PROCEEDINGS OF SCIENCE

Neutron Stars: EoS, Hyperons and Dark Matter

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Finding the correct EoS for matter at the densities encountered in neutron stars presents many challenges. We discuss the so-called hyperon puzzle and its solution before turning to the potential effects of dark matter.

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1. Introduction

With the first gravitational wave detection of the merger of two neutron stars (NS) [1, 2] and the promise of more, as well as the first results from satellite observations [3] of hot-spots [4], there is considerable excitement concerning the composition of neutron stars. Modern theories need to account for stars with masses in excess of 2 $M_\odot$ and in the most common range of masses, around 1.4 $M_\odot$, satisfy the latest constraints on tidal deformability and radii.

Historically the particle content of NS was assumed to consist primarily of neutrons [5], along with protons and electrons. As the time scale for the formation of a neutron star is seconds and the time scale for weak interactions nano-seconds, one expected the matter to be in β-equilibrium with $\mu_n = \mu_p + \mu_e$. However, as the central density rises and the star gets heavier, the chemical potential of the neutron will rise to the point that hyperons can also appear under β-equilibrium [6]. They are stable because of Pauli blocking in the dense medium.

Indeed, it seems inevitable that hyperons *must* appear. Yet, the appearance of a new baryon species will initially mean they have low momentum and hence contribute less to the pressure. Lower pressure makes it difficult to sustain a large mass. Non-relativistic calculations including hyperons universally led to predictions of maximum masses for NS around 1.6 $M_\odot$ or less [7]. This is far below the observed maximum mass, which is a little over 2 $M_\odot$; hence the ”hyperon puzzle”.

This paper summarizes a contribution to a plenary panel discussion at the QCHS Conference. We address the hyperon puzzle in the next section, along with a discussion of the effect of hyperons if they do indeed appear. In section 3 we explore some ideas about the occurrence and effects of dark matter in NS. Section 4 contains some concluding remarks.

2. Hyperons in neutron stars

Since the original suggestion that one might indeed have heavy NS containing hyperons, there have been many studies of this problem. Although more exotic explanations, such as a modification of gravity [8], there is a consensus that, in order to satisfy the maximum mass constraint, there must be a repulsive three-body force contributing to the EoS at higher density. The first proposal for such a force was made using the quark-meson coupling (QMC) model [9] *before* the first heavy star was discovered by Demorest *et al.* [10, 11]. In that model [12–14] such a force is generated naturally between all baryons, without additional parameters, by their self-consistent response to the large scalar mean field in the dense medium [15]. More recent studies have suggested phenomenological three-body forces involving hyperons so large that they never appear [16] but this does appear somewhat extreme.

There is a consensus among modern relativistic calculations of NS structure that the first hyperons to appear are the Λ-hyperons, with a threshold somewhat over three times nuclear matter density ($3\,n_0$). There is disagreement over what comes next, with the majority of models suggesting the Σ^-. (Recall that β-equilibrium requires $\mu_{\Sigma^-} = \mu_n + \mu_e$.) Of course, with little data on $\Sigma - N$ scattering and only one very light Σ-hypernucleus known, the constraints on phenomenological ΣN forces are very weak. Within the QMC model there are no additional parameters associated with introducing the Σ. There is, however, some new physics; the strong scalar field in-medium enhances the color hyperfine interaction [17], which is the reason that the Σ lies higher in mass than the Λ in

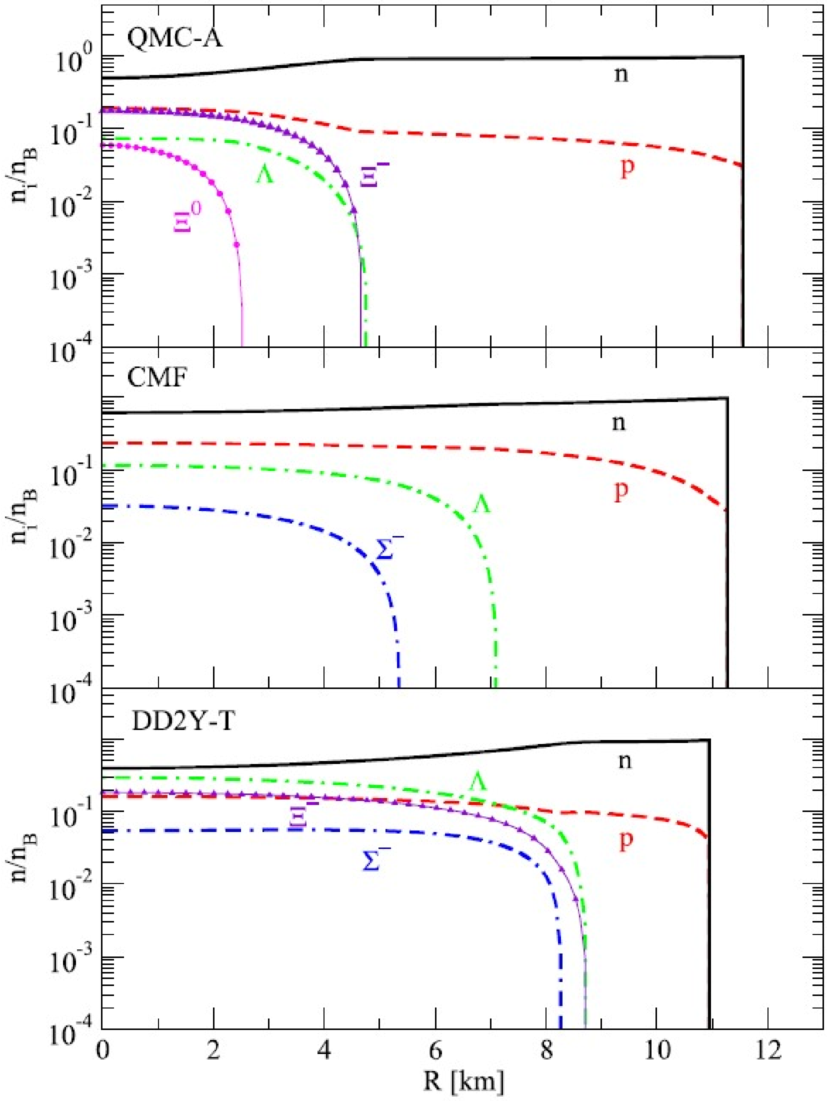

Figure 1: Radial distribution of particles in maximum mass neutron stars in three relativistic models – taken from Fig. 7 of ”Equation of state of hot dense hyperonic matter in the Quark–Meson-Coupling (QMC-A) model”, J. R. Stone *et al.*, MNRAS **502** 3476 (2021) [19].

free space. This effect means that within QMC the Σ^- plays no role in NS. This same effect also excludes Δ^- baryons [18].

The amazingly rich structure of a heavy NS containing hyperons is illustrated in Fig. 1.There we show the radial distribution of the nucleons and hyperons within a star for three relativistic models which produce stars with a maximum mass around 2 $M_\odot$. We see the remarkable result that there is an enormous amount of strange matter ranging out as far as 5-8 km from the centre of the star.

One of the potentially observable consequences of the presence of hyperons is that they lower the speed of sound in the dense medium [20]. This is especially important in the light of the work of Annala *et al.* [21], who derived the constraints on the EoS of matter in a NS by considering

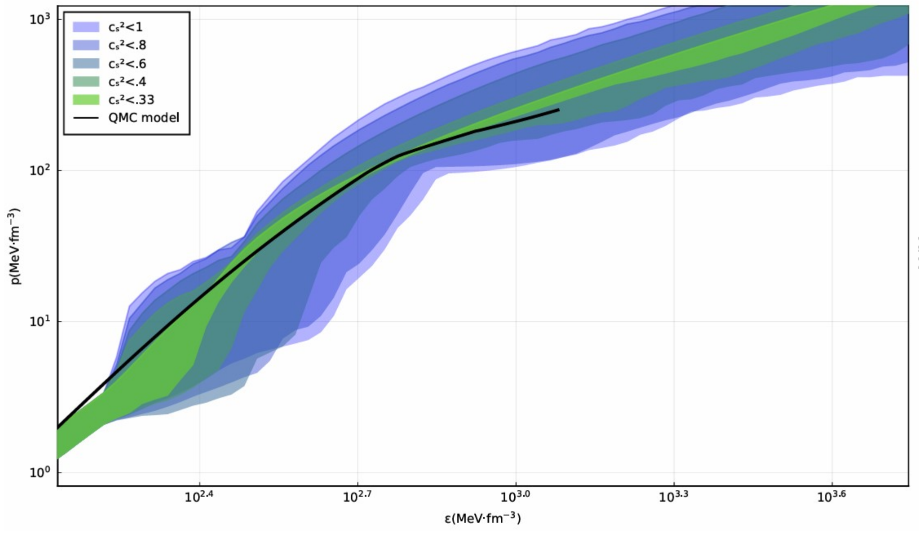

Figure 2: The shaded areas show the constraints on the EoS of dense matter in a neutron star [21], while the dark line shows the QMC prediction – taken from Fig. 4 of "On the sound speed in hyperonic stars", T. F. Motta *et al.*, Nucl. Phys. **A1009** 122157 (2021) [20].

constraints on the speed of sound. Their resulting EoS is shown in Fig. 2 and the conclusion that finding a low speed of sound (c_s^2 $1/3$) would signal the presence of deconfined quark matter. The dark curve labelled QMC agrees very well with their constraints on the EoS because of the presence of hyperons. Clearly one will need another signature in order to distinguish these possibilities.

3. Dark matter

There is tremendous interest at the moment in the potential effects of the capture of dark matter (DM) in our Sun, in stars and, of course, in NS [22]. Using data on their cooling, the estimated rate of capture in NS has been shown to set strong limits on the DM-nucleon cross section as a function of the DM mass [23, 24].

There are strong arguments which limit the maximum amount of DM that can be captured on a NS. However, such bounds can be finessed if there is a mechanism to create DM in the star. The remarkable discrepancy between two methods of measuring the neutron lifetime has provided just such a mechanism. Whereas the bottle method measures the total lifetime, the beam method, in which a decay proton is seen, is sensitive only to the lifetime for that decay. Fornal and Grinstein suggested that the roughly 1% difference, with the beam measurement being shorter, might indicate the existence of another decay mode, involving DM [25].

Within a few days of each other, three groups independently published the result that, if that rare decay mode were $n \to \chi + \phi$, where the DM χ must be almost degenerate with the neutron, there would be disastrous consequences for NS [26–28]. The high Fermi level in the degenerate Fermi gas would lead to the rapid decay of a large fraction of the neutrons and the maximum NS mass would drop to around 0.7 $M_\odot$. Clearly this rules out such a decay mode unless the DM experiences a relatively strong, repulsive self-interaction [29].

A more recent suggestion for the possible rare decay of the neutron involved the decay mode $n \to \chi\chi\chi$, with the DM χ particle having a mass almost exactly one third of the mass of the neutron [30]. In this case there is no need for a strong repulsive force in order to retain consistency with observed NS masses. There are potentially observable consequences of this decay mode, in that the NS would be expected to both heat up and spin up as the decay occurs [31, 32].

4. Outlook

With the projected increase in sensitivity of LIGO and the NICER detector in action, we can expect a great deal of new information on neutron stars and neutron star mergers. This should significantly reduce the errors on the radius of stars as a function of mass, as well as providing more accurate values of the tidal deformability. In addition to the potential for discovery of more heavy neutron stars, one may hope that the measurements of their masses will improve in accuracy. All of this will place extremely strong constraints on the equation of state of the most dense matter in the Universe. This in turn will deepen our understanding of QCD itself.

New ideas concerning the effects of dark matter on neutron stars emerge regularly and there is every chance that our understanding of this phenomenon will be advanced by the study of these remarkable objects.

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