The low-density EoS under corecollapse supernova and heavy-ion LEGELY I BELLET CONDIT LE BHAT The low-density; neutron start equation of state with light clusters

Helena Pais

CFisUC, University of Coimbra, Portugal

hpais@uc.pt

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In collaboration with:

- \overline{a} $\overline{$ T. Custódio, T. Malik, C. Providência (U. Coimbra)
- R. Bougault (for the INDRA collaboration), F. Gulminelli (LPC-Caen)

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Matéria em condições extremas

MagStarMatter 15/02/2024, 12:32

estrelas de neutrões na era multi-

2022.06460.PTDC eto atribuído no âmbito do concurso de projetos I&D de carácter exploratório em todos os domínios científicos da FCT.

PALAVRAS-CHAVE: *ESTRELAS DE NEUTRÕES, EQUAÇÃO DE ESTADO, CAMPOS MAGNÉTICOS FORTES, ONDAS GRAVITACIONAIS*

Where do these clusters form?

in http://essayweb.net/astronomy/blackhole.shtml

Credit: Soares-Santos et al. and DES Collab **EVOLUTION OF STARS** Planetary Nebula GW170817 GW170817 Small Star **Red Giant DECam observation DECam** observation White Dwarf $(0.5-1.5$ days post merger) (>14 days post merger) Neutron Star Supernova **Red Supergiant** Large Star **Stellar Cloud** with NS mergers Protostars Blac IMAGES NOT TO SCALE

in https://www.ligo.org/detections/GW170817.php

scenarios where these clusters are important: supernovae, NS mergers, (crust of) neutron stars

Why are these clusters important?

- They influence supernova properties: the clusters can modify the neutrino transport, affecting the cooling of the proto-neutron star and/or binary and accreting systems.
- •Transport coefficients are determined by the collision rates of electrons and/or neutrinos with clusters, which depend on the cluster abundances and sizes.
- •In binary mergers, the recombination of free nucleons into alpha particles can generate enough energy to induce mass outflows.

sity \bullet for all the EOS. The constraints on the symmetry energy from IAS Danielewicz & Lee (2014) is also displayed. Describing neutron stars

Figure 5. The symmetry energy *S*(⇢) as a function of den-

 min_{α} the α Solution: Need Constraints (Experiments, Observations, Need Constraints (Experiments, Observations, N as the PSR J0740 + 6620 (pink) Riley et al. (2021); Miller et al. (2021) from the NICER x-ray data are also shown. A and A Microscopic calculations)

Why are these phases important?

• They are present in the NS inner crust, and they do have an effect in the NS radius, but not in the NS maximum mass:

For **1.4M**⊙ **stars**, the RMF models that passed the **experimental and observational constrains** predict **R=13.6 ± 0.3 km,** with a crust thickness of **∆R=1.36 ± 0.06km**.

Choosing the EoS(s)

Problem: How to build the EoS for different star regions, Ts?

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Solution:Choose 1 EoS for each NS layer:

- •Outer crust EoS (BPS, HP, or RHS, ...) → M(R) not affected *•Inner crust EoS pasta phases ? unified core EoS ?*
- Core EoS \longrightarrow homogeneous matter

and then

- Match OC EoS at the neutron drip with IC EoS
- •Match IC EoS at *crust-core transition* with Core EoS

Supernova EoS with light clusters

- The SN EoS should incorporate: all relevant clusters, (mean-field) interaction between nucleons and clusters, and a suppression mechanism of clusters at high densities.
- •Different methods: nuclear statistical equilibrium, quantum statistical approach, and
- •RMF approach: clusters as new degrees of freedom, with effective mass dependent on density.
- In-medium effects: cluster interaction with medium described via the meson couplings, or effective mass shifts, or both
- Constrains are needed to fix the couplings: low densities: Virial EoS high densities: cluster formation has been measured in HIC

In-medium effects The total binding energy of a light cluster j is given $\overline{}$

• Binding energy of each cluster: $\ B_j = A_j m^* - M_j^* \, , \quad j = d, t, h, \alpha \, ,$

with $\quad m^*=m-g_s\phi_0\;$ the nucleon effective mass and ϕ_0 the nucleon effective mass and m_{ij} and masteon critically mass and

In-medium effects - g_{sj} and μ lustrea. The discolution of the discolution of the clusters will be a set of the cluster will be a set of the clusters will be section, we calculate the chemical equilibrium constants shift, *B^j* , and this factor *xs*. Substituting eqs. (12), (9) and \mathbf{I} in the set of \mathbf{I} \bm{v} *j* unu \bm{v} In modium offorte $a \cdot a \cdot d \cdot \hat{d}$ Lipel \mathbf{I} **In-medium effects -** $\mathbf{a}_{\textrm{e}i}$ **and** δF μ li-liedium eriecis – 983 diiu σ D *A* p *d* δR ^{*ll*} *j* and ∂D_j J_n \ldots J_{n+1} \ldots J_{n} work, its value was fixed to *x^s* = 0*.*85 *±* 0*.*05 from a fit $\mathsf{nd} \ \mathsf{SR}$ $\left| \begin{array}{ccc} 1 & 0 & D^T \end{array} \right|$ $\delta B_j|$

 \bar{b} and by a combination of both the binding energy \bar{b}

number *N^j* and proton number *Z^j* , and ⇢*p*, ⇢*ⁿ* are, respec-

For the two extreme cases, we have

energy.

work, its value was fixed to *x^s* = 0*.*85 *±* 0*.*05 from a fit

the tetraneutron survives even as a resonance. The larger

considering calculations where we do and do not include

clusters, and the presence or not of the tetraneutron.

discussed. The tetraneutron, just as the other light clus-

. The Binding energy of each cluster then becomes: shift, *B^j* , and this factor *xs*. Substituting eqs. (12), (9) a^{Tho Rinding} energy of each cluster than becomes: **and bulleting energy of each choose** • The Binding energy of each cluster then becomes: be a \sim combination of both the binding energy and by a combination of binding energy and binding energy and \sim ϵ to the ϵ in later was found to ϵ $\overline{11}$, $\overline{11}$, $\overline{12}$, $\overline{13}$, and as we will this work, and as we will this work, and as we will then $\overline{13}$ $\mathsf{vec}\text{omes:}\quad$

see, we will use the coupling to test its event of the coupling to test its electronic test in the coupling to

to the Virial EoS. In later works, the value was found to

$$
B_j = A_j g_s \phi_0 (x_{sj} - 1) + B_j^0 + \delta B_j.
$$

This implies that a larger *xsj* corresponds to a larger

data was considered α was considered α . In this work, and as we will be will b

A^j corresponds to the number of nucleons in cluster

to the Virial EoS. In later works, the value was found to

be a combination of both the binding energy and by a combination of both the binding energy and binding energy and binding energy and the binding energy and the binding energy and the binding energy and the binding energy

be a combination of both the binding energy and by a combination of both the binding energy and binding energy and

 \boldsymbol{x}_{si} can vary from 0 to 1 so for the two extreme cases, we have: considering calculations where we do not include where we do not include we do not include where we do not include α \bullet $\ x_{sj}$ can vary from 0 to 1 so for the two extreme cases, we have: $\mathsf{ve} \colon$ number *N^j* and proton number *Z^j* , and ⇢*p*, ⇢*ⁿ* are, respec-

$$
B_j = B_j^0 + \delta B_j, \text{if } x_{sj} = 1, B_j = B_j^0 + \delta B_j - A_j g_s \phi_0, \text{if } x_{sj} = 0.
$$

 \bullet This implies that a larger x_{si} corresponds to a larger B_i , and that binding energy, and, consequently, the dissolution of the t_{ref} is treated as \boldsymbol{D} as a point-like particle, and one may ask \boldsymbol{D} • This implies that a larger x_{sj} corresponds to a larger B_j , and that the cluster dissolution density will occur at larger densities. \Box that *B*₁
*B*₀ *j*_{*g*} $\frac{1}{2}$ *a*_{*j*} $\frac{1}{2}$ *a*_{*j*}*gs*¹ *a*_{*j*} *a*_{*j*} *a*^{*j*} *a* considering calculations where we do and do not include the 4*n*. This may give a hint on the abundance of the *g y y y i i y i i y i i i i i i* the cluster dissolutic tetraneutron, we will construct the other construction of the other construction of the other construction of
Separate it for the other clusters, we will construct the other construction of the other construction of the o

> $\int_0^{\mathcal{L}} s_j$ needs to be determined trom exp. constrain *B*^{*j*} + *B*¹ $\boldsymbol{x_{sj}}$ needs to be determined from exp. constraints \boldsymbol{z}

Exp Constraint: Equilibrium constants

PRC 97, 045805 2018 Yellow bands from Qin et al 0.035 0.035 PRL 108, 172701 (2012)Qin (a) (b) • Yellow bands: $x_{\rm s}$ =0.85 \pm 0.05 0.03 0.03 exp data from 0.025 0.025 ρ (fm-3) Qin et al ρ (fm⁻³) 0.02 0.02 • Red points: RMF $\left| \begin{array}{ccc} \infty & 0.015 \\ 0.015 & 0.015 \end{array} \right|$ 0.015 0.015 model calculated 0.01 0.01 *^j* + *B^j , x^s* = 1 *,* (2) $FSU, y_p = 0.41$ 0.005 0.005 at (T,rho,yp) of exp data with $\frac{1}{10^3}$ $\frac{1}{10^4}$ $\frac{1}{10^5}$ $\frac{1}{10^6}$ $\frac{1}{10^8}$ $\frac{1}{10^8}$ $\frac{1}{10^{10}}$ $\frac{1}{10^{11}}$ $0 \frac{L}{10^3}$ $0 \frac{L}{10^2}$ 10^2 10³ 10⁴ 10⁵ 10⁶ 10⁷ Kc $_{\alpha}$ (fm $^{9})$ Kc_h (fm 6) $x_s = 0.85 \pm 0.05$ 0.035 0.035 (d) (c) 0.03 0.03 $K_c[j] = \frac{\rho_j}{\rho_n^{N_j} \rho_p^{Z_j}}$ • x s first fitted to 0.025 0.025 the Virial EoS, ρ (fm-3) ρ (fm-3) 0.02 0.02 model-ind constraint, only 0.015 0.015 depends on exp B 0.01 0.01 and scattering 0.005 0.005 phase shifts. $0 \nightharpoonup 10$ $0 \frac{L}{10^2}$ 10 10^2 10^3 10^4 10^2 10^3 10^4 10^5 10^6 10^7 Provides correct Kc_{d} (fm 3) Kc_t (fm 6) zero-density limit • Our theoretical model describes quite well for finite-T EoS.

experimental data, except for deuteron

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Equilibrium constants and data from INDRA $\overline{}$

- Experimental data includes 4He, 3He, 3H, 2H, and 6He.
- R. Bougault et al, for the INDRA collab, J. Phys. G 47, 025103 (2020)
- $\ddot{}$ 10⁵ 10⁶ 10⁷ 10⁸ 10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ • 3 experimental systems: 136Xe+124Sn, 124Xe+124Sn, and 124Xe+112Sn at 32MeV/nucleon.

- . In an analysis where we considered in-medium effects: There we constant can threatent
- We obtain a higher x_s as compared to the previous fit of Qin et al data: $\frac{1}{2}$ tained assuming assuming assuming assuming an ideal gas expression for the determination for the determination of the determination for the determination of the determination of the determination of the determin igher **x_s** as compared to the <u>usin</u> et al dat
- \bullet The higher the \times _s, the bigger the binding energies (and the smaller effect of the $\,$ medium), and the higher the dissolution densities of the clusters. modynamic conditions explored by the Xe+Sn systems, culation can reproduce the INDRA data, only if the INDRA data, only if the INDRA data, only if the INDRA data, e clusters. Which points the validity of the v

statistical equilibrium hypothesis for both of the α

Analysing mass fractions from INDRA data

INDRA vaporization data [40], where multiplicities were \mathbf{v} and \mathbf{v} reproduced with the explicit hypothesis that the explicit hypothesis that \mathbf{v}

• Considerably higher value in E (and lower width) than previous result, Kisamori et al. 2016. e Considerably biober value in E Cand lower *Methods.* The relativistic mean-field (SMF) where we consider the state we consider the state was a two-fold way of the state was two-fold way of the state was two-fold was two-fold was two-fold was two-fold was two-fold $\frac{1}{2}$ that is, via a binding of the mesons, and via a binding energy shift $\frac{1}{2}$ and $\frac{1}{2}$ and state the low-density equation of states the low-density equation of states $\frac{1}{2}$ • Considerably higher value in E (and lower width) than previous result,

• Here, we consider 4n energy given by two bands:
\n
$$
B_{4n}^{0} = -2.37 \pm \sqrt{0.38^{2} + 0.44^{2}} = [-2.95 : -1.79],
$$
\n
$$
B_{4n}^{0} = -2.37 \pm 1.8\Gamma = [-5.52 : 0.78],
$$

helions, and 6He – immersed in a gas of protons and neutrons, and we calculate their abundances and chemical e
Distribution and chemical equilibrium abundances and chemical equilibrium abundances and chemical equilibrium

↵-particle fractions considerably. This may have an influence on the dissolution of the accretion disk of the merger of two NSs.

|Inclusion of 4n - effect of including 4n on Yi || $P - 211551$

· All clusters dissolve below 0.1 fm-3; $\overline{1}$ na,

 $\mathbf{F}_{\mathbf{r}}$ this small proton fraction, it is striking that at the max-

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- The fraction maxima goes from ~0.01 at T=4MeV to ~0.03fm-3 at T=20MeV; \mathbf{S} ϵ Hachon maxima goes from ϵ .01 at r-fives to 0.001111-0 at r-60 o fraction mayima gooc f 2 H $\mathord{\text{--}}$ 1 $\mathord{\text{=}}$ 3 He 2 $\overline{}$ raction maxima goes from - 0.01 af 1=4
- \bullet The p-rich and symmetric clusters increase abundance with 4n; the n-rich decrease as n are being consumed by 4n. p-rich and symmetric clusters increase abundance with 4n; the n-T
as ending the series of the consum $\mathsf{in.}$ \overline{a} 3 \bullet n
Eci
Ci
- \bullet The higher the T, the weaker this effect is. At T=20MeV, p-rich are not as abundant, and 4He even decreases. abundant and 4He even decreases \bullet (\bullet) e
4n
C 10-2 10-1 re comgressements of the community of the weaker this effect is. At T=20MeV, p-rich are no fraction of *y*^p = 0.3 (left), and *y*^p = 0.1 (right), in a calculation where we consider a fixed binding energy for the 4*n*, taken as *B*0(4*n*) = 2.37 MeV. ϵ weard this effect is. π T T- ϵ UNEV, p-fich are \overline{a}
- \bullet The scalar cluster-meson coupling gives strong effect! -> Calibrating EoS very important! ¹⁷ iportant! a Tho scalar clustor moson counti L, ettect! -> Calibrating EoS Calib Fig. 4. Ratio of the mass fractions of the clusters and of the gas (top panels) with (*Yi*(w)) and without (*Yi*(w*o*)) the tetraneutron, for a fixed proton In the bottom panels, the chemical equilibrium constants, *K*c[*i*], in a calculation with (w) and without (w*o*) the tetraneutron, are shown in the same \cdot The scalar cluster–meson coupling gives strong effect! –> Calibrati $\frac{1}{2}$ $\frac{1}{2}$ 10-3 10-2 10-1 \mathcal{L} 0.5 yp=0.1 10-3 10-2 10-1 > Cali<mark>t</mark>

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The impact of 4*n* clusters would be higher in more neutron-rich

fraction of *y*^p = 0.3 (left), and *y*^p = 0.1 (right), in a calculation where we consider a fixed binding energy for the 4*n*, taken as *B*0(4*n*) = 2.37 MeV.

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1.5

- **• Our model reproduces both the virial limit and Kc from HIC data (NIMROD and INDRA) with success.**
- **• INDRA data was reanalysed based on a new method, with in-medium effects.**
- **• Fitting our theoretical RMF model to the new data: a larger scalar coupling (more attractive interaction) is obtained than the one found NOT including in-medium effects in the data analysis.**
- **• This implies bigger binding energies => larger melting densities => MORE clusters in CCSN matter!!**
- **• More recently, a weaker attractive interaction at higher T was found and, as a consequence, a dissolution of the clusters at lower T is obtained.**
- **• The effect of 4n is stronger in very n-rich matter and for very low T.**
- **• 4n increases the abundances of free protons and 4He, while decreasing the abundance of free neutrons —> transport properties can be affected.**