O_2scl_eos - Equation of State Sub-Library for O_2scl

Version 0.905

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1.1 Quick Reference to User's Guide

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, nambujl_eos is the Nambu-Jona-Lasinio model. The CFL and 2SC phases are described by cfl_njl_eos, and cfl6_eos adds the color-superconducting 't Hooft interaction.

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 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 Example source code

1.6.1 Example list

- Cold neutron star example

1.6.2 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);

  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
```

1.7 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...

1.8 Bibliography

Some of the references which contain links should direct you to the work referred to directly through dx.doi.org.

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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_temp_e() 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 Convert tables to **table_units**

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 mu.

Class rmf_delta_eos Finish the finite temperature EOS

Class rmf_eos

- 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.
- Fix calc_p() to be better at guessing

- The number of couplings is getting large, maybe new organization is required.
- Overload hadronic_eos::fcomp() with an exact version

Global rmf_eos::calc_e(fermion &ne, fermion &pr, thermo &lth) Improve the operation of this function when the proton density is zero.

Global rmf_eos::calc_e_fields(fermion &ne, fermion &pr, thermo &lth, 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

Global tov_solve::bio Is this really required?

3 Todo List

Global cfl_njl_eos::calc_eq_temp_p(quark &u, quark &d, quark &s, double &qq1, double &qq2, double &qq3, double &gap1, double &
It surprises me that n3 is not -res[11]. Is there a sign error in the color densities?

Global cfl_njl_eos::gapped_eigenvalues(double m1, double m2, double lmom, double mu1, double mu2, double tdelta, double lam[4], do
In the code, the equal mass case seems to be commented out. Why?

Global ddc_eos::calc_eq_e(fermion &neu, fermion &p, double sig, double ome, double rho, double &f1, double &f2, double &f3, thermo
Is the thermodynamic identity is satisfied even when the field equations are not solved? Check this.

Class rmf_eos
- Check the formulas in the "Background" section
- 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
- The error handler is called sometimes when calc_e() is used to compute pure neutron matter. This should be fixed.

Global rmf_eos::fix_saturation(double guess_cs=4.0, double guess_cw=3.0, double guess_b=0.001, double guess_c=-0.001)
- Fix this for zm_mode=true
- Ensure solver is more robust

Global rmf_eos::fkprime_fields(double sig, double ome, double nb, double &k, double &kprime) Does this work? Fix fkprime_fields() if it does not.

Global rmf_eos::n_charge Should use hadronic_eos::proton_frac instead?

Global rmf_eos::check_naturalness(rmf_eos &re) 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.

Global schematic_eos::set_a_from_mstar(double u_msom, double mnuc) This was computed in schematic_sym.nb, which might be added to the documentation?

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_interp_eos Warn that the pressure in the low-density eos is not strictly increasing! (see at P=4.3e-10)

Class tov_solve
- 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

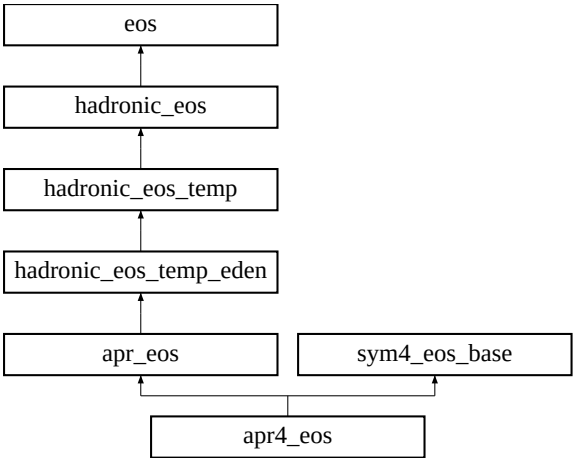
5 Data Structure Documentation

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

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:

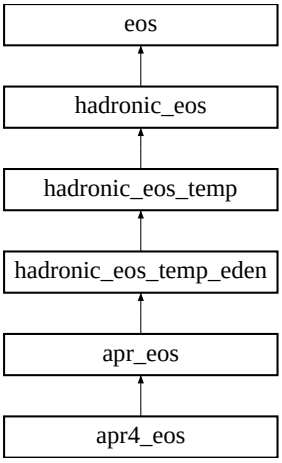
- sym4_eos.h

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

The EOS of Akmal, Pandharipande, and Ravenhall, from Akmal98 (APR).

The Hamiltonian is:

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

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

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

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

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

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

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

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

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

Note:

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 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_temp_e() that possibly could be removed.

Definition at line 120 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, 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 &dqnndnn, double &dqnndnp, 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]

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]

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 & *dqnndnn*, double & *dqnndnp*, double & *dqnpdnn*, double & *dqnpdnp*, double & *dqppdnn*, double & *dqppdnp*)

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

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

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*)

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

This can be set to true to check the difference in the compressibility wbetween the exact expressions and the numerical values from class hadronic_eos.

Definition at line 277 of file apr_eos.h.

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

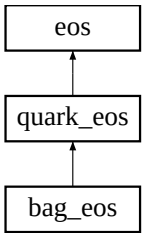
- apr_eos.h

5.3 bag_eos Class Reference

Naive bag model EOS.

`#include <bag_eos.h>`

Inheritance diagram for bag_eos::



5.3.1 Detailed Description

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, 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, 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*, double *temper*, thermo & *th*) [virtual]

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*, double *temper*, thermo & *th*) [virtual]

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:

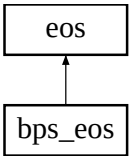
- bag_eos.h

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

This calculates the equation of state of electrons and nuclei using the approach of Baym71 (based on the discussion in Shapiro83) between about 8×10^6 g/cm^3 and 4.3×10^{11} 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

$$\begin{aligned} M(A,Z) &= (A-Z)m_n + Z(m_p+m_e) - 15.76A - 17.81A^{2/3} \\ &\quad -0.71Z^2/A^{1/3} - 94.8/A\,(A/2-Z)^2 + E_{\rm pair} \end{aligned}$$

where

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

if the **nucleus** is odd-odd (plus sign) or even-even (minus sign) and $E_{\rm pair}$ 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

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

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]

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]

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 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

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:

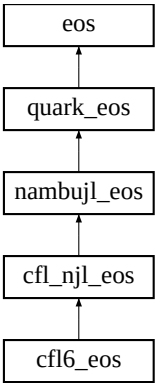
- bps_eos.h

5.5 cfl6_eos Class Reference

An EOS like cfl_njl_eos but with a color-superconducting 't Hooft interaction.

`#include <cfl6_eos.h>`

Inheritance diagram for cfl6_eos::



5.5.1 Detailed Description

Beginning with the Lagrangian:

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

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

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

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

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

Using the definition:

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

and the ansatzes:

$$(\bar{q}_1q_2)(\bar{q}_3q_4) \rightarrow \bar{q}_1q_2\left\langle\bar{q}_3q_4\right\rangle + \bar{q}_3q_4\left\langle\bar{q}_1q_2\right\rangle - \left\langle\bar{q}_1q_2\right\rangle\left\langle\bar{q}_3q_4\right\rangle$$
$$(\bar{q}_1q_2)(\bar{q}_3q_4)(\bar{q}_5q_6) \rightarrow \bar{q}_1q_2\left\langle\bar{q}_3q_4\right\rangle\left\langle\bar{q}_5q_6\right\rangle + \bar{q}_3q_4\left\langle\bar{q}_1q_2\right\rangle\left\langle\bar{q}_5q_6\right\rangle + \bar{q}_5q_6\left\langle\bar{q}_1q_2\right\rangle\left\langle\bar{q}_3q_4\right\rangle - 2\left\langle\bar{q}_1q_2\right\rangle\left\langle\bar{q}_3q_4\right\rangle\left\langle\bar{q}_5q_6\right\rangle$$

for the mean field approximation, we can rewrite the Lagrangian

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

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, 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*, double *temper*) [virtual]

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 nambujl_eos and nambujl_temp_eos does not work here and will return an error.

If all of the gaps are less than gap_limit, then the nambujl_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]

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 assocated 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]

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:

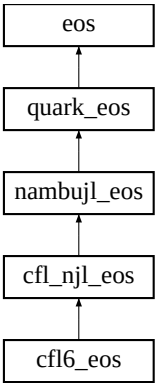
- cfl6_eos.h

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

The variable B0 must be set before use.

The original Lagrangian is

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

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

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

$$\mathcal{L}_{6-{\rm fermion}} = -G_D\left[{\rm d}et_{ij}\,\bar{q}_{i\alpha}\left(1+i\gamma_5\right)q_{j\beta} + {\rm d}et_{ij}\,\bar{q}_{i\alpha}\left(1-i\gamma_5\right)q_{j\beta}\right]\delta_{\alpha\beta}$$

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

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

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

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

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 $\mu_Q = \mu_{\rm Flavor(Q)} + \mu_{\rm Color(Q)}$ with

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

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

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

The individual terms are

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

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

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

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

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 nambujl_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, 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, double result_abs, 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*, double *temper*) [virtual]

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 nambujl_eos and nambujl_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 nambujl_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]

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]

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

In the code, the equal mass case seems to be commented out. Why?

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

- 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]

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 nambujl_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

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

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 nambujl_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

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

This is analogous to gsl_inte::epsabs

Definition at line 376 of file cfl_njl_eos.h.

5.6.3.5 double inte_epsrel

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

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

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

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,

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

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 adabatic 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

Convert tables to **table_units**

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 100 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)

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]

This should be set before calling calc_eos().

Definition at line 112 of file cold_nstar.h.

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

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 234 of file cold_nstar.h.

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

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 253 of file cold_nstar.h.

5.7.3 Field Documentation

5.7.3.1 double acausal

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

Definition at line 187 of file cold_nstar.h.

5.7.3.2 double acausal_ed

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

Definition at line 203 of file cold_nstar.h.

5.7.3.3 double acausal_pr

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

Definition at line 195 of file cold_nstar.h.

5.7.3.4 double allow_urca

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

Definition at line 170 of file cold_nstar.h.

5.7.3.5 double deny_urca

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 179 of file cold_nstar.h.

5.7.3.6 double min_bad

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

Definition at line 162 of file cold_nstar.h.

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

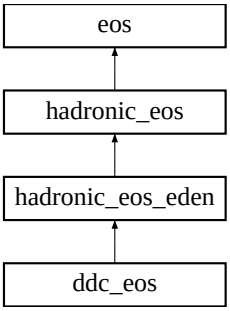
- cold_nstar.h

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

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 $\Gamma_\sigma(\rho_{\mathrm{sat}})$.
- double Gw
  The coupling $\Gamma_\omega(\rho_{\mathrm{sat}})$.
- double Gr
  The coupling $\Gamma_\rho(\rho_{\mathrm{sat}})$.
- 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]

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:

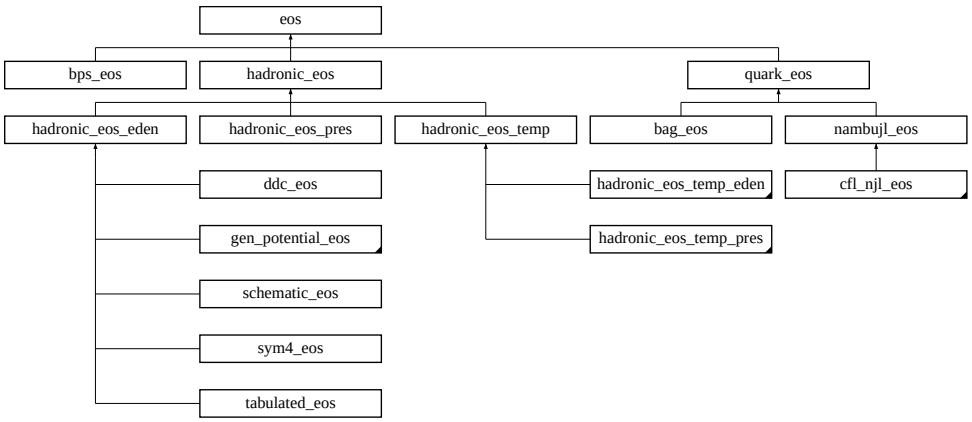
- ddc_eos.h

5.9 eos Class Reference

Equation of state base.

`#include <eos.h>`

Inheritance diagram for eos::



5.9.1 Detailed Description

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:

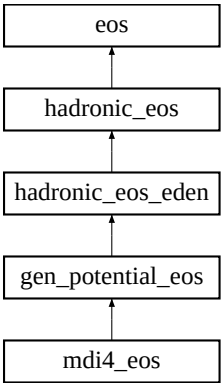
- eos.h

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

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

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

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 :

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

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

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

where

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

Otherwise, if form == bgbd_form, bpalb_form or sl_form, then the potential energy density is given by Bombaci01 :

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

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

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

where

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

The term V_C is:

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

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** &lt)
  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 **Cl**
- 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 modifed 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 of 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:

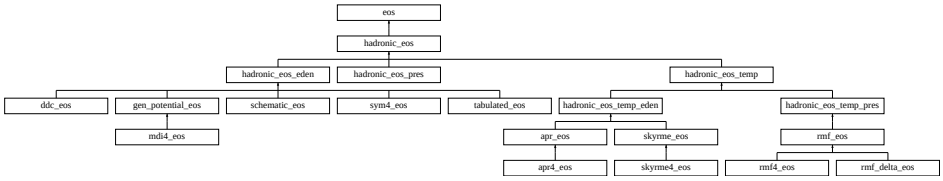
- gen_potential_eos.h

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

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

See more about Svprime 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 &dqnndnn, double &dqnndnp, 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 (double nb)
  Calculate compressibility of nuclear matter using calc_e().
- virtual double feoa (double nb, double pf=0.5)
  Calculate binding energy using calc_e().
- virtual double fesym (double nb, double pf=0.5)
  Calculate symmetry energy of matter using calc_e().
- virtual double fesym_slope (double nb, bool alt_sym=false)
  The symmetry energy slope parameter.
- virtual double fesym_diff (double nb)

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

- virtual double fsprime (double nb, double pf=0.5)
  Calculate S' in matter using calc_e().
- virtual double fkprime (double nb)
  Calculate skewness of nuclear matter using calc_e().
- virtual double fmsom (double nb, double pf=0.5)
  Calculate reduced neutron effective mass using calc_e().
- virtual double fn0 (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 the second **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 defaut neutron.
- **fermion** def_proton
  The defaut 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*)

Used by fesym(), `pa` is unused.

5.11.2.2 double calc_esym (double *nb*, bool & *alt*)

Used by fesym_slope().

5.11.2.3 double calc_esym (double *nb*, int & *pa*)

Used by fsprime(), `pa` is unused.

5.11.2.4 double calc_press_on2 (double *nb*, int & *pa*)

Used by fkprime(), `pa` is unused.

5.11.2.5 double calc_pressure (double *nb*, int & *pa*)

Used by fcomp(), `pa` is unused.

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

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 $K_2 = 9n^2d^2(\epsilon/n)/(dn^2)$ by $18P/n$ at any density except the saturation density.

Reimplemented in apr_eos, and skyrme_eos.

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

`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 (double *nb*, double *pf* = `0.5`) [virtual]

`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 (double *nb*) [virtual]

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 (double *nb*, bool *alt_sym* = `false`) [virtual]

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 (double *nb*) [virtual]

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

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 (double *nb*, double *pf* = 0.5) [virtual]

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 (double *protfrac*, double & *leoa*) [virtual]

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 (double *nb*, double *pf* = 0.5) [virtual]

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 $\delta = 1 - 2x$, $\delta_0 = 1 - 2(\mathrm{pf})$ 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 & *dqnndnn*, double & *dqnndnp*, double & *dqnpdnn*, double & *dqnpdnp*, double & *dqppdnn*, double & *dqppdnp*)

Note:

This is still somewhat experimental.

We want the gradient part of the Hamiltonian in the form

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

The expression for the gradient terms from Pethick95 is

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

This can be rewritten

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

$$
\begin{aligned}
&-\frac{1}{2}[]\cdot\nabla n\frac{dQ_1}{dn}\\
&-\frac{1}{4}(\nabla n)^2 P_2-\frac{1}{4}\left[(\nabla n_n)^2+(\nabla n_p)^2\right]Q_2
\end{aligned}
$$

or

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

or

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

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*)

Used by fn0().

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

Computing the slope of the symmetry energy at the saturation density requires two derivative objects, because it has to take an isospin derivative and a density derivative. Thus this second **deriv** object is used in the function fesym_slope().

5.11.3 Field Documentation

5.11.3.1 gsl_deriv<int,funct<int> > def_deriv

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

Definition at line 419 of file hadronic_eos.h.

5.11.3.2 gsl_deriv<bool,funct<bool> > def_deriv2

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

Definition at line 427 of file hadronic_eos.h.

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

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 435 of file hadronic_eos.h.

5.11.3.4 cern_mroot_root<int,funct<int> > def_sat_root

Used by fn0() (which is called by saturation()) to solve saturation_matter_e() (1 variable).

Definition at line 443 of file hadronic_eos.h.

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

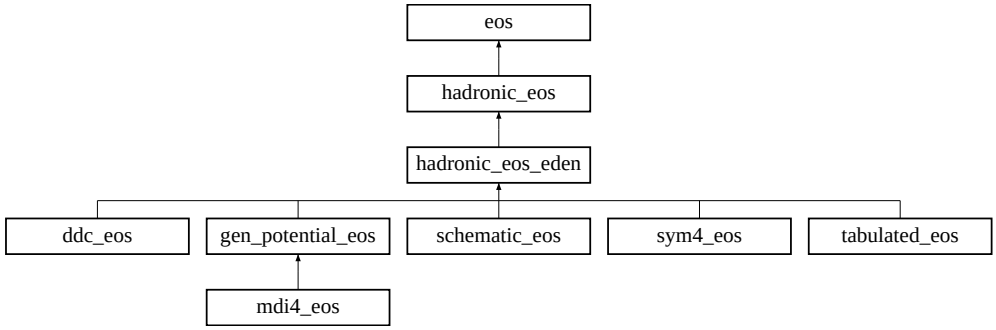
- hadronic_eos.h

5.12 hadronic_eos_eden Class Reference

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

`#include <hadronic_eos.h>`

Inheritance diagram for hadronic_eos_eden::



5.12.1 Detailed Description

Definition at line 488 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:

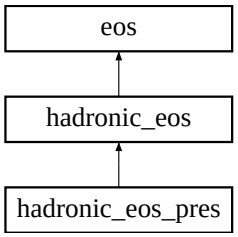
- hadronic_eos.h

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

Definition at line 506 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:

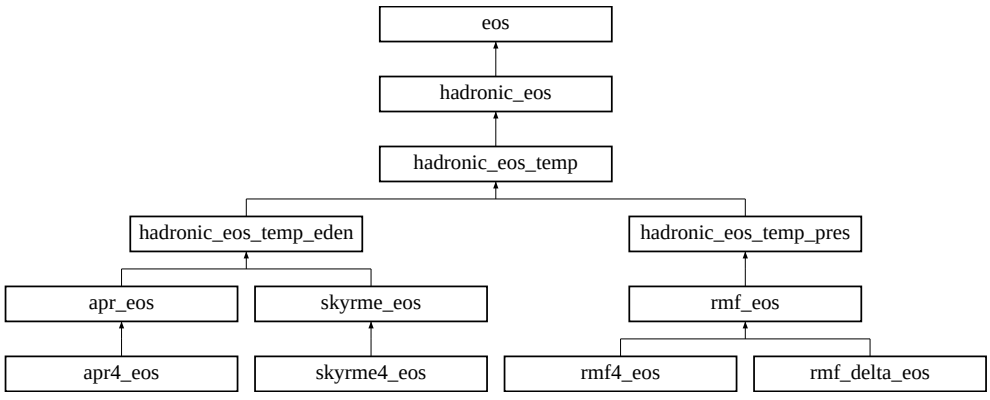
- hadronic_eos.h

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

Definition at line 522 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, 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, 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 defaut neutron.
- **eff_fermion** def_proton_T
  The defaut 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 lT
  The temperature.

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

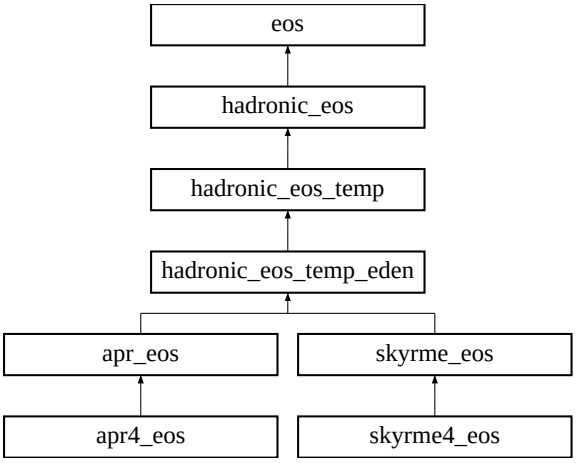
- hadronic_eos.h

5.15 hadronic_eos_temp_eden 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_eden::



5.15.1 Detailed Description

Definition at line 598 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, 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, 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:

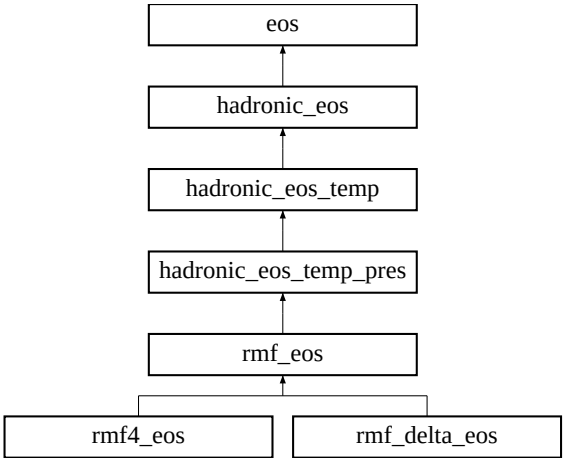
- hadronic_eos.h

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

Definition at line 630 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, 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, 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:

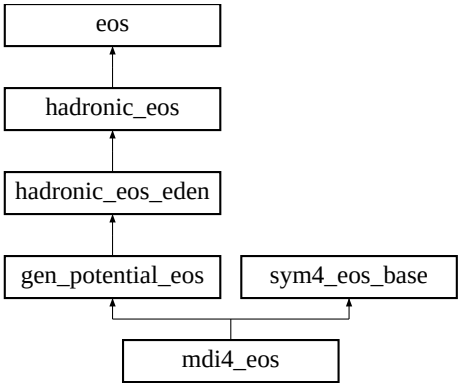
- hadronic_eos.h

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

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:

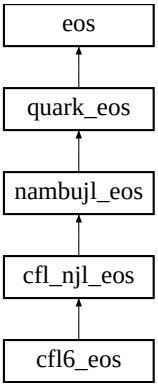
- sym4_eos.h

5.18 nambujl_eos Class Reference

Nambu Jona-Lasinio EOS at zero temperature.

`#include <nambujl_eos.h>`

Inheritance diagram for nambujl_eos::



5.18.1 Detailed Description

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

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

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

And the corresponding thermodynamic potential is

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

where Ω_{FG} is the Fermi gas contribution and

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

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

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 nambujl_eos.h.

Data Structures

- struct njtp_s
  A structure for passing parameters to the integrands.

Public Types

- typedef struct nambujl_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** &lth)
  Equation of state as a function of chemical potentials.
- virtual int calc_temp_p (**quark** &u, **quark** &d, **quark** &s, 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** &lth)
  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** &lth)
  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, 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 ("nambujl_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 njbag (**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 & *lth*) [virtual]

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*, double *T*, thermo & *th*) [virtual]

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*)

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*)

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*)

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*)

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]

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*)

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

5.18.3 Field Documentation

5.18.3.1 bool fromqq

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

Definition at line 166 of file nambujl_eos.h.

5.18.3.2 double limit

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

Definition at line 158 of file nambujl_eos.h.

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

- nambujl_eos.h

5.19 nambujl_eos::njtp_s Struct Reference

A structure for passing parameters to the integrands.

`#include <nambujl_eos.h>`

5.19.1 Detailed Description

Definition at line 299 of file nambujl_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:

- nambujl_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

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

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

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

The baryon number density and electron fraction are then given by

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

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 mu.

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*)

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*)

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:

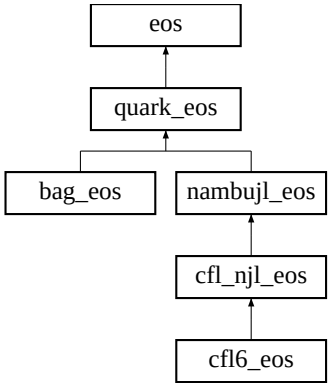
- nse_eos.h

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

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, 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, 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:

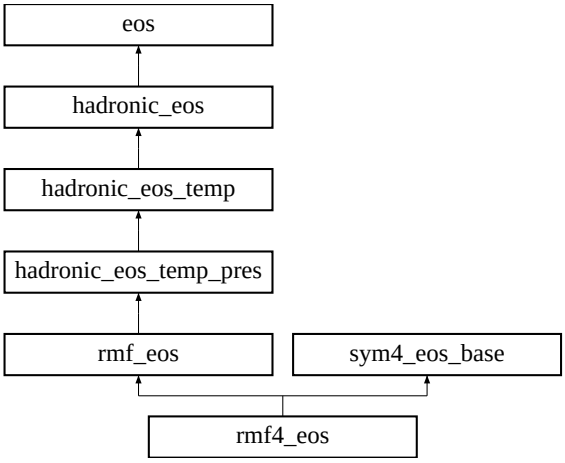
- quark_eos.h

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

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:

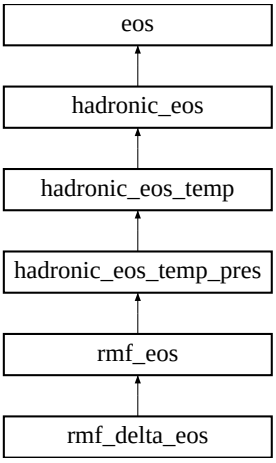
- sym4_eos.h

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

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:

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

$$\begin{aligned}
\mathcal{L}_{Dirac} &= \bar{\Psi}\left[i\partial\!\!\!/ - g_\omega \omega\!\!\!/ - \frac{g_\rho}{2}\vec{\rho}\!\!\!/\,\vec{\tau} - M + g_\sigma\sigma - \frac{e}{2}\left(1+\tau_3\right)A_\mu\right]\Psi \\
\mathcal{L}_\sigma &= \tfrac{1}{2}\left(\partial_\mu\sigma\right)^2 - \tfrac{1}{2}m_\sigma^2\sigma^2 - \frac{bM}{3}\left(g_\sigma\sigma\right)^3 - \frac{c}{4}\left(g_\sigma\sigma\right)^4 \\
\mathcal{L}_\omega &= -\tfrac{1}{4}f_{\mu\nu}f^{\mu\nu} + \tfrac{1}{2}m_\omega^2\omega^\mu\omega_\mu + \frac{\zeta}{24}g_\omega^4\left(\omega^\mu\omega_\mu\right)^2 \\
\mathcal{L}_\rho &= -\tfrac{1}{4}\vec{B}_{\mu\nu}\cdot\vec{B}^{\mu\nu} + \tfrac{1}{2}m_\rho^2\vec{\rho}^{\,\mu}\cdot\vec{\rho}_{\,\mu} + \frac{\xi}{24}g_\rho^4\left(\vec{\rho}^{\,\mu}\right)\cdot\vec{\rho}_{\,\mu} + g_\rho^2 f(\sigma,\omega)\vec{\rho}^{\,\mu}\cdot\vec{\rho}_{\,\mu}
\end{aligned}$$

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** &lth)

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** &lth)
  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]`

This requires initial guesses to the chemical potentials, etc.

Reimplemented from rmf_eos.

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

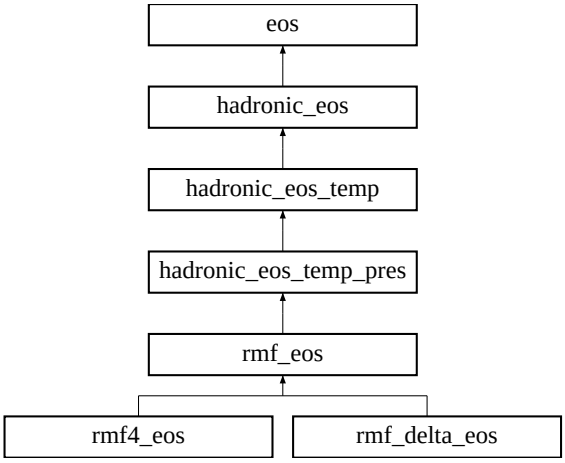
- rmf_delta_eos.h

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

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

- Check the formulas in the "Background" section
- 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
- The error handler is called sometimes when calc_e() is used to compute pure neutron matter. This should be fixed.

Idea for future

- 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.
- Fix calc_p() to be better at guessing
- The number of couplings is getting large, maybe new organization is required.
- Overload hadronic_eos::fcomp() with an exact version

Background

The full Lagragian is:

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

$$\begin{aligned}
\mathcal{L}_{Dirac} &= \bar{\Psi}\left[i\partial\!\!\!/ - g_\omega \omega\!\!\!/ - \frac{g_\rho}{2}\vec{\rho}\!\!\!/\vec{\tau} - M + g_\sigma\sigma - \frac{e}{2}\left(1+\tau_3\right)A\!\!\!/\right]\Psi \\
\mathcal{L}_\sigma &= \tfrac{1}{2}\left(\partial_\mu\sigma\right)^2 - \tfrac{1}{2}m_\sigma^2\sigma^2 - \frac{bM}{3}\left(g_\sigma\sigma\right)^3 - \frac{c}{4}\left(g_\sigma\sigma\right)^4 \\
\mathcal{L}_\omega &= -\tfrac{1}{4}f_{\mu\nu}f^{\mu\nu} + \tfrac{1}{2}m_\omega^2\omega^\mu\omega_\mu + \frac{\zeta}{24}g_\omega^4\left(\omega^\mu\omega_\mu\right)^2 \\
\mathcal{L}_\rho &= -\tfrac{1}{4}\vec{B}_{\mu\nu}\cdot\vec{B}^{\mu\nu} + \tfrac{1}{2}m_\rho^2\vec{\rho}^{\,\mu}\cdot\vec{\rho}_{\,\mu} + \frac{\xi}{24}g_\rho^4\left(\vec{\rho}^{\,\mu}\right)\cdot\vec{\rho}_{\,\mu} + g_\rho^2 f(\sigma,\omega)\vec{\rho}^{\,\mu}\cdot\vec{\rho}_{\,\mu}
\end{aligned}$$

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:

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

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

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

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

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

The symmetry energy of bulk matter is given by

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

In the above equations, the subscipt " 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 214 of file rmf_eos.h.

Solver

- **gsl_mroot_hybrids**< int, **mm_funct**< int > > def_sat_mroot
  The default solver for calculating the saturation density.
- virtual int set_sat_mroot (**mroot**< int, **mm_funct**< int > > &mrx)
  Set class **mroot** *object for use calculating saturation density.*

Public Member Functions

- int load (std::string model, bool external=false)
  Load parameters for model named 'model'.
- 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.

Compute EOS

- virtual int calc_e (**fermion** &ne, **fermion** &pr, **thermo** &lth)
  Equation of state as a function of density.
- virtual int calc_e_fields (**fermion** &ne, **fermion** &pr, **thermo** &lth, double &sig, double &ome, double &rho)
  Equation of state as a function of density returning the meson fields.
- virtual int calc_p (**fermion** &ne, **fermion** &pr, **thermo** &lth)
  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.
- virtual int calc_eq_temp_p (**fermion_T** &ne, **fermion_T** &pr, 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, double T, **thermo** &lth)
  Equation of state as a function of chemical potential.
- int calc_temp_e (**fermion_T** &ne, **fermion_T** &pr, double T, **thermo** &lth)
  Equation of state as a function of densities at finite temperature.

Saturation properties

- 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 compressibilty and `kprime` *assuming the field equations have already been solved.*

Fields and field equations

- 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.

Data Fields

- bool zm_mode
  Modifies method of calculating effective masses.

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
  Temperature storage for calc_temp_e().

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]

Used by fix_saturation().

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

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.

5.24.2.3 virtual int calc_e_fields (fermion & *ne*, fermion & *pr*, thermo & *lth*, double & *sig*, double & *ome*, double & *rho*) [virtual]

Idea for future

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

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]

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]

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*, double *T*, thermo & *lth*) [virtual]

Solves for the field equations automatically.

Implements hadronic_eos_temp_pres.

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

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:

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

which are equivalent to

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

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

$$\begin{aligned}
\frac{bM}{3}g_\sigma^3\sigma^3 &= a_{300}\,\sigma^3 \\
\frac{c}{4}g_\sigma^4\sigma^4 &= a_{400}\,\sigma^4 \\
\frac{\zeta}{24}g_\omega^4\omega^4 &= a_{020}\,\omega^4 \\
\frac{\xi}{24}g_\rho^4\rho^4 &= a_{002}\,\rho^4 \\
b_1 g_\rho^2\omega^2\rho^2 &= a_{011}\,\omega^2\rho^2
\end{aligned}$$

$$
\begin{aligned}
b_2 g_\rho^2 \omega^4 \rho^2 &= a_{021}\, \omega^4 \rho^2 \\
b_3 g_\rho^2 \omega^6 \rho^2 &= a_{031}\, \omega^6 \rho^2 \\
a_1 g_\rho^2 \sigma^1 \rho^2 &= a_{101}\, \sigma^1 \rho^2 \\
a_2 g_\rho^2 \sigma^2 \rho^2 &= a_{201}\, \sigma^2 \rho^2 \\
a_3 g_\rho^2 \sigma^3 \rho^2 &= a_{301}\, \sigma^3 \rho^2 \\
a_4 g_\rho^2 \sigma^4 \rho^2 &= a_{401}\, \sigma^4 \rho^2 \\
a_5 g_\rho^2 \sigma^5 \rho^2 &= a_{501}\, \sigma^5 \rho^2 \\
a_6 g_\rho^2 \sigma^6 \rho^2 &= a_{601}\, \sigma^6 \rho^2
\end{aligned}
$$

Note that Muller and Serot use the notation

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

which differs slightly from the "standard" notation above.

We need to compare the values of

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

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 567 of file rmf_eos.h.

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

This may only work at saturation density.

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

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*)

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*)

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)

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*)

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]

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 461 of file rmf_eos.h.

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

Presently accepted values from file rmfdata/model_list:

```
word[] models 46
BMPI BMPII FPWC 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 spher1d, these need to be run manually
# using the input files in ~/spher1d/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=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 O_2scl library data directory.

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

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 604 of file rmf_eos.h.

5.24.2.17 virtual int saturation () [virtual]

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

Used by fn0() (which is called by saturation()) to solve saturation_matter_e() (1 variable).

Definition at line 648 of file rmf_eos.h.

5.24.3.2 double mnuc

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

Definition at line 229 of file rmf_eos.h.

5.24.3.3 double n_charge [protected]

Todo

Should use hadronic_eos::proton_frac instead?

Definition at line 660 of file rmf_eos.h.

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

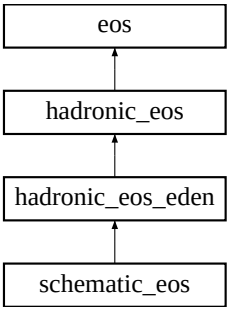
- rmf_eos.h

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

A schematic equation of state defined by the energy density:

$$\epsilon = n\left\{M + eoa + \frac{comp}{18}(n/n0-1)^2 + \frac{kprime}{162}(n/n0-1)^3 + \frac{kpp}{1944}(n/n0-1)^4 + (1-2x)^2\left[a\left(\frac{n}{n0}\right)^{2/3} + b\left(\frac{n}{n0}\right)^{\gamma}\right]\right\}$$

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** &lth)
  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 eoa_zeroden ()
  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]

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]

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 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:

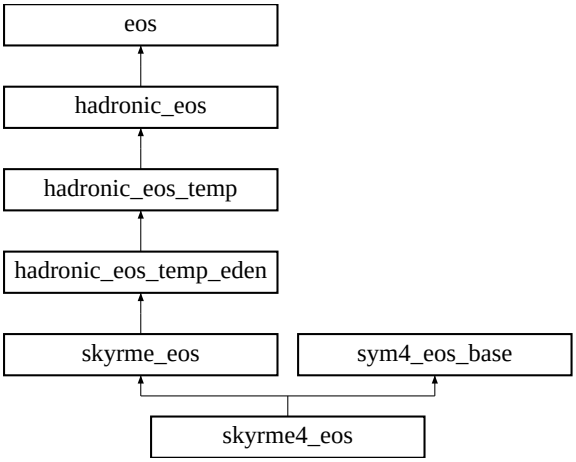
- schematic_eos.h

5.26 skyrme4_eos Class Reference

A version of skyrme_eos to separate potential and kinetic contributions.

`#include <sym4_eos.h>`

Inheritance diagram for skyrme4_eos::



5.26.1 Detailed Description

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:

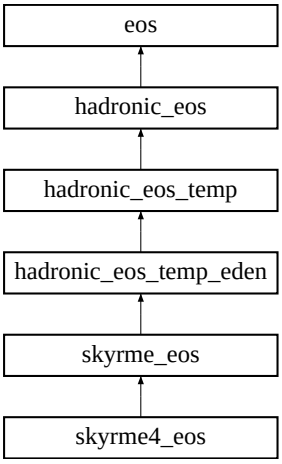
- sym4_eos.h

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

Background:

The Hamiltonian is defined as

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

The kinetic terms are:

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

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

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

The potential terms are:

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

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

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

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

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

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

The values $a = 0, b = 1$ give the standard definition of the Skyrme Hamiltonian Skyrme59, while $a = 1, b = 0$ contains the modifications suggested by Onsi94.

Also, couple useful definitions

$$t_3' = (a+b)\, t_3 \, ,$$

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

and

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

Units:

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 fm^3
- t_1 - MeV fm^5
- t_2 - MeV fm^5
- t_3 - MeV fm$^{3(1+\alpha)}$

These are stored internally with units of:

- t_0 - fm^2
- t_1 - fm^4
- t_2 - fm^4
- t_3 - fm$^{2+3\alpha}$

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.

Misc:

The functions for the usual saturation properties are based partly on Brack85.

Models are taken from the references: Bartel79, Beiner75, Chabanat95, Chabanat97, Danielewicz08, Dobaczewski94, Dutta86, Friedrich86, Onsi94, Reinhard95, and Tondeur84, and VanGiai81 .

See Mathematica notebook at

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

The variables n.nu and p.nu contain the expressions (-mu_n+V_n)/temper and (-mu_p+V_p)/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.

Note:

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().
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

- 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 209 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, double temper, **thermo** &th)
  Equation of state as a function of densities.
- virtual int calc_e (**fermion** &ne, **fermion** &pr, **thermo** &lt)
  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 (double nb, 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*)

See comments under skyrme_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`)

In nuclear matter:

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

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

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

$M^* = M^*(n_0, t_1, t_2, x_2)$ (the x_1 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 t0, t3, alpha, t1, and t2 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*)

This returns zero if there are no instabilities.

5.27.3.3 virtual double fcomp (double *nb*) [virtual]

$$K = 10Cn_B^{2/3} + \frac{27}{4}t_0 n_B + 40C\beta n_B^{5/3} + \frac{9t_3'}{16}\alpha\left(\alpha+1\right)n_B^{1+\alpha} + \frac{9t_3'}{8}\left(\alpha+1\right)n_B^{1+\alpha}$$

Reimplemented from hadronic_eos.

5.27.3.4 virtual double feoa (double *nb*) [virtual]

$$\frac{E}{A} = Cn_B^{2/3}\left(1+\beta n_B\right) + \frac{3t_0}{8}n_B + \frac{t_3'}{16}n_B^{\alpha+1}$$

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

If pf=0.5, then the exact expression below is used. Otherwise, the method from class hadronic_eos is used.

$$E_{sym} = \frac{5}{9}Cn^{2/3} + \frac{10Cm}{3}\left[\frac{t_2}{6}\left(1+\frac{5}{4}x_2\right) - \frac{1}{8}t_1x_1\right]n^{5/3} - \frac{t_3'}{24}\left(\tfrac{1}{2}+x_3\right)n^{1+\alpha} - \frac{t_0}{4}\left(\tfrac{1}{2}+x_0\right)n$$

Reimplemented from hadronic_eos.

5.27.3.6 virtual double fkprime (double *nb*) [virtual]

$$2Cn_B^{2/3}\left(9-5/M^*/M\right) + \frac{27t_3'}{16}n^{1+\alpha}\alpha\left(\alpha^2-1\right)$$

Reimplemented from hadronic_eos.

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

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

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

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*)

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`)

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 SkMDIxm1 SkMDIxm2 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 Skyrme1p 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

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 367 of file skyrme_eos.h.

5.27.4.2 double W0

This is unused, but included for possible future use and present in the internally stored models.

Definition at line 220 of file skyrme_eos.h.

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

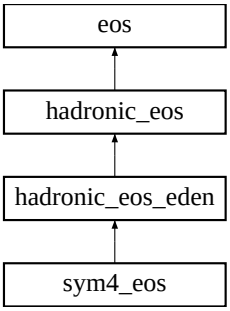
- skyrme_eos.h

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

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** &lth)
  Test the equation of state.
- virtual int calc_e (**fermion** &ne, **fermion** &pr, **thermo** &lth)
  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]

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:

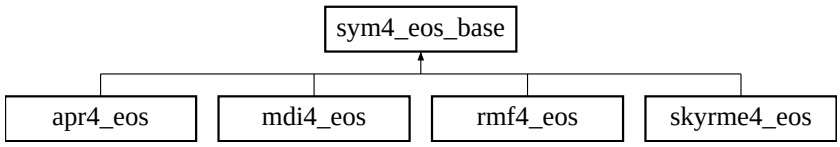
- sym4_eos.h

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

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** &lth, double &alphak, double &alphap, double &alphat, 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:

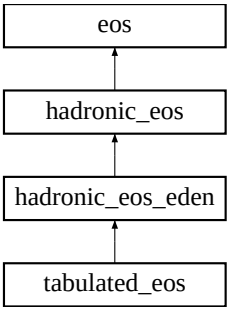
- sym4_eos.h

5.30 tabulated_eos Class Reference

EOS from a **table**.

`#include <tabulated_eos.h>`

Inheritance diagram for tabulated_eos::



5.30.1 Detailed Description

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 tabulated 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

- 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 Member Functions

- int free_table ()
  Free the **table** *memory.*

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:

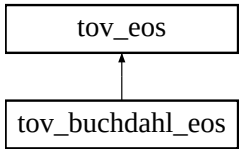
- tabulated_eos.h

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

Given the eos

$$\rho = 12\sqrt{p_* P} - 5P$$

the TOV equation has an analytical solution

$$R = (1-\beta)\sqrt{\frac{\pi}{288 p_* G(1-2\beta)}}$$

where $\beta = GM/R$.

The central pressure and energy density are

$$P_c = 36 p_* \beta^2$$
$$\rho_c = 72 p_* \beta (1 - 5\beta/2)$$

Physical solutions are obtained only for $P < 25p_*/144$ and $\beta < 1/6$.

Based on Lattimer01.

Idea for future

Figure out what to do with the buchfun() function

Definition at line 325 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 quanities.

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_eden (double *P*, double & *e*, double & *nb*) [inline, virtual]

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 348 of file tov_eos.h.

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

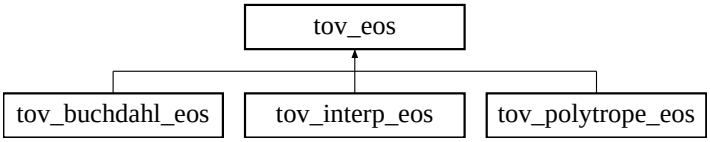
- tov_eos.h

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

Definition at line 54 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 quanities.

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_eden (double *P*, double & *e*, double & *nb*) [inline, virtual]

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:

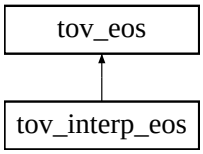
- tov_eos.h

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

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.

Todo

Warn that the pressure in the low-density eos is not strictly increasing! (see at P=4.3e-10)

Definition at line 121 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 quanities.
- 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 nbld
  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*)

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*)

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 $P = \mathrm{ptrans}/pmathrmpw$ and $P = \mathrm{ptrans} \times pmathrmpw$.

5.33.3 Field Documentation

5.33.3.1 bool ldeos_read [protected]

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 224 of file tov_eos.h.

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

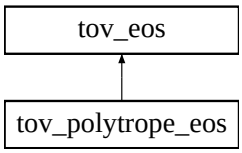
- tov_eos.h

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

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 392 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 quanities.

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]`

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 417 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

Mathematical background:

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 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.

General usage notes:

The equation of state may be changed at any time, by specifying the appropriate tov_eos object

Screen output:

- `verbose=0` - Nothing
- `verbose=1` - Basic information
- `verbose=2` - For each profile computation, report solution information at every kilometer.

- `verbose=3` - Report profile information at every 20 grid points. A keypress is required after each profile.

Accuracy:

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.

Other details and todos:

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

- 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

Definition at line 148 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 schwarzchild 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 calcgpot
  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}*).*
- double max_begin
  Beginning pressure for maximum mass guess (default 7.0e-5).
- double max_end
  Ending pressure for maximum mass guess (default 5.0e-3).
- double max_inc

Increment for pressure for maximum mass guess (default 1.3).

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

- tov_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`)

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* = `""`)

Valid entries for the units of energy density and pressure are:

- "g/cm^3"
- "erg/cm^3"
- "MeV/fm^3"
- "fm^-4"
- "Msun/km^3" (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]`

Idea for future

Is this really required?

Definition at line 351 of file tov_solve.h.

5.35.3.2 bool generel

These parameters can be changed at any time.

Definition at line 169 of file tov_solve.h.

5.35.3.3 double presmin [protected]

This can't be much smaller since we need to compute numbers near exp(-presmin)

Definition at line 380 of file tov_solve.h.

5.35.3.4 double prguess

This guess is used in the function fixed().

Definition at line 202 of file tov_solve.h.

5.35.3.5 double tmass

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 221 of file tov_solve.h.

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

- tov_solve.h

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