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Universal Nuclear Equation of State Introducing the Hypothetical X17 Boson

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Abstract: Within the scope of the Symmetry journal special issue on: "The Nuclear Physics of Neutron Stars", we complemented the nuclear equation of state (EoS) with a hypothetical 17 MeV boson and observed that only instances with an admixture of 30%–40% satisfy all of the constraints. The successful EoS resulted in a radius of around 13 km for a neutron star with mass $M_{NS} \approx 1.4 M\odot$ and in a maximum mass of around $M_{NS} \approx 2.5 M\odot$. The value of the radius is in agreement with the recent measurement by NICER. The maximum mass is also in agreement with the mass of the remnant of the gravitational wave event GW190814. Thus, it appears that these EoSs satisfy all of the existing experimental constraints and can be considered as universal nuclear equations of state.

Keywords: X17; EoS; neutron star

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1. Introduction

In 2016, Krasznahorkay et al. [1] reported an anomaly in the angular correlation of the electron–positron decay of the 1^+ excited level of a ^{8}Be nucleus at 18.15 MeV. An enhancement at a folding angle close to 140 degrees was interpreted as a signature of decay via the emission of a neutral boson with a mass of around $m_X = 17$ MeV. Subsequently, a similar effect was reported by the same group in the decay of the lower 1^+ excited state of ^{8}Be at 17.6 MeV [2] and later in the 0^- excited state of ^{4}He at 21.01 MeV [3], at a folding angle close to 115 degrees. Also recently, the same group investigated the 17.2 MeV $1^- \rightarrow 0^+$ transition of the ^{12}C nucleus, resulting in an excess in the folding angle of around 155 degrees [4]. These reported observations placed the hypothetical X17 boson as a dark matter candidate, and, in that spirit, since then, several theoretical works pursued this claim [5,6].

However, an explanation relating this particle to the QCD vacuum was also proposed [7]. In this picture, the 17 MeV particle mediates nucleon–nucleon interactions at large distances between nucleons in the otherwise unbound cluster configuration. A corresponding equation of state was obtained, which was also applied to neutron stars [8].

Since the assumption that the 17 MeV boson is the only carrier of nuclear interactions is somewhat extreme, we explored the possibility of constructing a nuclear equation of state (EoS), introducing both an ω meson with mass 782.5 MeV and a 17 MeV boson in an admixture, which were then tested using experimental constraints on nuclear matter, finite nuclei and heavy ion collisions. The presented analysis falls within the scope of the Symmetry journal special issue on: "The Nuclear Physics of Neutron Stars".

The paper is organized as follows: in Section 2, we introduce the universal nuclear EoS, in Section 3 we present our findings and in Section 4, we discuss the results.

2. Tolman–Oppenheimer–Volkoff Equations and the Equation of State

The structure of a neutron star is usually described using the Tolman–Oppenheimer–Volkoff (TOV) equations (Equations (1) and (2)) based on general relativity:

$$\frac{dP}{dr} = \frac{-G}{c^2} \frac{(P+\epsilon)(m + \frac{4\pi r^3 P}{c^2})}{r(r - \frac{2Gm}{c^2})} \tag{1}$$

$$\frac{dm}{dr} = 4\pi r^2 \frac{\epsilon}{c^2} \tag{2}$$

where $m(r)$ is the total mass contained within radius r and pressure P. The only model-dependent input is the EoS of nuclear matter, which is what makes the neutron star an ideal laboratory for nuclear physics. The EoS of nuclear matter can be described by relativistic mean field theory [9]. The corresponding equations for infinite symmetric nuclear matter are:

$$\begin{aligned} \epsilon = {} & \frac{g_v^2}{2m_v^2}\rho_N^2 + \frac{m_s^2}{2g_s^2}(m_N - m_N^*)^2 + \frac{\kappa}{6g_s^3}(m_N - m_N^*)^3 \\ & + \frac{\lambda}{24g_s^4}(m_N - m_N^*)^4 + \frac{\gamma}{(2\pi)^3}\int_0^{k_F} d^3k\sqrt{k^2 + (m_N^*)^2} \end{aligned} \tag{3}$$

$$\begin{aligned} P = {} & \frac{g_v^2}{2m_v^2}\rho_N^2 - \frac{m_s^2}{2g_s^2}(m_N - m_N^*)^2 + \frac{\kappa}{6g_s^3}(m_N - m_N^*)^3 \\ & + \frac{\lambda}{24g_s^4}(m_N - m_N^*)^4 + \frac{1}{3}\frac{\gamma}{(2\pi)^3}\int_0^{k_F} d^3k\frac{k^2}{\sqrt{k^2 + (m_N^*)^2}} \end{aligned} \tag{4}$$

where ϵ is the energy density, P is the pressure for pure neutron matter, g_s and g_v are the couplings of the scalar and vector boson, respectively, m_s and m_v are the rest masses of scalar and vector bosons, κ and λ are the couplings of the cubic and quartic self-interaction of the scalar boson, m_N and m_N^* are the rest mass and the effective mass of the nucleon, ρ_N is the nucleonic density, k_F is the Fermi momentum of nucleons at zero temperature and γ is the degeneracy (with value γ = 4 for symmetric nuclear matter and γ = 2 for neutron matter).

The EoSs (Equations (3) and (4)), which are regularly used with the ω-meson in the role of the vector boson, were used in [8] for TOV calculations under the assumption that the nuclear force is being mediated by a 17 MeV boson, as reported in the study of the anomalous electron–positron pair production in the excited states of ^{8}Be [1,2], ^{4}He [3] and ^{12}C [4]. Here, we extended our previous work by using the assumption that both the ω-meson and the 17 MeV boson mediate the nuclear force as vector bosons.

After writing the corresponding relativistic mean field (RMF) Lagrangian:

$$\begin{aligned} L_{MFT} = \overline{\psi}\{i\partial^\mu\gamma_\mu - g_v V_0\gamma_0 - (M - g_s\Phi_0)\}\psi - \frac{1}{2}m_s^2\Phi_0^2 - \frac{1}{3!}k\Phi_0^3 - \frac{1}{4!}\lambda\Phi_0^4 \\ + \frac{1}{2}m_\omega^2(1-q)^2V_0^2 + \frac{1}{2}m_X^2 q^2 V_0^2 \end{aligned} \tag{5}$$

with duplicate vector boson terms, we conclude that the resulting EoS will be identical to the above, with "effective" vector boson mass:

$$m_v^{*2} = q^2 m_X^2 + (1-q)^2 m_\omega^2 \tag{6}$$

where q is the admixture coefficient of the $m_X = 17$ MeV boson to the total vector potential. Depending on the value of q, the effective mass can range from $m_\omega = 782.5$ MeV to 17 MeV. We decided to test this theory using various available constraints, ranging from properties of finite nuclei, through heavy ion collisions all the way to the neutron stars.

3. Analysis Results

As a first step, we generated the EoS of infinite symmetric nuclear matter using values of the vector boson effective mass corresponding to an admixture of a 17 MeV boson ranging between 20% to 50% and choosing the values of couplings within corresponding ranges depicted in Table 1. Each set of parameters was tested for binding energy (16 MeV) and saturation density ρ_0 = 0.15–0.16 fm^{-3}. Successful sets of parameters were further tested for incompressibility within the range: K_0 = 250 $\pm$ 20 MeV.

Table 1. Constrained parameter sets for three EoSs with three admixtures q and incompressibility K_0 = 250 $\pm$ 20 MeV.

K_0	q	κ	λ	g_v	g_s	m^*_v [MeV]	m_σ [MeV]
235.95	0.3	21.50	−163.33	8.38	9.20	547.77	482.16
269.14	0.4(A)	11.00	−50.00	6.85	7.23	469.55	391.44
257.50	0.4(B)	11.50	−60.00	6.85	7.23	469.55	391.44

The parameter sets that passed the first step were used to calculate properties of the finite nucleus ^{208}Pb; in particular, its binding energy (1636 MeV) and neutron skin $\Delta R_{PREX2} = 0.283 \pm 0.071$ fm. The latter value is of special interest since recent measurements [10] reported a value larger than the predictions of theory. The RMF code of Ring, Gambhir and Lalazissis from CPC [11] was used for calculation. The code also uses the ρ-meson as a mediator of the isovector interaction and thus a measure of the symmetry energy. We kept the ρ-meson coupling identical to the NL3 EoS [12]. The NL3 EoS can reproduce the values of the binding energy and neutron skin of ^{208}Pb; however, the incompressibility is unrealistically high and constraints from nuclear reactions are not satisfied.

A typical picture is shown in Figure 1, where the values of the binding energy and the neutron skin $\Delta R = R_n - R_p$ are plotted. The main sequence does not seem to fulfill both constraints; nevertheless, several combinations of parameters appeared to satisfy both constraints. These were parameter sets with the 17 MeV boson admixture ranging between 20% and 40%. However, the parameter sets with a 20% admixture fail to satisfy constraints from heavy ion collisions [13], and thus only parameter sets with an admixture of 30% to 40% remain, signalling that there is some range of admixtures that satisfies all of the constraints. Such an observation can have physical meaning.

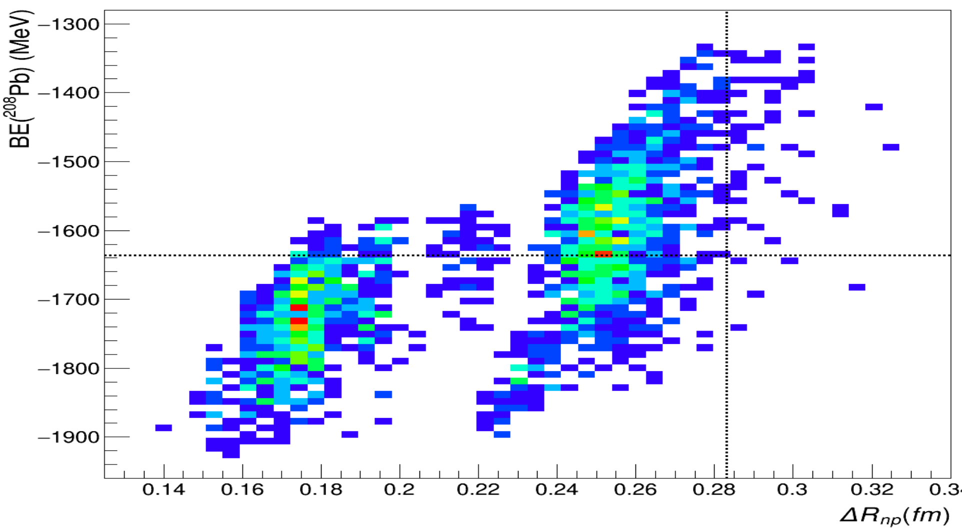

Figure 1. (Color online). Binding energy (BE) of the ^{208}Pb versus its neutron skin using 30% admixture of the 17 MeV boson in an EoS.

For the TOV calculations, the equation of state $P(\rho)$ needed to be expressed in the form of polytropes. For that reason, three transition densities were defined—ρ_1 =

2.8×10^{14} g/cm^3, ρ_2 = $10^{14.7}$ g/cm^3 and ρ_3 = 10^{15} g/cm^3—and four parameters were calculated: three exponents of the power law polytropes $\Gamma_1, \Gamma_2, \Gamma_3$, respectively, and the value a_0 (where $a_0 = log(p(\rho_1)) + \Gamma_1(log(\rho_2) - log(\rho_1))$. In the last step, the remaining equations of state, specifically their versions for pure neutron matter, were used as an input to the TOV equation, and the resulting mass–radius plot is shown in Figures 2 and 3. The three EoSs listed in Table 2 result in a radius of the neutron star of 1.4 solar masses around 13 km and a maximum mass of the neutron star of around 2.5 solar masses. The value of the radius is in agreement with the recent measurement by NICER [14,15], and the value of the maximum mass is in agreement with the recently reported mass of pulsar 2.35 solar masses [16] and potentially also with the mass of the remnant of the gravitational wave event GW190814 [17]. Thus, it appears that these three EoSs satisfy all of the existing experimental constraints and can be considered as universal equations of state of nuclear matter.

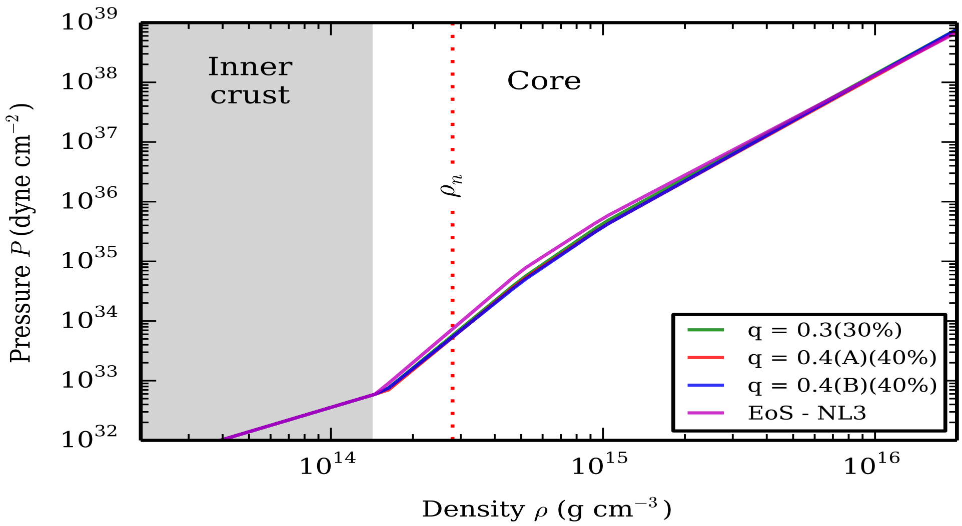

Figure 2. (Color online). The pressure as function of nuclear density for three EoSs with admixtures of 30% and 40% of the 17 MeV boson plus the NL3 EoS. The parameters are defined in Table 2.

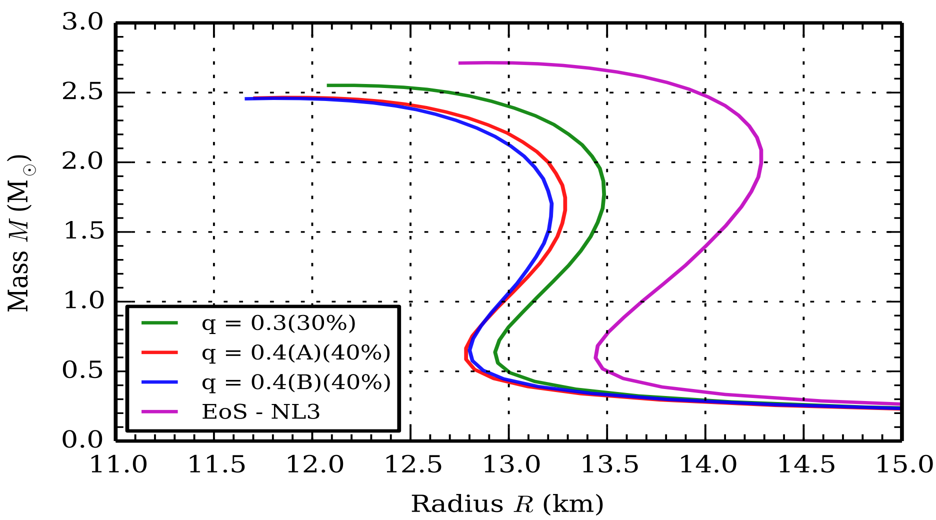

Figure 3. (Color online). The mass–radius relation for three EoSs plus the NL3 with admixtures of 30% and 40% of the 17 MeV boson plus the NL3 EoS.

Table 2. Polytropes for three EoSs plus the NL3 EoS used for the Tolman–Oppenheimer–Volkoff calculations. The 0.3 EoS represents a 30% admixture of the $X17$ boson and the 0.4A and 0.4B EoSs represent a 40% admixture with different values of parameters κ and λ.

EoS q-Admixture (%)	a_0	Γ_1	Γ_2	Γ_3	K_0 (MeV)
0.3 (30%)	34.703	3.741	3.118	2.497	235.95
0.4(A) (40%)	34.673	3.744	3.036	2.517	269.14
0.4(B) (40%)	34.653	3.643	3.095	2.540	257.50
NL3 (0%)	34.846	3.872	2.925	2.394	332

4. Conclusions

In summary, within the scope of the Symmetry journal special issue on: "The Nuclear Physics of Neutron Stars", we implemented a hypothetical 17 MeV boson to a nuclear EoS complementing the ω meson and observed that only instances with an admixture of 30–40% satisfy all of the experimental constraints. When applied to TOV equations, the successful EoSs result in a radius of around 13 km for a neutron star with a mass of $M_{NS} \approx 1.4 M\odot$ and in a maximum mass of around $M_{NS} \approx 2.5 M\odot$. The values of our results are in good agreement with the recent measurement reported by NICER [14,15]. The obtained value of the maximum mass is also in agreement with the recently reported mass of a pulsar [16] and potentially also with the mass remnant of the gravitational wave event GW190814 [17]. Thus, it appears that these EoSs satisfy all of the existing experimental constraints and can be considered as universal EoSs of nuclear matter.

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