Infinite nuclear matter within the relativistic Hartree-Fock (HF) approximation

Role of pions and retardation

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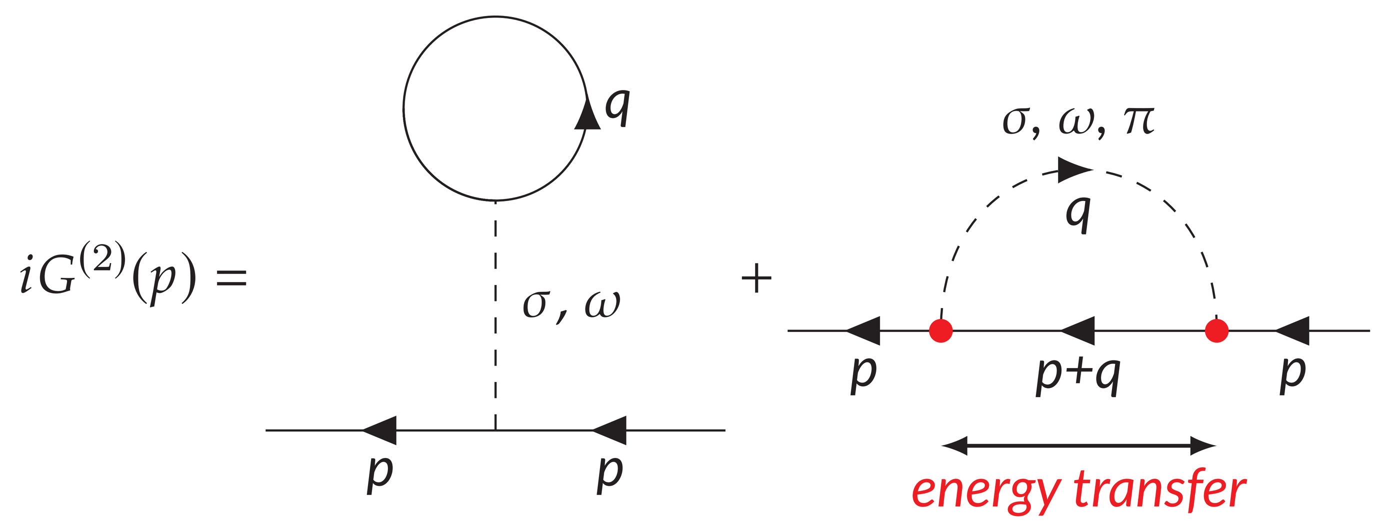
1) Formalism

General Lagrangian for the Walecka model with σ, ω and π mesons:

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu\partial_\mu - m_N)\psi + \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu$$
$$+ \frac{1}{2}(\partial_\mu\boldsymbol{\pi}\cdot\partial^\mu\boldsymbol{\pi} - m_\pi^2\boldsymbol{\pi}^2) + g_\sigma\sigma\bar{\psi}\psi - g_\omega\omega_\mu\bar{\psi}\gamma^\mu\psi - \frac{f_\pi}{m_\pi}\bar{\psi}\gamma^5\gamma^\mu\partial_\mu\boldsymbol{\pi}\cdot\boldsymbol{\tau}\psi$$

Feynman diagrams of the baryon propagator at the second order:



- π's are coupled via the pseudovector representation,
- Renormalizable model,
- Divergent vacuum is dropped,
- No-sea approx. - negative energies are not included.

Green's functions used in the HF approx.:

$$i\Delta^{(\sigma)}(p) = \frac{i}{p^2 - m_\sigma^2 + i\epsilon},\quad iD^{(\omega)}_{\mu\nu}(p) = \frac{-ig_{\mu\nu}}{p^2 - m_\omega^2 + i\epsilon},\quad i\Delta^{(\pi)}_{ab}(p) = \frac{i\delta_{ab}}{p^2 - m_\pi^2 + i\epsilon}$$

$$iG^{(N)}_{ab}(p) = i(\gamma^\mu p_\mu + m_N)_{ab}\Bigg[\underbrace{\frac{1}{p^2 - m_N^2 + i\epsilon}}_{\text{vacuum - omitted}} + \frac{i\pi}{E(\boldsymbol{p})}\delta(p^0 - E(\boldsymbol{p}))\theta(p_F - |\boldsymbol{p}|)\Bigg].$$

Gap equations ($p^0 = E(\boldsymbol{p})$ - nucleons and mesons are on-shell):

$$|\boldsymbol{p}^*(\boldsymbol{p})| = |\boldsymbol{p}| + \Sigma_v(\boldsymbol{p}),\qquad E^*(\boldsymbol{p}) = E(\boldsymbol{p}) - \Sigma_0(\boldsymbol{p}),$$
$$m^*(\boldsymbol{p}) = m_N + \Sigma_s(\boldsymbol{p}),\qquad E^*(\boldsymbol{p}) = \sqrt{|\boldsymbol{p}^*(\boldsymbol{p})|^2 + m^{*2}(\boldsymbol{p})},$$

with the self-energies:

$$\Sigma_s(\boldsymbol{p}) = -\left(\frac{g_\sigma}{m_\sigma}\right)^2 n_s + \frac{1}{(4\pi)^2}\frac{1}{|\boldsymbol{p}|}\int_0^{q_F} d|\boldsymbol{q}||\boldsymbol{q}|\frac{m^*(\boldsymbol{q})}{E^*(\boldsymbol{q})}\sum_{i=\sigma,\omega,\pi} B_i(\boldsymbol{p},\boldsymbol{q}),$$

$$\Sigma_0(\boldsymbol{p}) = \left(\frac{g_\omega}{m_\omega}\right)^2 n_B + \frac{1}{(4\pi)^2}\frac{1}{|\boldsymbol{p}|}\int_0^{q_F} d|\boldsymbol{q}||\boldsymbol{q}|\sum_{i=\sigma,\omega,\pi} A_i(\boldsymbol{p},\boldsymbol{q}),$$

$$\Sigma_v(\boldsymbol{p}) = \frac{1}{(4\pi)^2}\frac{1}{|\boldsymbol{p}|}\int_0^{q_F} d|\boldsymbol{q}||\boldsymbol{q}|\frac{|\boldsymbol{q}^*(\boldsymbol{q})|}{E^*(\boldsymbol{q})}\sum_{i=\sigma,\omega,\pi} C_i(\boldsymbol{p},\boldsymbol{q}).$$

Retardation term, $E(\boldsymbol{p}) - E(\boldsymbol{q})$:

$$A_i, B_i, C_i \propto \ln\left[\frac{(\boldsymbol{p}+\boldsymbol{q})^2 + m_i^2 - (E(\boldsymbol{p}) - E(\boldsymbol{q}))^2}{(\boldsymbol{p}-\boldsymbol{q})^2 + m_i^2 - (E(\boldsymbol{p}) - E(\boldsymbol{q}))^2}\right] \quad \text{or} \quad \propto (E(\boldsymbol{p}) - E(\boldsymbol{q}))^n$$

or $\propto$ a product of both, where $n \in \{1, 2, 3, 4\}$.

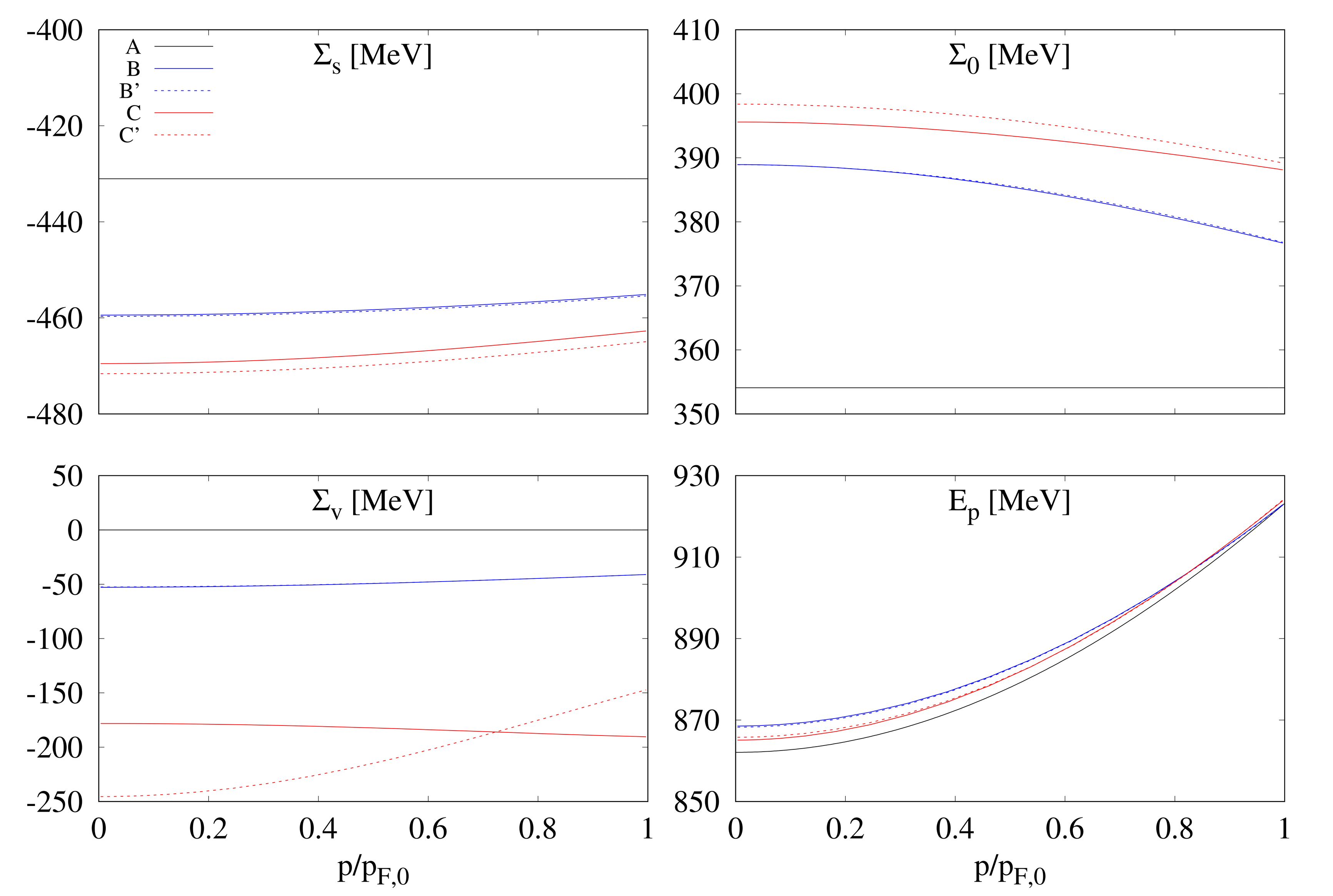
2) Parametrization and nuclear properties

$m_N = 939$ MeV, $m_\sigma = 550$ MeV, $m_\omega = 783$ MeV, $m_\pi = 138$ MeV, $f_\pi^2 = 0.9771$

		g_σ^2	g_ω^2	n_0 [fm^{-3}]	E/A [MeV]	K [MeV]	E_{sym} [MeV]
A	H σ,ω	122.62	190.38	0.1484	-15.76	544.8	20.3
B	HF σ,ω, ret.	108.80	149.40	0.1484	-15.77	581.2	34.2
B'	no ret.	108.90	149.50	0.1484	-15.77	588.6	34.4
C	HF σ,ω,π, ret.	116.93	145.25	0.1484	-15.74	544.0	33.2
C'	no ret.	117.66	145.96	0.1484	-15.74	582.2	33.6

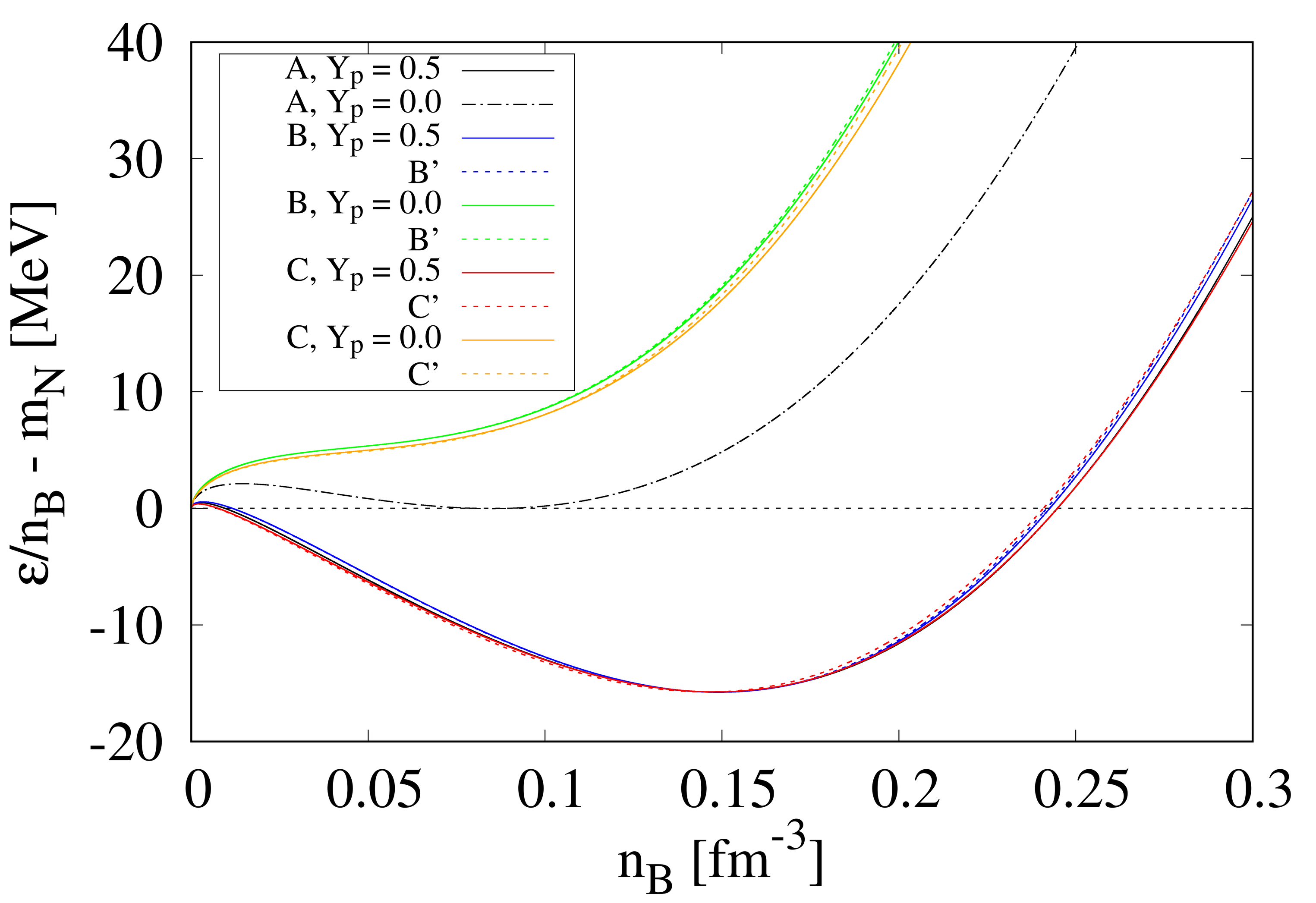
3) Self-energies for $Y_p = 0.5$

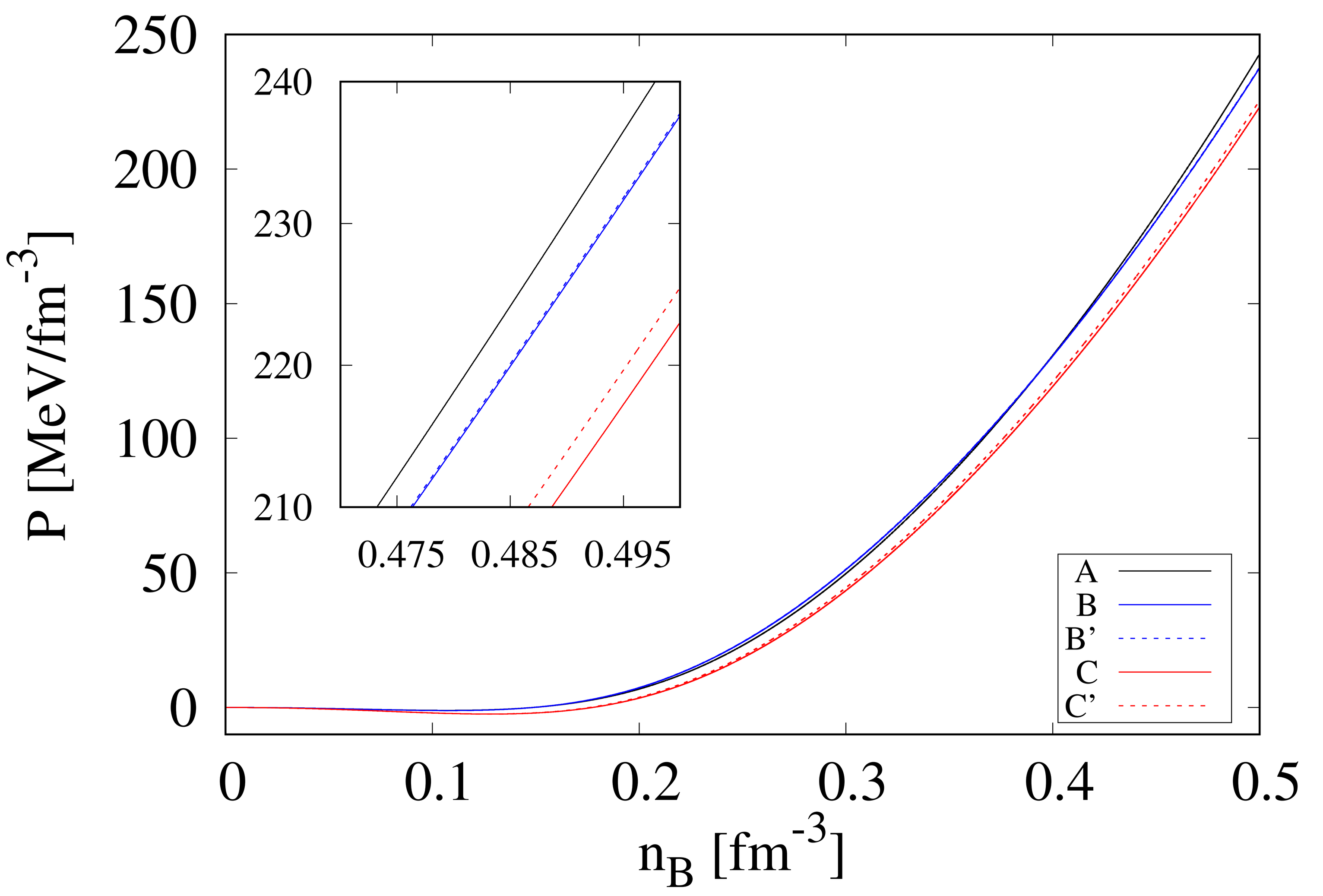
Self-energies and single-particle energy at n_0:



4) Thermodynamic quantities

The assumption of the ideal fluid with $T^{\mu\nu} = \mathrm{diag}(\varepsilon, P, P, P)$ is used to calculate the energy density and pressure:





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