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EQUATION OF STATE OF DENSE MATTER: PAULI DEGENERACY, PAIRING CORRELATIONS, AND IMPLICATIONS FOR NEUTRON STARS

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Abstract

We develop a unified description of dense fermionic matter that consistently incorporates Pauli degeneracy, interaction effects, and pairing correlations. The condition that the temperature is much smaller than the Fermi energy leads to a natural separation between Sommerfeld, Fermi-liquid, and pairing regimes, and how these contributions enter the equation of state. The resulting EOS is applied to the Tolman–Oppenheimer–Volkoff equations to analyze neutron-star structure. We demonstrate that Pauli degeneracy provides the dominant pressure, interactions determine the stiffness of the EOS, and pairing correlations produce subleading but potentially significant corrections, especially in quark matter. Implications for mass–radius constraints and modern observations are discussed.

Keywords: equation of state, dense QCD matter, Pauli degeneracy, pairing correlations, color superconductivity, van der Waals model, quark matter, neutron stars, Tolman–Oppenheimer–Volkoff equations

Introduction

The study of strongly interacting matter under extreme conditions remains one of the central problems of modern nuclear and high-energy physics. Experimental observations of elliptic flow in non-central heavy-ion collisions provide compelling evidence for the formation of a strongly interacting quark–gluon plasma (QGP), followed by its evolution toward a hadronic phase [1].

After hadronization, the system can be described as a hadron resonance gas in the grand canonical ensemble, where conserved charges rather than individual particle numbers determine the relevant chemical potentials. Among such approaches, the van der Waals (vdW) model provides a natural framework to incorporate short-range repulsion and intermediate-range attraction between hadrons [2, 3]. This provides an effective phenomenological description.

However, the standard vdW model is incomplete in two important aspects. First, it neglects quantum-statistical (Pauli) effects, which generate universal exchange contributions even in the absence of interactions. Second, it does not include pairing (BCS-type) correlations, which can significantly modify thermodynamic properties at low temperatures.

In this work, we develop a consistent extension of the vdW-based equation of state that incorporates both Pauli and pairing corrections and analyze their impact on the thermodynamics of hadronic and quark matter, as well as on the macroscopic structure of compact stars through the Tolman–Oppenheimer–Volkoff equations [4, 5, 6].

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1. Quantum-statistical (Pauli) corrections

In addition to interaction effects, fermionic systems exhibit universal quantum-statistical corrections due to the Pauli exclusion principle [7].

In the dilute regime, the virial expansion reads with the convention

$$\frac{P}{T} = n + B_2(T)n^2 + \mathcal{O}(n^3), \tag{1}$$

the fermionic exchange correction is positive,

$$B_2^{\mathrm{Pauli}}(T) = \frac{\lambda_T^3}{2^{5/2}g}, \tag{2}$$

which can be interpreted as a temperature-dependent excluded volume.

Thus, the effective virial coefficient becomes

$$B_{ij}^{\mathrm{eff}}(T) = b_{ij} - \frac{a_{ij}}{T} + \delta_{ij}B_i^{\mathrm{Pauli}}(T). \tag{3}$$

The virial Pauli correction is applicable only in the dilute regime $n\lambda_T^3 \ll 1$. In neutron-star interiors, where $T \ll \varepsilon_F$, the appropriate manifestation of the Pauli principle is instead the degenerate Fermi pressure.

Table 1. Pauli contribution to the proton–proton virial coefficient for $R_p^0 = 0.5$ fm and $g = 4$.

T (MeV)	$B_2^{\rm Pauli}$ (fm^3)	$B_{pp}^{\rm eff}$ (fm^3)
10	5.88	7.97
20	2.08	4.17
50	0.526	2.62
100	0.186	2.28
150	0.101	2.20
200	0.066	2.16

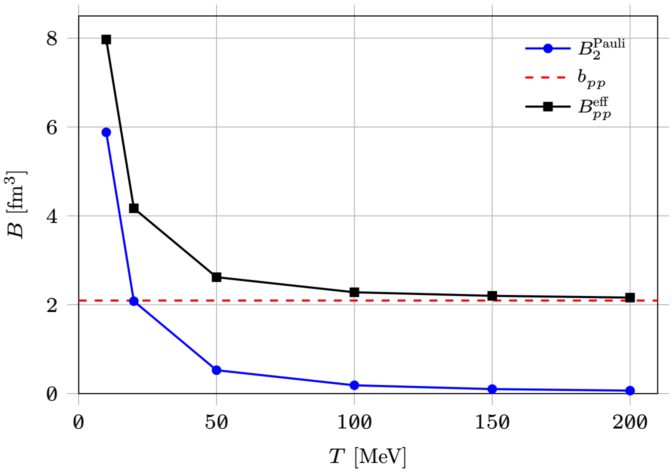

Figure 1. Comparison of the Pauli contribution, the classical excluded-volume term, and the resulting effective proton–proton virial coefficient.

2. Pairing (BCS) corrections

At temperatures $T \ll T_c$, fermionic systems undergo pairing [8] , leading to a modification of the thermodynamic potential.

In the BCS approximation, the condensation energy is

$$\Delta\Omega \simeq -\frac{1}{2}N(0)\,\Delta^2, \tag{4}$$

where $N(0)$ is the density of states at the Fermi surface.

At fixed chemical potential, this leads to a pressure increase

$$\delta P_{\rm pair} \simeq \frac{1}{2}N(0)\,\Delta^2, \tag{5}$$

and a corresponding decrease in energy density.

At fixed chemical potential this increases the pressure. Its impact on the EOS stiffness at fixed density depends on neutrality, beta equilibrium, and the density dependence of the gap.

3. Implications for compact stars

The equation of state determines the structure of compact stars through the Tolman–Oppenheimer–Volkoff equations.

Pairing and Pauli corrections modify the EOS:

$$P(\varepsilon) = P_0(\varepsilon) + \delta P(\varepsilon), \tag{6}$$

which in turn affects the mass–radius relation.

Table 2. Relative pairing correction to the degenerate quark pressure, $\delta P_{\rm pair}/P_F = 4(\Delta/\mu_q)^2$, for representative values of quark chemical potential μ_q and pairing gap Δ.

μ_q (MeV)	Δ (MeV)	$\delta P_{\rm pair}/P_F$
400	25	0.0156
400	50	0.0625
400	75	0.1406
400	100	0.2500
450	25	0.0123
450	50	0.0494
450	75	0.1111
450	100	0.1975
500	25	0.0100
500	50	0.0400
500	75	0.0900
500	100	0.1600
550	25	0.0083
550	50	0.0331
550	75	0.0744
550	100	0.1322
600	25	0.0069
600	50	0.0278
600	75	0.0625
600	100	0.1111

To leading order, the relative change of the maximum mass scales as

$$\frac{\delta M_{\rm max}}{M_{\rm max}} \sim f_{\rm eff}\left\langle \frac{\delta P}{P} \right\rangle, \tag{7}$$

where $f_{\rm eff}$ characterizes the volume fraction of the star affected by the correction.

For ultrarelativistic quark matter, the relative pairing correction to the degenerate Fermi pressure is

$$\frac{\delta P_{\rm pair}}{P_F} = 4\left(\frac{\Delta}{\mu_q}\right)^2. \tag{8}$$

Thus, the effect decreases as μ_q^{-2} and grows with Δ^2. For $\mu_q = 400$–600 MeV and $\Delta = 25$–100 MeV, one finds

$$\frac{\delta P_{\rm pair}}{P_F} \sim 0.7\%\text{–}25\%, \tag{9}$$

which shows that color-superconducting pairing can provide a substantial correction to the quark-matter equation of state.

4. Simultaneous inclusion of Pauli degeneracy and pairing correlations in quark matter

For cold quark matter in neutron-star interiors, the Pauli principle and pairing correlations must be incorporated simultaneously at the level of the degenerate equation of state.

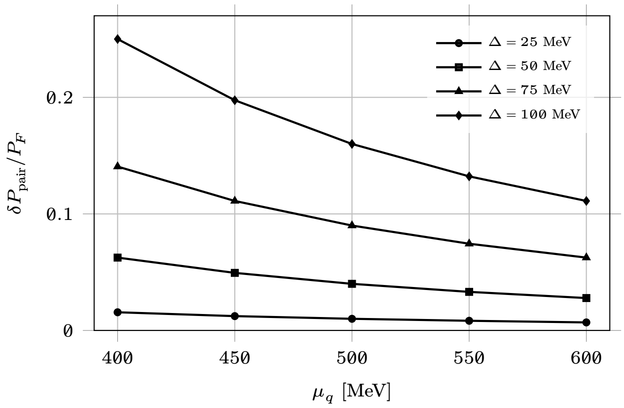

Figure 2. Relative pairing correction to the degenerate quark pressure as a function of quark chemical potential for several values of the pairing gap.

In the ultrarelativistic limit, the Pauli principle generates [1] the dominant degeneracy pressure,

$$P_F = \frac{g\mu_q^4}{24\pi^2(\hbar c)^3}, \qquad \varepsilon_F = 3P_F, \qquad n_B = \frac{g\mu_q^3}{18\pi^2(\hbar c)^3}, \tag{10}$$

where $g = 18$ for three colors and three light flavors.

Pairing correlations in the color-superconducting phase [9] produce an additional condensation contribution

$$\delta P_{\rm pair} \simeq 3\,\frac{\mu_q^2\Delta^2}{\pi^2(\hbar c)^3}, \qquad \delta\varepsilon_{\rm pair} \simeq -\delta P_{\rm pair}. \tag{11}$$

Thus, the total equation of state can be written as

$$P_{\rm tot}(\mu_q) = \frac{g\mu_q^4}{24\pi^2(\hbar c)^3} + 3\,\frac{\mu_q^2\Delta^2}{\pi^2(\hbar c)^3} - B_{\rm bag}, \tag{12}$$

$$\varepsilon_{\rm tot}(\mu_q) = \frac{g\mu_q^4}{8\pi^2(\hbar c)^3} - 3\,\frac{\mu_q^2\Delta^2}{\pi^2(\hbar c)^3} + B_{\rm bag}. \tag{13}$$

The relative importance of pairing with respect to the Pauli degeneracy pressure is

$$\frac{\delta P_{\rm pair}}{P_F} = \frac{72}{g}\frac{\Delta^2}{\mu_q^2} = 4\frac{\Delta^2}{\mu_q^2}, \qquad (g = 18). \tag{14}$$

Therefore, in quark cores of neutron stars the Pauli principle provides the dominant background stiffness of the EOS, while pairing correlations produce a substantial correction that can reach the level of several percent and, for large gaps, up to $\mathcal{O}(10\%)$–$\mathcal{O}(20\%)$.

Table 3 shows representative numerical estimates for cold quark matter when the Pauli degeneracy pressure and pairing correlations are included simultaneously. One sees that the Pauli principle provides the dominant background stiffness of the equation of state through the degenerate Fermi pressure $P_F \propto \mu_q^4$, whereas the pairing contribution produces an additional positive correction of order $\delta P_{\rm pair} \propto \mu_q^2\Delta^2$.

For moderate gaps, $\Delta \sim 50$ MeV, the pairing contribution remains at the level of several percent of P_F. For larger gaps, $\Delta \sim 100$ MeV, the effect can reach the level of $\sim 10\%$–20%, which is large enough to noticeably modify the equation of state and, consequently, the TOV mass–radius relation.

Table 3. Representative estimates for quark matter with simultaneous Pauli and pairing contributions.

μ_q (MeV)	Δ (MeV)	n_B (fm^{-3})	P_F (MeV fm^{-3})	$\delta P_{\rm pair}/P_F$
400	50	0.844	253	0.063
450	50	1.20	406	0.049
450	100	1.20	406	0.197
500	100	1.65	618	0.160
550	100	2.19	905	0.132
600	100	2.85	1281	0.111

5. Low-temperature regimes of dense fermionic matter in neutron stars

The thermodynamic properties of dense matter in neutron-star interiors are controlled by the hierarchy between the temperature T, the Fermi energy ε_F, and, when present, the pairing gap Δ and critical temperature T_c. In realistic neutron stars one typically has

$$T \ll \varepsilon_F, \tag{15}$$

which places the system deep in the degenerate regime. In this section, we summarize the appropriate theoretical descriptions in different temperature domains.

6. Degenerate regime: $T \ll \varepsilon_F$

For all relevant components (electrons, nucleons, and possibly quarks), the Fermi energy is of order

$$\varepsilon_F \sim 10\text{–}100 \text{ MeV} \tag{16}$$

for nucleons and up to several hundred MeV for quarks, while the stellar temperature satisfies

$$T \sim 10^{-2}\text{–}10^{-1} \text{ MeV}. \tag{17}$$

Thus,

$$\frac{T}{\varepsilon_F} \ll 1. \tag{18}$$

In this regime, thermodynamic quantities admit the Sommerfeld expansion. For a generic observable

$$I(T) = \int_0^\infty d\epsilon\,\phi(\epsilon)\,\frac{1}{e^{(\epsilon-\mu)/T}+1}, \tag{19}$$

one obtains

$$I(T) = \int_0^\mu \phi(\epsilon)\,d\epsilon + \frac{\pi^2}{6}T^2\phi'(\mu) + \mathcal{O}(T^4). \tag{20}$$

As a consequence, the equation of state (EOS) takes the form

$$P(T,\mu) = P_0(\mu) + \mathcal{O}(T^2), \qquad \varepsilon(T,\mu) = \varepsilon_0(\mu) + \mathcal{O}(T^2), \tag{21}$$

so that the zero-temperature EOS provides the dominant contribution.

In this regime, the Pauli principle manifests itself through the degeneracy pressure

$$P_F \propto \mu^4, \tag{22}$$

rather than through the virial expansion valid for dilute gases.

7. Interacting normal phase: Landau Fermi liquid

For nucleonic matter, the interparticle interaction is strong. Nevertheless, at low temperatures the system can be described within the framework of Landau Fermi-liquid theory.

In this approach, the system is represented as a gas of quasiparticles with dispersion relation $\varepsilon(p)$ near the Fermi surface. The effects of interactions are encoded in:

- the effective mass m^*,
- the Landau parameters F_ℓ, G_ℓ, ...,
- the renormalized density of states $N^*(0)$.

The thermodynamic quantities retain the same functional structure as in the ideal Fermi gas, but with renormalized parameters. In particular, the pressure may be schematically written as

$$P = P_F(m^*) + P_{\text{int}}, \tag{23}$$

where P_F represents the degeneracy (Pauli) contribution and P_{int} encodes interaction effects.

Thus, the statement that dense matter becomes "more ideal" at high density should be understood in the sense that the low-energy excitations are well described by weakly interacting quasiparticles, rather than that the underlying interaction is weak.

8. Superfluid phase: $T < T_c$

At sufficiently low temperatures, attractive channels in the interaction lead to Cooper pairing and the formation of a superfluid or superconducting phase. The critical temperature is related to the pairing gap as

$$T_c \simeq 0.57\,\Delta(0). \tag{24}$$

In the paired phase, the thermodynamic potential acquires an additional condensation contribution,

$$\Delta\Omega \simeq -\frac{1}{2}N(0)\Delta^2, \tag{25}$$

which leads to a correction to the pressure at fixed chemical potential,

$$\delta P_{\text{pair}} \simeq \frac{1}{2}N(0)\Delta^2. \tag{26}$$

The total pressure can therefore be written as

$$P = P_F + P_{\text{int}} + \delta P_{\text{pair}}. \tag{27}$$

At fixed chemical potential the pairing contribution increases the pressure. At fixed density, however, its effect on the EOS stiffness depends on the self-consistent adjustment of chemical potentials under neutrality and beta-equilibrium conditions.

In contrast to the normal phase, low-temperature corrections are no longer polynomial in T, but instead become exponentially suppressed,

$$\delta P(T) \sim e^{-\Delta/T}. \tag{28}$$

9. Hierarchy of regimes

The above discussion leads to the following hierarchy of physical regimes:

- **Dilute regime:** $n\lambda_T^3 \ll 1$
  Virial expansion applies; Pauli effects appear as corrections to b_2.
- **Degenerate regime:** $T \ll \varepsilon_F$
  Sommerfeld expansion; Pauli principle manifests as degeneracy pressure.
- **Interacting regime:** $T \ll \varepsilon_F$
  Landau Fermi-liquid description; interactions encoded in quasiparticles.
- **Paired regime:** $T < T_c$
  Superfluid/superconducting phase; pairing corrections $\propto \Delta^2$.

10. Physical interpretation

In neutron-star matter, the pressure is dominated by Pauli degeneracy. Strong interactions modify this background via renormalization of quasiparticle properties, while pairing correlations provide an additional, typically subleading but non-negligible correction.

Thus, the equation of state of dense matter can be viewed as a superposition of three physically distinct contributions:

$$\boxed{P = P_{\text{Pauli}} + P_{\text{interaction}} + P_{\text{pairing}}.} \tag{29}$$

11. Connection between the low-temperature hierarchy, the TOV equations, and the mass–radius relation

The hierarchy of temperature scales discussed above determines not only the microscopic description of dense matter, but also the way in which the equation of state enters the stellar structure problem.

The hydrostatic equilibrium of a spherically symmetric compact star is governed by the Tolman–Oppenheimer–Volkoff (TOV) equations,

$$\frac{dP}{dr} = -\frac{G[\varepsilon(r) + P(r)/c^2][m(r) + 4\pi r^3 P(r)/c^2]}{r^2\left[1 - \dfrac{2Gm(r)}{rc^2}\right]}, \tag{30}$$

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon(r), \tag{31}$$

supplemented by the equation of state

$$P = P(\varepsilon). \tag{32}$$

Therefore, any change in the microscopic physics affects the stellar mass–radius relation only through the induced modification of the EOS.

Degenerate regime: $T \ll \varepsilon_F$. Since neutron-star matter is deeply degenerate, the dominant EOS is its zero-temperature form,

$$P(\varepsilon, T) = P_0(\varepsilon) + \delta P_T(\varepsilon), \qquad \delta P_T = \mathcal{O}(T^2), \tag{33}$$

as follows from the Sommerfeld expansion. Because $T/\varepsilon_F \ll 1$, these thermal corrections are usually small compared with the bulk pressure and produce only negligible changes in the TOV solutions for mature neutron stars.

Thus, for the global structure problem one may usually approximate

$$P(\varepsilon, T) \simeq P_0(\varepsilon). \tag{34}$$

Interacting normal phase: Landau Fermi liquid. In the normal phase, strong interactions do not invalidate the low-temperature description, but instead renormalize it. The EOS may then be written schematically as

$$P(\varepsilon) = P_{\text{Pauli}}(\varepsilon) + P_{\text{int}}(\varepsilon), \tag{35}$$

where P_{Pauli} denotes the degeneracy-pressure background and P_{int} contains the interaction-induced renormalization of the quasiparticle spectrum and compressibility.

From the point of view of the TOV equations, the crucial quantity is not the microscopic separation between these terms, but the net stiffness of the EOS, that is, the rate at which the pressure increases with energy density. A stiffer EOS generally provides stronger resistance against gravitational compression and therefore tends to increase both the radius and the maximum mass of the star.

Paired phase: $T < T_c$. When the temperature falls below the critical value, pairing correlations modify the thermodynamic potential and add an additional contribution to the pressure. The EOS then takes the form

$$P(\varepsilon) = P_{\text{Pauli}}(\varepsilon) + P_{\text{int}}(\varepsilon) + \delta P_{\text{pair}}(\varepsilon), \tag{36}$$

with

$$\delta P_{\text{pair}} \sim \frac{1}{2} N(0) \Delta^2 \tag{37}$$

in the simplest BCS estimate at fixed chemical potential.

In the paired phase, low-temperature corrections are no longer controlled only by the Sommerfeld T^2 expansion, because the pairing gap suppresses fermionic excitations and qualitatively changes the thermodynamics. Nevertheless, for the structure problem the main effect is again encoded in the modified zero-temperature EOS.

Impact on the TOV solutions. The above hierarchy implies a clear ordering of structural effects:

1. The Pauli principle provides the dominant degeneracy pressure and thus sets the basic scale of stellar support against gravity.
2. Strong interactions modify the compressibility and symmetry properties of dense matter, thereby determining the detailed stiffness of the EOS and hence the quantitative shape of the mass–radius curve.
3. Pairing correlations provide an additional correction to the pressure, which is usually small for nucleonic superfluidity but can be much larger in paired quark matter.

Thus, the TOV mass–radius relation is controlled by the effective hierarchy

$$P_{\text{Pauli}} \quad\Longrightarrow\quad P_{\text{Pauli}} + P_{\text{int}} \quad\Longrightarrow\quad P_{\text{Pauli}} + P_{\text{int}} + \delta P_{\text{pair}}. \tag{38}$$

Scaling estimate for $M(R)$. If pairing or residual thermal effects provide only a small correction to the background EOS,

$$|\delta P| \ll P_0, \qquad |\delta\varepsilon| \ll \varepsilon_0, \tag{39}$$

their impact on the TOV solution may be estimated perturbatively. To leading order, one expects

$$\frac{\delta R}{R} \sim \left\langle \frac{\delta P}{P_0} \right\rangle_{\text{core}}, \qquad \frac{\delta M}{M} \sim f_{\text{eff}} \left\langle \frac{\delta P}{P_0} \right\rangle_{\text{core}}, \tag{40}$$

where f_{eff} denotes the effective volume fraction of the star in which the correction is operative.

This estimate immediately explains why the various regimes contribute differently to the global structure:

- Sommerfeld T^2 corrections are extremely small because $T/\varepsilon_F \ll 1$, so their effect on $M(R)$ is negligible for cold stars.
- Landau-Fermi-liquid renormalizations are built into the bulk EOS and therefore strongly affect the entire mass–radius curve.
- Nucleonic pairing usually changes the pressure only weakly and hence produces small corrections to $M(R)$.
- Color-superconducting quark pairing may generate a sizable correction to the pressure in the inner core and can therefore noticeably shift both the radius and the maximum mass.

Physical interpretation. The low-temperature hierarchy is therefore directly reflected in the macroscopic structure problem. The condition $T \ll \varepsilon_F$ justifies the use of a degenerate zero-temperature EOS as the baseline input for the TOV equations. Landau theory describes how interactions renormalize this baseline. Pairing then modifies the same EOS at the next level of approximation.

As a result, the mass–radius relation of a cold neutron star should be viewed as a macroscopic manifestation of the hierarchy

$$T \ll \varepsilon_F, \qquad T \lessgtr T_c, \tag{41}$$

together with the decomposition

$$\boxed{P(\varepsilon) = P_{\text{Pauli}}(\varepsilon) + P_{\text{interaction}}(\varepsilon) + P_{\text{pairing}}(\varepsilon).} \tag{42}$$

In this sense, the TOV equations provide the bridge between the microscopic physics of degenerate fermions and the observable global characteristics of compact stars.

12. Observational implications

The hierarchy of contributions to the equation of state discussed above has direct consequences for observable properties of neutron stars. In particular, the existence of neutron stars with masses close to $2\,M_\odot$ [6] imposes a strong lower bound on the stiffness of the high-density EOS. Any realistic model must therefore provide sufficient pressure at several times nuclear saturation density, which in our framework is primarily ensured by the Pauli degeneracy pressure together with interaction-induced stiffening.

Recent measurements of neutron-star radii from *NICER* observations indicate typical values in the range

$$R \sim 11\text{–}13 \text{ km} \tag{43}$$

for stars with masses around $1.4\,M_\odot$. These constraints disfavour equations of state that are either too soft (insufficient pressure at intermediate densities) or too stiff (overly large radii), thereby placing nontrivial bounds on the interaction contribution P_{int}.

Within this context, pairing effects play a qualitatively different role in nucleonic and quark matter. In nucleonic matter, the pairing gap is small compared to the Fermi energy, and the corresponding pressure correction is negligible for the global structure, although it is crucial for thermal evolution. In contrast, if a quark core is present, color-superconducting pairing may generate corrections at the level of $\sim$ 10%–20% of the degeneracy pressure, potentially leading to observable shifts in the mass–radius relation.

Therefore, precision measurements of neutron-star masses and radii provide an indirect probe of the hierarchy

$$P_{\text{Pauli}} \rightarrow P_{\text{interaction}} \rightarrow P_{\text{pairing}}, \tag{44}$$

and may help to constrain not only the stiffness of dense matter, but also the possible presence of paired quark phases in the inner core.

Conclusion

In this work, we have developed a consistent extension of the van der Waals equation of state [10], [3], [2] for hadronic matter by incorporating both quantum-statistical (Pauli) and pairing (BCS) corrections.

The Pauli principle generates a temperature-dependent contribution to the second virial coefficient, acting as an effective repulsion.

In contrast, pairing correlations produce a positive correction to the pressure at fixed chemical potential, leading to a stiffening of the equation of state at low temperatures.

We demonstrated that these effects operate in different physical regimes: Pauli corrections dominate in the dilute and moderately degenerate regime, while pairing effects become important near the Fermi surface.

The impact of these corrections on macroscopic observables was analyzed using scaling arguments within the Tolman–Oppenheimer–Volkoff framework. It was shown that nucleonic pairing produces only small corrections to the mass–radius relation, whereas color-superconducting quark matter may lead to significant modifications if pairing occurs in a substantial fraction of the stellar core.

Thus, the combined inclusion of Pauli and pairing effects provides a systematic and physically transparent framework for connecting microscopic many-body physics with the thermodynamics of dense matter and the structure of compact stars.

We have shown that the EOS of dense matter is governed by the hierarchy

$$P_{\text{Pauli}} \rightarrow P_{\text{interaction}} \rightarrow P_{\text{pairing}}. \tag{45}$$

Pauli degeneracy provides the dominant pressure, interactions determine the stiffness of the EOS, and pairing correlations produce subleading but potentially significant corrections.

The TOV equations translate this hierarchy into observable neutron-star properties.

References

1. *Fukushima K.*, *Hatsuda T.* The Phase Diagram of Dense QCD // Reports on Progress in Physics. — 2011. — Vol. 74. — P. 014001.
2. *Krivenko-Emetov Y. D.* Multicomponent Model of Ultra-Dense Nucleonic Matter under Extreme Conditions // Letters in High Energy Physics. — 2023. — Vol. 6. — P. 401.
3. Multicomponent van der Waals Equation of State: Applications in Nuclear and Hadronic Physics / V. Vovchenko [et al.] // Physical Review C. — 2017. — Vol. 96. — P. 045202.
4. *Tolman R. C.* Static Solutions of Einstein's Field Equations for Spheres of Fluid // Physical Review. — 1939. — Vol. 55. — P. 364.
5. *Oppenheimer J. R.*, *Volkoff G. M.* On Massive Neutron Cores // Physical Review. — 1939. — Vol. 55. — P. 374.
6. *Lattimer J. M.*, *Prakash M.* Neutron Star Structure and the Equation of State // Astrophysical Journal. — 2001. — Vol. 550. — P. 426.
7. *Landau L. D.*, *Lifshitz E. M.* Statistical Physics. Vol. 5. — Butterworth-Heinemann, 1980. — (Course of Theoretical Physics).
8. *Bardeen J.*, *Cooper L. N.*, *Schrieffer J. R.* Theory of Superconductivity // Physical Review. — 1957. — Vol. 108. — P. 1175.
9. Color superconductivity in dense quark matter / M. G. Alford, A. Schmitt, K. Rajagopal, T. Schäfer // Reviews of Modern Physics. — 2008. — Vol. 80. — P. 1455.
10. *Krivenko-Emetov Y. D.* Interparticle attractive forces account of the multicomponent hadron gas in the grand canonical ensemble // Proceedings of the XXIV Annual Scientific Conference of the Institute for Nuclear Research of the National Academy of Sciences of Ukraine. — Kyiv, Ukraine : INR NAS of Ukraine, 2017. — P. 36. — in Ukrainian.