Clusters in nuclei, nuclear matter, heavy ion collisions and astrophysics- report on the ECT* workshop, June 13-17, Trento, Italy

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Correlations in nuclear systems are of fundamental interest for different phenomena in nuclear structure and reaction physics, but also for the nuclear matter equation of state which is crucial for the modeling of astrophysical systems. A better understanding of correlations and more realistic descriptions are crucial since usually the described systems are very complex and subject to many uncertainties. Therefore, understanding and applying state of the art techniques with respect to cluster formation promise to give much better insight into the physics of the investigated phenomena.

Nuclear systems are important examples for strongly interacting quantum liquids. New experiments in nuclear physics and observations of compact astrophysical objects require an adequate description of correlations, in particular with respect to the formation of clusters and the occurrence of quantum condensates in low-density nuclear systems. An important task is to join different approaches such as virial expansions and the nuclear statistical equilibrium, valid in the low-density limit, with approaches that are applicable near the saturation density, such as Dirac-Brueckner-Hartree-Fock or relativistic mean-field (RMF) approximations. A quantum statistical approach has been elaborated that allows to include few-nucleon clusters like deuterons, tritons, ^{3}He, and ^{4}He embedded in nuclear matter, but can also be extended to describe the formation of larger nuclei in low-density matter. The final goal is the formulation of a unified approach which describes the properties of nuclear matter and bound states over the whole range of relevant temperatures, densities and asymmetries.

We have discussed important issues related to three fields where correlations in nuclear systems are of fundamental interest: nuclear structure and reaction physics, heavy-ion collisions and the structure and evolution of compact astrophysical objects. In particular, we focused on bound states (clusters) in nuclear matter. We discussed the issues of:

1. Correlations in nuclear matter: nuclei in matter, quantum condensates: pairing, quartetting.
2. Clusters and the equation of state (EoS): nuclear statistical equilibrium, virial expansion, RMF, quantum statistical approach to clusters in the low-density EoS; astrophysical applications: supernovae, neutron stars.
3. Heavy-ion collisions: symmetry energy.
4. Clusters in nuclei: Alpha cluster and Hoyle state, tritons and further clusters; reactions and astrophysical applications.

In the following we summarize some results and highlights of the workshop which serve as motivations for further work:

1. Correlations, in particular cluster formation, has to be considered in low-density nuclear systems. Any single-nucleon quasiparticle approach fails in that region. A possible approach is the introduction of clusters as effective degrees of freedom in the model description. The full antisymmetrization (Pauli blocking) is indispensable at increasing densities.

2. Nuclear structure: pairing is well accepted. We need a theory that includes quartetting, i.e. four-particle correlations. First steps have been done for ^{8}Be and ^{12}C (Hoyle state) and related low-density state in light nuclei. Similar to Hartree-Fock-Bogoliubov theory, we need an approach that joins shell structure calculations and alpha cluster-like correlations. Promising approaches such as Fermionic Molecular Dynamics should be studied further. At present, one can use a local density approach to estimate the role of four-nucleon correlations.

3. Heavy ion collisions: the formation of light elements is a nonequilibrium process that has to be described with adequate equilibrium approaches as inputs (freeze-out, coalescence, transport codes). The extraction of thermodynamic parameters, including the symmetry energy, should go beyond the nuclear statistical equilibrium (NSE) taking into account in-medium effects.
4. Astrophysics: we need improved equations of state (EOS) to analyse the evolution of supernovae, including neutrino transport. At present, different attempts are performed to include few-nucleon correlations (light elements) as well as the full table of all known nuclei. The unification of mean-field approaches and NSE (in-medium description of clusters) as well as the contribution of continuum states (virial coefficients) has to be implemented.