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The nuclear EoS: From experiments to astrophysical observation

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Summary. — We briefly review different experimental and astrophysical constraints of the nuclear equation of state as well as several phenomenological models and *ab initio* theoretical approaches commonly used in its description.

1. – Introduction

The equation of state (EoS) of isospin asymmetric nuclear matter is a fundamental ingredient in the description of the static and dynamical properties of neutron stars, core-collapse supernova and compact-star mergers [1, 2]. Its determination, however, is very challenging due to the wide range of densities, temperatures and isospin asymmetries found in these astrophysical scenarios, and it constitutes nowadays one of the main problems in nuclear astrophysics. The main difficulties are associated to our lack of a precise knowledge of the behavior of the in-medium nuclear interaction and to the very complicated resolution of the so-called nuclear many-body problem [3].

Models of the nuclear EoS are based on reliable experimental data on atomic nuclei and nucleon scattering. Current nuclear physics experiments, however, cannot probe the physical state of matter under extreme conditions of density, isospin asymmetry and temperature. Therefore, theoretical models and methods of the nuclear many-body theory, which have been applied with some success in the description of ordinary nuclear structure, are required to built the EoS in these unknown regions. However, the reliability of these models and methods decreases when the conditions of density, isospin asymmetry and temperature become more and more extreme. Theoretical calculations of the nuclear EoS at such extreme conditions can be tested almosy exclusively by astrophysical observations.

In this work we reviewed some of the experimental and astrophysical constraints of the nuclear EoS as well as several of the phenomenological models and *ab initio* theoretical approaches commonly used in its description. For a more complete and detailed review we refer the interested reader to refs. [1, 2] for two recent excellent publications on this topic.

The manuscript is organized in the following way. The experimental constraints on the nuclear EoS are presented in sect. **2** whereas the astrophysical ones are discussed in sect. **3**. A brief overview of different theoretical models for the nuclear EoS is given in sect. **4** followed by a short summary in sect. **5**.

2. – Experimental constraints of the nuclear EoS

Around saturation density ρ_0 and isospin asymmetry $\beta = (\rho_n - \rho_p)/(\rho_n + \rho_p) = 0$ the nuclear EoS can be characterized by a set of few isoscalar (E_0, K_0, Q_0) and isovector (S, L, K_{sym}, Q_{sym}) parameters. These parameters can be constrained by nuclear experiments and are related to the coefficients of a Taylor expansion of the energy per particle of asymmetric nuclear matter in density and isospin asymmetry:

$$\frac{E}{A}(\rho,\beta) = E_0 + \frac{1}{2}K_0x^2 + \frac{1}{6}Q_0x^3 + \left(S_0 + Lx + \frac{1}{2}K_{sym}x^2 + \frac{1}{6}Q_{sym}x^3\right)\beta^2 + \mathcal{O}(4). \tag{1}$$

Here $x = (\rho - \rho_0)/3\rho_0$, E_0 is the energy per particle of symmetric nuclear matter at ρ_0, K_0 the incompressibility parameter, Q_0 the so-called skewness, S_0 the value of the nuclear symmetry energy at ρ_0, L the slope of the symmetry energy, K_{sym} the symmetry incompressibility, and Q_{sym} the third derivative of the symmetry energy with respect to the density.

2˙1. *Experimental constraints of the isoscalar parameters.* – Measurements of nuclear masses [4] and density distributions [5] yield $E_0 = -16 \pm 1\,\mathrm{MeV}$ and $\rho_0 = 0.15$–$0.16\,\mathrm{fm}^{-3}$, respectively. The value of K_0 can be extracted from the analysis of isoscalar giant monopole resonances in heavy nuclei. However, its extraction is complicated and not unambiguous. Results of ref. [6] suggest $K_0 = 240 \pm 10\,\mathrm{MeV}$, whereas in ref. [7] a value of $K = 248 \pm 8\,\mathrm{MeV}$ is reported, while in ref. [8] $K = 210 \pm 30\,\mathrm{MeV}$ is given. Recently, Khan *et al.* [9] have shown that the third derivative M of the energy per unit volume of symmetric nuclear matter is constrained by giant monopole resonance measurements not at ρ_0 but rather around what has been called crossing density $\rho \approx 0.11\,\mathrm{fm}^{-3}$. These authors found $M = 1100 \pm 70\,\mathrm{MeV}$, whose extrapolation at ρ_0 gives $K_0 = 230 \pm 40\,\mathrm{MeV}$. Heavy-ion collision experiments would rather point to a rather "soft" EoS, *e.g.*, a lower value of K_0 [10]. However, the constraints inferred from heavy-ion collisios are model dependent because the analysis of the measured data requires the use of transport models. The value of the skewness parameter Q_0 is more uncertain and is not very well constrained yet, being the estimated value in the range $-500 \leq Q_0 \leq 300\,\mathrm{MeV}$.

2˙2. *Experimental constraints of the isovector parameters.* – Experimental information on the isovector parameters of the nuclear EoS can be obtained from several sources such as the analysis of giant [11] and pygmy [12, 13] resonances, isospin difussion measurements [14], isobaric analog states [15], isoscaling [16], measurements of the neutron skin thickness in heavy nuclei [17-23] or meson production in heavy-ion collisions [24, 25]. However, whereas S_0 is more or less well established ($\approx 30\,\mathrm{MeV}$), the values of L, and specially those of K_{sym} and Q_{sym}, are still uncertain and poorly constrained. For example, combining different data the authors of ref. [26] give $29.0 < S_0 < 32.7\,\mathrm{MeV}$ and $40.5 < L < 61.9\,\mathrm{MeV}$, while a more recent work [27] suggests $30.2 < S_0 < 33.7\,\mathrm{MeV}$ and $35 < L < 70\,\mathrm{MeV}$. Why the isovector part of the nuclear EoS is so uncertain is still an open question whose answer is related to our limited knowledge of the nuclear force and, in particular, to its spin and isospin dependence.

3. – Astrophysical constraints

The main astrophysical constraints on the nuclear EoS are those arising from the observation of neutron stars. After fifty years of observations we have collected an enourmous amount of data on different neutron star observables from which it is possible to infer valuable information on the internal structure of these objects and, therefore, also on the nuclear EoS, which is the only ingredient needed to solve the structure equations of neutron stars. In the following lines we shortly review some of these observables.

3˙1. *Masses.* – Neutron star masses can be inferred directly from observations of binary systems and likely also from supernova explosions. There are five orbital (or Keplerian) parameters which can be precisely measured in any binary system. These are: the orbital period (P_b), the projection of the pulsar's semimajor axis on the line of sight ($x \equiv a_1 \sin i/c$, where i is inclination of the orbit), the eccentricity of the orbit (e), and the time (T_0) and longitude (ω_0) of the periastron. Using Kepler's Third Law, these parameters can be related to the masses of the neutron star (M_p) and its companion (M_c) though the so-called mass function

$$f(M_p, M_c, i) = \frac{(M_c \sin i)^3}{(M_p + M_c)^2} = \frac{P_b v_1^3}{2\pi G}, \tag{2}$$

where $v_1 = 2\pi a_1 \sin i/P_b$ is the projection of the orbital velocity of the neutron star along the line of sight. If only one mass function can be measured for a binary system, then one cannot proceed further than eq. (2) without additional assumptions. Fortunately, deviations from the Keplerian orbit due to general relativity effects can be detected. These relativistic corrections are parametrized in terms of one or more post-Keplerian parameters. The most significant ones are: the advance of the periastron of the orbit ($\dot{\omega}$), the combined effect of variations in the transverse Doppler shift and gravitational redshift around an elliptical orbit (γ), the orbital decay due to the emission of quadrupole gravitational radiation ($\dot{P}_b$), and the range (r) and shape (s) parameters that characterizes the Shapiro time delay of the pulsar signal as it propagates through the gravitational field of its companion. These post-Kepletian parameters can be written in terms of measured quantities and the masses of the star and its companion as [28]:

$$\dot{\omega} = 3n^{5/3} T_\odot^{2/3} \frac{(M_p + M_c)^{2/3}}{1 - e}, \tag{3}$$

$$\gamma = e T_\odot^{2/3} \frac{M_c(M_p + 2M_c)}{n^{1/3}(M_p + M_c)^{4/3}}, \tag{4}$$

$$\dot{P}_b = -\frac{192\pi}{5}(nT_\odot)^{5/3}\left(1 + \frac{73}{24}e^2 + \frac{37}{96}e^4\right)\frac{1}{(1-e^2)^{7/2}}\frac{M_p M_c}{(M_p + M_c)^{1/3}}, \tag{5}$$

$$r = T_\odot M_c, \tag{6}$$

$$s = x\frac{n^{2/3}}{T_\odot^{1/3}} \frac{(M_p + M_c)^{2/3}}{M_c}, \tag{7}$$

where $n = 2\pi/P_b$ is the orbital angular frequency and $T_\odot \equiv GM_\odot/c^3 = 4.925490947 \times 10^{-6}$ s. The measurement of any two of these post-Keplerian parameters together with mass function f is sufficient to determine uniquely the masses of the two components of the system. An example of a high-precision mass measurement is that of the famous Hulse-Taylor binary pulsar [29] with measured masses $M_p = 1.4408 \pm 0.0003 M_\odot$ and $M_c = 1.3873 \pm 0.0003 M_\odot$. Another examples are those of the recently observed millisecond pulsars PSR J1614-2230 [30] and PSR J0348+0432 [31] with masses $M_p = 1.928 \pm 0.017 M_\odot$ and $M_p = 2.01 \pm 0.04 M_\odot$, respectively. These are binary systems formed by a neutron star and white dwarf. The measurement of these two unusually high neutron star masses constitutes nowadays one of the most stringent astrophysical constraints on the nuclear EoS.

3˙2. *Radii.* – Neutron star radii are very difficult to measure mainly because neutron stars are very small objects and are very far away from us (*e.g.*, the closest neutron star is probably the object RX J1856.5-3754 which is about 400 light-years from Earth). Direct measurements of radii do not exist. However, a possible way to determine them is to use the thermal emission of low-mass X-ray binaries. The observed X-ray flux (F) and temperature (T), assumed to be originated from a uniform blackbody, together with a determination of the distance (D) of the star can be used to obtained an effective radius

$$R_\infty = \sqrt{\frac{FD^2}{\sigma T^4}}. \tag{8}$$

Here σ is the Stefan-Boltzmann constant. The neutron star radius R can be then obtained from R_∞ through the equation

$$R = R_\infty \sqrt{1 - \frac{2GM}{c^2 R}}, \tag{9}$$

where M is the mass of the star. The major uncertainties in the measurement of the radius throug eqs. (8)–(9) come from the determination of the temperature, which requires the assumption of an atmospheric model, and the estimation of the distance of the star. However, the analysis of present observations from quiescent low-mass X-ray binaries is still controversial. Whereas the analyis of Steiner *et al.* [32, 33] indicates neutron star radii in the range of 10.4–12.9 km, that of Guillot *et al.* [34, 35] points towards smaller radii of ~ 10 km or less.

As the reader can imagine the simultaneous measurement of both mass and radius of the same neutron star would provide the most definite observational constraint on the nuclear EoS. Unfortunately, althought it is very much desiderable, such a measurement does not exists yet.

3˙3. *Rotational periods.* – The major part of the known neutron stars are observed as radio pulsars many of which exhibit very stable rotational periods. Thanks to highly accurate pulsar timing, observers have been able to measure the rotational period P and the first time derivative $\dot{P}$ and sometimes even the second one $\ddot{P}$ of many radio pulsars (see *e.g.* [36-38] and references therein). Observed pulsar rotational periods show the existence of two different classes of pulsars: that of the *normal* pulsars with rotational periods of the order of ~ 1 s, and that of the so-called *millisecond* pulsars with rotational periods three orders of magnitude smaller. The first millisecond pulsar was discovered in 1982 with the help of the Arecibo radio telescope and nowadays more than 200 pulsars of this class are known. At present the fastest pulsar known till now, with a rotational period of 1.39595482 ms, is the object named PSR J1748-2446ad which was discovered in 2005 in the globular cluster Terzan 5 in the Sagittarius constellation.

3˙4. *Surface temperatures.* – The detection of thermal photons from the stellar surface in X-ray binaries allows to determine effective surface temperatures of neutron stars by fitting the observed spectra to blackbody ones. However, one should keep in mind that neutron stars are not blackbodies, because the hydrogen and helium (or even carbon) in their atmospheres modifies the blackbody spectrum. In addition the presence of strong magnetic fields can also modify the surface emission. Surface temperatures are in fact reduced when realistic atmosphere models are used in the fit of the measured spectrum. We note that any uncertainty in the determination of the surface temperature changes the corresponding luminosity L of the star by a large factor according to the Stefan-Boltzmann law, $L = 4\pi R^2 \sigma T^4$. Therefore, it is not appropiate to use the surface temperature when comparing with observational data but the luminosity instead.

3˙5. *Gravitational redshift.* – An important source of information on the structure of a neutron star is provided by the measurement of its gravitational redshift

$$z = \left(1 - \frac{2GM}{c^2 R}\right)^{-1/2} - 1, \tag{10}$$

which allows to constrain the M/R ratio and, therfore, the nuclear EoS. The interpretation of measured γ-ray bursts, as gravitationally redshifted 511 keV $e^{\pm}$ annihilation lines from the surface of neutron stars, supports a neutron star redshift range of $0.2 \leq z \leq 0.5$ with the highest concentration in the narrower range $0.25 \leq z \leq 0.35$ [39].

3˙6. *Quasiperiodic oscillations.* – Quasiperiodic X-ray oscillations (QPOs) in X-ray binaries measure of the difference between the rotational frequency of the neutron star and the Keplerian frequency of the innermost stable orbit of matter elements in the accretion disk formed by the diffused material of the companion in orbital motion around the star. Their observation and analysis can provide very useful information to understand better the innermost regions of accretion disks as well as to put stringent constraints on the masses, radii and rotational periods of neutron stars. QPOs may also serve as unique proves of strong field general relativity. However, the theoretical interpretation of QPOs is not simple and remains still controversial.

3˙7. *Magnetic fields.* – Since the suggestion of Gold [40] pulsars are generally believed to be rapidly rotating neutron stars with strong surface magnetic fields. The strength of the field could be of the order of 10^8–10^9 G in the case of millisecond pulsars, about 10^{12} G in normal pulsars, or even 10^{14}–10^{15} G in the so-called *magnetars*. The magnetic field strength of a pulsar can be estimated from the observation of its rotational period P and its first derivative $\dot{P}$.

3˙8. *Glitches.* – Pulsars are observed to spin down gradually due to the transfer of their rotational energy to the emitted electromagnetic radiation. Sudden jumps $\Delta\Omega$ of the rotational frequency Ω, however, have been observed in several pulsars followed by a slow partial relaxation that can last days, months or years. These jumps, mainly observed from relative young radio pulsars, are known as *glitches*. The relative increase of the rotational frequency $\Delta\Omega/\Omega$ vary from $\sim 10^{-10}$ to $\sim 5 \times 10^{-6}$. The first glitches were detected from the Crab and Vela pulsars [41-43]. Nowadays we know more than 520 glitches in more than 180 pulsars.

3˙9. *Timing noise*. – One of the most remarkable properties of radio pulsars is their rotational stability. However, some of them show slow irregular or quasiregular variations of their pulses over time scales of months, years and longer which have been called *pulsar timing noise*. These timing imperfections appear as random walks in the pulsar rotation (with relative variations of the rotational period $\leq 10^{-10}$–10^{-8}), the spindown rate or the pulse phase. Their nature is still uncertain and many hypotheses have been made (see, *e.g.*, ref. [44]). Careful studies of the pulsar timing noise can provide valuable information on the internal structure of neutron stars.

3˙10. *Gravitational waves*. – Gravitational waves originated from the oscillation modes of neutron stars or during the coalescence of two neutron stars or a black hole and a neutron star constitute also a valuable source of information. Very recently, on August 17th, 2017, the graviational wave signal from a binary neutron star merger was detected for the first time by the Advanced LIGO and Advanced VIRGO Collaborations [45] inaugurating, with the detection of this event (known as GW170817), a new era in the observation of neutron stars. The very first and preliminary analysis of GW170817 seems to indicate that neutron star radii should be $R < 13$ km or even smaller than 12 km (some analysis suggest $R < 11$ km). That could put an additional stringent constraint on the nuclear EoS, since those predicting large radii would be excluded. In addition, a low value of the upper limit of the tidal deformability seems to favor a soft EoS.

4. – Theoretical approaches of the nuclear EoS

Theoretically the nuclear EoS has been determined by many authors using both phenomenological and microscopic many-body approaches. Phenomenological approaches, either nonrelativistic or relativistic, are based on effective interactions that are frequently built to reproduce the properties of nuclei [46]. Skyrme interactions [47-49] and relativistic mean-field (RMF) models [50-52] are among the most used ones. Many of such interactions are built to describe nuclear systems close to the isospin symmetric case and, therefore, predictions at high isospin asymmetries should be taken with care. Most Skyrme forces are, by construction, well behaved close to ρ_0 and moderate values of the isospin asymmetry. However, only certain combinations of the parameters of these forces are well determined experimentally. As a consequence, there exists a large proliferation of different Skyrme interactions that produce a similar EoS for symmetric nuclear mattter but predict a very different one for pure neutron matter. Few years ago, Stone *et al* [53] made an extensive and sistematical test of the capabilities of almost 90 existing Skyrme forces to provide good neutron star candidates, finding that only 27 of these forces passed the restrictive tests imposed. A more stringent constraint has been recenty done by Dutra *et al.* [54] who have examined the suitability of 240 Skyrme interactions with respect to 11 constraints derived from experimental data and the empirical properties of symmetric matter at and close to saturation density. These authors found that only 5 of the 240 analyzed interactions satisfied all the constraints imposed.

Relativistic mean-field models are based on effective Lagrangians densities where the interaction between baryons is described in terms of meson exchanges. The couplings of nucleons with mesons are usually fixed by fitting masses and radii of nuclei and the properties of nuclear bulk matter, whereas those of other baryons, like hyperons, are fixed by symmetry relations and hypernuclear observables. Recently, Dutra *et al.* [55] have analyzed, as in the case of Skyrme, 263 parametrizations of 7 different types of RMF models impossing constraints from symmetric nuclear matter, pure neutron matter, symmetry energy and its derivatives finding that only a very small number of these parametrizations is consistent with all the nuclear constraints considered in that work.

Microscopic approaches, on other hand, are based on realistic two- and three-body forces that describe scatterinng data in free space and the properties of the deuteron. These interactions are based on meson-exchange [56-65] or, very recently, on chiral perturbation theory [66-69]. To obtain the EoS one has to solve then the complicated many-body problem [3] whose main dificulty lies in the treatment of the repulsive core, which dominates the short range of the interaction. Different microscopic many-body approaches have been extensively used for the study of the nuclear matter EoS. These include among others: the Brueckner-Bethe-Goldstone [3, 70] and the Dirac-Brueckner-Hartree-Fock [71-73] theories, the variational method [74], the correlated basis function formalism [75], the self-consistent Green's function technique [76, 77], the $V_{\mathrm{low}\,k}$ approach [78] or Quantum Monte Carlo techniques [79-81]. The interested reader is referred to any of the quoted works for details on these approaches.

5. – Summary

We have briefly reviewed different experimental and astrophysical constraints of the nuclear EoS as well as of several phenomenological models and *ab initio* theoretical approaches commonly used in its description. Although major experimental, observational and theoretical advances on understanding the nuclear EoS have been done in the last decades and will be done in the near future, only its isoscalar part is rather well constrained. Why the isovector part of the nuclear EoS is less well constrained is still an open question whose answer is probably related to our limited knowledge of the nuclear force and, in particular, of it spin and isospin dependence.

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