Quarkyonic model for dark matter admixed neutron Star: A RMF perspective

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I. INTRODUCTION

Neutron stars (NS) are extremely dense and compact celestial objects formed from supernova explosions which typically have a minuscule radius of approximately 10-15 km and can possess a massive mass ranging from $1.1M_\odot$ to $<$3-4$M_\odot$ times that of our sun. The recent observation of gravitational wave data, specifically from the GW190814 event, has imposed a significant limitation on our understanding of the equation of state (EOS) of neutron star matter. This observation has led to an estimate that the mass range of the secondary object should be higher than $2.5M_\odot$. The relativistic mean-field (RMF) formalism is considered to be one of the most accomplished theories for finite nuclei to extremely dense nuclear matter. The inner composition of neutron stars remains a subject of ongoing scientific investigation. This challenge arises primarily from our inability to replicate these extreme states of matter in laboratory settings. Nevertheless, we can gain valuable insights into the interior of neutron stars by examining astrophysical observations and conducting theoretical investigations. Due to high densities, the constituents of NS can be consisted of numerous subatomic particles and exotic states of matter such as the presence of free quarks , hyperons, or pion condensation, dark matter etc. Within the framework of quarkyonic matter a cross over transition between nucleons and quarks takes place inside the NS[2]. Due to the extremely compact state of matter, it is impossible to dismiss the existence of dark matter, and could significantly influence the overall behavior of the star on a large scale. We take into account the presence of fermionic dark matter, which is confined within the star and interacts directly with nucleons through the exchange of standard model Higgs bosons[3].

II. FORMALISM

In our methodology, we have incorporated the relativistic-mean field (RMF) formalism, employing a designated set of RMF parameters known as "IOPB-I". We can represent the associated Lagrangian density in the following manner:

$$\mathcal{L} = \mathcal{L_{RMF}} + \mathcal{L_{QM}} + \mathcal{L_{DM}}, \quad (1)$$

,

where, $\mathcal{L_{RMF}}$ is the conventional Lagrangian density derived for hadronic part as defined in [1].

$$\mathcal{L_{QM}} = \sum_{j=u,d} \bar{\psi}_j (i\gamma_\nu \partial^\nu - m_j)\psi_j, \quad (2)$$

and

$$\mathcal{L_{DM}} = \bar{\chi}\left[i\gamma^\mu \partial_\mu - M_\chi + yh\right]\chi + \frac{1}{2}\partial_\mu h \partial^\mu h, \\ -\frac{1}{2}M_h^2 h^2 + f\frac{M_{nucl.}}{v}\bar{\varphi}h\varphi \quad (3)$$

are the quarkyonic matter and dark matter part of the total Lagrangian density, respectively.

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III.RESULTS

Now the mass (M) and radius (R) of a static and isotropic neutron star for the obtained EOSs are determined by solving a set of coupled differential equations, which are collectively known as the TOV equations:

$$\frac{dp(r)}{dr} = -\frac{[p(r)+\epsilon(r)][m(r)+4\pi r^3 p(r)]}{r[r-2m(r)]}, \quad (4)$$

$$\frac{dm(r)}{dr} = 4\pi r^2 \epsilon(r). \quad (5)$$

The mass-radius profile of a quarkyonic star mixed with dark matter exhibits remarkable sensitivity to variations in the quantity of dark matter within the neutron star shown in Fig.1, while keeping the transition density at $n_t = 0.3 fm^{-3}$ and confinement scale Λ=800 MeV. It has been observed that when quark matter is incorporated, the maximum mass of the neutron star reaches a value of 2.50 $M_\odot$, which aligns well with the data observed in GW190814 event. However, the presence of fermionic dark matter results in a reduction in both the maximum mass and the radius of the neutron star. It is observed that dark matter momentum k_f=0.03 GeV is consistent with the observation of J0952-0607 pulsar. The detailed results shown in Table 1, illustrating the pivotal roles played by both quark matter and dark matter in shaping the structure of neutron stars.

TABLE I: Table for maximum mass, corresponding radius and cannonical star for the above mentioned EOS at $n_t = 0.3 fm^{-3}$, Λ_{cs} = 800MeV

	Pure Baryonic	k^f_{DM}(GeV)		
		0.00	0.03	0.06
$M(M_\odot)$	2.14	2.50	2.34	1.66
R (km)	11.74	13.64	12.73	9.54
$R_{1.4}$ (km)	12.72	13.52	12.62	9.62

IV.CONCLUSION:

We investigate the properties of neutron stars infused with dark matter within the framework of the quarkyonic model, specifically focusing on the IOPB-I parameter set. For the first time, our study introduces a novel approach that combines dark matter and quarkyonic matter while employing the relativistic mean-field formalism.

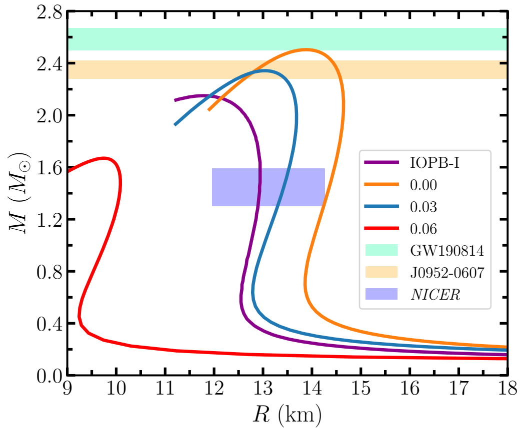

FIG. 1: Mass-radius profile at transition density(n_t)= 0.3 fm^{-3} and confinement parameter (Λ_{cs})=800 MeV with permissible value of dark matter momentum(k^f_{DM})

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References

[1] Bharat Kumar, S. K. Patra and B. K. Agrawal, Phys Rev C, **96**, 045806 (2018)

[2] Zhao, Tianqi and Lattimer, James M, Phys. Rev. D, **96**, 023021 (2020)

[3] G. Panotopoulos, and I. Lopes, Phys. Rev. D, **96**, 083004 (2017).