CompOSE Quick Guide for Providers

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1 Introduction

CompOSE is an online repository that provides information and data tables for different equations of states (EoSs) which are ready for use in astrophysical applications, nuclear physics, and beyond. For more information see Refs. [1] and the full instruction manual available at `https://compose.obspm.fr/manual`. The CompOSE data format allows the storage of a large number of thermodynamic properties, chemical (particle) composition of dense matter, and microphysical quantities. CompOSE additionally offers the user tools to interpolate tables, extract relevant quantities with selected grids, and add additional information (not stored in the original data tables). See the CompOSE Quick Guide for Users available on the CompOSE website for more details.

The success of CompOSE depends on the support of nuclear physicists providing their tables. Some well-known EoS models are already incorporated in the CompOSE data base, however, a larger collection of EoS from different models is highly desirable. You should contact the CompOSE core team (`develop.compose@obspm.fr`) to contribute. If you make use of the tables provided in CompOSE, please cite the publications describing the respective EoS models (available on the CompOSE web pages where the models are described) together with the original CompOSE publications [2, 3] and the CompOSE website [4].

2 Preparation of Tables

In the CompOSE database, the equation of state is assumed to describe dense matter in thermodynamic equilibrium, i.e., thermal and mechanic equilibrium. In addition, it is assumed that all the constituents are in chemical equilibrium with respect to reactions mediated by the strong and electromagnetic interactions. In contrast, only some tables assume equilibrium with respect to weak reactions, in particular β equilibrium, reducing in this case the number of independent particle number densities, i.e. thermodynamic parameters. For EoS models with strangeness bearing particles, it is assumed that the strangeness chemical potential vanishes, meaning that the strangeness changing weak interactions are in equilibrium. Except for the tables of pure hadronic and/or quark matter (without leptons), charge neutrality is assumed to hold. Neutrinos are never included in the present tables, since they are usually treated independently from the EoS in astrophysical simulations, not assuming thermodynamic equilibrium. Photons can be included in finite-temperature tables, except for the pure-neutron one, which is defined as not containing them.

Quantities in CompOSE are given in natural units $\hbar = c = k_B = 1$ (for details on unit conversion see the NIST [5] or CODATA [6] websites). Particle number densities of all particles i are given by $n_i = N_i/V$ [fm^{-3}], where N_i is the particle number inside the volume V. For particles with half-integer spin at finite temperature, n_i represents the net particle density, i.e. the difference between the number density of particles and antiparticles (see full manual for the possibility of entering particles and antiparticles separately). For particles with integer spin, particle and antiparticle number densities are given separately. The baryon number density n_b is given by $n_b = N_b/V = \sum_i B_i n_i$ [fm^{-3}], where N_b is the total baryonic number and B_i the baryon number of a given particle, e.g., the baryon number for a quark is 1/3.

The hadronic (and quark) charge density is given by $n_q = Q/V = \sum_i' Q_i n_i$ [fm^{-3}], where Q is the total electric charge and Q_i is the electric charge of a given particle. The prime indicates that the summation excludes leptons. For a nucleus ${}^{A_i}Z_i$, the baryon number and electric charge are the mass number A_i and atomic number Z_i, respectively. Particle fractions are defined as $Y_i = n_i/n_b$ [dimensionless].

The hadronic (and quark) charge fraction, hereon simply charge fraction, is defined as $Y_q = n_q/n_b$ [dimensionless]. In models with electrons and muons, charge neutrality requires $Y_q = Y_e + Y_\mu = Y_l$, where Y_l is the lepton fraction.

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Because of the imposed physical conditions, the state of the system is uniquely characterized by the three quantities temperature T [MeV], baryon number density n_b [fm^{-3}], and charge fraction Y_q. The latter variable is used because it is also defined in pure hadronic EoS models that do not include charged leptons.

Table 1 introduces an indexing scheme for the most relevant particles that identifies them uniquely (more can be added upon request - see full manual). For a nucleus ${}^{A}Z$, the index is $1000 \cdot A + Z$ and, for the photon γ, the index is 600. Note that it should be stated in the accompanying information if a given EoS includes photon contributions. This should appear in a pdf file (the so-called 'data sheet') that includes a short characterisation of the EoS model, relevant references, the meaning of an index I_{phase} for the phases that appear in the tables, considered particle species, parameter ranges, additional quantities provided, etc.

Table 1: particle indices

e^-	μ^-	n	p	Δ^-	Δ^0	Δ^+	Δ^{++}	Λ	Σ^-	Σ^0	Σ^+	Ξ^-	Ξ^0	ω	σ	η	η'
0	1	10	11	20	21	22	23	100	110	111	112	120	121	200	210	220	230
ρ^-	ρ^0	ρ^+	δ^-	δ^0	δ^+	π^-	π^0	π^+	ϕ	σ_s	K^-	K^0	$\bar{K}^0$	K^+	u	d	s
300	301	302	310	311	312	320	321	322	400	410	420	421	422	423	500	501	502

3 EoS Tables and Data Format

There are at least four files with numerical data required for an EoS to be included in the CompOSE repository: three files that specify the discretization scheme of the independent variables temperature, baryon number density and charge fraction (`eos.t`, `eos.nb`, and `eos.yq`) and a file (`eos.thermo`) with the table of thermodynamic quantities. Additional data on the chemical composition and on microscopic quantities can be collected in two additional files (`eos.compo` and `eos.micro`) and on neutron star properties in `eos.mr`.

The variables T, n_b, and Y_q are given on a provider-defined grid in which each point is identified by three indices. The values corresponding to these indices are given in separate files (and should ideally have at least eight significant digits):

- **temperature** T [MeV] in file `eos.t` recommended to increase logarithmically (at least at large temperatures),
- **baryon number density** n_b [fm^{-3}] in file `eos.nb` recommended to increase logarithmically,
- **charge fraction** Y_q [dimensionless] in file `eos.yq` recommended to increase linearly in Y_q.

In Sec. 3.5 we list recommended ranges of these parameters for the different types of tables. In these files, the first two lines should be the minimum and maximum indices (representing the respective minimum and maximum values that are given). The following lines give the numerical values of the variables for the indices in ascending order. Each line of the data files `eos.thermo`, `eos.compo`, and `eos.micro`, except the first line in `eos.thermo`, starts with the indices corresponding to the three variables in the order T, n_b, Y_q. In the particular case of β equilibrium and zero temperature, the files `eos.t` and `eos.yq` are simply:

0	1
0	1
0.00000000E+00	0.00000000E+00

3.1 Thermodynamic properties

These are listed in the file `eos.thermo`. It contains in the first line three entries: the masses of the neutron and proton in MeV and an integer that indicates if the EoS contains leptons (1) or not (0). The remaining lines contain the following entries:

$$i_T \quad i_{n_b} \quad i_{Y_q} \quad p/n_b \quad s/n_b \quad \mu_b/m_n - 1 \quad \mu_q/m_n \quad \mu_l/m_n \quad f/(n_b m_n) - 1 \quad e/(n_b m_n) - 1 \quad N_{\text{add}} \quad \underbrace{q_1 \quad q_2 \quad \ldots}_{N_{\text{add}} \text{ quantities}}$$

corresponding to the indices for temperature, baryon number density, and charge fraction, followed by seven mandatory thermodynamic quantities. These are

- pressure divided by baryon number density p/n_b (MeV)
- entropy per baryon (or entropy density per baryon number density) s/n_b
- scaled and shifted baryon chemical potential $\mu_B/m_n - 1$
- scaled charge chemical potential μ_q/m_n
- scaled effective lepton chemical potential (set to zero in models without leptons) μ_l/m_n
- scaled and shifted free energy per baryon $f/(m_n n_B) - 1$
- scaled and shifted energy per baryon $\epsilon/(m_n n_B) - 1$

An integer follows, indicating the absence (0) or presence (N_{add}) of N_{add} additional optional thermodynamic quantities (specified in the data sheet). If the table contains repeated rows with identical indices i_T, i_{n_b}, i_{Y_q}, only the last row is used.

From thermodynamic identities, the free energy density is $f(T, n_b, Y_q) = -p + \sum_i \mu_i n_i$, with particle chemical potentials $\mu_i = B_i\mu_b + Q_i\mu_q + L_i\mu_l$ and lepton numbers L_i that do not distinguish between electrons and muons. In pure hadronic (and quark) models without leptons, it can be written as $f(T, n_b, Y_q) = -p + (\mu_b + Y_q\mu_q)\, n_b$. In the case that charged leptons are present, charge neutrality requires $Y_l = Y_q$. The condition of (neutrinoless) β equilibrium corresponds to $\mu_l = 0$ assuming identical lepton chemical potentials of electrons and muons, $\mu_{e^-} = \mu_{\mu^-} = \mu_l - \mu_q$.

3.2 Composition of matter (optional)

This is listed in the file `eos.compo` containing in all lines the entries

$$i_T \quad i_{n_b} \quad i_{Y_q} \quad I_{\text{phase}} \quad N_{\text{pairs}} \quad \underbrace{I_1 \quad Y_{I_1} \quad \ldots}_{N_{\text{pairs}}\text{pairs}} \quad N_{\text{quad}} \quad \underbrace{I_1 \quad A^{\text{av}}_{I_1} \quad Z^{\text{av}}_{I_1} \quad Y_{I_1} \quad \ldots}_{N_{\text{quad}}\ \text{quadruples}}$$

corresponding again to the indices for temperature, baryon number density, and charge fraction, followed by an index encoding the type of phase (chosen by provider and identified in the data sheet), number of particles (pairs) for which the composition is given, particle pairs in no particular order (particle indices from Table 1 followed by the respective particle charge fractions), number of particle quadruples, particle quadruples (particle indices from Table 1 followed by the respective average mass and charge numbers of the representative nucleus and respective combined charge fraction). In each quadruple, the index I_i specifies a group of nuclei $\mathcal{M}_{I_i}$ with average mass number $A^{\text{av}}_{I_i} = \sum_{j\in\mathcal{M}_{I_i}}(A_jY_j)/\sum_{j\in\mathcal{M}_{I_i}} Y_j$, average charge number $Z^{\text{av}}_{I_i} = \sum_{j\in\mathcal{M}_{I_i}}(Z_jY_j)/\sum_{j\in\mathcal{M}_{I_i}} Y_j$, and combined charge fraction $Y_{I_i} = \sum_{j\in\mathcal{M}_{I_i}} Y_j$. In the case that there are no quadruples to report, $N_{\text{quad}} = 0$. The correlation between the I_i and $\mathcal{M}_{I_i}$ should appear in the data sheet.

3.3 Stellar information (optional)

This is listed in the file `eos.mr` containing in the first line the provided quantities (with units) preceeded by a '#' sign and in the remaining lines:

$$R \quad M \quad \Lambda \quad n_c \tag{1}$$

corresponding to the radius (in km), mass (in solar masses), dimensionless tidal deformability, and central density (in fm^{-3}) of a family of cold β-equilibrated spherical neutron stars obtained from the provided equation of state. The third and fourth columns are optional and more relevant quantities can be added in additional columns.

3.4 Microscopic information (optional)

This is listed in the file `eos.micro` containing in all lines the entries

$$i_T \quad i_{n_b} \quad i_{Y_q} \quad N_{\text{qty}} \quad \underbrace{K_1 \quad q_{K_1} \quad K_2 \; q_{K_2} \quad \ldots}_{N_{\text{qty}}\ \text{pairs}} \tag{2}$$

corresponding again to the indices for temperature, baryon number density, and charge fraction, followed by the number of stored quantities (pairs), the composite correlation indices that identify uniquely the particle or correlation with the physical quantity $K_i = 1000\, I_i + J_i$ (J_i found in Table 2), and the microscopic quantity index (found in Table 3). The microscopic quantities available so far are the Landau mass m_i^L, the effective Dirac mass m_i^D, the single-particle potential U_i, the vector self-energy V_i, the scalar self-energy S_i and the size of superconductivity or superfluidity pairing gaps Δ_i (see full manual for more details).

Table 2: two body correlation indices (with most relevant channel)

nn ($^1S_0$)	np ($^1S_0$)	pp ($^1S_0$)	np ($^3S_1$)
700	701	702	703

Table 3: indices for microscopic quantities

$m^L_{I_i}/m_{I_i}$ [dimensionless]	$m^D_{I_i}/m_{I_i}$ [dimensionless]	U_{I_i} [MeV]	V_{I_i} [MeV]	S_{I_i} [MeV]	Δ_{I_i} [MeV]
40	41	50	51	52	60

3.5 Dimensionality of tables

The recommended dimensions of the EoS data grids are:

- 3D: **general-purpose EoS table** with $N_T^{\max} \times N_{n_b}^{\max} \times N_{Y_q}^{\max} = 81(62) \times 301 \times 60 = 1462860$ (1119720) data points, not including points with $T = 0$ MeV or $Y_q = 0$. The quantities in parentheses indicate temperature increasing logarithmically at least at large temperatures. The temperature should start at 0.1 MeV and the baryon number density at 10^{-12} fm^{-3} or below,
- 2D: **zero-temperature EoS table** with $N_{n_b}^{\max} \times (N_{Y_q}^{\max} + 1) = 301 \times 61 = 18361$ data points. The baryon number density should start at 10^{-12} fm^{-3} or below,
- 2D: **symmetric-matter EoS table** with $N_T^{\max} \times N_{n_b}^{\max} = 81(62) \times 301 = 24381$ (18963) data points, not including points with $T = 0$ MeV when increasing logarithmically all the way. The temperature should start at 0.1 MeV and the baryon number density at 10^{-12} fm^{-3} or below,
- 2D: **neutron-matter EoS table** with $N_T^{\max} \times N_{n_b}^{\max} = 81(62) \times 301 = 24381$ (18963) data points, not including points with $T = 0$ MeV when increasing logarithmically all the way. The temperature should start at 0.1 MeV and the baryon number density at 10^{-12} fm^{-3} or below,
- 2D: **EoS table of β-equilibrated matter** with $N_T^{\max} \times N_{n_b}^{\max} = 81(62) \times 301 = 24381$ (18963) data points, not including points with $T = 0$ MeV when increasing logarithmically all the way. The charge fraction is determined by the condition of charge neutrality and weak chemical equilibrium. The temperature should start at 0.1 MeV and the baryon number density at 10^{-12} fm^{-3} or below,
- 1D: **EoS table of cold-symmetric matter** with $N_{n_b}^{\max} = 301$ data points with $Y_q = 0.5$ and $T = 0$ MeV. The baryon number density should start at 10^{-12} fm^{-3} or below,
- 1D: **EoS table of cold-neutron matter** with $N_{n_b}^{\max} = 301$ data points with $Y_q = 0.0$ and $T = 0$. The baryon number density should start at 10^{-12} fm^{-3} or below,
- 1D: **EoS table of cold β-equilibrated matter** with $N_{n_b}^{\max} = 301$ data points with $T = 0$ MeV. The baryon number density should start at 10^{-12} fm^{-3} or below. Charge fraction is determined by the conditions of charge neutrality and weak neutrinoless chemical equilibrium. This table can be used to generate neutron-star properties, such as maximum mass with the COMPOSE EoS class within the Lorene library. This could also be done using one of the other tables with dependence on Y_q if leptons are included.

References

[1] M. Oertel, M. Hempel, T. Klähn and S. Typel, Rev. Mod. Phys. **89**, 015007 (2017).

[2] S. Typel, M. Oertel, and T. Klähn, Physics of Particles and Nuclei **46**, 633 (2015).

[3] S. Typel, M. Oertel, T. Klähn et al, Eur. Phys. J. A **58**, 221 (2022).

[4] https://compose.obspm.fr

[5] http://physics.nist.gov/cuu/Constants/index.html

[6] www.codata.org