Hyperons in the pasta phase

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We have investigated under which conditions hyperons (particularly $\Lambda$ and $\Sigma^-$) can be found in the pasta phase. The larger the density and the temperature and the smaller the electron fraction the higher the probability that these particles appear but always in very small amounts. $\Lambda$-hyperons only occur in the gas and in smaller amounts than would occur if matter were homogeneous, never with abundancies above $10^{-5}$. The amount of $\Sigma^-$ in the gas is at least two orders of magnitude smaller and can be disregarded in practical calculations.

I. INTRODUCTION

Not long ago, two massive stars were confirmed\cite{1,2} giving rise to the hyperon puzzle: while nuclear physics favours soft EOS at low densities, massive stars can only be described by stiff EOS at high densities. Meanwhile, some constraints were imposed to neutron stars radii and it is now believed that the radii of canonical $1.4\,M_\odot$ pulsars are lower than what most of the models foresee\cite{3}.

On the other hand, the observation of supernova explosions is not trivial, a fact that contributed to the increasing importance of simulations of core-collapse supernova and its remnants. An appropriate EOS for these simulations would range from very low to high densities and from zero temperature to temperatures higher than 100 MeV, a not very easy task to be accomplished. Hence, the very small number of these EOS in the market, most of them publicly available in the CompOSE (CompStar Online Supernova Equations of State) database\cite{4}.

Many attempts have been made to circumvent these two problems and next we only mention some of the examples of the propositions found in the literature. These problems can be tackled by choosing appropriate meson-hyperon couplings\cite{5}, and introducing strange mesons as mediators of the baryons in relativistic models\cite{6,9} in already existing models or by using combinations of different parts of models available in the literature\cite{10}.

In all cases, the existence of a degree of freedom that carries strangeness is important, see\cite{11} for a recent review.

In this context, the low density part of the EOS plays a role that cannot be disregarded. The pasta phase results from the competition between the strong and the Coulomb interactions at densities compatible with the ones in the inner crust of neutron stars. Such competition generates a frustrated system\cite{12,13} and the name pasta refers to specific shapes acquired by matter, namely: droplets, bubbles, rods, tubes and slabs. The inclusion of the pasta phase in the EOS practically does not influence the stellar maximum masses, but certainly affects the radii\cite{14,15}. So far, the pasta phase has only been treated with nucleonic degrees of freedom.

From the considerations made above, it is obvious that the constituents present in the equations of state (EOS) that describe neutron stars and supernova cores are the essential ingredients in the determination of thermodynamic quantities and macroscopic properties. Hence, the existence of the strangeness degree of freedom in the pasta phase has to be investigated and this is the aim of the present work. At zero temperature hyperons do not occur at densities below two times the saturation density. However, at finite temperature the appearance of hyperons is mainly governed by their mass and, the larger the temperature the larger the probability that they appear at smaller and smaller densities. We restrict our work to finite temperature systems when the hyperons may occur at densities typical of non-homogeneous matter. We first consider the possibility that $\Lambda$ particles are present in the pasta phase and check the conditions for their existence and later discuss situations that could give rise to the onset of $\Sigma^-$ as well. These are the strangeness carrying baryons that usually appear first in stellar matter due to the values of their masses. Typical density values of the hyperon onset in the homogeneous phase are given in the next section. The values encountered are used to justify the presence of hyperons in the pasta phase.

We next show only the most important formulae for the understanding of our calculations and then display the results alongside some comments and conclusions.

II. FORMALISM

We have chosen to describe hadronic matter within the framework of the relativistic non-linear Walecka model (NLWM)\cite{16} with non-linear terms\cite{17}. In this model the nucleons are coupled to the scalar $\sigma$, isoscalar-vector $\omega^\mu$ and isovector-vector $\rho^\mu$ meson fields. We include a $\omega^\mu \rho^\nu$ meson coupling term as in\cite{14,18,21} because this term was shown to control the symmetry energy and its slope, resulting in equations of state that can satisfy most of the nuclear matter saturation properties and observational...
where $m_j^* = m_j - g_{\tau_j} \sigma$ is the baryon effective mass, 
\[ \Omega_{\mu\nu} = \partial_\mu \omega_\nu - \partial_\nu \omega_\mu, \quad R_{\mu\nu} = \partial_\nu R_\mu - \partial_\mu R_\nu - g_{\rho} (\bar{\rho}_\mu \times \bar{\rho}_\nu), \]
$g_{\tau_j}$ are the coupling constants of mesons $i = \sigma, \omega, \rho$ with baryon $j$, $m_i$ is the mass of meson $i$. The couplings $k (k = 2 M_N g_\sigma^2 b)$ and $\lambda (\lambda = 6 g_\sigma^4 c)$ are the weights of the non-linear scalar terms and $\tau^j$ is the isospin operator. The sum over $j$ extends over the lightest 4 baryons ($n, p, \Lambda, \Sigma$). In the present work we have opted to use the NL3\omega\rho parametrisation [18], which is an extension of the NL3 parametrisation [22] with the inclusion of the $\omega - \rho$ interaction. For the hyperon-$\omega$ interaction we take SU(6) symmetry, and for the hyperon-$\sigma$ interaction we consider that the $\Lambda, \Sigma$ and $\Xi$ potentials in symmetric nuclear matter at saturation are, respectively, -28 MeV, +30 MeV and -18 MeV. The parameters are: $m_\sigma = 508.194$ MeV, $m_\omega = 782.501$ MeV, $m_\rho = 763$ MeV, $g_{\sigma n} = 10.217$ (n stands for protons and neutrons), $g_{\sigma\Lambda} = 6.323$, $g_{\sigma\Sigma} = 4.708$, $g_{\omega n} = 12.868$, $g_{\omega\Lambda} = 8.578$, $g_{\omega\Sigma} = 11.276$, $k/M = 2 \times 10.431$, $\lambda = -6 \times 28.885$ and the corresponding saturation properties are: density at 0.148 fm$^{-3}$, binding energy of -16.2 MeV, compressibility equal to 271.6 MeV, symmetry energy of 31.7 MeV and slope equal to 55.5 MeV. From the results in [24], one can see that this model predicts stellar masses above 2$M_\odot$ and satisfies several presently accepted experimental and theoretical constraints.

The pasta phase is obtained for charge neutral matter and leptons are usually incorporated because their presence is expected both in the interior of neutron stars and in the core-collapse supernova. The leptonic Lagrangian density is simply

\[ \mathcal{L} = \bar{\psi}_l (i\gamma_\mu \partial^\mu - m_l) \psi_l, \]

where $l$ represents only the $e^-$ in the present work, whose mass is 0.511 MeV. The leptons enter the calculations only via the weak interaction.

The construction of the pasta phase obeys the well known Gibbs conditions for phase coexistence and in the present work we opt for the coexistence phase (CP) method extensively discussed in previous works [12, 14, 23, 27], which we do not repeat here. The particle chemical potentials are defined in terms of a baryon chemical potential ($\mu_B$) and a charge chemical potential ($\mu_Q$), which are the quantities enforced as identical in both phases, such as

\[ \mu_j = \mu_B + q_j \mu_Q, \]

where $q_j$ is the electric charge of each particle. The electron fraction is fixed by the imposition of charge neutrality:

\[ Y_e = \frac{\rho_e}{\rho} = Y_Q = \frac{\rho_Q}{\rho}, \quad \rho_Q = \rho_p - \rho_\Sigma. \]

We also define the fraction of $\Lambda$ and $\Sigma^-$ particles as:

\[ Y_{\Lambda_1} = \frac{\rho_{\Lambda_1}}{\rho}, \quad Y_{\Lambda_2} = \frac{\rho_{\Lambda_2}}{\rho}, \]

\[ Y_{\Sigma^-_1} = \frac{\rho_{\Sigma^-_1}}{\rho}, \quad Y_{\Sigma^-_2} = \frac{\rho_{\Sigma^-_2}}{\rho}, \]

where the subscript 1 refers to the dense phase and 2 to the gas phase and $\rho = \rho_p + \rho_n + \rho_\Lambda + \rho_\Sigma$.

An important aspect generally discussed is the surface tension coefficient ($\sigma$). We use the $\sigma$ parametrisation given in [24].

Before we discuss the presence of hyperons in the pasta phase, it is important to investigate their onset in homogeneous matter. We start by analysing the two usually considered scenarios at zero temperature. The first one refers to stellar matter, where the equation of state is obtained with the assumption of charge neutrality and $\beta$-equilibrium and the fraction of leptons includes electrons and muons, varies with density and it is an output of the calculation. In the second scenario, we have considered the electron fraction as a fixed quantity that enters as an input, as in the finite temperature case examined throughout this work. In this case, no muons are incorporated in our calculations. As seen in table 4 no hyperons appear at sub-saturation density at $T = 0$, as already expected. It is interesting to notice the competition between the contribution from the $\rho$-meson that in asymmetric matter favors the hyperons with the smallest charges, and the $\sigma$-meson that favor the hyperons with an attractive potential in symmetric nuclear matter at saturation. In symmetric matter, the $\rho$-meson contribution is zero, and the hyperons of each isospin multiplet with smaller mass are favored.

In table I we display the onset of hyperons at different temperatures and electron fractions. We have considered the three hyperons with a larger fraction at low densities and we are interested in the occurrence of hyperons at densities below 0.1 fm$^{-3}$. From the table we see that this is only possible for $T > 5$ MeV, taking as reference a hyperon fraction larger than $10^{-12}$. While at very low $T$ the sequence of hyperons may be different, at higher $T$ the sequence is generally $\Lambda, \Sigma$ and $\Xi$. For a large electron fraction, close to $Y_e = 0.5$ the hyperon of the $\Sigma$
triplet or Ξ doublet with the largest charge is the first to appear due to the smaller mass and the small contribution of the ρ-meson. In fact, at $Y_c = 0.5$ the members of each isospin multiplet come very close together, being only distinguished by the mass. A small value of $Y_c$ originates a large contribution from the $\rho$-meson and the hyperon with the most negative isospin projection is the favoured one, i.e. $\Sigma^-$ and $\Xi^-$. Temperature washes quite fastly the differences due to the different optical interactions taken at $T = 0$ and therefore, the $\Sigma$ hyperon with a smaller mass than the $\Xi$ hyperon ends up being favored. The $\Lambda$-meson is always the one with the largest abundance, and we next concentrate our study in the occurrence of this hyperon. For reference, we also show some results for $\Sigma$ but from table III we conclude that when they occur at densities of the pasta phases they are 2 to 3 orders of magnitude less abundant than the $\Lambda$s. The $\Xi$-hyperon fractions are negligible for the densities and temperatures where pasta phases occur.

| $Y_c$ (MeV) | $\rho_\Lambda$ (fm$^{-3}$) | $\rho_{\Sigma^+}$ (fm$^{-3}$) | $\rho_{\Sigma^-}$ (fm$^{-3}$) | $\rho_{\Xi^+}$ (fm$^{-3}$) | $\rho_{\Xi^-}$ (fm$^{-3}$) |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $0.001$     | 0.31            | -               | -               | 0.64            | 0.35            |
| $0.1$       | 0.30            | -               | -               | 0.61            | 0.34            |
| $0.30$      | 0.33            | 0.77            | -               | 0.60            | -               |
| $0.50$      | 0.36            | 0.60            | -               | 0.57            | -               |

TABLE I: Hyperon onset densities obtained at zero temperature.

III. RESULTS AND DISCUSSIONS

![FIG. 1: Free energy versus baryon density for homogeneous matter (dotted line) and for the pasta phase (solid line) for $T = 10$ MeV and $Y_c = 0.3$](image)

In the present section, we discuss under which conditions the fraction of hyperons, in particular, of $\Lambda$s, is largest in the range of densities where pasta phases occur. The calculations are performed within the formalism presented in the last section. Although in the CP approach to the pasta phases, the surface energy and the Coulomb energy are added after the minimisation of the free energy, we consider it is enough to get the correct idea of the amount of hyperons that occur in the non-homogeneous sub-saturation warm stellar matter. We perform the study within the NL3ωρ parametrisation described in the last section.

We illustrate how the free energy per particle decreases when non-homogeneous matter is considered instead of homogeneous matter in Fig. 1, taking $T = 10$ MeV and $Y_c = 0.3$. The range of densities where the non-homogeneous matter occurs varies with temperature and electron fraction. In particular, it decreases as the temperature increases and eventually disappears above a certain critical temperature, which is around 14.45 MeV for this model [28]. Moreover, the electron fraction has a strong effect in the extension of the pasta phase: since

| $T$ (MeV) | $\rho_\Lambda$ (fm$^{-3}$) | $\rho_{\Sigma^+}$ (fm$^{-3}$) | $\rho_{\Sigma^-}$ (fm$^{-3}$) | $\rho_{\Xi^+}$ (fm$^{-3}$) | $\rho_{\Xi^-}$ (fm$^{-3}$) |
|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $0.001$   | 0.31            | -               | -               | 0.64            | 0.35            |
| $0.1$     | 0.30            | -               | -               | 0.61            | 0.34            |
| $0.30$    | 0.33            | 0.77            | -               | 0.60            | -               |
| $0.50$    | 0.36            | 0.60            | -               | 0.57            | -               |

TABLE II: Hyperon onset densities for hyperon fraction equal or above 10$^{-12}$. Only results for $\Lambda$, $\Sigma^-$ and $\Xi^-$ are shown. For $Y_c = 0.5$ the $\Xi^0$, $\Sigma^+$ and $\Sigma^0$ appear before, respectively, $\Xi^-$ and $\Sigma^-$ but the differences are small and the fractions are always very small.
we have determined which are the conditions that most favor the appearance of hyperons, taking the temperature between 4 and 14 MeV, the electron fraction between 0.05 and 0.6 and sub-saturation densities, see Fig. 3. Hyperon fractions above $10^{-7}$ were possible only for $T > 10$ MeV. At these temperatures, pasta phases do not occur for too high or too low densities, neither for too small electron fractions. However, the smaller the electron fraction the larger the $\Lambda$ fraction at a given temperature, which is distinguishable by a color index, since these conditions favour the replacement of neutrons by $\Lambda$s and decrease the free energy density.

There are, in fact, two competing factors related to the electron fraction: while more hyperons are favored with a smaller electron fraction to release the neutron pressure, the pasta extension is smaller for a smaller value of $Y_e$. As a result, it is not possible to attain so large temperatures with a small value of $Y_e$, and this explains the decrease of the $\Lambda$ fraction with a decrease of $Y_e$ if $Y_e < 0.35$ as seen in Fig. 4(b).

The internal structure of the pasta phase depends on the density, temperature and amount of charged particles, and for $Y_e > 10^{-7}$ practically only droplets survive.

In the present calculation only heavy clusters have been taken into account. The size of the clusters that occur under the conditions that favour hyperons can give an important information. In Fig. 4 we illustrate the number of nucleons in the clusters for the $\Lambda$ fractions above $10^{-7}$. The largest fractions occur precisely for the smaller clusters. On the other hand the present approach is not good enough to describe the non-homogeneous matter at the boundary to the core and at the low density where the light clusters are most probable. The figure indicates that a study similar to the present one should be performed considering explicitly light clusters. Under these conditions larger fractions of $\Lambda$s as obtained in [29] are expected.

For the sake of completeness, we also allow for the presence of $\Sigma^-$ particles and their fraction is plotted in Fig 5 as a function of (a) the electron fraction for $T = 10$ MeV and (b) the temperature for $Y_e = 0.3$. The dotted lines represent the fraction of $\Lambda$s that would occur in homogeneous matter. In (a) the thick and the thin lines are the fractions of $\Lambda$s with respect to the total density in the dense (cluster) and gas phases, as given in eq. 4. Since there is no distillation effect for strangeness as there is for isospin [27], the larger/smaller fraction in the dense/gas phases simply reflects the fact that the larger the density the larger the probability that hyperons occur. Notice that under the conditions for pasta to occur these fractions are really very small. We may also conclude that the clusters contain no hyperons since the fraction is so small that it is not enough to predict a whole hyperon inside the clusters. This implies that in the non-homogenous phase hyperons only occur in the gas and in smaller amounts than would occur if matter were homogeneous. This is illustrated in Fig 4(a) where the black marks refer to the gas phase and the red ones to the dense phase.

Since the amount of strangeness seems to be so small stellar matter is neutral, the larger the electron fraction the larger the proton fraction and the larger the non-homogeneous matter extension.

In Fig. 2 the fraction of $\Lambda$s is plotted as a function of (a) the electron fraction $Y_e$ for $T = 10$ MeV and (b) the temperature for $Y_e = 0.3$. The dotted lines represent the fraction of $\Lambda$s that would occur in homogeneous matter. In (a) the thick and the thin lines are the fractions of $\Lambda$s with respect to the total density in the dense (cluster) and gas phases, as given in eq. 4. Since there is no distillation effect for strangeness as there is for isospin [27], the larger/smaller fraction in the dense/gas phases simply reflects the fact that the larger the density the larger the probability that hyperons occur. Notice that under the conditions for pasta to occur these fractions are really very small. We may also conclude that the clusters contain no hyperons since the fraction is so small that it is not enough to predict a whole hyperon inside the clusters. This implies that in the non-homogenous phase hyperons only occur in the gas and in smaller amounts than would occur if matter were homogeneous. This is illustrated in Fig 4(a) where the black marks refer to the gas phase and the red ones to the dense phase.

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a larger fraction is expected in denser matter; b) $\Sigma^-$ has isospin projection -1 and is favoured in asymmetric nuclear matter as the one occurring in the background gas of the non-homogeneous matter. This explains why the fraction of $\Sigma^-$s is larger in the gas phase. In Fig. 4c we compare the abundances of $\Lambda$s and $\Sigma^-$s in the background gas, in the conditions that most favour the appearance of these hyperons in the core-collapse supernova matter. It is seen that the $\Sigma^-$s fraction are essentially two orders of magnitude smaller than the $\Lambda$ ones.

IV. CONCLUSIONS

We report a study on the presence of hyperons in the non-homogeneous phase of core-collapse supernova matter. This was performed within the framework of a RMF EoS with properties compatible with the ones presently accepted. The non-homogeneous phase was described within a coexisting phase approach which does not take into account in a self-consistent way the finite size effects. However, the results obtained within this approach above $\rho \sim 0.01$ fm$^{-3}$ give a prediction not far from a self-consistent Thomas Fermi calculation \cite{10}, and it is within this range of densities that the hyperons most contribute.

We have shown that the contribution of hyperons to the non-homogeneous matter is generally negligible: the fraction of $\Lambda$s obtained in all ranges of temperatures, densities and electron fraction is always below $10^{-5}$. The largest fractions occur for temperatures above 10 MeV, electron fractions between 0.3 and 0.5 and densities between 0.025 and 0.035 fm$^{-3}$. Other hyperons such as the $\Sigma^-$ occur with two to six orders of magnitude smaller.

One interesting conclusion is that the heavy clusters carry no hyperons and the fraction of $\Lambda$s in the gas phase is smaller than the expected fraction in homogeneous matter at the same density because these hyperons are not sensitive to the isospin distillation effect. On the other hand $\Sigma^-$s are sensitive to isospin but in the best conditions their abundance is two to three orders of magnitude below the $\Lambda$s abundance. This seems to indicate that the role of hyperons in matter with heavy clusters is negligible and can be taken into account by properly including hyperons in the background gas. A different problem concerns the appearance of hyperons together with light clusters which in the present study were not included: it was shown that the largest amounts of hyperons occur precisely with the smaller heavy clusters. Since our approach fails in the region of light clusters a calculation taking these degrees of freedom into account should be performed.

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FIG. 3: Λ fraction as a function of (a) temperature in the clustered (red) and gas (black) phases; (b) electron fraction; (c) density under the conditions that predict fractions above $10^{-7}$. In (a), to improve the visibility, the temperature of the clusters was shifted to the right by $\Delta T = 0.1$ MeV. In (b) and (c) only the Λ fractions in the clustered phase are shown, and temperature (in MeV) is indicated by a color index.
FIG. 4: A fraction as a function of the number of nucleons in the heavy clusters under the conditions that predict fractions above $10^{-7}$. The temperature (in MeV) is indicated by a color index.
FIG. 5: Hyperon fractions obtained with $\rho = 0.05$ fm$^{-3}$ as function of a) the charge fraction at $T=10$ MeV and b) $Y_\Sigma$ obtained as a function of the temperature with $Y_e = 0.3$. In c) the fractions of $\Lambda$s and $\Sigma^-$s are given as a function of temperature for a range of densities between 0.015 and 0.035 fm$^{-3}$ and electron fraction $Y_e$ between 0.15 and 0.5. Blue lines refer to $\Sigma$s and red lines to $\Lambda$s.