CompOSE
(COMPSTAR ONLINE SUPERNOVAE EQUATIONS OF STATE): HARMONIZING THE CONCEPT OF NUCLEAR PHYSICS AND ASTROPHYSICS

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A comprehensive knowledge of properties of dense matter is essential for many applications in astrophysics and nuclear physics. Various models have been developed in the past, but their results are often not accessible in a simple or standardized way. The CompOSE database (compose.obspm.fr) provides a web-based repository of equation of state tables in a common data format. They contain information on the thermodynamic properties, the chemical composition and microphysical quantities of nuclear and stellar matter. This manual explains the basic features and options of the CompOSE database as well as the accompanying programs for storing, handling and extracting the data. The notation and conventions for the tabulation are established and presented extensively. The derivation of thermodynamic quantities from basic potentials is displayed and characteristic nuclear matter parameters are discussed. Technical details of the interpolation scheme are given in Appendixes.

Понимание всех свойств плотной материи является ключевым во многих приложениях астрофизики и ядерной физики. В прошлом было предложено множество различных моделей для описания этих свойств, однако их результаты часто невозможно получить простым и доступным способом. База данных CompOSE (compose.obspm.fr) представляет собой онлайн-хранилище таблиц уравнений состояния в едином формате. Она содержит информацию о термодинамических свойствах, химическом составе и микрофизических характеристиках ядерной и звездной материи. Данное руководство объясняет основные возможности и особенности базы CompOSE, так же как

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и программы, используемые для сбора данных, работы с ними и получающимися на их основе результатами. Все вводимые обозначения и соглашения детально поясняются. В работе описывается процедура вычисления термодинамических величин из базовых потенциалов, а также обсуждаются параметры ядерной материи. Технические детали схемы интерполяции приведены в приложении.

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Part I. INTRODUCTION

1. WHAT CompOSE CAN DO AND WHAT NOT

The online service CompOSE provides information and data tables for different equations of states (EoS) ready for further use in astrophysical applications, nuclear physics and beyond. This service has three major purposes:

• CompOSE is a repository of the EoS tables in a common format for direct usage with information on a large number of thermodynamic properties, on the chemical composition of dense matter and, if available, on microphysical quantities of the constituents.

• CompOSE allows one to interpolate the provided tables using different schemes to obtain the relevant quantities, selected by the user, for grids that are tailored to specific applications.

• CompOSE can provide information on additional thermodynamic quantities, which are not stored in the original data tables, and on further quantities, which charactize an EoS such as nuclear matter parameters and compact star properties.

The format of the files as well as the calculational mesh is mainly determined according to the needs of scientific groups performing extensive numerical simulations of astrophysical objects.

We cannot offer an online service for all features of CompOSE, e.g., to run all codes online. This is mostly due to limitations in storage and computation times but also gives better control on avoiding unphysical input parameters. However, we offer several computational tools that allow the user to extract the data from the tables that are relevant for her/him. We try to provide the tables in a large parameter space to cover most applications.

If you make use of the tables provided, you will be guided on the CompOSE web pages to the scientific publications where the particular EoS models have been described in detail. Please cite them when using the tables for scientific purposes.

CompOSE is designed in a modular way, thus allowing to extend the service over time. More and more models and parameter sets will be provided in time. It is foreseen that additional features will be added in the future, too.

2. HOW TO READ THIS DOCUMENT

While reading this document please always keep in mind: this document was written by physicists for physicists. It is divided into three major parts.

The first one is relevant both to providers and users of equations of state since it serves as a basis for the discussions in the following parts of the manual and the web site. Both, contributors and users, should first of all have a look at the introductory Sec. 3, where we will discuss general conventions and the notation used throughout CompOSE. In addition, we give definitions and details on the system of units that is used within CompOSE and on physical constants that should be used in order to standardize the generation of new equations of state.

The second part concerns those persons who wish to contribute to an extension of the CompOSE data base by active development of an EoS. CompOSE allows them to make their favourite EoS available for a broad range of astrophysical and nuclear physics applications. In part II, detailed instructions, minimal requirements and recommendations are specified for the preparation of the EoS tables that can be incorporated in future versions of the CompOSE data base. If you plan to contribute your EoS, you should contact the CompOSE core team, see Appendix B. A summary of possible future extensions of the CompOSE data base are summarized in Sec. 5.

Part III concerns the users of the EoS data, that are provided by CompOSE, who want to test various equations of state in their simulations of core-collapse supernovae, neutron-star mergers and other scenarios. In general, they can safely skip the second part and go directly to the third one. This part gives a brief introduction on nuclear matter properties relevant for the construction of an EoS as well as a classification of different types of the EoS models. The models can be distinguished either by using different techniques to treat the many-body system of strongly interacting particles or by assuming a different particle composition. The main aim is to give the relevant information for the interpretation of the data sheets, provided with each available EoS table on the web site.

On the latter, you will find remarks on the range of applicability of the various models, i.e., the range of parameters where the code is tested and/or the made approximations are still valid. Characteristic parameters of each model will be specified. For more detailed information about the physics behind each model, we refer to the original references. In addition, the third part of the manual explains how to proceed in order to download the EoS table and the computational tools. The latter allow, in particular, the generation of tables with a mesh different from the original one via interpolation, in order to adapt the table to the need of the user. In addition, several thermodynamic quantities can be calculated which are not contained in the original tables. The use of the online service and web interface is described in Sec. 7.

3. DEFINITIONS AND NOTATION

The equations of state in the CompOSE data base are provided under some common assumptions on the physical conditions of the matter that are specified in this Section. In order to fix the notation in the present document, the definition of all relevant quantities is given.

3.1. Units and Conventions. We use natural units $\hbar = c = k_B = 1$ throughout this document as is customary in nuclear physics. Energies and temperatures are measured in MeV; lengths, in fm. Units are given in parentheses [...] for all quantities when they are defined within this Section. For conversion, among your favourite units the use of the CODATA values [1] (http://physics.nist.gov/cuu/Constants/index.html, www.codata.org) is recommended, see Table 1*. They should also be used in the preparation of new EoS tables to be incorporated in the CompOSE data base.

Table 1. **Recommended values for physical constants from the 2010 CODATA evaluation. The elementary charge is denoted by the symbol** e

Quantity	Symbol	Value	Unit
Speed of light in vacuum	c	299792458	$\mathrm{m \cdot s^{-1}}$
Planck's constant	$\hbar$	$1.054571726 \cdot 10^{-34}$	$\mathrm{J \cdot s}$
		$6.58211928 \cdot 10^{-22}$	$\mathrm{MeV \cdot s}$
		197.3269718	$\mathrm{MeV \cdot fm \cdot} c^{-1}$
Boltzmann's constant	k_B	$1.3806488 \cdot 10^{-23}$	$\mathrm{J \cdot K^{-1}}$
		$8.6173324 \cdot 10^{-11}$	$\mathrm{MeV \cdot K^{-1}}$
Gravitational constant	G	$6.67384 \cdot 10^{-11}$	$\mathrm{m^3 \cdot kg^{-1} \cdot s^{-2}}$
		$6.70837 \cdot 10^{-39}$	$\mathrm{GeV^{-2} \cdot} c^{-4}$
Fine structure constant	$\alpha = e^2/(\hbar c)$	$1/137.035999074$	—
Neutron mass	m_n	939.565379	$\mathrm{MeV \cdot} c^{-2}$
Proton mass	m_p	938.272046	$\mathrm{MeV \cdot} c^{-2}$
Electron mass	m_e	0.510998928	$\mathrm{MeV \cdot} c^{-2}$
Muon mass	m_μ	105.6583715	$\mathrm{MeV \cdot} c^{-2}$

For experimental binding energies of nuclei, the values of the 2012 Atomic Mass Evaluation [2] (AME2012, http://amdc.impcas.ac.cn) or corresponding updates are recommended. Ground state spin assignments should be taken from the Nubase2012 [3] evaluation of nuclear properties (http://amdc.impcas.ac.cn) or corresponding updates.

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*The compilation on physical constants by the Particle Data Group, pdg.lbl.gov, contains the CODATA values together with some additional constants concerning the interaction of elementary particles.

3.2. Physical Conditions. Predictions for the properties of dense matter can differ considerably depending on the employed model, the considered constituents, and interactions. In the CompOSE data base, the equation of state is considered to describe dense matter in thermodynamic equilibrium that is defined as follows. It is assumed that all the constituents are in chemical equilibrium regardless of the time scales and reaction rates for the relevant conversion reactions mediated by strong and electromagnetic interactions. This condition leads to relations between the chemical potentials of all particles.

In contrast, an equilibrium with respect to weak interaction reactions, in particular β-equilibrium, is not supposed in general. Similarly, the chemical potentials of the massive leptons of all generations, i.e., electrons and muons (tauons are irrelevant for the considered conditions) cannot assumed to be equal. There is an option available such that the EoS tables can be provided in particular cases which also take β-equilibrium into account, reducing the number of independent parameters. Assumptions on the relation between the electron and muon chemical potentials are discussed in the description of each model separately.

For the EoS models with strangeness bearing particles, e.g., hyperons or kaons, it is assumed that the strangeness chemical potential vanishes. This means that we assume the strangeness changing weak interactions to be in equilibrium. Note that this is not the case in heavy-ion collisions, where, on the contrary, strangeness is conserved, i.e., there is no net strangeness.

Except for the tables of pure hadronic or quark matter without massive leptons, also local charge neutrality is assumed to hold. Neutrinos and their contribution to thermodynamic properties are never included in the present tables since they are usually treated independently of the EoS in astrophysical simulations because a thermodynamic equilibrium cannot be assumed in general.

Photons are usually included in equations of state for astrophysical applications. Their treatment is discussed in Subsec. 3.8.

3.3. Particle Number Densities and Particle Fractions. Particle number densities of all particles i are given by

$$n_i = \frac{N_i}{V} \ [\text{fm}^{-3}], \tag{1}$$

where N_i [dimensionless] is the particle number inside the volume V [fm^3]. Note that for particles with half-integer spin, n_i represents the net particle density, i.e., it is the difference between the particle and antiparticle density. For example, for electrons we have $n_e = n_{e^-} - n_{e^+}$. For particles with integer spin, e.g., mesons, particle and antiparticle densities are distinguished and given separately.

From the individual particle number densities several new *composite* number densities can be deduced that are convenient to characterize the state of the system. The baryon number density n_b and the total number of baryons N_b

[dimensionless] are given by

$$n_b = \frac{N_b}{V} = \sum_i B_i n_i \ [\text{fm}^{-3}] \tag{2}$$

with the baryon number B_i [dimensionless] for a particle i. The baryon number of a nucleus i is just the mass number A_i [dimensionless] and for a quark i one has $B_i = 1/3$.

Warning. In many astrophysical applications, a mass density $\varrho = m\,n_b$ is introduced as a parameter with m representing, e.g., the neutron mass or the atomic mass unit. But, ϱ is not identical to the total mass (= total internal energy) density. Hence, ϱV is not a conserved quantity.

The strangeness number density n_s and total strangeness number N_s

$$n_s = \frac{N_s}{V} = \sum_i S_i n_i \ [\text{fm}^{-3}] \tag{3}$$

and the lepton number densities n_{le}, $n_{l\mu}$ and number of leptons N_{le}, $N_{l\mu}$

$$n_{le} = \frac{N_{le}}{V} = \sum_i L_i^e n_i \ [\text{fm}^{-3}], \tag{4}$$

$$n_{l\mu} = \frac{N_{l\mu}}{V} = \sum_i L_i^\mu n_i \ [\text{fm}^{-3}] \tag{5}$$

with strangenes numbers S_i [dimensionless] and lepton numbers L_i^e, L_i^μ [dimensionless], respectively, are defined similar to the baryon number density. Since neutrinos are not included in the CompOSE EoS, $n_{le} = n_e$ and $n_{l\mu} = n_\mu$. We also consider the charge density of strongly interacting particles n_q and corresponding charge number N_q

$$n_q = \frac{N_q}{V} = \sum_i{}' Q_i n_i \ [\text{fm}^{-3}] \tag{6}$$

with charge numbers Q_i [dimensionless]. The prime at the sum symbol indicates that the summation runs over all particles (including quarks) except leptons. For a nucleus $^{A_i}Z_i$, the baryon number B_i and the charge number Q_i are simply given by the mass number A_i and atomic number Z_i, respectively. Table 2 summarizes baryon, strangeness, charge and lepton numbers of the most relevant particles that appear in the definition of the composite number densities.

Corresponding to the particle number densities n_i, the particle number fractions

$$Y_i = \frac{n_i}{n_b} \quad [\text{dimensionless}] \tag{7}$$

are defined. Due to this definition with n_b we have the normalization condition

$$\sum_i B_i Y_i = 1, \tag{8}$$

with a summation over all particles. Note that Y_i is not necessarily identical to the particle mass number fraction

$$X_i = B_i Y_i \quad \text{[dimensionless]} \tag{9}$$

that are often introduced. We prefer to use Y_i and not X_i, since the latter quantity is zero for all particles with baryon number $B_i = 0$, e.g., mesons.

Because of the imposed physical conditions (see Subsec. 3.2), the state of the system is uniquely characterized by the three quantities: temperature T [MeV], baryon number density n_b [fm^{-3}] and charge density of strongly interacting particles n_q [fm^{-3}]. Charge neutrality implies $n_q = n_{le} + n_{l\mu}$ and the strangeness number density n_s is fixed by the condition $\mu_s = 0$. Instead of n_q, it is more convenient to use the charge fraction of strongly interacting particles

$$Y_q = \frac{n_q}{n_b} \quad \text{[dimensionless]} \tag{10}$$

as the third independent quantity. The choice of Y_q instead of the electron fraction

$$Y_e = \frac{n_e}{n_b} \quad \text{[dimensionless]} \tag{11}$$

as a parameter is motivated by the following facts. In pure hadronic (quark) equations of state (i.e., without leptons) only Y_q and not Y_e is defined. In the EoS models with the condition of charge neutrality that contain electrons as the only considered charged lepton, the charge fraction of strongly interacting particles Y_q is identical to the electronic charge fraction Y_e. In models with electrons and muons, charge neutrality requires

$$Y_q = Y_e + Y_\mu = Y_l \tag{12}$$

with the muon fraction

$$Y_\mu = \frac{n_\mu}{n_b} \quad \text{[dimensionless]} \tag{13}$$

and the total lepton fraction Y_l [dimensionless]. In this case, the balance between the electron and muon densities depends on the assumed relation of the electron and muon chemical potentials.

Table 2. **Baryon (B_i), strangeness (S_i), charge (Q_i), and lepton (L_i^e, L_i^μ) numbers and indices I_i of the most relevant particles i in dense matter**

Particle class	Symbol of particle i	B_i	S_i	Q_i	L_i^e	L_i^μ	Particle index I_i
Leptons	e^-	0	0	-1	1	0	0
	μ^-	0	0	-1	0	1	1
Nuclei ($A > 1$)	$^Z A$	A	0	Z	0	0	$1000\,A + Z$
Baryons	n	1	0	0	0	0	10
	p	1	0	$+1$	0	0	11
	Δ^-	1	0	-1	0	0	20
	Δ^0	1	0	0	0	0	21
	Δ^+	1	0	$+1$	0	0	22
	Δ^{++}	1	0	$+2$	0	0	23
	Λ	1	-1	0	0	0	100
	Σ^-	1	-1	-1	0	0	110
	Σ^0	1	-1	0	0	0	111
	Σ^+	1	-1	$+1$	0	0	112
	Ξ^-	1	-2	-1	0	0	120
	Ξ^0	1	-2	0	0	0	121
Mesons	ω	0	0	0	0	0	200
	σ	0	0	0	0	0	210
	η	0	0	0	0	0	220
	η'	0	0	0	0	0	230
	ρ^-	0	0	-1	0	0	300
	ρ^0	0	0	0	0	0	301
	ρ^+	0	0	$+1$	0	0	302
	δ^-	0	0	-1	0	0	310
	δ^0	0	0	0	0	0	311
	δ^+	0	0	$+1$	0	0	312
	π^-	0	0	-1	0	0	320
	π^0	0	0	0	0	0	321
	π^+	0	0	$+1$	0	0	322
	ϕ	0	0	0	0	0	400
	σ_s	0	0	0	0	0	410
	K^-	0	-1	-1	0	0	420
	K^0	0	$+1$	0	0	0	421
	$\bar{K}^0$	0	-1	0	0	0	422
	K^+	0	$+1$	$+1$	0	0	423
Quarks	u	1/3	0	$+2/3$	0	0	500
	d	1/3	0	$-1/3$	0	0	501
	s	1/3	-1	$-1/3$	0	0	502
Photon	γ	0	0	0	0	0	600

3.4. Particle Indexing. The composition of dense matter can rapidly change with temperature T [MeV], baryon number density n_b [fm^{-3}] and the charge fraction of strongly interacting particles Y_q [dimensionless]. We introduce an indexing scheme for the particles that allows one to identify them uniquely in order to store only the most abundant particles in the EoS tables. In Table 2, an overview of indices for most of the relevant particles is presented. Indices of missing particles can be added on request.

Table 3. **Baryon (B_i), strangeness (S_i), and charge (Q_i) numbers and indices I_i of the most relevant two-particle correlations i in dense matter. The lepton numbers L_i^e and L_i^μ are always zero for these correlations**

Correlation class	Particles	Channel	B_i	S_i	Q_i	Index I_i of correlation
Two-body	nn	$^1S_0$	2	0	0	700
	np	$^1S_0$	2	0	1	701
	pp	$^1S_0$	2	0	2	702
	np	$^3S_1$	2	0	1	703

In addition to the various particles that can appear in dense matter, there is the possibility of strong two- or even three-particle correlations such as pairing of nucleons or quarks and phenomena such as superfluidity can arise. Hence, an indexing scheme for identifying these channels is introduced, too. In Table 3, the notation is given for these correlations. Again, indices of missing particle correlations can be added on request.

3.5. Thermodynamic Potentials and Basic Quantities. All thermodynamic properties of a system are completely determined if a thermodynamic potential is known as a function of its natural variables. In the general case, this can be formulated as follows. The properties can be derived from the thermodynamic potential $\Xi = \Xi(x_i, \xi_j)$ depending on n natural variables x_i, $i = 1, \ldots, n_1$ and ξ_j, $j = 1, \ldots, n_2$ with $n_1 + n_2 = n$. The quantities x_i and ξ_i represent extensive and intensive variables, respectively. The relations

$$\xi_i = \left. \frac{\partial \Xi}{\partial x_i} \right|_{x_k, k \neq i; \xi_j} = \xi_i(x_i, \xi_j) \tag{14}$$

and

$$x_j = -\left. \frac{\partial \Xi}{\partial \xi_j} \right|_{\xi_k, k \neq j; x_i} = x_j(x_i, \xi_j) \tag{15}$$

are the thermodynamic equations of state and define the variables ξ_i that are conjugate to x_i as first partial derivatives of Ξ, and vice versa. Due to Euler's

theorem on homogeneous functions, the thermodynamic potential is given by the sum

$$\Xi(x_i, \xi_j) = \sum_{i=1}^{n_1} \xi_i x_i \tag{16}$$

running over all $i = 1, \ldots, n_1$ intensive variables. Thus, the knowledge of all relevant equations of state or first derivatives is sufficient to recover the thermodynamic potential Ξ completely. For the mixed second partial derivatives of a thermodynamic potential Ξ the result is independent of the order of differentiation, and the Maxwell relations

$$\left.\frac{\partial \xi_l}{\partial x_k}\right|_{x_j, j \neq k} = \left.\frac{\partial \xi_k}{\partial x_l}\right|_{x_j, j \neq l} \tag{17}$$

are obtained. For a more detailed discussion of these and further aspects we refer the reader to standard text books on thermodynamics.

In the most models for the EoS of dense matter, the temperature T [MeV], the volume V [fm^3], and the individual particle numbers N_i [dimensionless] are selected as natural variables. This case corresponds to the (Helmholtz) free energy $F = F(T, V, N_i)$ [MeV] as the relevant thermodynamic potential that contains all information. Note that we assume that the free energy includes contributions by the rest masses of the particles. Keeping the volume V fixed, it is convenient to define the free energy density

$$f(T, n_i) = \frac{F}{V} \qquad [\text{MeV} \cdot \text{fm}^{-3}], \tag{18}$$

and the entropy density

$$s(T, n_i) = -\left.\frac{\partial f}{\partial T}\right|_{n_i} \qquad [\text{fm}^{-3}] \tag{19}$$

with the entropy

$$S(T, V, N_i) = V s(T, n_i) = -\left.\frac{\partial F}{\partial T}\right|_{V, N_i} \qquad [\text{dimensionless}]. \tag{20}$$

The chemical potential of a particle i is given by

$$\mu_i = \left.\frac{\partial F}{\partial N_i}\right|_{T, V, N_j, j \neq i} = \left.\frac{\partial f}{\partial n_i}\right|_{T, n_j, j \neq i} \qquad [\text{MeV}] \tag{21}$$

including the rest mass m_i [MeV]. The pressure is obtained from

$$p = -\left.\frac{\partial F}{\partial V}\right|_{T, N_i} = n_b^2 \left.\frac{\partial (f/n_b)}{\partial n_b}\right|_{T, Y_q} = \sum_i \mu_i n_i - f \qquad [\text{MeV} \cdot \text{fm}^{-3}]. \tag{22}$$

Each of the composite densities n_b, n_s, n_{le}, $n_{l\mu}$, n_q is accompanied by a corresponding chemical potential, i.e., we have the baryon number chemical potential μ_b [MeV], the strangeness number chemical potential μ_s [MeV], the electron lepton number chemical potential μ_{le} [MeV], the muon lepton number chemical potential $\mu_{l\mu}$ [MeV], and the charge chemical potential μ_q [MeV]. The chemical potential of the particle i is then given by

$$\mu_i = B_i \mu_b + Q_i \mu_q + S_i \mu_s + L_i^e \mu_{le} + L_i^\mu \mu_{l\mu} \quad [\text{MeV}], \qquad (23)$$

e.g., $\mu_n = \mu_b$, $\mu_p = \mu_b + \mu_q$, and $\mu_e = \mu_{le} - \mu_q$. Note again that we use the relativistic definition of chemical potentials including rest masses. It has to be mentioned that n_b, n_s, n_{le}, and $n_{l\mu}$ are conjugate to μ_b, μ_s, μ_{le}, and $\mu_{l\mu}$, respectively. However, this is not true for n_q and μ_q if leptons are included in the EoS. In general, it is assumed that $\mu_s = 0$ since strangeness changing weak interaction reactions are in equilibrium. Nevertheless, the strangeness density n_s can be nonzero if particles with strangeness are considered in the EoS.

In addition to the free energy density, several other thermodynamic potentials can be defined by applying Legendre transformations, e.g., the internal energy

$$E = E(S, V, N_i) = F + TS \quad [\text{MeV}], \qquad (24)$$

the free enthalpy (Gibbs potential)

$$G = G(T, p, N_i) = F + pV = \sum_i \mu_i N_i \quad [\text{MeV}], \qquad (25)$$

the enthalpy

$$H = H(S, p, N_i) = E + pV \quad [\text{MeV}], \qquad (26)$$

and the grand canonical potential

$$\Omega = \Omega(T, V, \mu_i) = F - \sum_i \mu_i N_i = -pV \quad [\text{MeV}] \qquad (27)$$

with the corresponding densities $e = E/V$, $g = G/V$, $h = H/V$, and $\omega = \Omega/V$ [MeV $\cdot$ fm^{-3}], respectively.

It is convenient to define the free energy per baryon

$$\mathcal{F} = \frac{F}{N_b} = \frac{f}{n_b} \quad [\text{MeV}], \qquad (28)$$

the internal energy per baryon

$$\mathcal{E} = \frac{E}{N_b} = \frac{e}{n_b} \quad [\text{MeV}], \qquad (29)$$

the enthalpy per baryon

$$\mathcal{H} = \frac{H}{N_b} = \frac{h}{n_b} \quad [\text{MeV}], \tag{30}$$

and the free enthalpy per baryon

$$\mathcal{G} = \frac{G}{N_b} = \frac{g}{n_b} \quad [\text{MeV}] \tag{31}$$

by dividing the corresponding thermodynamic potential by the total number of baryons

$$N_b = n_b V \quad [\text{dimensionless}]. \tag{32}$$

3.6. Thermodynamic Coefficients. In many applications, tabulated values of the thermodynamic potentials and their first derivatives are not sufficient and additional quantities that depend on second derivatives of the thermodynamic potentials are needed. In general, the relevant thermodynamic potential can depend on a large number of independent variables such as temperature, volume, and particle densities or chemical potentials. In applications, however, this number often reduces due to physical constraints. For example, the condition of chemical equilibrium between certain particle species reduces the number of independent chemical potentials. In a simular way, the condition of charge neutrality relates the particle numbers of charged constituents. In the following, we consider only systems that are completely determined by the temperature T, the volume V, the total number of baryons $N_b = n_b V$, and the charge number $N_q = Y_q N_b = Y_q n_b V$, or, in the case of an equation of state where leptons are present, by the number of charged leptons, which are equal to N_q due to charge neutrality. Then we have with the free energy per baryon $\mathcal{F}(T, n_b, Y_q)$ [MeV] the specific heat capacity at constant volume

$$c_V = \frac{T}{N_b} \left. \frac{dS}{dT} \right|_{V,N_b,N_q} = -T \left. \frac{\partial^2 \mathcal{F}}{\partial T^2} \right|_{n_b,Y_q} \quad [\text{dimensionless}], \tag{33}$$

the tension coefficient at constant volume

$$\beta_V = \left. \frac{dp}{dT} \right|_{V,N_b,N_q} = \left. \frac{dS}{dV} \right|_{T,N_b,N_q} = n_b^2 \left. \frac{\partial^2 \mathcal{F}}{\partial T \partial n_b} \right|_{Y_q} \quad [\text{fm}^{-3}], \tag{34}$$

the isothermal compressibility

$$\kappa_T = -\frac{1}{V} \left. \frac{dV}{dp} \right|_{T,N_b,N_q} = \left(n_b \left. \frac{\partial p}{\partial n_b} \right|_{T,Y_q} \right)^{-1} =$$
$$= \left(n_b^2 \left. \frac{\partial^2 (\mathcal{F} n_b)}{\partial n_b^2} \right|_{T,Y_q} \right)^{-1} \quad [\text{MeV}^{-1} \cdot \text{fm}^3], \tag{35}$$

the expansion coefficient at constant pressure

$$\alpha_p = \frac{1}{V} \left. \frac{dV}{dT} \right|_{p,N_b,N_q} = \kappa_T \beta_V \quad [\text{MeV}^{-1}], \tag{36}$$

the specific heat capacity at constant pressure

$$c_p = \frac{T}{N_b} \left. \frac{dS}{dT} \right|_{p,N_b,N_q} = c_V + \frac{T}{n_b} \alpha_p \beta_V \quad [\text{dimensionless}], \tag{37}$$

the adiabatic index

$$\Gamma = \frac{c_p}{c_V} \quad [\text{dimensionless}], \tag{38}$$

and the adiabatic compressibility

$$\kappa_S = -\frac{1}{V} \left. \frac{dV}{dp} \right|_{S,N_b,N_q} = \frac{\kappa_T}{\Gamma} \quad [\text{MeV}^{-1} \cdot \text{fm}^3]. \tag{39}$$

The square of the speed of sound (isoscalar longitudinal compression wave) in the medium for a one-fluid flow is given by the relativistic definition

$$c_s^2 = \left. \frac{dp}{de} \right|_{S,N_b,N_q} = \frac{1}{h\kappa_S} \quad [\text{dimensionless}] \tag{40}$$

with the enthalpy density $h = e + p$ [MeV$\cdot$fm^{-3}]. Alternatively, the expression

$$c_s^2 = \frac{n_b}{h} \left. \frac{\partial p}{\partial n_b} \right|_{Y_q,e} + \left. \frac{\partial p}{\partial e} \right|_{n_b,n_q} \quad [\text{dimensionless}] \tag{41}$$

can be used. All of the above quantities can be calculated with the help of the second derivatives of $\mathcal{F}$ or f with respect to the parameters T, n_b, and n_q.

3.7. Microscopic Quantities. Most EoS models are based on more or less microscopic models that can give information on microscopic particle properties in addition to the thermodynamic and compositional quantities. Only a few models are just simple parameterizations of thermodynamic quantities without recurrence to the underlying microphysics. The CompOSE database allows one to store these microscopic values, too, such that they can be used in applications. In the present version, we consider a small set of quantities that are discussed in the following. It can be easily extended if required.

In particular, we consider the effective masses of the particles where one has to distinguish between different definitions. The effective Landau mass

$$m_i^L \quad [\text{MeV}] \tag{42}$$

of the particle i is related to the single-particle density of states and defined as

$$\frac{1}{m_i^L} = \frac{1}{p_i^F} \frac{dE_i}{dp}\bigg|_{p=p_i^F},$$ (43)

where p_i^F denotes the respective Fermi-momentum and E_i is the single-particle energy. In nonrelativistic Skyrme–Hartree–Fock models it appears in the kinetic energy contribution

$$T_i = \frac{p_i^2}{2m_i^L} \quad [\text{MeV}]$$ (44)

to the total single-particle energy. In addition to the kinetic single-particle energy T_i, a single-particle potential

$$U_i \quad [\text{MeV}]$$ (45)

contributes to the single-particle energy

$$E_i = T_i + U_i + m_i$$ (46)

in nonrelativistic models. The effective Dirac mass

$$m_i^D = m_i - S_i \quad [\text{MeV}]$$ (47)

is found in the single-particle Hamiltonian of relativistic models, such as relativistic mean-field approaches. This quantity does not reflect directly the density of single-particle states. At zero temperature, the corresponding effective Landau mass can be obtained from

$$m_i^L = \sqrt{(m_i^D)^2 + (p_i^F)^2}.$$ (48)

The effective Dirac mass depends on the scalar self-energy

$$S_i = \Sigma_i \quad [\text{MeV}]$$ (49)

that enters the relativistic single-particle Hamiltonian together with the vector self-energy

$$V_i = \Sigma_i^0 \quad [\text{MeV}]$$ (50)

that is the time-component of the general four-vector self-energy Σ_i^μ.

In certain parameter regions of an EoS, the phenomena of superconductivity or superfluidity can be found. In this case it is worthwhile to know the size of the pairing gaps

$$\Delta_i \quad [\text{MeV}],$$ (51)

e.g., in the $i = nn(^1S_0)$ channel in case of neutron pairing.

3.8. Contribution of Photons. If photons are considered in an EoS, they are treated as a gas of massless bosons with simple analytical expressions for the relevant basic thermodynamic quantities. The contribution of the photon can be simply added to the thermodynamic quantities of the other constituents. We have the photon free energy density

$$f_\gamma(T) = -\frac{\pi^2}{45}T^4 \quad [\text{fm}^{-3}], \tag{52}$$

the photon entropy density

$$s_\gamma(T) = \frac{4\pi^2}{45}T^3 \quad [\text{fm}^{-3}], \tag{53}$$

and the photon pressure

$$p_\gamma(T) = \frac{\pi^2}{45}T^4 \quad [\text{MeV} \cdot \text{fm}^{-3}] \tag{54}$$

depending only on the temperature. The chemical potential of the photon vanishes

$$\mu_\gamma = 0 \quad [\text{MeV}] \tag{55}$$

since it is its own antiparticle. From these quantities, all other relevant photon thermodynamic quantities can be derived.

Part II. FOR CONTRIBUTORS

The success of the CompOSE data base depends on the support of nuclear physicists providing tables with their favourite EoS. Some well-known EoS used extensively in astrophysical applications are already incorporated in the CompOSE data base and are ready for use. However, a larger collection of EoS from different models is highly desirable. In order to be suitable for a simple usage, contributors should follow the guidelines specified in this part of the manual.

4. HOW TO PREPARE EoS TABLES

In general, tables with the EoS data contain a wealth of information on the thermodynamic properties, the composition of dense matter and on the microphysical properties of the constituents. In order to minimize the memory size, only the essential thermodynamic quantities should be stored in the tables that are used in the CompOSE data base. These quantities are selected such that they are

sufficient to calculate a particular thermodynamic potential, here the free energy F [MeV], and its first derivatives with respect to the parameters that correspond to the natural variables of F, i.e., temperature T [MeV], volume V [fm³] and particle numbers N_i [dimensionless]. However, it is worthwhile to have redundant information in order to check the consistency of the EoS tables or to simplify the determination of additional quantities. Further, thermodynamic quantities relevant for astrophysical applications can, if not directly available, be generated with the help of thermodynamic identities and, for quantities depending on higher derivatives, by using appropriate interpolation schemes. The organization of the data concerning composition, etc., depends on the particular EoS. Thus it is required that three separate tables are provided with unique formats that contain the thermodynamic quantities, the information on the composition of matter (depending on the choice of the constituents of the model) and the microscopic properties of the particles, respectively. Details of the employed discretization mesh of the parameters have to be supplied in additional tables. Additional information that is not contained in the Eos tables has to be provided by the contributor. It will appear in the data sheet that accompanies each EoS and is available on the CompOSE web site.

4.1. Tabulation of Quantities. *4.1.1. Parameters and Parameter Ranges.* Because of the imposed physical conditions, see Subsec. 3.2, the state of the system is uniquely characterized by only three quantities, see Subsec. 3.5, that are used as parameters in the EoS tables with the properties of dense matter:

1) temperature T [MeV],

2) baryon number density n_b [fm^{-3}],

3) charge fraction of strongly interacting particles Y_q [dimensionless].

In order to be useful in many applications, the parameter ranges should be chosen as wide as possible and the mesh spacing as fine as possible, i.e., the number of grid points as large as possible. In some cases it might be useful to adapt the resolution of the tables, in particular for the baryon density, to the physical situation and occurring phenomena. For example, a rapid change in some quantities or a phase transition can occur. For this purpose, several tables for different blocks in density with different resolution can be supplied for a single EoS model.

The recommended discretization scheme for a general purpose EoS table depends on the parameters:

1. **Temperature.** In this case, two standards are suggested:

a) linear mesh in $\ln T$, i.e.,

$$T(i_T) = T^{\mathrm{ref}}(f_T)^{i_T-1}, \quad f_T = 10^{1/M_T}, \quad i_T = N_T^{\mathrm{min}}, N_T^{\mathrm{min}}+1, \ldots, N_T^{\mathrm{max}} \tag{56}$$

with parameters $T^{\mathrm{ref}} > 0$ MeV, $1 \leqslant N_T^{\mathrm{min}} < N_T^{\mathrm{max}} \leqslant 101$, and $M_T > 1$ points per decade in temperature;

b) a mesh that is linear in T at low temperatures and linear in $\ln T$ at high temperatures, i.e.,

$$T(i_T) = T^{\mathrm{ref}}\frac{\sinh\left(f_T i_T\right)}{\sinh\left(f_T\right)}, \quad i_T = N_T^{\min}, N_T^{\min} + 1, \ldots, N_T^{\max} \tag{57}$$

with parameters $T^{\mathrm{ref}} > 0$ MeV, $1 \leqslant N_T^{\min} < N_T^{\max} \leqslant 101$ and $f_T > 0$. The resolution parameter $M_T > 0$ determines $f_T = \ln\left(10\right)/M_T$.

In both cases the index $i_T = 0$ is reserved for $T = 0$ MeV.

2. **Baryon Number Density.** Linear mesh in $\ln n_b$, i.e.,

$$n_b(i_{n_b}) = n_b^{\mathrm{ref}}(f_{n_b})^{i_{n_b}-1}, \; f_{n_b} = 10^{1/M_{n_b}}, \; i_{n_b} = N_{n_b}^{\min}, N_{n_b}^{\min} + 1, \ldots, N_{n_b}^{\max} \tag{58}$$

with parameters $n_b^{\mathrm{ref}} > 0$ fm^{-3}, $1 \leqslant N_{n_b}^{\min} < N_{n_b}^{\max} \leqslant 401$ and $M_{n_b} > 1$ points per decade in the baryon number density.

3. **Charge Fraction of Strongly Interacting Particles.** Linear mesh in Y_q, i.e.,

$$Y_q(i_{Y_q}) = \frac{i_{Y_q}}{M_{Y_q}}, \quad i_{Y_q} = N_{Y_q}^{\min}, N_{Y_q}^{\min} + 1, \ldots, N_{Y_q}^{\max} \tag{59}$$

with parameters $0 \leqslant N_{Y_q}^{\min} < N_{Y_q}^{\max} < 100$ and $M_{Y_q} > N_{Y_q}^{\max}$ with a resolution in Y_q of $1/M_{Y_q}$; the indices $i_{Y_q} = 0$, and $i_{Y_q} = 100$ should correspond to $Y_q = 0$ and $Y_q = 1$, respectively.

Each grid point in the table is identified with the triple (i_T, i_{n_b}, i_{Y_q}) of indices. The recommended values for the parameters are given in Subsubsec. 4.2.1. Actually used meshes for particular EoS are specified in the online documentation for each individual EoS table.

4.1.2. Thermodynamic Consistency. The equations of state included in the CompOSE data base are required to fullfill some basic thermodynamic consistency relations. Of course, the consistency can only hold up to some numerical level. Measures of the thermodynamic consistency are included in the characterization of the EoS tables on the web site.

Because the free energy density is considered in the present case as the basic thermodynamic potential, the homogeneity condition, cf. Eq. (16),

$$f(T, n_b, Y_q) = -p + \mu_b n_b + \mu_q \left(n_q - n_{le} - n_{l\mu}\right) + \mu_{le} n_{le} + \mu_{l\mu} n_{l\mu} \tag{60}$$

with the pressure p, the chemical potentials μ_b, μ_q, μ_{le}, $\mu_{l\mu}$, and corresponding densities n_b, n_q, n_{le}, $n_{l\mu}$ should hold. Note that n_q contains only the contribution of strongly interacting particles to the charge density, that a fixed relation between μ_{le} and $\mu_{l\mu}$ is assumed, and that $n_{le} + n_{l\mu} = n_q = Y_q n_b$ due to local charge neutrality if leptons are considered in the equation of state. Additionally, in Eq. (60) it was assumed that the strangeness chemical potential μ_s is zero.

It is convenient to define the effective lepton density as

$$n_l = n_{le} + n_{l\mu} \quad [\text{fm}^{-3}] \tag{61}$$

and the effective lepton chemical potential

$$\mu_l = \frac{\mu_{le} n_{le} + \mu_{l\mu} n_{l\mu}}{n_l} \quad [\text{MeV}] \tag{62}$$

such that

$$f(T, n_b, Y_q) = -p + (\mu_b + Y_q \mu_q) \, n_b \tag{63}$$

in case of an EoS without leptons and

$$f(T, n_b, Y_q) = -p + (\mu_b + Y_l \mu_l) \, n_b \tag{64}$$

in the case with leptons and charge neutrality ($Y_l = Y_q$), respectively. The tabulated values for the entropy density, pressure, and chemical potentials should be given by the first partial derivatives as

$$s = -\left. \frac{\partial f}{\partial T} \right|_{n_b, Y_q}, \tag{65}$$

$$p = n_b^2 \left. \frac{\partial (f/n_b)}{\partial n_b} \right|_{T, Y_q}, \tag{66}$$

$$\mu_b + Y_i \mu_i = \left. \frac{\partial f}{\partial n_b} \right|_{T, Y_q}, \tag{67}$$

$$\mu_i = \frac{1}{n_b} \left. \frac{\partial f}{\partial Y_i} \right|_{T, n_b}, \tag{68}$$

where $i = l(q)$ if leptons are (not) included in the EoS. These relations will be used to derive the first derivatives of f from the tabulated thermodynamic quantities s, p, μ_b, μ_q, and μ_l in some particular interpolation schemes.

For a mixed second partial derivative, the Maxwell relations

$$-n_b^2 \left. \frac{\partial (s/n_b)}{\partial n_b} \right|_{T, Y_q} = \left. \frac{\partial p}{\partial T} \right|_{n_b, Y_q}, \tag{69}$$

$$-\left. \frac{\partial s}{\partial n_x} \right|_{T, n_y, y \neq x} = \left. \frac{\partial \mu_x}{\partial T} \right|_{n_y}, \tag{70}$$

$$\left. \frac{\partial p}{\partial n_x} \right|_{T,n_y,y\neq x} = n_b \left. \frac{\partial \mu_x}{\partial n_b} \right|_{T,n_y,y\neq b}, \tag{71}$$

$$\left. \frac{\partial \mu_x}{\partial n_y} \right|_{T,n_z,z\neq y} = \left. \frac{\partial \mu_y}{\partial n_x} \right|_{T,n_z,z\neq x}, \tag{72}$$

where $x, y, z \in \{b, q, le, l\mu\}$, should hold.

The knowlegde of three functions $p = p(T, n_b, Y_q)$, $\mu_b = \mu_b(T, n_b, Y_q)$, and $\mu_q = \mu_q(T, n_b, Y_q)$ or $\mu_l = \mu_l(T, n_b, Y_q)$ is sufficient to recover the free energy density $f = f(T, n_b, Y_q)$ for the particular physical conditions of Subsec. 3.2 ($\mu_s = 0$ and $n_q = n_l$). Further quantities can be derived by partial derivatives with respect to the parameters T, n_b, and Y_q.

Thus, it would be convenient to store only these three quantities in the EoS table for the thermodynamic properties in order to reduce the memory size. However, we require that the pressure, the entropy, the three chemical potentials and also the free and internal energy densities should be provided independently in the EoS tables for checking purposes. It is also allowed to store more than these seven basic quantities.

4.2. Structure of Tables. The CompOSE data base contains for each EoS model data tables that specify the used *parameter grid* and tables that contain the *thermodynamic properties, the compositional information*, and *the microscopic information*, respectively.

4.2.1. Types of the EoS Tables. In general, three types of the EoS input tables should be available for each EoS model in order to address different applications:

1. **Three-Dimensional Tables.** These tables depend on all three indepedent parameters T, n_b, and Y_q. There is only one case:

• *General Purpose EoS Table.* The recommended parameter values for the definition of the grid are given in Table 4. This choice of discretization corresponds to a table with $N_T^{\max} \times N_{n_b}^{\max} \times N_{Y_q}^{\max} = 1119720(1462860)$ data points for the case a (b) in the T grid. The table includes neither points with $T = 0$ MeV nor with $Y_q = 0$.

Table 4. **Parameter values for the recommended discretization in T, n_b, and Y_q for a general purpose EoS table**

Quantity	Reference value(s)	Minimum index	Maximum index	Resolution parameter
T, case a	$T^{\mathrm{ref}} = 0.1$ MeV	$N_T^{\min} = 1$	$N_T^{\max} = 81$	$M_T = 25$
T, case b	$T^{\mathrm{ref}} = 0.1$ MeV	$N_T^{\min} = 1$	$N_T^{\max} = 62$	$M_T = 25$
n_b	$n_b^{\mathrm{ref}} = 10^{-12}$ fm^{-3}	$N_{n_b}^{\min} = 1$	$N_{n_b}^{\max} = 301$	$M_{n_b} = 25$
Y_q	N/A	$N_{Y_q}^{\min} = 1$	$N_{Y_q}^{\max} = 60$	$M_{Y_q} = 100$

2. **Two-Dimensional Tables.** These tables depend on two of the three independent parameters T, n_b, and Y_q. Four cases are considered here:

• *Zero-Temperature EoS Table.* The recommended parameter values for the definition of the grid are given in Table 5. This choice of discretization corresponds to a table with $N_{n_b}^{\max} \times (N_{Y_q}^{\max} + 1) = 18361$ data points. Only $T = 0$ MeV is considered. Data points for $Y_q = 0$, i.e., pure neutron matter, are included in this EoS table.

Table 5. **Parameter values for the recommended discretization in n_b and Y_q for a zero-temperature EoS table**

Quantity	Reference value	Minimum index	Maximum index	Resolution parameter
n_b	$n_b^{\mathrm{ref}} = 10^{-12}$ fm^{-3}	$N_{n_b}^{\min} = 1$	$N_{n_b}^{\max} = 301$	$M_{n_b} = 25$
Y_q	N/A	$N_{Y_q}^{\min} = 0$	$N_{Y_q}^{\max} = 60$	$M_{Y_q} = 100$

• *Symmetric Matter EoS Table.* The recommended parameter values for the definition of the grid are given in Table 6. This choice of discretization corresponds to a table with $N_T^{\max} \times N_{n_b}^{\max} = 18963(24381)$ data points for the case a (b) in the T grid. Only $Y_q = 0.5$ is considered. $T = 0$ MeV, i.e., the zero-temperature case, is (not) included in this EoS table for case b (a).

Table 6. **Parameter values for the recommended discretization in T and n_b for EoS tables of symmetric matter, neutron matter, or β-equilibrated matter**

Quantity	Reference value	Minimum index	Maximum index	Resolution parameter
T, case a	$T^{\mathrm{ref}} = 0.1$ MeV	$N_T^{\min} = 1$	$N_T^{\max} = 81$	$M_T = 25$
T, case b	$T^{\mathrm{ref}} = 0.1$ MeV	$N_T^{\min} = 0$	$N_T^{\max} = 62$	$M_T = 25$
n_b	$n_b^{\mathrm{ref}} = 10^{-12}$ fm^{-3}	$N_{n_b}^{\min} = 1$	$N_{n_b}^{\max} = 301$	$M_{n_b} = 25$

• *Neutron Matter EoS Table.* The recommended parameter values for the definition of the grid are given in Table 6. This choice of discretization corresponds to a table with $N_T^{\max} \times N_{n_b}^{\max} = 18963(24381)$ data points for case a (b). Only $Y_q = 0$ is considered. $T = 0$ MeV, i.e., the zero-temperature case, is (not) included in this EoS table for case b (a).

• *EoS Table of β-Equilibrated Matter.* The recommended parameter values for the definition of the grid are given in Table 6. This choice of discretization corresponds to a table with $N_T^{\max} \times N_{n_b}^{\max} = 18963(24381)$ data points for the case a (b) in the T grid. The charge fraction of strongly interacting particles Y_q is determined by the condition of β equilibrium. $T = 0$ MeV, i.e., the zero-temperature case is (not) included in this EoS table for case b (a).

3. **One-Dimensional Tables.** These tables depend only on the parameter n_b. Three cases are considered here:

• *EoS Table of Cold Symmetric Matter.* The recommended parameter values for the definition of the grid are given in Table 7. This choice of discretization corresponds to a table with $N_{n_b}^{\max} = 301$ data points. Only $Y_q = 0.5$ and $T = 0$ MeV is considered.

Table 7. **Parameter values for the recommended discretization in n_b for one-dimensional EoS tables**

Quantity	Reference value	Minimum index	Maximum index	Resolution parameter
n_b	$n_b^{\text{ref}} = 10^{-12}$ fm^{-3}	$N_{n_b}^{\min} = 1$	$N_{n_b}^{\max} = 301$	$M_{n_b} = 25$

• *EoS Table of Cold Neutron Matter.* The recommended parameter values for the definition of the grid are given in Table 7. This choice of discretization corresponds to a table with $N_{n_b}^{\max} = 301$ data points. Only $Y_q = 0.0$ and $T = 0$ is considered.

• *EoS Table of Cold β-Equilibrated Matter.* The recommended parameter values for the definition of the grid are given in Table 7. This choice of discretization corresponds to a table with $N_{n_b}^{\max} = 301$ data points. Only $T = 0$ MeV is considered, and the charge fraction of strongly interacting particles Y_q is determined by the conditions of β-equilibrium and local charge neutrality.

Every set of EoS tables contains up to three tables: the first that specifies the thermodynamic state of the system (always required), the second that contains information on the composition of the matter (optional), and the third that gives microscopic information (optional).

The format of the thermodynamic, the compositional and the microscopic tables, respectively, has to follow the following prescriptions.

4.2.2. Table with Thermodynamic Quantities. The first row of this table contains three entries: the mass of the neutron m_n and that of the proton m_p in MeV of the particular EoS model and then an integer I_l that indicates whether the EoS contains leptons or not. If electrons (and/or muons) are considered in the EoS, one sets $I_l = 1$. For other values of I_l, it is assumed that there are no electrons (and/or muons), and the lepton chemical potential μ_l should be set to zero. The neutron mass m_n is used for scaling certain quantities as specified below. The following rows in this table contain information on the particular grid point in the table and the relevant thermodynamic quantities. The actually tabulated quantities are given by

1) pressure divided by the baryon number density $Q_1 = p/n_b$ [MeV],

2) entropy per baryon $Q_2 = s/n_b$ [dimensionless],

3) scaled and shifted baryon chemical potential $Q_3 = \mu_b/m_n - 1$ [dimensionless],

4) scaled charge chemical potential $Q_4 = \mu_q/m_n$ [dimensionless],

5) scaled effective lepton chemical potential $Q_5 = \mu_l/m_n$ [dimensionless],

6) scaled free energy per baryon $Q_6 = f/(n_b m_n) - 1$ [dimensionless],

7) scaled internal energy per baryon $Q_7 = e/(n_b m_n) - 1$ [dimensionless].

For an ideal gas Q_1 is just the temperature T. The traditional scaling of the chemical potentials and the energies per baryon with the neutron mass m_n has been introduced.

Each line in the thermodynamic table (except the first) has to contain the following quantities

$$i_T \ i_{n_b} \ i_{Y_q} \ Q_1 \ Q_2 \ Q_3 \ Q_4 \ Q_5 \ Q_6 \ Q_7 \ N_{\text{add}} \ \underbrace{q_1 \ q_2 \ \cdots \ q_{N_{\text{add}}}}_{N_{\text{add}} \text{ quantities}} \qquad (73)$$

with seven required quantities Q_i and N_{add} additional optional thermodynamic quantities q_i. The meaning of the additional quantities is specified in the data sheet for each EoS table. It is assumed that the order of all quantities q_i does not change within an EoS table. Since the triple of table indices (i_T, i_{n_b}, i_{Y_q}) is explicitly specified, the order of tabulation with respect to the grid points is not relevant. If the table contains rows with identical indices i_T, i_{n_b}, i_{Y_q}, then table entries for the quantities Q_i, N_{add}, and q_i are used from the row that is read last.

4.2.3. Table with the Composition of Matter. The predicted chemical composition of matter depends strongly on the employed theoretical model. In principle, the particle content and hence the data that are required to be stored can depend on the particular point in the parameter space, too. Thus the format of the table has to be adapted to this situation. The essential information is contained in the particle fractions Y_i, but in some cases additional information, e.g., on the type of phase, might be useful.

The tabulated quantities in the EoS composition table are typically given by

1) particle fractions Y_i [dimensionless],

2) average mass number of a representative nucleus A^{av} [dimensionless],

3) average charge number of a representative nucleus Z^{av} [dimensionless],

4) index encoding the type of phase I_{phase} [dimensionless].

(The correspondence of the phase index I_{phase} with the actual structure of the phase is defined for each EoS model on the corresponding web page.)

In the following, a standard format for the tabulation of compositional information is defined. It is suitable for most of the presently available EoS tables of hadronic and quark EoS models. It allows one to change from point to point the particle fractions that are given in the table. Thus, it is possible to select only those particles that are most abundant under the considered local conditions.

Each row of the table contains the following entries:

$$i_T \ i_{n_b} \ i_{Y_q} \ I_{\text{phase}} \ N_{\text{pairs}} \underbrace{I_1 \ Y_{I_1} \ \dots \ I_{N_{\text{pairs}}} \ Y_{I_{N_{\text{pairs}}}}}_{N_{\text{pairs}} \text{ pairs}}$$

$$N_{\text{quad}} \ \underbrace{I_1 \ A^{\text{av}}_{I_1} \ Z^{\text{av}}_{I_1} \ Y_{I_1} \ \dots \ I_{N_{\text{quad}}} \ A^{\text{av}}_{I_{N_{\text{quad}}}} \ Z^{\text{av}}_{I_{N_{\text{quad}}}} \ Y_{I_{N_{\text{quad}}}}}_{N_{\text{quad}} \text{ quadruples}} \tag{74}$$

with N_{pairs} pairs that combine the particle index I_i as defined in Tables 2 and 3 and the corresponding particle fraction Y_i. (Note the definition of particle fractions in Eq. (7).) In addition, there are N_{quad} quadruples that contain an index I_i that specifies a group of nuclei $\mathcal{M}_{I_i}$ with average mass number

$$A^{\text{av}}_{I_i} = \frac{\sum\limits_{j \in \mathcal{M}_{I_i}} A_j Y_j}{\sum\limits_{j \in \mathcal{M}_{I_i}} Y_j}, \tag{75}$$

average charge number $Z^{\text{av}}_{I_i}$

$$Z^{\text{av}}_{I_i} = \frac{\sum\limits_{j \in \mathcal{M}_{I_i}} Z_j Y_j}{\sum\limits_{j \in \mathcal{M}_{I_i}} Y_j}, \tag{76}$$

and combined fraction

$$Y_{I_i} = \frac{\sum\limits_{j \in \mathcal{M}_{I_i}} A_j Y_j}{A^{\text{av}}_{I_i}} = \sum\limits_{j \in \mathcal{M}_{I_i}} Y_j. \tag{77}$$

In case that there are no pairs (quadruples) to be stored, the number N_{pairs} (N_{quad}) has to be set to zero. The average mass and charge numbers correspond to those of a representative heavy nucleus if there is only one group of nuclei except the lightest that are considered explicitly. However, it is also possible to define several subsets of nuclei with corresponding average mass numbers, charge numbers and fractions. The correlation between the index I_i and the set of nuclei $\mathcal{M}_{I_i}$ is defined for each EoS model separately and given in the data sheet on the CompOSE web pages. Since the composition of matter can vary rapidly with a change of the parameters, it is not required that the fractions of all particles or particle sets have to be given in each row. It is sufficient to list only those that are relevant, e.g., with positive Y_i. Others can be omitted.

4.2.4. Table with Information on Microscopic Quantities. Besides the information on thermodynamic and compositional quantities, most EoS models

can provide additional information on microscopic quantities of an individual particle i, e.g.,

1) Landau effective mass divided by the particle mass m_i^L/m_i [dimensionless],

2) Dirac effective mass divided by the particle mass m_i^D/m_i [dimensionless],

3) nonrelativistic single-particle potential U_i [MeV],

4) relativistic vector self-energy V_i [MeV],

5) relativistic scalar self-energy S_i [MeV],

6) pairing gap Δ_i [MeV].

These quantities are stored in an additional table if available. In this case, each line has the format

$$i_T \ i_{n_b} \ i_{Y_q} \ N_{\mathrm{qty}} \ \underbrace{K_1 \ q_{K_1} \ K_2 \ q_{K_2} \ \ldots \ K_{N_{\mathrm{qty}}} \ q_{K_{N_{\mathrm{qty}}}}}_{N_{\mathrm{qty}} \text{ pairs}}, \tag{78}$$

where N_{qty} is the number of stored quantities q_{K_i}. The composite index K_i identifies uniquely both the particle or correlation and the physical quantity. It is formed as

$$K_i = 1000 I_i + J_i \tag{79}$$

with the particle or correlation index I_i from Table 2 or 3, respectively, and the quantity index J_i from Table 8.

4.2.5. Tables with Parameters. The mesh points for the general purpose EoS are stored in three individual data files that are used as an input in addition to the three tables containing the thermodynamic, compositional and microphysical information. It is assumed that the discretization scheme for the relevant parameters in the zero-temperature and in the neutron-matter table is identical to the grid for the general purpose table. Parameter values should be given with at least eight significant digits. For the parameter temperature, the corresponding table contains a single entry in each row. In the first row, N_T^{min} is given, and N_T^{max} in the second row. Then the parameter values $T(N_T^{\mathrm{min}})$, $T(N_T^{\mathrm{min}} + 1)$, ..., $T(N_T^{\mathrm{max}})$ are given in every following row. In total, the table contains $N_T^{\mathrm{max}} - N_T^{\mathrm{min}} + 3$ rows. The same storage scheme applies for the parameters n_b and Y_q.

4.2.6. Identification of Tables. Each Eos table is identified by a unique name and a unique extension that correspond to the model and type of the table, respectively. Using the generic name `eos` for a particular EoS model, there are always three parameter tables:

- `eos.t` (required),
- `eos.nb` (required),
- `eos.yq` (required)

that define the discretization mesh for the three parameters T, n_b, and Y_q as discussed in the previous section. All three tables are required even for the EoS tables with less than three dimensions.

Table 8. **Thermodynamic quantities which are stored in the data tables with their units**

Index J	Quantity/ expression	Unit	Description
1	p	$\text{MeV} \cdot \text{fm}^{-3}$	Total pressure
2	$\mathcal{S}$	Dimensionless	Total entropy per baryon
3	$\mu_b - m_n$	MeV	Baryon chemical potential with respect to neutron mass
4	μ_q	MeV	Charge chemical potential
5	μ_l	MeV	Lepton chemical potential
6	$\mathcal{F}/m_n - 1$	Dimensionless	Free energy per baryon with respect to neutron mass
7	$\varepsilon = \mathcal{E}/m_n - 1$	Dimensionless	Internal energy per baryon with respect to neutron mass
8	$\mathcal{H}/m_n - 1$	Dimensionless	Enthalpy per baryon with respect to neutron mass
9	$\mathcal{G}/m_n - 1$	Dimensionless	Free enthalpy per baryon with respect to neutron mass
10	$(\partial p/\partial n_b)\big|_{\mathcal{E}}$	MeV	Partial derivative of pressure with respect to baryon number density
11	$(\partial p/\partial \mathcal{E})\big|_{n_b}$	fm^{-3}	Partial derivative of pressure with respect to internal energy per baryon
12	c_s^2	Dimensionless	Speed of sound squared
13	c_V	Dimensionless	Specific heat capacity at constant volume
14	c_p	Dimensionless	Specific heat capacity at constant pressure
15	$\Gamma = c_p/c_V$	Dimensionless	Adiabatic index
16	α_p	MeV^{-1}	Expansion coefficient at constant pressure
17	β_V	fm^{-3}	Tension coefficient at constant volume
18	κ_T	fm^3/MeV	Isothermal compressibility
19	κ_S	fm^3/MeV	Adiabatic compressibility

The thermodynamic, compositional and microscopic quantities are stored in three tables with the generic names

- `eos.thermo` (required),
- `eos.compo` (optional),
- `eos.micro` (optional),

where only the first one is required for every EoS model since information on the composition or microscopic details is not always available.

4.2.7. Precision of Tabulated Quantities. The EoS quantities of a particular model have a limited precision in practical calculations. Maschine precision is hardly ever reached. The format of the tabulated data should reflect this fact and only the significant number of digits should be given to avoid excessive memory size. Usually eight significant digits are sufficient since the error in the interpolation can be considerably larger.

4.3. Data Sheet. Information on an EoS that is not provided directly in the tables but relevant for the characterization of the particular model can be found in a data sheet that comes along with the tables on the CompOSE web pages. Some quantities are extracted automatically from the tabulated data, others need to be specified by the contributor. For example, characteristic nuclear matter parameters (see Subsec. 6.1) are obtained by using the program `compose.f90` (see Subsec. 7.4) if an EoS table for pure nuclear matter without electrons or muons is available. Similarly, information on the parameter grid, type, and dimension of the Eos table, considered particles and additionally stored quantities are extracted by the program. The EoS of stellar matter in β-equilibrium is generated by using `compose.f90` if the EoS table for matter with electrons of muons is provided by the contributor. From this extracted EoS table, characteristic properties of neutron stars, e.g., maximum masses, are calculated and given in the data sheet. It also contains information on the considered constituent particles in the model. The contributor has to supply a short characterization of the EoS model and relevant references. He/she also needs to define the meaning of the index I_{phase} for the phases considered in the EoS.

5. EXTENDING CompOSE

CompOSE is meant to be under constant development. The main aim is to enlarge the data base by adding the EoS tables of more and more models. The most simple way is to convert tables of existing model calculations to the generic CompOSE scheme of tabulation in the data files. A more involved task is to develop a new EoS model and to provide the results in the appropriate format. In either case, we ask you to contact the CompOSE core team by sending an e-mail to `develop.compose@obspm.fr`. You will be contacted and all questions will be clarified on how your results can be incorporated in the CompOSE data base and made accessible to the public.

For the future it is foreseen that the functionality of the CompOSE data base will be extended in order to make even more results of EoS model calculations available that are not included in the present sets of data. It is also envisioned to add more quantities to the data tables that might be relevant for astrophysical applications and beyond.

Part III. FOR USERS

6. MODELS FOR THE EQUATION OF STATE

There is a large number of model equations of state. They fall into different classes depending on the theoretical approach. We use a rough classification scheme that takes the type of model and complexity into account. The main difficulty in generating an equation of state is the description of the strongly interacting constituents, hadrons and/or quarks.

Details and characteristic parameters of each particular EoS can be found in a data sheet that accompanies the data tables on the CompOSE web site http://compose.obspm.fr.

For electrons and muons, a uniform Fermi gas model is employed in many cases. This assumption simplifies the calculation significantly in case of spatially inhomogeneous charge distributions. Details on the treatment of electrons and muons are given for each EoS separately on the data sheet.

At positive temperatures, photons contribute to the thermodynamic properties of the system. Their treatment is discussed in Subsec. 3.8. For each EoS in the database a remark is given whether photons are considered or not.

Before theoretical models for the EoS are summarized, the definition of commonly used nuclear matter parameters is given in Subsec. 6.1. They characterize the essential properties of nuclear matter and can serve in a first comparison of the various models. Be, however, careful since these parameters are only valid in the vicinity of saturation for symmetric, i.e., the same number of protons and neutrons, matter. Specific values of these parameters are given in the data sheet for the individual models.

In Subsec. 6.2, a general overview on the most common approaches to describe the EoS of nuclear matter is presented and their major features are summarized.

Some comments on phase transitions within the EoS are presented in Subsec. 6.3. In the last section a few remarks of caution are given.

6.1. Nuclear Matter Properties. Realistic models of nuclear, i.e., purely hadronic, matter without leptons show some general features that are related to the occurrence of the saturation phenomenon. Due to the symmetries of the strong interaction uniform nuclear matter at zero temperature reaches a state with the largest binding energy per nucleon at a finite saturation density n_b^{sat} with equal concentrations of neutrons and protons[*]. For $T = 0$ MeV, the energy per nucleon $\mathcal{E}$ can be considerd as a function of the baryon number density n_b and

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[*]This is exactly true only if the mass difference between neutrons and protons is neglected.

the asymmetry

$$\alpha = \frac{n_n - n_p}{n_n + n_p} = 1 - 2Y_q \quad \text{[dimensionless]} \tag{80}$$

that vanishes for symmetric nuclear matter, i.e., $\alpha = 0$ and $Y_q = 0.5$. It can be expanded in a power series around the saturation point as

$$\mathcal{E}(n_b, \alpha) = -B_{\text{sat}} + \frac{1}{2}Kx^2 + \frac{1}{6}K'x^3 + \ldots +$$
$$+ \alpha^2 \left(J + Lx + \frac{1}{2}K_{\text{sym}}x^2 + \ldots \right) + \ldots \quad \text{[MeV]} \tag{81}$$

with the relative deviation of the actual density from the saturation density

$$x = \frac{1}{3}\left(\frac{n_b}{n_b^{\text{sat}}} - 1 \right) \quad \text{[dimensionless]} \tag{82}$$

and the asymmetry α. The coefficients B_{sat}, K, K', J, L, K_{sym} [MeV], $\ldots$ and n_b^{sat} [fm^{-3}] characterize the behaviour of the EoS. They can, of course, only give an indication of the general features of the EoS, since these quantities are relevant essentially in the vicinity of the saturation density at zero temperature and close to symmetric nuclear matter (equal number of protons and neutrons). Extrapolations based on this polynomial expansion might be dangerous. The numerical factor in Eq. (82) is of historical origin since the Fermi momentum k_F [fm^{-1}] instead of the density $n_b = k_F^3/\pi^2$ of symmetric nuclear matter at zero temperature was originally used as the expansion parameter. Note that contributions linear in α and linear in x for $\alpha = 0$ are absent in the expansion due to the condition of minimum energy per baryon.

In order to study the dependence on the asymmetry α, it is also convenient to introduce the symmetry energy

$$E_{\text{sym}}(n_b) = \frac{1}{2}\frac{\partial^2 \mathcal{E}(n_b, \alpha)}{\partial \alpha^2}\bigg|_{\alpha=0} \quad \text{[MeV]} \tag{83}$$

that is a function of the baryon number density n_b only. In many cases, the quadratic approximation in α in Eq. (81) is sufficient. Then the symmetry energy can also be calculated from the finite difference approximation

$$E_{\text{sym}}(n_b) = \frac{1}{2}\left[\mathcal{E}(n_b, -1) - 2\mathcal{E}(n_b, 0) + \mathcal{E}(n_b, 1) \right] \quad \text{[MeV]} \tag{84}$$

comparing symmetric matter with pure neutron and pure proton matter.

In the following, the coefficients appearing in Eq. (81) are discussed in more detail and typical values are given.

• The **saturation density** n_b^{sat} [fm^{-3}] of symmetric nuclear matter is defined by the condition that the pressure vanishes, i.e.,

$$p = n_b^2 \frac{d\mathcal{E}(n_b, 0)}{dn_b}\bigg|_{n_b = n_b^{\text{sat}}} = 0 \quad [\text{MeV} \cdot \text{fm}^{-3}], \tag{85}$$

and the energy per baryon becomes minimal. Typical values are in the range $0.15 < n_b^{\text{sat}} < 0.17$ fm^{-3} [4].

• The **binding energy at saturation** B_{sat} [MeV] of symmetric nuclear matter typically lies in the range $15.6 < B_{\text{sat}} < 16.2$ MeV [4]. This quantity can be obtained from Bethe–Weizsäcker mass formulas for nuclei $^A Z$ by an extrapolation of $A = 2Z$ to infinity.

• The **incompressibility of bulk nuclear matter** K [MeV] quantifies the curvature of the binding energy per baryon with respect to the density variation at saturation since it is defined by

$$K = 9n_b^2 \frac{\partial^2 \mathcal{E}(n_b, 0)}{\partial n_b^2}\bigg|_{n_b = n_b^{\text{sat}}} = 9n_b \frac{\partial(p/n_b)}{\partial n_b}\bigg|_{n_b = n_b^{\text{sat}}} \quad [\text{MeV}]. \tag{86}$$

It is related to the isothermal compressibility κ_T (35) at zero temperature, zero asymmetry and saturation density by

$$K = \frac{9}{\kappa_T n_b^{\text{sat}}} \quad [\text{MeV}]. \tag{87}$$

Thus K would be better called compression modulus. Today, the preferred value for K from nuclear experiments is (240 ± 10) MeV [5]. It can be derived, e.g., from studies of isoscalar giant monopole excitations of nuclei. Obviously, the given error is rather small, such that many EoS should be disfavored because the value of K lies well outside the range given above. We will, however, keep these EoS in our data base for two reasons. The first one is purely historical: in many simulations EoS with values for the incompressibility outside the range given above have been used, such that for comparison with the existing literature it is interesting to have tables at hand with these values. The most prominent example is perhaps the Lattimer–Swesty EoS [6] with the parameter set, where $K = 180$ MeV. The second one is that the experimental result of (240 ± 10) MeV is not uncontested. In particular, the extraction of this value from data on isoscalar giant monopole resonances depends on the density dependence of the nuclear symmetry energy, a quantity under intensive debate in recent years. We therefore think that a wider range of values should be considered and it can give an indication about the uncertainties in the simulations coming from the uncertainties in the EoS.

• The **skewness coefficient of bulk nuclear matter** K' [MeV] is defined by the third derivative of the energy per baryon as

$$K' = 27n_b^3 \left. \frac{\partial^3 \mathcal{E}(n_b, 0)}{\partial n_b^3} \right|_{n_b = n_b^{\mathrm{sat}}} = 27n_b^2 \left. \frac{\partial^2 (p/n_b)}{\partial n_b^2} \right|_{n_b = n_b^{\mathrm{sat}}} - 6K \quad [\text{MeV}]. \quad (88)$$

The value of K' in combination with K determines the surface properties of nuclei, e.g., the ratio of the surface tension to the surface thickness. Thus, in order to fix K' in a particular model, it is important to include quantities like radii and the surface thickness in the procedure to fit the model parameters.

• The **symmetry energy at saturation** J [MeV] is just given by

$$J = E_{\mathrm{sym}}(n_b^{\mathrm{sat}}) \quad [\text{MeV}]. \quad (89)$$

This coefficient mainly determines the isospin dependence of the binding energy of nuclei. It is important in predicting masses of exotic nuclei far away from the valley of stability in the chart of nuclei. Recently there has been a lot of discussion about its value, the commonly assumed range is $26 \lesssim J \lesssim 36$ MeV [4, 7–12].

• The **symmetry energy slope coefficient** L [MeV] that is obtained from

$$L = 3n_b \left. \frac{dE_{\mathrm{sym}}(n_b)}{dn_b} \right|_{n_b = n_b^{\mathrm{sat}}} \quad [\text{MeV}]. \quad (90)$$

This coefficient is related to the density dependence of the neutron matter EoS near the saturation density. It is strongly correlated with the neutron skin thickness of heavy nuclei like ^{208}Pb. Unfortunately, experimentally determined values of the neutron skin thickness are not very precise so far and a large range of values for L is found by comparing different EoS models. Typical values lie in the range $28 \lesssim L \lesssim 100$ MeV [7–13].

• The **symmetry incompressibility** K_{sym} [MeV] quantifies the curvature of the symmetry energy with respect to the density variation at saturation. It is defined by

$$K_{\mathrm{sym}} = 9n_b^2 \left. \frac{d^2 E_{\mathrm{sym}}}{dn_b^2} \right|_{n_b = n_b^{\mathrm{sat}}} \quad [\text{MeV}]. \quad (91)$$

Typical values lie in the range $-500 < K_{\mathrm{sym}} < 100$ MeV [4].

For each EoS in the CompOSE data base, the actual values of the nuclear matter coefficients are given if available.

6.2. Overview of Models. Models for the equation of state of dense matter can be grouped into three major categories concerning the fundamental constituents. In each category there are models that are more or less microscopic using different approximations. In the following, a short overview is given. Details on a particular EoS model can be found on the corresponding web pages of the

CompOSE web site. Of course, there are cases where it is not possible to sort a particular model uniquely into a category because concepts of different models are combined.

1. Hadronic models.

a) Statistical models: e.g., nuclear statistical equilibrium (NSE) models, virial equation of state (VEoS).

b) Density functional models: e.g., phenomenological parameter functional models, Skyrme–Hartree–Fock (SHF) models, relativistic mean-field (RMF) models.

c) Models with realistic microscopic potentials: e.g., (Dirac) Brueckner–Hartree–Fock [(D)BHF] models, antisymmetrized or fermionic molecular dynamics (AMD, FMD) models, quantum Monte Carlo (QMC) models.

2. Quark models.

a) Bag models: e.g., MIT bag models, thermodynamic bag models.

b) (Polyakov loop) Nambu–Jona-Lasinio [(P)NJL] models.

3. Hybrid models.

6.3. Phase Transitions. Many EoS models exhibit features that require the construction of a phase transition with a coexistence region of different phases in certain regions of the parameter space. This is the consequence of thermodynamic rules that require the system to take on a particular state in equilibrium respecting the convexity/concavity of a certain thermodynamic potential such that a thermodynamically stable minimim/maximum is reached. This depends on the supposed conditions and chosen parameters. A prominent example is the Van der Waals equation of state with the occurrence of a liquid-gas phase transition below a critical temperature that connects a low-density gas phase with a high-density liquid phase. Pure nuclear matter without leptons and in the absence of electromagnetic interactions exhibits such a liquid-gas type first-order phase transition. In the case of dense stellar matter, the situation is more complicated due to several facts. First of all, electrons and the electromagnetic interaction cannot be neglected. This means that at the transition from inhomogeneous matter at low densities containing nuclei to a homogeneous phase with nucleons at high densities, there is a formation of spatial inhomogeneities at microscopic scales and there is no first-order phase transition. The thermodynamic quantities are perfectly continuous (see, e.g., [14]). It can, of course, be appealing for simplicity, to describe this transition within a model still by a first-order phase transition, but it has to be kept in mind that this is an approximation. The second point is that the relevant degrees of freedom can change within the parameter space, e.g., from nuclei to nucleons and even to quarks.

In general, the correct approach to a phase transition in an equilibrated system is given by the so-called Gibbs construction. It requires the equality of all intensive variables of the relevant thermodynamic potential on the two points

of the coexistence manifold in the parameter space that connect the two phases. Technically, this can be achieved in various ways and the final EoS should be independent of the construction. However, in many EoS tables, only simplified phase transition constructions are used, if considered at all. In the present version of CompOSE, all EoS tables are included as given by the authors without any discrimination with respect to the applied construction of the phase transition. In a future version of CompOSE it is planned to offer the computational tools to construct phase transitions on top of the available EoS tables.

6.4. Remarks of Caution. We provide the equations of state tables in the CompOSE data base that cover large ranges in temperature, baryon number density and charge fraction of strongly interacting particles. However, we cannot guarantee that the physical description of matter under these conditions is close to reality. The user has to judge whether a particular EoS is suitable for her or his application.

The user also has to keep in mind that the thermodynamic and compositional properties of nuclear matter without electrons (and muons) and dense stellar matter with electrons (and muons) are rather different because in the former case the Coulomb interaction is artificially neglected. This can have drastic consequences for the occurrence and type of phase transitions. Thus it is not recommended to generate a dense matter EoS from a nuclear matter EoS simply by adding the contribution from electrons (and muons).

In many cases it is desirable to extend a particular EoS to densities and temperatures below or above the available or recommended parameter ranges. In these regimes, an equation of state depending only on temperature, charge fraction of strongly interacting particles and baryonic density to describe matter might not be sufficient, e.g., at very low densities and temperatures where the time scales of thermodynamic equilibration reaction rates become large and full reaction networks have to be considered. However, for many purposes a detailed description of matter in these regime is not necessary, such that we decided to furnish tables for these conditions, too.

Our knowledge about the QCD phase diagram suggests that there could be a transition from a hadronic phase to a quark-gluon plasma within the range of densities and temperatures reachable in core-collapse supernovae, hence within the range of our tables. Of course, there are lots of uncertainties about this phase transition, so that its occurrence cannot be affirmed, but the possibility has to be kept in mind when employing a purely hadronic EoS up to densities well above nuclear matter saturation density and temperatures as high as several tens of MeV. Within CompOSE there will be tables available including this phase transition. Even without thinking about a QCD phase transition, other forms of (exotic) matter shall appear at high densities and temperatures. Already for cold matter EoS used for neutron star modelization for a long time, hyperons, pions and kaons have been considered. At temperatures above about 20 MeV, this point

becomes even more crucial. Thus, using a purely nuclear EoS in this regime can be a first approximation, technically very appealing, but again it has to be kept in mind that probably the considered physics is too poorly described.

7. ONLINE SERVICES AND DATA HANDLING

7.1. User Registration. If you want to use the EoS data and routines that are provided by CompOSE through the online service, you should register to our system. Registration is simple and helps us to see who uses our services. It also avoids traffic. The tables and codes are offered free of charge but come without warranty. Please acknowledge and give proper reference to CompOSE if you use our service for your applications, presentations, and publications.

For the purpose of registration use the registration form that can be accessed through the CompOSE homepage at http://compose.obspm.fr. After approval by one of the administrators maintaining the site you will receive your personal access data via e-mail and are ready to use the CompOSE data base for generating your individual EoS tables.

7.2. EoS Data Sheets. Each EoS of the CompOSE data base is accompanied with a data sheet available for download from the web site. The data sheet provides essential information that allows the user to decide whether the EoS is suitable for her/his application. It contains information on the origin and creation of the EoS table, a short abstract of the physical model, references, the parameter ranges and considered particle species, a summary of the available data files and fundamental quantities that characterize the EoS such as nuclear matter and neutron star properties, if available.

7.3. Options for Using EoS Data. There are different options for downloading and/or generating the EoS data and tables. It is possible to obtain the EoS tables for different models and for different purposes. The original EoS tables are given as plain ASCII files that allow every user to read the data without the need for further codes. The general idea is that a user chooses a particular model from those available on the CompOSE web site. Then, there are two different ways of accessing the EoS data:

1. The user downloads data tables of an available EoS in the original form and uses her or his own routines to handle the data. For every model EoS there are three tables that contain the details of the discretization of the parameters: `eos.t`, `eos.nb` and `eos.yq`. The original EoS data are stored as functions of temperature T, baryon number density n_b, and charge fraction of strongly interacting particles Y_q. The last quantity is identical to the electron fraction Y_e if electrons are the only charged leptons considered in the EoS model. The abbreviation `eos` is the name of a particular EoS identifying the model and the type of table uniquely. The actual data on the thermodynamic, compositional and microscopic properties are stored in the files `eos.thermo`, `eos.compo` and `eos.micro`,

respectively, as far as available for that particular model. See Subsec. 4.2 for the format of all the tables.

2. The user downloads the original data tables for a particular EoS as described above and, in addition, several files that contain routines for reading, testing, interpolating and transforming the data. These codes serve four major purposes:

• to interpolate the original EoS data tables in order to obtain the quantities at parameter values different from the original tabulation,

• to calculate additional quantities that are not given in the original data files,

• to select those quantities that are relevant for a particular application and to store them in separate data files in a format more convenient for the user,

• to provide the EoS data tables in the advanced HDF5 format (see http://www. hdfgroup.org/HDF5/) that is widely used in the astrophysics community.

Details on how to work with the subroutines are described in the next section.

7.4. Handling and Transforming EoS Data. The handling of EoS data is considerably simplified by using the program files as such or the subroutines included in these files. There are only few steps required in order to generate customized data tables from the original sets of EoS tables. In addition to these data files, the user has to provide input files that contain the control parameters if the program `compose`, generated from the program files, is used directly. Alternatively, the parameters can be given as arguments of the various subroutines.

All quantities describing the thermodynamic, compositional and microscopic properties of the matter are found for arbitrary values of the table parameters with an interpolation scheme that is described in detail in Appendix A.1. It is possible to create tables with different mesh settings and ranges. Of course, the ranges should be chosen only within the ranges of the basis table for each model. If they are outside these ranges error messages will indicate the problems.

7.4.1. Downloading and Compiling. The file `composemodules.f90` contains all the necessary modules and the file `compose.f90` all required (sub-)routines and functions in order to read, interpolate and write the EoS data in ASCII format. If output of the EoS data in HDF5-format is needed, in addition the files `hdf5compose.f90` and `hdf5writecompose.c` are required. All the files can be downloaded from the corresponding CompOSE web page and they have to be compiled with an appropriate FORTRAN90 or C compiler. The program was written using the GNU compilers `gfortran` and `gcc`, and the use of these compilers is encouraged. A sample `Makefile` is available on the CompOSE web page. It contains in line 26 a switch to select the compilation without (`HDF = 0`, default setting) and with (`HDF = 1`) the option for the HDF5 output. For using the HDF5 routines, the HDF5 library has to be installed. Compiling the program files with the provided `Makefile` generates an executable with the name `compose`.

7.4.2. Direct Use of `compose`. In this subsection, the details are described how customized EoS tables from the EoS models on the CompOSE web site can be obtained by supplying tables with the relevant input values and running the program `compose`. The operation proceeds in the following steps:

1. **Selection of EoS.** In a first step the user selects the EoS that is appropriate for her/his application from the list given on the CompOSE web pages. Often, there are different types of tables available for a single EoS model as described in Subsec. 4.2. The tabulated data can depend on one, two or three of the independent parameters T, n_b, and Y_q. There are at least four different files needed for the successful application of the program `compose` as specified in Subsubsec. 4.2.6: three files containing information on the parameter grid and at least one file with the thermodynamic data.

2. **Preparation of Input Files.** The downloaded parameter and EoS files are always identified with a particular name and a file name extension that specifies the type of stored quantities. The program `compose` uses generic names for the input files. Thus the downloaded files have to be renamed such that the specific EoS name is changed to "eos" and the extension, e.g., ".thermo", ".compo", ".micro", ".t", ".nb" or "yq", is kept. In addition to the downloaded files, the user has to supply two files (in ASCII format) that specify the parameter values and the quantities that will be stored in the customized EoS output table. Generic files `eos.parameters` and `eos.quantities` can be downloaded from the CompOSE web pages. They have the following structure:

- **eos.parameters.** Rows one, three, five, and seven of the file `eos.parameters` (in ASCII format) are comment lines indicated by the first character #. The second row of this file contains three integer numbers I_T, I_{n_b}, and I_{Y_q} that specify the interpolation scheme for the temperature, baryon number density and charge fraction of strongly interacting particles, respectively. Presently, there is the choice between first-order ($I_x = 1$, $x = T, n_b, Y_q$), second-order ($I_x = 2$) and third-order ($I_x = 3$) interpolations available with continuity of all quantities $Q(x)$, all quantities $Q(x)$ and their first derivative $\partial Q/\partial x$ or all quantities $Q(x)$, their first and second derivatives $\partial Q/\partial x$ and $\partial^2 Q/\partial x^2$, respectively. See Appendix A.1 for details on the interpolation scheme.

The fourth row of the file `eos.parameters` contains a single integer I_β that determines whether the EoS in the output file `eos.table` will be generated for matter in β equilibrium ($I_\beta = 1$) or not ($I_\beta \neq 1$). Of course, this option is only effective for the EoS tables that include electrons (and muons) and depend on the parameter Y_q, i.e., three-dimensional general purpose EoS tables and two-dimensional zero-temperature EoS tables.

In the sixth row of the file, the tabulation scheme for the parameters is defined by the integer I_{tab}. For $I_{\text{tab}} = 0$, the parameter values of T, n_b, and Y_q are listed explicitly in the file `eos.parameters` as follows: The eigth row contains the number of data points N_{data} to be generated and each line of the next N_{data}

rows contains the three parameter values in the form

$$T \ n_b \ Y_q \tag{92}$$

that define the grid points. The EoS data that will be stored in the final EoS table will appear in the same sequence of the parameters as given in the file eos.parameters. For $I_\beta = 1$, Y_q can be set to any value. For two- and one-dimensional EoS tables, the parameters that are not used can be set to arbitrary values, e.g., for a zero-temperature EoS the first entry in each row can have any finite value. An example file eos.parameters for the tabulation scheme with $I_{\text{tab}} = 0$ is given by

```
# interpolation rules for T, n_b and Y_q
3 3 3
# calculation of beta equilibrium (1) or not (else)
0
# tabulation scheme of parameter values (see manual)
0
# parameter values depending on tabulation scheme
5
0.1 0.1 0.5
0.1 0.2 0.5
0.1 0.3 0.5
0.1 0.4 0.5
0.1 0.5 0.5
```

for generating a table using third-order interpolations in T, n_b, and Y_q. Five data points are calculated for constant $T = 0.1$ MeV and $Y_q = 0.5$ at densities of $n_b = 0.1$, 0.2, 0.3, 0.4, and 0.5 fm^{-3}.

For $I_{\text{tab}} \neq 0$, the parameter values are generated in a similar way as suggested in Subsubsec. 4.1.1. In this case, only three additional rows follow the comment line below the row with the specification of I_{tab}. Each of these rows (in the order temperature, density, charge fraction) contains the four quantities

$$p_{\text{min}}, \quad p_{\text{max}}, \quad N_p, \quad I_p, \tag{93}$$

where p stands for the parameters T, n_b, or Y_q, respectively. The minimum and maximum values of the parameter p in the EoS table are denoted by p_{min} and p_{max}, respectively. $N_p > 0$ is the number of data points in the mesh of the parameter p and I_p defines the discretization scheme. If $I_p = 0$, the individual points are given by a linear interpolation

$$p_i = p_{\text{min}} + (p_{\text{max}} - p_{\text{min}}) \frac{i-1}{N_p - 1} \tag{94}$$

for $i = 1, \ldots, N_p$ with $N_p > 1$ and

$$p_1 = p_{\text{min}} \tag{95}$$

for $N_p = 1$. For $I_p \neq 0$, a logarithmic scaling is used with

$$p_i = p_{\min} \left(\frac{p_{\max}}{p_{\min}} \right)^{\frac{i-1}{N_p-1}} \tag{96}$$

for $i = 1, \ldots, N_p$ with $N_p > 1$ and

$$p_1 = p_{\min} \tag{97}$$

for $N_p = 1$. For this tabulation scheme an example file `eos.parameters` has the form

```
# interpolation rules for T, n_b and Y_q
3 3 3
# calculation of beta equilibrium (1) or not (else)
0
# tabulation scheme of parameter values (see manual)
1
# parameter values depending on tabulation scheme
5.0 5.0 1 0
0.01 1.0 201 1
0.3 0.3 1 0
```

Here, $T = 5$ MeV and $Y_q = 0.3$ are kept constant and the densities n_b cover the range from 0.01 to 1.0 fm^{-3} in 200 intervals with a logarithmic scaling.

In case the option $I_\beta = 1$ is set in the third row of the file `eos.parameters`, the specification of the parameter grid in Y_q is irrelevant.

• **EoS.quantities.** This file contains 18 rows. They determine which and how quantities will be stored in the final EoS table with the name `eos.table`. Rows with odd number (one, three, ...) are comment lines beginning with the character `#`. The second and fourth lines define the thermodynamic quantities that will be stored in the output file `eos.table`. The first entry N_{thermo} in row two specifies the number of thermodynamic quantities that are selected from Table 8 followed by the number N_{add} of quantities that are selected from the stored quantities of the EoS file `eos.thermo` in addition to the seven standard quantities as described in Subsubsec. 4.2.2. The fourth line of the file `eos.quantities` lists the N_{thermo} indices from the second column of Table 9 that define the available thermodynamic quantities and the N_{add} indices of the additionally stored quantities. For example, the first four lines

```
# number of regular and additional thermodynamic quantities
3 1
# indices of regular and additional thermodynamic quantities
6 1 2 1
```

of the file `eos.quantities` denote that the quantities $\mathcal{F}/m_n - 1$, p, $\mathcal{S}$, and q_1 will appear in the output file `eos.table` or `eoscompose.h5`. Regular thermodynamic quantities are those that are obtained by a direct interpolation of the

Table 9. **Quantities containing information on the composition which are stored in the data tables with their units. The particle index I_i has been defined in Tables 2 and 3. The symbols % denote the group of nuclei**

Index J	Quantity/ expression	Unit	Description
	I_{phase}	Dimensionless	Phase index
	Y_{I_i}	Dimensionless	Fraction of particle I_i
1	$Y_\%^{\mathrm{av}}$	Dimensionless	Combined fraction of group % of nuclei
2	$A_\%^{\mathrm{av}}$	Dimensionless	Average mass number of group % of nuclei
3	$Z_\%^{\mathrm{av}}$	Dimensionless	Average charge number of group % of nuclei

tabulated quantities $\mathcal{Q}_1, \ldots, \mathcal{Q}_7$ stored in the file `eos.thermo` or those that are obtained from them by applying the thermodynamic relations of Subsec. 3.6. The indices of the regular thermodynamic quantities can have values of $1, 2, \ldots, 19$ corresponding to the definition in Table 8. Additional thermodynamic quantities are those that are denoted $q_1, \ldots, q_{N_{\mathrm{add}}}$ in the file `eos.thermo`. Their number N_{add} and meaning depends on the specific EoS table. Their values are found by a direct interpolation. If both N_{thermo} and N_{add} are zero, the fourth line of the file `eos.quantities` is empty.

The sixth row of the file `eos.quantities` contains the numbers N_p and N_q of pairs and quadruples that are selected from the compositional quantities that are stored in the file `eos.compo` as described in Subsubsec. 4.2.3. In the eigth line, the N_p particle indices $I_1, \ldots, I_{N_p}$ as defined in Tables 2 and 3 are followed by the N_q indices that identify a particular group of nuclei, see Subsubsec. 4.2.3. For example, the four lines

```
# number of pairs and quadruples for composition data
3 1
# indices of pairs and quadruples for composition data
10 11 0 1
```

denote that the fractions Y_n, Y_p, Y_e are stored in the file `eos.table` followed by A_1^{av}, Z_1^{av}, and Y_1^{av} of the first set of nuclei. If both N_p and N_q are zero, the eighth line of the file `eos.quantities` is empty.

The tenth line of the file `eos.quantities` contains the number N_{mic} of microscopic quantities in the file `eos.micro` to be stored in the output file `eos.table`. Then line 12 is a list of N_{mic} composite indices K_i as defined in Subsubsec. 4.2.4, e.g., the four lines

```
# number of microscopic quantities
2
# indices of microscopic quantities
10050 11050
```

denote that the nonrelativistic single-particle potentials U_n and U_p are stored in the file eos.table. If N_{mic} is zero, the twelfth line of the file eos.quantities is empty.

In addition to the quantities considered above, error estimates for the interpolation of the thermodynamic quantities $\mathcal{F}$, $\mathcal{E}$, p/n_b, and $\mathcal{S}$ are available. The free energy per baryon $\mathcal{F}$ can be obtained by direct interpolation or by using the homogeneity condition (60) with the interpolated values for the pressure and chemical potentials. An estimate for the absolute error in $\mathcal{F}$ is then given by

$$\Delta\mathcal{F} = \mathcal{F} + \frac{p}{n_b} - (\mu_b + Y_q\mu_q) \tag{98}$$

in case of an EoS without leptons and

$$\Delta\mathcal{F} = \mathcal{F} + \frac{p}{n_b} - (\mu_b + Y_l\mu_l) \tag{99}$$

in case of an EoS with leptons and charge neutrality. The relative error is then given by $\Delta\mathcal{F}/\mathcal{F} - 1$. The consideration above also applies to the internal energy per baryon $\mathcal{E}$. An estimate for the absolute error in p/n_b is obtained by comparing the directly interpolated pressure p with that derived from the first derivative of the free energy per baryon, i.e.,

$$\Delta\frac{p}{n_b} = \frac{p}{n_b} - n_b \left.\frac{\partial\mathcal{F}}{\partial n_b}\right|_{T,Y_q}. \tag{100}$$

Similarly, an error estimate for the entropy per baryon is calculated from

$$\Delta\mathcal{S} = \mathcal{S} - \left.\frac{\partial\mathcal{F}}{\partial T}\right|_{n_b,Y_q}. \tag{101}$$

The sixteenth line of the file eos.quantities defines the number N_{err} of error quantities to be stored in the output file. Line 18 is a list of the N_{err} indices J as defined in Table 10, e.g., the four lines

```
# number of error quantities
2
# indices of error quantities
1 2
```

denote that the estimates $\Delta\mathcal{F}$ and $\Delta\mathcal{F}/\mathcal{F}$ are stored in the file eos.table. If N_{err} is zero the eighteenth line of the file eos.quantities is empty.

Table 10. **Microscopic quantities which are stored in the data tables with their unit**

Index J	Quantity/ expression	Unit	Description
40	$m_{I_i}^L/m_{I_i}$	Dimensionless	Effective Landau mass with respect to the particle mass
41	$m_{I_i}^D/m_{I_i}$	Dimensionless	Effective Dirac mass with respect to the particle mass
50	U_{I_i}	MeV	Nonrelativistic single-particle potential
51	V_{I_i}	MeV	Relativistic vector self-energy
52	S_{I_i}	MeV	Relativistic scalar self-energy
60	Δ_{I_i}	MeV	Gap

The last row of the file `eos.quantities` defines the format of the output file by a single integer I. There are two methods that are used for storing the EoS data. The first ($I = 1$) is the simple ASCII format using the file name `eos.table` that easily allows one to read the data without the need for further codes. The second method ($I \neq 1$) uses the more advanced HDF5 format (see http://www.hdfgroup.org/HDF5/) that is widely used in the astrophysics community. In this case, the output file carries the name `eoscompose.h5` and each data set is designated with a particular identifier \$ of the stored quantity Q. Tables 11 and 12 give a list of all tabulated quantities and corresponding identifiers \$.

Note that $\varepsilon = \mathcal{E}/m_n - 1$ in Table 9 is *not* the specific internal energy, since the total mass density is not given by $m_n n_b$. We do not store $\mathcal{E}/m_n$ because it is in many regimes largely dominated by the rest mass contribution, such that it is numerically difficult to keep trace of small variations in the internal energy in that case. The same argument applies to the other thermodynamic quantities $\mathcal{F}$, $\mathcal{G}$, and $\mathcal{H}$. The present choice of storing ε is also motivated by the fact that the total mass density is not a conserved quantity throughout the hydrodynamic evolution, but only the baryon number density, n_b.

The individual chemical potentials for all the particles (baryons, mesons, nuclei, quarks, ...) can be calculated from the three ones given in the tables. Note that we use the relativistic definition of the chemical potentials.

Particle fractions Y_i are stored in the data sets with identifier $y\#$, where $\#$ stands for the particle index I_i as defined in Tables 2 and 3. For example, the data identifiers y20 and y400 contain the particle fractions of Δ^- and K^-

Table 11. **Error quantities which are stored in the data tables with their unit**

Index J	Quantity/ expression	Unit	Description
1	$\Delta\mathcal{F}$	MeV of free energy per baryon	Absolute error estimate
2	$\Delta\mathcal{F}/\mathcal{F}$	[Dimensionless] of free energy per baryon	Relative error estimate
3	$\Delta\mathcal{E}$	MeV of internal energy per baryon	Absolute error estimate
4	$\Delta\mathcal{E}/\mathcal{E}$	[Dimensionless] of internal energy per baryon	Relative error estimate
5	$\Delta\left(\dfrac{p}{n_b}\right)$	MeV of pressure-to-density ratio	Absolute error estimate
6	$\Delta\left(\dfrac{p}{n_b}\right)/\left(\dfrac{p}{n_b}\right)$	[Dimensionless] of pressure-to-density ratio	Relative error estimate
7	$\Delta\mathcal{S}$	[Dimensionless] of entropy per baryon	Absolute error estimate
8	$\Delta\mathcal{S}/\mathcal{S}$	[Dimensionless] of entropy per baryon	Relative error estimate

particles, respectively. Similarly, yav1 stands for the fraction of the first group of nuclei.

Combining the examples above, the file eos.quantities assumes the form

```
# number of regular and additional thermodynamic quantities
3 1
# indices of regular and additional thermodynamic quantities
6 1 2 1
# number of pairs and quadruples for composition data
3 1
# indices of pairs and quadruples for composition data
10 11 0 1
# number of microscopic quantities
2
# indices of microscopic quantities
10050 11050
# number of error quantities
2
# indices of error quantities
1 2
```

Table 12. **Modules, (sub)routines and functions in the file `compose.f90` with their dependencies (continued on next page)**

File	Uses `MODULE`	Uses `SUBROUTINE`	Uses `FUNCTION`
PROGRAM			
`compose`		`init_eos_table` `define_eos_table` `get_eos_table`	
SUBROUTINE			
`init_eos_table`		`read_eos_tables_tny` `read_eos_table_thermo` `read_eos_table_compo` `read_eos_table_micro` `get_diff_rules` `init_ipl_rule` `get_eos_report`	
`define_eos_table`	`compose_internal`	`write_errors`	
`get_eos_table`	`compose_internal`	`get_eos` `write_errors`	
`get_eos`	`compose_internal`	`get_eos_beta` `get_eos_sub` `write_errors`	
`get_eos_beta`	`compose_internal`	`get_eos_sub`	
`get_eos_sub`	`compose_internal`	`get_eos_grid_para` `eos_interpol`	
`get_eos_grid_para`	`compose_internal`		
`eos_interpol`	`compose_internal`	`get_idx_arg1` `get_idx_arg2` `get_diff_rules2` `get_interpol_yq` `get_interpol_nb` `get_derivatives` `get_coefficients` `get_interpol_xy`	`get_ipl_rule`
`get_idx_arg1`	`compose_internal`		
`get_idx_arg2`	`compose_internal`		

and, consequently, each line of the output file `eos.table` will contain the following entries:

$$T \quad n_b \quad Y_q \mathcal{F}/m_n - 1 \quad p \quad \mathcal{S} \quad q_1 \quad Y_n \quad Y_p \quad Y_e$$
$$A_1^{\mathrm{av}} \quad Z_1^{\mathrm{av}} \quad Y_1^{\mathrm{av}} \quad U_n \quad U_p \quad \Delta \mathcal{F} \quad \Delta \mathcal{F}/\mathcal{F},$$

i.e., in total 17 quantities.

3. **Running** compose. After starting the compose program, the relevant input data files are read: first, the files with the parameter grids eos.t, eos.nb and eos.yq, second, the EoS data files eos.thermo, eos.compo (if available) and eos.micro (if available). The read data are analyzed, checked for consistency and a report of the results is written to the file eos.report that is also used to extract data for the EoS data sheet provided on the web page. Next, the user supplied input files eos.parameters and eos.quantities are read and the output file eos.table is generated.

Each row of the output file eos.table contains the three parameter values of the user-chosen grid as defined in the file eos.parameters and then the selected quantities as specified and in the order of the file eos.quantities. Note that for each quadruple index I_i in the fourth row of the file eos.quantities three quantities ($A_{I_i}^{\mathrm{av}}$, $Z_{I_i}^{\mathrm{av}}$ and Y_{I_i}) are given. See the example given above.

7.4.3. Using Subroutines and Modules. Instead of using the code compose.f90 as given, the user can employ the subroutines directly in her/his program. The file compose.f90 contains one main program, 24 subroutines and one function. The structure of the program with the dependencies of the subroutines and functions is depicted in Tables 13 and 14. The file

Table 13. **Modules, (sub)routines and functions in the file** compose.f90 **with their dependencies (continued from previous page)**

File	Uses MODULE	Uses SUBROUTINE	Uses FUNCTION
PROGRAM			
get_diff_rules	compose_internal		
get_diff_rules2	compose_internal		get_ipl_rule
get_interpol_yq	compose_internal		
get_interpol_nb	compose_internal		
get_interpol_xy	compose_internal		
get_derivatives	compose_internal		
get_coefficients	compose_internal		
init_ipl_rule	compose_internal		
get_eos_report	compose_internal	get_eos_nmp get_eos write_errors	
get_eos_nmp	compose_internal	get_eos_sub	
write_errors	compose_internal		
read_eos_tables_tny	compose_internal	write_errors	
read_eos_table_thermo	compose_internal	write_errors	
read_eos_table_compo	compose_internal	write_errors	
read_eos_table_micro	compose_internal	write_errors	
FUNCTION			
get_ipl_rule			

Table 14. **Thermodynamical quantities which are stored in the HDF5 data file together with their units and the name of the corresponding data set. If there are two lines in the second column, the first one always corresponds to $I_{tab} = 0$; and the second one, to $I_{tab} \neq 0$**

Name of data set	Quantity/ expression	Unit	Description
t	T	MeV	Temperature
pointst	N_{data} N_T	Dimensionless	Number of points in T
nb	n_b	fm^{-3}	Baryon number density
pointsnb	N_{data} N_{n_b}	Dimensionless	Number of points in n_b
yq	Y_q	Dimensionless	Charge fraction of strongly interacting particles
pointsyq	N_{data} N_{Y_q}	Dimensionless	Number of points in Y_q
thermo	$Q(N_{data}, 1, 1, N_{thermo})$ $Q(N_{n_b}, N_T, N_{Y_q}, N_{thermo})$	Varying	Array of thermodynamical quantities, see Table 8
pointsthermo	N_{thermo}	Dimensionless	Number of thermodynamical quantities, see Table 8
index_thermo	$J(N_{thermo})$	Dimensionless	Index identifying the thermodynamical quantities, see Table 8
thermo_add	$q(N_{data}, 1, 1, N_{add})$ $q(N_{n_b}, N_T, N_{Y_q}, N_{add})$	Varying	Array of additional quantities $q_{\%}$ in file `eos.thermo`
pointsadd	N_{add}	Dimensionless	Number of additional thermodynamical quantities in file `eos.thermo`
index_thermo_add	$I_{add}(N_{add})$	Dimensionless	Index identifying the additional quantities $q_{\%}$ from file `eos.thermo`, see Eq. (73)

`composemodules.f90` contains two modules. In the module `eos_tables` the dimensions `dim_t=101`, `dim_n=401`, and `dim_y=100` for the maximum values N_T^{max}, $N_{n_b}^{max}$, and $N_{Y_q}^{max}$, respectively, are defined, see Subsubsec. 4.1.1. They can be adjusted to larger values if required. Note that `dim_a` has to be set to the maximum value of `dim_t`, `dim_n`, and `dim_y`.

The user needs to call the following three subroutines:

```
init_eos_table(iwr)
define_eos_table(iwr)
get_eos(t,n,y,ipl_t,ipl_n,ipl_y)
```

from the file `compose.f90` in order to generate EoS data. The first two subroutines depend on a single integer parameter `iwr`. For `iwr = 1` a progress report during the execution of the subroutine will be written to the terminal. Otherwise, this action will be suppressed. The subroutine `get_eos` has three `double precision` parameters (t, n, y) and three `integer` parameters (ipl_t, ipl_n, ipl_y) as arguments, see below. Be sure to include all (sub)routines, functions and the two modules `eos_tables` and `compose_internal` in your code.

The subroutine `init_eos_table` has to be called only once in order to initialize all relevant tables and quantities. The files `eos.t`, `eos.nb`, `eos.yq`, and `eos.thermo` have to exist in order that `init_eos_table` is executed properly. The files `eos.compo` and `eos.micro` are optional.

The subroutine `define_eos_table` defines the quantities that are interpolated and that will be stored in the EoS table. It reads the file `eos.quantities`. The subroutine needs to be called only once. Instead of calling `define_eos_table` in the user's program, it is possible that the relevant parameters are defined directly in the user's code. Thus it is possible to change the selection of quantities that are interpolated during the execution of the user's program. In the following, the variable names to be specified by the user are given according to the structure of the input file `eos.quantities`:

```
# number of regular and additional thermodynamic quantities
n_qty   n_add
# indices of regular and additional thermodynamic quantities
idx_qty(1) ... idx_qty(n_qty) idx_add(1)  ...  idx_add(n_add)
# number of pairs and quadruples for composition data
n_p   n_q
# indices of pairs and quadruples for composition data
idx_p(1)   ...   idx_p(n_p)   idx_q(1)   ...   idx_q(n_q)
# number of microscopic quantities
n_m
# indices of microscopic quantities
idx_m(1)   ...   idx_m(n_m)
# number of error quantities
n_err
# indices of error quantities
idx_err(1)   ...   idx_err(n_err)
# format of output file
iout
```

Note that all variables are `integers`. The appearing vectors are defined in the module `compose_internal`:

```
idx_qty(dim_qtyt)   with   dim_qtyt = 19
idx_add(dim_qty)    with   dim_qty = 15
idx_p(dim_qtyp)     with   dim_qtyp = 10
idx_q(dim_qtyq)     with   dim_qtyq = 2
idx_m(dim_qtym)     with   dim_qtym = 16
idx_err(dim_qtye)   with   dim_qtye = 8,
```

where the dimensions are defined in the module `eos_tables`.

Finally, the subroutine `get_eos` can be called as often as needed with the appropriate arguments. The `double precision` variables `t`, `n`, and `y` define the temperature T [MeV], baryon number density n_b [fm^{-3}] and the charge fraction of strongly interacting particles Y_q [dimensionless], respectively, where the EoS is evaluated. The `integer` indices `ipl_t`, `ipl_n` and `ipl_y` define the interpolation rule in T, n_b, and Y_q, respectively. For `ipl_t = 1` all selected quantities are interpolated linearly such that the interpolated values agree with the tabulated values at the grid points of the EoS table. For `ipl_t = 2` the interpolated values of a quantity and its first derivative with respect to temperature agree with those at the grid points. For `ipl_t = 3`, a continuity of the second derivatives at the grid points are also demanded. Similarly, the interpolation rules for n_b and Y_q are determined. If the index is outside the range $[1,3]$, it is set to 3. See Appendix A.1. for details of the interpolation scheme.

The results of the interpolation are stored in five `double precision` vectors/arrays with dimensions defined in the module `eos_tables`:

```
eos_thermo(dim_qtyt)    with   dim_qtyt = 19
eos_thermo_add(dim_qty) with   dim_qty = 15
eos_compo_p(dim_qtyp)   with   dim_qtyp = 10
eos_compo_q(dim_qtyq,3) with   dim_qtyq = 2
eos_micro(dim_qtym)     with   dim_qtym = 16
eos_err(dim_qtye)       with   dim_qtye = 8.
```

The vector index in `eos_thermo` corresponds to the index J given in Table 9. The vector index in `eos_thermo_add` is just the index $i = 1, \ldots, N_{\text{add}}$ of the additional quantities stored in each row of the file `eos.thermo`. The (first) index of the vectors/arrays `eos_compo_p`, `eos_compo_q` and `eos_compo_m` corresponds to the index of the vectors `idx_p`, `idx_q` and `idx_m` that are defined in the file `eos.quantities` or by the user before the subroutine `get_eos` is called. The second index of the array `eos_compo_q` is correlated with the index J as given in Table 15. The vector index in `eos_err` corresponds to the index J given in Table 10.

7.4.4. HDF5 Table. The organization of the data in case of the HFD5 table is different as compared to the ASCII table. All data are stored in a single data

Table 15. **Compositional and microscopic quantities which are stored in the HDF5 data file together with their units and the name of the corresponding data set. If there are two lines in the second column, the first one always corresponds to $I_{tab} = 0$; and the second one, to $I_{tab} \neq 0$**

Name of data set	Quantity/ expression	Unit	Description
yi	$Y_I(N_{data}, 1, 1, N_p)$ $Y_I(N_{n_b}, N_T, N_{Y_q}, N_p)$	Dimensionless	Array of particle fractions
pointspairs	N_p	Dimensionless	Number of pairs for compositional data
index_yi	$I_i(N_p)$	Dimensionless	Index identifying the particle i, see Table 2
yav	$Y^{av}(N_{data}, 1, 1, N_q)$ $Y^{av}(N_{n_b}, N_T, N_{Y_q}, N_q)$	Dimensionless	Array of combined fractions of groups of nuclei
aav	$A^{av}(N_{data}, 1, 1, N_q)$ $A^{av}(N_{n_b}, N_T, N_{Y_q}, N_q)$	Dimensionless	Average mass number of groups of nuclei
zav	$Z^{av}(N_{data}, 1, 1, N_q)$ $Z^{av}(N_{n_b}, N_T, N_{Y_q}, N_q)$	Dimensionless	Average charge number of groups of nuclei
pointsav	N_q	Dimensionless	Number of quadruples for compositional data
index_av	$I_{av}(N_q)$	Dimensionless	Index identifying the group % of nuclei, see Table 2
micro	$q_{mic}(N_{data}, 1, 1, N_{mic})$ $q_{mic}(N_{n_b}, N_T, N_{Y_q}, N_{mic})$	Varying	Array of microscopic quantities
pointsmicro	N_{mic}	Dimensionless	Number of microscopic quantities
index_micro	$K(N_{mic})$	Dimensionless	Index identifying the microscopic quantities, see Subsec. 4.2
Error	$q_{err}(N_{data}, 1, 1, N_{err})$ $q_{err}(N_{n_b}, N_T, N_{Y_q}, N_{err})$	Varying	Array of error quantities
pointserr	N_{err}	Dimensionless	Number of microscopical quantities
index_err	$J_{err}(N_{err})$	Dimensionless	Index identifying the error quantities, see Table 11

file that is denominated `eoscompose.h5`. The names of the data sets are given by the identifiers in Tables 11 and 12. Note, too, that the values of the different quantities at all grid points are stored together in one data set. The data sets can in addition contain a group of quantities, e.g., the N_{thermo} thermodynamic quantities, see Tables 11 and 12 for details.

7.4.5. Information for Data Sheet. During the execution of the program `compose`, a file `eos.report` is generated that contains information on the EoS derived from the tabulated data. The information is used for the creation of the data sheet that accompanies each EoS on the CompOSE web pages. If possible, a second file `eos.beta` is produced with the EoS of β-equilibrated matter for the lowest available temperature. Each row consists of four quantities, the density n_b, the charge fraction Y_q, the (free) energy density f (including rest mass contributions), and the pressure p. These data are used to derive characteristic neutron star parameters for the data sheet.

7.4.6. Error Messages. During the execution of the subroutines, errors can occur due to several reasons, e.g., parameters out of range, etc. In this case, the execution is stopped and a corresponding error message is generated.

Part IV. APPENDIXES

Appendix A
TECHNICAL DETAILS

The basic EoS tables only give a selected set of thermodynamic quantities at the grid points that are identified with the index triple (i_T, i_{n_b}, i_{Y_q}). From the stored quantities Q_i, $i = 1, \ldots, 6$, see Subsubsec. 4.2.2, further relevant thermodynamic quantities can be derived by a smooth interpolation for all possible values of the parameters T, n_b, and Y_q within the tabulated ranges. For these quantities, thermodynamic consistency should be respected as far as possible, when the thermodynamic quantities are interpolated separately, however, this condition is usually not exactly fulfilled. On the other hand, a separate interpolation often leads to smoother dependencies of the thermodynamic quantitities on the parameters avoiding unphysical oscillations. In addition, different ways of determining a single quantity gives the opportunity to estimate the error in the interpolation. Thus, in the present code `compose.f90` the strategy of a direct interpolation of individual quantities is followed.

A.1. Interpolation. The interpolation scheme for a quantity in the thermodynamic, compositional and microscopic EoS tables generally proceeds in several steps. In the following, the procedure will be explained for a three-dimensional general purpose EoS table. The interpolation scheme follows the method proposed in [15] using polynomials of sufficiently high order.

In the sequel, the generic symbol Q will be used for any tabulated quantity. Its values are given at the grid points that are specified by a triple of indices $(i_T, i_{n_b}, i_{Y_q}) = (i, j, k)$, see Subsubsec. 4.1.1, corresponding to temperature, baryon number density and charge fraction of strongly interacting particles. Thus all values $Q(T(i), n_b(j), Y_q(k))$ are known at the grid points. In order to

calculate the quantity Q at given values of T, n_b, and Y_q, first, the values of the indices $i = i_T$, $j = i_{n_b}$ and $k = i_{Y_q}$ are determined such that

$$T(i) \leqslant T < T(i+1), \tag{102}$$

$$n_b(j) \leqslant n_b < n_b(j+1), \tag{103}$$

$$Y_q(k) \leqslant Y_q < Y_q(k+1). \tag{104}$$

Then the interpolation parameters

$$\xi = \frac{T - T(i)}{T(i+1) - T(i)}, \tag{105}$$

$$\eta = \frac{n_b - n_b(j)}{n_b(j+1) - n_b(j)}, \tag{106}$$

$$\zeta = \frac{Y_q - Y_q(k)}{Y_q(k+1) - Y_q(k)} \tag{107}$$

are introduced with

$$0 \leqslant \xi < 1, \quad 0 \leqslant \eta < 1, \quad 0 \leqslant \zeta < 1. \tag{108}$$

For the interpolation of a quantity Q at given (T, n_b, Y_q) we need the tabulated values at least at the eight corners of the cube with grid points (i, j, k), $(i+1, j, k)$, $(i, j+1, k)$, $(i, j, k+1)$, $(i+1, j+1, k)$, $(i+1, j, k+1)$, $(i, j+1, k+1)$, $(i+1, j+1, k+1)$.

The interpolation proceeds in two steps: first, an interpolation in the variable Y_q such that the three-dimensional grid is mapped to a two-dimensional grid with four corners of each square; second, a two-dimensional interpolation in the variables T and n_b.

For the interpolation in Y_q in the three-dimensional cube as defined above, four separate one-dimensional interpolations along the lines that connect the grid points (i, j, k) and $(i, j, k+1)$, $(i+1, j, k)$ and $(i+1, j, k+1)$, $(i, j+1, k)$ and $(i, j+1, k+1)$, $(i+1, j+1, k)$ and $(i+1, j+1, k+1)$ have to be performed. After this first step, the interpolation proceeds in the parameters T and n_b by a two-dimensional scheme as discussed in Subsubsec. A.1.2.

The interpolation in the variables T, n_b, and Y_q can be of different order in general, defined by the value I of the variables `ipl_t`, `ipl_n` and `ipl_y`, see Subsec. 7.4. In the following, the case of the highest order ($I = 3$) is considered first.

A.1.1. Interpolation in One Dimension. The order $I = 3$ of the interpolation requires that the function values, its first and second derivatives have to be continuous at the two corner points of each line, i.e., six values have to be reproduced by the interpolation polynomial. Hence, a polynomial of at least

the fifth degree has to be used. The six independent coefficients q_n of a single polynomial

$$Q(T(i), n_b(j), Y_q) = \sum_{n=0}^{5} q_n \zeta^n \tag{109}$$

can be determined from the function values and derivatives at the corner points directly. One finds

$$q_0 = Q_{ijk}^{(0)}, \quad q_1 = Q_{ijk}^{(1)}, \quad q_2 = \frac{1}{2} Q_{ijk}^{(2)} \tag{110}$$

with

$$Q_{ijk}^{(n)} = [Y_q(k+1) - Y_q(k)]^n \left. \frac{\partial^n Q}{\partial Y_q^n} \right|_{T(i), n_b(j), Y_q(k)}, \tag{111}$$

for $n = 0, 1, 2$, and

$$Q_{ijk}^{(0)} = \left. \frac{\partial^0 Q}{\partial Y_q^0} \right|_{T(i), n_b(j), Y_q(k)} = Q(T(i), n_b(j), Y_q(k)), \tag{112}$$

in particular. The remaining three coefficients are given by

$$q_3 = 10A - 4B + \frac{1}{2}C, \tag{113}$$

$$q_4 = -15A + 7B - C, \tag{114}$$

$$q_5 = 6A - 3B + \frac{1}{2}C \tag{115}$$

with

$$A = Q_{ijk+1}^{(0)} - Q_{ijk}^{(0)} - Q_{ijk}^{(1)} - \frac{1}{2}Q_{ijk}^{(2)}, \tag{116}$$

$$B = Q_{ijk+1}^{(1)} - Q_{ijk}^{(1)} - Q_{ijk}^{(2)}, \tag{117}$$

$$C = Q_{ijk+1}^{(2)} - Q_{ijk}^{(2)}. \tag{118}$$

Alternatively, the approach of [15] can be followed. The value of the quantity Q at given ζ is found with the help of the quintic basis functions

$$\psi_0^{(0)}(z) = 1 - 10z^3 + 15z^4 - 6z^5, \tag{119}$$

$$\psi_1^{(0)}(z) = z - 6z^3 + 8z^4 - 3z^5, \tag{120}$$

$$\psi_2^{(0)}(z) = \frac{1}{2}\left(z^2 - 3z^3 + 3z^4 - z^5\right) \tag{121}$$

that have the properties

$$\psi_m^{(n)}(0) = \delta_{nm}, \quad \psi_m^{(n)}(1) = 0 \tag{122}$$

for

$$\psi_m^{(n)}(z) = \frac{d^n \psi_m^{(0)}}{dz^n} \tag{123}$$

with $n, m \in \{0, 1, 2\}$. Then one has

$$Q(T(i), n_b(j), Y_q) = \sum_{n=0}^{2} \left[Q_{ijk}^{(n)} \psi_n^{(0)}(\zeta) + (-1)^n Q_{ijk+1}^{(n)} \psi_n^{(0)}(1 - \zeta) \right] \tag{124}$$

with six interpolation coefficients that are given directly by the function values and derivatives at the corner points defined by the indices. Derivatives are easily found as

$$\frac{\partial^s}{\partial Y_q^s} Q(T(i), n_b(j), Y_q) = \frac{1}{[Y_q(k+1) - Y_q(k)]^s} \times$$

$$\times \sum_{n=0}^{2} \left[Q_{ijk}^{(n)} \psi_n^{(s)}(\zeta) + (-1)^{n+s} Q_{ijk+1}^{(n)} \psi_n^{(s)}(1 - \zeta) \right]. \tag{125}$$

The numerical determination of the derivatives depends on the order of interpolation. For $I = 3$, centered five-point finite difference formulas are used to calculate the first and second derivative of a function. Close to the boundaries of the EoS, centered difference formulas cannot be applied. In this case, off-center formulas are used. In the case $I = 2$, three-point finite difference formulas are employed. A continuity of the second derivatives at the corner points is not required. Only the function and the first derivative are demanded to be continuous, corresponding to four independent quatities. Hence, a polynomial of third degree is suffiecient and $q_4 = q_5 = 0$ in Eq. (109). Then, the coefficients of the second derivatives have to be defined as

$$Q_{ijk}^{(2)} = 6 \left[Q_{ijk+1}^{(0)} - Q_{ijk}^{(0)} \right] - 2Q_{ijk+1}^{(1)} - 4Q_{ijk}^{(1)}, \tag{126}$$

$$Q_{ijk+1}^{(2)} = -6 \left[Q_{ijk+1}^{(0)} - Q_{ijk}^{(0)} \right] + 4Q_{ijk+1}^{(1)} + 2Q_{ijk}^{(1)}. \tag{127}$$

For $I = 1$, the function has to be continuous at the grid points but there is no condition on the derivatives. In this case, one sets

$$Q_{ijk}^{(1)} = Q_{ijk+1}^{(1)} = Q_{ijk+1}^{(0)} - Q_{ijk}^{(0)}, \quad Q_{ijk}^{(2)} = Q_{ijk+1}^{(2)} = 0 \tag{128}$$

for given function values $Q_{ijk}^{(0)}$ and $Q_{ijk+1}^{(0)}$. Then the polynomial (109) reduces to a linear function with $q_2 = q_3 = q_4 = q_5 = 0$.

A.1.2. Interpolation in Two Dimensions. The interpolation in two dimensions with conditions on the continuity of the function and its derivatives is more complicated than in the one-dimensional case. For an interpolation order $I = 3$ in both variables ξ and η, there are four function values, eight first derivatives and the twelve second derivatives, hence 24 values in total, that can be used to determine the coefficients of a polynomial in ξ and η. From this consideration, it would seem to be sufficient to use a polynomial

$$Q(T, n_b, Y_q) = \sum_{m=0}^{4} \sum_{n=0}^{4} q_{mn} \xi^m \eta^n \qquad (129)$$

that includes powers up to four in both variables, resulting in $5 \times 5 = 25$ coefficients q_{nm} in total, i.e., one more than required. However, such a form does not guarantee that the function and the derivatives are continuous not only at the grid points but also along the boundaries of the interpolation square. In fact, a continuity of the function Q, the first derivatives $\partial Q/\partial T$ and $\partial Q/\partial n_b$, the second derivatives $\partial^2 Q/\partial T^2$, $\partial^2 Q/\partial T \partial n_b$, and $\partial^2 Q/\partial n_b^2$, the third derivatives $\partial^3 Q/\partial T^2 \partial n_b$ and $\partial^3 Q/\partial T \partial n_b^2$ and the fourth derivative $\partial^4 Q/\partial T^2 \partial n_b^2$ at the corners has to be demanded, determining $4 \times 9 = 36 = 6 \times 6$ coefficients of a polynomial

$$Q(T, n_b, Y_q) = \sum_{m=0}^{5} \sum_{n=0}^{5} q_{mn} \xi^m \eta^n \qquad (130)$$

with degree six in each variable.

Instead of determining the coefficients directly as in the case of one-dimensional interpolation, it is more advantageous to use the biquintic interpolation scheme as in [15] with

$$Q(T, n_b, Y_q) =$$

$$= \sum_{m=0}^{2} \sum_{n=0}^{2} \Big[Q_{ij}^{(mn)} \psi_m^{(0)}(\xi) \psi_n^{(0)}(\eta) + (-1)^m Q_{i+1j}^{(mn)} \psi_m^{(0)}(1-\xi) \psi_n^{(0)}(\eta) +$$

$$+ (-1)^n Q_{ij+1}^{(mn)} \psi_m^{(0)}(\xi) \psi_n^{(0)}(1-\eta) + (-1)^{m+n} Q_{i+1j+1}^{(mn)} \psi_m^{(0)}(1-\xi) \psi_n^{(0)}(1-\eta) \Big] \qquad (131)$$

and $4 \times 9 = 36$ coefficients

$$Q_{ij}^{(mn)} = [T(i+1) - T(i)]^m \, [n_b(j+1) - n_b(j)]^n \, \frac{\partial^{m+n} Q}{\partial T^m \partial n_b^n} \Big|_{T(i), n_b(j), Y_q}, \qquad (132)$$

$$Q_{i+1j}^{(mn)} = [T(i+1) - T(i)]^m \, [n_b(j+1) - n_b(j)]^n \, \frac{\partial^{m+n} Q}{\partial T^m \partial n_b^n} \Big|_{T(i+1), n_b(j), Y_q}, \qquad (133)$$

$$Q_{ij+1}^{(mn)} = [T(i+1) - T(i)]^m \, [n_b(j+1) - n_b(j)]^n \, \left. \frac{\partial^{m+n} Q}{\partial T^m \partial n_b^n} \right|_{T(i), n_b(j+1), Y_q},$$

(134)

$$Q_{i+1j+1}^{(mn)} = [T(i+1) - T(i)]^m \, [n_b(j+1) - n_b(j)]^n \, \left. \frac{\partial^{m+n} Q}{\partial T^m \partial n_b^n} \right|_{T(i+1), n_b(j+1), Y_q},$$

(135)

where $m, n \in \{0, 1, 2\}$. Of course, it is possible to express the coefficients q_{mn} of the polynomial (130) through the coefficients $Q_{ij}^{(mn)}$, as done in the code compose.f90. The derivatives are obtained in the same way as in the one-dimensional case for the different interpolation orders I. Derivatives of the function Q with respect to Y and n_b can be found with the help of the relation

$$\frac{\partial^{s+t}}{\partial T^s \partial n_b^t} Q(T, n_b, Y_q) =$$

$$= \frac{1}{[T(i+1) - T(i)]^s} \frac{1}{[n_b(j+1) - n_b(j)]^t} \times$$

$$\times \sum_{m=0}^{2} \sum_{n=0}^{2} \Big[Q_{ij}^{(mn)} \psi_m^{(s)}(\xi) \psi_n^{(t)}(\eta) + (-1)^{m+s} Q_{i+1j}^{(mn)} \psi_m^{(s)}(1-\xi) \psi_n^{(t)}(\eta) +$$

$$+ (-1)^{n+t} Q_{ij+1}^{(mn)} \psi_m^{(s)}(\xi) \psi_n^{(t)}(1-\eta) +$$

$$+ (-1)^{m+n+s+t} Q_{i+1j+1}^{(mn)} \psi_m^{(s)}(1-\xi) \psi_n^{(t)}(1-\eta) \Big]. \quad (136)$$

Above considerations apply to the interpolation in all three parameters for a general purpose EoS table. For neutron matter, i.e., $Y_q = 0$, the interpolation in the charge fraction of strongly interacting particles is trivial since $\zeta = 0$ and the tabulated values of the quantities can be used directly in the second interpolation step in T and n_b. A similar procedure applies to the case of an EoS for symmetric nuclear matter of β-equilibrium. In the case of a zero-temperature table, the second interpolation step reduces from two to one dimension.

A.2. Matter in β-Equilibrium. In the case of matter in β-equilibrium, there is an additional condition on the chemical potentials that reduces the number of independent parameters by one. Requiring that the weak interaction reactions

$$p + e^- \leftrightarrow n + \nu_e, \quad p + \bar{\nu}_e \leftrightarrow n + e^+ \tag{137}$$

and, if muons are considered in the model,

$$p + \mu^- \leftrightarrow n + \nu_\mu, \quad p + \bar{\nu}_\mu \leftrightarrow n + \mu^+ \tag{138}$$

are in equilibrium, the relations

$$\mu_p + \mu_e = \mu_n + \mu_{\nu_e} \tag{139}$$

and

$$\mu_p + \mu_\mu = \mu_n + \mu_{\nu_\mu}, \tag{140}$$

respectively, should hold. The chemical potentials of the neutrinos are considered to be zero, i.e., $\mu_{\nu_e} = \mu_{\nu_\mu} = 0$. Because $\mu_p = \mu_n + \mu_q$, $\mu_e = \mu_{le} - \mu_q$ and $\mu_\mu = \mu_{l\mu} - \mu_q$, the constraint can be formulated as

$$\mu_l = 0 \tag{141}$$

with the effective lepton chemical potential $\mu_l = \mu_{le} = \mu_{l\mu}$. For given temperature T and baryon number density n_b there is a unique charge fraction of strongly interacting particles Y_q that is found by determining the zero of the function

$$f(Y_q) = \mu_l(Y_q). \tag{142}$$

Appendix B
ORGANIZATION OF THE CompOSE TEAM

CompOSE is developed in close collaboration with the communities the service is meant for. These are mainly physicists who develop equations of state or simulate astrophysical phenomena numerically on the computer. Direct interaction with the users is an essential part in the concept of the project.

There is a *core team* that is engaged in the preparation of the web site, the manual and the tools, numerical codes and tables. Members of the core team are

Thomas Klähn	U Wrocław (Poland),
Micaela Oertel	LUTH Meudon (France),
Stefan Typel	GSI Darmstadt (Germany).

The core team is surrounded by a group of closely collaborating physicists that contribute to various aspects of the CompOSE project, e.g., in preparing EoS tables for particular models or testing the CompOSE web site and tools. Presently, the *support team* consists of

David Blaschke	JINR Dubna (Russia), U Wrocław (Poland),
Tobias Fischer	GSI Darmstadt (Germany), U Wrocław (Poland),
Matthias Hempel	U Basel (Switzerland),
Daniel Zabłocki	U Wrocław (Poland).

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