Attachment no. 2

SUMMARY OF PROFESSIONAL ACHIEVEMENTS

PhD Jacek Rożynek

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ŚWIERK-OTWOCK

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Table of contents

1. Personal data

Name and surname: Jacek Rożynek
Workplace: National Centre for Nuclear Research
ŚWIERK, 05-400 Otwock

2. Education and scientific degrees

Master's: University of Maria Curie-Skłodowska in Lublin
Specialization: theoretical physics
Master's thesis entitled*: Self-consistent Hartree-Fock method in the area of doubly magic nuclei*.
Supervisor Prof. PhD Stanisław Szpikowski.
Thesis defence: 1974

PhD: University of Warsaw
Specialization: theoretical physics
Doctoral thesis entitled: *Role of the Λ Σ conversion in the nuclear matter*.
Supervisor Prof. Janusz Dąbrowki.
Thesis defence: 1984

3. Information on the previous employment in scientific units

Assistant – Institute of Nuclear Research of A. Sołtan (1978-1986)
Assistant Professor – Institute of Nuclear Research of A. Sołtan (1986-2010)
Assistant Professor – National Centre for Nuclear Research, Warsaw (2010-now)

4. **Scientific achievements constituting the ground for the habilitation proceedings**.

4.a Indication of the scientific achievement constituting the ground for initiating the habilitation procedure.

The scientific achievement which constitutes the ground for initiating the habilitation procedure is the cycle of thematically related publications entitled:

“Nucleons in dense and hot nuclear matter”.

4.b List of works constituting the achievement:

A1. *Jacek Rożynek, Grzegorz Wilk, “A Model for the Parton Distribution in Nuclei”, Phys.Lett. B* ***473*** *(2000) 167-171.*

A2. *Jacek Rożynek, “ The nuclear scalar potential and the EMC effect”, Int. J. of Modern Physics E* ***9*** *(2000) 195-203.*

A3*. Jacek Rożynek, Grzegorz Wilk, „The Single Particle Sum Rules in the Deep-Inelastic Region ”, Physical Review C 7 (2006) 068202.*

B1. *Jacek Rożynek, “Nuclear Equation of State and Finite Nuclear Volumes”, J. Phys. G* ***42*** *(2015) 045109 .*

C1. *Jacek Rożynek, “Nonextensive distributions for a relativistic Fermi Gas”, Physica A* ***440*** *(2015) 27-32.*

C2. *Jacek Rożynek, Grzegorz Wilk “ Nonextensive Nambu Jona-Lasinio model of QCD matter”, Eur. Phys. J. A* ***52*** *(2016) 13.*

C3. *Jacek Rożynek, Grzegorz Wilk “ An example of the interplay on nonextensivity and dynamics in the description of QCD matter”, Eur. Phys. J. A* ***52****, (2016) 294****.***

4.c Discussion of the scientific aim of the above-mentioned works and the obtained results with the discussion of their potential use.

Scientific aim of the works.

The submitted works [A1-A3,B1,C1-C3] comprising my habilitation present the new results in three areas, which are briefly discussed:
(i) changes in the parton nucleon structure in the nucleon matter (NM) and its impact on the nucleon mass and its size (M and R_N) [A1-A3] ;
(ii) changes in the compressibility of NM and Equation of State (EoS) induced by the change of nucleon mass M and a radius R_N [B1];
(iii) examination, based on the non-extensive thermodynamics, of the critical region, where the transition between nucleons in a dense NM to the strongly correlated quark gluon matter takes place [C1-C3].
The analysis of changes in the nucleon properties (and creating them quarks) is the theme of the presented works, depending on the environment in which they are located – from atomic nuclei to the dense hot NM. In particular, these works described the possible changes of the mass M and the nucleon size R_N in NM for different statistics (extensive and non-extensive) of quarks an gluons, both for the NM in equilibrium (which properties are extrapolated from the properties of heavy nuclei) and for the dense quark and gluon matter, which exists inside the neutron stars and in the scattering of heavy ions.

In the phenomenological single-particle description of the properties of atomic nuclei, it is usually assumed that the effects of the nucleon sizes are negligible, and the mass of nucleons is constant, independent of the local density in the nucleus [0]. It turns out that these assumptions allow to describe the total energy and single-particle spectra with very good accuracy for almost all nuclei. Therefore, it was assumed in nuclear models describing the single-particle structure that the mass of a "point like" nucleon (proton or neutron) is constant and it does not change with the equilibrium density and size of the atomic nucleus. In addition, most structural calculations of atomic nuclei are performed for the zero pressure, so the volume of nucleons does not play a significant role (although the presence of the repulsive hard core ensuring saturation of nuclear forces [1] and proves the finite size of nucleons, which volume is at least 10% of the nuclear volume at equilibrium). However, the determination of the quantities, which depend on a pressure derivative in the equilibrium, such as, e.g., compressibility, depends on the selected model [2]. Moreover, the size of nucleons is important for the parameterization of specific nuclear distributions measured in the low energy electron scattering on nuclei. In this case, one use the single-particle model distributions of nucleons, in which the radius of the nucleon is one of the fitting parameters [0].

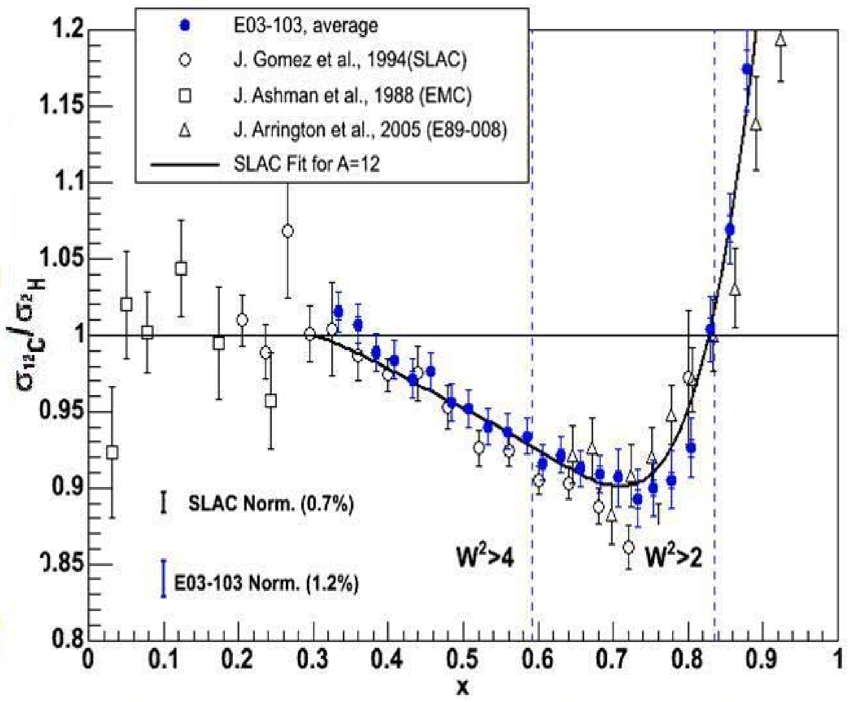


Fig.1: *The ratio of inelastic active cross-sections on carbon and deuterium for the sufficiently large values of invariant hadron mass $W^2=(M+q)^2$ and transfer of the proton momentum $q^2>1GeV$.*

The discovery of the change in parton distribution function (PDF) of the nucleon in the nucleus was a big surprise. This effect, known as the "EMC effect", and observed for the first time in [3], showed that the ratio of cross-section on the nuclear target to the cross-section on the ^{2}D target departures from the unity, which is particularly evident for large values of the Björken variable *x* [3]. Fig. 1 shows the EMC effect for the ^{12}C nuclei measured by different collaborations (SLAC, EMC). While the departures for large values x is of the kinematic origin (for nuclear nucleons x>1 is possible), departures from the unity for small x result only from dynamics. The fits of the nuclear PDF for small values of *x* show, that already for the nuclear density we can observe significant modifications of the sea quark distributions $q\bar{q}$ resulting from the nonabelian structure of interaction in QCD. Thus, a question arises, whether studying the parton structure of NM we will see changes of nucleon properties like its size or mass?

To describe the EMC effect, we cannot assume that nucleons are the point objects, which is the most serious, uncontrolled approximation in the single-particle models used in nuclear physics [4]. There are many theoretical works dedicated to the explanation of the EMC effect through the change of the nucleon mass and they can be classified in two main approaches. The first approach describes nucleons as soliton solutions (skyrmions) of the system of interacting pions in the non-perturbative limit of quantum chromodynamics (QCD) for a large number of colours. In this non-linear field theory the topological charge is preserved, which is identified with a baryon charge. This way, nucleons are generated as non-linear solutions of the effective field theory, and their interactions are associated with the deformations in the configuration space of 2-soliton field solutions. Unfortunately, despite achieving the attracting potential at an appropriate distance, an agreement with the realistic potential nucleon-nucleon is obtained only at the qualitative level, just like the possible changes of the nucleon mass [5]. The similar, qualitative description we have in nuclear models based on chiral expansion [6]. Our works [A1-A3] describe the EMC effect in the convolution model, where the quark distribution in nucleons are convolute with the nucleon distributions in a nucleus.

Possible changes in the nucleon size affect the compressibility of the nuclear matter, which value determines the course of the equation of state (EoS) for the density above the nuclear equilibrium. It is known that nucleons have their own "compressibility", so it seems obvious that the NM compressibility will also depend on the compressibility of the nucleons. Usually, nucleons are described as a kind of "bags" filled with quarks with properties dependent on the environment. The existing implementations of the model of such a bag in the nuclear medium, however, do not include the dynamic relation of its size R_N and its mass M [7]. The existing calculations consider fixed radius R_N and fixed mass M for the entire course of density and pressure [8]. In paper [B1] calculations took into account correlations between M and R_N. It is shown that the proposed correlations leads to the significant modification of the EoS.

Dense quark-gluon plasma resulting in the scattering of heavy nuclei is far from equilibrium and quickly undergoes hadronization. This means that the system formed in such an event is not homogenous and temperature fluctuations may occur inside it. In fact, the conditions which allow to describe it with the commonly used Boltzmann-Gibbs (BG) distribution are not satisfied. This is confirmed by many experiments indicating, that the observed distributions differ from the commonly expected BG distributions demonstrating rather a power behaviour. In turn, power distributions are well known from other fields of physics and are associated with the description of the so-called nonextensive systems [9]. Nonextensive effects, apart from the situation mentioned above, appear when the interaction is of the long-range character. In our case, it is a long-range exchange of gluons with the intensity proportional to the distance between attracting quarks which are spaced from each other up to 1fm. In the literature, for the description of nonextensive effects, we use the approach based on the nonextensive Tsallis entropy [10] and the whole process will be based on the nonextensive thermodynamics [C1-C3].

Application area.

We can distinguish two physical systems, in which knowledge of the nuclear EoS for the density several times bigger than the density of atomic nuclei is significant: the interior of neutron stars and high-energy scattering of heavy ions. In the recently discovered heavy neutron stars (with the mass of ~$2M_{☼}$ and the radius of 10 km) the gravity compress the nuclear matter to the density of 10^{15} g/cm^3. Thus, the neutron matter has a density which exceeds the density achieved inside the heavy atomic nuclei twice and it is surrounded by the crust of a lower density [11]. In good approximation this is the relativistic gas of neutrons with an admixture of protons immersed in the meson field of mutual attraction at greater distances and repulsion at small distances, less than 1 fm (10^{-13}m).

Higher density and higher temperatures of the nuclear matter occur in the scattering of heavy ions, where quarks and gluons are the basic degrees of freedom of NM description. Their mutual interactions have a long-range nature leading to correlations, which become important with the increase of density and persist above the temperature of the phase transition from the hadron matter to the quark-gluon matter. To obtain the full information about the EoS of the nuclear matter, heavy-ion experiments are conducted for different energies and using different nuclear targets. This way we can change the basic parameters of the state equation – temperature T and density ρ ; e.g. in RHIC for Au+Au beams of energy $\sqrt{s_{NN}}$ =(7.7, 11.5, 19.6, 27, 39) GeV were used, which allows us to get distributions for the increasing temperatures inside the created "fireball" of the quark-gluon matter [12] -QCD plasma. Due to the long-ranged gluon interactions, the quark-gluon plasma created in the event after the collision is in the excited state and then it seeks the thermal and chemical balance between quarks and gluons.

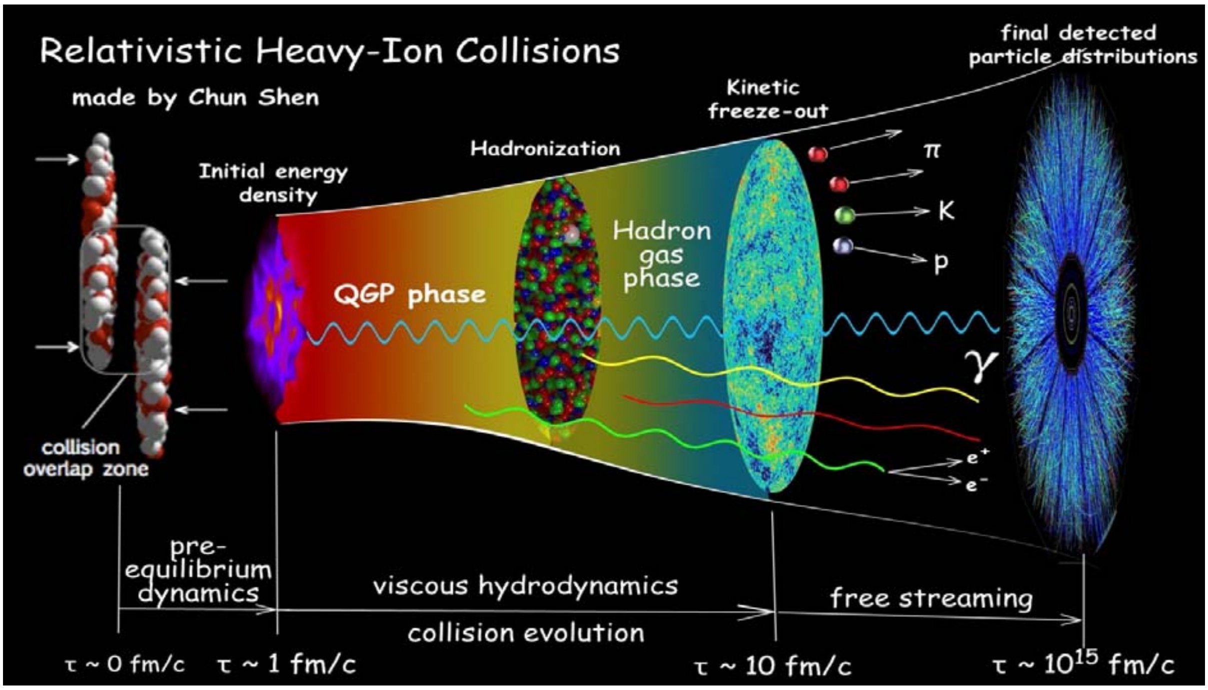
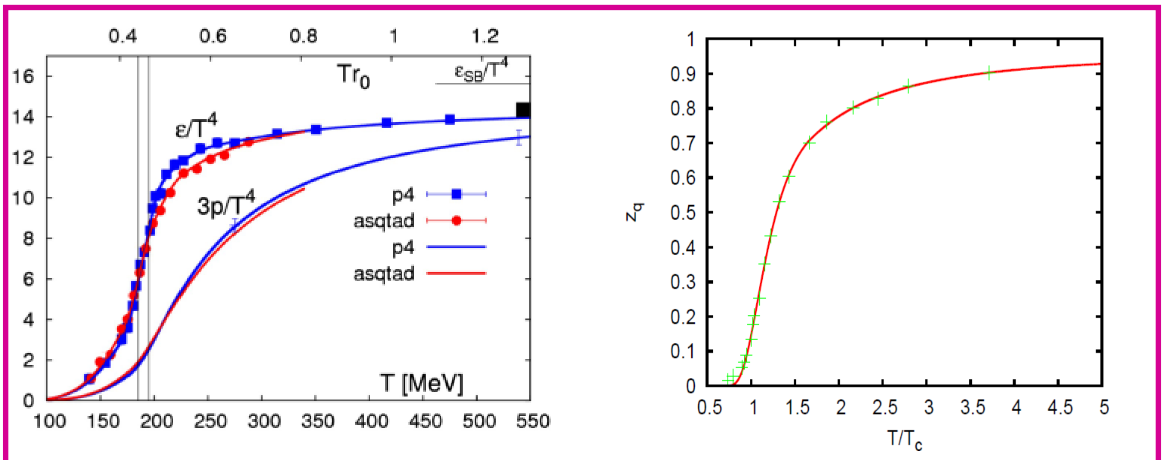


Fig. 2: *Schematic formation of the Quark-Gluon Plasma (QGP) in the scattering of heavy ions – possible temperature fluctuations. [13]*

Fig. 2 presents the schematic scattering of heavy ions with energies in the centre of mass *~(10-40)* GeV. The quark-gluon plasma begins formation after the initial alignment of the energy distribution, when $\tau = 1\text{-}4$ fm/c [14,15]. Then, after a period about $\tau = 5$ fm/c, it hadronizes into independent hadrons and its temperature drops in the process of kinematic freezing. When forming the quark-gluon plasma the high-energy gluons are created, which by emitting the quark-anti-quark pairs increase the system entropy. This process can be phenomenologically described quite easily and clearly [16] thanks to the distributions of the quarks, corrected by the appropriate interaction factor - a fugacity ***z(τ),*** model-dependent on time and nature of the expansion (or, equivalently, on the initial energy (temperature) and deviation from equilibrium). This factor would be equal to the unity in the state of chemical equilibrium, provided that the quarks would create the effectively weekly-interacting system of Fermi gas. For the system dominated by gluons, the fugacity ***z(τ)*** coefficient is much smaller than the unity for the entire time of evolution ***τ*** to the state of equilibrium [16]. Such a picture corresponds to the long-range nature of the gluon interactions, which for this reason will not be sufficiently well described by the BG statistics. This is confirmed by the equilibrium quasi-particle calculations [17] adapted to the dynamic computations on the network [18] and presented in Fig. 3.



Rys. 3 *Results of the network calculations of energy density ε and pressure p[8].*
On the right – quark fugacity which was fitted as a function of ratio $T_/ / T_c$ [3]

They indicate that the equilibrium value of fugacity z_q modifying the single-particle distribution of quark n_q is smaller than the unity in the limit of high temperatures and for quarks is equal $z_q \sim 0.9$ for temperature $T=500$ MeV. This means that quarks remain strongly correlated, despite high temperatures above the critical temperature T_c of phase transition from nucleons to QGP.

Such a strongly correlated system can be well described by using the nonextensive Tsallis approach [10]. In this approach, the entropy of the system S_q is not the sum of entropies of individual subsystems, and in addition to the standard parameter T (temperature) occurring in the normal BG statistics, there is a new parameter q called the nonextensive parameter. For the system composed of two subsystems A and B in we have:

$$S_q(A+B)/k=[S_q(A)/k] + [S_q(B)/k] + (q-1)\,[S_q(A)/k]\,[S_q(B)/k] \qquad (2)$$

For $q=1$ BG and Tsallis distributions are identical, so the quantity |q-1| is the measure of departure from the equilibrium (usually to the state of being some type of stationary state). Relations $S_q(q>1) > S_{BG}(q=1) > S_q(q<1)$; in the literature determine appropriate systems, as being “superadditive”, “additive” and “subadditive”. This happens wherever the investigated system is “small” (which means that it is of the size comparable to the range of operating forces), when non-statistical fluctuations, correlations and all types of “memory” effects occur in it [9]. From the point of view of thermodynamics, this means that the so-called “heat bath” is finite and inhomogeneous.

In the [C1-C3] papers we will use this description for the dense quark-gluon matter.

A. Presenting the results for density of equilibrium - the EMC effect

To trace the evolution of the nucleon size R_N and the nucleon mass M in dense NM one should examine these parameters for the equilibrium density (that is in atomic nuclei). This can be done in the experiments with the deep non-elastic scattering of electrons on the nuclear targets, in which the elementary process takes place on nucleons, moving in the nucleus with the Fermi motion.

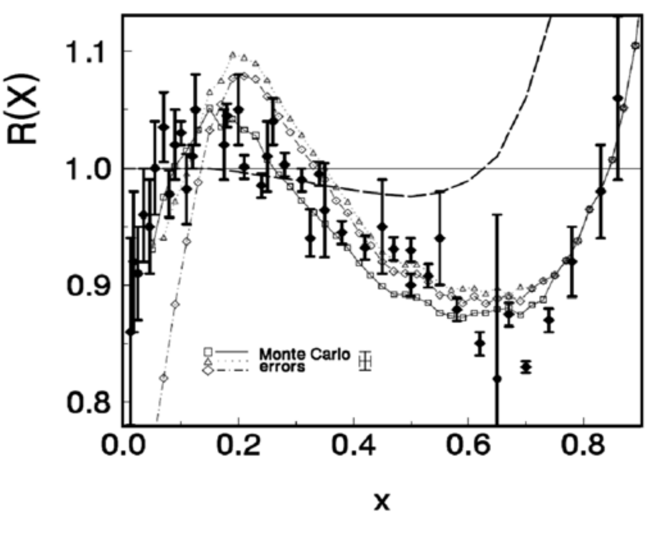


Fig.4 *R(x) – ratio of experimental sections on Fe/D targets*

For this purpose, the paper [A1] used a relativistic description of nucleon distribution in the nucleus on the light cone front, where one determines the nuclear PDF, that is the Parton Distributions Function of the Björken x. It turns out that without a change of PDF, both of valence and sea quarks , the description of the deep non-elastic scattering in such a model of convolution is not able to reproduce the EMC effect. Fig. 4 from the paper [A1] shows that good fit of $R(x)$ (the ratio of experimental cross-sections on the Fe and D targets) for the existing experimental data is obtained with the assumption of the nucleon moving along with the Fermi motion with unchanged mass. Only the width of the nucleon PDF was changed, that is the light-cone distribution of $x_{LC} \sim p_L/M$ (the ratio of the longitudinal momentum component p_L carried by the valence partons to the nucleon mass measured in the rest system) , and the distribution of sea quarks has been shifted, determined by the virtual mass (m_π=0) of "nuclear" pions, according to the implementation of the chiral symmetry in the medium. This ratio corresponds in a good approximation to the Björken variable $x_{LC} \sim x=Q^2/(2M\nu)$ determined experimentally by the four-momentum transfer Q^2 , with energy ν, from the scattered electron to the bound nucleon.

The paper [A2] showed how the nuclear interaction (model by the meson exchanges) is associated with the increase in the sea quark contribution for the small x values. This was exploited in the paper [A3] to meet the momentum sum rules.

The paper [A3] provided the relation of the EMC effect with the virtual scale determined by the mean path of free partons, $d=1/(Mx)$. On this basis it was shown how the effective (dependent on x) nucleon mass changes with the description of the EMC effect and with the description of nuclear Drell-Yana processes. For very fast processes, e.g., for $x>0.6$, the ``life time" of the "struck" parton, $d=0.35$fm**,** is much shorter than the nucleon size R_N and distance between nucleons in the medium. That's why for such value of the x variable, in the momentum sum rule:

$$\frac{1}{A}\sum_{i=1}^{nA} k_{Ai}^{+} = \frac{M_A}{A} \equiv M_N + \epsilon = \int^{p_F} d^3p\sqrt{{M_B}^2 + \vec{p}^2} + V_N \text{ (dla x <0.25)} \qquad (3)$$

the potential interaction V_N is not included in the energy balance (3) in the nucleus. For these processes (that is for $x>0.6$) the equation (3) gives effective value $\boldsymbol{M_B}$ of mass, which is the sum of quark energies dependent on the nucleus mass $M_A=A(M_N+\varepsilon)$ and on the Fermi motion with Fermi momentum p_F . For longer times of interaction with the parton ($d>0.8$ fm) (exceeding the size of nucleon R_N and corresponding to $x<0.25$) the scattering on the correlated nucleon pair takes place. Therefore, in the single-particle balance (3) the nucleon interaction energy V_N with another nucleons should be additionally taken into account on the right side, so the mass M_B returns to the value M_N. As a result, we obtain, including only the Fermi motion energy and the unchanged form of the parton structure function, gradual reduction of the effective nucleon mass in the range of $0.3<x<0.6$ and a good description of the EMC effect (presented in figure 5, left panel).

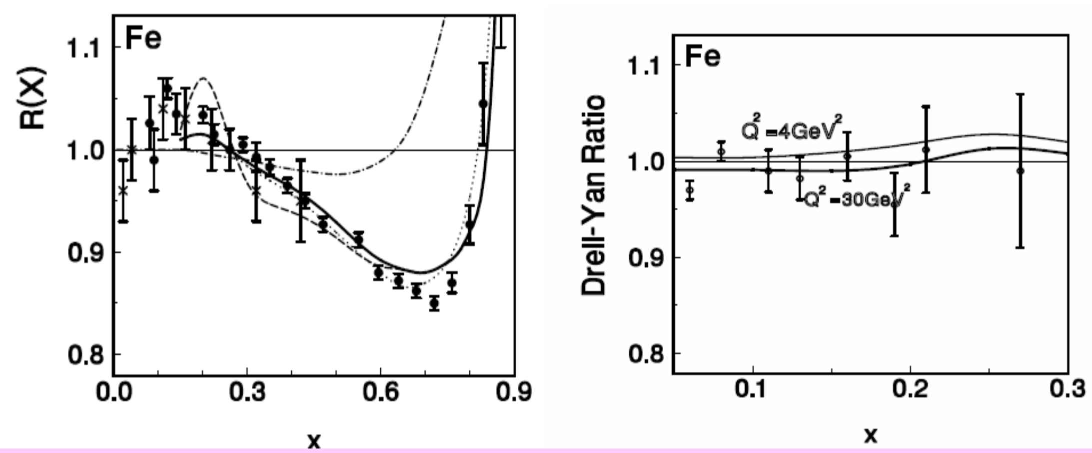


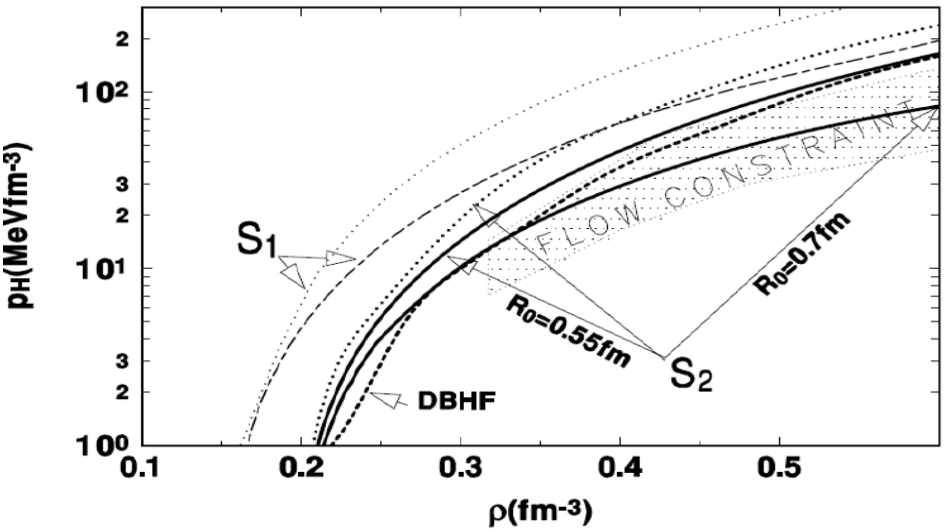
Fig.5 *R(x) – ratio of experimental cross sections on Fe/D targets. On the left side the EMC effect, on the right side, the nuclear Drell-Yan*

The effective mass $M_B < M_N$ is smaller for large x, thus the momentum sum rule is broken. To correct it, the sea quark contribution to the nuclear structure function was increased by 1%, according to the results of paper [A2]. A significant verification of this correction and the entire model is a good description of the EMC effect combined with the equally good description of the nuclear Drell-Yan process, which is particularly sensitive to the distributions of sea quarks in $\boldsymbol{x}$ (right panel Fig. 5). Summing up [A1-A3], it was shown, that the nucleon mass and its size are not changed for the processes taking place in time comparable to the interaction of nucleons in the nucleus and are the same as for the free nucleon. However, the single particle approximation is insufficient to describe the EMC effect because the additional contribution of the sea quarks to PDF is necessary to meet the momentum rule of sums, which has its source in the dynamics of 2-nucleon correlations.

This finding is fully consistent with the low energy experimental data provided that we distinguish the nucleon mass from its effective approximations (such as, e.g.: effective mass dependent on the momentum squared occurring in the propagators or the scalar mass being the sum of mass and the scalar potential in RMF).

B. Presentation and discussion of the dynamic model of the nucleon bag in NM.

We show in the work [B1] that effects related to the change of volume and nucleon mass in the nuclear matter play an extremely important role in the EoS, and therefore, are important in all areas of applications: from calculations of compressibility for the equilibrium density through heavy-ion experiments to the model calculations of neutron stars. The compressibility of the nuclear matter K^{-1} is a fundamental and very interesting quantity of NM for equilibrium density. It is used in the description of nuclear monopoly resonances [2], where is calculated in different models.



Rys.6 *EoS - presssure as a function of densityi ρ [B1]. For choice S_2 (Walecka [19a]) solid lines denote scenario (1) dotted line scenario (2).*

The appropriate fits give the value of $K^{-1}=200\text{-}300$ MeV but this value cannot be calculate properly in the frame of the nuclear relativistic mean field (RMF) theory using the linear, scalar-vector version, which gave $K^{-1}=550MeV$ [19a]. In order to obtain a reasonable fit to all experimental data, such as binding energy, equilibrium density and compressibility, two non-linear scalar fields with two additional parameters, were introduced, which are used until now [19b].

The paper [B1] presents the thermodynamic extension of the nuclear RMF theory with nucleons characterised by the finite volume and containing the interacting quarks described by the MIT bags [20]. So far, the volume effects of EoS in the dense NM were calculated with the constant nucleon mass M and with the constant radius R_N. To obtain new equation of state for NM with finite size nucleons, paper [B1] introduced enthalpy; the energy, which takes into account a work under the pressure, necessary to create space for the extended nucleon in the compressed nuclear medium. The relation of the nucleon size and mass with the pressure has been shown for the first time in the literature, in particular a significant reduction of NM compressibility at the equilibrium density: from K^{-1}=560MeV to K^{-1}~250MeV. The new dependence of pressure on density above the equilibrium density is weaker than the previously obtained in the original equation of Walecka [19a].

To explain such a serious reduction of the compressibility K^{-1}, please note the necessary work to maintain the nucleon volume in the environment with the increasing pressure between nucleons, that imply the chance of nucleon enthalpy (connected to a chemical potential) which is proportional to $1/R_N$. For this purpose, two extreme cases were discussed in the dynamic bag model [B1]: (1) constant nucleon volume (constant enthalpy) and (2) constant nucleon mass (increasing enthalpy):

(1) The nucleon mass has to be reduced while maintaining its volume in compressed medium. In that case we get the value K^{-1}~*250* MeV for *R=0.7*fm [B1]. Subsequently, the EoS was calculated for the constant radius R_N in the dense NM. In this scenario, the reduction of *M* with the density gives the softening of the EoS. We can see in Fig.6 that the course of the EoS covers with the realistic calculations obtained in the Dirac-Bruckner-Hartree-Fock method (DBHF) [22] using the realistic one-boson-exchange potential with non-linear terms of the mean scalar field in NM [19b].

(2) For constant nucleon mass the situation is more complicated. It was shown in [B1] how the nucleon radius R_N decreases, therefore enthalpy increases in the constant mass scenario. Such an increase may require the work of the repulsive interaction and an appropriate rearrangement of the single particle energy. It was not discussed in the paper [B1] , therefore the equation of state remained unchanged with similar Fermi energy of nucleon and K^{-1}~500 MeV - Rys.6.

However if we consider the possible correction to single particle energy, resulting from the compression to the smaller nucleon sizes with the increase of enthalpy (and constant M), then we will obtain a decrease of the nucleon Fermi energy (as a compensation of a necessary work) by a term $(p\Omega)$, similar to the scenario with constant volume. For small departures from the equilibrium density the volume corrections, in both scenarios, are almost the same, therefore our results for K^{-1} are independent from the case (1) or (2). This way we obtain correct values of saturation properties in equilibrium in both scenarios, without expanding the scalar field with non-linear components.

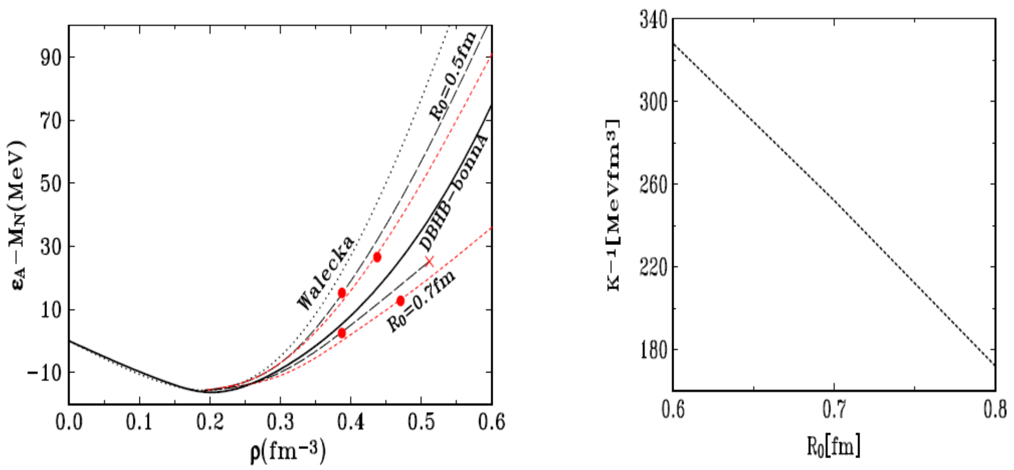


***Fig.** 7 On the left: NM energy in the scalar-vector theory of mean field is determined as Walecka. The marked modifications for the respective nucleon radii: R_0=0.5fm and 0.7 fm. Dashed curves represent a scenario of a constant nucleon radius, dotted curves – constant mass. On the right: dependence of NM compressibilitye on the radius R_0.*

In Fig. 7 (derived from the yet unpublished arXiv:1406.3832) there is a presentation of the EoS modification for the scenario of constant mass with the volume correction (dotted curve) or constant radius (dashed curve). Similar courses of energy and pressure for small densities indicate, that the compressibility depends only on the initial radius R_0 of the nucleon. The behaviour for large densities is different, and this is caused by the the increasing radius R_N for constant M which diminish the volume correction.

Concluding, the abowe correction to the energy in scenario (2) with the constant mass is similar to an analogous correction in the scenario (1) with the constant radius of the nucleon. In both scenarios, it lowers the nuclear Fermi energy by $(p\Omega)$. A resulting reduction of compressibility to the value K^{-1}~ 250MeV without additional non-linear scalar fields [19b], is of a fundamental importance in determining the parameters of a single particle potential and the equation of state describing the recently discovered, relatively heavy (about 2 mass of the sun) neutron stars.

In [B1] we calculated also the compressibility of the nucleon. The result $K_N^{-1}>M$ is compatible with the semi-empirical estimate and other nucleon models [21] and justifies the assumptions of our dynamic model of the bag .

C. Nonextensive description of dense quark-gluon matter.

Until now, there was no fully relativistic formulation of nonextensive thermodynamics for the system of fermions, which would include the propagation of anti-particles. In **[C1]**, using the principle of entropy maximisation (MaxEnt) (1,2), for the first time ever it has been correctly determined how in the relativistic description one should take into account the contribution coming from the virtual anti-particles of the fermions sea.

In the extensive approach, appropriate distributions of particles (n_i) and anti-particles ($\bar{n}_i$) can be obtained by maximising entropy

$$S = \Sigma_i [\, n_i \ln(n_i) + (1-n_i) \ln(1-n_i)] + [n_i \rightarrow \bar{n}_i] \qquad (1)$$

with constrains imposed on the entire number of particles $\hat{N}$ and on the entire system energy $\hat{E}$:

$$\sum_i (n_i - \bar{n}_i) = \hat{N} \qquad \text{oraz} \qquad \sum_i (n_i + \bar{n}_i)\, E_i = \hat{E}, \qquad (2)$$

In the nonextensive approach, one should use the nonextensive form of entropy, $\boldsymbol{S_q}$. From many choices of $\boldsymbol{S_q}$ in [C1] the Tsallis entropy was selected, characterised by the nonextensive parameter q. In the limit $q \rightarrow 1$ we get the normal extensive approach (1). It turns out, that for thermodynamic consistency distributions n_i and $\bar{n}_i$ (corresponding to the micro-states in the extensive approaches), should be in (1) and (2) replaced with the q-th power of the appropriate nonextensive distributions n_{qi} .

New distributions n_{qi} are obtained from MaxEnt for the nonextensive counterpart S_q of entropy S replacing in the expressions (1) and (2)

$$n_i \to (n_{qi})^q \quad \ln x \to \ln_q x = (1-x^{1-q})/(1-q) \quad \{ dla \;\; q \to 1, \;\; \ln_q x \to \ln x \}. \qquad \textbf{(3)}$$

The obtained distributions, n_{qi} for particles and $\bar{n}_{qi}$ for anti-particles, have the form analogous to the Fermi-Dirac distribution, in which the exponential function *exp(x)* was replaced with the so-called q-exponent $e_q(x)=exp_q(x)=[1+(q-1)x]^{1/(q-1)}$; where $x_{qi}=(E_{qi}-\mu)/T$, $\bar{x}_{qi}=(E_{qi}+\mu)/T$ and in the limit $q \to 1$, $e_q(x) \to e(x)$:

$$n_{qi} = \frac{1}{e_q(x_{qi})+1}, \qquad \bar{n}_{qi} = \frac{1}{e_q(\bar{x}_{qi})+1}. \qquad \textbf{(4)}$$

These models still require additional conditions, which was one of the main objectives of the work [C1]. Namely, one should determine the required limitations for the available phase space accompanying the particular selection of the nonextensive parameter q ($q>1$, or $q<1$) so that the quantity $e_q(x)$ is well defined.

In nuclear physics many publications using the nonextensive approximation to describe the dense and hot NM appeared recently. However, most of them [23] proved to be thermodynamically inconsistent; in addition, they differ in the definition of nonextensive one-particle distributions $(n_q)^q$. The paper [C1] compared and systematised the previously used approximations (with particular emphasis of the anti-particles) and the physical consequences of these methods were indicated, their past mistakes and the conditions for applications.

The paper [C2] shows, using the results of the works [C1], that the equations of thermodynamics, expressed by the appropriate nonextensive quantities, are still satisfied by nonextensive entropy S_q, among others.

In particular, the basic relations of thermodynamics are still met:

$$T = \frac{\partial \varepsilon_q}{\partial s_q}\bigg|_{\rho_q}, \quad \mu = \frac{\partial \varepsilon_q}{\partial \rho_q}\bigg|_{s_q}, \quad \rho_q = \frac{\partial P_q}{\partial \mu}\bigg|_{T}, \quad s_q = \frac{\partial P_q}{\partial T}\bigg|_{\mu}, \qquad (5)$$

where nonextensive density of energy $\boldsymbol{\varepsilon_q}$ and pressure P_q are expressed through density of particles ρ_q and entropy s_q, similarly as in a conventional thermodynamics based on BG entropy,

$$d\varepsilon_q = T ds_q + \mu d\rho_q, \quad dP_q = s_q dT + \rho_q d\mu.$$

For this purpose, the following thermodynamics relations were used, allowing the expression of the above relations through the partial derivatives with respect to temperature T and chemical potential μ.

$$T = \frac{\partial \varepsilon_q}{\partial s_q}\Big|_{\rho_q} = \frac{\frac{\partial \varepsilon_q}{\partial T} + \frac{\partial \varepsilon_q}{\partial \mu}\frac{d\mu}{dT}}{\frac{\partial s_q}{\partial T} + \frac{\partial s_q}{\partial \mu}\frac{d\mu}{dT}} \quad \text{where} \quad \frac{d\mu}{dT} = -\frac{\frac{\partial \rho_q}{\partial T}}{\frac{\partial \rho_q}{\partial \mu}},$$

$$\mu = \frac{\partial \varepsilon_q}{\partial \rho_q}\Big|_{s_q} = \frac{\frac{\partial \varepsilon_q}{\partial T} + \frac{\partial \varepsilon_q}{\partial \mu}\frac{d\mu}{dT}}{\frac{\partial \rho_q}{\partial T} + \frac{\partial \rho_q}{\partial \mu}\frac{d\mu}{dT}} \quad \text{where} \quad \frac{d\mu}{dT} = -\frac{\frac{\partial s_q}{\partial T}}{\frac{\partial s_q}{\partial \mu}}.$$

This is an important result (5), which shows that the nonextensive entropy $\boldsymbol{S_q}$ is related to other values in the same way as in the extensive BG thermodynamics. As a result, the probabilistic interpretation of entropy, as the measure of the degree of the ordering in a system, remains unchanged.

Based on the above results, the nonextensive variant of the Nambu-Jona Lasinio model (NJL) was formulated for the dense quark matter, with the liquid and gas phase, in the paper [C2]. Here, among others, we analysed, in the area of phase transition, the critical temperature as a function of the departure from the BG statistics, given by the parameter $|q-1|$. Let us note that in the critical area of the phase transition from hadrons to the quark-gluon plasma, the volume effects or nonextensive effects have the same source, namely a release of volume energy related to the disappearance of the hadron structure. Thus, the dependence of pressure, entropy, specific heat and baryon susceptibility (related to the observed fluctuations of the baryon numbers) from the nonextensive parameter q, density ρ and temperature T, was analysed. The behaviour of these parameters in the critical area (that is for density and temperature near the phase transition) allowed the examination of possible changes of the phase transition for the nonextensive systems. The nature of the phase transition and the location of the critical point in the coordinates of density and temperature depend on this. The main result of this part of the paper is the presentation of differences between the NJL calculations with different arrangements (entropies) of the quark system (Fig. 8 below or Fig. 3 in [C2]). With a better ordering, there is smaller entropy of the quark system ($q<1$), and the nuclear matter is characterised by a lower pressure in the critical area. Also, the expected phase transition is smoother compared to the system of higher entropy **($q>1$)** in which the change of such critical parameters, like specific heat or baryon susceptibility, have a more singular course.

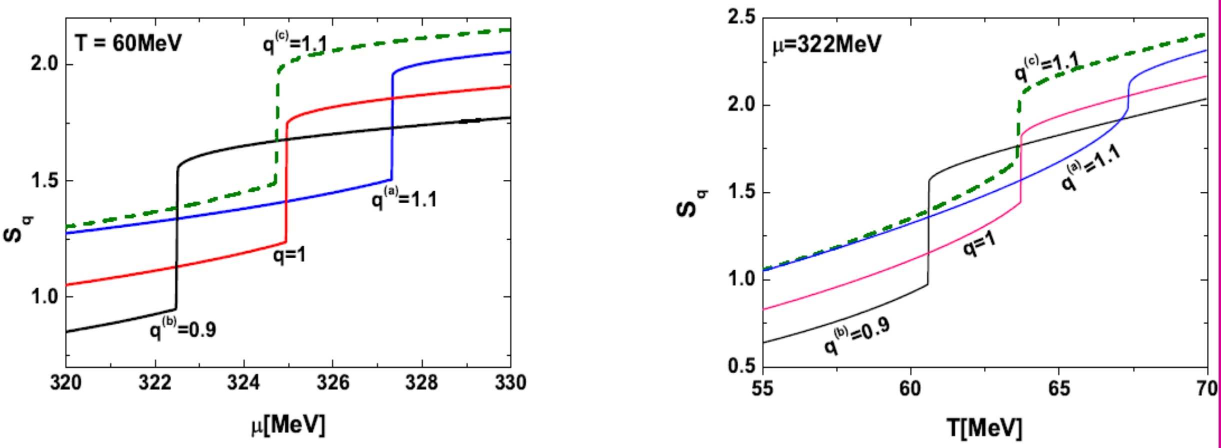


Fig.8 Nonextensive entropy S_q as the function chemical potential (with the constant T) or temperature T (with the constant chemical potential).

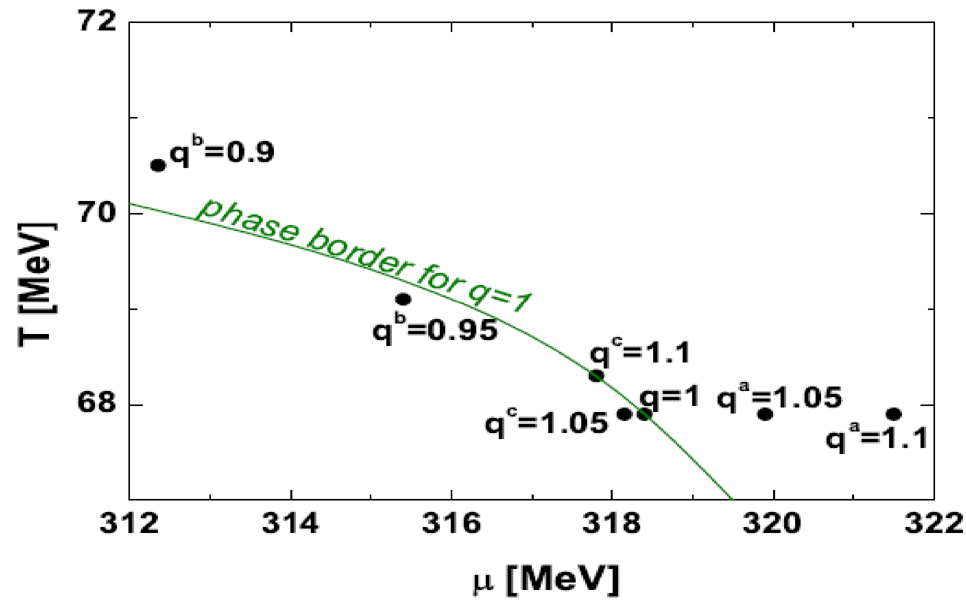
The parametrization of the effects of nonextensive statistics recently proposed in [24], which involves the description of two areas of the phase space, below and above the Fermi surface using dual values of the nonextensive parameter q_1 *and* q_2 , has been examined ($q_1 -1<0$ a $q_2 -1>0$, *and* $q_1 + q_2=1$). Such a selection of q-statistics, in which (q-1) changes the sign in one-particle distributions allows to avoid all limitations of the phase space, seems to be interesting.

However, there appears a very significant problem of the physical interpretation of change $q_1 \longrightarrow q_2$ on the Fermi surface, associated with the jump of the distribution function n_{qi} and $\overline{n}_{qi}$ on the Fermi surface, and in consequence jumps in other thermodynamic functions. The paper [C2] showed that it is important how parameter q changes its value on the Fermi surface. Two cases can be considered.

In the first one, the change of q parameter is an approximation describing the gradual changes of the mean field, in which the particle is located. Such a change is, for example, the crossing through the Fermi level, which is determined by the minimal energy of separation of the one-particle. For the bound particle, where the momentum is located below the Fermi level, parameter $q-1$ takes the negative values, which reduce the entropy of the system increasing its arrangement. The transition to the positive values of the parameter $q-1$ above the Fermi level, where particles are no longer bound, is a gradual transition, in which we expect values $q\sim 1$ for the Fermi momentum. In this case, there is no actual discontinuity of thermodynamic functions, because in reality, the transition should be described by the continuous transition of the parameter q.

In the second case, when we deal with the discontinuous change of the parameter q, we describe rather a more complex system – e.g. a crystal network, interacting with the gas of electrons or systems of quantum dots, which we can control changing the external potential. In this case, the real jumps of the nonextensive parameter are possible (discontinuities), which in effect may discontinuously change the number of particles or one-particle energies. We can also describe the phase transitions, in which each phase is described by another value of parameter (q-1), not necessarily related to the change of sign. However, it seems that the above-mentioned discontinuities, are not confirmed in the nuclear physics and that is why this method is not applicable in our case (and that is why it was not used in the paper [C3]).

Summary of NJL calculations of the quark distributions [C2] in the area of phase transition from the hadron matter to the quark matter can be found in Fig. 9. It presents the distribution of critical points for the quark and gluon plasma as the function of temperature and chemical potential for different values of parameter *q*. Changes of the critical temperature of the BG statistics, were examined for all possible implementations of the nonextensive Tsallis statistics giving different thermodynamic dependence between density or chemical potential and the basic thermodynamic functions, such as entropy, pressure or energy. It turns out that for the systems with $q<1$, for which entropy decreases (that is the ordering increases), the critical temperature of the transition from the hadron phase to the quark phase increases for $q=0.9$ (from 68 MeV to 71 MeV Rys. 9). It is the temperature where constituent quark mass ~300MeV (part of the nucleon mass) changes to current quark mass ~5MeV. In this case the smaller chemical potential (by 6 MeV), confirms long range correlations responsible for the better arrangement of quarks inside NM. Such a change of a quark chemical potential gives the increase of positive correlations and approximately compensates for a lack of nucleon degrees of freedom in the NJL model by energy 3*6MeV=18MeV (in a reasonable comparison with the nucleon binding energy in NM - 16 MeV). In other words, the lower entropy is obtained by the attractive correlations, therefore we need higher critical temperature at which the quark mass decreases to the current mass ~5MeV, associated with the "dissociation" of nucleons in the phase transition of hadron matter do QGP.



Rys.9 Phase border in NJL calculations for different values of the parametr q: $q^a>1$, $q^b<1$, q^c denotes hybrid model

The paper [C3] has once again showed the relation of nonextensivity and dynamics in the QCD description. This time, this was done using the phenomenological quasi-particle model for QCD [17] (selected from many possible ones in terms of simplicity and transparency of description). The nonextensive version of this model was formulated, where the previous parameter of fugacity z, dependent on temperature, has been replaced by its nonextensive analog, z_q, and nonextensive distributions of particles now have the form:

$$n_q(x_i) = \frac{1}{\frac{1}{z_q^{(i)}} e_q(x_i) - \xi} \tag{6}$$

Using these distributions, z_q was fitted to the temperature distribution of pressure P_q obtained from the calculations on the network [18] using the relation of this pressure with the nonextensive partition function Ξ_q:

$$P_q \beta V = \ln_q(\Xi_q)\,. \tag{7}$$

As a result, it was shown how for the nonextensive system with the increased entropy (that is parameter $q>1$) we obtain the limiting value $z_q \sim 1$ of the fugacity parameter of the quarks for the sufficiently high temperature T and the value of nonextensive parameter q. This agrees with the analysis [16] of non-equilibrium states, in which the process of a quark emission by gluons increases the entropy of the system. The entropy increase of this system also concerns the process of terminalisation, that is the equalizing of the initial inhomogeneities in distributions. So, parameter $q>1$ describes the departures from the thermodynamic equilibrium, which appears in formation of the quark-gluon plasma in the scattering of heavy ions.

In NM in the equilibrium the ordering of quarks in the system increases due to transition to the lowest ground state, which is the hadronic matter consisting of nucleons interacting through the meson exchange. The reason for such a behaviour are the long-range correlations, which maintain above the phase transition from the hadron matter to QGP [17]. Therefore, we expect the reduction of entropy also above the critical temperature in the "free" phase, where quarks are strongly correlated and the system entropy is probably sub-additive ($q<1$), like in the hadron phase. The crucial result of the work [C3] shows how the coefficient of quark fugacity z_q decreases with the decreasing $q<1$ (and entropy) , even in the limit of high temperatures (compare the black and blue curve in Fig. 10 (Fig. 1 from [C3]). Another words, the associated nonextensive long-range dynamics reduces entropy of the quark system for $q<1$ and that is why we will not obtain the free quark gas (even for very high temperatures, above the Hagedorn temperature [25]).

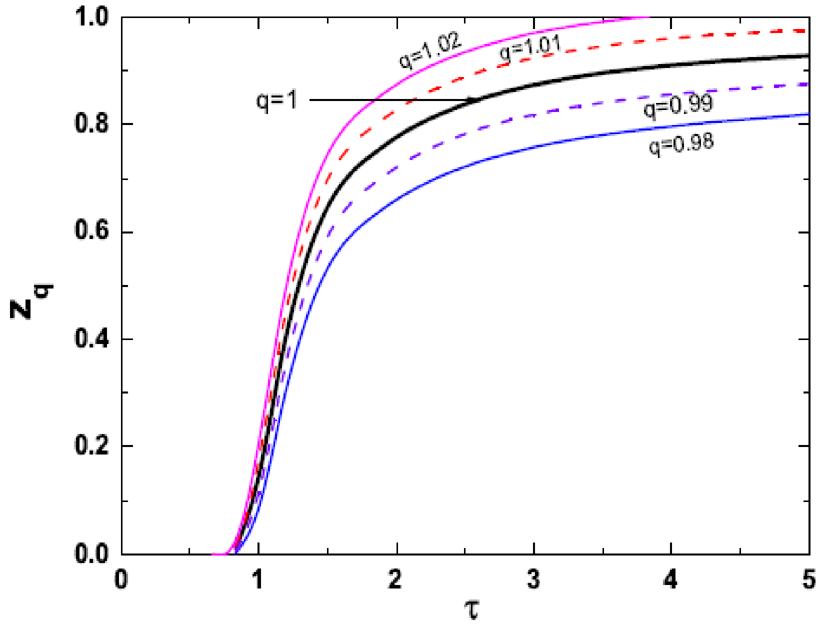


Fig.10 *Dependence of the fugacity of the relative temperatur*
T/T_{cl} and the parameter q.

In summary, the papers [C2, C3] showed how the nonextensive description allows to include the entropy changes created by the long-range correlations of hadron interactions but absent in equilibrium Boltzmann-Gibbs thermodynamics (which assumes the short-range interaction and the resulting additivity of the entropy). The presented approach described both the non-equilibrium systems with the increased entropy when forming the quark-gluon plasma and the dense nuclear matter predicted inside the neutron stars; with one additional nonextensive parameter q. The presented relations of the system ordering with the nonextensive statistics can be used successfully in other models, not only nuclear, describing the phase transitions in the critical region.

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5. Discussion of the other scientific and research achievements.

A. Study of the effects of hyperon Σ^- nucleus and atom.

The issue of Σ^- nucleus and Σ^- nucleon interactions is crucial for the entire hyper-nuclear physics. While the beginning of hyper-nuclear physics (inaugurated in Poland) today seems relatively simple, a hyperon Λ create numerous nuclear bound states (which were discover and described), the situation with hyperon Σ is much more difficult. It does not create any nuclear bound states (hyper-nuclei Σ) – perhaps with one exception [1]. Thus, our knowledge of the interaction of hyperon Σ with nucleons and with nuclei is incomplete, and each attempt to determine these interactions is very important.

I dealt with this problem in my doctoral dissertation [2], which concerned two-channel calculations of the binding energy and width of the hyperons Λ and Σ Sigma in NM using the realistic potential of the single-boson exchange constructed by the group from Nijmegen [3]. Using, to a large extent, the results contained in my doctorate from 1984, where I determined the Bruckner reaction matrix of hyperon in nuclear matter, we estimated in the years (1985-2010) [4-7] the complex potential V_Σ-iW_Σ of the Σ -nucleus interaction, analysing the carefully measured spectra of the kaons from the reaction (π^-,K^+). In order to determine the potential
Σ- nucleus and the interaction Σ- nucleon we chose several ways. One way is described by the paper [6] with analysis of the measured spectrum of pions from the reaction (K^-,p), which depends on the interaction in the entrance channel of hyperon Σ. Then, we have analysed the sigma atoms [8-10] in which the shift of levels and the width of these levels depends on U_Σ. Yet another way is based on (few, unfortunately) scattering data hyperon-nucleon to which we can match the potential of interaction and calculate U_Σ using it.

All these ways have led to a conclusion that the realistic interactions of hyperons with nucleons is well represented by model F of the baryon-baryon interaction developed in Nijmegen, and the real part of the potential - V_Σ is repulsive with the force of about 25MeV for the equilibrium density of nuclear matter.

A relatively new source of information about U_Σ is the examination in KEK [11,12] of the Σ hyperon interaction in the exit channel in the reaction of the associate production (π,K^+). Existing analyses [11-13], based on the impulse approximation of this experiment in KEK suggested the unexpectedly strong repulsive potential of V_Σ ~100MeV. This result is, of course, contrary to the aforementioned estimations of V_Σ ~25MeV.

We were able to remove this contradiction by describing the reaction (π^-,K^+) on the target ^{28}Si [14] using the complex optical potential U_Σ ,by taking into account the absorption part of the contribution W_Σ to the total imaginary part of the potential U_Σ and also thanks to the dependence of the real part V_Σ on the hyperon momentum. Here we emphasis the crucial role of a Pauli Principle dependent of the hyperon momentum: it decreases suppression for the elastic part W_Σ and grows suppression of the W_{Σ} part - related to the conversion of hyperon Σ to hyperon Λ. Only because the contribution to the imaginary part W_{Σ} was taken into account in the analysis of (π^-,K^+) reaction, derived from elastic scattering Σ -nucleon, one could obtain consistent results on real part V_{Σ} in the analysis of (π^-,K^+) reaction with the other results obtained in the reaction (K^-,π), as well as in the analysis Σ^- atoms. These results are also consistent with the results of calculations based on the F model of the baryon-baryon interaction developed in Nijmegen.

B. Parton distribution function in the nucleus and in the nuclear matter.
In addition to the works associated with the “EMC” effect published in [A1-A2] I want to emphasise that the study of the parton structure has been initiated soon after the first results of deep-inelastic scattering of electrons on nuclear targets [15]. During the yearly stay at the Victoria University in Manchester we have studied, in collaboration with M. Birse, nucleon correlations in the final state for the area x>1. Taking into account the particle-hole correlations on the Fermi surface, we have obtained corrections to the nuclear structure function for the finite value of the four-momentum transfer[16]. The paper [17] has also studied the momentum sum rule in the convolution model for the deep-inelastic scattering including the meson (pions and vector mesons ω) degrees of freedom. The paper [18] examined the possible changes in the nucleon mass and the related changes of the distribution of parton transverse momenta. The paper [19] examined the role of the Fermi motion above the saturation density and discussed it for different models of the relativistic mean field, while in [20] we presented the possible evolution of the parton structure function. Further considerations of this evolution are possible using a better quark model for the nucleon, e.g., the bag model presented in paper [B1].

C. Nuclear Nambu-Jona-Lasinio Model (NJL).
The paper [21] presented the optimized expansion which was used to calculated the effective action in the NJL model. In this work we achieved the systematic method improving the approximation of the mean Hartree field with expressions obtained by the method of random phase (RPA). Nonextensive effects in the NJL model were thoroughly analysed in [22] where we showed the evolution of quark condensates and quark masses, also mesons π and σ, with the density and nonextensive parameter q. We have also found, among others, the critical temperature dependence on the nonextensive parameter. Critical effects were discussed in details in [23] with particular emphasis of the baron susceptibility and specific heat [24]. However, these papers used old approach, which later on proved to be thermodynamically inconsistent (however, these papers found their fairly wide resonance in the literature of this period).

D. Dense Nuclear Matter. In the works [25-27] we investigated properties and stability of neutron and nuclear matter with hard core interaction.

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