

Proceeding Paper

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Proceeding Paper

# Novel Concepts of Nuclear Physics in a Neutron Star Environment <sup>†</sup>

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**Abstract:** Neutron stars are like nuclear physics laboratories, providing a unique opportunity to apply and search for new physics. In that spirit, we explored novel concepts of nuclear physics studied in a neutron star environment. Firstly, we investigated the reported 17 MeV boson, which has been proposed as an explanation to the  $^8\text{Be}$ ,  $^4\text{He}$  and  $^{12}\text{C}$  anomaly, in the context of its possible influence on the neutron star structure, defining a universal Equation of State. Next, we investigated the synthesis of hyper-heavy elements under conditions simulating the neutron star environment.

**Keywords:** X17; EoS; CoMD; hyper-heavy nuclei; neutron star



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## 1. Introduction

In this review article, we present parts of our earlier work on neutron stars concerning two concepts [1,2]. In the first concept, the reported 17 MeV (hereafter X17) boson—proposed as an explanation to the  $^8\text{Be}$ ,  $^4\text{He}$  and  $^{12}\text{C}$  anomalies—was investigated in the context of its possible influence on the neutron star structure, resulting a universal Equation of State (EoS). In the second concept, the formation of hyper-heavy nuclei was investigated and simulated for a neutron star environment. Using Constrained Molecular Dynamics (CoMD) code, it appears that in a nucleonic background surrounding, such as that found inside a neutron star, fusion can become possible even in temperatures as low as  $10^8$  K.

## 2. Novel Method of Constructing a Universal Equation of State

From 2016 to the present day, Krasznahorkay and his group reported an anomaly in the angular correlation of the electron–positron emission in the excited states of the  $^8\text{Be}$ ,  $^4\text{He}$  and  $^{12}\text{C}$  [3–6]. This anomaly at a folding angle was interpreted as a signature of a new neutral boson with a mass of approximately 17 MeV. An experimental cross-check determining the existence (or lack thereof) of that new boson is still in need of investigation. In this context, it is interesting to stress that a narrow peak of similar energy was observed in a recent experiment which was not dedicated to X17 boson research [7]. In our work, we followed a different phenomenological approach investigating the construction of a nuclear EoS, introducing both an  $\omega$  meson with mass 782.5 MeV and a X17 boson in an admixture from 20% to 50%. In our investigation, for consistency, we tried to include all the experimental constraints of nuclear matter for finite nuclei and heavy ion collisions.

### 2.1. The Equation of State and the RMF Lagrangian

A model-dependent EoS of nuclear matter can be described by Relativistic Mean Field (RMF) theory [8], providing us with the possibility to use the neutron star as an ideal laboratory for nuclear physics. When admixing the X17 as an addition vector boson, the corresponding RMF Lagrangian becomes:

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

The “effective” vector boson mass can then be written as:

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

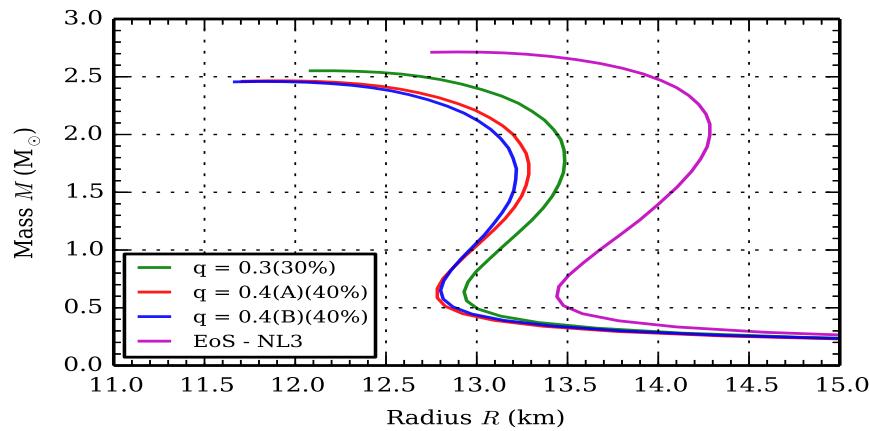
where  $q$  is the admixture coefficient of the  $m_X = 17$  MeV boson to the total vector potential. The value of  $q$  can range the effective mass from  $m_\omega = 782.5$  MeV to 17 MeV. We tested this admixture scenario using constraints from properties of finite nuclei and heavy ion collisions all the way to the neutron stars.

### 2.2. Analysis Results

In our analysis, we constructed an EoS for infinite symmetric nuclear matter using the “effective” mass of Equation (2) in an admixture with 17 MeV between 20% and 50%. Several sets of parameters tested using binding energy of 16 MeV and saturation density  $\rho_0 = 0.15 - 0.16 \text{ fm}^{-3}$ . The successful sets were investigated further to determine incompressibility ranges:  $K_0 = 250 \pm 20$  MeV.

The successful parameters sets were used to recalculate properties of the  $^{208}\text{Pb}$  finite nucleus: in particular, its binding energy (1636 MeV) and the neutron skin thickness ( $\Delta R_{PREX2} = 0.283 \pm 0.071$  fm) [9]. Parameter sets for 20% and 50% admixture failed to satisfy the constraints from heavy ion collisions [10], leaving us with only parameter sets with an admixture of 30% to 40%. This signals the existence of a range of admixtures that satisfies all the constraints. The final EoSs, specifically their versions for pure neutron matter, applied to the Tolman–Oppenheimer–Volkoff (TOV) equations and the resulting mass–radius plot are shown in Figure 1.

The resulted radius agrees with the measurement recently reported by NICER [11,12]. The maximum mass also agrees with the reported mass of the pulsar  $\approx 2.35 M_\odot$  [13] and the mass remnant from the gravitational wave event GW190814 [14]. These overlaps lead us to the conclusion that the three EoSs—which satisfy all the existing experimental constraints—can be considered as universal EoSs of nuclear matter.



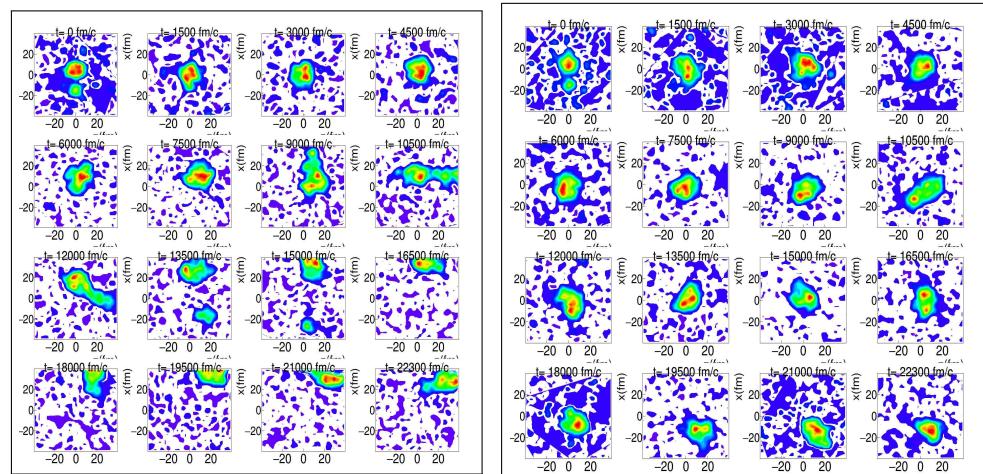
**Figure 1.** (Color online). The mass–radius relation for three EoSs in admixtures of 30% and 40% for the 17 MeV boson. The EoS for  $q = 0.4(A)$  and  $q = 0.4(B)$ , represents different sets for  $\kappa$  and  $\lambda$  couplings for cubic and quartic self-interaction, respectively. We include also the NL3 EoS in comparison. Reproduced with permission from M. Veselský, Symmetry, 15(1), 49 [1], published by MDPI, 2022.

### 3. Novel Concept: Hyper-Heavy Nuclei Inside Neutron Stars

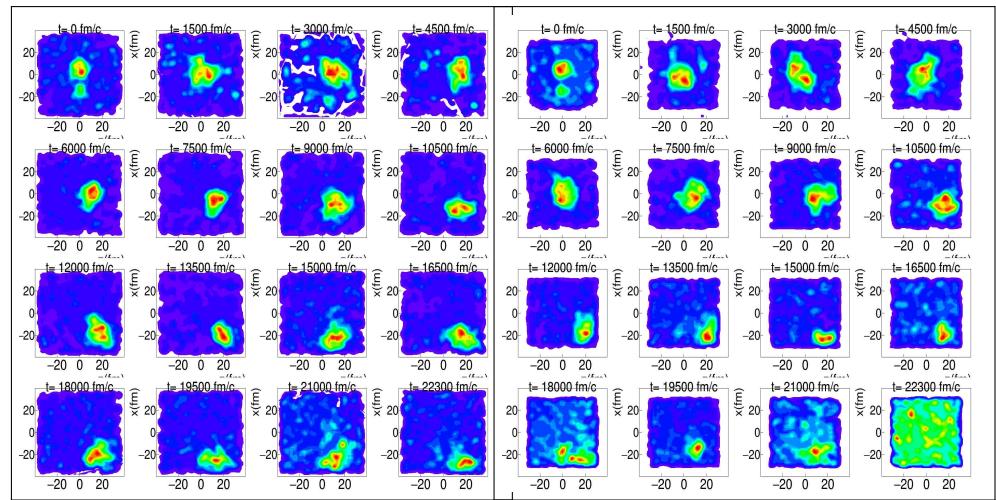
In this concept, using a CoMD code and an EoS with incompressibility  $K_0 = 254$  MeV, the evolution of a hyper-heavy system with  $N/Z = 4$  ( $^{140}\text{Ni} + ^{460}\text{U}$ ) in a nucleon bath with 10% of protons and beam energies from 10 keV to 1 MeV was investigated. In addition, a Debye screening cutoff at 10 fm, 7 fm, 5 fm, 4 fm, 3 fm and 2 fm applied, corresponding to nucleon bath densities of  $\rho_0/100$ ,  $\rho_0/50$ ,  $\rho_0/30$ ,  $\rho_0/17$ ,  $\rho_0/10$ , and  $\rho_0/5$ , respectively.

#### Simulations Inside Neutron Star Environment and Analysis Results

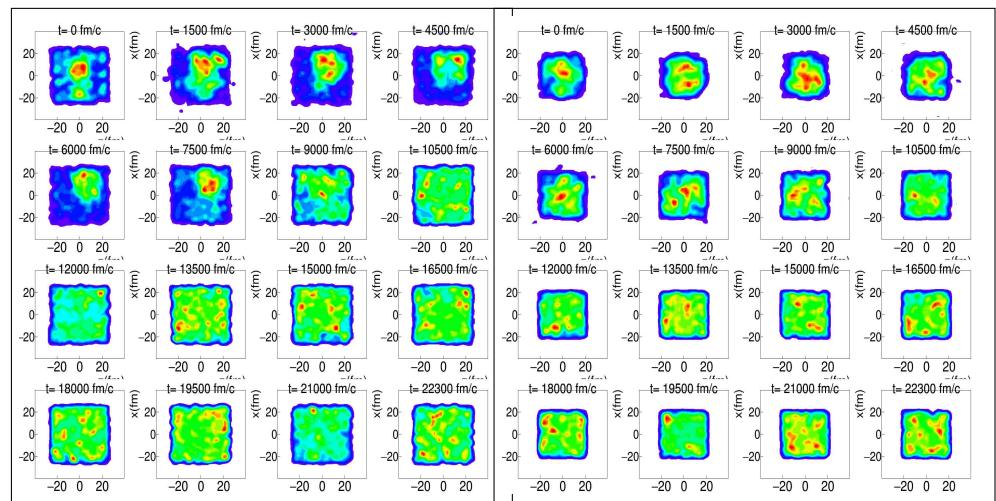
In order to simulate a neutron star environment, the CoMD code was modified, introducing a low-density nucleonic bath by placing 2000 nucleons inside a cell: in this case, a box with periodic boundary conditions. For convenience and due to limited space, we present only results for stiff density dependence of symmetry energy, as depicted in Figures 2–4. When running the simulations in a time scale up to 25,000 fm/c, the resulted nucleus appeared to dissolve inside a nucleon bath density above  $\rho_0/30$ . At lowest density, the fusion appeared to take over, providing a maximum lifetime window between densities  $\rho_0/50$  and  $\rho_0/30$ .



**Figure 2.** Evolution of the  $^{140}\text{Ni} + ^{460}\text{U}$  system in the nucleon bath with 10% of protons calculated using the CoMD code at beam energy 0.01 MeV/nucleon and Coulomb interaction cutoff at 10 fm and 7 fm with densities  $\rho_0/100$  and  $\rho_0/50$ , respectively (from left to right). Reproduced with permission from M. Veselský, Phys. Rev. C Letters, 106, L012802 [2], published by APS, 2022.



**Figure 3.** Evolution of the  $^{140}\text{Ni} + ^{460}\text{U}$  system in the nucleon bath with 10% of protons calculated using the CoMD code at beam energy 0.01 MeV/nucleon and Coulomb interaction cutoff at 5 fm and 4 fm with densities  $\rho_0/30$  and  $\rho_0/17$ , respectively (from left to right). Reproduced with permission from M. Veselský, Phys. Rev. C Letters, 106, L012802 [2], published by APS, 2022.



**Figure 4.** Evolution of the  $^{140}\text{Ni} + ^{460}\text{U}$  system in the nucleon bath with 10% of protons using the CoMD code at beam energy 0.01 MeV/nucleon and Coulomb interaction cutoff at 3 fm and 2 fm with densities  $\rho_0/10$  and  $\rho_0/5$ , respectively (from left to right). Reproduced with permission from M. Veselský, Phys. Rev. C Letters, 106, L012802 [2], published by APS, 2022.

#### 4. Conclusions

In the first concept, we implemented a hypothetical X17 boson to a nuclear EoS in admixture with the  $\omega$  meson, concluding that only 30% to 40% satisfy all the experimental constraints. Using the TOV equations, the successful EoSs resulted a radius of around 13 km with mass of  $M_{\text{NS}} \approx 1.4M_{\odot}$  and a maximum mass of around  $M_{\text{NS}} \approx 2.5M_{\odot}$ . These results agree with the measurement recently reported by NICER [11,12]. The maximum mass also agrees with the reported mass of the pulsar  $\approx 2.35M_{\odot}$  [13] and the mass remnant from the gravitational wave event GW190814 [14]. These overlaps lead us to conclude that the three EoSs—which satisfy all the existing experimental constraints—can be considered universal EoSs of nuclear matter.

In the second concept, we investigated the formation of hyper-heavy nuclei in a neutron star environment, suggesting that they could provide an extra coherent neutrino scattering, affecting the neutron stars' cooling rate. Local fusion cascades could lead to the formation of hyper-heavy nuclei and the release of energy due to minimization of their surface energy. That in turn, may result to an additional mechanism of X-ray bursts. Meanwhile, due to the local density profile modifications, deeper within the neutron star, gravitational wave signals may result from a violation of rotational symmetry [15].

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**Conflicts of Interest:** The authors declare no conflict of interest.

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