Neutron star structure with a new force between quarks

Jeffrey M. Berryman
Department of Physics, University of California, Berkeley, CA 94720, USA and
Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055, USA

Susan Gardner
Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055, USA

The discovery of nondiffuse sources of gravitational waves through compact-object mergers opens new prospects for the study of physics beyond the Standard Model. In this paper, we study the effects of a new force between quarks, suggested by the gauging of baryon number, on pure neutron matter at supranuclear densities. This leads to a stiffening of the equation of state, allowing neutron stars to be both larger and heavier and possibly accommodating the light progenitor of GW190814 as a neutron star. The role of conventional three-body forces in neutron star structure is still poorly understood, though they can act in a similar way, implying that the mass and radius do not in themselves resolve whether new physics is coming into play. However, a crucial feature of the scenario we propose is that the regions of the new physics parameter space that induce observable changes to neutron star structure are testable at low-energy accelerator facilities. This testability distinguishes our scenario from other classes of new phenomena in dense matter.

Introduction. The environment of a proto-neutron star (NS) has long been known to be exquisitely sensitive to the appearance of light, new physics (NP), such as axions [1–7] or dark photons [8–10], through cooling effects. Dark matter can also be captured by NSs, altering them so severely that the established existence of NSs constrains dark matter properties [11, 12]. With the advent of gravitational wave (GW) observations of compact object mergers [13], new windows on the nature of matter at supranuclear densities open [14]. There has been much discussion of emergent phenomena within QCD at near-zero temperature $T$ with neutron chemical potential $\mu_n$, with transitions to condensed phases [15] of pions [16] and kaons [17], or to a spin-color-flavor-locked $qq$ phase [18, 19], or to states with substantial admixtures of $s$ and $\bar{s}$ quarks all possible [20,22]. The structure of NSs is also sensitive to new neutron decay channels, as noted in new physics models for the neutron lifetime anomaly [23–24], yielding severe constraints [25,27].

Here, we consider minimal extensions of the Standard Model (SM) that give rise to new, short-range interactions between quarks. In particular, we consider U(1)$_X$ extensions that couple to baryon number $B$; such models have proven popular in searches for light hidden sectors in low-energy accelerator experiments [28] because the possibility that the neutrino has a Majorana mass predicates that the $B - L$ symmetry of the SM is broken. If $B$ symmetry is spontaneously broken to give a gauge boson $X$ no lighter than a few hundred MeV, then the new interaction is largely shielded from constraints from low-energy experiments. In particular, its contribution to the nucleon-nucleon ($NN$) force can be hidden within the short-distance repulsion of the phenomenological $NN$ force in the SM, recalling, e.g., the repulsive hard core of the Reid potential at separations of $r_{nc} = 0.5$ fm [29], yet it can modify the neutron matter equation of state (EoS) at supranuclear densities, i.e., beyond the saturation number density of ordinary nuclear matter, $n_{sat}$ [30]. We expect these models to be accompanied by electromagnetic signatures, such as, e.g., brighter kilonovae, due to $X - \gamma$ mixing, but reserve this for later work [31].

Theoretical Framework. The lighter compact object in GW190814 is of $2.50 - 2.67 M_\odot$ (90% credible level) in mass [32], and is likely too heavy to be a NS, at least within a nonrelativistic many-body approach using $NN$ forces from chiral effective theory, with low-energy constants (LECs) determined from nuclear data [32]. Relativistic mean-field models can generate masses in excess of $2.6 M_\odot$ [33], though they are challenged by constraints from heavy-ion collisions (HIC) [34]; we note Refs. [35–56] for further discussion of the light progenitor of GW190814 as a neutron star. We consider our NP model within a nonrelativistic many-body framework. Drischler et al. [57] recognize the importance of relativistic corrections but also think that knowledge of the high-density EoS is likely inadequate. In particular, they adopt a piecewise EoS: beyond some density cutoff, the EoS is given by the stiffest form allowed by causality. They choose a cutoff density in the region $(1 - 2)n_{sat}$ and claim that the modified EoS and NS outcomes below that cutoff can be made without relativistic corrections.

The chiral effective theory approach uses $NN$ and nuclear data to determine the LECs, with independent two- and three-body forces coming into play [58,59]. In contrast, our Abelian NP model directly yields two-body forces only. To sharpen the distinction between SM and NP effects, we employ the AV18 $NN$ interaction [60], whose properties are determined by $NN$ observables only. Studies of the AV18 interaction in pure neutron matter (PNM) with different nonrelativistic methods show that it compares favorably with other interactions up to about $4n_{sat}$ [61]. Here, we compare
computations of the PNM EoS using Brueckner-Hartree-Fock (BHF) theory with the AV18 interaction with and without NP.

Secret Interactions of Quarks. That new interactions could exist between quarks is a long-standing possibility [62,66], and SM extensions in which a new vector mediator couples to baryon number $B$ could give rise to Eq. (1) and thus be operative. For example, if $X$ models [65, 78] could give rise to Eq. (1) and thus be operative. We consider partial waves up to $J_{\text{max}} = 11$, facilitating comparison with Ref. [61]. Considering only the AV18 potential, we obtain $E/A = 13.7$ MeV at $n = n_{\text{sat}} = 0.16$ fm$^{-3}$, compared to 13.4 MeV [61]; for $n = 0.3$ fm$^{-3}$, we obtain 26.0 MeV, in perfect agreement.

A primary source of uncertainty in nuclear matter calculations is the precise many-body technique employed. For instance, Ref. [61] contrasts several such methods and finds that the in-medium potential energies may differ by a factor of $\approx 2$ at supernuclear densities for the same $NN$ potential. However, our purpose is to identify the new interaction produces significant changes to NS properties. To remedy this, we have also considered partial waves up to $J_{\text{max}} = 11$, facilitating comparison with Ref. [61]. Considering only the AV18 potential, we obtain $E/A = 13.7$ MeV at $n = n_{\text{sat}} = 0.16$ fm$^{-3}$, compared to 13.4 MeV [61]; for $n = 0.3$ fm$^{-3}$, we obtain 26.0 MeV, in perfect agreement.

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PNM. The results are also shown in Fig. 1a; the curves have the same interpretation as for the BHF case. Here we find $M_{\text{TOV}} \sim 2.1 M_\odot$ — this is consistent with the mass of PSR J0740+6620, $2.14^{+0.10}_{-0.09} M_\odot$, but is still too light to explain GW190814. In both cases, the new interaction generates larger NS masses, as anticipated, but also increases the radius of NSs of a given mass.

To contextualize Fig. 1a, we show the region in the $M$-$R$ plane in which the NS becomes a black hole (BH), as well as a limit on NS properties from causality [93]. Moreover, we show the posterior probability on the radius of a $1.4 M_\odot$ NS, $P(R_{1.4}|d)$, conditioned on data $d$ from heavy pulsars, gravitational wave events and NICER observations of PSR J0030+0451, adapted from Fig. 10 of Ref. [86]. Lastly, we have included the EoS derived for quarkyonic matter in Ref. [85] as an example with a quark/hadron QCD phase transition. The salient feature of this EoS is that the transition from hadronic to mixed hadron-quark matter induces a spike in $c_s^2$ at a few times saturation density; similar features are present in some of the sound speed profiles considered in Ref. [94]. This rapid stiffening of the EoS is sufficient to allow for heavier NSs and is consistent with inferences of $c_s^2$ from HIC, shown in shading. As with PNM, the pure BHF EoS is too soft to accommodate observations, but the APR EoS is a plausible candidate. The new interaction stiffens the EoS, as expected, but not so much that the HIC constraint is violated. For context, we show several mean-field EoS [33, 95–97]. We note that the pressure for APR+NP is nonzero at empirical saturation density; we expect this to be resolved with a more refined treatment, while still generating nontrivial effects at higher densities.

Constraints. In Fig. 3 we show the region in the $\alpha_B M_X^2 = (600 \text{ MeV})^{-2}$ for four finite values of $M_X$. Also shown are the contact-interaction limit and the baseline APR EoS. Lighter states generate larger contributions to the EoS, and thus to NS properties, owing largely to their effects on higher partial-wave potentials. Contact interactions only contribute to $s$-wave scattering, whereas finite-mass states contribute at all orders. Because higher partial waves become more important at higher densities, the outcome is shown in Fig. 1b. The pure contact interaction produces a result that is barely distinguishable from the nominal APR curve.

In Fig. 1b, we fix the interaction strength to be $\alpha_B M_X^2 = (600 \text{ MeV})^{-2}$ for four finite values of $M_X$. Also shown are the contact-interaction limit and the baseline APR EoS. Lighter states generate larger contributions to the EoS, and thus to NS properties, owing largely to their effects on higher partial-wave potentials. Contact interactions only contribute to $s$-wave scattering, whereas finite-mass states contribute at all orders. Because higher partial waves become more important at higher densities, the outcome is shown in Fig. 1b. The pure contact interaction produces a result that is barely distinguishable from the nominal APR curve.

We also calculate the EoS of symmetric nuclear matter (SNM) using the same techniques with $J_{\text{max}} = 8$. In Fig. 2 we show the pressure determined in our BHF and APR schemes, and we include NP with $\alpha_B = 1$ and $M_X = 600$ MeV. We compare these with inferences of the EoS from HIC, shown in shading. As with PNM, the pure BHF EoS is too soft to accommodate observations, but the APR EoS is a plausible candidate. The new interaction stiffens the EoS, as expected, but not so much that the HIC constraint is violated. For context, we show several mean-field EoS [33, 95–97]. We note that the pressure for APR+NP is nonzero at empirical saturation density; we expect this to be resolved with a more refined treatment, while still generating nontrivial effects at higher densities.

Constraints. In Fig. 3 we show the region in the $\alpha_B -$
$M_X$ plane in which $M_{TOV}$ is increased by $0.1 - 0.5M_\odot$ relative to the APR EoS. We now turn to potential constraints on this scenario from low-energy physics. The presence of NP induces a contribution to the $NN$ scattering lengths. In the Born limit, the $n\,^1S_0$ scattering length is modified by

$$\Delta a_{1S_0} = \frac{\alpha_B a m_N}{M_X^2} \approx (0.5 \text{ fm}) \times \alpha_B \left( \frac{600 \text{ MeV}}{M_X} \right)^2.$$  

We emphasize the AV18 potential is phenomenological — it is fit to low-energy $NN$ data, not derived from first principles. If the potential parameters were determined in the presence of NP, the effects of NP would presumably be obscured; we leave a detailed study to future work [31].

Therefore, low-energy $NN$ scattering does not provide a robust constraint on this scenario. New baryon-coupled physics can also be probed by lead-neutron scattering [104, 105]. Ref. [105] presents a constraint for masses below 40 MeV; Ref. [70] extends this into the $O(100)$ MeV mass range. However, if the range of the new force is not longer than the range of the nuclear force, then it is difficult to disentangle the two without a first-principles description of the latter, and the treatments of Refs. [104, 105] are unsuitable to this mass region. As such, we do not consider this constraint further.

We calculate the contribution of our new boson to several rare $\eta^0$ decays using the vector meson dominance model [106–109]. We assume that the decays proceed via $\eta^0 \rightarrow X\gamma$, $X \rightarrow \pi^0\gamma$, $\pi^+\pi^-\pi^0\eta$, through $X$-meson mixing and that the SM contribution is zero. The observables are ratios of the rare decay widths to the widths for $\eta \rightarrow \pi^0\gamma$ [103]. The solid curve in Fig. 3 shows the constraint derived from $\eta \rightarrow \pi^0\gamma$. Following Ref. [70], we require that the contribution from $X$ not exceed $3 \times 10^{-4}$ [103]; equality gives the curve shown. The SM contributions to $\eta^0 \rightarrow \pi^0\gamma$ are not negligible; moreover, different width assessments exist [98–102] and further exploration is needed [31]. The upcoming JLab Eta Factory (JEF) experiment [110, 111] can perform a bump hunt in $\pi^0\gamma$ invariant mass, greatly enhancing the sensitivity to the $X$ gauge boson while mitigating sensitivity to the theoretical production rate [112].

Figure 3 also shows constraints from decays of $\eta'$ to $\pi^0\gamma$ [113], $\pi^+\pi^-\pi^0\eta$ [114] and $\eta\gamma$ [115]. The possibility of gluonium content in the $\eta'$ [116, 117] also complicates their interpretation. Analyses of neutral meson radiative decays do not agree on its size [118, 119], where the inclusion of $\Gamma(\eta' \rightarrow \gamma\gamma)/\Gamma(\pi^0 \rightarrow \gamma\gamma)$ data drives this difference and a larger effect [119]. Our estimates assume this is zero, so that observed deviations between SM predictions and experiment could also derive from this effect. An alternative strategy for observing $X$ would be to search for bumps in invariant mass distributions in these decays. We caution, however, that there are regions in parameter space in which we expect the $X$ to be wide: this is so for $\alpha_B \gtrsim O(10^{-1})$ around the $\omega$ resonance, and for $\alpha_B \gtrsim O(1)$ above $M_X \sim 1 \text{ GeV}$. In these regimes, the $X$ would not present as a localized feature in invariant mass and bump hunts would become less effective. These decays could be measured precisely at JEF.
and REDTOP [120][122], though the sensitivities have not been benchmarked. Additionally, the ultimate sensitivity of GlueX to X photoproduction ($\gamma p \rightarrow p X$) affords a sensitivity to couplings of order $O(10^{-5} - 10^{-4})$ for narrow X off the $\omega$ resonance [124]; this is also shown in Fig. 3.

Summary. We have considered how a new force between first-generation quarks can make NSs for a fixed EoS and many-body method both heavier and puffier. This mechanism has not been considered previously, though new forces for strange quarks have been considered [125]; the attractive AN interaction has long made the existence of $\approx 2M_\odot$ NSs a puzzle [88], though three-body forces may reduce the effect [126]. We have described how our NP scenario can be tested through studies of rare $\eta$ and $\eta'$ decays [112][122] and of X photoproduction [124] at low-energy accelerators. Finally, we have not resolved the nature of the $\approx 2.6M_\odot$ compact object in GW190814, this mechanism allows it to more naturally be a NS. The spin of that object, though poorly determined, may have been sufficient to increase its mass by $(0.1-0.4)M_\odot$; differential rotation can push this even higher [133][135], but these configurations are not expected to be stable over long time scales. Combining spin effects with NP could yield additional heavy NSs; thus more compact objects in excess of $2M_\odot$ may eventually be identified, promoting the possibility of new baryonic interactions.

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