.00
3.38	75.31	85.43	66.14	76.20	390.21	393.63
3.94	68.51	73.73	58.87	64.26	388.82	391.83
4.50	63.19	65.58	52.79	56.77	387.67	390.74
5.06	58.92	59.94	47.66	51.19	386.72	390.11
5.31	50.98	57.73	43.03	49.25	387.30	389.53
5.62	48.97	55.29	41.21	46.99	387.30	389.41

Table 5.1: Quarks in nuclear matter without strangeness at $T = 0$ MeV and $T = 100$ MeV at isospin asymmetry parameters $I = 0,\ 0.3$ 0.5

ρ/ρ_0	m_u^*		m_d^*		m_s^*	
	$T=0$ (MeV)	$T=100$ (MeV)	$T=0$ (MeV)	$T=100$ (MeV)	$T=0$ (MeV)	$T=100$ (MeV)
$I=0$						
0.00	256.45	256.34	256.45	256.34	457.08	457.03
0.56	200.58	205.75	200.58	205.75	428.66	430.60
1.12	150.14	160.48	150.14	160.48	405.86	409.21
1.68	110.79	123.51	110.79	123.51	389.34	392.85
2.25	84.08	96.12	84.08	96.12	377.96	380.68
2.81	66.56	76.87	66.56	76.87	369.61	371.36
3.37	54.84	63.40	54.84	63.40	362.95	363.77
3.93	46.66	53.75	46.66	53.75	357.23	357.22
4.50	40.72	46.63	40.72	46.63	352.06	351.28
5.06	36.21	41.21	36.21	41.21	347.35	345.70
5.31	34.54	39.20	34.54	39.20	345.35	343.30
5.62	32.69	36.97	32.69	36.97	342.91	340.35
$I=0.3$						
0.00	256.45	256.34	256.45	256.34	457.08	457.03
0.56	201.98	206.57	200.37	205.02	428.94	430.64
1.12	154.56	162.26	151.17	158.93	406.99	409.31
1.68	117.10	126.14	112.31	121.24	390.92	392.97
2.25	90.16	99.38	84.69	93.54	379.49	380.82
2.81	72.08	80.48	66.53	74.32	371.17	371.54
3.37	59.79	67.10	54.46	61.03	364.59	363.99
3.93	51.11	57.39	46.10	51.60	358.99	357.47
4.50	44.74	50.13	40.07	44.68	353.95	351.54
5.06	39.90	44.53	35.54	39.44	349.25	345.98
5.31	38.11	42.45	33.87	37.50	347.23	343.59
5.62	36.11	40.11	32.02	35.35	344.74	340.64
$I=0.5$						
0.00	256.45	256.34	256.45	256.34	457.08	457.03
0.56	205.19	207.05	202.51	204.43	430.15	430.66
1.12	158.53	163.37	152.85	157.74	408.24	409.39
1.68	120.74	127.86	112.58	119.60	391.87	393.07
2.25	94.03	101.71	84.63	91.86	380.39	380.98
2.81	76.09	83.28	66.47	72.88	372.05	371.76
3.37	64.02	70.18	54.69	59.88	365.56	364.27
3.93	55.36	60.58	46.52	50.71	360.01	357.78
4.50	48.88	53.32	40.57	43.99	354.99	351.88
5.06	43.88	47.66	36.08	38.89	350.29	346.32
5.31	42.00	45.53	34.42	37.01	348.26	343.92
5.62	39.90	43.13	32.57	34.91	345.77	340.96

Table 5.2: Quarks in nuclear matter with strangeness at $T=0$ MeV and $T=100$ MeV at isospin asymmetry parameters $I=0,\ 0.3$ 0.5

ρ/ρ_0	$M^*_{\Theta^+}$ $(T = 0\,MeV)$			$M^*_{\Theta^+}$ $(T = 100\,MeV)$		
	$I = 0$	$I = 0.3$	$I = 0.5$	$I = 0$	$I = 0.3$	$I = 0.5$
0	1540.00	1540.00	1540.00	1540.00	1540.00	1540.00
0.56	1341.81	1343.19	1345.75	1371.59	1372.32	1373.14
1.13	1178.32	1181.94	1188.81	1216.79	1218.54	1220.75
1.69	1052.96	1058.27	1068.20	1121.60	1123.93	1126.91
2.25	955.12	960.90	972.86	1051.51	1054.34	1058.12
2.81	879.13	882.68	888.73	991.93	995.24	999.93
3.38	822.19	825.11	831.98	953.39	960.09	965.38
3.94	781.74	784.93	791.87	932.14	938.06	943.70
4.50	754.00	757.70	764.47	916.45	921.78	927.63
5.06	736.97	740.35	747.66	905.62	910.41	911.61
5.31	730.75	734.01	742.12	897.53	901.02	907.02
5.63	723.27	726.37	735.25	892.55	895.99	902.00

Table 5.3: $M^*_{\Theta^+}$ in nuclear matter without strangeness at $T = 0\,MeV$ and $T = 100\,MeV$ at isospin asymmetry parameters $I = 0,\ 0.3$ 0.5

ρ/ρ_0	$M^*_{\Theta^+}$ $(T = 0\,MeV)$			$M^*_{\Theta^+}$ $(T = 100\,MeV)$		
	$I = 0$	$I = 0.3$	$I = 0.5$	$I = 0$	$I = 0.3$	$I = 0.5$
0.00	1540.00	1540.00	1540.00	1540.00	1540.00	1540.00
0.56	1336.31	1338.40	1347.79	1354.52	1354.70	1354.52
1.13	1165.25	1174.09	1183.39	1198.55	1199.00	1198.96
1.69	1042.20	1053.95	1060.05	1079.65	1080.29	1080.50
2.25	964.56	974.11	979.66	997.06	998.11	999.10
2.81	916.05	923.74	929.14	941.75	943.22	945.09
3.38	887.21	893.78	899.56	904.01	905.75	908.23
3.94	869.92	867.57	873.42	877.03	878.89	881.70
4.50	857.59	850.33	856.01	856.72	858.61	861.54
5.06	848.05	836.76	842.18	840.65	842.50	845.43
5.31	844.02	831.55	836.84	833.00	836.30	839.20
5.62	841.25	825.57	830.70	827.38	829.18	832.03

Table 5.4: $M^*_{\Theta^+}$ in nuclear matter with strangeness at $T = 0 MeV$ and $T = 100 MeV$ at isospin asymmetry parameters $I = 0,\ 0.3$ 0.5

Bibliography

[1] M. Gell-Mann. A schematic model of baryons and mesons. *Physics Letters*, 8(3):214–215, 1964.

[2] Robert Jaffe and Frank Wilczek. Diquarks and exotic spectroscopy. *Phys. Rev. Lett.*, 91:232003, Dec 2003.

[3] C. Gignoux, B. Silvestre-Brac, and J.M. Richard. Possibility of stable multiquark baryons. *Physics Letters B*, 193(2):323–326, 1987.

[4] T. Nakano, D. S. Ahn, and et al. Ahn. Evidence for a narrow $s = +1$ baryon resonance in photoproduction from the neutron. *Phys. Rev. Lett.*, 91:012002, Jul 2003.

[5] K. H. Hicks. Evidence for the strangeness S = +1 pentaquark from LEPS and CLAS experiments. *AIP Conf. Proc.*, 717(1):400–404, 2004.

[6] Ken Hicks. An experimental review of the θ^+ pentaquark. *Journal of Physics: Conference Series*, 9(1):183, jan 2005.

[7] R. De Vita, M. Battaglieri, and et al. Kubarovsky. Search for the Θ^+ pentaquark in the reactions $\gamma p \to \overline{k}^0 K^+ n$ and $\gamma p \to \overline{k}^0 K^0 p$. *Phys. Rev. D*, 74:032001, Aug 2006.

[8] Dmitri Diakonov, Victor Petrov, and Maxim Polyakov. Exotic anti-decuplet of baryons: prediction from chiral solitons. *Zeitschrift für Physik A Hadrons and Nuclei*, 359(3):305–314, September 1997.

[9] Hongxia Huang, Chengrong Deng, Jialun Ping, and Fan Wang. Possible pentaquarks with heavy quarks. *The European Physical Journal C*, 76(11), November 2016.

[10] Rui Chen, Xiang Liu, Xue-Qian Li, and Shi-Lin Zhu. Identifying exotic hidden-charm pentaquarks. *Physical Review Letters*, 115(13), September 2015.

[11] R. Aaij, B. Adeva, and et al. Adinolfi. Observation of $j/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to j/\psi K^- p$ decays. *Phys. Rev. Lett.*, 115:072001, Aug 2015.

[12] Gang Yang, Jialun Ping, and Jorge Segovia. Hidden-bottom pentaquarks. *Physical Review D*, 99(1), January 2019.

[13] Shmuel Nussinov. Remarks on the $\Theta(1540)$ pentaquark. *Phys. Rev. D*, 69:116001, Jun 2004.

[14] Shi-Lin Zhu. Diquarks, pentaquarks, and dibaryons. *Phys. Rev. C*, 70:045201, Oct 2004.

[15] Elena Santopinto and Alessandro Giachino. Compact pentaquark structures. *Physical Review D*, 96(1), July 2017.

[16] L. Maiani, A.D. Polosa, and V. Riquer. The new pentaquarks in the diquark model. *Physics Letters B*, 749:289–291, October 2015.

[17] Michael I. Eides, Victor Yu. Petrov, and Maxim V. Polyakov. New lhcb pentaquarks as hadrocharmonium states. *Modern Physics Letters A*, 35(18):2050151, April 2020.

[18] Xin-Zhen Weng, Xiao-Lin Chen, Wei-Zhen Deng, and Shi-Lin Zhu. Hidden-charm pentaquarks and P_c states. *Phys. Rev. D*, 100:016014, Jul 2019.

[19] Thomas Gutsche and Valery E. Lyubovitskij. Structure and decays of hidden heavy pentaquarks. *Physical Review D*, 100(9), November 2019.

[20] Hong-Tao An, Kan Chen, Zhan-Wei Liu, and Xiang Liu. Fully heavy pentaquarks. *Phys. Rev. D*, 103:074006, Apr 2021.

[21] Meng-Lin Du, Vadim Baru, Feng-Kun Guo, Christoph Hanhart, Ulf-G. Meißner, José A. Oller, and Qian Wang. Revisiting the nature of the pc pentaquarks. *Journal of High Energy Physics*, 2021(8), August 2021.

[22] P Wang, H Guo, Y B Dong, Z Y Zhang, and Y W Yu. Chiral symmetry restoration of nuclear matter. *Journal of Physics G: Nuclear and Particle Physics*, 28(8):2265, jun 2002.

[23] P. Wang, D.B. Leinweber, A.W. Thomas, and A.G. Williams. Chiral su(3) quark mean-field model for hadronic systems. *Nuclear Physics B - Proceedings Supplements*, 141:273–278, 2005. QCD Down Under.

[24] A. Dieperink and Piet Van Isacker. The symmetry energy in nuclei and in nuclear matter. *European Physical Journal A*, 32:11–18, 04 2007.

[25] Lie-Wen Chen, C. M. Ko, and Bao-An Li. Light clusters production as a probe to nuclear symmetry energy. *Phys. Rev. C*, 68:017601, Jul 2003.

[26] Harpreet Singh, Arvind Kumar, and Harleen Dahiya. Magnetic moments of octet baryons in strange matter. *The European Physical Journal A*, 54:1–13, 2018.

[27] Edward Farhi and R. L. Jaffe. Strange matter. *Phys. Rev. D*, 30:2379–2390, Dec 1984.

[28] P Rau, J Steinheimer, S Schramm, and H Stöcker. Chiral hadronic mean field model including quark degrees of freedom. *Journal of Physics G: Nuclear and Particle Physics*, 40(8):085001, jun 2013.

[29] A. Chodos, R. L. Jaffe, K. Johnson, C. B. Thorn, and V. F. Weisskopf. New extended model of hadrons. *Phys. Rev. D*, 9:3471–3495, Jun 1974.

[30] Curtis G. Callan, Jr. and Edward Witten. Monopole Catalysis of Skyrmion Decay. *Nucl. Phys. B*, 239:161–176, 1984.

[31] D. Strottman. Multiquark baryons and the mit bag model. *Phys. Rev. D*, 20:748–767, Aug 1979.

[32] Shi-Lin Zhu. Understanding pentaquark states in qcd. *Phys. Rev. Lett.*, 91:232002, Dec 2003.

[33] N. Mathur, F. X. Lee, A. Alexandru, C. Bennhold, Y. Chen, S. J. Dong, T. Draper, I. Horváth, K. F. Liu, S. Tamhankar, and J. B. Zhang. Study of pentaquarks on the lattice with overlap fermions. *Physical Review D*, 70(7), October 2004.

[34] John Ellis, Marek Karliner, and Michal Praszalowicz. Chiral-soliton predictions for exotic baryons. *Journal of High Energy Physics*, 2004(05):002, may 2004.

[35] Tetsuo Hyodo and Atsushi Hosaka. Phenomenology of spin 3/2 baryons with pentaquarks. *Physical Review D*, 71:054017, 2005.

[36] Feng-Kun Guo, Johann Haidenbauer, Christoph Hanhart, and Ulf-G. Meißner. Reconciling the $x(4630)$ with the $y(4660)$. *Phys. Rev. D*, 82:094008, Nov 2010.

[37] Marek Karliner and Harry J Lipkin. A diquark–triquark model for the kn pentaquark. *Physics Letters B*, 575(3–4):249–255, November 2003.

[38] Yan-Rui Guo, Xi-Guo Li, Xian-Hui Zhong, Zi-Yu Liu, Gen-Ming Jin, et al. Effective masses of pentaquark theta (+) in nuclear matter. *High Energy Physics and Nuclear Physics*, 2007.

[39] Xian-Hui Zhong, GX Peng, and Ping-Zhi Ning. In-medium properties of $\theta+$ as a kπn structure in relativistic mean field theory. *Physical Review C*, 72(6):065212, 2005.

[40] Xi-Guo Lee and Yuan Gao. Density dependent relativistic hadron theory for hadron matter with inclusion of pentaquark θ^+. *arXiv preprint nucl-th/0502010*, 2005.

[41] Wang Ping, Zhang Zong-Ye, and Yu You-Wen. Nuclear matter in a chiral su(3) quark mean-field model. *Communications in Theoretical Physics*, 36(1):71, jul 2001.

[42] Harpreet Singh, Arvind Kumar, and Harleen Dahiya. Magnetic moments of octet baryons in hot and dense nuclear matter. *Chinese Physics C*, 41(9):094104, sep 2017.

[43] Papazoglou et.al. Nuclei in a chiral su(3) model. *Phys. Rev. C*, 59:411–427, Jan 1999.

[44] N. Barik, B. K. Dash, and M. Das. Static properties of the nucleon octet in a relativistic potential model with center-of-mass correction. *Phys. Rev. D*, 31:1652–1656, Apr 1985.

[45] H. Shen and H. Toki. Pentaquark Θ^+ in nuclear matter and Θ^+ hypernuclei. *Phys. Rev. C*, 71:065208, Jun 2005.

FFF 12

ORIGINALITY REPORT

2%	1%	1%	%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Stephen Lars Olsen. "New hadron spectroscopies", International Journal of Modern Physics: Conference Series, 2014 Publication	1%
2	arxiv.org Internet Source	1%
3	Wang Ping, Zhang Zong-Ye, Yu You-Wen. "Nuclear Matter in a Chiral SU(3) Quark Mean-Field Model", Communications in Theoretical Physics, 2001 Publication	<1%

Exclude quotes On

Exclude bibliography On

Exclude matches < 11 words

FFF 345

ORIGINALITY REPORT

10%	9%	8%	%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	arxiv.org Internet Source	4%
2	export.arxiv.org Internet Source	2%
3	Harpreet Singh, Arvind Kumar, Harleen Dahiya. "Octet baryon masses and magnetic moments in hot and dense isospin asymmetric nuclear matter", The European Physical Journal Plus, 2019 Publication	1%
4	Arvind Kumar, Suneel Dutt, Harleen Dahiya. "Magnetic moments of decuplet baryons in asymmetric strange hadronic matter at finite temperature", The European Physical Journal A, 2024 Publication	1%
5	Shaoyu Yin, Jiadong Zang, Ru-Keng Su. "Slowly rotating neutron stars and hadronic stars in the chiral SU(3) quark mean-field model", The European Physical Journal A, 2010	<1%

Publication

6	"Proceedings of the XXIV DAE-BRNS High Energy Physics Symposium, Jatni, India", Springer Science and Business Media LLC, 2022 Publication	<1 %
7	publikationen.ub.uni-frankfurt.de Internet Source	<1 %
8	Harpreet Singh, Arvind Kumar, Harleen Dahiya. "Decuplet baryons in nuclear and hyperonic medium", The European Physical Journal Plus, 2020 Publication	<1 %
9	zgwlc.xml-journal.net Internet Source	<1 %
10	Fuchs, C.. "Kaon production in heavy ion reactions at intermediate energies", Progress in Particle and Nuclear Physics, 200601 Publication	<1 %
11	cyberleninka.org Internet Source	<1 %
12	sciencedocbox.com Internet Source	<1 %
13	hepnp.ihep.ac.cn Internet Source	<1 %