Relativistic Mean-Field Model with Scaled Hadron Masses and Couplings.

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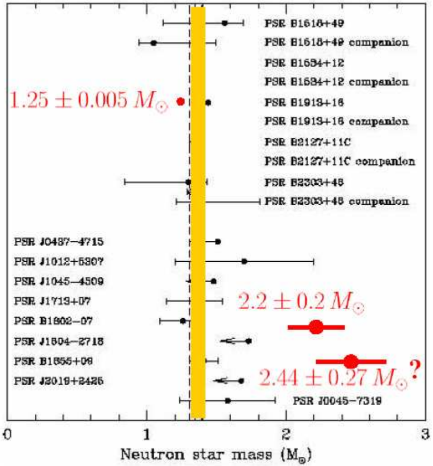
V.Toneev and D.Voskresensky

- Lagrangian, pressure and equations of motion
- Determination of parameters
- Model properties at T$=$0 and T$\neq$0
- Application to HIC
- Conclusions and perspectives

Introduction: Model choice

Neutron star masses



- EoS of Urbana–Argonne group (A18$+\delta v+$UIX*)
- There might exist heavy NSs

$\Rightarrow$ **KVOR**

E.Kolomeitsev, D.Voskresensky, Nucl. Phys. **A759** (2005) 373

Introduction: Aims

We want to generalize the RMF model with density-dependent hadron masses and couplings to finite temperatures for further application to hydrodynamics. (Nucl. Phys. **A 791** (2007),180, nucl-th/0802.3999)

- mean-field thermodynamics for density-dependent model
- lowest baryon resonances and Goldstone bosons
- excitations of σ, ω and ρ fields and their interactions (beyond MF)
- properties of dense and hot hadronic matter

Lagrangian

We start from generalized KVOR based lagrangian and expand it retaining only quadratic terms in the fields of excitations.

$$\widetilde{\mathscr{L}}[f,\omega_0,R_0] = \underbrace{\sum_b \Psi_b^+ \left(i\gamma^0\gamma^\mu\partial_\mu - X_b - \beta m_b^*\right)\Psi_b}_{baryons} \underbrace{-\widetilde{U}(f) + V(f)}_{\mathscr{L}_{MF}}$$

$$+ \underbrace{\mathscr{L}_{\sigma'} + \mathscr{L}_{\omega'} + \mathscr{L}_{\rho'}}_{ideal\ \ gases\ \ of\ \ excitations} + \underbrace{\mathscr{L}_{\pi^0} + \mathscr{L}_{\eta'} + \mathscr{L}_{\phi} + \mathscr{L}_{K^*}}_{ideal\ \ gases} + \mathscr{L}_\eta + \sum_{\varphi\in G}\mathscr{L}_\varphi$$

$$\mathscr{L}_\varphi = \left[\left(\partial_\mu - iX_\phi\delta_{\mu0}\right)\varphi^+\right]\left(\partial^\mu + iX_\phi\delta^{\mu0}\right)\varphi - m_\varphi^{*\,2}\varphi^+\varphi$$

where mean field approximation is already taken into account:

$$X_b = g_{\omega b}\chi_\omega\omega_0 + g_{\rho b}t_b^3\chi_\rho R_0, \quad X_\varphi = g_{\omega\varphi}^*\omega_0 + g_{\rho\varphi}^* t_\varphi^3 R_0$$

$$V(f) = \frac{1}{2}m_\omega^{*\,2}\omega_0^2 + \frac{1}{2}m_\rho^{*\,2}R_0^2$$

$$\widetilde{U}(f) = \frac{1}{2}m_\sigma^{*\,2}\sigma^2 + U(f) = \frac{m_N^4 f^2}{2C_\sigma^2}\eta_\sigma(f) + U(f)$$

Notations

with
$$m_N^* = m_N\,\Phi_N(f), \qquad m_b^* = m_b - g_{\sigma B}\chi_\sigma\,\sigma,$$
$$m_j^* = m_j\,\Phi_j(f), \qquad m_\varphi^* = m_\varphi - g_{\sigma\varphi}^*\,\sigma,$$

and scaling functions $\chi_j = \chi_j(f)$, $\quad j \in \mathscr{M}$

Non-linear self-interaction term

$$U = m_N^4\left(\frac{b}{3}f^3 + \frac{c}{4}f^4\right)$$

The variable has been introduced

$$f = \frac{g_{\sigma N}\chi_\sigma\sigma}{m_N}$$

$$C_i = \frac{g_{iN}m_N}{m_i}, \quad \eta_i(f) = \frac{\Phi_i^2(f)}{\chi_i^2(f)}, \quad g_{iH} = x_{iH}\,g_{iN}, \quad i = \sigma,\omega,\rho$$

Sets of hadrons
$$B = \{N,\Delta,\Lambda,\Sigma,\Xi,\Sigma^*(1385),\Xi^*(1530),\Omega^-\}$$
$$G = \{\pi^+, K\}, \quad \mathscr{M} = \{\sigma,\omega,\rho\}$$

Pressure and equations of motions

Then the pressure is given by

$$P[f,\omega_0,R_0] = \sum_b (p_b + \bar{p}_b) + \sum_\phi (p_\phi + \bar{p}_\phi) + \sum_{j\in\mathscr{M}} p_j$$
$$+ p_{\pi^0} + p_\eta + p_{\eta'} + p_\phi + p_{K^*} + \underbrace{V(f) - \widetilde{U}(f)}_{P_{MF}[f,\omega_0,R_0]}$$

where p_j – the pressure of ideal gas of particles ($\bar{p}_j$ – antiparticles) with mass m^* and effective chemical potential

$$\mu_j^* = \mu_j - X_j = b_j\mu_B + s_j\mu_S - X_j$$

Self-consistency conditions

$$\frac{\partial P}{\partial\omega_0} = 0, \quad \frac{\partial P}{\partial R_0} = 0, \quad \frac{\partial P}{\partial f} = 0$$

are equivalent to equations of motions

Excitations. Masses

Masses of excitations

$$m^{*}_{\omega'}{}^{2} = \frac{\partial^2}{\partial\omega_0^2} P_{MF}[f,\omega_0,R_0] = m^{*}_{\omega}{}^{2}$$

$$m^{*}_{\rho'}{}^{2} = \frac{\partial^2}{\partial R_0^2} P_{MF}[f,\omega_0,R_0] = m^{*2}_{\rho},$$

$$m^{*}_{\sigma'}{}^{2} = -\frac{\partial^2}{\partial\sigma^2} P_{MF}[f,\omega_0(f),R_0(f)] = -\left(\frac{df}{d\sigma}\right)^2 \frac{\mathrm{d}^2 P_{MF}}{\mathrm{d}f^2}$$

Why is P_{MF} used in these formulaes?

- We keep only quadratic terms in lagrangian, so $P_{bos.es}$ is disregarded.
- Including P_B is equal to taking into account of the baryon loops that leads to some problems. Our aim is the construction of a thermodynamically consistent model so in the final version of our model we suppress P_B to keep thermodynamical consistency and for simplicity sake.

Basic parameters

We take the Brown-Rho scaling ansatz (1991) in the simplest form

$$\Phi_N = \Phi_\sigma = \Phi_\omega = \Phi_\rho = 1 - f \quad \left(\Phi = \frac{m^*}{m}\right)$$

An appropriate behavior of EoS for $T = 0$ is obtained with

$$\eta_\sigma = 1, \quad \eta_\omega = \frac{1 + zf_0}{1 + zf}, \quad \eta_\rho = \frac{\eta_\omega}{\eta_\omega + 4\frac{C_\omega^2}{C_\rho^2}(\eta_\omega - 1)}$$

with $f_0 \equiv f(T = 0, n_0)$, $z = 0.65$

Input parameters (at the saturation point)

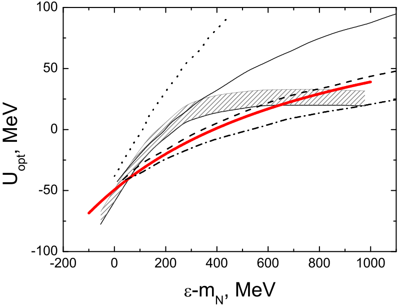
$$n_0 = 0.16\ fm^{-3}, \quad E_{bind} = -16\ MeV, \quad K = 275\ MeV$$

$$m_N^*/m_N = 0.805$$

- $x_{\omega H}$ – from quark counting
- free pion

T=0 MeV

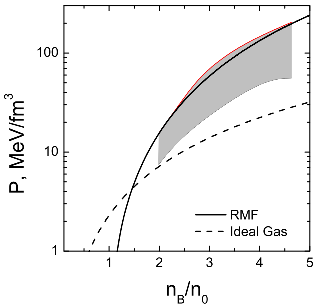
Nucleon optical potential



$m_N^*/m_N = 0.54,\ 0.71,\ 0.8,\ 0.85$ (dotted, thin continuous, dashed and dashed-dotted lines)
Shaded area - uncertainties in extrapolation from finite nuclei to cold nuclear matter

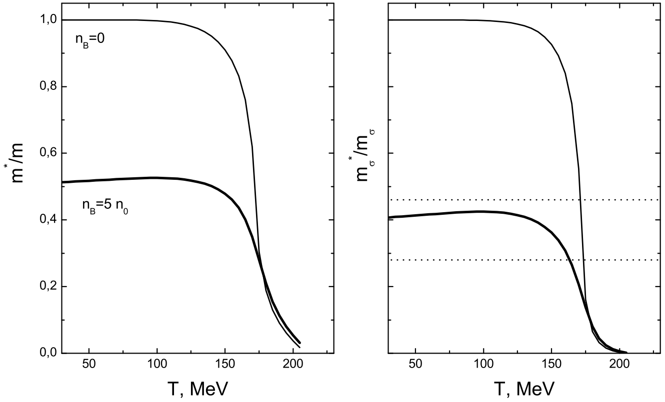
H.Feldmeier, J. Lindner, Z.Phys. A341 (1991) 83

Pressure



P. Danielewicz, nucl-th/0512009

$T \neq 0$. Effective-to-bare mass ratios

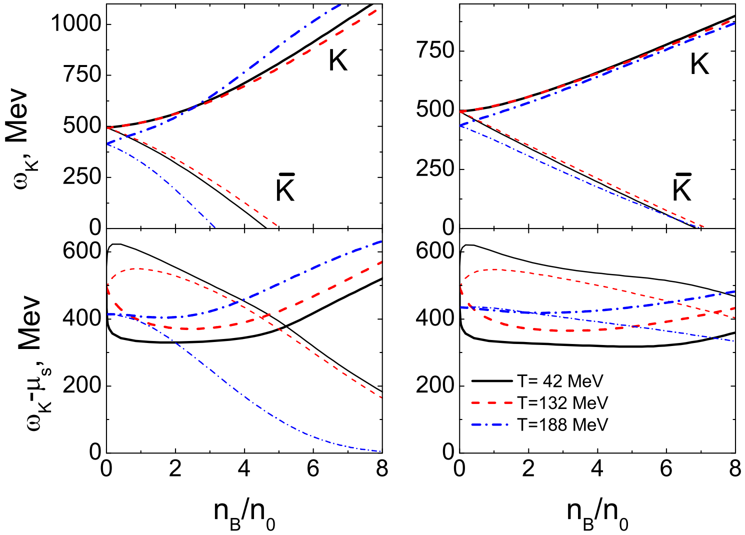


N, ω, ρ masses $\qquad$ σ mass

dotted straight lines show the σ mass levels $m_\sigma = 2m_\pi$ *and* m_π

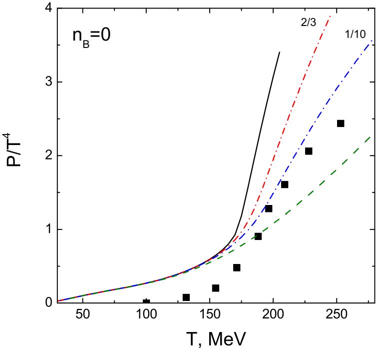
$T \neq 0$. Kaon energies

Left panel: set (A) without scailing Right panel: set (B) with scailing

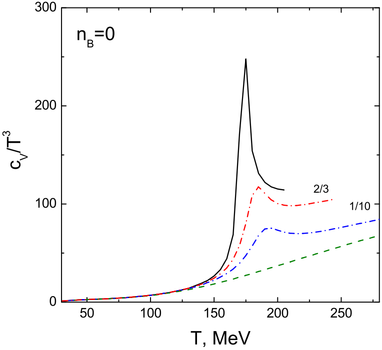


T-dependence of pressure and specific heat

Pressure

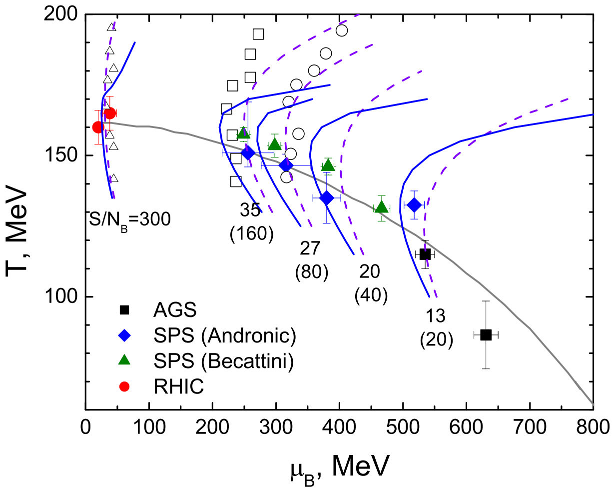


Specific heat



dashed - ideal gas
solid - our model
dashed-dotted, dashed-dotted - our model with suppressed σ-couplings
squares - lattice QCD for the 2+1 flavor

Isentropic trajectories for RHIC and SPS



Solid lines - our model with default set of parameters
dashed lines - with suppressing σ-couplings by the factor 1/10 for all baryons besides nucleons
open circles, squares, triangles - lattice 2-flavor QCD results for $S/N_B = 30,\ 45$ *and* 300
Our S/N_B from hydro-calculations by
M. Reiter,A. Dumitru, J. Brachman, J.A. Maruhn, H. Stöcker and W. Greiner, nucl-th/9801068

Results and perspectives

- The modified RMF $\sigma - \omega - \rho$ model with scaled hadron masses and couplings (SHMC model) was generalized to finite temperatures, simulating a chiral symmetry restoration with a temperature increase.
- Besides nucleon and mean fields, the model includes low-lying baryon resonances and their antiparticles, boson excitations (Goldstone bosons) and σ-, ω-, ρ-excitations.
- The EoS for T=0 satisfies general constraints known from atomic nuclei, neutron stars and those coming from the flow analysis of HIC data.
- Study of thermodynamic properties of hot and dense hadronic matter was started with the constructed EoS.
- We want to extend the model by matching it with a quark phase, including finite-size effects of a mixed phase and applying to hydrodynamics (dynamics and observables)

Parameters of hyperons, kaons and pions

From quark counting

$$x_{\omega\Lambda} = x_{\omega\Sigma} = x_{\omega\Sigma^*} = 2x_{\omega\Xi} = x_{\rho\Lambda} = x_{\rho\Sigma} = x_{\rho\Sigma^*} = 2x_{\rho\Xi} = \frac{2}{3}$$

$$x_{\omega K} = \frac{1}{3}$$

$x_{\sigma b}$ for Λ, Σ, Xi are found from

$$E_{bind}^{hyp} = \mu_{hyp}(T=0,n_0) - m_{hyp} = \frac{C_\omega^2}{m_N^2\eta_\omega(f_0)} x_{\omega B} n_0 - x_{\sigma B}(m_N - m_N^*(n_0))$$

with $E_{bind}^{\Lambda} = -30\ MeV$, $E_{bind}^{\Sigma} = -10\ MeV$, $E_{bind}^{\Xi} = -18\ MeV$
$x_{\sigma K}$ is deduced from

$$U_{K^-}(T=0,n_0) = -g_{\sigma K}^* \sigma - g_{\omega K}^* \omega_0$$

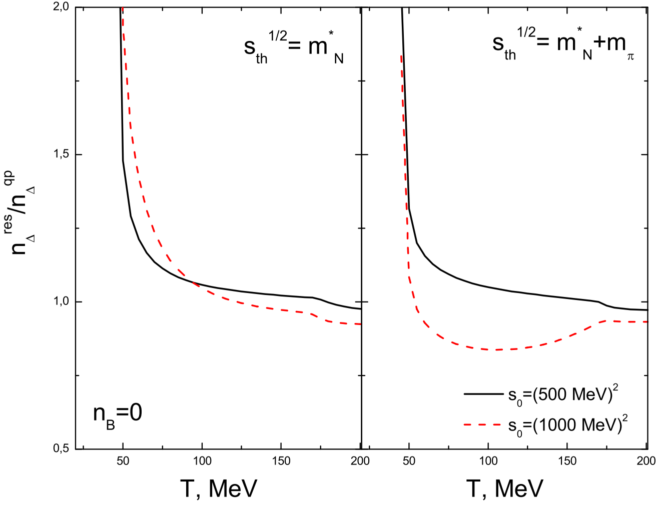
with $U_{K^-}(n_0) = -120 \div -130\ MeV$, $U_{K^+}(n_0) = 20 \div 30\ MeV$

$$(A): \quad g_{\omega K}^* = x_{\omega K} g_{\omega N}, \quad g_{\sigma K}^* = x_{\sigma K} g_{\sigma N}$$

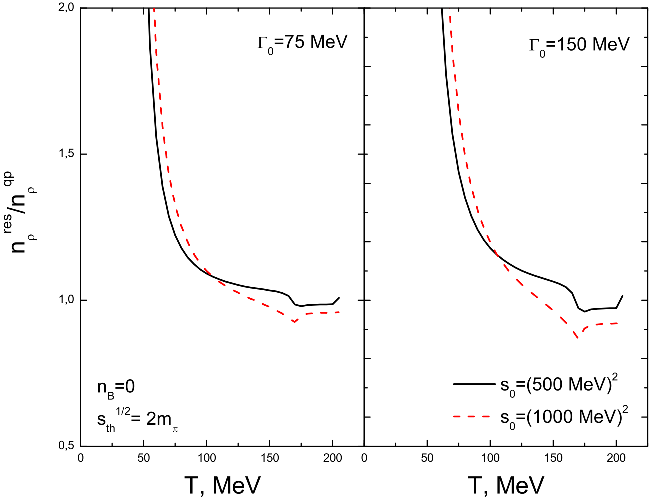
$$(B): \quad g_{\omega K}^* = x_{\omega K} g_{\omega N} \frac{\chi_\omega}{\chi_\omega(f_0)}, \quad g_{\sigma K}^* = x_{\sigma K} g_{\sigma N} \frac{\chi_\sigma}{\chi_\sigma(f_0)}$$

$$x_{\omega\pi} = x_{\sigma\pi} = 0 \quad \text{(free pion)}$$

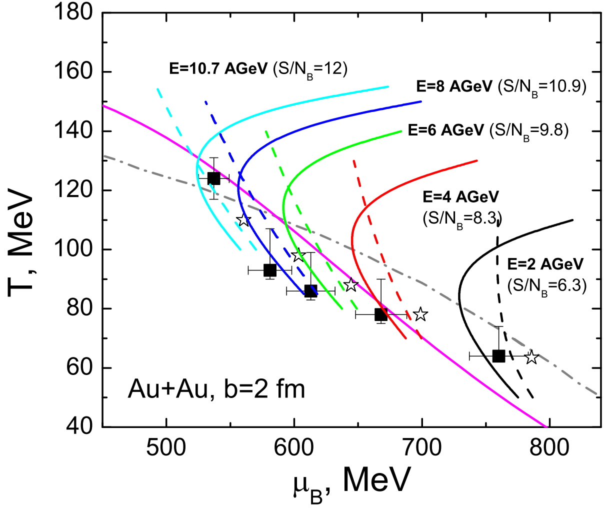
Δ-baryon. Nonzero width



ρ-meson. Nonzero width



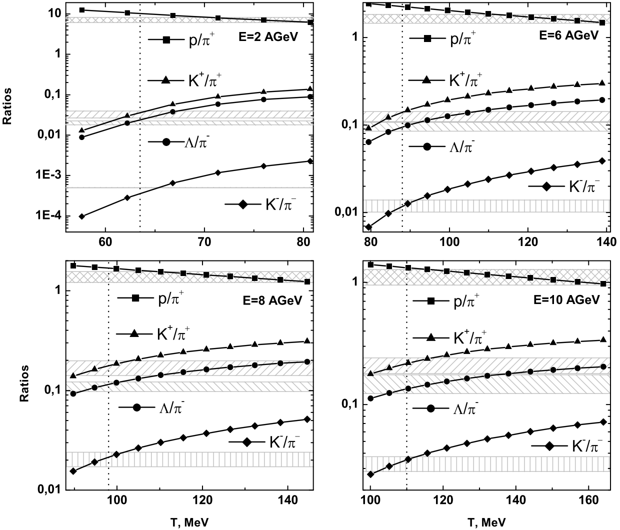
Isentropic trajectories for AGS



Solid lines - our model, dashed lines - ideal gas model
thin solid, dash-dotted lines - freeze-out curves
squares - experimental points
S/N_B from QGSM model

A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. **A772** (2006) 167

Particle ratios for other energies



Strangeness suppression was taken into account!
Shaded bands correspond to uncertainties of experimental data

A. Andronic, P. Braun-Munzinger and J. Stachel, Nucl. Phys. **A772** (2006) 167