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Novel Concepts of Nuclear Physics in a Neutron Star Environment†

Vlasios Petousis [1,*,‡], Martin Veselský [1,‡], Jozef Leja [2,‡], Ch. C. Moustakidis [3,‡], G. A. Souliotis [4,‡], A. Bonasera [5,‡] and Laura Navarro [6,‡]

1 Institute of Experimental and Applied Physics, Czech Technical University, Prague, 110 00, Czechia
2 Faculty of Mechanical Engineering - Slovak University of Technology in Bratislava, Bratislava, 812 31, Slovakia
3 Aristotle University of Thessaloniki, Thessaloniki, 541 24, Greece
4 Laboratory of Physical Chemistry, Department of Chemistry, National and Kapodistrian University of Athens, Athens, 157 72, Greece
5 Cyclotron Institute, Texas A&M University, College Station, Texas, TX 77840, USA and Laboratori Nazionali del Sud, INFN, Catania, 95125, Italy
6 Department of Physics and Mathematics, University of Zaragoza, 50009, Spain

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‡ These authors contributed equally to this work.

Abstract: Neutron stars are 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: In the first concept, the reported 17 MeV boson, which has been proposed as an explanation to the ^{8}Be, ^{4}He and ^{12}C anomaly, was investigated in the context of its possible influence the neutron star structure, defining a universal Equation of State as well. In the second concept, the synthesis of hyper-heavy elements was investigated 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 or 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}Be, ^{4}He and ^{12}C anomalies - was investigated in the context of its possible influence to 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 - like inside a neutron star - fusion can become possible even in temperatures down to 10^{8} K.

2. Novel Method of Constructing a Universal Equation of State

Since 2016 till today, Krasznahorkay and his group, reported an anomaly in the angular correlation of the electron - positron emission in the excited states of the ^{8}Be, ^{4}He and ^{12}C [3–6]. This anomaly at a folding angle was interpreted as a signature of a new neutral boson with a mass of about 17 MeV. The experimental cross-check about the existence or not of that new boson, is till today a matter of investigation. In this context, it is interesting to stress that a narrow peak of similar energy was observed in a recent experiment 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 ω 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 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:

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

the "effective" vector boson mass then can be written as:

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

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, 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 the Eq.2 in admixture with 17 MeV between 20% to 50%. Several sets of parameters tested using binding energy of 16 MeV and saturation density ρ_0 = 0.15 - 0.16 fm^{-3}. The successful sets investigated further for incompressibility ranges: K_0 = 250 $\pm$ 20 MeV.

The successful parameters sets were used to recalculate properties of the ^{208}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], left us only parameter sets with an admixture of 30% to 40%. That signals the existence of a range in 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 is shown in Figure 1.

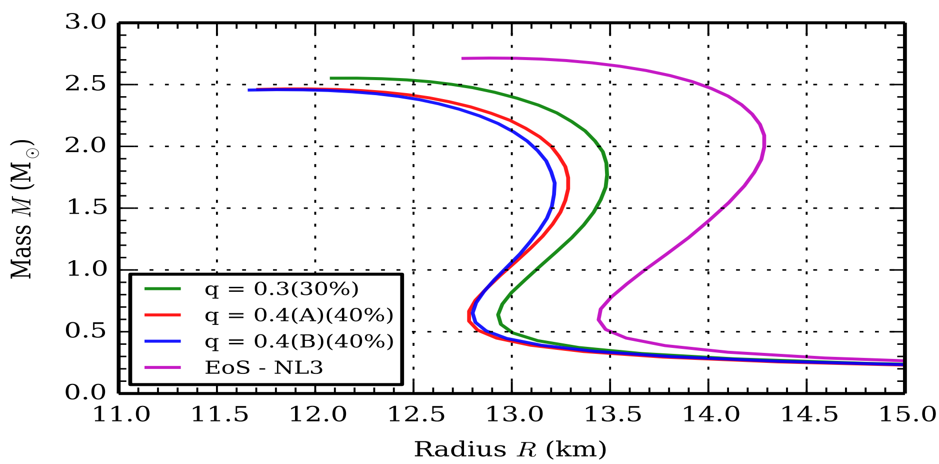

Figure 1. (Color online). The mass - radius relation for three EoSs in admixtures of 30% and 40% for the 17 MeV boson. The EoS for q = 0.4(A) and q = 0.4(B), represents different sets for κ and λ couplings for cubic and quartic self-interaction respectively. We include also the NL3 EoS in comparison.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

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

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}Ni+^{460}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.

3.1. 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, practically 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 the figures. 2, 3 and 4. Running the simulations in a time scale up to 25000 fm/c, the resulted nucleus appears to dissolve inside a nucleon bath density above $\rho_0/30$. At lowest density the fussion appears to take over providing a maximum lifetime window between densities $\rho_0/50$ and $\rho_0/30$.

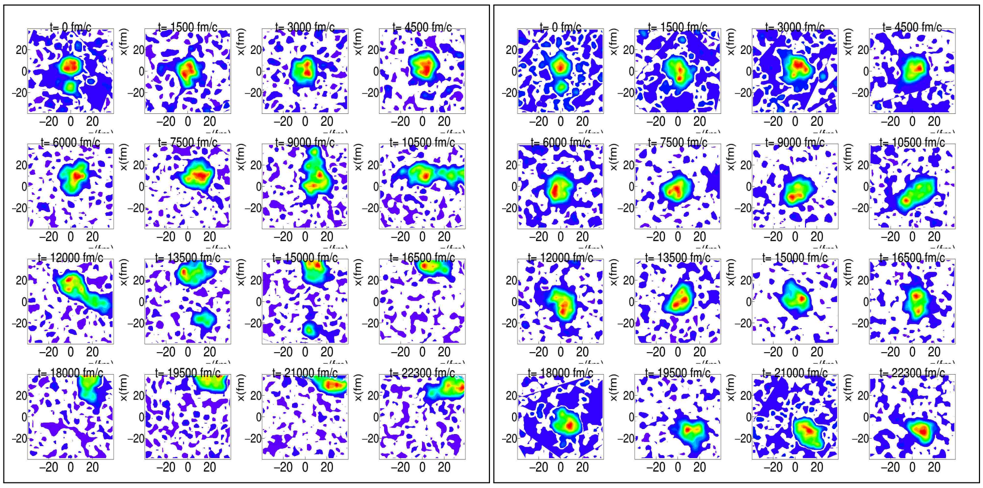

Figure 2. Evolution of the ^{140}Ni+^{460}U system in the nucleon bath with 10% of protons calculated using the CoMD code at beam energy 0.01 MeV/nucleon and Coulomb interaction cutoff at 10 fm and 7 fm with densities $\rho_0/100$ and $\rho_0/50$ respectively (from left to right). Reproduced with permission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

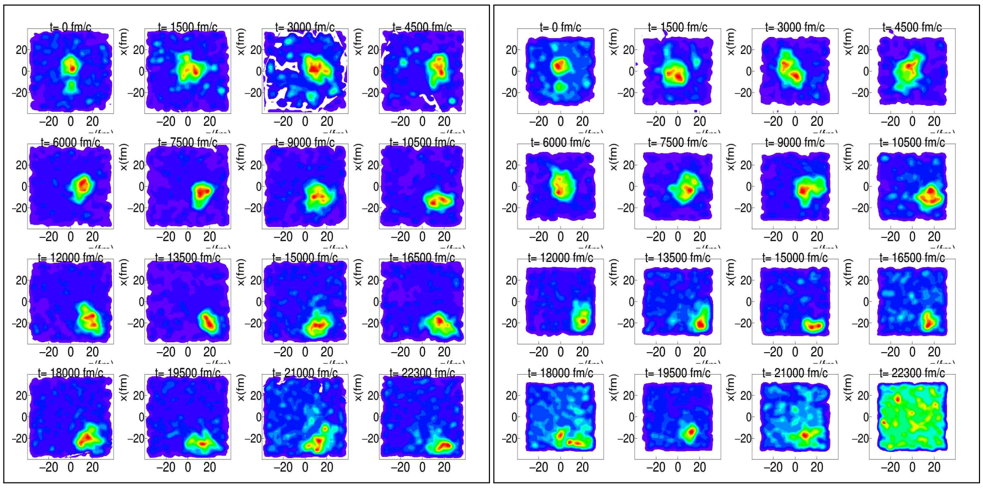

Figure 3. Evolution of the ^{140}Ni+^{460}U system in the nucleon bath with 10% of protons calculated using the CoMD code at beam energy 0.01 MeV/nucleon and Coulomb interaction cutoff at 5 fm and 4 fm with densities $\rho_0/30$ and $\rho_0/17$ respectively (from left to right). Reproduced with permission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

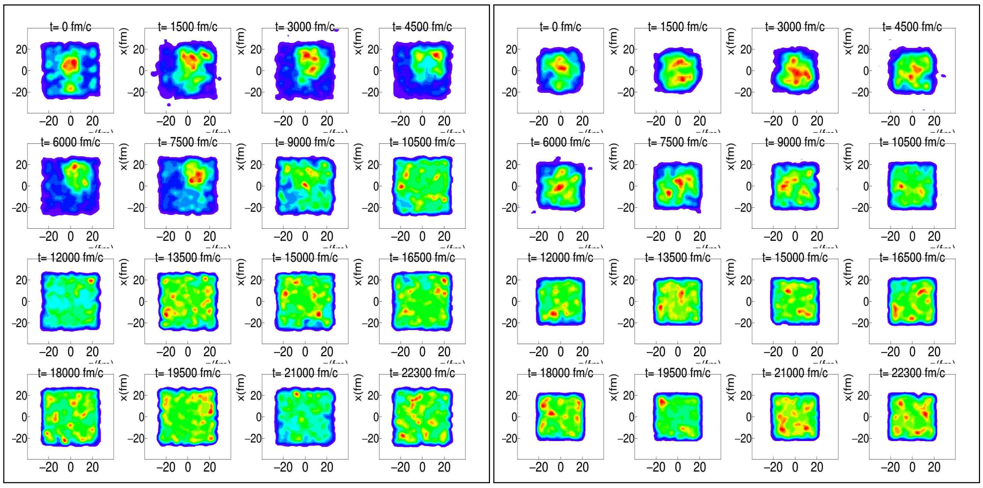

Figure 4. Evolution of the ^{140}Ni+^{460}U system in the nucleon bath with 10% of protons using the CoMD code at beam energy 0.01 MeV/nucleon and Coulomb interaction cutoff at 3 fm and 2 fm with densities $\rho_0/10$ and $\rho_0/5$ respectively (from left to right). Reproduced with permission from M. 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 ω 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 $M_{NS} \approx 1.4M\odot$ and a maximum mass of around $M_{NS} \approx 2.5M\odot$. These results agree with the measurement recently reported by NICER [11,12]. The maximum mass agrees as well 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 some conclusion that the three EoSs - which they satisfy all the existing experimental constraints - can be considered as 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. Also 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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