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Evaluation report of the doctoral dissertation entitled *Effective-Model Perspective on QCD Phenomenology* submitted by Michał Marczneko

The dissertation, which has been prepared under a supervision of dr. hab. Chihiro Sasaki, reports on a theoretical study of strongly interacting matter in terms of phenomenological models. The subject is a field of active research as strongly interacting matter is studied experimentally in relativistic heavy-ion collisions and theoretically by means of a broad spectrum of methods of theoretical physics. The content and context of the study under consideration is extended by the fact that properties of the matter are crucial for our understanding of compact astrophysical objects such as neutron stars.

The thesis is based on seven original publications coauthored by Michał Marczenko. The articles are published in well-known journals of high reputation. There are also four publications in conference proceedings coauthored by the candidate.

Content of the thesis

The dissertation written in English is of almost 150 pages and it consists of seven chapters. After a general overview of the thesis, one finds in Chapter 2 a brief introduction to quantum chromodynamics and symmetries of the theory. The gauge, center and chiral symmetries are briefly explained. Further on, main concepts of thermodynamics of strongly interacting matter and of fluctuations of conserved charges are presented.

Original considerations start in Chapter 3 which is devoted to an extensive analysis of thermal properties of hadron gas. Lattice simulation data are commonly expected to represent actual strongly interacting matter governed by quantum chromodynamics (QCD). The data on pressure and some other thermodynamic characteristics of QCD matter are described qualitatively and quantitatively to some extend in terms of the Hardon Resonance Gas model which takes into account known hadron states. The author considers various ways to improve the description. The goal can be achieved by including some heavy hadron resonances which are absent in the known spectrum of hadron states. Extra strange hadrons seem particularly needed to improve the Hadron Resonance Gas model.

Further on the S-matrix approach to thermodynamics of strongly interacting matter is discussed and it is shown that the effect of "extra strange hadrons" appears when a kaon-pion scattering is taken into account in the partition function. The section 3.5 deals with the problem of finite widths of hadron resonances which are shown to be important to properly model the pion momentum distribution.

A commonly used Van-der-Waals correction to the ideal gas of hadrons is also discussed and it is argued that the idea of excluded hadron volume is hard to reconcile with a current knowledge on microscopic interactions among hadrons.

In Chapter 4 a discussion of cold but dense hadron matter starts. A chiral symmetry is expected to be a crucial factor which controls properties of the matter in a broad range of baryon density. For this reason there are discussed in some detail two different schemes of the symmetry breakdown and its restoration. The conventional one that is as in the Gell-Mann-Levy model and the *mirror* one proposed by De Tar and Kunihiro. Within the latter scheme, which allows one to have massive nucleons even in the chirally symmetric phase, the Hybrid Quark-Meson-Nucleon model is formulated. The model is solved in the mean-field approximation and its parameters are chosen to reproduce properties of the isospin-symmetric nuclear matter (as in usual nuclei) at the saturation density.

In Chapter 5 the Hybrid Quark-Meson-Nucleon model is applied to strongly interacting matter of neutron stars. The matter is isotopically strongly asymmetric and it reaches densities far beyond the saturation one. Consequently, the matter can experience both the chiral and deconfinement phase transitions. The author discusses several characteristics of neutron stars which are controlled by the equation of state of QCD matter and its composition. The range of observed masses of neutron stars, which extends up to the double solar mass, and of estimated radii provide a severe constraint on the equation of state. The required rate of cooling of the forming star due to Urca process demands a sufficiently high admixture of protons in the strongly interacting matter. Tidal deformation of neutron stars, which plays an important role in the process of generation of gravitational waves when two neutron stars merge, introduces another constraint. The author discusses how these neutron star characteristics limit a space of parameters of the Hybrid Quark-Meson-Nucleon model.

In Chapter 6 fluctuations of net-baryon density, which are experimentally studied in relativistic heavy-ion collisions, are analyzed. The matter is again assumed to be isospin symmetric and the predictions of the Hybrid Quark-Meson-Nucleon model are confronted with that of the frequently used Nambu-Jona-Lasinio model. The second, the third and the forth order cumulants of net-baryon density, which rapidly change at phase boundaries, are computed and discussed.

The thesis is completed with a rather detailed summery of main results, two appendices dealing with the SU(N) group and baryon-density cumulats. A long list of references closes the thesis.

Most important results

There are several interesting and original results presented in the thesis. A suggestion that the lattice data point to the existence of yet-undiscovered strange-hadron states is an interesting finding. The analysis showing that the effect of missing strange hadrons can be reproduced taking into account a kaon-pion scattering in the partition function is even more interesting. The observation that the Van-der-Waals correction is hard to reconcile with our knowledge on microscopic interactions among hadrons is also interesting and worth further studies.

I like the discussion of the Hybrid Quark-Meson-Nucleon model in the context of neutron stars. The idea to combine various characteristics of the stars to constrain the model parameters is very useful and will certainly be developed in future. Finally, a demonstration how strongly the cumulants of net-baryon density vary at phase boundaries can be exploited in experimental searches of a QCD critical point in relativistic heavy-ion collisions.

Critical remarks

I have a list of critical remarks. My general and the most important criticism is that a reliability of phenomenological modes under study is not sufficiently discussed.

It would be worth, I believe, to consider what is missing when a dynamics of strongly interacting matter is modelled solely through a mass spectrum of hadron states. Why the model, where the hadron mass spectrum is the only dynamical information, should reproduce the lattice data?

When a kaon-pion scattering is taken into account in the S-matrix approach to thermodynamics of strongly interacting matter, one asks what about other numerous channels of hadron-hadron scattering. Can these channels be ignored? Is it sufficient to consider only binary interactions of lightest hadrons? I am fully aware that there are no simple answers to these question, but a few comments would be in order.

My most important criticism concerns a range of validity of the Hybrid Quark-Meson-Nucleon model which is the main theme of the thesis. The model is solved in the mean-field approximation which is used for a very broad range of baryon densities. In my opinion an applicability of the approximation should be carefully analyzed. Then, a validity of the results presented the chapters 5 and 6 could be critically assessed. The Walecka or Walecka-like models, which are solved within the mean-field approximation, are often questioned even at the saturation density because, for example, the effective nucleon mass is unrealistically small (about half of a free nucleon mass) due to a large value of the sigma or scalar field.

There are also numerous minor shortcomings or errors in the thesis. I list them not according to their importance as they appear in the text.

1) Already in the abstract and repeatedly in the body text, the term "density" is used instead of the "baryon density" which really matters.
2) The formula (2.8) of the gauge transformation law is erroneous.
3) The space arguments are needed in Eq. (2.11) to make the equation meaningful. The factor ½ in formulas (2.12) and (2.13) is redundant and it appears to be not a typographical error. This is an important point that in the limit of large separation, the free-energy of the quark-antiquark pair equals the sum of the free energies of the quark and of the antiquark. The latter one equals the free energy of the quark and the relevant formula reads $F_{q\bar{q}} \xrightarrow[r\to\infty]{} F_q + F_{\bar{q}} = 2F_q$. There should be F_q not $F_{q\bar{q}}$ in Table 2.2.
4) There is a mistake in the definition (2.16) of the element of the center symmetry.
5) The formulas (2.25), (2.26), (2.30) are ambiguous as long as the indices R and L and not assigned.
6) There is a misprint in Eq. (2.31).
7) The formula (3.10) represent not the non-relativistic limit of the expression (3.9) but the classical approximation which neglects quantum statistics. The expression (3.10) is perfectly relativistic.
8) At the bottom of page 32, the left and right panels of Fig. 3.3 are confused.
9) The prefactor (3.15) with a specific power 5/4 requires, in my opinion, an explanation and justification.
10) It seems to me that there should a sum over hadron species in the formula (3.24).
11) The sentence just below Eq. (3.26) does not explain to my mind the normalization in Eq. (3.25).
12) I would be glad to learn more about the concept of tidal deformability which is hardly explained.

Conclusion

In spite of my critical remarks, I am convinced that the thesis submitted by Michał Marczenko meets all formal and customary requirements of doctoral dissertations in physics. The thesis is generally well written and it reports some new, original and important results published in the well-known journals of high reputation. The results, I believe, significantly contribute to our knowledge of strongly interacting matter. So, I recommend the dissertation for a defense.