Walecka model with fractional exclusion statistics

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Fractional exclusion statistics (I)

Ideal gas of several kinds of particles

Grand canonical ensemble (T,V,$\{\mu_\lambda\}$)

$$\hat{\rho} = \frac{1}{Z} e^{-\frac{\hat{H} - \sum_\lambda \mu_\lambda \hat{N}_\lambda}{T}}$$

$$Z = Tr\left(e^{-\frac{\hat{H} - \sum_\lambda \mu_\lambda \hat{N}_\lambda}{T}} \right)$$

The second quantization method:

- the partition function:

$$Z = \sum_{\{n_{\vec{p}\lambda}\}} e^{-\frac{1}{T}\sum_{\vec{p}\lambda}(\varepsilon_{\vec{p}\lambda} - \mu_\lambda) n_{\vec{p}\lambda}}$$

λ – *species of particles*

- the total energy and total number of particles of the given microstate:

$$\hat{H} = \sum_{\vec{p}\lambda} \varepsilon_{\vec{p}\lambda} n_{\vec{p}\lambda},$$

$$\hat{N}_\lambda = \sum_{\vec{p}} n_{\vec{p}\lambda},$$

The occupation number representation:

(spineless particles)

- the single-particle energies:

$$\varepsilon_{\vec{p}\lambda} = \sqrt{\vec{p}^{\,2} + m_\lambda^2}$$

- the single-particle states (momentum):

$$p_\alpha = \Delta p_\alpha n_\alpha, n_\alpha = 0, \pm 1, \ldots, \Delta p_\alpha = \frac{2\pi\hbar}{L},$$

$$L = V^{1/3}, \alpha = 1,2,3$$

-cubic box V
-infinite momentum lattice

- the occupation numbers:

$n_{\vec{p}\lambda} = 0, 1, 2, \ldots.$ (bosons)

$n_{\vec{p}\lambda} = 0, 1$ (fermions)

-the number of spineless particles in the given single-particle state

Representation of the partition function using group of states (standard statistics)

$$Z = \sum_{\{n_{i\lambda}\}} W\{n_{i\lambda}\} e^{-\frac{1}{T}\sum_{i,\lambda}(\varepsilon_{i\lambda}-\mu_{\lambda})n_{i\lambda}}$$

the number of states of the system corresponding to the set $\{n_{i\lambda}\}$

$$W\{n_{i\lambda}\} = \prod_{i,\lambda\in\Lambda_f} \frac{g_{i\lambda}!}{n_{i\lambda}!(g_{i\lambda}-n_{i\lambda})!} \times$$
$$\times \prod_{k,\lambda'\in\Lambda_b} \frac{(g_{k\lambda'}+n_{k\lambda'}-1)!}{n_{k\lambda'}!(g_{k\lambda'}-1)!}$$

i – enumerates the sets of single-particle states
λ – index of species of particles
Λ_f – fermionic species, Λ_b – bosonic species

Splitting of the continuum single-particle energy spectrum into sets:

$$V \to \infty \qquad \text{(continuum spectrum)}$$

- the set of single-particle states:

  $g_{i\lambda}$ – number of states in the set (i,λ)

- The set's average energy:

$$\varepsilon_{i\lambda} \approx \varepsilon_{\vec{p}\lambda}, \vec{p} \in d_{i\lambda}$$

- the number of particles in the set (i,λ) :

$$n_{i\lambda} = \sum_{\vec{p}\in d_{i\lambda}} n_{\vec{p}\lambda},$$

Fractional exclusion statistics

- The partition function :

$$Z = \sum_{\{n_{i\lambda}\}} W\{n_{i\lambda}\} e^{-\frac{1}{T}\sum_{i,\lambda}(\varepsilon_{i\lambda}-\mu_{i\lambda})n_{i\lambda}}$$

- the same as standard one!

-But, the number of states of the system corresponding to the set $\{n_{i\lambda}\}$ *is defined as*

$$W\{n_{i\lambda}\} = \prod_i \prod_\lambda \frac{[g_{i\lambda} + n_{i\lambda} - 1 - \sum_{k\lambda'} \alpha_{i\lambda,k\lambda'}(n_{k\lambda'} - \delta_{ik}\delta_{\lambda\lambda'})]!}{n_{i\lambda}!(g_{i\lambda} - 1 - \sum_{k\lambda'} \alpha_{i\lambda,k\lambda'}(n_{k\lambda'} - \delta_{ik}\delta_{\lambda\lambda'}))!}$$

- The diagonal case:

$$W\{n_{i\lambda}\} = \prod_i \prod_\lambda \frac{[g_{i\lambda} + n_{i\lambda} - 1 - \alpha_{i\lambda}(n_{i\lambda} - 1)]!}{n_{i\lambda}!(g_{i\lambda} - 1 - \alpha_{i\lambda}(n_{i\lambda} - 1))!}, \qquad \alpha_{i\lambda,k\lambda'} = \delta_{ik}\delta_{\lambda\lambda'}\alpha_{i\lambda}$$

- Particular cases (limits):

$$W\{n_{i\lambda}\} = \prod_i \prod_\lambda \frac{(g_{i\lambda} + n_{i\lambda} - 1)!}{n_{i\lambda}!(g_{i\lambda} - 1)!}, \qquad \alpha_{i\lambda} = 0, \qquad \text{(bosons)}$$

$$W\{n_{i\lambda}\} = \prod_i \prod_\lambda \frac{g_{i\lambda}!}{n_{i\lambda}!(g_{i\lambda} - n_{i\lambda}!)!}, \qquad \alpha_{i\lambda} = 1 \qquad \text{(fermions)}$$

Approximate partition function:

$$Z = W\{\bar{n}_{i\lambda}\} e^{-\frac{1}{T}\sum_{i,\lambda}(\varepsilon_{i\lambda}-\mu_{i\lambda})\bar{n}_{i\lambda}}$$

The mean occupation numbers (general):

$$\prod_{k\lambda'} w_{k\lambda'}^{\alpha_{k\lambda',i\lambda}} (1+w_{k\lambda'})^{\delta_{ik}\delta_{\lambda\lambda'}\alpha_{k\lambda',i\lambda}} = e^{\frac{\varepsilon_{i\lambda}-\mu_{i\lambda}}{T}},$$

$$w_{i\lambda} = \frac{1}{\bar{n}_{i\lambda}}\left(g_{i\lambda} - \sum_{k,\lambda'}\alpha_{i\lambda,k\lambda'}\bar{n}_{k\lambda'}\right)$$

The mean occupation numbers for single-particle state:

$$\bar{n}_{\vec{p}\lambda} = \frac{\bar{n}_{i\lambda}}{g_{i\lambda}},\ \vec{p} \in d_{i\lambda}$$

The mean occupation numbers

- *The diagonal representation:* $\alpha_{i\lambda,k\lambda'} = \delta_{ik}\delta_{\lambda\lambda'}\alpha_{\lambda}$

$$\frac{\bar{n}_{i\lambda}}{g_{i\lambda}} = \frac{1}{w_{i\lambda}+\alpha_{\lambda}},$$

$$w_{i\lambda}^{\alpha_{\lambda}}(1+w_{i\lambda})^{1-\alpha_{\lambda}} = e^{\frac{\varepsilon_{i\lambda}-\mu_{i\lambda}}{T}}$$

- *Bosons* ($\alpha_{\lambda} = 0$) *and Fermions* ($\alpha_{\lambda} = 1$)*:*

$$\bar{n}_{i\lambda} = \frac{g_{i\lambda}}{e^{\frac{\varepsilon_{i\lambda}-\mu_{i\lambda}}{T}} \mp 1}$$

Fractional exclusion statistics (V)

Thermodynamic quantities:

- Thermodynamic potential:

$$\Omega = -T\ln Z = -T\sum_{i\lambda} g_{i\lambda}\ln(1+w_{i\lambda}^{-1})$$

- The average energy:

$$\langle H \rangle = \sum_{i\lambda} \varepsilon_{i\lambda}\overline{n}_{i\lambda}$$

- Pressure:

$$p = \sum_{i\lambda}\left(-\frac{\partial \varepsilon_{i\lambda}}{\partial V}\right)\overline{n}_{i\lambda}$$

- Entropy:

$$S = \frac{1}{T}\left(-\Omega + \langle H\rangle - \sum_{i\lambda}\mu_{i\lambda}\overline{n}_{i\lambda}\right)$$

Thermodynamic relations:

- The differential relation:

$$d\Omega = -SdT - pdV - \sum_{i\lambda}\overline{n}_{i\lambda}d\mu_{i\lambda}$$

- The Euler theorem:

$$\Omega = \langle H\rangle - TS - \sum_{i\lambda}\mu_{i\lambda}\overline{n}_{i\lambda}$$

- The fundamental equation of thermodynamics:

$$TdS = d\langle H\rangle + pdV - \sum_{i\lambda}\mu_{i\lambda}d\overline{n}_{i\lambda}$$

Walecka model (I)

The quantum field theory

- The Lagrangian density:

$$L = \overline{\psi}[\gamma_\mu (i\partial^\mu - g_v V^\mu) - (m - g_s\phi)]\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_v^2 V_\mu V^\mu + \frac{1}{2}(\partial_\mu\phi\partial^\mu\phi - m_s^2\phi^2),$$

$$F_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$$

-gauge invariant
-Lorentz invariant
-point like particles

- The Euler-Lagrange equations:

$$[\gamma^\mu (i\partial_\mu - g_v V_\mu) - (m - g_s\phi)]\psi = 0,$$

$$(\partial_\mu\partial^\mu + m_s^2)\phi = g_s\overline{\psi}\psi,$$

$$\partial_\mu F^{\mu\nu} + m_v^2 V^\nu = g_v\overline{\psi}\gamma^\nu\psi.$$

- The conserved baryon current: (Noether theorem)

$$B^\mu = \overline{\psi}\gamma^\mu\psi$$

- The energy-momentum tensor:

$$T_{\mu\nu} = \frac{1}{2}\left(-\partial_\lambda\phi\partial^\lambda\phi + m_s^2\phi^2 + \frac{1}{2}F_{\lambda\sigma}F^{\lambda\sigma} - m_v^2 V_\lambda V^\lambda\right)g_{\mu\nu} + i\overline{\psi}\gamma_\mu\partial_\nu\psi + \partial_\mu\phi\partial_\nu\phi + \partial_\nu V^\lambda F_{\lambda\mu}$$

The mean-field approximation

$$\phi = \phi_0, V_\mu = \delta_{\mu 0} V_0$$

- The Lagrangian density:

$$L = \bar{\psi}[i\gamma_\mu \partial^\mu - g_v \gamma^0 V_0 - (m - g_s \phi_0)]\psi + \frac{1}{2}(m_v^2 V_0^2 - m_s^2 \phi_0^2),$$

- The equations of motion:

$$i\frac{\partial \psi}{\partial t} = \hat{H}_D \psi, \hat{H}_D = \vec{\alpha}\hat{\vec{p}} + \beta m^* + g_v V_0,$$

$$\phi_0 = \frac{g_s}{m_s^2}\bar{\psi}\psi,$$

$$V_0 = \frac{g_v}{m_v^2}\bar{\psi}\gamma^0\psi.$$

$$\vec{\alpha} = \gamma^0 \vec{\gamma}, \beta = \gamma^0,$$

$$\hat{\vec{p}} = -i\vec{\nabla},$$

$$m^* = m - g_s \phi_0$$

- The conserved baryon current:

$$B^\mu = \bar{\psi}\gamma^\mu \psi$$

- The energy-momentum tensor:

$$T_{\mu\nu} = i\bar{\psi}\gamma_\mu \partial_\nu \psi - \frac{1}{2}\left(m_v^2 V_0^2 - m_s^2 \phi_0^2\right) g_{\mu\nu}$$

The mean-field approximation. The second quantization method

- The plane wave solution for Dirac equation:

$$\psi(x)=\sum_{\vec{p},\sigma}\frac{1}{\sqrt{2E^{*}V}}\left(a_{\vec{p}\sigma}u_{p,\sigma}e^{-ip^{(+)}x}+b^{+}_{\vec{p}\sigma}u_{-p,-\sigma}e^{ip^{(-)}x}\right),$$

$$E^{*}=\sqrt{\vec{p}^{2}+m^{*2}},\ p^{\mu}=(E^{*},\vec{p}),p^{2}=m^{*2},$$
$$p^{(\pm)\mu}=(\varepsilon^{(\pm)},\vec{p}),\varepsilon^{(\pm)}=E^{*}\pm g_{v}V_{0}$$

- Anti-commutation relations:

$$\left\{a_{\vec{p}\sigma},a^{+}_{\vec{p}'\sigma'}\right\}=\delta_{\vec{p}\vec{p}'}\delta_{\sigma\sigma'},\ \left\{b_{\vec{p}\sigma},b^{+}_{\vec{p}'\sigma'}\right\}=\delta_{\vec{p}\vec{p}'}\delta_{\sigma\sigma'}$$

-create and annihilate particles

- The energy, baryon charge, scalar and vector fields:

$$\hat{H}=\int_{V}d^{3}rT_{00}=\sum_{\vec{p},\sigma}E^{*}\left[a^{+}_{\vec{p}\sigma}a_{\vec{p}\sigma}+b^{+}_{\vec{p}\sigma}b_{\vec{p}\sigma}-1\right]+g_{v}V_{0}\hat{B}-\frac{1}{2}\left(m_{v}^{2}V_{0}^{2}-m_{s}^{2}\phi_{0}^{2}\right)V,$$

$$\hat{B}=\int_{V}d^{3}rB^{0}=\sum_{\vec{p},\sigma}\left[a^{+}_{\vec{p}\sigma}a_{\vec{p}\sigma}-b^{+}_{\vec{p}\sigma}b_{\vec{p}\sigma}+1\right],$$

-vacuum terms

$$\phi_{0}=\frac{g_{s}}{m_{s}^{2}V}\int_{V}d^{3}r\bar{\psi}\psi=\frac{g_{s}}{m_{s}^{2}V}\sum_{\vec{p},\sigma}\frac{m^{*}}{E^{*}}\left[a^{+}_{\vec{p}\sigma}a_{\vec{p}\sigma}+b^{+}_{\vec{p}\sigma}b_{\vec{p}\sigma}-1\right],$$

$$V_{0}=\frac{g_{v}}{m_{v}^{2}V}\int_{V}d^{3}r\bar{\psi}\gamma^{0}\psi=\frac{g_{v}}{m_{v}^{2}V}\sum_{\vec{p},\sigma}\left[a^{+}_{\vec{p}\sigma}a_{\vec{p}\sigma}-b^{+}_{\vec{p}\sigma}b_{\vec{p}\sigma}+1\right]$$

-The condition of positive energies:
Spin-statistics theorem (spin=1/2-fermi,
Spin=0,1,… - bose)

Walecka model with fractional exclusion statistics (I) (equilibrium statistical mechanics)

Grand canonical ensemble (T,V,μ_B)

$$\hat{\rho} = \frac{1}{Z} e^{-\frac{\hat{H} - \mu_B \hat{B}}{T}},$$

$$Z = Tr\left(e^{-\frac{\hat{H} - \mu_B \hat{B}}{T}} \right),$$

$$\langle A \rangle = Tr\,(\hat{\rho}\hat{A}).$$

- the occupation number representation:

$$\hat{H} = \sum_{\vec{p}\lambda} \varepsilon_{\vec{p}\lambda} n_{\vec{p}\lambda} - \frac{1}{2}(m_v^2 V_0^2 - m_s^2 \phi_0^2)V,$$

$$\hat{B} = \sum_{\vec{p}\lambda} b_\lambda n_{\vec{p}\lambda},$$

$$\phi_0 = \frac{1}{m_s^2 V} \sum_{\vec{p}\lambda} g_{s\lambda} \frac{m_\lambda^*}{\sqrt{\vec{p}^2 + m_\lambda^{*2}}} n_{\vec{p}\lambda},$$

$$V_0 = \frac{1}{m_v^2 V} \sum_{\vec{p}\lambda} g_{v\lambda} b_\lambda n_{\vec{p}\lambda},$$

$$\varepsilon_{\vec{p}\lambda} = \sqrt{\vec{p}^2 + m_\lambda^{*2}} + b_\lambda g_{v\lambda} V_0.$$

The fractional exclusion statistics

(diagonal representation)

$$Z = e^{\frac{C}{T}} \sum_{\{n_{i\lambda}\}} W\{n_{i\lambda}\} e^{-\frac{1}{T}\sum_{i,\lambda}(\varepsilon_{i\lambda} - b_\lambda \mu_B) n_{i\lambda}},$$

$$W\{n_{i\lambda}\} = \prod_{i,\lambda} \frac{[\tilde{g}_{i\lambda} + n_{i\lambda} - 1 - \alpha_\lambda (n_{i\lambda} - 1)]!}{n_{i\lambda}![\tilde{g}_{i\lambda} - 1 - \alpha_\lambda (n_{i\lambda} - 1)]!},$$

$$C = \frac{1}{2}(m_v^2 V_0^2 - m_s^2 \phi_0^2)V,$$

$$n_{i\lambda} = \sum_{\vec{p} \in d_{i\lambda}} n_{\vec{p}\lambda},$$

$$\varepsilon_{i\lambda} \approx \varepsilon_{\vec{p}\lambda},\ \vec{p} \in d_{i\lambda}.$$

Walecka model with fractional exclusion statistics (II) (equilibrium statistical mechanics)

- The mean occupation numbers:

$$\bar{n}_{\vec{p}\lambda} = \frac{1}{w_{\vec{p}\lambda} + \alpha_\lambda},$$

$$w_{\vec{p}\lambda}^{\alpha_\lambda}(1 + w_{\vec{p}\lambda})^{1-\alpha_\lambda} = e^{\frac{\varepsilon_{\vec{p}\lambda} - b_\lambda \mu_B}{T}}$$

$$\bar{n}_{\vec{p}\lambda} = \frac{\bar{n}_{i\lambda}}{\tilde{g}_{i\lambda}}, \vec{p} \in d_{i\lambda}$$

- The thermodynamic quantities:

$$\langle H \rangle = \sum_{\vec{p}\lambda} \varepsilon_{\vec{p}\lambda} \bar{n}_{\vec{p}\lambda} - \frac{1}{2}(m_v^2 V_0^2 - m_s^2 \phi_0^2) V,$$

$$\langle B \rangle = \sum_{\vec{p}\lambda} b_\lambda \bar{n}_{\vec{p}\lambda},$$

$$\phi_0 = \frac{1}{m_s^2 V} \sum_{\vec{p}\lambda} g_{s\lambda} \frac{m_\lambda^*}{\sqrt{\vec{p}^2 + m_\lambda^{*2}}} \bar{n}_{\vec{p}\lambda},$$

$$V_0 = \frac{1}{m_v^2 V} \sum_{\vec{p}\lambda} g_{v\lambda} b_\lambda \bar{n}_{\vec{p}\lambda},$$

$$p = \frac{1}{3V} \sum_{\vec{p}\lambda} \frac{\vec{p}^2}{\sqrt{\vec{p}^2 + m_\lambda^{*2}}} \bar{n}_{\vec{p}\lambda} + \frac{1}{2}(m_v^2 V_0^2 - m_s^2 \phi_0^2),$$

$$\Omega = -T \ln Z = -T \sum_{\vec{p}\lambda} \ln(1 + w_{\vec{p}\lambda}^{-1}) - \frac{1}{2}\left(m_v^2 V_0^2 - m_s^2 \phi_0^2\right) V,$$

$$S = \frac{1}{T}\left(-\Omega + \langle H \rangle - \mu_B \langle B \rangle\right),$$

$$\frac{\partial \Omega}{\partial \phi_0} = 0, \qquad \frac{\partial \Omega}{\partial V_0} = 0$$

Example: Nuclear matter at finite temperature (I)

The variables of state: (T, V, μ_B)

- Parameters g_s, g_v are determined from the characteristics of cold nuclear matter at T=0.

$$c_s = \frac{g_s^2}{m_s^2}, c_v = \frac{g_v^2}{m_v^2}$$

- The densities of the scalar and vector fields are calculated from the system of two equations:

$$\rho_s = \frac{\gamma}{V} \sum_{\vec{p}} \frac{m - c_s \rho_s}{\sqrt{\vec{p}^2 + (m - c_s \rho_s)^2}} \left[\overline{n}_{\vec{p}}^{(+)} + \overline{n}_{\vec{p}}^{(-)} \right],$$

$$\rho_v = \frac{\gamma}{V} \sum_{\vec{p}} \left[\overline{n}_{\vec{p}}^{(+)} - \overline{n}_{\vec{p}}^{(-)} \right], \qquad \gamma = 4$$

- Single particles energies:

$$\varepsilon_{\vec{p}}^{(+)} = \sqrt{\vec{p}^2 + (m - c_s \rho_s)^2} + c_v \rho_v,$$
$$\varepsilon_{\vec{p}}^{(-)} = \sqrt{\vec{p}^2 + (m - c_s \rho_s)^2} - c_v \rho_v,$$

- The parameter of fractional exclusion statistics: α

Description	Particles	Mass, MeV	J^{π}	I
Baryon	$p, n, \overline{p}, \overline{n}$	$m = 938$	1/2	1/2
Neutral scalar meson	σ	$m_s = 550$	0^+	0
Neutral vector meson	ω	$m_v = 783$	1^-	0

$$\rho_s = \frac{m_s^2}{g_s} \phi_0, \rho_v = \frac{m_v^2}{g_v} V_0,$$

$$\overline{n}_{\vec{p}}^{(+)} = \frac{1}{w_{\vec{p}}^{(+)} + \alpha}, w_{\vec{p}}^{(+)\alpha} (1 + w_{\vec{p}}^{(+)})^{1-\alpha} = e^{\frac{\varepsilon_{\vec{p}}^{(+)} - \mu_B}{T}},$$

$$\overline{n}_{\vec{p}}^{(-)} = \frac{1}{w_{\vec{p}}^{(-)} + \alpha}, w_{\vec{p}}^{(-)\alpha} (1 + w_{\vec{p}}^{(-)})^{1-\alpha} = e^{\frac{\varepsilon_{\vec{p}}^{(-)} + \mu_B}{T}},$$

Example: Nuclear matter at finite temperature (II)

The thermodynamic quantities for nuclear matter at finite temperature:

$$\frac{\Omega}{V} = -T\,\frac{\gamma}{V}\sum_{\vec{p}}\left[\ln(1+w_{\vec{p}}^{(+)^{-1}}) + \ln(1+w_{\vec{p}}^{(-)^{-1}})\right] - \frac{1}{2}\left(c_v\rho_v^2 - c_s\rho_s^2\right),$$

$$\varepsilon = \frac{\langle H\rangle}{V} = \frac{\gamma}{V}\sum_{\vec{p}}\sqrt{\vec{p}^{\,2} + (m - c_s\rho_s)^2}\,[n_{\vec{p}}^{(+)} + n_{\vec{p}}^{(-)}] + \frac{1}{2}\left(c_v\rho_v^2 + c_s\rho_s^2\right),$$

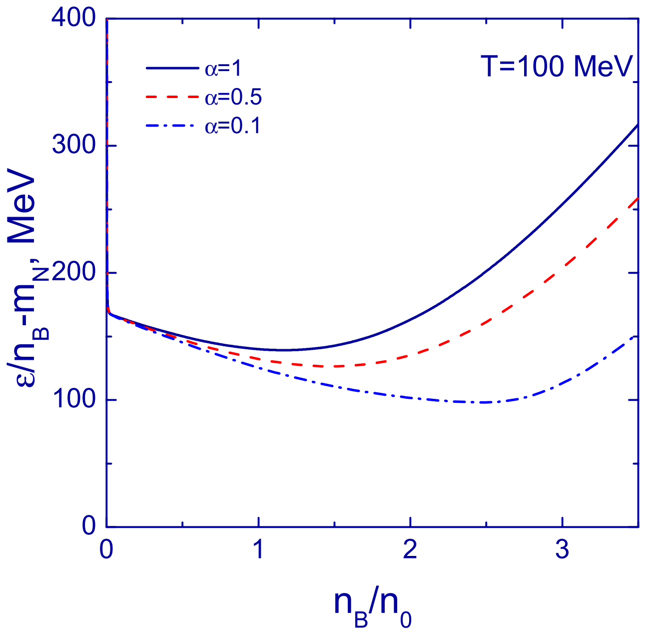
$$p = \frac{\gamma}{3V}\sum_{\vec{p}}\frac{\vec{p}^{\,2}}{\sqrt{\vec{p}^{\,2} + (m - c_s\rho_s)^2}}[n_{\vec{p}}^{(+)} + n_{\vec{p}}^{(-)}] + \frac{1}{2}\left(c_v\rho_v^2 - c_s\rho_s^2\right)$$

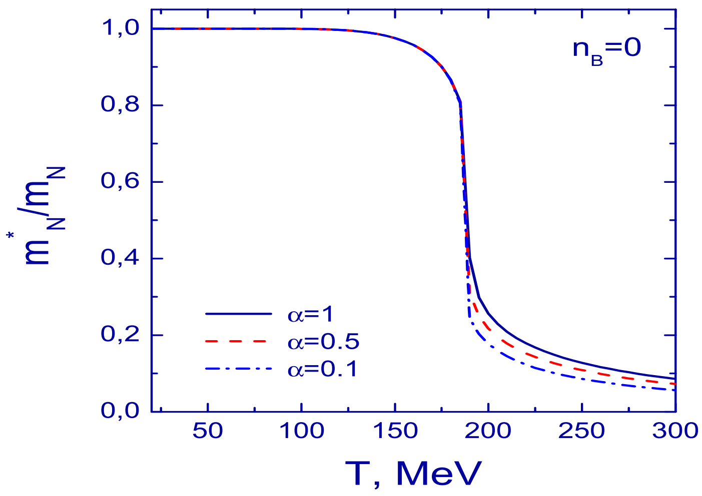
$$\rho_B = \frac{\langle B\rangle}{V} = \frac{\gamma}{V}\sum_{\vec{p}}\left[\overline{n}_{\vec{p}}^{(+)} - \overline{n}_{\vec{p}}^{(-)}\right] = \rho_v,$$

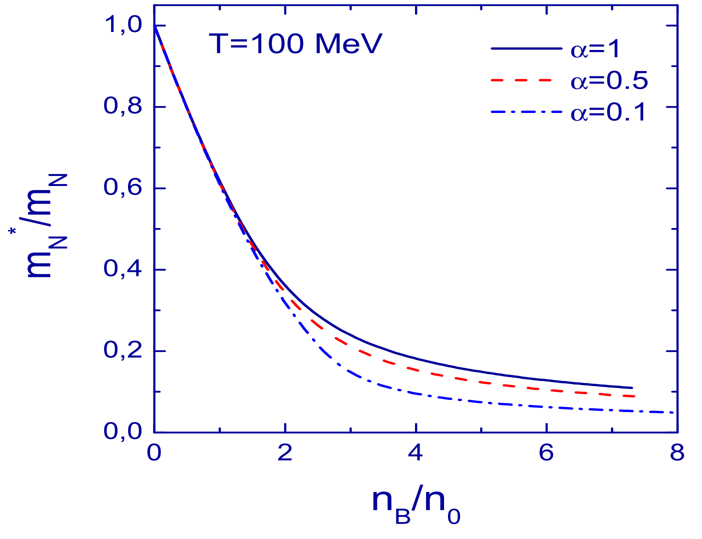
$$\rho = \frac{\gamma}{V}\sum_{\vec{p}}\left[\overline{n}_{\vec{p}}^{(+)} + \overline{n}_{\vec{p}}^{(-)}\right],$$

$$s = \frac{S}{V} = \frac{1}{T}\left(-\frac{\Omega}{V} + \varepsilon - \mu_B\rho_B\right)$$

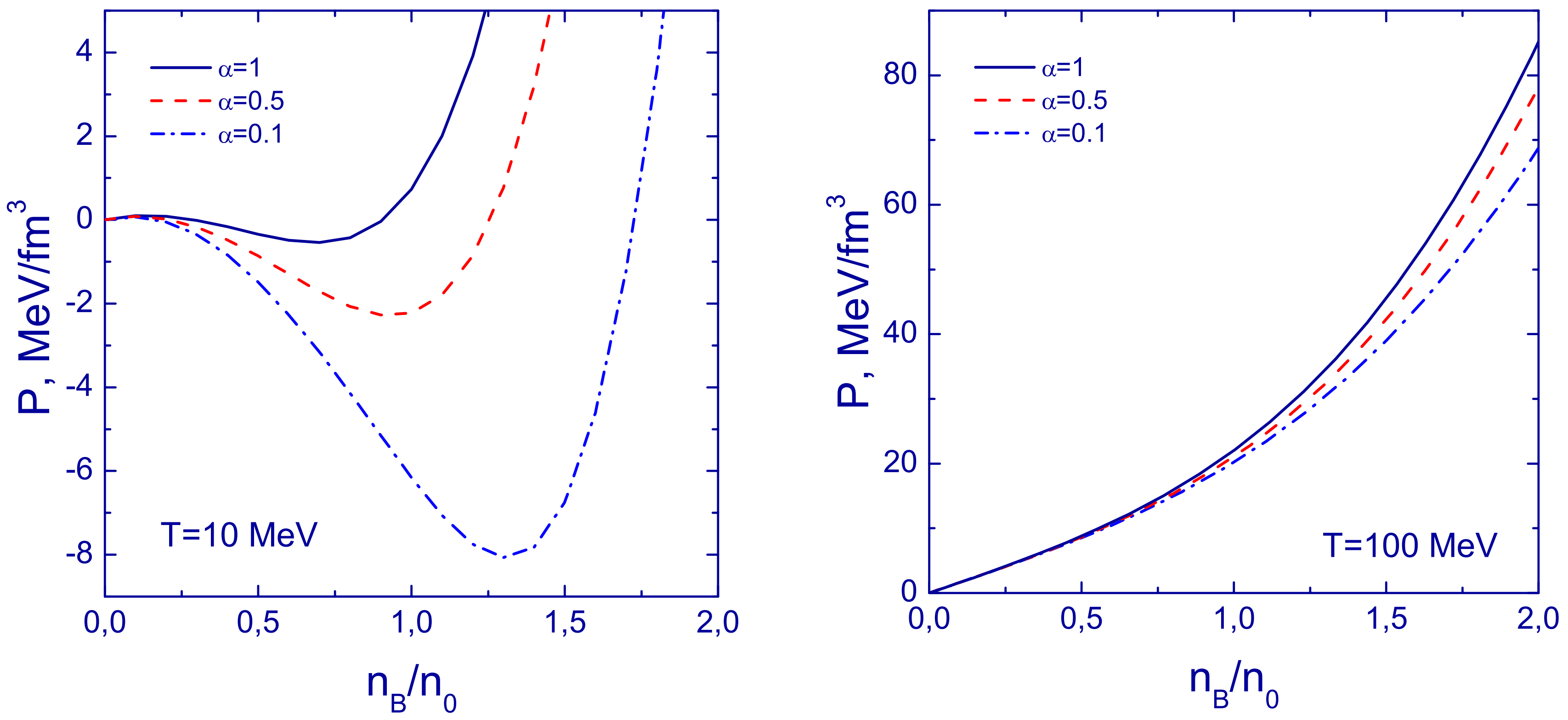
Example: Nuclear matter at finite temperature (III)







Example: Nuclear matter at finite temperature (IV)



Summary

1. The relativistic mean-field theory (Walecka model) was generalized by introducing the fractional exclusion statistics
2. The change of statistics, expressed by the fractional exclusion statistics parameter, α, has a strong influence on the nuclear matter equation of state at low temperatures—for example in the region of phase transition
3. The phase transition parameters range depends on the exclusion statistics parameter α.