*Alexander von Humboldt Polish Honorary Research Scholarship Programme*

**Title: Few-body correlations and clusters in hot and dense nuclear matter**

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Abstract: A Green's function approach is used to investigate correlations and cluster formation of nucleons in nuclear matter at temperatures up to $10^2$ MeV. This thermodynamic Green's function approach is applied to hadronic matter at subsaturation densities where light nuclei as well as continuum correlations determine the thermodynamic and transport properties, in particular phase transitions and neutrino transport. The quantum statistical approach is also applied to hadronization phenomena in the quark-gluon plasma, which occur at higher densities and temperatures. Clusters are described as quasiparticles, medium modifications owing to self-energy terms and Pauli-blocking effects are calculated. In particular, the role of unstable nuclei is investigated. Consequences for the structure and time evolution of neutron stars are shown. In laboratory experiments, properties of matter at extreme energy densities are investigated with heavy-ion collisions, e.g., at LHC. Medium modifications as well as nonequilibrium approaches are applied to explain the observed yields of light clusters.

## I. STATE OF THE ART

The investigation of few-body correlations is of high interest in recent investigations such as the equation of state of nuclear matter, the development of transport codes, and the structure of nuclei. This is of relevance for the evaluation of data from heavy-ion collisions as well as astrophysics of compact objects such as supernova collapses and the structure of neutron stars. A quantum statistical approach has been worked out which treats the light elements (2H, 3H, 3He, 4He) as quasiparticles with medium dependent energies, see [1] and references given there. More recently, also larger nuclei as well as unstable nuclei have been included [2].

These light elements are of interest to describe the evolution of supernova explosions [3], in particular the neutrino transport is determined by the formation of clusters. In a recent work together with the Wroclaw group [4] this issue is discussed and further references are given. The inclusion of unstable nuclei as proposed, e.g., in Ref. [5] is controversially discussed. The correct treatment of excited states and unstable nuclei is one of the subjects of the present application.

There are different laboratory experiments to investigate matter under extreme conditions. Heavy-ion collisions have been analyzed to derive the equation of state, in particular the symmetry energy, for hot and dense nuclear matter. A systematic quantum statistical approach has been given, see Ref. [6] and references therein. It has been shown [7] that medium modifications must be included to describe the observed yields of light nuclei. Heavy-ion collisions at highest energies are performed at the LHC/CERN and other facilities, in future also FAIR at Darmstadt and NICA at Dubna. Experiments of the ALICE and HADES collaborations show the formation of correlations and light clusters [8, 9]. Continuum contributions are included using measured scattering data, for instance via the Beth-Uhlenbeck formula [10, 11] or the Dashen, Ma, and Bernstein approach [12]. However, medium effects are not considered. The group at Wroclaw is very active in that field of research, and I intend to strengthen the activities by joint work. Not only the ALICE results, also the expected results from FAIR and NICA are of high interest, see our joint work [13]. A new issue to be investigated here, will be the inclusion of in-medium effects, which are expected to become of more relevance at lower energies (HADES, NICA).

Also of interest is the application of the theory of bound state formation in a hot and dense medium to hadronization in the quark-gluon plasma. Here, the Wroclaw group has done a lot of investigations and applications to explain the structure and mass distribution of neutron stars, looking for the occurrence of a quark matter core. I intend to finish the work with D. Blaschke, M. Cierniak, and P. Schuck on "Thermodynamics of quark matter with multiquark clusters in a simple Beth-Uhlenbeck approach".

The theory of nuclear matter at highest energy density is very complex. It demands not only the treatment of correlations in hot and dense matter, but also the use of methods to describe non-equilibrium processes. Despite simple models such as the freeze-out model are recently applied, a fundamental theory is missing so far which describes the process of cluster formation. There are first steps to formulate a quantum statistical approach to non-equilibrium processes, see [14, 15]. This is an urgent problem in heavy-ion collisions. The present application contributes to solve this fundamental problem.

## II. SCIENTIFIC AIMS OF THE PROJECT

The aim of the project is the investigation of the effective few-particle Schrödinger equation for nucleons in a nuclear environment (in homogeneous nuclear matter at arbitrary temperature, density, and asymmetry), as well as for quarks in a quark-gluon plasma. Of special interest is the Mott effect, the dissolution of bound states at high densities because of self-energy effects and Pauli blocking. According to the Levinson theorem, the dissolution of a bound state is connected with a strong modification of the scattering phase shifts. Therefore, continuum correlations must also be considered. An important issue is to find appropriate expressions to describe the medium-dependent phase shifts. Results are known for the two-particle system. For clusters consisting of more than two particles, approximations have to be found.

Having an accurate description of correlations in hot and dense matter to our disposal, a second aim of the project is the application to solve specific problems, which are of interest for the group at the University of Wroclaw investigating the structure of neutron stars, neutron star mergers, supernova explosions, and signals of a possible deconfinement phase transition where the hadronization of quark-gluon matter happens. The influence of correlations on the equation of state in hot and dense nuclear matter is a fundamental issue of the present application, in particular the systematic inclusion of weakly bound clusters and unstable nuclei. Our aim is also to understand better the strongly correlated quarkonia phase which appears near the hadronization phase transition.

Closely related to astrophysical applications are laboratory experiments at highest energies. The group at the University of Wroclaw is closely connected with experimental groups at CERN, GSI Darmstadt, NICA at Dubna, and others. Measures yields of nuclei and correlations of particles emitted from heavy-ion collisions allow to infer the properties of the fireball, which gives the possibility to check the different theories. It is a further aim of the collaboration with the group at the University of Wroclaw to describe cluster formation from the hot and dense fireball. In particular, different approaches are known to treat weakly bound states such as the deuteron or the hypertriton, which are formed from the expanding fireball. A non-equilibrium approach will be worked out to give a consistent theory of cluster formation.

## III. EXECUTION OF TASKS

A first milestone is the investigation of few-particle continuum correlations which determine, e.g., the details of the equation of state. This refers to the properties of the quark-gluon system near the hadronization phase transition, but also to weakly bound or unstable nuclei in the hadronic phase. Work in these directions is already in preparation.

The Wroclaw group is very experienced to perform numerical simulations of the evolution of exploding supernovae, neutron star mergers, and the cooling of pre-neutron stars. A main input is a precise equation of state, which includes the appearance of correlations and the formation of light nuclei. For instance, phase transitions and neutrino transport which are determined by correlations in the nuclear medium are relevant for the evolution of compact objects in astrophysics.

As a second milestone, the equation of state taking continuum correlations into account will be implemented in these calculations.

A third milestone is the description of cluster formation from heavy-ion collisions. In-medium effects obtained from the quantum statistical approach are considered to interpret the observed cluster yields. The Wroclaw group has excellent access to new experiments so that comparison with data and predictions for new experiments are worked out.

## IV. EXPECTED OUTCOMES

The results of the investigations described within the present project should be published in several articles. The visits at the University of Wroclaw (6 times for 1 month) intend to include young scientists in Poland in the work of quantum statistical approaches to investigate dense nuclear systems. Lectures on Green functions methods and non-equilibrium statistical physics have already been given during former visits. I intend to present lectures and seminars also during my future visits.

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