

O₂scl_eos - Equation of State Sub-Library for O₂scl

Version 0.904

Copyright © 2006, 2007, 2008, 2009 Andrew W. Steiner

Permission is granted to copy, distribute and/or modify this document under the terms of the GNU Free Documentation License, Version 1.2 or any later version published by the Free Software Foundation; with no Invariant Sections, no Front-Cover Texts, and no Back-Cover Texts. A copy of the license is included in the section entitled “License Information”.

Contents

1	Main Page	2
1.1	Quick Reference to User's Guide	2
1.2	Hadronic equations of state	2
1.3	Equations of state of quark matter	2
1.4	Solution of the Tolman-Oppenheimer-Volkov equations	2
1.5	Naive Cold Neutron Stars	3
1.6	Non-relativistic Finite Temperature Approximations	3
1.7	Example source code	4
1.8	Other Todos	5
1.9	Bibliography	5
2	Ideas for future development	7
3	Todo List	8
4	Bug List	9
5	Data Structure Documentation	9
5.1	apr4_eos Class Reference	9
5.2	apr_eos Class Reference	10
5.3	bag_eos Class Reference	14
5.4	bps_eos Class Reference	15
5.5	cfl6_eos Class Reference	18
5.6	cfl_njl_eos Class Reference	21
5.7	cold_nstar Class Reference	27
5.8	ddc_eos Class Reference	31
5.9	eos Class Reference	33
5.10	gen_potential_eos Class Reference	34
5.11	hadronic_eos Class Reference	38
5.12	hadronic_eos_edden Class Reference	44
5.13	hadronic_eos_pres Class Reference	45
5.14	hadronic_eos_temp Class Reference	46
5.15	hadronic_eos_temp_edden Class Reference	47
5.16	hadronic_eos_temp_pres Class Reference	48
5.17	mdi4_eos Class Reference	49
5.18	nambu_njl_eos Class Reference	50
5.19	nambu_njl_eos::njtp_s Struct Reference	54
5.20	nse_eos Class Reference	55
5.21	quark_eos Class Reference	56
5.22	rmf4_eos Class Reference	57
5.23	rmf_delta_eos Class Reference	58
5.24	rmf_eos Class Reference	60
5.25	schematic_eos Class Reference	69
5.26	skyrme4_eos Class Reference	70
5.27	skyrme_eos Class Reference	71
5.28	sym4_eos Class Reference	78
5.29	sym4_eos_base Class Reference	79
5.30	tabulated_eos Class Reference	80
5.31	tov_buchdahl_eos Class Reference	81
5.32	tov_eos Class Reference	83
5.33	tov_interp_eos Class Reference	83
5.34	tov_polytrope_eos Class Reference	86
5.35	tov_solve Class Reference	87

1 Main Page

1.1 Quick Reference to User's Guide

- [Hadronic equations of state](#)
 - [Equations of state of quark matter](#)
 - [Solution of the Tolman-Oppenheimer-Volkov equations](#)
 - [Naive Cold Neutron Stars](#)
 - [Non-relativistic Finite Temperature Approximations](#)
 - [Example source code](#)
 - [Bibliography](#)
-

1.2 Hadronic equations of state

The hadronic equations of state are all inherited from [hadronic_eos](#): [schematic_eos](#), [skyrme_eos](#), [rmf_eos](#), [apr_eos](#), and [gen_potential_eos](#).

[hadronic_eos](#) includes several methods that can be used to calculate the saturation properties of nuclear matter. These methods are sometimes overloaded in descendants when exact formulas are available.

There is also a set of classes to modify the quartic term of the symmetry energy: [rmf4_eos](#), [apr4_eos](#), [skyrme4_eos](#), and [mdi4_eos](#) all based on [sym4_eos_base](#) which can be used in [sym4_eos](#).

1.3 Equations of state of quark matter

The equations of state of quark matter are all inherited from [quark_eos](#): [bag_eos](#) is a simple bag model, [nambu_jl_eos](#) is the Nambu–Jona-Lasinio model.

1.4 Solution of the Tolman-Oppenheimer-Volkov equations

The class [tov_solve](#) provide a solution to the Tolman-Oppenheimer-Volkov (TOV) equations given an equation of state. This is particularly useful for static neutron star structure: given any equation of state one can calculate the mass vs. radius curve and the properties of any star of a given mass. An adaptive integration is employed and calculates the gravitational mass, the baryonic mass (if the baryon density is supplied), and the gravitational potential. The remaining columns is the equation of state are also interpolated into the solution, e.g. if a chemical potential is given, then the radial dependence of the chemical potential for a 1.4 solar mass star can be automatically computed. The equation of state may be specified in arbitrary units so long as an appropriate conversion factor is supplied. An equation of state for low densities (baryon density $< 0.08 \text{ fm}^{-3}$) is provided and can be automatically appended to the user-defined equation of state.

This is still experimental.

1.5 Naive Cold Neutron Stars

There is also a class to calculate zero-temperature neutron stars: `cold_nstar`. It uses `tov_solve` to compute the structure, given a hadronic equation of state (of type `hadronic_eos`). It also computes the adiabatic index, the speed of sound, and determines the possibility of the direct Urca process as a function of density or radius.

This is still experimental.

1.6 Non-relativistic Finite Temperature Approximations

This is taken from the [Prakash87](#).

The entropy is

$$s = - \sum_k [n_k \ln n_k + (1 - n_k) \ln (1 - n_k)]$$

The low-temperature (degenerate) approximation to the entropy is

$$s = \pi^2/3N(0)T$$

where the density of states at the Fermi surface is

$$N(0) = \sum_k \delta(\epsilon_k - \mu) = \frac{3\rho}{k_F v_F}$$

where the Fermi velocity is

$$v_F = \left. \frac{\partial \epsilon_k}{\partial k} \right|_{k_F} = \frac{k_F}{m^*}$$

The latter equation defines the effective mass. The level density parameter is given by

$$a = \frac{\pi^2 N(0)}{6\rho}$$

Defining the Fermi temperature:

$$T_F = \frac{1}{2} k_F v_F = k_F^2/2/m^*$$

another expression for the entropy is

$$s = \frac{\pi^2}{2} \rho(T/T_F)$$

Expressions for the remaining quantities are

$$P = P(T=0) + \frac{\rho}{3} a T^2 \left(1 + \frac{d \ln v_F}{d \ln k_F} \right)$$

$$E/A = E/A(T=0) + a T^2$$

$$\mu = \mu(T=0) - \frac{1}{3} a T^2 \left(2 - \frac{d \ln v_F}{d \ln k_F} \right)$$

Typically, the leading correction to

$$s = \frac{\pi^2}{2} \rho(T/T_F)$$

is of order $(T/T_F)^2$ unless soft collective modes give rise to a $(T/T_F)^3 \ln(T/T_F)$ correction.

At high temperature (non-degenerate approximation), a stationary phase approximation gives

$$\begin{aligned} \rho(T) &\sim \frac{\gamma}{2\pi^2} e^{\mu/T} \cdot k^2 e^{-\epsilon_k/T} \sqrt{2\pi} \left[\frac{2}{k^2} + \frac{1}{T} \frac{\partial v_k}{\partial k} \right]^{-1/2} \\ &= e^{\mu/T} f(T)|_{k=k_\rho} \end{aligned}$$

where γ is the spin and isospin degeneracy and the velocity function is $v_k = \partial \epsilon_k / \partial k$. The function $f(T)$ is evaluated at momentum k_ρ which is obtained by solving $T - k v_k / 2 = 0$. The chemical potential is obtained by inverting the above relation for $\rho(T)$:

$$\mu \sim T \ln \rho - T \ln f(T)$$

From this value of μ we can derive the entropy density using

$$Ts \sim \sum_k n_k \epsilon_k + \rho T - \mu \rho$$

Using the stationary phase method:

$$\begin{aligned} \sum_k n_k \epsilon_k &\sim \frac{\gamma}{2\pi^2} e^{\mu/T} \cdot k^2 \epsilon_k e^{-\epsilon_k/T} \sqrt{2\pi} \left[\frac{2}{k^2} - \left(\frac{1}{\epsilon_k} - \frac{1}{T} \right) \frac{\partial v_k}{\partial k} + \left(\frac{v_k}{\epsilon_k} \right)^2 \right]^{-1/2} \\ &= e^{\mu/T} g(T)|_{k=k_E} \end{aligned}$$

where k_E is the solution of

$$\frac{2}{k} + v_k \left(\frac{1}{\epsilon_k} - \frac{1}{T} \right) = 0$$

This provides a first approximation to the energy and together with the thermodynamic identity gives the pressure.

1.7 Example source code

1.7.1 Example list

- [Cold neutron star example](#)

1.7.2 Cold neutron star example

```
/* Example: ex_cold_nstar.cpp
-----
This example solves the TOV equations using class cold_nstar using a
relativistic mean-field EOS from class rmf_eos.
*/

#include <o2scl/collection.h>
#include <o2scl/text_file.h>
#include <o2scl/cold_nstar.h>
#include <o2scl/rmf_eos.h>
#include <o2scl/test_mgr.h>

using namespace std;
using namespace o2scl;

// For hc_mev_fm
using namespace o2scl_const;

int main(void) {

    cout.setf(ios::scientific);

    test_mgr t;
    t.set_output_level(1);

    def_err_hnd.set_mode(0);

    cold_nstar nst;

    // Initialize EOS
```

```

rmf_eos rmf;

rmf.load("NL3");

rmf.saturation();
cout << "Saturation density: " << rmf.n0 << endl;
cout << "Binding energy: " << rmf.eoa*hc_mev_fm << endl;
cout << "Effective mass: " << rmf.msom << endl;
cout << "Symmetry energy: " << rmf.esym*hc_mev_fm << endl;
cout << "Compressibility: " << rmf.comp*hc_mev_fm << endl;

// Compute EOS, include muons
nst.include_muons=true;
nst.set_eos(rmf);
nst.calc_eos();
table &te=nst.get_eos_results();

// Output EOS results to a file
collection co;
text_out_file *tof=new text_out_file("ex_cold_nstar.out");
co.out_one(tof,"table","tov",&te);
delete tof;

// Compute mass vs. radius
nst.calc_nstar();
table &tr=nst.get_tov_results();
cout << "Maximum mass: " << tr.max("gm") << endl;
cout << "Radius of maximum mass star: "
    << tr.get("r",tr.lookup("gm",tr.max("gm"))) << endl;
cout << "Central baryon density of maximum mass star: ";
cout << tr.get("nb",tr.lookup("gm",tr.max("gm"))) << endl;

t.report();
return 0;
}
// End of example

```

1.8 Other Todos

Idea for future

Right now, the equation of state classes depend on the user to input the correct value of `non_interacting` for the particle inputs. This is not very graceful...

1.9 Bibliography

Some of the references which contain links should direct you to the work referred to directly through [dx.doi.org](https://doi.org/).

Akmal98: [Akmal](#), [Pandharipande](#), and [Ravenhall](#), Phys. Rev. C **58**, 1805 (1998).

Bartel79: [J. Bartel](#), [P. Quentin](#), [M. Brack](#), [C. Guet](#), and [Håkansson](#), Nucl. Phys. A **386** (1982) 79.

Baym71: G. Baym, C. Pethick, and P. Sutherland, Astrophys. J. **170** (1971) 299.

Beiner75: [M. Beiner](#), [H. Flocard](#), [Nguyen van Giai](#), and [P. Quentin](#), Nucl. Phys. A **238** (1975) 29.

Bernard88: [V. Bernard](#), [R. L. Jaffe](#), and [U.-G. Meissner](#), Nucl. Phys. B **308** (1988) 753.

Bombaci01: I. Bombaci, "Equation of State for Dense Isospin Asymmetric Nuclear Matter for Astrophysical Applications Equation of State for Isospin-Asymmetric Nuclear Matter and Neutron Star Properties", in "Isospin physics in heavy-ion collisions at

intermediate energies" ed. by B-A. Li and W. U. Schröder (2001) Nova Science, New York.

Brack85: **M. Brack, C. Guet, and H.-B. Håkansson**, Phys. Rep. **123** (1985) 275.

Buballa99: **M. Buballa and M. Oertel**, Phys. Lett. B **457** (1999) 261.

Buballa04: **M. Buballa**, Phys. Rep. **407** (2005) 205-376.

Chabanat95: **E. Chabanat**, Ph. D. Thesis 1995

Chabanat97: **E. Chabanat, J. Meyer, P. Bonche, R. Schaeffer, and P. Haensel**, Nucl. Phys. A **627** (1997) 710.

Danielewicz08: **P. Danielewicz, J. Lee**, arXiv.org:0807.3743.

Das03: **C.B. Das, S. Das Gupta, C. Gale, and B.-A. Li**, Phys. Rev. C **67** (2003) 034611.

Dobaczewski94: **J. Dobaczewski, H. Flocard, and J. Treiner**, Nucl. Phys. A **422** (1984) 103.

Dutta86: **A.K.Dutta, J.-P.Arcoragi, J.M.Pearson, R.Behrman, F.Tondeur**, Nucl. Phys. A **458** (1986) 77.

Friedrich86: **J. Friedrich, and P.-G. Reinhard**, Phys. Rev. C **33** (1986) 335.

Gaitanos04: **T. Gaitanos, M. Di Toro, S. Typel, V. Barana, C. Fuchs, V. Greco, and d H. H. Wolter**, Nucl. Phys. A **732** (2004) 24.

Gale87: **C. Gale, G. Bertsch, and S. Das Gupta**, Phys. Rev. C **35** (1986) 1666.

Hatsuda94: **T. Hatsuda and T. Kunihiro**, Phys. Rep. **247** (1994) 221.

Horowitz01: **C. J. Horowitz and J. Piekarewicz**, Phys. Rev. Lett. **86** (2001) 5647.

Kubis97: **S. Kubis and M. Kutschera**, Phys. Lett. B **399** (1997) 191.

Margueron02: **J. Margueron, J. Navarro, and N. V. Giai**, Phys. Rev. C **66** (2002) 014303.

Muller96: **H. Muller and B. D. Serot**, Nucl. Phys. A **606** (1996), 508.

Osni94: **M. Onsi, H. Przysieznik, J.M. Pearson**, Phys. Rev. C **50** (1994) 460.

Pethick95: **C. J. Pethick, D. G. Ravenhall, and C. P. Lorenz**, Nucl. Phys. A **584** (1995) 675.

Prakash87: **M. Prakash, T. L. Ainsworth, J. P. Blaizot, and H. Wolter**, in *Windsurfing the Fermi Sea*, Volume II edited by T. T. S. Kuo and J. Speth, Elsevier 1987, pg. 357.

Prakash88: **M. Prakash, T. L. Ainsworth, and J. M. Lattimer**, Phys. Rev. Lett. **61** (1988) 2518.

Prakash97: **Madappa Prakash, I. Bombaci, Manju Prakash, P. J. Ellis, J. M. Lattimer, and R. Knorren**, Phys. Rep. **280** (1997) 1.

Reinhard95: **P.-G. Reinhard and H. Flocard**, Nucl. Phys. A **584** (1995) 467.

Reinhard99: **P.-G. Reinhard, D.J. Dean, W. Nazarewicz, J. Dobaczewski, J.A. Maruhn, M.R. Strayer**, Phys. Rev. C **60**, (1999) 014316.

Shapiro83: **S. L. Shapiro and S. A. Teukolsky**, "Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects", John Wiley and Sons, New York, 1983.

Steiner00: **A. W. Steiner, M. Prakash, and J.M. Lattimer**, Phys. Lett. B, **486** (2000) 239.

Steiner02: **A. W. Steiner, S. Reddy, and M. Prakash**, Phys. Rev. D, **66** (2002) 094007.

Steiner05: **A. W. Steiner**, Phys. Rev. D, **72** (2005) 054024.

Steiner06: **A. W. Steiner**, Phys. Rev. C, **74** (2006) 045808.

Tondeur84: **F. Tondeur, M. Brack, M. Farine, and J.M. Pearson**, Nucl. Phys. A **420** (1984) 297.

Typel99: **S. Typel and H. H. Wolter**, Nucl. Phys. A **656** (1999) 331.

VanGiai81: **Nguyen van Giai and H. Sagawa**, Phys. Lett. B **106** (1981) 379.

Zimanyi90: **Zimanyi and Moszkowski**, Phys. Rev. C **42** (1990) 1416.

2 Ideas for future development

page [Main Page](#) Right now, the equation of state classes depend on the user to input the correct value of `non_interacting` for the particle inputs. This is not very graceful...

Class [apr_eos](#) There might be room to improve the testing of the finite temperature **part** a bit.

Class [apr_eos](#) There is some repetition between `calc_e()` and `calc_e_temp()` that possibly could be removed.

Class [bps_eos](#) Can the pressure be made to match more closely?

Class [bps_eos](#) Convert to a [hadronic_eos](#) object and offer an associated interface?

Class [cfl_njl_eos](#) This class internally mixes `ovector`, `omatrix`, `gsl_vector` and `gsl_matrix` objects in a confusing and non-optimal way. Fix this.

Class [cfl_njl_eos](#) Allow user to change derivative object? This isn't possible right now because the stepsize parameter of the derivative object is used.

Class [cold_nstar](#) Ensure that the adiabatic index of the central density is greater than $4/3$

Class [cold_nstar](#) Warn if the EOS becomes pure neutron matter.

Class [ddc_eos](#) Implement the finite temperature EOS properly.

Class [gen_potential_eos](#) Calculate the chemical potentials analytically

Class [hadronic_eos](#) Could write a function to compute the "symmetry free energy" or the "symmetry entropy"

Class [nse_eos](#) Right now `calc_density()` needs a very good guess. This could be fixed, probably by solving for the $\log(\mu/T)$ instead of μ .

Class [rmf_delta_eos](#) Finish the finite temperature EOS

Global [rmf_eos::calc_e\(fermion &ne, fermion &pr, thermo <h\)](#) Improve the operation of this function when the proton density is zero.

Global [rmf_eos::calc_e\(fermion &ne, fermion &pr, thermo <h, double &sig, double &ome, double &rho\)](#) Improve the operation of this function when the proton density is zero.

Class [tov_buchdahl_eos](#) Figure out what to do with the `buchfun()` function

Class [tov_solve](#) • Turn numbers in `max()` function into variables

Global [tov_solve::bio](#) Is this really required?

- Class [skyrme_eos](#)**
- Make sure that this class properly handles particles for which `inc_rest_mass` is true/false
 - What about the spin-orbit units?
 - Need to write a function that calculates saturation density?
 - Remove use of `mnuc` in `calparfun()`?
 - The compressibility could probably use some simplification
 - Make sure the finite-temperature **part** is properly tested
 - The testing code doesn't work if `err_mode` is 2, probably because of problems in `load()`.

Global [skyrme_eos::calpar](#)(double `gt0=-10.0`, double `gt3=70.0`, double `galpha=0.2`, double `gt1=2.0`, double `gt2=-1.0`) Does this work for both 'a' and 'b' non-zero?

Global [skyrme_eos::calpar](#)(double `gt0=-10.0`, double `gt3=70.0`, double `galpha=0.2`, double `gt1=2.0`, double `gt2=-1.0`)
Compare to similar formulae from [Margueron02](#)

Global [skyrme_eos::landau_neutron](#)(double `n0`, double `m`, double `&f0`, double `&g0`, double `&f1`, double `&g1`) This needs to be checked

Global [skyrme_eos::landau_nuclear](#)(double `n0`, double `m`, double `&f0`, double `&g0`, double `&f0p`, double `&g0p`, double `&f1`, double `&g1`)
This needs to be checked.

Class [tov_buchdahl_eos](#) Fix the reference above

- Class [tov_solve](#)**
- The error handler is called in `tov_solve()` for pressures less than the minimum even in normal circumstances. This should be fixed, so that errors are more rare
 - baryon mass doesn't work for `fixed()` (This may be fixed. We should make sure it's tested.)
 - Combine `maxoutsize` and `kmax`?
 - Document column naming issues
 - Document surface gravity and redshift

4 Bug List

Class [gen_potential_eos](#) The BGBD EOS doesn't work and the effective mass for the GBD EOS doesn't work

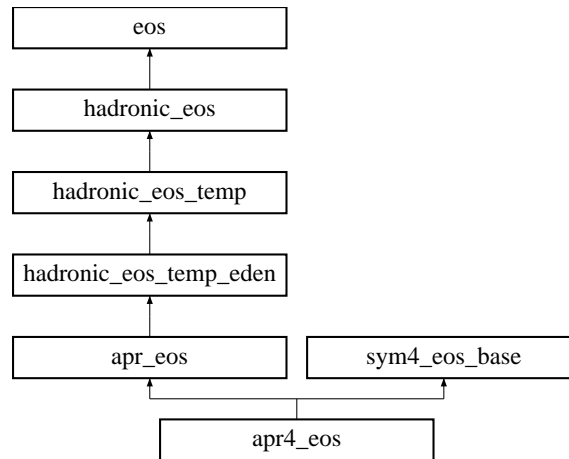
5 Data Structure Documentation

5.1 [apr4_eos](#) Class Reference

A version of [apr_eos](#) to separate potential and kinetic contributions.

```
#include <sym4_eos.h>
```

Inheritance diagram for `apr4_eos::`



5.1.1 Detailed Description

A version of [apr_eos](#) to separate potential and kinetic contributions.

References:

Created for [Steiner06](#).

Definition at line 119 of file `sym4_eos.h`.

Public Member Functions

- virtual int [calc_e_sep](#) (**fermion** &ne, **fermion** &pr, double &ed_kin, double &ed_pot, double &mu_n_kin, double &mu_p_kin, double &mu_n_pot, double &mu_p_pot)
Compute the potential and kinetic parts separately.

The documentation for this class was generated from the following file:

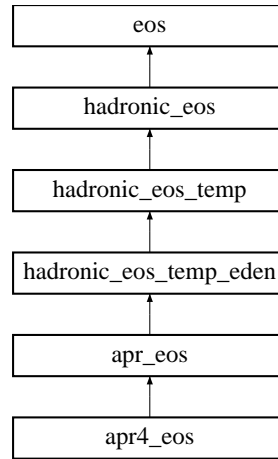
- `sym4_eos.h`

5.2 apr_eos Class Reference

EOS from Akmal, Pandharipande, and Ravenhall.

```
#include <apr_eos.h>
```

Inheritance diagram for `apr_eos`:



5.2.1 Detailed Description

EOS from Akmal, Pandharipande, and Ravenhall.

Taken from [Akmal98](#).

The chemical potentials include the rest mass energy and the energy density includes the rest mass energy density.

Note that APR seems to have been designed to be used with non-relativistic neutrons and protons with equal masses of 939 MeV. This gives a saturation density very close to 0.16.

The Hamiltonian is:

$$\mathcal{H}_{APR} = \mathcal{H}_{kin} + \mathcal{H}_{pot}$$

$$\mathcal{H}_{kin} = \left(\frac{\hbar^2}{2m} + (p_3 + (1-x)p_5) n e^{-p_4 n} \right) \tau_n + \left(\frac{\hbar^2}{2m} + (p_3 + x p_5) n e^{-p_4 n} \right) \tau_p$$

$$\mathcal{H}_{pot} = g_1 \left(1 - (1 - 2x)^2 \right) + g_2 (1 - 2x)^2$$

The following are definitions for g_i in the low-density phase (LDP) or the high-density phase (HDP):

$$g_{1,LDP} = -n^2 \left(p_1 + p_2 n + p_6 n^2 + (p_{10} + p_{11} n) e^{-p_9^2 n^2} \right)$$

$$g_{2,LDP} = -n^2 \left(p_{12}/n + p_7 + p_8 n + p_{13} e^{-p_9^2 n^2} \right)$$

$$g_{1,HDP} = g_{1,LDP} - n^2 \left(p_{17} (n - p_{19}) + p_{21} (n - p_{19})^2 e^{p_{18}(n-p_{19})} \right)$$

$$g_{2,HDP} = g_{2,LDP} - n^2 \left(p_{15} (n - p_{20}) + p_{14} (n - p_{20})^2 e^{p_{16}(n-p_{20})} \right)$$

The variables ν_n and ν_p contain the expressions $(-\mu_n + V_n)/T$ and $(-\mu_p + V_p)/T$ respectively, where V is the potential **part** of the single particle energy for particle i (i.e. the derivative of the Hamiltonian w.r.t. density while energy density held constant). Equivalently, ν_n is just $-k_{F_n}^2/2m^*$.

The selection between the LDP and HDP is controlled by [pion](#). The default is to use the LDP at densities below 0.16 fm^{-3} , and for larger densities to just use whichever minimizes the energy.

The finite temperature approximations from [Prakash97](#) are used in testing.

Note:

Since this EOS uses the effective masses and chemical potentials in the **fermion** class, the values of **part::non_interacting** for neutrons and protons are set to false in many of the functions.

Idea for future

There might be room to improve the testing of the finite temperature **part** a bit.

Idea for future

There is some repetition between **calc_e()** and **calc_e_temp()** that possibly could be removed.

Definition at line 119 of file **apr_eos.h**.

Choice of phase

- static const int **best** = 0
use LDP for densities less than 0.16 and for higher densities, use the phase which minimizes energy (default)
- static const int **ldp** = 1
LDP (no pion condensation).
- static const int **hdp** = 2
HDP (pion condensation).
- int **pion**
*Choice of phase (default **best**).*
- int **last_phase** ()
*Return the phase of the most recent call to **calc_e()**.*

Public Member Functions

- virtual int **calc_e** (**fermion** &n, **fermion** &p, **thermo** &th)
Equation of state as a function of density.
- virtual int **calc_temp_e** (**fermion_T** &n, **fermion_T** &pr, const double temper, **thermo** &th)
Equation of state as a function of densities.
- double **fcomp** (double nb)
Compute the compressibility.
- double **fesym_diff** (double nb)
Calculate symmetry energy of matter as energy of neutron matter minus the energy of nuclear matter.
- void **select** (int model_index)
Select model.
- int **gradient_qij2** (double nn, double np, double &qnn, double &qnp, double &qpp, double &dqnnndnn, double &dqnnndnp, double &dqnpdnn, double &dqnpdnp, double &dqppdnn, double &dqppdnp)
Calculate Q's for semi-infinite nuclear matter.
- double **get_par** (int n)
Get the value of one of the parameters.
- int **set_par** (int n, double x)
Set the value of one of the parameters.
- virtual const char * **type** ()
Return string denoting type ("apr_eos").

Data Fields

- **nonrel_fermion** **def_nr_neutron**
Default nonrelativistic neutron.
- **nonrel_fermion** **def_nr_proton**
Default nonrelativistic proton.
- bool **parent_method**
*If true, use the methods from **hadronic_eos** for **fcomp()**.*

Protected Attributes

- double * **par**
Storage for the parameters.
- int **lp**
An integer to indicate which phase was used in `calc_e()`.
- int **choice**
The variable indicating which parameter set is to be used.

5.2.2 Member Function Documentation

5.2.2.1 double fcomp (double nb) [virtual]

Compute the compressibility.

See general notes at [hadronic_eos::fcomp\(\)](#). This computes the compressibility (at fixed proton fraction = 0.5) exactly, unless `parent_method` is true in which case the derivative is taken numerically in [hadronic_eos::fcomp\(\)](#).

Reimplemented from [hadronic_eos](#).

5.2.2.2 double fesym_diff (double nb) [virtual]

Calculate symmetry energy of matter as energy of neutron matter minus the energy of nuclear matter.

This function returns the energy per baryon of neutron matter minus the energy per baryon of nuclear matter. This will deviate significantly from the results from [fesym\(\)](#) only if the dependence of the symmetry energy on δ is not quadratic.

Reimplemented from [hadronic_eos](#).

5.2.2.3 int gradient_qij2 (double nn, double np, double & qnn, double & qnp, double & qpp, double & dqnnndnn, double & dqnpndnp, double & dqnpdnn, double & dqnpdnp, double & dqppdnn, double & dqppdnp)

Calculate Q's for semi-infinite nuclear matter.

For general discussion, see the documentation to [hadronic_eos::qs\(\)](#).

For APR, we set $x_1 = x_2 = 0$ so that $Q_i = P_i/2$ and then

$$\begin{aligned} P_1 &= \left(\frac{1}{2} p_3 - p_5 \right) e^{-p_4 n} \\ P_2 &= \left(\frac{1}{2} p_3 + p_5 \right) e^{-p_4 n} \end{aligned}$$

This gives

$$\begin{aligned} Q_{nn} &= \frac{1}{4} e^{-p_4 \rho} [-6p_5 - p_4(p_3 - 2p_5)(n_n + 2n_p)] \\ Q_{np} &= \frac{1}{8} e^{-p_4 \rho} [4(p_3 - 4p_5) - 3p_4(p_3 - 2p_5)(n_n + n_p)] \\ Q_{pp} &= \frac{1}{4} e^{-p_4 \rho} [-6p_5 - p_4(p_3 - 2p_5)(n_p + 2n_n)] \end{aligned}$$

See the Mathematica notebook

doc/o2scl/extras/apr_eos.nb
doc/o2scl/extras/apr_eos.ps

5.2.2.4 void select (int *model_index*)

Select model.

Valid values for `model_index` are:

1 - A18+UIX*+deltav (preferred by Akmal, et. al. - this is the default)

2 - A18+UIX*

3 - A18+deltav

4 - A18

If any other integer is given, A18+UIX*+deltav is assumed.

5.2.3 Field Documentation

5.2.3.1 bool parent_method

If true, use the methods from [hadronic_eos](#) for `fcomp()`.

This can be set to true to check the difference in the compressibility between the exact expressions and the numerical values from class [hadronic_eos](#).

Definition at line 276 of file `apr_eos.h`.

The documentation for this class was generated from the following file:

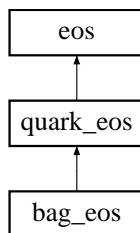
- `apr_eos.h`

5.3 bag_eos Class Reference

Naive bag model EOS.

```
#include <bag_eos.h>
```

Inheritance diagram for `bag_eos`:



5.3.1 Detailed Description

Naive bag model EOS.

An equation of state with $P = -B + P_{u,FG} + P_{d,FG} + P_{s,FG}$ where $P_{i,FG}$ is the Fermi gas contribution from particle i and B is a density- and temperature-independent bag constant.

The finite temperature functions run the zero temperature code if the temperature is less than or equal to 0.

Definition at line 47 of file `bag_eos.h`.

Public Member Functions

- virtual int `calc_p`(`quark &u`, `quark &d`, `quark &s`, `thermo &th`)
Calculate equation of state as a function of chemical potentials.
- virtual int `calc_e`(`quark &u`, `quark &d`, `quark &s`, `thermo &th`)
Calculate equation of state as a function of density.
- virtual int `calc_temp_p`(`quark &u`, `quark &d`, `quark &s`, const double `temper`, `thermo &th`)
Calculate equation of state as a function of the chemical potentials.
- virtual int `calc_temp_e`(`quark &u`, `quark &d`, `quark &s`, const double `temper`, `thermo &th`)
Calculate equation of state as a function of the densities.
- virtual const char * `type`()
Return string denoting type ("bag_eos").

Data Fields

- double `bag_constant`
The bag constant in fm^{-4} (default $200/(\hbar c)$).

5.3.2 Member Function Documentation

5.3.2.1 virtual int `calc_temp_e`(`quark &u`, `quark &d`, `quark &s`, const double `temper`, `thermo &th`) [virtual]

Calculate equation of state as a function of the densities.

This function returns zero (success) unless the call to `quark::pair_density()` fails.

Reimplemented from `quark_eos`.

5.3.2.2 virtual int `calc_temp_p`(`quark &u`, `quark &d`, `quark &s`, const double `temper`, `thermo &th`) [virtual]

Calculate equation of state as a function of the chemical potentials.

This function returns zero (success) unless the call to `quark::pair_mu()` fails.

Reimplemented from `quark_eos`.

The documentation for this class was generated from the following file:

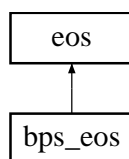
- `bag_eos.h`

5.4 bps_eos Class Reference

Baym-Pethick-Sutherland equation of state.

```
#include <bps_eos.h>
```

Inheritance diagram for `bps_eos`:



5.4.1 Detailed Description

Baym-Pethick-Sutherland equation of state.

This calculates the equation of state of electrons and nuclei using the approach of [Baym71](#) (based on the discussion in [Shapiro83](#)) between about $8 \times 10^6 \text{ g/cm}^3$ and $4.3 \times 10^{11} \text{ g/cm}^3$. Below these densities, more complex Coulomb corrections need to be considered, and above these densities, neutron drip is important.

The default mass formula is semi-empirical

$$M(A, Z) = (A - Z)m_n + Z(m_p + m_e) - 15.76A - 17.81A^{2/3} - 0.71Z^2/A^{1/3} - 94.8/A(A/2 - Z)^2 + E_{\text{pair}}$$

where

$$E_{\text{pair}} = \pm 39/A^{3/4}$$

if the **nucleus** is odd-odd (plus sign) or even-even (minus sign) and E_{pair} is zero for odd-even and even-odd nuclei. The nuclei are assumed not to contribute to the pressure. The electronic contribution to the pressure is assumed to be equal to the Fermi gas contribution plus a "lattice" contribution

$$\varepsilon_L = -1.444Z^{2/3}e^2n_e^{4/3}$$

This is Eq. 2.7.2 in [Shapiro83](#). The rest mass energy of the nucleons is included in the energy density.

The original results from [Baym71](#) are stored as a **table** in file `data/o2scl/bps.eos`. The testing code for this class compares the calculations to the **table** and matches to within .2 percent for the energy density and 9 percent for the pressure (for a fixed baryon number density).

Idea for future

Can the pressure be made to match more closely?

Idea for future

Convert to a [hadronic_eos](#) object and offer an associated interface?

Definition at line 83 of file `bps_eos.h`.

Public Member Functions

- virtual int [calc_density](#) (double barn, **thermo** &th, int &Z, int &A)
Calculate the equation of state as a function of the baryon number density barn.
- virtual int [calc_pressure](#) (**thermo** &th, double &barn, int &Z, int &A)
Calculate the equation of state as a function of the pressure.
- virtual double [lattice_energy](#) (int Z)
The electron lattice energy.
- virtual **fermion** * [get_electron](#) ()
Get a pointer to the electron.
- virtual double [mass_formula](#) (int Z, int A)
The mass formula.
- virtual const char * [type](#) ()
Return string denoting type ("bps_eos").
- int [set_mass_formula](#) (**nuclear_mass** &nm)
Set the nuclear mass formula to be used.
- int [calc_density_fixedA](#) (double barn, **thermo** &th, int &Z, int A)
Compute the ground state assuming a fixed atomic number.

Data Fields

- **semi_empirical_mass** [def_mass](#)
Default mass formula.
- **fermion** [e](#)
The electron thermodynamics.

Protected Member Functions

- virtual int [eq274](#) (size_t nv, const **ovector_base** &nx, **ovector_base** &ny, int &Zt)
Solve Equation 2.7.4 for a given pressure.
- double [gibbs](#) (int Z, int A)
The Gibbs free energy.
- double [energy](#) (double barn, int Z, int A)
The energy density.

Protected Attributes

- **gsl_mroot_hybrids**< int, **mm_funct**< int > > [gs](#)
A solver to solve Eq. 2.7.4.
- **nuclear_mass** * [nmp](#)
The nuclear mass formula.

5.4.2 Member Function Documentation

5.4.2.1 virtual int calc_density (double barn, thermo & th, int & Z, int & A) [virtual]

Calculate the equation of state as a function of the baryon number density barn.

This calculates the equation of state as a function of the baryon number density in fm^{-3} , returning the representative **nucleus** with proton number Z and atomic number A. The pressure and energy density are returned in th in fm^{-4} .

5.4.2.2 virtual int calc_pressure (thermo & th, double & barn, int & Z, int & A) [virtual]

Calculate the equation of state as a function of the pressure.

This calculates the equation of state as a function of the pressure, returning the representative **nucleus** with proton number Z and atomic number A and the baryon number density barn in fm^{-3} . The energy density is also returned in fm^{-4} in th.

5.4.2.3 virtual double mass_formula (int Z, int A) [virtual]

The mass formula.

The nuclear mass without the contribution of the rest mass of the electrons. The electron rest mass energy is included in the electron thermodynamics elsewhere.

5.4.3 Field Documentation

5.4.3.1 fermion e

The electron thermodynamics.

Note:

The electron rest mass is included by default in the energy density and the chemical potential

Definition at line 149 of file bps_eos.h.

The documentation for this class was generated from the following file:

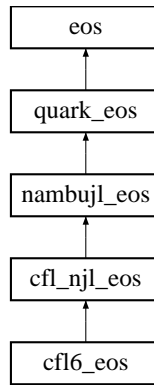
- bps_eos.h

5.5 cfl6_eos Class Reference

CFL NJL EOS with a color-superconducting 't Hooft interaction.

```
#include <cfl6_eos.h>
```

Inheritance diagram for cfl6_eos::



5.5.1 Detailed Description

CFL NJL EOS with a color-superconducting 't Hooft interaction.

Beginning with the Lagrangian:

$$\begin{aligned}
 \mathcal{L} &= \mathcal{L}_{Dirac} + \mathcal{L}_{NJL} + \mathcal{L}_{tHooft} + \mathcal{L}_{SC} + \mathcal{L}_{SC6} \\
 \mathcal{L}_{Dirac} &= \bar{q} (i\partial - m - \mu\gamma^0) q \\
 \mathcal{L}_{NJL} &= G_S \sum_{a=0}^8 \left[(\bar{q}\lambda^a q)^2 - (\bar{q}\lambda^a \gamma^5 q)^2 \right] \\
 \mathcal{L}_{tHooft} &= G_D \left[\det_f \bar{q} (1 - \gamma^5) q + \det_f \bar{q} (1 + \gamma^5) q \right] \\
 \mathcal{L}_{SC} &= G_{DIQ} (\bar{q}_{i\alpha} i\gamma^5 \varepsilon^{ijk} \varepsilon^{\alpha\beta\gamma} q_{j\beta}^C) (\bar{q}_{\ell\delta} i\gamma^5 \varepsilon^{\ell mn} \varepsilon^{\delta\epsilon\eta} q_{m\epsilon}^C) \\
 \mathcal{L}_{SC6} &= K_D (\bar{q}_{i\alpha} i\gamma^5 \varepsilon^{ijk} \varepsilon^{\alpha\beta\gamma} q_{j\beta}^C) (\bar{q}_{\ell\delta} i\gamma^5 \varepsilon^{\ell mn} \varepsilon^{\delta\epsilon\eta} q_{m\epsilon}^C) (\bar{q}_{k\gamma} q_{n\eta})
 \end{aligned}$$

We can simplify the relevant terms in \mathcal{L}_{NJL} :

$$\mathcal{L}_{NJL} = G_S \left[(\bar{u}u)^2 + (\bar{d}d)^2 + (\bar{s}s)^2 \right]$$

and in \mathcal{L}_{tHooft} :

$$\mathcal{L}_{NJL} = G_D (\bar{u}u\bar{d}d\bar{s}s)$$

Using the definition:

$$\Delta^{k\gamma} = \langle \bar{q} i\gamma^5 \epsilon q^C \rangle$$

and the ansatzes:

$$(\bar{q}_1 q_2)(\bar{q}_3 q_4) \rightarrow \bar{q}_1 q_2 \langle \bar{q}_3 q_4 \rangle + \bar{q}_3 q_4 \langle \bar{q}_1 q_2 \rangle - \langle \bar{q}_1 q_2 \rangle \langle \bar{q}_3 q_4 \rangle$$

$$(\bar{q}_1 q_2)(\bar{q}_3 q_4)(\bar{q}_5 q_6) \rightarrow \bar{q}_1 q_2 \langle \bar{q}_3 q_4 \rangle \langle \bar{q}_5 q_6 \rangle + \bar{q}_3 q_4 \langle \bar{q}_1 q_2 \rangle \langle \bar{q}_5 q_6 \rangle + \bar{q}_5 q_6 \langle \bar{q}_1 q_2 \rangle \langle \bar{q}_3 q_4 \rangle - 2 \langle \bar{q}_1 q_2 \rangle \langle \bar{q}_3 q_4 \rangle \langle \bar{q}_5 q_6 \rangle$$

for the mean field approximation, we can rewrite the Lagrangian

$$\begin{aligned} \mathcal{L}_{NJL} &= 2G_S \left[(\bar{u}u) \langle \bar{u}u \rangle + (\bar{d}d) \langle \bar{d}d \rangle + (\bar{s}s) \langle \bar{s}s \rangle - \langle \bar{u}u \rangle^2 - \langle \bar{d}d \rangle^2 - \langle \bar{s}s \rangle^2 \right] \\ \mathcal{L}_{tHooft} &= -2G_D \left[(\bar{u}u) \langle \bar{u}u \rangle \langle \bar{s}s \rangle + (\bar{d}d) \langle \bar{u}u \rangle \langle \bar{s}s \rangle + (\bar{s}s) \langle \bar{u}u \rangle \langle \bar{d}d \rangle - 2 \langle \bar{u}u \rangle \langle \bar{d}d \rangle \langle \bar{s}s \rangle \right] \\ \mathcal{L}_{SC} &= G_{DIQ} \left[\Delta^{k\gamma} (\bar{q}_{\ell\delta} i\gamma^5 \epsilon^{\ell mk} \epsilon^{\delta\epsilon\gamma} q_{m\epsilon}^C) + (\bar{q}_{i\alpha} i\gamma^5 \epsilon^{ijk} \epsilon^{\alpha\beta\gamma} q_{j\beta}^C) \Delta^{k\gamma\dagger} - \Delta^{k\gamma} \Delta^{k\gamma\dagger} \right] \\ \mathcal{L}_{SC6} &= K_D \left[(\bar{q}_{m\epsilon} q_{n\eta}) \Delta^{k\gamma} \Delta^{m\epsilon\dagger} + (\bar{q}_{i\alpha} i\gamma^5 \epsilon^{ijk} \epsilon^{\alpha\beta\gamma} q_{j\beta}^C) \Delta^{m\epsilon\dagger} \langle \bar{q}_{m\epsilon} q_{n\eta} \rangle \right] \\ &\quad + K_D \left[\Delta^{k\gamma} (\bar{q}_{\ell\delta} i\gamma^5 \epsilon^{\ell mn} \epsilon^{\delta\epsilon\eta} q_{m\epsilon}^C) \langle \bar{q}_{m\epsilon} q_{n\eta} \rangle - 2 \Delta^{k\gamma} \Delta^{m\epsilon\dagger} \langle \bar{q}_{m\epsilon} q_{n\eta} \rangle \right] \end{aligned}$$

If we make the definition $\tilde{\Delta} = 2G_{DIQ}\Delta$

References:

Created for [Steiner05](#).

Definition at line 187 of file cfl6_eos.h.

Public Member Functions

- virtual int [calc_eq_temp_p](#) (**quark** &u, **quark** &d, **quark** &s, double &qq1, double &qq2, double &qq3, double &gap1, double &gap2, double &gap3, double mu3, double mu8, double &n3, double &n8, **thermo** &qb, const double [temper](#))
Calculate the EOS.
- virtual int [integrands](#) (double p, double res[])
The momentum integrands.
- virtual int [test_derivatives](#) (double lmom, double mu3, double mu8, **test_mgr** &t)
Check the derivatives specified by [eigenvalues\(\)](#).
- virtual int [eigenvalues6](#) (double lmom, double mu3, double mu8, double egv[36], double dedmuu[36], double dedmud[36], double dedmus[36], double dedmu[36], double dedmd[36], double dedms[36], double dedu[36], double dedd[36], double deds[36], double dedmu3[36], double dedmu8[36])
Calculate the energy eigenvalues and their derivatives.
- virtual int [make_matrices](#) (double lmom, double mu3, double mu8, double egv[36], double dedmuu[36], double dedmud[36], double dedmus[36], double dedmu[36], double dedmd[36], double dedms[36], double dedu[36], double dedd[36], double deds[36], double dedmu3[36], double dedmu8[36])
Construct the matrices, but don't solve the eigenvalue problem.
- virtual const char * [type](#) ()
Return string denoting type ("cfl6_eos").

Data Fields

- double [KD](#)
The color superconducting 't Hooft coupling (default 0).
- double [kdlimit](#)
The absolute value below which the CSC 't Hooft coupling is ignored(default 10⁻⁶).

Protected Member Functions

- int [set_masses](#) ()
*Set the **quark** effective masses from the gaps and the condensates.*
-

Protected Attributes

- **omatrix_cx** [iprop6](#)
Storage for the inverse propagator.
- **omatrix_cx** [eivec6](#)
The eigenvectors.
- **omatrix_cx** [dipdgapu](#)
The derivative wrt the ds gap.
- **omatrix_cx** [dipdgapd](#)
The derivative wrt the us gap.
- **omatrix_cx** [dipdgaps](#)
The derivative wrt the ud gap.
- **omatrix_cx** [dipdqqu](#)
*The derivative wrt the up **quark** condensate.*
- **omatrix_cx** [dipdqqd](#)
*The derivative wrt the down **quark** condensate.*
- **omatrix_cx** [dipdqqs](#)
*The derivative wrt the strange **quark** condensate.*
- **ovector** [eval6](#)
Storage for the eigenvalues.
- [gsl_eigen_hermv_workspace](#) * [w6](#)
GSL workspace for the eigenvalue computation.

Static Protected Attributes

- static const int [mat_size](#) = 36
The size of the matrix to be diagonalized.

Private Member Functions

- **cfl6_eos** (const [cfl6_eos](#) &)
- **cfl6_eos** & **operator=** (const [cfl6_eos](#) &)

5.5.2 Member Function Documentation

5.5.2.1 virtual int calc_eq_temp_p (quark & *u*, quark & *d*, quark & *s*, double & *qq1*, double & *qq2*, double & *qq3*, double & *gap1*, double & *gap2*, double & *gap3*, double *mu3*, double *mu8*, double & *n3*, double & *n8*, thermo & *qb*, const double *temper*) [virtual]

Calculate the EOS.

Calculate the EOS from the **quark** condensates. Return the mass gap equations in *qq1*, *qq2*, *qq3*, and the normal gap equations in *gap1*, *gap2*, and *gap3*.

Using *fromqq=true* as in [nambuyl_eos](#) and *nambuyl_temp_eos* does not work here and will return an error.

If all of the gaps are less than *gap_limit*, then the *nambuyl_temp_eos::calc_temp_p()* is used, and *gap1*, *gap2*, and *gap3* are set to equal *u.del*, *d.del*, and *s.del*, respectively.

Reimplemented from [cfl_njl_eos](#).

5.5.2.2 virtual int eigenvalues6 (double *lmom*, double *mu3*, double *mu8*, double *egv*[36], double *dedmuu*[36], double *dedmud*[36], double *dedmus*[36], double *dedmu*[36], double *dedmd*[36], double *dedms*[36], double *dedu*[36], double *dedd*[36], double *deds*[36], double *dedmu3*[36], double *dedmu8*[36]) [virtual]

Calculate the energy eigenvalues and their derivatives.

Given the momentum `mom`, and the chemical potentials associated with the third and eighth gluons (`mu3` and `mu8`), this computes the eigenvalues of the inverse propagator and the associated derivatives.

Note that this is not the same as `cfl_njl_eos::eigenvalues()` which returns `dedmu` rather `dedqqu`.

5.5.2.3 virtual int make_matrices (double *lmom*, double *mu3*, double *mu8*, double *egv*[36], double *dedmuu*[36], double *dedmud*[36], double *dedmus*[36], double *dedmu*[36], double *dedmd*[36], double *dedms*[36], double *dedu*[36], double *dedd*[36], double *deds*[36], double *dedmu3*[36], double *dedmu8*[36]) [virtual]

Construct the matrices, but don't solve the eigenvalue problem.

This is used by `check_derivatives()` to make sure that the derivative entries are right.

The documentation for this class was generated from the following file:

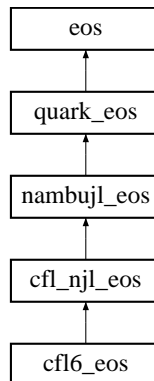
- `cfl6_eos.h`

5.6 cfl_njl_eos Class Reference

Nambu Jona-Lasinio model with a schematic CFL di-quark interaction at finite temperature.

```
#include <cfl_njl_eos.h>
```

Inheritance diagram for `cfl_njl_eos`:



5.6.1 Detailed Description

Nambu Jona-Lasinio model with a schematic CFL di-quark interaction at finite temperature.

The variable `B0` must be set before use.

The original Lagrangian is

$$\mathcal{L} = \mathcal{L}_{\text{Dirac}} + \mathcal{L}_{4\text{-fermion}} + \mathcal{L}_{6\text{-fermion}} + \mathcal{L}_{CSC1} + \mathcal{L}_{CSC2}$$

$$\mathcal{L}_{\text{Dirac}} = \bar{q}_{i\alpha} \left(i\partial\delta_{ij}\delta_{\alpha\beta} - m_{ij}\delta_{\alpha\beta} - \mu_{ij, \alpha\beta}\gamma^0 \right) q_{j\beta}$$

$$\mathcal{L}_{4\text{-fermion}} = G_S \sum_{a=0}^8 \left[\left(\bar{q}\lambda_f^a q \right)^2 + \left(\bar{q}^i\gamma_5\lambda_f^a q \right)^2 \right]$$

$$\mathcal{L}_{6\text{-fermion}} = -G_D [\det_{ij} \bar{q}_{i\alpha} (1 + i\gamma_5) q_{j\beta} + \det_{ij} \bar{q}_{i\alpha} (1 - i\gamma_5) q_{j\beta}] \delta_{\alpha\beta}$$

$$\mathcal{L}_{CSC1} = G_{DIQ} \sum_k \sum_\gamma [(\bar{q}_{i\alpha} \epsilon_{ijk} \epsilon_{\alpha\beta\gamma} q_{j\beta}^C) (\bar{q}_{i'\alpha'}^C \epsilon_{i'j'k} \epsilon_{\alpha'\beta'\gamma} q_{j'\beta'})]$$

$$\mathcal{L}_{CSC2} = G_{DIQ} \sum_k \sum_\gamma [(\bar{q}_{i\alpha} i\gamma_5 \epsilon_{ijk} \epsilon_{\alpha\beta\gamma} q_{j\beta}^C) (\bar{q}_{i'\alpha'}^C i\gamma_5 \epsilon_{i'j'k} \epsilon_{\alpha'\beta'\gamma} q_{j'\beta'})],$$

where μ is the quark number chemical potential. couplings G_S , G_D , and G_{DIQ} ultra-violet three-momentum cutoff, Λ

The thermodynamic potential is

$$\Omega(\mu_i, \langle \bar{q}q \rangle_i, \langle qq \rangle_i, T) = \Omega_{\text{vac}} + \Omega_{\text{stat}} + \Omega_0$$

where i runs over all nine (three colors times three flavors) quarks. We assume that the condensates are independent of color and that the quark chemical potentials are of the form $\mu_Q = \mu_{\text{Flavor}(Q)} + \mu_{\text{Color}(Q)}$ with

$$\mu_{\text{red}} = \mu_3 + \mu_8/\sqrt{3} \quad \mu_{\text{green}} = -\mu_3 + \mu_8/\sqrt{3} \quad \mu_{\text{blue}} = -2\mu_8/\sqrt{3}$$

With these assumptions, the thermodynamic potential as given by the function `thd_potential()`, is a function of 12 variables

$$\Omega(\mu_u, \mu_d, \mu_s, \mu_3, \mu_8, \langle \bar{u}u \rangle, \langle \bar{d}d \rangle, \langle \bar{s}s \rangle, \langle u\bar{d} \rangle, \langle u\bar{s} \rangle, \langle d\bar{s} \rangle, T)$$

The individual terms are

$$\Omega_{\text{stat}} = -\frac{1}{2} \int \frac{d^3p}{(2\pi)^3} \sum_{i=1}^{72} \left[\frac{\lambda_i}{2} + T \ln(1 + e^{-\lambda_i/T}) \right]$$

$$\Omega_{\text{vac}} = -2G_S \sum_{i=u,d,s} \langle \bar{q}_i q_i \rangle^2 + 4G_D \langle \bar{u}u \rangle \langle \bar{d}d \rangle \langle \bar{s}s \rangle + \sum_k \sum_\gamma \frac{|\Delta^{k\gamma}|^2}{4G_{DIQ}}$$

where λ_i are the eigenvalues of the (72 by 72) matrix (calculated by the function `eigenvalues()`)

$$D = \begin{bmatrix} -\gamma^0 \vec{\gamma} \cdot \vec{p} - M_i \gamma^0 + \mu_{i\alpha} & \Delta i \gamma^0 \gamma_5 C \\ i \Delta \gamma^0 C \gamma_5 & -\gamma^0 \vec{\gamma}^T \cdot \vec{p} + M_i \gamma^0 - \mu_{i\alpha} \end{bmatrix}$$

and C is the charge conjugation matrix (in the Dirac representation).

The values of the various condensates are usually determined by the condition

$$\frac{\partial \Omega}{\partial \langle \bar{q}q \rangle_i} = 0 \quad \frac{\partial \Omega}{\partial \langle qq \rangle_i} = 0$$

Note that setting `fixed_mass` to `true` and setting all of the gaps to zero when `gap_limit` is less than zero will reproduce an analog of the bag model with a momentum cutoff.

The variable `nambu_njl_eos::fromqq` is automatically set to `true` in the constructor, as computations with `fromqq=false` are not implemented.

Idea for future

This class internally mixes `ovector`, `omatrix`, `gsl_vector` and `gsl_matrix` objects in a confusing and non-optimal way. Fix this.

Idea for future

Allow user to change derivative object? This isn't possible right now because the stepsize parameter of the derivative object is used.

References:

Created for [Steiner02](#).

Definition at line 208 of file cfl_njl_eos.h.

Public Member Functions

- virtual int [set_parameters](#) (double lambda=0.0, double fourferm=0.0, double sixferm=0.0, double fourgap=0.0)
Set the parameters and the bag constant 'B0'.
- virtual int [calc_eq_temp_p](#) (**quark** &u, **quark** &d, **quark** &s, double &qq1, double &qq2, double &qq3, double &gap1, double &gap2, double &gap3, double mu3, double mu8, double &n3, double &n8, **thermo** &qb, const double [temper](#))
Calculate the EOS.
- virtual int [test_derivatives](#) (double lmom, double mu3, double mu8, **test_mgr** &t)
Check the derivatives specified by [eigenvalues\(\)](#).
- virtual int [eigenvalues](#) (double lmom, double mu3, double mu8, double egv[36], double dedmuu[36], double dedmud[36], double dedmus[36], double dedmu[36], double dedmd[36], double dedms[36], double dedu[36], double dedd[36], double deds[36], double dedmu3[36], double dedmu8[36])
Calculate the energy eigenvalues as a function of the momentum.
- int [set_quartic](#) (**quartic_real_coeff** &q)
Set the routine for solving quartics.
- int [test_integration](#) (**test_mgr** &t)
Test the integration routines.
- int [test_normal_eigenvalues](#) (**test_mgr** &t)
Test the routine to compute the eigenvalues of non-superfluid fermions.
- int [test_gapped_eigenvalues](#) (**test_mgr** &t)
Test the routine to compute the eigenvalues of superfluid fermions.
- virtual const char * [type](#) ()
Return string denoting type ("cfl_njl_eos").

Data Fields

- double [eq_limit](#)
The equal mass threshold.
 - bool [integ_test](#)
Set to true to test the integration (default false).
 - **cern_quartic_real_coeff** [def_quartic](#)
The default quartic routine.
 - double [gap_limit](#)
Smallest allowable gap (default 0.0).
 - bool [zerot](#)
If this is true, then finite temperature corrections are ignored (default false).
 - bool [fixed_mass](#)
*Use a fixed **quark** mass and ignore the **quark** condensates.*
 - bool [color_neut](#)
If true, then ensure color neutrality.
 - double [GD](#)
Diquark coupling constant (default 3 G/4).
 - double [inte_epsabs](#)
The absolute precision for the integration (default 10^{-4}).
 - double [inte_epsrel](#)
The relative precision for the integration (default 10^{-4}).
 - size_t [inte_npoints](#)
The number of points used in the last integration (default 0).
-

Protected Member Functions

- virtual int [integrands](#) (double p, double res[])

The integrands.
- int [normal_eigenvalues](#) (double m, double lmom, double mu, double lam[2], double dldmu[2], double dldm[2])

Compute ungapped eigenvalues and the appropriate derivatives.
- int [gapped_eigenvalues](#) (double m1, double m2, double lmom, double mu1, double mu2, double tdelta, double lam[4], double dldmu1[4], double dldmu2[4], double dldm1[4], double dldm2[4], double dldg[4])

Treat the simply gapped quarks in all cases gracefully.

For the integration

- double [rescale_error](#) (double err, const double result_abs, const double result_asc)

The error scaling function for integ_err.
- int [integ_err](#) (double a, double b, const size_t nr, **ovector** &res, double &err2)

A new version of [gsl_inte_qng](#) to integrate several functions at the same time.

Protected Attributes

- double [temper](#)

Temperature.
- double [smu3](#)

3rd gluon chemical potential
- double [smu8](#)

8th gluon chemical potential

Numerical methods

- **quartic_real_coeff** * [quartic](#)

The routine to solve quartics.

For computing eigenvalues

- **omatrix_cx** [iprop](#)

Inverse propagator matrix.
- **omatrix_cx** [eivec](#)

The eigenvectors.
- **omatrix_cx** [dipdgapu](#)

The derivative of the inverse propagator wrt the ds gap.
- **omatrix_cx** [dipdgapd](#)

The derivative of the inverse propagator wrt the us gap.
- **omatrix_cx** [dipdgaps](#)

The derivative of the inverse propagator wrt the ud gap.
- **ovector** [eval](#)

The eigenvalues.
- [gsl_eigen_hermv_workspace](#) * **w**

Workspace for eigenvalue computation.

Private Member Functions

- **cfl_njl_eos** (const [cfl_njl_eos](#) &)
- [cfl_njl_eos](#) & **operator=** (const [cfl_njl_eos](#) &)

5.6.2 Member Function Documentation

5.6.2.1 `virtual int calc_eq_temp_p (quark & u, quark & d, quark & s, double & qq1, double & qq2, double & qq3, double & gap1, double & gap2, double & gap3, double mu3, double mu8, double & n3, double & n8, thermo & qb, const double temper)` [virtual]

Calculate the EOS.

Calculate the EOS from the **quark** condensates in `u.qq`, `d.qq` and `s.qq`. Return the mass gap equations in `qq1`, `qq2`, `qq3`, and the normal gap equations in `gap1`, `gap2`, and `gap3`.

Using `fromqq=false` as in [nambu_jl_eos](#) and [nambu_jl_eos](#) does not work here and will return an error. Also, the quarks must be set through `quark_eos::quark_set()` before use.

If all of the gaps are less than `gap_limit`, then the [nambu_jl_eos::calc_temp_p\(\)](#) is used, and `gap1`, `gap2`, and `gap3` are set to equal `u.del`, `d.del`, and `s.del`, respectively.

Todo

It surprises me that `n3` is not `-res[11]`. Is there a sign error in the color densities?

Reimplemented in [cfl6_eos](#).

5.6.2.2 `virtual int eigenvalues (double lmom, double mu3, double mu8, double egv[36], double dedmuu[36], double dedmud[36], double dedmus[36], double dedmu[36], double dedmd[36], double dedms[36], double dedu[36], double dedd[36], double deds[36], double dedmu3[36], double dedmu8[36])` [virtual]

Calculate the energy eigenvalues as a function of the momentum.

Given the momentum `mom`, and the chemical potentials associated with the third and eighth gluons (`mu3` and `mu8`), the energy eigenvalues are computed in `egv[0] ... egv[35]`.

5.6.2.3 `int gapped_eigenvalues (double m1, double m2, double lmom, double mu1, double mu2, double tdelta, double lam[4], double dldmu1[4], double dldmu2[4], double dldm1[4], double dldm2[4], double dldg[4])` [protected]

Treat the simply gapped quarks in all cases gracefully.

This function uses the quarks `q1` and `q2` to construct the eigenvalues of the inverse propagator, properly handling the either zero or finite **quark** mass and either zero or finite **quark** gaps. In the case of finite **quark** mass and finite **quark** gaps, the quartic solver is used.

The chemical potentials are separated so we can add the color chemical potentials to the **quark** chemical potentials if necessary.

This function is used by [eigenvalues\(\)](#). It does not work for the "ur-dg-sb" set of quarks which are paired in a non-trivial way.

Todo

Only the "ms" **part** of the quarks is referenced, so we should rewrite to use only double's as function arguments, and avoid passing pointers to **quark** objects.

5.6.2.4 `virtual int integrands (double p, double res[])` [protected, virtual]

The integrands.

- `res[0]` is the thermodynamic potential, Ω
- `res[1]` is $d - \Omega/dT$
- `res[2]` is $d\Omega/d\mu_u$

- res[3] is $d\Omega/d\mu_d$
- res[4] is $d\Omega/d\mu_s$
- res[5] is $d\Omega/dm_u$
- res[6] is $d\Omega/dm_d$
- res[7] is $d\Omega/dm_s$
- res[8] is $d\Omega/d\Delta_{ds}$
- res[9] is $d\Omega/d\Delta_{us}$
- res[10] is $d\Omega/d\Delta_{ud}$
- res[11] is $d\Omega/d\mu_3$
- res[12] is $d\Omega/d\mu_8$

Reimplemented in [cfl6_eos](#).

5.6.2.5 virtual int set_parameters (double *lambda* = 0.0, double *fourferm* = 0.0, double *sixferm* = 0.0, double *fourgap* = 0.0) [virtual]

Set the parameters and the bag constant 'B0'.

This function allows the user to specify the momentum cutoff, *lambda*, the four-fermion coupling *fourferm*, the six-fermion coupling from the 't Hooft interaction *sixferm*, and the color-superconducting coupling, *fourgap*. If 0.0 is given for any of the values, then the default is used ($\Lambda = 602.3/(\hbar c)$, $G = 1.835/\Lambda^2$, $K = 12.36/\Lambda^5$).

If the four-fermion coupling that produces a gap is not specified, it is automatically set to 3/4 G, which is the value obtained from the Fierz transformation.

The value of the shift in the bag constant [nambuyl_eos::B0](#) is automatically calculated to ensure that the vacuum has zero energy density and zero pressure. The functions [set_quarks\(\)](#) and [set_thermo\(\)](#) must be used before hand to specify the **quark** and **thermo** objects.

5.6.3 Field Documentation

5.6.3.1 cern_quartic_real_coeff def_quartic

The default quartic routine.

Slightly better accuracy (with slower execution times) can be achieved using [gsl_poly_real_coeff](#) which polishes the roots of the quartics. For example

```
cfl_njl_eos cfl;
gsl_poly_real_coeff gp;
cfl.set_quartic(gp);
```

Definition at line 318 of file [cfl_njl_eos.h](#).

5.6.3.2 double gap_limit

Smallest allowable gap (default 0.0).

If any of the gaps are below this value, then it is assumed that they are zero and the equation of state is simplified accordingly. If all of the gaps are less than *gap_limit*, then the results from [nambuyl_eos](#) are used in [calc_eq_temp_p\(\)](#), [calc_temp_p\(\)](#) and [thd_potential\(\)](#).

Definition at line 342 of file [cfl_njl_eos.h](#).

5.6.3.3 double GD

Diquark coupling constant (default 3 G/4).

The default value is the one derived from a Fierz transformation. ([Buballa04](#))

Definition at line 368 of file cfl_njl_eos.h.

5.6.3.4 double inte_epsabs

The absolute precision for the integration (default 10^{-4}).

This is analogous to `gsl_inte::epsabs`

Definition at line 376 of file cfl_njl_eos.h.

5.6.3.5 double inte_epsrel

The relative precision for the integration (default 10^{-4}).

This is analogous to `gsl_inte::epsrel`

Definition at line 384 of file cfl_njl_eos.h.

5.6.3.6 size_t inte_npoints

The number of points used in the last integration (default 0).

This returns 21, 43, or 87 depending on the number of function evaluations needed to obtain the desired precision. If it the routine failes to obtain the desired precision, then this variable is set to 88.

Definition at line 395 of file cfl_njl_eos.h.

5.6.3.7 bool zerot

If this is true, then finite temperature corrections are ignored (default false).

This implements some simplifications in the momentum integration that are not possible at finite temperature.

Definition at line 351 of file cfl_njl_eos.h.

The documentation for this class was generated from the following file:

- cfl_njl_eos.h

5.7 cold_nstar Class Reference

Naive static cold neutron star.

```
#include <cold_nstar.h>
```

5.7.1 Detailed Description

Naive static cold neutron star.

This uses `hadronic_eos::calc_e()` to compute the equation of state of zero-temperature beta-equilibrated neutron star matter and `tov_solve::mvsr()` to compute the mass versus radius curve.

The electron and muon are given masses `o2scl_fm_const::mass_electron` and `o2scl_fm_const::mass_muon`, respectively.

The energy density and pressure are both calculated in units fm^{-4} and the baryon density in fm^{-3}

The condition for Urca is the area of the triangle formed by the neutron, proton, and electron Fermi momenta.

Using the definition of the semi-perimeter,

$$s \equiv (k_{F,n} + k_{F,p} + k_{F,e}) / 2$$

Heron's formula gives the triangle area as

$$a = \sqrt{s(s - k_{F,n})(s - k_{F,p})(s - k_{F,e})}$$

The column in the **eos table** labeled `urca` is a^2 . If this quantity is positive, then direct Urca is allowed.

The squared speed of sound (in units of c) is calculated by

$$c_s^2 = \frac{dP}{d\varepsilon}$$

and this is placed in the column labeled `cs2`.

The adiabatic index is calculated by

$$\Gamma = \frac{d \ln P}{d \ln \varepsilon}$$

Note that Γ must be greater than $4/3$ at the center of the neutron star for stability. (This is a necessary, but not sufficient condition.)

Note that if the speed of sound is non-monotonic, then `calc_eos()` will only record the lowest density for which the EOS becomes acausal.

There is an example for the usage of this class given in `examples/ex_cold_nstar.cpp`.

Idea for future

Ensure that the adiabatic index of the central density is greater than $4/3$

Idea for future

Warn if the EOS becomes pure neutron matter.

Definition at line 99 of file `cold_nstar.h`.

Output

- double `min_bad`
The smallest baryon density where the pressure decreases.
- double `allow_urca`
The smallest density where Urca becomes allowed.
- double `deny_urca`
The smallest density where Urca becomes disallowed.
- double `acausal`
The density at which the EOS becomes acausal.
- double `acausal_pr`
The pressure at which the EOS becomes acausal.
- double `acausal_ed`
The energy density at which the EOS becomes acausal.
- double `solver_tol`
Solver tolerance (default 10^{-4}).
- **table** & `get_eos_results()`
*Get the **eos table** (after having called `calc_eos()`).*
- **table** & `get_tov_results()`
Get the results from the TOV (after having called `calc_nstar()`).

The thermodynamic information

- **thermo hb**
- **thermo h**
- **thermo l**

Basic operation

- int **set_eos** (**hadronic_eos** &he)
Set the equation of state.
- int **calc_eos** (double np_0=0.0)
Calculate the given equation of state.
- double **calc_urca** (double np_0=0.0)
Compute the density at which the direct Urca process is allowed.
- int **calc_nstar** ()
Calculate the M vs. R curve.

Public Member Functions

- int **set_n_and_p** (**fermion** &n, **fermion** &p)
Set the neutron and proton.
- int **set_tov** (**tov_solve** &ts)
Specify the object for solving the TOV equations.
- int **set_root** (**root**< int, **funct**< int > > &rf)
Set the equation solver for the EOS.

Data Fields

- double **nb_start**
The starting baryon density (default 0.05).
- double **nb_end**
The final baryon density (default 2.0).
- double **dnb**
The baryon density stepsize (default 0.01).
- bool **include_muons**
If true, include muons (default false).
- **eff_fermion** **def_n**
The default neutron.
- **eff_fermion** **def_p**
The default proton.
- **tov_solve** **def_tov**
The default TOV equation solver.
- **cern_mroot_root**< int, **funct**< int > > **def_root**
The default equation solver for the EOS.
- **tov_interp_eos** **def_tov_eos**
Default EOS object for the TOV solver.

Protected Member Functions

- int **solve_fun** (double x, double &y, int &vp)
Solve to ensure zero charge in β -equilibrium.

Protected Attributes

- **bool** `eos_set`
True if equation of state has been set.
- **fermion** `e`
The electron.
- **fermion** `mu`
The muon.
- **hadronic_eos** * `hep`
A pointer to the equation of state.
- **fermion** * `np`
A pointer to the neutron.
- **fermion** * `pp`
A pointer to the proton.
- **tov_solve** * `tp`
A pointer to the TOV object.
- **root**< int, **funct**< int > > * `rp`
A pointer to the solver.
- **table** `eost`
Storage for the EOS table.
- **double** `barn`
The baryon density.

5.7.2 Member Function Documentation

5.7.2.1 **double** `calc_urca` (**double** `np_0` = 0.0)

Compute the density at which the direct Urca process is allowed.

This is faster than using `calc_eos()` since it does nothing other than computes the critical density. It does not store the equation of state.

5.7.2.2 **int** `set_eos` (**hadronic_eos** & `he`) [inline]

Set the equation of state.

This should be set before calling `calc_eos()`.

Definition at line 111 of file `cold_nstar.h`.

5.7.2.3 **int** `set_n_and_p` (**fermion** & `n`, **fermion** & `p`) [inline]

Set the neutron and proton.

The default objects are of type **fermion**, with mass `o2scl_fm_const::mass_neutron` and `o2scl_fm_const::mass_proton`. These defaults will give incorrect results for non-relativistic equations of state.

Definition at line 233 of file `cold_nstar.h`.

5.7.2.4 **int** `set_tov` (**tov_solve** & `ts`) [inline]

Specify the object for solving the TOV equations.

The default uses the low-density equation of state with `tov::verbose=0`. In `calc_nstar()`, the units are set by calling `tov_solve::set-units()`.

Definition at line 252 of file `cold_nstar.h`.

5.7.3 Field Documentation

5.7.3.1 double acausal

The density at which the EOS becomes acausal.

If this is zero, then the EOS is causal at all baryon densities in the specified range

Definition at line 186 of file cold_nstar.h.

5.7.3.2 double acausal_ed

The energy density at which the EOS becomes acausal.

If this is zero, then the EOS is causal at all baryon densities in the specified range

Definition at line 202 of file cold_nstar.h.

5.7.3.3 double acausal_pr

The pressure at which the EOS becomes acausal.

If this is zero, then the EOS is causal at all baryon densities in the specified range

Definition at line 194 of file cold_nstar.h.

5.7.3.4 double allow_urca

The smallest density where Urca becomes allowed.

If this is zero after calling `calc_eos()`, then direct Urca is never allowed.

Definition at line 169 of file cold_nstar.h.

5.7.3.5 double deny_urca

The smallest density where Urca becomes disallowed.

If this is zero after calling `calc_eos()`, then direct Urca is not disallowed at a higher density than it becomes allowed.

Definition at line 178 of file cold_nstar.h.

5.7.3.6 double min_bad

The smallest baryon density where the pressure decreases.

If this is zero after calling `calc_eos()`, then the pressure does not decrease in the specified range of baryon density

Definition at line 161 of file cold_nstar.h.

The documentation for this class was generated from the following file:

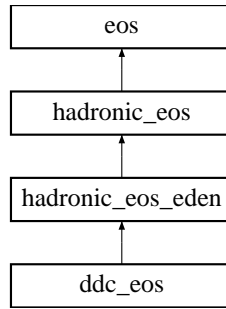
- cold_nstar.h

5.8 ddc_eos Class Reference

Relativistic mean field EOS with density dependent couplings.

```
#include <ddc_eos.h>
```

Inheritance diagram for ddc_eos::



5.8.1 Detailed Description

Relativistic mean field EOS with density dependent couplings.

Based on [Typel99](#).

Idea for future

Implement the finite temperature EOS properly.

Definition at line 48 of file ddc_eos.h.

Public Member Functions

- virtual int [calc_e](#) (**fermion** &n, **fermion** &p, **thermo** &th)
Equation of state as a function of the densities.
- virtual int [calc_eq_e](#) (**fermion** &neu, **fermion** &p, double sig, double ome, double rho, double &f1, double &f2, double &f3, **thermo** &th)
Equation of state and meson field equations as a function of the density.
- virtual const char * [type](#) ()
Return string denoting type ("ddc_eos").

Data Fields

- double **rho0**

Masses

- double [mnuc](#)
nucleon mass
- double [ms](#)
 ϕ mass (in fm⁻¹)
- double [mw](#)
 A_ω mass (in fm⁻¹)
- double [mr](#)
 A_ρ mass (in fm⁻¹)

Parameters for couplings

- double [Gs](#)
The coupling $\Gamma_\sigma(\rho_{\text{sat}})$.
- double [Gw](#)
The coupling $\Gamma_\omega(\rho_{\text{sat}})$.
- double [Gr](#)

The coupling $\Gamma_\rho(\rho_{\text{sat}})$.

- double **as**
 a_σ
- double **aw**
 a_ω
- double **ar**
 a_ρ
- double **bs**
 b_σ
- double **bw**
 b_ω
- double **cs**
 c_σ
- double **cw**
 c_ω
- double **ds**
 d_σ
- double **dw**
 d_ω

5.8.2 Member Function Documentation

5.8.2.1 virtual int calc_eq_e (fermion & neu, fermion & p, double sig, double ome, double rho, double &f1, double &f2, double &f3, thermo &th) [virtual]

Equation of state and meson field equations as a function of the density.

This calculates the pressure and energy density as a function of $\mu_n, \mu_p, \phi, A_\omega, A_\rho$. When the field equations have been solved, f1, f2, and f3 are all zero.

Todo

Is the thermodynamic identity is satisfied even when the field equations are not solved? Check this.

The documentation for this class was generated from the following file:

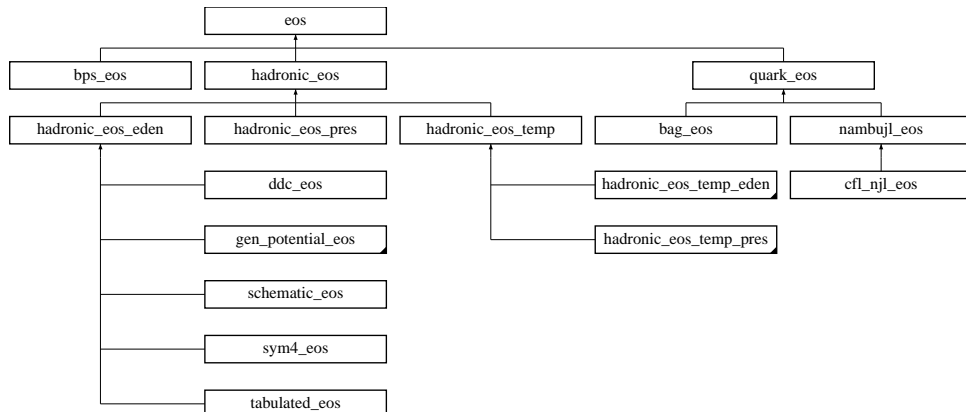
- ddc_eos.h

5.9 eos Class Reference

Equation of state base.

```
#include <eos.h>
```

Inheritance diagram for eos::



5.9.1 Detailed Description

Equation of state base.

A base class for the computation of an equation of state

Definition at line 41 of file eos.h.

Public Member Functions

- virtual int [set_thermo](#) (**thermo** &th)
*Set class **thermo** object.*
- virtual int [get_thermo](#) (**thermo** *&th)
*Get class **thermo** object.*
- virtual const char * [type](#) ()
Return string denoting type ("eos").

Data Fields

- **thermo** [def_thermo](#)
*The default **thermo** object.*

Protected Attributes

- **thermo** * [eos_thermo](#)
*A pointer to the **thermo** object.*

The documentation for this class was generated from the following file:

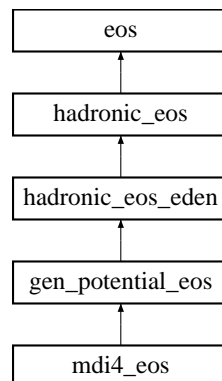
- eos.h

5.10 gen_potential_eos Class Reference

Generalized potential model equation of state.

```
#include <gen_potential_eos.h>
```

Inheritance diagram for gen_potential_eos::



5.10.1 Detailed Description

Generalized potential model equation of state.

The single particle energy is defined by the functional derivative of the energy density with respect to the distribution function

$$e_\tau = \frac{\delta \varepsilon}{\delta f_\tau}$$

The effective mass is defined by

$$\frac{m^*}{m} = \left(\frac{m}{k} \frac{de_\tau}{dk} \right)_{k=k_F}^{-1}$$

In all of the models, the kinetic energy density is $\tau_n + \tau_p$ where

$$\tau_i = \frac{2}{(2\pi)^3} \int d^3k \left(\frac{k^2}{2m} \right) f_i(k, T)$$

and the number density is

$$\rho_i = \frac{2}{(2\pi)^3} \int d^3k f_i(k, T)$$

When `form == mdi_form` or `gbd_form`, the potential energy density is given by [Das03](#) :

$$V(\rho, \delta) = \frac{Au}{\rho_0} \rho_n \rho_p + \frac{A_l}{2\rho_0} (\rho_n^2 + \rho_p^2) + \frac{B}{\sigma + 1} \frac{\rho^{\sigma+1}}{\rho_0^\sigma} (1 - x\delta^2) + V_{mom}(\rho, \delta)$$

where $\delta = 1 - 2\rho_p/(\rho_n + \rho_p)$. If `form == mdi_form`, then

$$V_{mom}(\rho, \delta) = \frac{1}{\rho_0} \sum_{\tau, \tau'} C_{\tau, \tau'} \int \int d^3k d^3k' \frac{f_\tau(\vec{k}) f_{\tau'}(\vec{k}')}{1 - (\vec{k} - \vec{k}')^2 / \Lambda^2}$$

where $C_{1/2, 1/2} = C_{-1/2, -1/2} = C_\ell$ and $C_{1/2, -1/2} = C_{-1/2, 1/2} = C_u$. Otherwise if `form == gbd_form`, then

$$V_{mom}(\rho, \delta) = \frac{1}{\rho_0} [C_\ell (\rho_n g_n + \rho_p g_p) + C_u (\rho_n g_p + \rho_p g_n)]$$

where

$$g_i = \frac{\Lambda^2}{\pi^2} [k_{F,i} - \Lambda \tan^{-1}(k_{F,i}/\Lambda)]$$

Otherwise, if `form == bgbd_form`, `bpalb_form` or `sl_form`, then the potential energy density is given by [Bombaci01](#) :

$$V(\rho, \delta) = V_A + V_B + V_C$$

$$V_A = \frac{2A}{3\rho_0} \left[\left(1 + \frac{x_0}{2} \right) \rho^2 - \left(\frac{1}{2} + x_0 \right) (\rho_n^2 + \rho_p^2) \right]$$

$$V_B = \frac{4B}{3\rho_0^\sigma} \frac{T}{1 + 4B'T/(3\rho_0^{\sigma-1}\rho^2)}$$

where

$$T = \rho^{\sigma-1} \left[\left(1 + \frac{x_3}{2} \right) \rho^2 - \left(\frac{1}{2} + x_3 \right) (\rho_n^2 + \rho_p^2) \right]$$

The term V_C is:

$$V_C = \sum_{i=1}^{i_{\max}} \frac{4}{5} (C_i + 2z_i) \rho (g_{n,i} + g_{p,i}) + \frac{2}{5} (C_i - 8z_i) (\rho_n g_{n,i} + \rho_p g_{p,i})$$

where

$$g_{\tau,i} = \frac{2}{(2\pi)^3} \int d^3k f_\tau(k, T) g_i(k)$$

For `form == bgbd_form` or `form == bpalb_form`, the form factor is given by

$$g_i(k) = \left(1 + \frac{k^2}{\Lambda_i^2}\right)^{-1}$$

while for `form == sl_form`, the form factor is given by

$$g_i(k) = 1 - \frac{k^2}{\Lambda_i^2}$$

where Λ_1 is specified in the parameter `Lambda` when necessary.

See Mathematica notebook at

```
doc/o2scl/extras/gen_potential_eos.nb
doc/o2scl/extras/gen_potential_eos.ps
```

Bug

The BGBD EOS doesn't work and the effective mass for the GBD EOS doesn't work

Idea for future

Calculate the chemical potentials analytically

Definition at line 172 of file `gen_potential_eos.h`.

The mode for the energy() function [protected]

- int **mode**
- static const int **nmode** = 1
- static const int **pmode** = 2
- static const int **normal** = 0

Public Member Functions

- virtual int **calc_e** (**fermion** &ne, **fermion** &pr, **thermo** <)
Equation of state as a function of density.
- int **set_mu_deriv** (**deriv**< int, **funct**< int > > &de)
Set the derivative object to calculate the chemical potentials.
- virtual const char * **type** ()
Return string denoting type ("gen_potential_eos").

Data Fields

- int **form**
Form of potential.
- **gsl_deriv**< int, **funct**< int > > **def_mu_deriv**
The default derivative object for calculating chemical potentials.
- **nonrel_fermion** **def_nr_neutron**
Default nonrelativistic neutron.
- **nonrel_fermion** **def_nr_proton**
Default nonrelativistic proton.

The parameters for the various interactions

- double **x**
- double **Au**
- double **Al**
- double **rho0**
- double **B**
- double **sigma**
- double **C1**
- double **Cu**
- double **Lambda**
- double **A**
- double **x0**
- double **x3**
- double **Bp**
- double **C1**
- double **z1**
- double **Lambda2**
- double **C2**
- double **z2**
- double **bpal_esym**
- int **sym_index**

Static Public Attributes

- static const int **mdi_form** = 1
The "momentum-dependent-interaction" form.
- static const int **bgbd_form** = 2
The modified GBD form.
- static const int **bpalb_form** = 3
The form from [Prakash88](#) as formulated in [Bombaci01](#).
- static const int **sl_form** = 4
The "SL" form. See [Bombaci01](#).
- static const int **gbd_form** = 5
The Gale, Bertsch, Das Gupta from [Gale87](#).
- static const int **bpal_form** = 6
The form from [Prakash88](#).

Protected Member Functions

- double **mom_integral** (double pft, double pftp)
Compute the momentum integral for [mdi_form](#).
- double **energy** (double x)
Compute the energy.

Protected Attributes

- bool **mu_deriv_set**
True if the derivative object has been set.
- **deriv**< int, **funct**< int > > * **mu_deriv_ptr**
The derivative object.

The documentation for this class was generated from the following file:

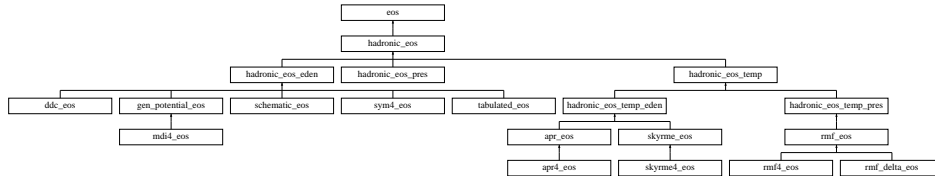
- [gen_potential_eos.h](#)

5.11 hadronic_eos Class Reference

Hadronic equation of state [abstract base].

```
#include <hadronic_eos.h>
```

Inheritance diagram for hadronic_eos::



5.11.1 Detailed Description

Hadronic equation of state [abstract base].

In the method documentation below, n is baryon number density, ϵ is energy density, and P is pressure.

See more about Syprime in the Mathematica notebook at

```
doc/o2scl/extras/hadronic_eos.nb
doc/o2scl/extras/hadronic_eos.ps
```

Idea for future

Could write a function to compute the "symmetry free energy" or the "symmetry entropy"

Definition at line 66 of file hadronic_eos.h.

Public Member Functions

- `int gradient_qij (fermion &n, fermion &p, thermo &th, double &qnn, double &qnp, double &qpp, double &dqnnndnn, double &dqnnndnp, double &dqnpdnn, double &dqnpdnp, double &dqppdnn, double &dqppdnp)`
Calculate coefficients for gradient part of Hamiltonian.
- `virtual const char * type ()`
Return string denoting type ("hadronic_eos").

Equation of state

- `virtual int calc_p (fermion &n, fermion &p, thermo &th)=0`
Equation of state as a function of the chemical potentials.
- `virtual int calc_e (fermion &n, fermion &p, thermo &th)=0`
Equation of state as a function of density.

Physical properties

- `virtual double fcomp (const double nb)`
Calculate compressibility of nuclear matter using [calc_e\(\)](#).
- `virtual double feoa (const double nb, const double pf=0.5)`
Calculate binding energy using [calc_e\(\)](#).
- `virtual double fesym (const double nb, const double pf=0.5)`
Calculate symmetry energy of matter using [calc_e\(\)](#).
- `virtual double fesym_slope (const double nb, bool alt_sym=false)`

The symmetry energy slope parameter.

- virtual double [fesym_diff](#) (const double nb)
Calculate symmetry energy of matter as energy of neutron matter minus the energy of nuclear matter.
- virtual double [fsprime](#) (const double nb, const double pf=0.5)
Calculate S' in matter using [calc_e\(\)](#).
- virtual double [fkprime](#) (const double nb)
Calculate skewness of nuclear matter using [calc_e\(\)](#).
- virtual double [fmsom](#) (const double nb, const double pf=0.5)
Calculate reduced neutron effective mass using [calc_e\(\)](#).
- virtual double [fn0](#) (const double protfrac, double &leoa)
Calculate saturation density using [calc_e\(\)](#).
- virtual int [saturation](#) ()
Calculates all of the properties at the saturation density.

Functions for calculating physical properties

- double [calc_pressure](#) (double nb, int &pa)
Calculate pressure of nuclear matter as a function of baryon density.
- double [calc_press_on2](#) (double nb, int &pa)
Calculate pressure / baryon density squared in nuclear matter as a function of baryon density.
- double [calc_edensity](#) (double delta, int &pa)
Calculate energy density as a function of 'delta'.
- double [calc_esym](#) (double nb, int &pa)
Calculate symmetry energy as a function of 'delta'.
- double [calc_esym](#) (double nb, bool &alt)
Return the symmetry energy at density nb.
- int [saturation_matter_e](#) (double x, double &y, int &pa)
Solve for zero pressure as a function of baryon density.

Other functions

- int [nuc_matter_p](#) (size_t nv, const [ovector_base](#) &x, [ovector_base](#) &y, double *&pa)
Nucleonic matter from [calc_p\(\)](#).
- int [nuc_matter_e](#) (size_t nv, const [ovector_base](#) &x, [ovector_base](#) &y, double *&pa)
Nucleonic matter from [calc_e\(\)](#).

Set auxilliary objects

- virtual int [set_mroot](#) ([mroot](#)< double *, [mm_funct](#)< double * > > &mr)
Set class [mroot](#) object for use in calculating chemical potentials from densities.
- virtual int [set_sat_root](#) ([root](#)< int, [funct](#)< int > > &mr)
Set class [mroot](#) object for use calculating saturation density.
- virtual int [set_sat_deriv](#) ([deriv](#)< int, [funct](#)< int > > &de)
Set [deriv](#) object to use to find saturation properties.
- virtual int [set_sat_deriv2](#) ([deriv](#)< bool, [funct](#)< bool > > &de)
Set [deriv](#) object to use to find saturation properties.
- virtual int [set_n_and_p](#) ([fermion](#) &n, [fermion](#) &p)
Set neutron and proton.

Data Fields

- double [eoa](#)
Binding energy.
- double [comp](#)
Compressibility.
- double [esym](#)
Symmetry energy.
- double [n0](#)
Saturation density.
- double [msom](#)
Effective mass.

- double [kprime](#)
Skewness.
- double [sprime](#)
Symmetry energy derivative.
- fermion [def_neutron](#)
The default neutron.
- fermion [def_proton](#)
The default proton.

Default solvers and derivative classes

- [gsl_deriv](#)< int, [funct](#)< int > > [def_deriv](#)
The default object for derivatives.
- [gsl_deriv](#)< bool, [funct](#)< bool > > [def_deriv2](#)
The second default object for derivatives.
- [gsl_mroot_hybrids](#)< double *, [mm_funct](#)< double * > > [def_mroot](#)
The default solver.
- [cern_mroot_root](#)< int, [funct](#)< int > > [def_sat_root](#)
The default solver for calculating the saturation density.

Protected Member Functions

- double [t1_fun](#) (double barn, int &vp)
Compute t1 for [gradient_qij\(\)](#).
- double [t2_fun](#) (double barn, int &vp)
Compute t2 for [gradient_qij\(\)](#).

Protected Attributes

- [mroot](#)< double *, [mm_funct](#)< double * > > * [eos_mroot](#)
The EOS solver.
- [root](#)< int, [funct](#)< int > > * [sat_root](#)
The solver to compute saturation properties.
- [deriv](#)< int, [funct](#)< int > > * [sat_deriv](#)
The derivative object for saturation properties.
- [deriv](#)< bool, [funct](#)< bool > > * [sat_deriv2](#)
The second derivative object for saturation properties.
- fermion * [neutron](#)
The neutron object.
- fermion * [proton](#)
The proton object.
- double [proton_frac](#)
Temporary proton fraction.
- double [n_baryon](#)
Temporary baryon number.

5.11.2 Member Function Documentation

5.11.2.1 double calc_edensity (double *delta*, int & *pa*)

Calculate energy density as a function of 'delta'.

Used by [fesym\(\)](#), *pa* is unused.

5.11.2.2 double calc_esym (double nb, bool & alt)

Return the symmetry energy at density nb.

Used by [fesym_slope\(\)](#).

5.11.2.3 double calc_esym (double nb, int & pa)

Calculate symmetry energy as a function of 'delta'.

Used by [fsprime\(\)](#), pa is unused.

5.11.2.4 double calc_press_on2 (double nb, int & pa)

Calculate pressure / baryon density squared in nuclear matter as a function of baryon density.

Used by [fkprime\(\)](#), pa is unused.

5.11.2.5 double calc_pressure (double nb, int & pa)

Calculate pressure of nuclear matter as a function of baryon density.

Used by [fcomp\(\)](#), pa is unused.

5.11.2.6 virtual double fcomp (const double nb) [virtual]

Calculate compressibility of nuclear matter using [calc_e\(\)](#).

The compression modulus is defined here by: $\chi = -1/V(dV/dP) = 1/n(dP/dn)^{-1}$ It is customary to use the incompressibility modulus $K = 9/(n\chi)$. This is the value denoted `comp` in the code and can be written: $K = 9nd^2\epsilon/(dn^2) = 9dP/(dn)$. It is often referred to as the "compressibility" and is about 220 MeV at saturation density. (Taken from Chabanat, et. al. NPA 627 (1997) 710.) Note that this differs from $K_2 = 9n^2 d^2(\epsilon/n)/(dn^2)$ by $18P/n$ at any density except the saturation density.

Reimplemented in [apr_eos](#), and [skyrme_eos](#).

5.11.2.7 virtual double feoa (const double nb, const double pf = 0.5) [virtual]

Calculate binding energy using [calc_e\(\)](#).

`eoA` = (energy density/baryon number density-nucleon mass) at $n = n_0$. $E_b \approx -16/(\hbar c)$

5.11.2.8 virtual double fesym (const double nb, const double pf = 0.5) [virtual]

Calculate symmetry energy of matter using [calc_e\(\)](#).

`esym` =

$$\left(\frac{1}{2n} \frac{d^2\epsilon}{d\delta^2} \right)_{n=n_B, \delta=\delta_0}$$

where $\delta = 1 - 2x$, $\delta_0 = 1 - 2x$ and x is the proton fraction (for $x=0.5$ at saturation density, $esym \approx 32/\hbar c$)

Reimplemented in [skyrme_eos](#).

5.11.2.9 virtual double fesym_diff (const double nb) [virtual]

Calculate symmetry energy of matter as energy of neutron matter minus the energy of nuclear matter.

This function returns the energy per baryon of neutron matter minus the energy per baryon of nuclear matter. This will deviate significantly from the results from [fesym\(\)](#) only if the dependence of the symmetry energy on δ is not quadratic.

Reimplemented in [apr_eos](#).

5.11.2.10 virtual double fesym_slope (const double nb, bool alt_sym = false) [virtual]

The symmetry energy slope parameter.

This returns the value of the "slope parameter" of the symmetry energy

$$L = 3n_B \left(\frac{\partial E_{sym}}{\partial n_B} \right)$$

in inverse Fermis.

where n_B is the baryon density. This ranges between about zero and 200 MeV for many EOSs. If `alt_sym` is false (the default), then `fesym()` is used to compute the symmetry energy, otherwise `fesym_diff()` is used.

5.11.2.11 virtual double fkprime (const double nb) [virtual]

Calculate skewness of nuclear matter using `calc_e()`.

The skewness is defined to be $27n^3 d^3(\epsilon/n)/(dn^3) = 27n^3 d^2(P/n^2)/(dn^2)$

and is denoted 'kprime'. This definition seems to be ambiguous for densities other than the saturation density and is not quite analogous to the compressibility.

Reimplemented in `skyrme_eos`.

5.11.2.12 virtual double fmsom (const double nb, const double pf = 0.5) [virtual]

Calculate reduced neutron effective mass using `calc_e()`.

Neutron effective mass (n.ms) divided by vacuum mass (n.m) in nuclear matter at saturation density. Note that this simply uses the value of n.ms from `calc_e()`, so that this effective mass could be either the Landau or Dirac mass depending on the context. Note that this may not be equal to the reduced proton effective mass.

5.11.2.13 virtual double fn0 (const double protfrac, double & leoa) [virtual]

Calculate saturation density using `calc_e()`.

This function finds the density for which the pressure vanishes in matter with $n_n = n_p$.

n_0 = baryon number density at which $P = 0$, $n_0 \approx 0.16$

5.11.2.14 virtual double fsprime (const double nb, const double pf = 0.5) [virtual]

Calculate S' in matter using `calc_e()`.

`sprime =`

$$\left[n \frac{d}{dn} \left(\frac{1}{2n} \frac{d^2 \epsilon}{d\delta^2} \right) \right]_{n=n_B, \delta=\delta_0}$$

where $\delta = 1 - 2x$, $\delta_0 = 1 - 2(pf)$ and x is the proton fraction

5.11.2.15 int gradient_qij (fermion & n, fermion & p, thermo & th, double & qnn, double & qnp, double & qpp, double & dqnnndnn, double & dqnnndnp, double & dqnpdnn, double & dqnpdnp, double & dqppdnn, double & dqppdnp)

Calculate coefficients for gradient part of Hamiltonian.

Note:

This is still somewhat experimental.

We want the gradient part of the Hamiltonian in the form

$$\mathcal{H}_{\text{grad}} = \frac{1}{2} \sum_{i=n,p} \sum_{j=n,p} Q_{ij} \vec{\nabla} n_i \cdot \vec{\nabla} n_j$$

The expression for the gradient terms from [Pethick95](#) is

$$\begin{aligned} \mathcal{H}_{\text{grad}} = & -\frac{1}{4} (2P_1 + P_{1;f} - P_{2;f}) \\ & + \frac{1}{2} (Q_1 + Q_2) (n_n \nabla^2 n_n + n_p \nabla^2 n_p) \\ & + \frac{1}{4} (Q_1 - Q_2) [(\nabla n_n)^2 + (\nabla n_p)^2] \\ & + \frac{1}{2} \frac{dQ_2}{dn} (n_n \nabla n_n + n_p \nabla n_p) \cdot \nabla n \end{aligned}$$

This can be rewritten

$$\begin{aligned} \mathcal{H}_{\text{grad}} = & \frac{1}{2} (\nabla n)^2 \left[\frac{3}{2} P_1 + n \frac{dP_1}{dn} \right] \\ & - \frac{3}{4} [(\nabla n_n)^2 + (\nabla n_p)^2] \\ & - \frac{1}{2} \nabla n \cdot \nabla n \frac{dQ_1}{dn} \\ & - \frac{1}{4} (\nabla n)^2 P_2 - \frac{1}{4} [(\nabla n_n)^2 + (\nabla n_p)^2] Q_2 \end{aligned}$$

or

$$\begin{aligned} \mathcal{H}_{\text{grad}} = & \frac{1}{4} (\nabla n)^2 \left[3P_1 + 2n \frac{dP_1}{dn} - P_2 \right] \\ & - \frac{1}{4} (3Q_1 + Q_2) [(\nabla n_n)^2 + (\nabla n_p)^2] \\ & - \frac{1}{2} \frac{dQ_1}{dn} [n_n \nabla n_n + n_p \nabla n_p] \cdot \nabla n \end{aligned}$$

or

$$\begin{aligned} \mathcal{H}_{\text{grad}} = & \frac{1}{4} (\nabla n)^2 \left[3P_1 + 2n \frac{dP_1}{dn} - P_2 \right] \\ & - \frac{1}{4} (3Q_1 + Q_2) [(\nabla n_n)^2 + (\nabla n_p)^2] \\ & - \frac{1}{2} \frac{dQ_1}{dn} \left[n_n (\nabla n_n)^2 + n_p (\nabla n_p)^2 + n \nabla n_n \cdot \nabla n_p \right] \end{aligned}$$

Generally, for Skyrme-like interactions

$$\begin{aligned} P_i &= \frac{1}{4} t_i \left(1 + \frac{1}{2} x_i \right) \\ Q_i &= \frac{1}{4} t_i \left(\frac{1}{2} + x_i \right) . \end{aligned}$$

for $i = 1, 2$.

This function uses the assumption $x_1 = x_2 = 0$ to calculate t_1 and t_2 from the neutron and proton effective masses assuming the Skyrme form. The values of Q_{ij} and their derivatives are then computed.

The functions `set_n_and_p()` and `set_thermo()` will be called by `gradient_qij()`, to facilitate the use of the `n`, `p`, and `th` parameters.

5.11.2.16 int saturation_matter_e (double x, double & y, int & pa)

Solve for zero pressure as a function of baryon density.

Used by [fn0\(\)](#).

5.11.2.17 virtual int set_sat_deriv2 (deriv< bool, funct< bool > > & de) [virtual]

Set **deriv** object to use to find saturation properties.

Todo

Document the distinction between this and [set_sat_deriv\(\)](#).

5.11.3 Field Documentation**5.11.3.1 gsl_deriv<int,funct<int> > def_deriv**

The default object for derivatives.

The value of **gsl_deriv::h** is set to 10^{-3} in the [hadronic_eos](#) constructor.

Definition at line 414 of file [hadronic_eos.h](#).

5.11.3.2 gsl_deriv<bool,funct<bool> > def_deriv2

The second default object for derivatives.

The value of **gsl_deriv::h** is set to 10^{-3} in the [hadronic_eos](#) constructor.

Definition at line 422 of file [hadronic_eos.h](#).

5.11.3.3 gsl_mroot_hybrids<double *,mm_funct<double *> > def_mroot

The default solver.

Used by [calc_e\(\)](#) to solve [nuc_matter_p\(\)](#) (2 variables) and by [calc_p\(\)](#) to solve [nuc_matter_e\(\)](#) (2 variables).

Definition at line 430 of file [hadronic_eos.h](#).

5.11.3.4 cern_mroot_root<int,funct<int> > def_sat_root

The default solver for calculating the saturation density.

Used by [fn0\(\)](#) (which is called by [saturation\(\)](#)) to solve [saturation_matter_e\(\)](#) (1 variable).

Definition at line 438 of file [hadronic_eos.h](#).

The documentation for this class was generated from the following file:

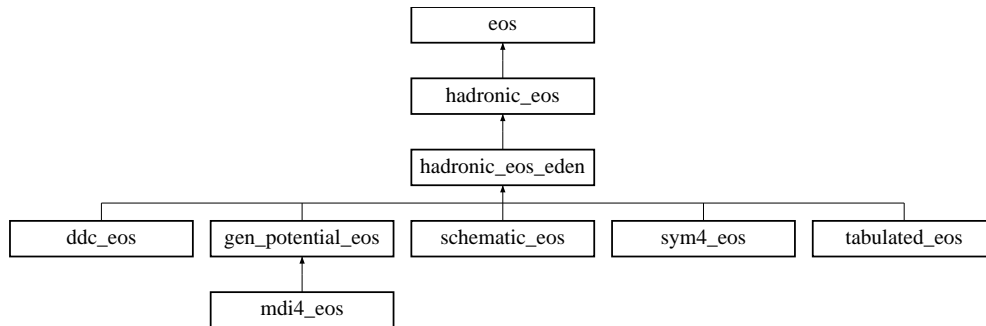
- [hadronic_eos.h](#)

5.12 hadronic_eos_edn Class Reference

A hadronic EOS based on a function of the densities [abstract base].

```
#include <hadronic_eos.h>
```

Inheritance diagram for [hadronic_eos_edn::](#)



5.12.1 Detailed Description

A hadronic EOS based on a function of the densities [abstract base].

Definition at line 483 of file hadronic_eos.h.

Public Member Functions

- virtual int **calc_e** (fermion &n, fermion &p, thermo &th)=0
Equation of state as a function of density.
- virtual int **calc_p** (fermion &n, fermion &p, thermo &th)
Equation of state as a function of the chemical potentials.

The documentation for this class was generated from the following file:

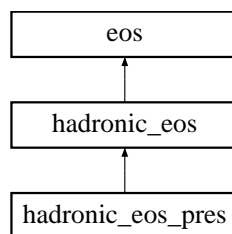
- hadronic_eos.h

5.13 hadronic_eos_pres Class Reference

A hadronic EOS based on a function of the chemical potentials [abstract base].

```
#include <hadronic_eos.h>
```

Inheritance diagram for hadronic_eos_pres::



5.13.1 Detailed Description

A hadronic EOS based on a function of the chemical potentials [abstract base].

Definition at line 501 of file hadronic_eos.h.

Public Member Functions

- virtual int [calc_p](#) (**fermion** &n, **fermion** &p, **thermo** &th)=0
Equation of state as a function of the chemical potentials.
- virtual int [calc_e](#) (**fermion** &n, **fermion** &p, **thermo** &th)
Equation of state as a function of density.

The documentation for this class was generated from the following file:

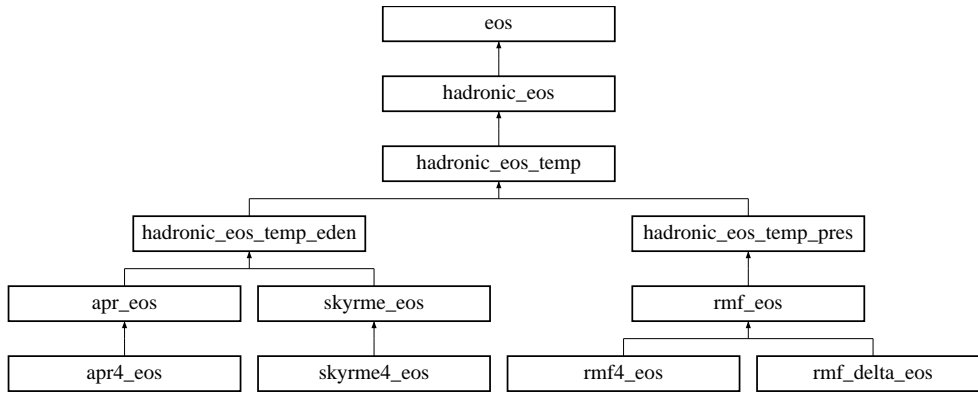
- hadronic_eos.h

5.14 hadronic_eos_temp Class Reference

A finite temperature hadronic EOS.

```
#include <hadronic_eos.h>
```

Inheritance diagram for hadronic_eos_temp::



5.14.1 Detailed Description

A finite temperature hadronic EOS.

Definition at line 517 of file hadronic_eos.h.

Public Member Functions

- virtual int [set_n_and_p_T](#) (**fermion_T** &n, **fermion_T** &p)
Set neutron and proton.
- virtual int [calc_e](#) (**fermion** &n, **fermion** &p, **thermo** &th)=0
Equation of state as a function of density.
- virtual int [calc_temp_e](#) (**fermion_T** &n, **fermion_T** &p, const double T, **thermo** &th)=0
Equation of state as a function of densities at finite temperature.
- virtual int [calc_p](#) (**fermion** &n, **fermion** &p, **thermo** &th)=0
Equation of state as a function of the chemical potentials.
- virtual int [calc_temp_p](#) (**fermion_T** &n, **fermion_T** &p, const double T, **thermo** &th)=0
Equation of state as a function of the chemical potentials at finite temperature.

Data Fields

- **eff_fermion** [def_neutron_T](#)
The default neutron.
- **eff_fermion** [def_proton_T](#)
The default proton.

Protected Member Functions

- int [nuc_matter_temp_e](#) (size_t nv, const **ovector_base** &x, **ovector_base** &y, double *&pa)
Solve for nuclear matter at finite temperature given density.
- int [nuc_matter_temp_p](#) (size_t nv, const **ovector_base** &x, **ovector_base** &y, double *&pa)
Solve for nuclear matter at finite temperature given mu.

Protected Attributes

- **fermion_T** * [neutron_T](#)
The neutron object.
- **fermion_T** * [proton_T](#)
The proton object.
- double [IT](#)
The temperature.

The documentation for this class was generated from the following file:

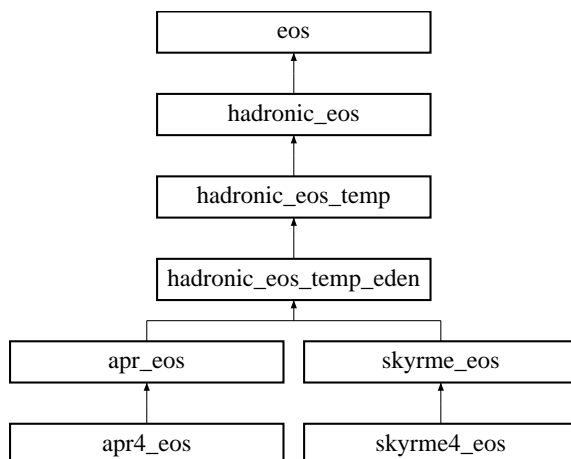
- [hadronic_eos.h](#)

5.15 hadronic_eos_temp_edn Class Reference

A hadronic EOS at finite temperature based on a function of the densities [abstract base].

```
#include <hadronic_eos.h>
```

Inheritance diagram for `hadronic_eos_temp_edn`:



5.15.1 Detailed Description

A hadronic EOS at finite temperature based on a function of the densities [abstract base].

Definition at line 593 of file `hadronic_eos.h`.

Public Member Functions

- virtual int `calc_e` (**fermion** &n, **fermion** &p, **thermo** &th)=0
Equation of state as a function of density.
- virtual int `calc_temp_e` (**fermion_T** &n, **fermion_T** &p, const double T, **thermo** &th)=0
Equation of state as a function of densities at finite temperature.
- virtual int `calc_p` (**fermion** &n, **fermion** &p, **thermo** &th)
Equation of state as a function of the chemical potentials.
- virtual int `calc_temp_p` (**fermion_T** &n, **fermion_T** &p, const double T, **thermo** &th)
Equation of state as a function of the chemical potentials at finite temperature.

The documentation for this class was generated from the following file:

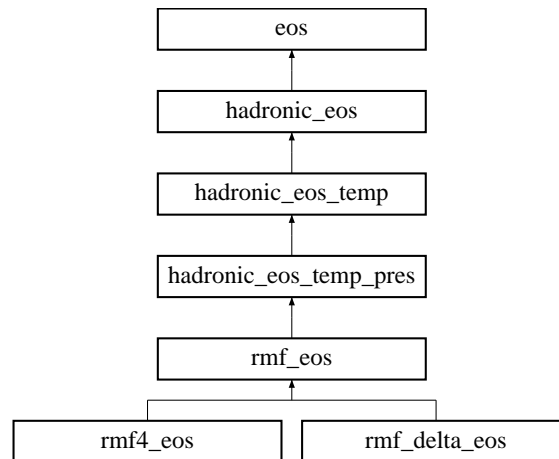
- hadronic_eos.h

5.16 hadronic_eos_temp_pres Class Reference

A hadronic EOS at finite temperature based on a function of the chemical potentials [abstract base].

```
#include <hadronic_eos.h>
```

Inheritance diagram for hadronic_eos_temp_pres::



5.16.1 Detailed Description

A hadronic EOS at finite temperature based on a function of the chemical potentials [abstract base].

Definition at line 625 of file `hadronic_eos.h`.

Public Member Functions

- virtual int `calc_p` (**fermion** &n, **fermion** &p, **thermo** &th)=0
Equation of state as a function of the chemical potentials.
- virtual int `calc_temp_p` (**fermion_T** &n, **fermion_T** &p, const double T, **thermo** &th)=0
Equation of state as a function of the chemical potentials at finite temperature.
- virtual int `calc_e` (**fermion** &n, **fermion** &p, **thermo** &th)
Equation of state as a function of density.
- virtual int `calc_temp_e` (**fermion_T** &n, **fermion_T** &p, const double T, **thermo** &th)
Equation of state as a function of densities at finite temperature.

The documentation for this class was generated from the following file:

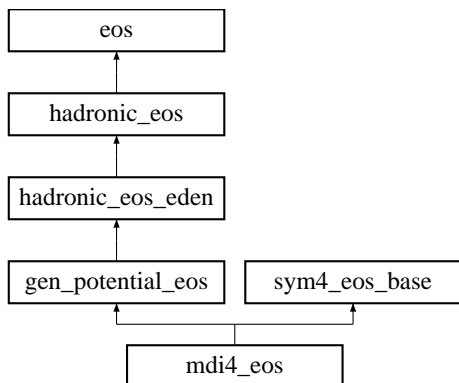
- hadronic_eos.h

5.17 mdi4_eos Class Reference

A version of [gen_potential_eos](#) to separate potential and kinetic contributions.

```
#include <sym4_eos.h>
```

Inheritance diagram for mdi4_eos::



5.17.1 Detailed Description

A version of [gen_potential_eos](#) to separate potential and kinetic contributions.

References:

Created for [Steiner06](#).

Definition at line 157 of file sym4_eos.h.

Public Member Functions

- virtual int [calc_e_sep](#) (**fermion** &ne, **fermion** &pr, double &ed_kin, double &ed_pot, double &mu_n_kin, double &mu_p_kin, double &mu_n_pot, double &mu_p_pot)
Compute the potential and kinetic parts separately.
- virtual int [test_separation](#) (**fermion** &ne, **fermion** &pr, **test_mgr** &t)
Test the separation of the potential and kinetic energy parts.

Protected Member Functions

- double [energy_kin](#) (double var)
*Compute the kinetic **part** of the energy density.*
- double [energy_pot](#) (double var)
*Compute the potential **part** of the energy density.*

The documentation for this class was generated from the following file:

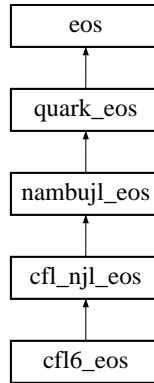
- sym4_eos.h
-

5.18 nambu_jl_eos Class Reference

Nambu Jona-Lasinio EOS at zero temperature.

```
#include <nambu_jl_eos.h>
```

Inheritance diagram for nambu_jl_eos::



5.18.1 Detailed Description

Nambu Jona-Lasinio EOS at zero temperature.

Calculates everything from the **quark** condensates ([uds].qq) and the chemical potentials ([uds].mu). If "fromqq" is set to false, then instead it calculates everything from the dynamical masses ([uds].ms) and the chemical potentials. L, G, K, and B0 are fixed constants. [uds].pr returns the pressure due to the Fermi-gas contribution plus the bag pressure contribution. [uds.ed] is the energy density for each **quark** so that e.g. u.ed+u.pr=u.mu*u.n. B0 should be fixed using calc_B0() beforehand to ensure that the energy density and pressure of the vacuum is zero.

The functions [set_parameters\(\)](#) should be called first.

The code is based on [Buballa99](#).

The Lagrangian is

$$\mathcal{L} = \bar{q}(i\cancel{D} - \hat{m}_0)q + G \sum_{k=0}^8 [(\bar{q}\lambda_k q)^2 + (\bar{q}i\gamma_5 \lambda_k q)^2] + \mathcal{L}_6$$

$$\mathcal{L}_6 = -K [\det_f(\bar{q}(1 + \gamma_5)q) + \det_f(\bar{q}(1 - \gamma_5)q)] .$$

And the corresponding thermodynamic potential is

$$\Omega = \Omega_{FG} + \Omega_{Int}$$

where Ω_{FG} is the Fermi gas contribution and

$$\frac{\Omega_{Int}}{V} = -2N_c \sum_{i=u,d,s} \int \frac{d^3p}{(2\pi)^3} \sqrt{m_{0,i}^2 + p^2} + \frac{\Omega_V}{V}$$

$$\frac{\Omega_V}{V} = \sum_{i=u,d,s} 2G \langle \bar{q}_i q_i \rangle^2 - 4K \langle \bar{q}_u q_u \rangle \langle \bar{q}_d q_d \rangle \langle \bar{q}_s q_s \rangle + B_0 .$$

where B_0 is a constant defined to ensure that the energy density and the pressure of the vacuum is zero.

Unlike [Buballa99](#), the bag constant, Ω_{Int}/V is defined without the term

$$\sum_{i=u,d,s} 2N_C \int_0^\Lambda \frac{d^3p}{(2\pi)^3} \sqrt{m_{0,i}^2 + p^2} dp$$

since this allows an easier comparison to the finite temperature EOS. The constant B_0 in this case is therefore significantly larger, but the energy density and pressure are still zero in the vacuum.

The Feynman-Hellman theorem ([Bernard88](#)), gives

$$\langle \bar{q}q \rangle = \frac{\partial m^*}{\partial m}$$

The functions [calc_e\(\)](#) and [calc_p\(\)](#) never return a value other than zero, but will give nonsensical results for nonsensical inputs.

Finite T documentation

Calculates everything from the **quark** condensates ([uds].qq) and the chemical potentials ([uds].mu). If "fromqq" is set to false, then instead it calculates everything from the dynamical masses ([uds].ms) and the chemical potentials. L, G, K, and B0 are fixed constants. [uds].pr returns the pressure due to the Fermi-gas contribution plus the bag pressure contribution. [uds.ed] is the energy density for each **quark** so that e.g. u.ed+u.pr=u.mu*u.n. B0 is fixed to ensure that the energy density and pressure of the vacuum is zero.

This implementation includes contributions from antiquarks.

References:

Created for [Steiner00](#). See also [Buballa99](#) and [Hatsuda94](#).

Definition at line 129 of file nambu_jl_eos.h.

Data Structures

- struct [njtp_s](#)
A structure for passing parameters to the integrands.

Public Types

- typedef struct [nambu_jl_eos::njtp_s](#) njtp
A structure for passing parameters to the integrands.

Public Member Functions

- virtual int [set_parameters](#) (double lambda=0.0, double fourferm=0.0, double sixferm=0.0)
Set the parameters and the bag constant B0.
 - virtual int [calc_p](#) (**quark** &u, **quark** &d, **quark** &s, **thermo** <h)
Equation of state as a function of chemical potentials.
 - virtual int [calc_temp_p](#) (**quark** &u, **quark** &d, **quark** &s, const double T, **thermo** &th)
Equation of state as a function of chemical potentials at finite temperature.
 - virtual int [calc_eq_p](#) (**quark** &u, **quark** &d, **quark** &s, double &gap1, double &gap2, double &gap3, **thermo** <h)
Equation of state and gap equations as a function of chemical potential.
 - virtual int [calc_eq_e](#) (**quark** &u, **quark** &d, **quark** &s, double &gap1, double &gap2, double &gap3, **thermo** <h)
Equation of state and gap equations as a function of the densities.
 - int [calc_eq_temp_p](#) (**quark** &tu, **quark** &td, **quark** &ts, double &gap1, double &gap2, double &gap3, **thermo** &qb, const double temper)
Equation of state and gap equations as a function of chemical potentials.
 - int [gapfunms](#) (size_t nv, const **ovector_base** &x, **ovector_base** &y, int &pa)
Calculates gap equations in y as a function of the constituent masses in x.
 - int [gapfunqq](#) (size_t nv, const **ovector_base** &x, **ovector_base** &y, int &pa)
Calculates gap equations in y as a function of the **quark** condensates in x.
 - int [gapfunmsT](#) (size_t nv, const **ovector_base** &x, **ovector_base** &y, int &pa)
Calculates gap equations in y as a function of the constituent masses in x.
 - int [gapfunqqT](#) (size_t nv, const **ovector_base** &x, **ovector_base** &y, int &pa)
Calculates gap equations in y as a function of the **quark** condensates in x.
-

- int **set_quarks** (**quark** &u, **quark** &d, **quark** &s)
*Set the **quark** objects to use.*
- virtual const char * **type** ()
Return string denoting type ("nambu_jl_eos").
- virtual int **set_solver** (**mroot**< int, **mm_funct**< int > > &s)
*Set solver to use in **set_parameters**().*
- virtual int **set_inte** (**inte**< const **njtp**, **funct**< const **njtp** > > &i)
Set integration object.

Data Fields

- double **limit**
Accuracy limit for Fermi integrals for finite temperature.
- bool **fromqq**
*Calculate from **quark** condensates if true (default true).*
- double **L**
The momentum cutoff.
- double **G**
The four-fermion coupling.
- double **K**
The 't Hooft six-fermion interaction coupling.
- double **B0**
The bag constant.
- **gsl_mroot_hybrids**< int, **mm_funct**< int > > **def_solver**
The default solver.
- **gsl_inte_qag**< const **njtp**, **funct**< const **njtp** > > **def_it**
The default integrator.

The default quark masses

These are the values from [Buballa99](#) which were used to fix the pion and kaon decay constants, and the pion, kaon, and eta prime masses. They are set in the constructor and are in units of fm^{-1} .

- double **up_default_mass**
- double **down_default_mass**
- double **strange_default_mass**

The default quark objects

The masses are automatically set in the constructor to **up_default_mass**, **down_default_mass**, and **strange_default_mass.c**

- **eff_quark def_up**
- **eff_quark def_down**
- **eff_quark def_strange**

Protected Member Functions

- int **B0fun** (size_t nv, const **ovector_base** &x, **ovector_base** &y, int &pa)
*Used by **calc_B0**() to compute the bag constant.*
- void **njbagg** (**quark** &q)
*Calculates the contribution to the bag constant from **quark** q.*
- double **iqq** (double x, const **njtp** &pa)
*The integrand for the **quark** condensate.*
- double **ide** (double x, const **njtp** &pa)
The integrand for the density.
- double **ied** (double x, const **njtp** &pa)
The integrand for the energy density.
- double **ipr** (double x, const **njtp** &pa)
The integrand for the pressure.

Protected Attributes

- **inte**< const [njtp](#), **funct**< const [njtp](#) > > * **it**
The integrator for finite temperature integrals.
- **mroot**< int, **mm_funct**< int > > * **solver**
The solver to use for [set_parameters\(\)](#).
- **quark** * **up**
The up quark.
- **quark** * **down**
The down quark.
- **quark** * **strange**
The strange quark.
- double **cp_temp**
The temperature for [calc_temp_p\(\)](#).

5.18.2 Member Function Documentation

5.18.2.1 virtual int calc_p (quark & u, quark & d, quark & s, thermo & th) [virtual]

Equation of state as a function of chemical potentials.

This function automatically solves the gap equations

Reimplemented from [quark_eos](#).

5.18.2.2 virtual int calc_temp_p (quark & u, quark & d, quark & s, const double T, thermo & th) [virtual]

Equation of state as a function of chemical potentials at finite temperature.

This function automatically solves the gap equations

Reimplemented from [quark_eos](#).

5.18.2.3 int gapfunms (size_t nv, const ovector_base & x, ovector_base & y, int & pa)

Calculates gap equations in y as a function of the constituent masses in x .

The function utilizes the **quark** objects which can be specified in [set_quarks\(\)](#) and the **thermo** object which can be specified in [eos::set_thermo\(\)](#).

5.18.2.4 int gapfunmsT (size_t nv, const ovector_base & x, ovector_base & y, int & pa)

Calculates gap equations in y as a function of the constituent masses in x .

The function utilizes the **quark** objects which can be specified in [set_quarks\(\)](#) and the **thermo** object which can be specified in [eos::set_thermo\(\)](#).

5.18.2.5 int gapfunqq (size_t nv, const ovector_base & x, ovector_base & y, int & pa)

Calculates gap equations in y as a function of the **quark** condensates in x .

The function utilizes the **quark** objects which can be specified in [set_quarks\(\)](#) and the **thermo** object which can be specified in [eos::set_thermo\(\)](#).

5.18.2.6 int gapfunqqT (size_t nv, const ovector_base & x, ovector_base & y, int & pa)

Calculates gap equations in y as a function of the **quark** condensates in x .

The function utilizes the **quark** objects which can be specified in [set_quarks\(\)](#) and the **thermo** object which can be specified in [eos::set_thermo\(\)](#).

5.18.2.7 virtual int set_parameters (double *lambda* = 0.0, double *fourferm* = 0.0, double *sixferm* = 0.0) [virtual]

Set the parameters and the bag constant `B0`.

This function allows the user to specify the momentum cutoff, `lambda`, the four-fermion coupling `fourferm` and the six-fermion coupling from the 't Hooft interaction `sixferm`. If 0.0 is given for any of the values, then the default is used ($\Lambda = 602.3/(\hbar c)$, $G = 1.835/\Lambda^2$, $K = 12.36/\Lambda^5$).

The value of the shift in the bag constant `B0` is automatically calculated to ensure that the energy density and the pressure of the vacuum are zero. The functions `set_quarks()` and `set_thermo()` can be used before hand to specify the **quark** and **thermo** objects.

5.18.2.8 int set_quarks (quark & *u*, quark & *d*, quark & *s*)

Set the **quark** objects to use.

The **quark** objects are used in `gapfunms()`, `gapfunqq()`, `gapfunmsT()`, `gapfunqqT()`, and `B0fun()`.

5.18.3 Field Documentation**5.18.3.1 bool fromqq**

Calculate from **quark** condensates if true (default true).

If this is false, then computations are performed using the effective masses as inputs

Definition at line 166 of file `nambuyl_eos.h`.

5.18.3.2 double limit

Accuracy limit for Fermi integrals for finite temperature.

limit is used for the finite temperature integrals to ensure that no numbers larger than $\exp(\text{limit})$ or smaller than $\exp(-\text{limit})$ are avoided. (Default: 20)

Definition at line 158 of file `nambuyl_eos.h`.

The documentation for this class was generated from the following file:

- `nambuyl_eos.h`

5.19 nambuyl_eos::njtp_s Struct Reference

A structure for passing parameters to the integrands.

```
#include <nambuyl_eos.h>
```

5.19.1 Detailed Description

A structure for passing parameters to the integrands.

Definition at line 299 of file `nambuyl_eos.h`.

Data Fields

- double **ms**
- double **m**
- double **mu**
- double **temper**

- double **limit**

The documentation for this struct was generated from the following file:

- nambuyl_eos.h

5.20 nse_eos Class Reference

Equation of state for nuclei in statistical equilibrium.

```
#include <nse_eos.h>
```

5.20.1 Detailed Description

Equation of state for nuclei in statistical equilibrium.

This class computes the composition of matter in nuclear statistical equilibrium. The chemical potential of a **nucleus** X with proton number Z_X and neutron number N_X is given by

$$\mu_X = N\mu_n + Z\mu_p - E_{\text{bind},X}$$

where μ_n and μ_p are the neutron and proton chemical potentials and $E_{\text{bind},X}$ is the binding energy of the **nucleus**.

The baryon number density and electron fraction are then given by

$$n_B = n_X(N_X + Z_X) \quad Y_e n_B = n_X Z_X$$

where n_X is the number density which is determined from the chemical potential above.

This implicitly assumes that the nuclei are non-interacting.

Idea for future

Right now [calc_density\(\)](#) needs a very good guess. This could be fixed, probably by solving for the $\log(\mu/T)$ instead of μ .

Definition at line 62 of file nse_eos.h.

Public Member Functions

- int [calc_mu](#) (double mun, double mup, double T, double &nb, double &Ye, **thermo** &th, **nuclear_dist** &nd)
Calculate the equation of state as a function of the chemical potentials.
- int [calc_density](#) (double nb, double Ye, double T, double &mun, double &mup, **thermo** &th, **nuclear_dist** &nd)
Calculate the equation of state as a function of the densities.
- int [set_mroot](#) (**mroot**< solve_parms, **mm_funct**< solve_parms > > &rp)
Set the solver for use in computing the chemical potentials.

Data Fields

- **gsl_mroot_hybrids**< solve_parms, **mm_funct**< solve_parms > > [def_root](#)
Default solver.

5.20.2 Member Function Documentation

5.20.2.1 int calc_density (double nb, double Ye, double T, double &mun, double &mup, thermo &th, nuclear_dist &nd)

Calculate the equation of state as a function of the densities.

Given the baryon number density nb, and the electron fraction Ye and the temperature T, this computes the composition (the individual densities are stored in the distribution nd) and the chemical potentials are given in mun and mup .

This function uses the solver to self-consistently compute the chemical potentials.

5.20.2.2 int calc_mu (double mun, double mup, double T, double &nb, double &Ye, thermo &th, nuclear_dist &nd)

Calculate the equation of state as a function of the chemical potentials.

Given mun, mup and T, this computes the composition (the individual densities are stored in the distribution nd) the baryon number density nb, and the electron fraction Ye.

This function does not use the solver.

The documentation for this class was generated from the following file:

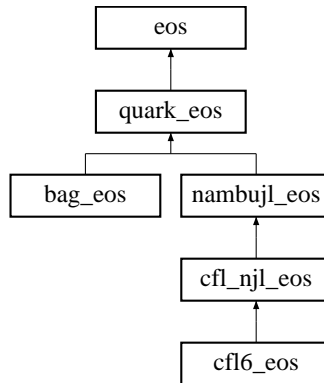
- nse_eos.h

5.21 quark_eos Class Reference

Quark matter equation of state base.

```
#include <quark_eos.h>
```

Inheritance diagram for quark_eos::



5.21.1 Detailed Description

Quark matter equation of state base.

Definition at line 39 of file quark_eos.h.

Public Member Functions

- virtual int [calc_p](#) (quark &u, quark &d, quark &s, thermo &th)
Calculate equation of state as a function of chemical potentials.
- virtual int [calc_e](#) (quark &u, quark &d, quark &s, thermo &th)

Calculate equation of state as a function of density.

- virtual int [calc_temp_p](#) (**quark** &u, **quark** &d, **quark** &s, const double temper, **thermo** &th)

Calculate equation of state as a function of chemical potentials.

- virtual int [calc_temp_e](#) (**quark** &u, **quark** &d, **quark** &s, const double temper, **thermo** &th)

Calculate equation of state as a function of density.

- virtual const char * [type](#) ()

Return string denoting type ("quark_eos").

The documentation for this class was generated from the following file:

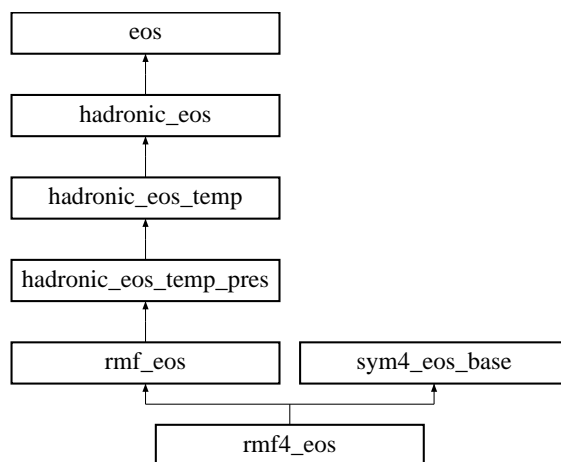
- quark_eos.h

5.22 rmf4_eos Class Reference

A version of [rmf_eos](#) to separate potential and kinetic contributions.

```
#include <sym4_eos.h>
```

Inheritance diagram for rmf4_eos::



5.22.1 Detailed Description

A version of [rmf_eos](#) to separate potential and kinetic contributions.

References:

Created for [Steiner06](#).

Definition at line 97 of file sym4_eos.h.

Public Member Functions

- virtual int [calc_e_sep](#) (**fermion** &ne, **fermion** &pr, double &ed_kin, double &ed_pot, double &mu_n_kin, double &mu_p_kin, double &mu_n_pot, double &mu_p_pot)

Compute the potential and kinetic parts separately.

The documentation for this class was generated from the following file:

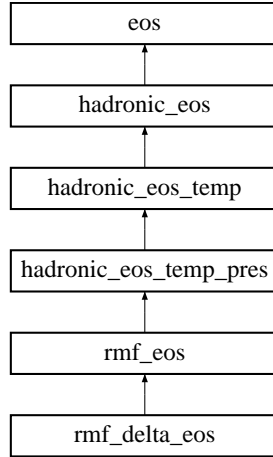
- sym4_eos.h
-

5.23 rmf_delta_eos Class Reference

Field-theoretical EOS with scalar-isovector meson,.

```
#include <rmf_delta_eos.h>
```

Inheritance diagram for rmf_delta_eos::



5.23.1 Detailed Description

Field-theoretical EOS with scalar-isovector meson,.

δ .

This essentially follows the notation in [Kubis97](#), except that our definitions of b and c follow their \bar{b} and \bar{c} , respectively.

Also discussed in [Gaitanos04](#), where they take $m_\delta = 980$ MeV.

The full Lagragian is:

$$\mathcal{L} = \mathcal{L}_{Dirac} + \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_\delta$$

$$\begin{aligned}
 \mathcal{L}_{Dirac} &= \bar{\Psi} \left[i\partial - g_\omega \not{\omega} - \frac{g_\rho}{2} \not{\vec{\rho}} \cdot \vec{\tau} - M + g_\sigma \sigma - \frac{e}{2} (1 + \tau_3) A_\mu \right] \Psi \\
 \mathcal{L}_\sigma &= \frac{1}{2} (\partial_\mu \sigma)^2 - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{bM}{3} (g_\sigma \sigma)^3 - \frac{c}{4} (g_\sigma \sigma)^4 \\
 \mathcal{L}_\omega &= -\frac{1}{4} f_{\mu\nu} f^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu + \frac{\zeta}{24} g_\omega^4 (\omega^\mu \omega_\mu)^2 \\
 \mathcal{L}_\rho &= -\frac{1}{4} \vec{B}_{\mu\nu} \cdot \vec{B}^{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}^\mu \cdot \vec{\rho}_\mu + \frac{\xi}{24} g_\rho^4 (\vec{\rho}^\mu \cdot \vec{\rho}_\mu)^2 + g_\rho^2 f(\sigma, \omega) \vec{\rho}^\mu \cdot \vec{\rho}_\mu
 \end{aligned}$$

where the additional terms are

$$\mathcal{L}_\delta = \bar{\Psi} \left(g_\delta \vec{\delta} \cdot \vec{\tau} \right) \Psi + \frac{1}{2} (\partial_\mu \vec{\delta})^2 - \frac{1}{2} m_\delta^2 \vec{\delta}^2$$

The new field equation for the delta meson is

$$m_\delta^2 \delta = g_\delta (n_{s,p} - n_{s,n})$$

Idea for future

Finish the finite temperature EOS

Definition at line 93 of file `rmf_delta_eos.h`.

Public Member Functions

- virtual int `calc_e` (**fermion** &ne, **fermion** &pr, **thermo** <h)
Equation of state as a function of density.
- virtual int `calc_p` (**fermion** &neu, **fermion** &p, double sig, double ome, double rho, double delta, double &f1, double &f2, double &f3, double &f4, **thermo** &th)
Equation of state as a function of chemical potentials.
- int `calc_temp_p` (**fermion_T** &ne, **fermion_T** &pr, double temper, double sig, double ome, double lrho, double delta, double &f1, double &f2, double &f3, double &f4, **thermo** <h)
Finite temperature (unfinished).
- virtual int `set_fields` (double sig, double ome, double lrho, double delta)
Set a guess for the fields for the next call to `calc_e()`, `calc_p()`, or `saturation()`.
- virtual int `saturation` ()
Calculate saturation properties for nuclear matter at the saturation density.

Data Fields

- double `md`
The mass of the scalar-isovector field.
- double `cd`
The coupling of the scalar-isovector field to the nucleons.
- double `del`
The value of the scalar-isovector field.

Protected Member Functions

- virtual int `calc_e_solve_fun` (size_t nv, const **ovector_base** &ex, **ovector_base** &ey, double *&pa)
The function for `calc_e()`.
- virtual int `zero_pressure` (size_t nv, const **ovector_base** &ex, **ovector_base** &ey, int &pa)
Compute matter at zero pressure (for `saturation()`).

Private Member Functions

- virtual int `set_fields` (double sig, double ome, double lrho)
Forbid setting the guesses to the fields unless all four fields are specified.

5.23.2 Member Function Documentation

5.23.2.1 virtual int saturation () [virtual]

Calculate saturation properties for nuclear matter at the saturation density.

This requires initial guesses to the chemical potentials, etc.

Reimplemented from `rmf_eos`.

The documentation for this class was generated from the following file:

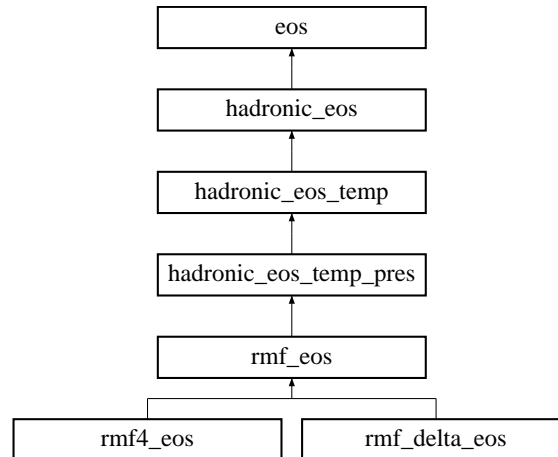
- `rmf_delta_eos.h`

5.24 rmf_eos Class Reference

Relativistic mean field theory EOS.

```
#include <rmf_eos.h>
```

Inheritance diagram for rmf_eos::



5.24.1 Detailed Description

Relativistic mean field theory EOS.

Before sending neutrons and protons to these member functions, the masses should be set to their vacuum values and the degeneracy factor should be 2. If an internal model is used (using `load()`), then the neutron and proton masses should be set to `mnuc`.

It is important to point out that expressions for the energy densities are often simplified in the literature using the field equations. These expressions are not used in this code since they are only applicable in infinite matter where the field equations hold, and are not suitable for use in applications (such as to finite nuclei) where the spatial derivatives of the fields are non-zero. Notice that in the proper expressions for the energy density the similarity between terms in the pressure up to a sign. This procedure allows one to verify the thermodynamic identity even if the field equations are not solved and allows the user to add **gradient** terms to the energy density and pressure.

Note:

Since this EOS uses the effective masses and chemical potentials in the `fermion` class, the values of `part::non_interacting` for neutrons and protons are set to false in many of the functions.

Todo

- The number of couplings is getting large, maybe new organization is required.
- Check the formulas in the "Background" section
- Overload `hadronic_eos::fcomp()` with an exact version
- Fix `calc_p()` to be better at guessing
- There are two `calc_e()` functions that solve. One is specially designed to work without a good initial guess. Possibly the other `calc_e()` function should be similarly designed?
- Make sure that this class properly handles particles for which `inc_rest_mass` is true/false
- It might be nice to remove explicit reference to the meson masses in functions which only compute nuclear matter since they are unnecessary. This might, however, demand redefining some of the couplings.
- The error handler is called sometimes when `calc_e()` is used to compute pure neutron matter. This should be fixed.

Background

The full Lagragian is:

$$\mathcal{L} = \mathcal{L}_{Dirac} + \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho$$

$$\begin{aligned}\mathcal{L}_{Dirac} &= \bar{\Psi} \left[i\vec{\partial} - g_\omega \not{\omega} - \frac{g_\rho}{2} \vec{\partial} \vec{\tau} - M + g_\sigma \sigma - \frac{e}{2} (1 + \tau_3) A_\mu \right] \Psi \\ \mathcal{L}_\sigma &= \frac{1}{2} (\partial_\mu \sigma)^2 - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{bM}{3} (g_\sigma \sigma)^3 - \frac{c}{4} (g_\sigma \sigma)^4 \\ \mathcal{L}_\omega &= -\frac{1}{4} f_{\mu\nu} f^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega^\mu \omega_\mu + \frac{\zeta}{24} g_\omega^4 (\omega^\mu \omega_\mu)^2 \\ \mathcal{L}_\rho &= -\frac{1}{4} \vec{B}_{\mu\nu} \cdot \vec{B}^{\mu\nu} + \frac{1}{2} m_\rho^2 \vec{\rho}^\mu \cdot \vec{\rho}_\mu + \frac{\xi}{24} g_\rho^4 (\vec{\rho}^\mu \cdot \vec{\rho}_\mu)^2 + g_\rho^2 f(\sigma, \omega) \vec{\rho}^\mu \cdot \vec{\rho}_\mu\end{aligned}$$

The coefficients b and c are related to the somewhat standard κ and λ by:

$$\kappa = 2Mb \quad \lambda = 6c;$$

The function f is the coefficient of $g_r^2 \rho^2$

$$f(\sigma, \omega) = b_1 \omega^2 + b_2 \omega^4 + b_3 \omega^6 + a_1 \sigma + a_2 \sigma^2 + a_3 \sigma^3 + a_4 \sigma^4 + a_5 \sigma^5 + a_6 \sigma^6$$

where the notation from [Horowitz01](#) is:

$$f(\sigma, \omega) = \lambda_4 g_s^2 \sigma^2 + \lambda_v g_w^2 \omega^2$$

This implies $b_1 = \lambda_v g_w^2$ and $a_2 = \lambda_4 g_s^2$

The field equations are:

$$0 = m_\sigma^2 \sigma - g_\sigma (n_{sn} + n_{sp}) + bM g_\sigma^3 \sigma^2 + c g_\sigma^4 \sigma^3 - g_\rho^2 \rho^2 \frac{\partial f}{\partial \sigma}$$

$$0 = m_\omega^2 \omega - g_\omega (n_n + n_p) + \frac{\zeta}{6} g_\omega^4 \omega^3 g_\rho^2 \rho^2 \frac{\partial f}{\partial \omega}$$

$$0 = m_\rho^2 \rho + \frac{1}{2} g_\rho (n_n - n_p) + 2g_\rho^2 \rho f + \frac{\xi}{6} g_\rho^4 \rho^3$$

When the variable `zm_mode` is true, the effective mass is fixed using the approach of [Zimanyi90](#).

Defining

$$U(\sigma) = \frac{1}{2} m_\sigma^2 \sigma^2 + \frac{bM}{3} (g_\sigma \sigma)^3 + \frac{c}{4} (g_\sigma \sigma)^4,$$

the binding energy per particle in symmetric matter at equilibrium is given by

$$\frac{E}{A} = \frac{1}{n_0} \left[U(\sigma_0) + \frac{1}{2} m_\omega \omega_0^2 + \frac{\zeta}{8} (g_\omega \omega_0)^4 + \frac{2}{\pi^2} \int_0^{k_F} dk k^2 \sqrt{k^2 + M^{*2}} \right].$$

where the Dirac effective mass is $M^* = M - g_\sigma \sigma_0$. The compressibility is given by

$$K = 9 \frac{g_\omega^2}{m_\omega^2} n_0 + 3 \frac{k_F^2}{E_F^*} - 9 n_0 \frac{M^{*2}}{E_F^{*2}} \left[\left(\frac{1}{g_\sigma^2} \frac{\partial^2}{\partial \sigma_0^2} + \frac{3}{g_\sigma M^*} \frac{\partial}{\partial \sigma_0} \right) U(\sigma_0) - 3 \frac{n_0}{E_F^*} \right]^{-1}.$$

The symmetry energy of bulk matter is given by

$$E_{sym} = \frac{k_F^2}{6E_F^*} + \frac{n}{8(g_\rho^2/m_\rho^2 + 2f(\sigma_0, \omega_0))}$$

In the above equations, the subscript “0” denotes the mean field values of σ and ω . For the case $f = 0$, the symmetry energy varies linearly with the density at large densities. The function f permits variations in the density dependence of the symmetry energy above nuclear matter density.

See also [Muller96](#), [Zimanyi90](#).

Definition at line 213 of file `rmf_eos.h`.

Public Member Functions

- `int load` (std::string model, bool external=false)
Load parameters for model named 'model'.
- `int calc_temp_e` (fermion_T &ne, fermion_T &pr, const double T, thermo <h)
Equation of state as a function of densities at finite temperature.
- `int fix_saturation` (double guess_cs=4.0, double guess_cw=3.0, double guess_b=0.001, double guess_c=-0.001)
Calculate cs, cw, cr, b, and c from the saturation properties.
- `virtual int saturation` ()
Calculate properties for nuclear matter at the saturation density.
- `double fesym_fields` (double sig, double ome, double nb)
Calculate symmetry energy assuming the field equations have already been solved.
- `double fcomp_fields` (double sig, double ome, double nb)
Calculate the compressibility assuming the field equations have already been solved.
- `int fkprime_fields` (double sig, double ome, double nb, double &k, double &kprime)
Calculate compressibility and kprime assuming the field equations have already been solved.
- `int field_eqs` (size_t nv, const ovector_base &x, ovector_base &y, double *&pa)
A function for solving the field equations.
- `int field_eqsT` (size_t nv, const ovector_base &x, ovector_base &y, double *&pa)
A function for solving the field equations at finite temperature.
- `virtual int set_fields` (double sig, double ome, double lrho)
Set a guess for the fields for the next call to `calc_e()`, `calc_p()`, or `saturation()`.
- `int get_fields` (double &sig, double &ome, double &lrho)
Return the most recent values of the meson fields.
- `virtual const char * type` ()
Return string denoting type ("rmf_eos").
- `int check_naturalness` (rmf_eos &re)
Set the coefficients of a `rmf_eos` object to their limits from naturalness.
- `int naturalness_limits` (double value, rmf_eos &re)
Provide the maximum values of the couplings assuming a limit on naturalness.
- `virtual int set_sat_mroot` (mroot< int, mm_funct< int > > &mrX)
Set class `mroot` object for use calculating saturation density.

Compute EOS from densities at zero temperature

- `virtual int calc_e` (fermion &ne, fermion &pr, thermo <h)
Equation of state as a function of density.
- `virtual int calc_e` (fermion &ne, fermion &pr, thermo <h, double &sig, double &ome, double &rho)
Equation of state as a function of density.

Compute EOS from chemical at zero temperature

- virtual int `calc_p` (`fermion &ne`, `fermion &pr`, `thermo <h`)
Equation of state as a function of chemical potential.
- virtual int `calc_eq_p` (`fermion &neu`, `fermion &p`, double `sig`, double `ome`, double `rho`, double `&f1`, double `&f2`, double `&f3`, `thermo &th`)
Equation of state and meson field equations as a function of chemical potentials.

Compute EOS from chemical potentials at finite temperature

- virtual int `calc_eq_temp_p` (`fermion_T &ne`, `fermion_T &pr`, const double `temper`, double `sig`, double `ome`, double `rho`, double `&f1`, double `&f2`, double `&f3`, `thermo &th`)
Equation of state and meson field equations as a function of chemical potentials.
- virtual int `calc_temp_p` (`fermion_T &ne`, `fermion_T &pr`, const double `T`, `thermo <h`)
Equation of state as a function of chemical potential.

Data Fields

- bool `zm_mode`
Modifies method of calculating effective masses.
- `gsl_mroot_hybrids` < int, `mm_funct` < int > > `def_sat_mroot`
The default solver for calculating the saturation density.

Masses

- double `mnuc`
nucleon mass
- double `ms`
 σ mass (in fm⁻¹)
- double `mw`
 ω mass (in fm⁻¹)
- double `mr`
 ρ mass (in fm⁻¹)

Standard couplings (including nonlinear sigma terms)

- double `cs`
- double `cw`
- double `cr`
- double `b`
- double `c`

Non-linear terms for omega and rho.

- double `zeta`
- double `xi`

Additional isovector couplings

- double `a1`
- double `a2`
- double `a3`
- double `a4`
- double `a5`
- double `a6`
- double `b1`
- double `b2`
- double `b3`

Protected Member Functions

- int [fix_saturation_fun](#) (size_t nv, const **ovector_base** &x, **ovector_base** &y, int &pa)
The function for [fix_saturation\(\)](#).
- virtual int [zero_pressure](#) (size_t nv, const **ovector_base** &ex, **ovector_base** &ey, int &pa)
Compute matter at zero pressure (for [saturation\(\)](#)).
- virtual int [calc_e_solve_fun](#) (size_t nv, const **ovector_base** &ex, **ovector_base** &ey, double *&pa)
The function for [calc_e\(\)](#).
- virtual int [calc_temp_e_solve_fun](#) (size_t nv, const **ovector_base** &ex, **ovector_base** &ey, double *&pa)
The function for [calc_temp_e\(\)](#).
- int [calc_cr](#) (double sig, double ome, double nb)
Calculate the cr coupling given sig and ome at the density 'nb'.

Protected Attributes

- double [n_charge](#)
Temporary charge density.
- double [fe_temp](#)
Temperature for solving field equations at finite temperature.
- bool [ce_neut_matter](#)
For [calc_e\(\)](#), if true, then solve for neutron matter.
- bool [ce_prot_matter](#)
For [calc_e\(\)](#), if true, then solve for proton matter.
- bool [guess_set](#)
True if a guess for the fields has been given.
- **mroot**< int, **mm_funct**< int > > * [sat_mroot](#)
The solver to compute saturation properties.
- double [ce_temp](#)

The meson fields

- double **sigma**
- double **omega**
- double **rho**

5.24.2 Member Function Documentation

5.24.2.1 int [calc_cr](#) (double *sig*, double *ome*, double *nb*) [protected]

Calculate the cr coupling given sig and ome at the density 'nb'.

Used by [fix_saturation\(\)](#).

5.24.2.2 virtual int [calc_e](#) (fermion & *ne*, fermion & *pr*, thermo & *lth*, double & *sig*, double & *ome*, double & *rho*) [virtual]

Equation of state as a function of density.

Idea for future

Improve the operation of this function when the proton density is zero.

Todo

Rename this function to distinguish between [calc_e\(\)](#)'s

5.24.2.3 virtual int calc_e (fermion & *ne*, fermion & *pr*, thermo & *lth*) [virtual]

Equation of state as a function of density.

Initial guesses for the chemical potentials are taken from the user-given values. Initial guesses for the fields can be set by [set_fields\(\)](#), or default values will be used. After the call to [calc_e\(\)](#), the final values of the fields can be accessed through [get_fields\(\)](#).

This is a little more robust than the standard version in the parent [hadronic_eos](#).

Idea for future

Improve the operation of this function when the proton density is zero.

Reimplemented from [hadronic_eos_temp_pres](#).

Reimplemented in [rmf_delta_eos](#).

5.24.2.4 virtual int calc_eq_p (fermion & *neu*, fermion & *p*, double *sig*, double *ome*, double *rho*, double & *f1*, double & *f2*, double & *f3*, thermo & *th*) [virtual]

Equation of state and meson field equations as a function of chemical potentials.

This calculates the pressure and energy density as a function of $\mu_n, \mu_p, \sigma, \omega, \rho$. When the field equations have been solved, *f1*, *f2*, and *f3* are all zero.

The thermodynamic identity is satisfied even when the field equations are not solved.

5.24.2.5 virtual int calc_p (fermion & *ne*, fermion & *pr*, thermo & *lth*) [virtual]

Equation of state as a function of chemical potential.

Solves for the field equations automatically.

Note:

This may not be too robust. Fix?

Implements [hadronic_eos_temp_pres](#).

5.24.2.6 virtual int calc_temp_p (fermion_T & *ne*, fermion_T & *pr*, const double *T*, thermo & *lth*) [virtual]

Equation of state as a function of chemical potential.

Solves for the field equations automatically.

Implements [hadronic_eos_temp_pres](#).

5.24.2.7 int check_naturalness (rmf_eos & *re*) [inline]

Set the coefficients of a [rmf_eos](#) object to their limits from naturalness.

As given in muller and Serot, npa 606, 508

The definition of the vector-isovector field and coupling matches what is done here. Compare the Lagrangian above with Eq. 10 from the reference.

The following couplings should all be of the same size:

$$\frac{1}{2c_s^2 M^2}, \frac{1}{2c_v^2 M^2}, \frac{1}{8c_\rho^2 M^2}, \text{ and } \frac{\bar{a}_{ijk} M^{i+2j+2k-4}}{2^{2k}}$$

which are equivalent to

$$\frac{m_s^2}{2g_s^2 M^2}, \frac{m_v^2}{2g_v^2 M^2}, \frac{m_\rho^2}{8g_\rho^2 M^2}, \text{ and } \frac{a_{ijk} M^{i+2j+2k-4}}{g_s^i g_v^{2j} g_\rho^{2k} 2^{2k}}$$

The connection the a_{ijk} 's and the coefficients that are used here is

$$\begin{aligned} \frac{bM}{3} g_\sigma^3 \sigma^3 &= a_{300} \sigma^3 \\ \frac{c}{4} g_\sigma^4 \sigma^4 &= a_{400} \sigma^4 \\ \frac{\zeta}{24} g_\omega^4 \omega^4 &= a_{020} \omega^4 \\ \frac{\xi}{24} g_\rho^4 \rho^4 &= a_{002} \rho^4 \\ b_1 g_\rho^2 \omega^2 \rho^2 &= a_{011} \omega^2 \rho^2 \\ b_2 g_\rho^2 \omega^4 \rho^2 &= a_{021} \omega^4 \rho^2 \\ b_3 g_\rho^2 \omega^6 \rho^2 &= a_{031} \omega^6 \rho^2 \\ a_1 g_\rho^2 \sigma^1 \rho^2 &= a_{101} \sigma^1 \rho^2 \\ a_2 g_\rho^2 \sigma^2 \rho^2 &= a_{201} \sigma^2 \rho^2 \\ a_3 g_\rho^2 \sigma^3 \rho^2 &= a_{301} \sigma^3 \rho^2 \\ a_4 g_\rho^2 \sigma^4 \rho^2 &= a_{401} \sigma^4 \rho^2 \\ a_5 g_\rho^2 \sigma^5 \rho^2 &= a_{501} \sigma^5 \rho^2 \\ a_6 g_\rho^2 \sigma^6 \rho^2 &= a_{601} \sigma^6 \rho^2 \end{aligned}$$

Note that Muller and Serot use the notation

$$\frac{\bar{\kappa} g_s^3}{2} = \frac{\kappa}{2} = b M g_s^3 \quad \text{and} \quad \frac{\bar{\lambda} g_s^4}{6} = \frac{\lambda}{6} = c g_s^4$$

which differs slightly from the "standard" notation above.

We need to compare the values of

$$\begin{aligned} &\frac{m_s^2}{2g_s^2 M^2}, \frac{m_v^2}{2g_v^2 M^2}, \frac{m_\rho^2}{8g_\rho^2 M^2}, \frac{b}{3}, \frac{c}{4} \\ &\frac{\zeta}{24}, \frac{\xi}{384}, \frac{b_1}{4g_\omega^2}, \frac{b_2 M^2}{4g_\omega^4}, \frac{b_3 M^4}{4g_\omega^6}, \frac{a_1}{4g_\sigma M}, \\ &\frac{a_2}{4g_\sigma^2}, \frac{a_3 M}{4g_\sigma^3}, \frac{a_4 M^2}{4g_\sigma^4}, \frac{a_5 M^3}{4g_\sigma^5}, \text{ and } \frac{a_6 M^4}{4g_\sigma^6}. \end{aligned}$$

These values are stored in the variables cs, cw, cr, b, c, zeta, xi, b1, etc. in the specified [rmf_eos](#) object. All of the numbers should be around 0.001 or 0.002.

For the scale M , [mnuc](#) is used.

Todo

I may have ignored some signs in the above, which are unimportant for this application, but it would be good to fix them for posterity.

Definition at line 565 of file [rmf_eos.h](#).

5.24.2.8 double fcomp_fields (double sig, double ome, double nb)

Calculate the compressibility assuming the field equations have already been solved.

This may only work at saturation density.

5.24.2.9 double fesym_fields (double *sig*, double *ome*, double *nb*)

Calculate symmetry energy assuming the field equations have already been solved.

This may only work at saturation density. Used by [saturation\(\)](#).

5.24.2.10 int field_eqs (size_t *nv*, const ovector_base & *x*, ovector_base & *y*, double *& *pa*)

A function for solving the field equations.

$x[0]$, $x[1]$, and $x[2]$ should be set to σ , ω , and ρ on input (in fm^{-1}) and on exit, $y[0]$, $y[1]$ and $y[2]$ contain the field equations and are zero when the field equations have been solved. The pa parameter is ignored.

5.24.2.11 int field_eqsT (size_t *nv*, const ovector_base & *x*, ovector_base & *y*, double *& *pa*)

A function for solving the field equations at finite temperature.

$x[0]$, $x[1]$, and $x[2]$ should be set to σ , ω , and ρ on input (in fm^{-1}) and on exit, $y[0]$, $y[1]$ and $y[2]$ contain the field equations and are zero when the field equations have been solved. The pa parameter is ignored.

5.24.2.12 int fix_saturation (double *guess_cs* = 4.0, double *guess_cw* = 3.0, double *guess_b* = 0.001, double *guess_c* = -0.001)

Calculate cs , cw , cr , b , and c from the saturation properties.

Note that the meson masses and [mnuc](#) must be specified before calling this function.

This function does not give correct results when `bool zm_mode` is true.

`guess_cs`, `guess_cw`, `guess_b`, and `guess_c` are initial guesses for cs , cw , b , and c respectively.

Todo

- Fix this for `zm_mode=true`
- Ensure solver is more robust

5.24.2.13 int fkprime_fields (double *sig*, double *ome*, double *nb*, double & *k*, double & *kprime*)

Calculate compressibility and k_{prime} assuming the field equations have already been solved.

This may only work at saturation density. Used by [saturation\(\)](#).

Todo

Does this work? Fix [fkprime_fields\(\)](#) if it does not.

5.24.2.14 int get_fields (double & *sig*, double & *ome*, double & *lrho*) [inline]

Return the most recent values of the meson fields.

This returns the most recent values of the meson fields set by a call to [saturation\(\)](#), [calc_e\(\)](#), or `calc_p(fermion &, fermion &, thermo &)`.

Definition at line 460 of file `rmf_eos.h`.

5.24.2.15 int load (std::string *model*, bool *external* = false)

Load parameters for model named '`model`'.

Presently accepted values from file `rmfdata/model_list`:

```
word[] models 46
BMPI BMPII FPMC FSUGold L-BF L-HS L-W L-Z L1 L2 L3 NL-06 NL-065 NL-07
NL-075 NL-B1 NL-B2 NL-SH NL-Z NL1 NL2 NL3 NL4 PL-40 PL-Z RAPR RAPRhdp
S271 SR1 SR2 SR3 TM1 TM2 Z271 es25 es25n15 es275 es275n15 es30 es30n15
es325 es325n15 es35 es35n15 es25small es25new es275new es30new
#
# Comments:
# PL-40 and PL-Z have a special m_infinity parameter that is
# described in P.-G. Reinhard, Rep. Prog. Phys., 52 (1989) 439 that
# I don't quite understand. For spherld, these need to be run manually
# using the input files in ~/spherld/data.
#
#
```

In these files, the nucleon and meson masses are by default specified in MeV, and *cs*, *cw*, and *cr* are given in fm. The parameters *b* and *c* are both unitless. If the bool 'oakstyle' is true, then [load\(\)](#) assumes that *gs*, *gw*, and *gr* have been given where *gs* and *gw* are as usual, but *gr* is a factor of two smaller than usual, and *g2* and *g3* have been given where $g2 = -b M gs^3$ and $g3 = c gs^4$. If *tokistyle* is true, then it is additionally assumed that *c3* is given where $c3 = \text{zeta}/6 * gw^4$.

If *external* is true, then *model* is the filename (relative to the current directory) of the file containing the model parameters. Otherwise, the model is assumed to be present in the *O2scl* library data directory.

5.24.2.16 **int naturalness_limits (double *value*, *rmf_eos* & *re*)** [inline]

Provide the maximum values of the couplings assuming a limit on naturalness.

The limits for the couplings are function of the nucleon and meson masses, except for the limits on *b*, *c*, *zeta*, and *xi* which are independent of the masses because of the way that these four couplings are defined.

Definition at line 602 of file *rmf_eos.h*.

5.24.2.17 **virtual int saturation ()** [virtual]

Calculate properties for nuclear matter at the saturation density.

This requires initial guesses to the chemical potentials, etc.

Reimplemented from [hadronic_eos](#).

Reimplemented in [rmf_delta_eos](#).

5.24.3 Field Documentation

5.24.3.1 **gsl_mroot_hybrids<int,mm_funct<int> > def_sat_mroot**

The default solver for calculating the saturation density.

Used by [fn0\(\)](#) (which is called by [saturation\(\)](#)) to solve [saturation_matter_e\(\)](#) (1 variable).

Definition at line 644 of file *rmf_eos.h*.

5.24.3.2 **double mnuc**

nucleon mass

This need not be exactly equal to the neutron or proton mass, but provides the scale for the coupling *b*.

Definition at line 228 of file *rmf_eos.h*.

5.24.3.3 **double n_charge** [protected]

Temporary charge density.

Todo

Should use `hadronic_eos::proton_frac` instead?

Definition at line 655 of file `rmf_eos.h`.

The documentation for this class was generated from the following file:

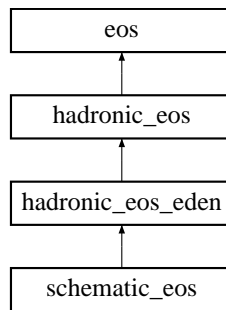
- `rmf_eos.h`

5.25 schematic_eos Class Reference

Schematic hadronic equation of state.

```
#include <schematic_eos.h>
```

Inheritance diagram for `schematic_eos`:



5.25.1 Detailed Description

Schematic hadronic equation of state.

Equation of state defined by the energy density:

$$\epsilon = n \left\{ M + eoa + \frac{comp}{18} (n/n_0 - 1)^2 + \frac{kprime}{162} (n/n_0 - 1)^3 + \frac{kpp}{1944} (n/n_0 - 1)^4 + (1 - 2x)^2 \left[a \left(\frac{n}{n_0} \right)^{2/3} + b \left(\frac{n}{n_0} \right)^\gamma \right] \right\}$$

Symmetry energy at nuclear matter density is $a+b$.

Note that it doesn't really matter what kind of particle object is used, since the `calc_e()` function doesn't use any of the particle thermodynamics functions.

Definition at line 52 of file `schematic_eos.h`.

Public Member Functions

- virtual int `calc_e (fermion &ln, fermion &lp, thermo <h)`
Equation of state as a function of density.
- virtual int `set_kprime_zeroden ()`
Set kprime so that the energy per baryon of zero-density matter is zero.
- virtual int `set_kpp_zeroden ()`
Set kpp so that the energy per baryon of zero-density matter is zero.
- virtual int `set_a_from_mstar (double u_msom, double mnuc)`
Fix the kinetic energy symmetry coefficient from the nucleon effective mass and the saturation density.
- virtual double `eoazeroden ()`
Return the energy per baryon of matter at zero density.
- virtual const char * `type ()`
Return string denoting type ("schematic_eos").

Data Fields

- double **a**
The kinetic energy symmetry coefficient in inverse fm (default 17/hc).
- double **b**
The potential energy symmetry coefficient in inverse fm (default 13/hc).
- double **kpp**
The coefficient of a density to the fourth term (default 0).
- double **gamma**
The exponent of the high-density symmetry energy (default 1.0).

5.25.2 Member Function Documentation

5.25.2.1 virtual double eoa_zeroden() [inline, virtual]

Return the energy per baryon of matter at zero density.

This is inaccessible from `calc_e()` so is available separately here. Using `set_kprime_zeroden()` or `set_kpp_zeroden()` will fix kprime or kpp (respectively) to ensure that this is zero.

The result provided here does not include the nucleon mass and is given in fm^{-1} .

Definition at line 125 of file `schematic_eos.h`.

5.25.2.2 virtual int set_a_from_mstar(double u_msom, double mnuc) [inline, virtual]

Fix the kinetic energy symmetry coefficient from the nucleon effective mass and the saturation density.

This assumes the nucleons are non-relativistic and that the neutrons and protons have equal mass. The relativistic corrections are around 1 **part** in 10^6 .

Todo

This was computed in `schematic_sym.nb`, which might be added to the documentation?

Definition at line 109 of file `schematic_eos.h`.

5.25.3 Field Documentation

5.25.3.1 double a

The kinetic energy symmetry coefficient in inverse fm (default 17/hc).

The default value corresponds to an effective mass of about 0.7.

Definition at line 63 of file `schematic_eos.h`.

The documentation for this class was generated from the following file:

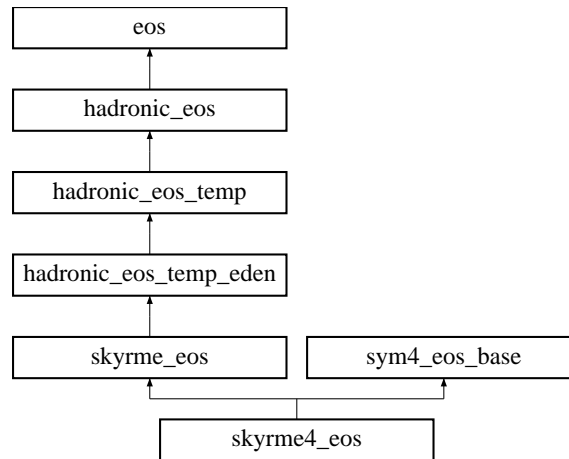
- `schematic_eos.h`

5.26 skyrme4_eos Class Reference

A version of `skyrm_eos` to separate potential and kinetic contributions.

```
#include <sym4_eos.h>
```

Inheritance diagram for `skyrm4_eos::`



5.26.1 Detailed Description

A version of [skyrme_eos](#) to separate potential and kinetic contributions.

References:

Created for [Steiner06](#).

Definition at line 138 of file `sym4_eos.h`.

Public Member Functions

- virtual int [calc_e_sep](#) (**fermion** &ne, **fermion** &pr, double &ed_kin, double &ed_pot, double &mu_n_kin, double &mu_p_kin, double &mu_n_pot, double &mu_p_pot)
Compute the potential and kinetic parts separately.

The documentation for this class was generated from the following file:

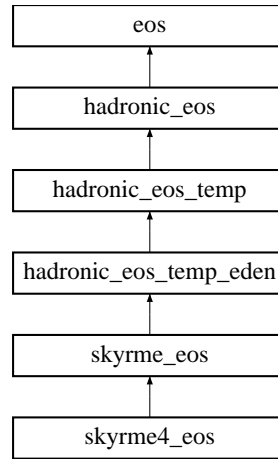
- `sym4_eos.h`

5.27 skyrme_eos Class Reference

Skyrme hadronic equation of state at zero temperature.

```
#include <skyrme_eos.h>
```

Inheritance diagram for `skyrme_eos::`



5.27.1 Detailed Description

Skyrme hadronic equation of state at zero temperature.

Quantities which have units containing powers of energy are divided by $\hbar c$ to ensure all quantities are in units of fm . The x_i and α are unitless, while the original units of the t_i are:

- t_0 - MeV fm³
- t_1 - MeV fm⁵
- t_2 - MeV fm⁵
- t_3 - MeV fm^{3(1+ α)}

These are stored internally with units of:

- t_0 - fm²
- t_1 - fm⁴
- t_2 - fm⁴
- t_3 - fm^{2+3 α}

The class `skyrme_eos_io` uses `o2scl_const::hc_mev_fm` for I/O so that all files contain the parameters in the original units.

The chemical potentials do include the rest mass energy.

`n.ed` and `p.ed` contain `tau_n` and `tau_p` which are in fm⁻⁵, not fm⁻⁴.

The functions for the usual saturation properties are based partly on [Brack85](#).

The Hamiltonian is defined below. $a = 0, b = 1$ gives the standard definition of the Skyrme Hamiltonian (ref?), while $a = 1, b = 0$ contains the modifications suggested by [Osni94](#). Check also [Dutta86](#).

$$\mathcal{H} = \mathcal{H}_{k1} + \mathcal{H}_{k2} + \mathcal{H}_{k3} + \mathcal{H}_{p1} + \mathcal{H}_{p2} + \mathcal{H}_{p3} + \mathcal{H}_{g1} + \mathcal{H}_{g2}$$

The kinetic terms are:

$$\mathcal{H}_{k1} = \frac{\tau_n}{2m_n} + \frac{\tau_p}{2m_p}$$

$$\mathcal{H}_{k2} = n (\tau_n + \tau_p) \left[\frac{t_1}{4} \left(1 + \frac{x_1}{2} \right) + \frac{t_2}{4} \left(1 + \frac{x_2}{2} \right) \right]$$

$$\mathcal{H}_{k3} = (\tau_n n_n + \tau_p n_p) \left[\frac{t_2}{4} \left(\frac{1}{2} + x_2 \right) - \frac{t_1}{4} \left(\frac{1}{2} + x_1 \right) \right]$$

The potential terms are:

$$\mathcal{H}_{p1} = \frac{t_0}{2} \left[\left(1 + \frac{x_0}{2} \right) n^2 - \left(\frac{1}{2} + x_0 \right) (n_n^2 + n_p^2) \right]$$

$$\mathcal{H}_{p2} = \frac{at_3}{6} \left[\left(1 + \frac{x_3}{2} \right) n^\alpha n_n n_p + 2^{\alpha-2} (1 - x_3) (n_n^{\alpha+2} + n_p^{\alpha+2}) \right]$$

$$\mathcal{H}_{p3} = \frac{bt_3}{12} \left[\left(1 + \frac{x_3}{2} \right) n^{\alpha+2} - \left(\frac{1}{2} + x_3 \right) n^\alpha (n_n^2 + n_p^2) \right]$$

The **gradient** terms are displayed here for completeness even though they are not computed in the code:

$$\mathcal{H}_{g1} = \frac{3}{32} [t_1 (1 - x_1) - t_2 (1 + x_2)] [(\nabla n_n)^2 + (\nabla n_p)^2]$$

$$\mathcal{H}_{g2} = \frac{1}{8} \left[3t_1 \left(1 + \frac{x_1}{2} \right) - t_2 \left(1 + \frac{x_2}{2} \right) \right] \nabla n_n \nabla n_p$$

A couple useful definitions:

$$t'_3 = (a + b) t_3$$

$$C = \frac{3}{10m} \left(\frac{3\pi^2}{2} \right)^{2/3}$$

$$\beta = \frac{M}{2} \left[\frac{1}{4} (3t_1 + 5t_2) + t_2 x_2 \right]$$

Models are taken from the references: [Friedrich86](#), [Dutta86](#), [VanGiai81](#), [Chabanat95](#), [Chabanat97](#), [Beiner75](#), [Reinhard95](#), [Bartel79](#), [Dobaczewski94](#), [Osni94](#), [Tondeur84](#) and others. Some of the model parameter sets were obtained from [Danielewicz08](#).

See Mathematica notebook at

```
doc/o2scl/extras/skyrme_eos.nb
doc/o2scl/extras/skyrme_eos.ps
```

Finite temperature documentation

The finite temperature extension is performed using the method [Prakash97](#) (see also the Windsurfing the Fermi Sea proceedings by Prakash).

Returned chemical potentials include the rest mass, and energy densities include the rest mass energy density.

The variables `n.nu` and `p.nu` contain the expressions $(-\mu_n + V_n)/\text{temper}$ and $(-\mu_p + V_p)/\text{temper}$ respectively, where V is the potential **part** of the single particle energy for particle i (i.e. the derivative of the Hamiltonian wrt density while energy density held constant). Equivalently, `n.nu` is just $-n.kf^2/2/mstar$.

For $y > 4$ we use a non-degenerate expansion, and for $y < -40$ we use a Sommerfeld expansion. For $y > 50$ the code fails, but this is well outside the regime of applicability of this model.

Runs the zero temperature code if `temper` ≤ 0.0 .

The finite temperature code does not include attempt to include antiparticles and uses `part::calc_density()`.

Note:

Since this EOS uses the effective masses and chemical potentials in the **fermion** class, the values of `part::non_interacting` for neutrons and protons are set to false in many of the functions.

Todos

Todo

- Make sure that this class properly handles particles for which `inc_rest_mass` is true/false
- What about the spin-orbit units?
- Need to write a function that calculates saturation density?
- Remove use of `mnuc` in `calparfun()`?
- The compressibility could probably use some simplification
- Make sure the finite-temperature **part** is properly tested
- The testing code doesn't work if `err_mode` is 2, probably because of problems in `load()`.

Definition at line 227 of file `skyrme_eos.h`.

Public Member Functions

- `skyrme_eos` (std::string model)
Load the model named 'model'.
- virtual int `calc_temp_e` (fermion_T &ne, fermion_T &pr, const double temper, thermo &th)
Equation of state as a function of densities.
- virtual int `calc_e` (fermion &ne, fermion &pr, thermo <)
Equation of state as a function of density.
- int `calpar` (double gt0=-10.0, double gt3=70.0, double galpha=0.2, double gt1=2.0, double gt2=-1.0)
Calculate t_0, t_1, t_2, t_3 and α from the saturation properties.
- int `load` (std::string model, bool external=false)
Load parameters from model 'model'.
- int `check_landau` (double nb, double m)
Check the Landau parameters for instabilities.
- int `landau_nuclear` (double n0, double m, double &f0, double &g0, double &f0p, double &g0p, double &f1, double &g1, double &f1p, double &g1p)
Calculate the Landau parameters for nuclear matter.
- int `landau_neutron` (double n0, double m, double &f0, double &g0, double &f1, double &g1)
Calculate the Landau parameters for neutron matter.
- virtual const char * `type` ()
Return string denoting type ("skyrme_eos").

Saturation properties

These calculate the various saturation properties exactly from the parameters at any density. These routines often assume that the neutron and proton masses are equal.

- virtual double [feoa](#) (double nb)
Calculate binding energy.
- virtual double [fmsom](#) (double nb)
Calculate effective mass.
- virtual double [fcomp](#) (double nb)
Calculate compressibility.
- virtual double [fesym](#) (const double nb, const double pf=0.5)
Calculate symmetry energy.
- virtual double [fkprime](#) (double nb)
skewness

Data Fields

- double **t0**
- double **t1**
- double **t2**
- double **t3**
- double **x0**
- double **x1**
- double **x2**
- double **x3**
- double **alpha**
- double **a**
- double **b**
- double [W0](#)
Spin-orbit splitting.
- bool [parent_method](#)
Use [hadronic_eos](#) methods for saturation properties.
- **nonrel_fermion** [def_nr_neutron](#)
Default nonrelativistic neutron.
- **nonrel_fermion** [def_nr_proton](#)
Default nonrelativistic proton.

5.27.2 Constructor & Destructor Documentation

5.27.2.1 skyrme_eos (std::string model)

Load the model named 'model'.

See comments under [skyrm_eos::load\(\)](#).

5.27.3 Member Function Documentation

5.27.3.1 int calpar (double gt0 = -10.0, double gt3 = 70.0, double galpha = 0.2, double gt1 = 2.0, double gt2 = -1.0)

Calculate t_0, t_1, t_2, t_3 and α from the saturation properties.

In nuclear matter:

$$E_b = E_b(n_0, M^*, t_0, t_3, \alpha)$$

$$P = P(n_0, M^*, t_0, t_3, \alpha)$$

$$K = K(n_0, M^*, t_3, \alpha) \text{ (the } t_0 \text{ dependence vanishes)}$$

$$M^* = M^*(n_0, t_1, t_2, x_2) \text{ (the } x_1 \text{ dependence cancels),}$$

$$E_{sym} = E_{sym}(x_0, x_1, x_2, x_3, t_0, t_1, t_2, t_3, \alpha)$$

To fix the couplings from the saturation properties, we take n_0, M^*, E_b, K as inputs, and we can fix t_0, t_3, α from the first three relations, then use M^*, E_b to fix t_2 and t_1 . The separation into two solution steps should make for better convergence. All of the x's are free parameters and should be set before the function call.

The arguments `gt0`, `gt3`, `galpha`, `gt1`, and `gt2` are used as initial guesses for t_0 , t_3 , α , t_1 , and t_2 respectively.

Todo

Does this work for both 'a' and 'b' non-zero?

Todo

Compare to similar formulae from [Margueron02](#)

5.27.3.2 int check_landau (double nb, double m)

Check the Landau parameters for instabilities.

This returns zero if there are no instabilities.

5.27.3.3 virtual double fcomp (double nb) [virtual]

Calculate compressibility.

$$K = 10Cn_B^{2/3} + \frac{27}{4}t_0n_B + 40C\beta n_B^{5/3} + \frac{9t'_3}{16}\alpha(\alpha+1)n_B^{1+\alpha} + \frac{9t'_3}{8}(\alpha+1)n_B^{1+\alpha}$$

Reimplemented from [hadronic_eos](#).

5.27.3.4 virtual double feoa (double nb) [virtual]

Calculate binding energy.

$$\frac{E}{A} = Cn_B^{2/3}(1 + \beta n_B) + \frac{3t_0}{8}n_B + \frac{t'_3}{16}n_B^{\alpha+1}$$

5.27.3.5 virtual double fesym (const double nb, const double pf=0.5) [virtual]

Calculate symmetry energy.

If $pf=0.5$, then the exact expression below is used. Otherwise, the method from class [hadronic_eos](#) is used.

$$E_{sym} = \frac{5}{9}Cn^{2/3} + \frac{10Cm}{3} \left[\frac{t_2}{6} \left(1 + \frac{5}{4}x_2 \right) - \frac{1}{8}t_1x_1 \right] n^{5/3} - \frac{t'_3}{24} \left(\frac{1}{2} + x_3 \right) n^{1+\alpha} - \frac{t_0}{4} \left(\frac{1}{2} + x_0 \right) n$$

Reimplemented from [hadronic_eos](#).

5.27.3.6 virtual double fkprime (double nb) [virtual]

skewness

$$2Cn_B^{2/3} (9 - 5/M^*/M) + \frac{27t'_3}{16}n^{1+\alpha}\alpha(\alpha^2 - 1)$$

Reimplemented from [hadronic_eos](#).

5.27.3.7 virtual double fmsom (double *nb*) [virtual]

Calculate effective mass.

$$M^*/M = (1 + \beta n_B)^{-1}$$

5.27.3.8 int landau_neutron (double *n0*, double *m*, double &*f0*, double &*g0*, double &*f1*, double &*g1*)

Calculate the Landau parameters for neutron matter.

Given 'n0' and 'm', this calculates the Landau parameters in neutron matter as given in [Margueron02](#)

Todo

This needs to be checked

(Checked once on 11/05/03)

5.27.3.9 int landau_nuclear (double *n0*, double *m*, double &*f0*, double &*g0*, double &*f0p*, double &*g0p*, double &*f1*, double &*g1*, double &*f1p*, double &*g1p*)

Calculate the Landau parameters for nuclear matter.

Given n0 and m, this calculates the Landau parameters in nuclear matter as given in [Margueron02](#)

Todo

This needs to be checked.

(Checked once on 11/05/03)

5.27.3.10 int load (std::string *model*, bool *external* = false)

Load parameters from model 'model'.

Presently accepted values from file skdata/model_list:

```
word[] models 164
a b BSk1 BSk10 BSk11 BSk12 BSk13 BSk14 BSk16 BSk2 BSk2p BSk3
BSk4 BSk5 BSk6 BSk7 BSk8 BSk9 E Es FitA FitB FitK FitKs FitL
Gs KDE0v KDE0v1 LNS Ly5 MSk1 MSk2 MSk3 MSk4 MSk5 MSk5s MSk6
MSk7 MSk8 MSk9 MSKa mst0.81 mst0.90 mst1 NRAPR NRAPR2 PeEVs
PeHF PeSIs QMC1 QMC2 QMC3 RATP Rs SGI SGII SI SII SIII SIIIs
SIp SIV SK255 SK272 SKI1 SKI2 SKI3 SKI4 SKI5 SKI6 SkkT8 SkM
SkM1 SkMDIx0 SkMDIx1 SkMDIxml SkMDIx2 SkMP SkMs SkNF1 SkNF2
SkO SkOp SkP SKRA SkSC1 SkSC10 SkSC11 SkSC14 SkSC15 SkSC2
SkSC3 SkSC4 SkSC4o SkSC5 SkSC6 SkT SkT1 SkT1s SkT2 SkT3 SkT3s
SkT4 SkT5 SkT6 SkT7 SkT8 SkT9 SkTK SkX SkXce SkXm Skxs15
Skxs20 Skxs25 Skyrmelp SKz0 SKz1 SKz2 SKz3 SKz4 SKzm1 SLy0
SLy1 SLy10 SLy2 SLy230a SLy230b SLy3 SLy4 SLy5 SLy6 SLy7 SLy8
SLy9 SV SVI SVII SV-K241 SV-kap06 SV-mas10 SV-sym32 SV-bas
SV-K218 SV-kap00 SV-mas07 SV-min SV-sym34 SV-K226 SV-kap02
SV-mas08 SV-sym28 SV-tls T v070 v075 v080 v090 v100 v105 v110 Z
Zs Zss
```

If `external` is true, then `model` is the filename (relative to the current directory) of the file containing the model parameters

5.27.4 Field Documentation

5.27.4.1 bool parent_method

Use [hadronic_eos](#) methods for saturation properties.

This can be set to true to check the difference between the exact expressions and the numerical values from class [hadronic_eos](#).

Definition at line 385 of file `skyrme_eos.h`.

5.27.4.2 double W0

Spin-orbit splitting.

This is unused, but included for possible future use and present in the internally stored models.

Definition at line 238 of file `skyrme_eos.h`.

The documentation for this class was generated from the following file:

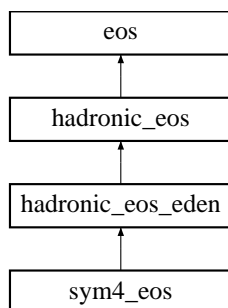
- `skyrme_eos.h`

5.28 sym4_eos Class Reference

Construct an EOS with an arbitrary choice for the terms in the symmetry energy that are quartic in the isospin asymmetry.

```
#include <sym4_eos.h>
```

Inheritance diagram for `sym4_eos`:



5.28.1 Detailed Description

Construct an EOS with an arbitrary choice for the terms in the symmetry energy that are quartic in the isospin asymmetry.

References:

Created for [Steiner06](#).

Definition at line 192 of file `sym4_eos.h`.

Public Member Functions

- int [set_base_eos](#) ([sym4_eos_base](#) &seb)
Set the base equation of state.
 - virtual int [test_eos](#) (**fermion** &ne, **fermion** &pr, **thermo** <h)
Test the equation of state.
 - virtual int [calc_e](#) (**fermion** &ne, **fermion** &pr, **thermo** <h)
-

Equation of state as a function of density.

Data Fields

- double [alpha](#)
The strength of the quartic terms.

Protected Attributes

- [sym4_eos_base * sp](#)
The base equation of state to use.

5.28.2 Member Function Documentation

5.28.2.1 virtual int test_eos (fermion & ne, fermion & pr, thermo & lth) [virtual]

Test the equation of state.

This compares the chemical potentials from calc_e_sep() to their finite-difference approximations in order to ensure that the separation into potential and kinetic parts is done properly.

The documentation for this class was generated from the following file:

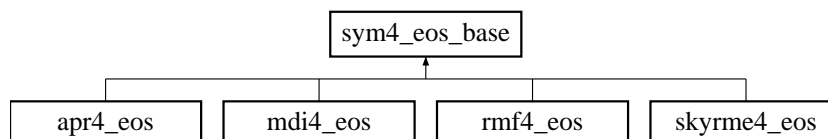
- sym4_eos.h

5.29 sym4_eos_base Class Reference

A class to compute quartic contributions to the symmetry energy [abstract base].

```
#include <sym4_eos.h>
```

Inheritance diagram for sym4_eos_base::



5.29.1 Detailed Description

A class to compute quartic contributions to the symmetry energy [abstract base].

The standard usage is that a child class implements the virtual function [calc_e_sep\(\)](#) which is then used by [calc_e_alpha\(\)](#) and [calc_muhat\(\)](#). These functions are employed by [sym4_eos](#) to compute the EOS for an arbitrary dependence of the symmetry energy on the isospin.

References:

Created for [Steiner06](#).

Definition at line 52 of file sym4_eos.h.

Public Member Functions

- virtual int `calc_e_alpha` (**fermion** &ne, **fermion** &pr, **thermo** <h, double &alphak, double &alphap, double &alphan, double &diff_kin, double &diff_pot, double &ed_kin_nuc, double &ed_pot_nuc)
Compute alpha at the specified density.
- virtual double `calc_muhat` (**fermion** &ne, **fermion** &pr)
Compute $\hat{\mu}$, the out-of-whack parameter.
- virtual int `calc_e_sep` (**fermion** &ne, **fermion** &pr, double &ed_kin, double &ed_pot, double &mu_n_kin, double &mu_p_kin, double &mu_n_pot, double &mu_p_pot)=0
Compute the potential and kinetic parts separately (to be overwritten in children).

Protected Attributes

- **fermion** `e`
An electron for the computation of the $\hat{\mu}$.

The documentation for this class was generated from the following file:

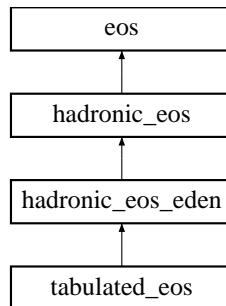
- sym4_eos.h

5.30 tabulated_eos Class Reference

EOS from a **table**.

```
#include <tabulated_eos.h>
```

Inheritance diagram for tabulated_eos::



5.30.1 Detailed Description

EOS from a **table**.

This assumes a symmetry energy which depends quadratically on the isospin asymmetry in order to construct an EOS from a **table** of baryon density and energy per baryon for both nuclear and pure neutron matter.

Note: If using a tabulated EOS to compute derivatives (like the compressibility which effectively requires a second derivative), it is important to tabulate the EOS precisely enough to ensure that the derivatives are accurate. In the case of ensuring that the compressibility at saturation density is well reproduced, I have needed the EOS to be specified with at least 6 digits of precision on a grid at least as small as 0.002 fm^{-3} .

Definition at line 53 of file tabulated_eos.h.

Public Member Functions

- int **free_table** ()
- virtual int **calc_e** (fermion &ne, fermion &pr, thermo &th)
Equation of state as a function of density.
- template<class vec_t >
int **set_eos** (size_t n, vec_t &rho, vec_t &Enuc, vec_t &Eneut)
Set the EOS through vectors specifying the densities and energies.
- template<class vec_t >
int **set_eos** (size_t n_nuc, vec_t &rho_nuc, vec_t &E_nuc, size_t n_neut, vec_t &rho_neut, vec_t &E_neut)
Set the EOS through vectors specifying the densities and energies.
- **table** & **get_nuc_table** ()
Return the internal table.
- **table** & **get_neut_table** ()
Return the internal table.

Protected Attributes

- bool **table_alloc**
True if the table has been allocated.
- bool **one_table**
If true, then tnuc and tneut point to the same table.

The EOS tables

- **table** * **tnuc**
- **table** * **tneut**

Strings for the column names

- std::string **srho_nuc**
- std::string **srho_neut**
- std::string **snuc**
- std::string **sneut**

The documentation for this class was generated from the following file:

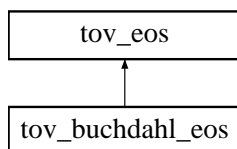
- tabulated_eos.h

5.31 tov_buchdahl_eos Class Reference

The Buchdahl EOS for the TOV solver.

```
#include <tov_eos.h>
```

Inheritance diagram for tov_buchdahl_eos::



5.31.1 Detailed Description

The Buchdahl EOS for the TOV solver.

Given the `eos`

$$\rho = 12\sqrt{p_*P} - 5P$$

the TOV equation has an analytical solution

$$R = (1 - \beta)\sqrt{\frac{\pi}{288p_*G(1 - 2\beta)}}$$

where $\beta = GM/R$.

The central pressure and energy density are

$$P_c = 36p_*\beta^2$$

$$\rho_c = 72p_*\beta(1 - 5\beta/2)$$

Physical solutions are obtained only for $P < 25p_*/144$ and $\beta < 1/6$.

(Lattimer & Prakash, 2001)

Todo

Fix the reference above

Idea for future

Figure out what to do with the `buchfun()` function

Definition at line 324 of file `tov_eos.h`.

Public Member Functions

- virtual int `get_edn` (double P, double &e, double &nb)
Given the pressure, produce the energy and number densities.
- virtual int `get_aux` (double P, size_t &np, `ovector_base` &auxp)
Given the pressure, produce all the remaining quantities.
- virtual int `get_names` (size_t &np, std::vector< std::string > &pnames)
Fill a list with strings for the names of the remaining quantities.

Data Fields

- double `Pstar`
The parameter with units of pressure in units of solar masses per km cubed (default value 3.2×10^{-5}).

5.31.2 Member Function Documentation

5.31.2.1 virtual int `get_edn` (double P, double & e, double & nb) [inline, virtual]

Given the pressure, produce the energy and number densities.

If the baryon density is not specified, it should be set to zero or `baryon_column` should be set to false

Reimplemented from `tov_eos`.

Definition at line 347 of file `tov_eos.h`.

The documentation for this class was generated from the following file:

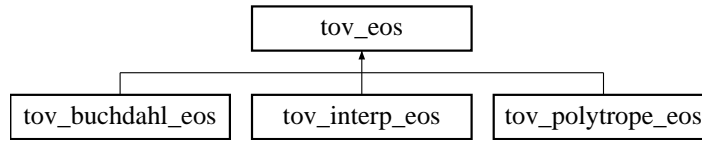
- `tov_eos.h`

5.32 `tov_eos` Class Reference

A EOS base class for the TOV solver.

```
#include <tov_eos.h>
```

Inheritance diagram for `tov_eos`:



5.32.1 Detailed Description

A EOS base class for the TOV solver.

Definition at line 54 of file `tov_eos.h`.

Public Member Functions

- virtual int [get_edn](#) (double *P*, double &*e*, double &*nb*)
Given the pressure, produce the energy and number densities.
- virtual int [get_aux](#) (double *P*, size_t &*np*, **ovector_base** &*auxp*)
Given the pressure, produce all the remaining quantities.
- virtual int [get_names](#) (size_t &*np*, std::vector< std::string > &*pnames*)
Fill a list with strings for the names of the remaining quantities.

Data Fields

- int [verbose](#)
control for output (default 1)
- bool [baryon_column](#)
Set to true if the baryon density is provided in the EOS (default false).

5.32.2 Member Function Documentation

5.32.2.1 virtual int [get_edn](#) (double *P*, double & *e*, double & *nb*) [`inline`, `virtual`]

Given the pressure, produce the energy and number densities.

If the baryon density is not specified, it should be set to zero or [baryon_column](#) should be set to false

Reimplemented in [tov_interp_eos](#), [tov_buchdahl_eos](#), and [tov_polytrope_eos](#).

Definition at line 74 of file `tov_eos.h`.

The documentation for this class was generated from the following file:

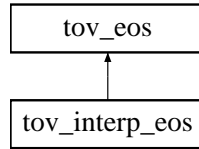
- `tov_eos.h`

5.33 `tov_interp_eos` Class Reference

An EOS for the TOV solver using simple linear interpolation and a default low-density EOS.

```
#include <tov_eos.h>
```

Inheritance diagram for `tov_interp_eos`:



5.33.1 Detailed Description

An EOS for the TOV solver using simple linear interpolation and a default low-density EOS.

Internally, energy and pressure are stored in units of solar masses per cubic kilometer and baryon density is stored in units of fm^{-3} . The user-specified EOS **table** is left as is, and unit conversion is performed as needed in `get_eden()` and other functions so that results are returned in the units specified by `set_units()`.

The function `set_units()` needs to be called before either of the functions `get_eden()` or `get_eden_ld()` are called. The function `set_units()` may be called after calling either the `read_table()` functions or the `set_low_density_eos()` function.

Definition at line 118 of file `tov_eos.h`.

Public Member Functions

- virtual int `get_eden` (double pres, double &ed, double &nb)
Given the pressure, produce the energy and number densities.
- virtual int `get_eden_user` (double pres, double &ed, double &nb)
Given the pressure, produce the energy and number densities from the user-specified EOS.
- virtual int `get_eden_ld` (double pres, double &ed, double &nb)
Given the pressure, produce the energy and number densities from the low-density EOS.
- virtual int `get_aux` (double P, size_t &nv, **ovector_base** &auxp)
Given the pressure, produce all the remaining quantities.
- virtual int `get_names` (size_t &np, std::vector< std::string > &pnames)
Fill a list with strings for the names of the remaining quantities.
- int `read_table` (**table** &eosat, std::string s_cole="ed", std::string s_colp="pr", std::string s_colnb="nb")
*Specify the EOS through a **table**.*
- int `read_table_file` (std::string eosfn, std::string s_cole="ed", std::string s_colp="pr", std::string s_colnb="nb")
*Specify the EOS through a **table** in a file.*
- int `set_low_density_eos` (bool s_ldeos, std::string s_nvpath, int s_nvcole=0, int s_nvcolp=1, int s_nvcolnb=2)
Set the low-density EOS.
- int `set_units` (double s_efactor, double s_pfactor, double s_nfactor)
Set the units of the user-specified EOS.
- int `set_units` (std::string leunits="", std::string lpunits="", std::string lnunits="")
Set the units of the user-specified EOS.
- int `get_transition` (double &pLOW, double &ptrans, double &phi)
Return limiting and transition pressures.
- int `set_transition` (double ptrans, double pw)
Set the transition pressure and "width".

Protected Member Functions

- int `check_eos` ()
Check that the EOS is valid.
- void `interp` (const **ovector_base** &x, const **ovector_base** &y, double xx, double &yy, int n1, int n2)
Linear EOS interpolation.

Protected Attributes

- **base_ioc** [bio](#)
A base I/O object for reading EOSs.
- **table_units_io_type** [table_units_io](#)
*For reading the **table**.*

Low-density EOS

- **bool** [ldeos](#)
true if we are using the low-density [eos](#) (false)
- **bool** [ldeos_read](#)
Low-density EOS switch.
- **std::string** [ldpath](#)
the path to the low-density EOS
- **int** [ldcole](#)
column in low-density [eos](#) for energy density
- **int** [ldcolp](#)
column in low-density [eos](#) for pressure
- **int** [ldcolnb](#)
column in low-density [eos](#) for baryon density
- **table_units** * [ld_eos](#)
file containing low-density EOS
- **double** [presld](#)
highest pressure in low-density EOS
- **double** [eld](#)
highest energy density in low-density EOS
- **double** [nblld](#)
highest baryon density in low-density EOS
- **double** [prest](#)
Transition pressure.
- **double** [pwidth](#)
Transition width.

User EOS

- **table** * [eost](#)
file containing [eos](#)
- **int** [nfile](#)
number of lines in [eos](#) file
- **int** [cole](#)
column for energy density in [eos](#) file
- **int** [colp](#)
column for pressure in [eos](#) file
- **int** [colnb](#)
column for baryon density in [eos](#) file
- **bool** [eos_read](#)
True if an EOS has been specified.

Units

- **std::string** [eunits](#)
Units for energy density.
- **std::string** [punits](#)
Units for pressure.
- **std::string** [nunits](#)
Units for baryon density.
- **double** [efactor](#)
unit conversion factor for energy density (default 1.0)
- **double** [pfactor](#)
unit conversion factor for pressure (default 1.0)
- **double** [nfactor](#)
unit conversion factor for baryon density (default 1.0)

5.33.2 Member Function Documentation

5.33.2.1 `int get_transition(double &plow, double &ptrans, double &phi)`

Return limiting and transition pressures.

Returns, in order:

- the highest pressure in the low-density EOS
- the transition pressure
- the lowest pressure in the high-density EOS

5.33.2.2 `int set_transition(double ptrans, double pw)`

Set the transition pressure and "width".

Sets the transition pressure and the width (specified as a number greater than unity in pw) of the transition between the two EOSs. The transition is done smoothly using linear interpolation between $P = p_{\text{trans}}/p_{\text{mathrmpw}}$ and $P = p_{\text{trans}} \times p_{\text{mathrmpw}}$.

5.33.3 Field Documentation

5.33.3.1 `bool ldeos_read` [protected]

Low-density EOS switch.

This is `true` if the `ldeos` has been read by `set_ldeos`. This is useful, since then we know whether or not we need to free the memory for the LD EOS in the destructor

Definition at line 221 of file `tov_eos.h`.

The documentation for this class was generated from the following file:

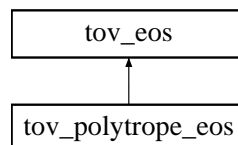
- `tov_eos.h`

5.34 `tov_polytrope_eos` Class Reference

Standard polytropic EOS $p = K\rho^{1+1/n}$.

```
#include <tov_eos.h>
```

Inheritance diagram for `tov_polytrope_eos`:



5.34.1 Detailed Description

Standard polytropic EOS $p = K\rho^{1+1/n}$.

Any units are permissible, but if this is to be used with `tov_solve`, then the units of K must be consistent with the units set in `tov_solve::set_units()`.

Definition at line 391 of file `tov_eos.h`.

Public Member Functions

- virtual int `get_eden` (double *P*, double &*e*, double &*nb*)
Given the pressure, produce the energy and number densities.
- virtual int `get_aux` (double *P*, size_t &*np*, **ovector_base** &*auxp*)
Given the pressure, produce all the remaining quantities.
- virtual int `get_names` (size_t &*np*, std::vector< std::string > &*pnames*)
Fill a list with strings for the names of the remaining quantities.

Data Fields

- double `K`
Coefficient (default 1.0).
- double `n`
Index (default 3.0).

5.34.2 Member Function Documentation

5.34.2.1 virtual int `get_eden` (double *P*, double &*e*, double &*nb*) [`inline`, `virtual`]

Given the pressure, produce the energy and number densities.

If the baryon density is not specified, it should be set to zero or `baryon_column` should be set to false

Reimplemented from `tov_eos`.

Definition at line 416 of file `tov_eos.h`.

The documentation for this class was generated from the following file:

- `tov_eos.h`

5.35 `tov_solve` Class Reference

Class to solve the Tolman-Oppenheimer-Volkov equations.

```
#include <tov_solve.h>
```

5.35.1 Detailed Description

Class to solve the Tolman-Oppenheimer-Volkov equations.

Integrate Tolman-Oppenheimer-Volkov (TOV) equations

The present code, as demonstrated in the tests, gives the correct central pressure and energy density of the analytical solution by Buchdahl to within less than 1 part in 10^5 .

The TOV equations (i.e. Einstein's equations for a static spherically symmetric object) are

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon$$

$$\frac{dP}{dr} = -\frac{G\varepsilon m}{r^2} \left(1 + \frac{P}{\varepsilon}\right) \left(1 + \frac{4\pi P r^3}{m}\right) \left(1 - \frac{2Gm}{r}\right)^{-1}$$

where r is the radial coordinate, $m(r)$ is the mass enclosed within a radius r , and $\varepsilon(r)$ and $P(r)$ are the energy density and pressure at r , and G is the gravitational constant. The boundary conditions are $m(r=0) = 0$ the condition $P(r=R) = 0$ for some fixed radius R . These boundary conditions give a series of solutions to the TOV equations as a function of the radius, although they do not necessarily have a solution for all radii.

The gravitational mass is given by

$$M_G = \int_0^R 4\pi r^2 \varepsilon dr$$

while the baryonic mass is given by

$$M_B = \int_0^R 4\pi r^2 n_B m_B \left(1 - \frac{Gm}{r}\right)^{-1/2} dr$$

where $n_B(r)$ is the baryon number density at radius r and m_B is the mass of one baryon.

The gravitational potential, $\Phi(r)$ can be determined from

$$\frac{d\Phi}{dr} = -\frac{1}{\varepsilon} \frac{dP}{dr} \left(1 + \frac{P}{\varepsilon}\right)^{-1}$$

The proper boundary condition for the gravitational potential is

$$\Phi(r = R) = \frac{1}{2} \ln \left(1 - \frac{2GM}{R}\right)$$

The equation of state may be changed at any time.

Note that the pressure in the low-density [eos](#) is not strictly increasing! (see at $P=4.3e-10$)

The surface gravity is computed as

$$g = \frac{GM}{R^2} \left(1 - \frac{2GM}{R}\right)^{-1/2}$$

which is given in inverse kilometers and the redshift is

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

which is unitless.

Screen output

- `verbose=0` - Nothing (even if an error occurs).
- `verbose=1` - Some basic information and any errors or warnings.
- `verbose=2` - For each profile computation, information at every kilometer.
- `verbose=3` - Profile information every 20 grid points. A keypress is required after each profile.

Note:

The function `star_fun()` returns `gsl_efailed` without calling the error handler in the case that the solver can recover gracefully from, for example, a negative pressure.

Todo

- The error handler is called in `tov_solve()`derivs for pressures less than the minimum even in normal circumstances. This should be fixed, so that errors are more rare
- baryon mass doesn't work for `fixed()` (This may be fixed. We should make sure it's tested.)
- Combine `maxoutsize` and `kmax`?
- Document column naming issues
- Document surface gravity and redshift

Idea for future

- Turn numbers in `max()` function into variables

Definition at line 146 of file `tov_solve.h`.

Public Member Functions

- int [solution_check](#) ()
Check the solution (unfinished).
- int [set_units](#) (double s_efactor=1.0, double s_pfactor=1.0, double s_nbfactor=1.0)
Set units.
- int [set_units](#) (std::string eunits="", std::string punits="", std::string nunits="")
Set units.
- int [set_kmax](#) (int s_maxoutsize=400, int s_kmax=40000)
Set maximum storage for integration.
- int [set_eos](#) ([tov_eos](#) &ter)
Set the EOS to use.
- int [set_mroot](#) ([mroot](#)< int, [mm_funct](#)< int > > &s_mrp)
Set solver.
- int [set_minimize](#) ([minimize](#)< int, [funct](#)< int > > &s_mp)
Set minimizer.
- int [set_stepper](#) ([adapt_step](#)< int, [ode_funct](#)< int > > &sap)
Set the adaptive stepper.

Results

- [table_units](#) & [get_results](#) ()
Return the results data [table](#).

Actual solution of equations

- int [mvsr](#) ()
Calculate the mass vs. radius curve.
- int [fixed](#) (double d_tmass)
Calculate the profile of a star with fixed mass.
- int [max](#) ()
Calculate the profile of the maximum mass star.

Data Fields

- [gsl_min_brent](#)< int, [funct](#)< int > > [def_min](#)
The default minimizer.
- [gsl_mroot_hybrids](#)< int, [mm_funct](#)< int > > [def_solver](#)
The default solver.
- [gsl_astep](#)< int, [ode_funct](#)< int > > [def_stepper](#)
The default adaptive stepper.
- bool [compute_ang_vel](#)
If true, compute the angular velocity (default false).
- double [cap_omega](#)
The angular velocity.
- double [schwarz_km](#)
The schwarzschild radius in km.

Basic properties

- double [mass](#)
mass
- double [rad](#)
radius
- double [bmass](#)
baryonic mass
- double [gpot](#)
gravitational potential

Solution parameters

- bool **generel**
Use general relativistic version (default true).
- bool **calcpot**
calculate the gravitational potential and the enclosed baryon mass (default false)
- double **hmin**
smallest allowed radial stepsize (default 1.0e-4)
- double **hmax**
largest allowed radial stepsize (default 0.05)
- double **hstart**
initial radial stepsize (default 4.0e-3)
- int **verbose**
control for output (default 1)
- double **maxradius**
maximum radius for integration in km (default 60)

Mass versus radius parameters

- double **prbegin**
Beginning pressure (default 7.0e-7).
- double **prend**
Ending pressure (default 8.0e-3).
- double **princ**
Increment for pressure (default 1.1).
- bool **logmode**
Use 'princ' as a multiplier, not an additive increment (default true).
- double **prguess**
Guess for central pressure in solar masses per km³ (default 5.2×10^{-5}).

Fixed mass parameters

- double **tmass**
Target mass.

Protected Member Functions

- int **make_unique_name** (std::string &col, std::vector< std::string > &cnames)
Ensure col does not match strings in cnames.
- virtual int **derivs** (double x, size_t nv, const **ovector_base** &y, **ovector_base** &dydx, int &pa)
The ODE step function.
- virtual int **derivs_ang_vel** (double x, size_t nv, const **ovector_base** &y, **ovector_base** &dydx, int &pa)
The ODE step function for the angular velocity.
- virtual int **profile_out** (double xx)
Output a stellar profile.
- virtual double **maxfun** (double maxx, int &pa)
The minimizer function to compute the maximum mass.
- virtual int **starfun** (size_t ndvar, const **ovector_base** &ndx, **ovector_base** &ndy, int &pa)
The solver function to compute the stellar profile.
- int **ang_vel** ()
Compute the angular velocity.

Protected Attributes

- **to_v_eos** * **te**
The EOS.
- bool **eos_set**
True if the EOS has been set.

- **base_ioc** `bio`
Define some necessary I/O objects.
- **int** `kmax`
maximum storage size (default 40000)
- **int** `maxoutsize`
maximum size of output file (default 400)
- **double** `presmin`
Smallest allowed pressure for integration (default: -100).
- **table_units** `out_table`
The output table.
- **mroot**< `int`, **mm_funct**< `int` > > * `mroot_ptr`
The solver.
- **minimize**< `int`, **funct**< `int` > > * `min_ptr`
The minimizer.
- **adapt_step**< `int`, **ode_funct**< `int` > > * `as_ptr`
The default adaptive stepper.
- **smart_interp** `smi`
Interpolation object for `derivs_ang_vel()`.

User EOS

- **std::string** `eunits`
Units for energy density.
- **std::string** `punits`
Units for pressure.
- **std::string** `nunits`
Units for baryon density.
- **double** `efactor`
unit conversion factor for energy density (default 1.0)
- **double** `pfactor`
unit conversion factor for pressure (default 1.0)
- **double** `nfactor`
unit conversion factor for baryon density (default 1.0)

Integration storage

- **ovector** `rky` [6]
- **ovector** `rkx`
- **ovector** `rkdydx` [6]

5.35.2 Member Function Documentation

5.35.2.1 `int set_kmax (int s_maxoutsize = 400, int s_kmax = 40000)`

Set maximum storage for integration.

The variable `s_kmax` is the maximum number of radial integration stepsk while `s_maxoutsize` is the maximum number of points that will be output for any profile.

If `s_kmax` is less than zero, there is no limit on the number of radial steps.

5.35.2.2 `int set_units (std::string eunits = "", std::string punits = "", std::string nunits = "")`

Set units.

Valid entries for the units of energy density and pressure are:

- "g/cm^3"
- "erg/cm^3"

- "MeV/fm³"
- "fm⁻⁴"
- "Msun/km³" (i.e. solar masses per cubic kilometer)

Valid entries for the units of baryon density are:

- "m⁻³"
- "cm⁻³"
- "fm⁻³"

5.35.3 Field Documentation

5.35.3.1 **base_ioc bio** [protected]

Define some necessary I/O objects.

Idea for future

Is this really required?

Definition at line 343 of file `to_v_solve.h`.

5.35.3.2 **bool general**

Use general relativistic version (default true).

These parameters can be changed at any time.

Definition at line 167 of file `to_v_solve.h`.

5.35.3.3 **double presmin** [protected]

Smallest allowed pressure for integration (default: -100).

This can't be much smaller since we need to compute numbers near $\exp(-\text{presmin})$

Definition at line 372 of file `to_v_solve.h`.

5.35.3.4 **double prguess**

Guess for central pressure in solar masses per km³ (default 5.2×10^{-5}).

This guess is used in the function `fixed()`.

Definition at line 200 of file `to_v_solve.h`.

5.35.3.5 **double tmass**

Target mass.

Use negative values to indicate a mass measured relative to the maximum mass. For example, if the EOS has a maximum mass of 2.0, then -0.15 will give the profile of a 1.85 solar mass star.

Definition at line 213 of file `to_v_solve.h`.

The documentation for this class was generated from the following file:

- `to_v_solve.h`

Index

a
 schematic_eos, 70
acausal
 cold_nstar, 31
acausal_ed
 cold_nstar, 31
acausal_pr
 cold_nstar, 31
allow_urca
 cold_nstar, 31
apr4_eos, 9
apr_eos, 10
 fcomp, 13
 fesym_diff, 13
 gradient_qij2, 13
 parent_method, 14
 select, 13

bag_eos, 14
 calc_temp_e, 15
 calc_temp_p, 15
bio
 tov_solve, 92
bps_eos, 15
 calc_density, 17
 calc_pressure, 17
 e, 17
 mass_formula, 17

calc_cr
 rmf_eos, 64
calc_density
 bps_eos, 17
 nse_eos, 56
calc_e
 rmf_eos, 64
calc_edensity
 hadronic_eos, 40
calc_eq_e
 ddc_eos, 33
calc_eq_p
 rmf_eos, 65
calc_eq_temp_p
 cfl6_eos, 20
 cfl_njl_eos, 25
calc_esym
 hadronic_eos, 40, 41
calc_mu
 nse_eos, 56
calc_p
 nambuyl_eos, 53
 rmf_eos, 65
calc_press_on2
 hadronic_eos, 41
calc_pressure
 bps_eos, 17
 hadronic_eos, 41
calc_temp_e
 bag_eos, 15
calc_temp_p
 bag_eos, 15
 nambuyl_eos, 53
 rmf_eos, 65
calc_urca
 cold_nstar, 30
calpar
 skyrme_eos, 75
cfl6_eos, 18
 calc_eq_temp_p, 20
 eigenvalues6, 20
 make_matrices, 21
cfl_njl_eos, 21
 calc_eq_temp_p, 25
 def_quartic, 26
 eigenvalues, 25
 gap_limit, 26
 gapped_eigenvalues, 25
 GD, 26
 inte_epsabs, 27
 inte_epsrel, 27
 inte_npoints, 27
 integrands, 25
 set_parameters, 26
 zerot, 27
check_landau
 skyrme_eos, 76
check_naturalness
 rmf_eos, 65
cold_nstar, 27
 acausal, 31
 acausal_ed, 31
 acausal_pr, 31
 allow_urca, 31
 calc_urca, 30
 deny_urca, 31
 min_bad, 31
 set_eos, 30
 set_n_and_p, 30
 set_tov, 30

ddc_eos, 31
 calc_eq_e, 33
def_deriv
 hadronic_eos, 44
def_deriv2
 hadronic_eos, 44

- def_mroot
 - hadronic_eos, 44
- def_quartic
 - cfl_njl_eos, 26
- def_sat_mroot
 - rmf_eos, 68
- def_sat_root
 - hadronic_eos, 44
- deny_urca
 - cold_nstar, 31
- e
 - bps_eos, 17
- eigenvalues
 - cfl_njl_eos, 25
- eigenvalues6
 - cfl6_eos, 20
- eo_a_zero_den
 - schematic_eos, 70
- eos, 33
- fcomp
 - apr_eos, 13
 - hadronic_eos, 41
 - skyrme_eos, 76
- fcomp_fields
 - rmf_eos, 66
- feoa
 - hadronic_eos, 41
 - skyrme_eos, 76
- fesym
 - hadronic_eos, 41
 - skyrme_eos, 76
- fesym_diff
 - apr_eos, 13
 - hadronic_eos, 41
- fesym_fields
 - rmf_eos, 66
- fesym_slope
 - hadronic_eos, 41
- field_eqs
 - rmf_eos, 67
- field_eqsT
 - rmf_eos, 67
- fix_saturation
 - rmf_eos, 67
- fkprime
 - hadronic_eos, 42
 - skyrme_eos, 76
- fkprime_fields
 - rmf_eos, 67
- fmsom
 - hadronic_eos, 42
 - skyrme_eos, 76
- fn0
 - hadronic_eos, 42
- fromqq
 - nambu_jl_eos, 54
- fsprime
 - hadronic_eos, 42
- gap_limit
 - cfl_njl_eos, 26
- gapfunms
 - nambu_jl_eos, 53
- gapfunmsT
 - nambu_jl_eos, 53
- gapfunqq
 - nambu_jl_eos, 53
- gapfunqqT
 - nambu_jl_eos, 53
- gapped_eigenvalues
 - cfl_njl_eos, 25
- GD
 - cfl_njl_eos, 26
- gen_potential_eos, 34
- generel
 - to_v_solve, 92
- get_edn
 - to_v_buchdahl_eos, 82
 - to_v_eos, 83
 - to_v_polytrope_eos, 87
- get_fields
 - rmf_eos, 67
- get_transition
 - to_v_interp_eos, 86
- gradient_qij
 - hadronic_eos, 42
- gradient_qij2
 - apr_eos, 13
- hadronic_eos, 38
 - calc_edensity, 40
 - calc_esym, 40, 41
 - calc_press_on2, 41
 - calc_pressure, 41
 - def_deriv, 44
 - def_deriv2, 44
 - def_mroot, 44
 - def_sat_root, 44
 - fcomp, 41
 - feoa, 41
 - fesym, 41
 - fesym_diff, 41
 - fesym_slope, 41
 - fkprime, 42
 - fmsom, 42
 - fn0, 42
 - fsprime, 42
 - gradient_qij, 42
 - saturation_matter_e, 43
 - set_sat_deriv2, 44

- hadronic_eos_edens, 44
- hadronic_eos_pres, 45
- hadronic_eos_temp, 46
- hadronic_eos_temp_edens, 47
- hadronic_eos_temp_pres, 48
- inte_epsabs
 - cfl_njl_eos, 27
- inte_epsrel
 - cfl_njl_eos, 27
- inte_npoints
 - cfl_njl_eos, 27
- integrands
 - cfl_njl_eos, 25
- landau_neutron
 - skyrme_eos, 77
- landau_nuclear
 - skyrme_eos, 77
- ldeos_read
 - to_v_interp_eos, 86
- limit
 - nambujl_eos, 54
- load
 - rmf_eos, 67
 - skyrme_eos, 77
- make_matrices
 - cfl6_eos, 21
- mass_formula
 - bps_eos, 17
- mdi4_eos, 49
- min_bad
 - cold_nstar, 31
- mnuc
 - rmf_eos, 68
- n_charge
 - rmf_eos, 68
- nambujl_eos, 50
 - calc_p, 53
 - calc_temp_p, 53
 - fromqq, 54
 - gapfunms, 53
 - gapfunmsT, 53
 - gapfunqq, 53
 - gapfunqqT, 53
 - limit, 54
 - set_parameters, 53
 - set_quarks, 54
- nambujl_eos::njtp_s, 54
- naturalness_limits
 - rmf_eos, 68
- nse_eos, 55
 - calc_density, 56
 - calc_mu, 56
- parent_method
 - apr_eos, 14
 - skyrme_eos, 78
- presmin
 - to_v_solve, 92
- prguess
 - to_v_solve, 92
- quark_eos, 56
- rmf4_eos, 57
- rmf_delta_eos, 58
 - saturation, 59
- rmf_eos, 60
 - calc_cr, 64
 - calc_e, 64
 - calc_eq_p, 65
 - calc_p, 65
 - calc_temp_p, 65
 - check_naturalness, 65
 - def_sat_mroot, 68
 - fcomp_fields, 66
 - fesym_fields, 66
 - field_eqs, 67
 - field_eqsT, 67
 - fix_saturation, 67
 - fkprime_fields, 67
 - get_fields, 67
 - load, 67
 - mnuc, 68
 - n_charge, 68
 - naturalness_limits, 68
 - saturation, 68
- saturation
 - rmf_delta_eos, 59
 - rmf_eos, 68
- saturation_matter_e
 - hadronic_eos, 43
- schematic_eos, 69
 - a, 70
 - eo_a_zeroden, 70
 - set_a_from_mstar, 70
- select
 - apr_eos, 13
- set_a_from_mstar
 - schematic_eos, 70
- set_eos
 - cold_nstar, 30
- set_kmax
 - to_v_solve, 91
- set_n_and_p
 - cold_nstar, 30
- set_parameters
 - cfl_njl_eos, 26
 - nambujl_eos, 53

set_quarks
 nambu_jl_eos, [54](#)

set_sat_deriv2
 hadronic_eos, [44](#)

set_tov
 cold_nstar, [30](#)

set_transition
 tov_interp_eos, [86](#)

set_units
 tov_solve, [91](#)

skyrme4_eos, [70](#)

skyrme_eos, [71](#)
 calpar, [75](#)
 check_landau, [76](#)
 fcomp, [76](#)
 feoa, [76](#)
 fesym, [76](#)
 fkprime, [76](#)
 fmsom, [76](#)
 landau_neutron, [77](#)
 landau_nuclear, [77](#)
 load, [77](#)
 parent_method, [78](#)
 skyrme_eos, [75](#)
 skyrme_eos, [75](#)
 W0, [78](#)

sym4_eos, [78](#)
 test_eos, [79](#)

sym4_eos_base, [79](#)

tabulated_eos, [80](#)

test_eos
 sym4_eos, [79](#)

tmass
 tov_solve, [92](#)

tov_buchdahl_eos, [81](#)
 get_edn, [82](#)

tov_eos, [83](#)
 get_edn, [83](#)

tov_interp_eos, [83](#)
 get_transition, [86](#)
 ldeos_read, [86](#)
 set_transition, [86](#)

tov_polytrope_eos, [86](#)
 get_edn, [87](#)

tov_solve, [87](#)
 bio, [92](#)
 generel, [92](#)
 presmin, [92](#)
 prguess, [92](#)
 set_kmax, [91](#)
 set_units, [91](#)
 tmass, [92](#)

W0
 skyrme_eos, [78](#)

zerot
 cfl_njl_eos, [27](#)
