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Editorial

Topical collection on light clusters in nuclei and nuclear matter: nuclear structure and decay, heavy-ion collisions, and astrophysics

David Blaschke[1,a], **Hisashi Horiuchi**[2], **Masaaki Kimura**[3,4], **Gerd Röpke**[5], **Peter Schuck**[6,7]

[1] Institute of Theoretical Physics, University of Wrocław, 50-204 Wrocław, Poland
[2] Research Center for Nuclear Physics (RCNP), Osaka University, Osaka 567-0047, Japan
[3] Department of Physics, Hokkaido University, 060-0810 Sapporo, Japan
[4] Nuclear Reaction Data Centre, Faculty of Science, Hokkaido University, Sapporo 060-0810, Japan
[5] Institut für Physik, Universität Rostock, 18051 Rostock, Germany
[6] Université Paris-Saclay, CNRS-IN2P3, IJCLab, 91405 Orsay, France
[7] Université Grenoble Alpes, CNRS, LPMMC, 38000 Grenoble, France

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Abstract Recent progress to treat clustering in nuclear systems has an impact to different branches of nuclear theory. Numerical methods as well as many-body theory (Green-function methods) have been worked out to describe few-body clusters in a nuclear environment where medium effects, in particular the antisymmetrization of the wave function (Pauli blocking) are of relevance. Nuclear structure (Hoyle – like states), nuclear reactions, and consequences for astrophysics (neutron stars, supernova explosions) are emerging applications. The main topics were (1) Cluster models, structure of light nuclei, cluster quantum phase transition; (2) Reaction theory, α-decay of heavy and superheavy nuclei; (3) Clustering in nuclear matter and consequences for thermodynamic properties (4) Heavy-ion collisions and clustering in nonequilibrium systems, transport codes; (5) Astrophysical consequences of clustering.

The workshop "Light Clusters in Nuclei and Nuclear Matter: Nuclear Structure and Decay, Heavy Ion Collisions, and Astrophysics" took place at the European Centre for Theoretical Nuclear Physics and Related Areas (ECT*) in Trento, from 2 to 6 September 2019. A very broad spectrum of different fields in research has been presented [1] where cluster formation is essential in nuclear systems, see the Contribution list shown in Table 1. The great interest and activities in this field of research inspired us to prepare a Topical Collection of articles for EPJA devoted to different aspects presented at this workshop, and to publish forthcoming research.

Nuclear systems are important examples for strongly interacting quantum liquids. A very efficient approach to describe dense quantum systems is the quasiparticle concept, which considers the approximation of uncorrelated single particle states in the mean field of the other particles. However, there exist special situations where correlations become important, in particular at low densities and low temperatures. The treatment of correlations beyond the mean-field theory has been discussed at the Workshop. Similar to pairing and the BEC-BCS transition, quartetting is important in nuclear systems because of the large binding energy of the α particle. A Bose-condensed state was introduced to investigate the structure of the famous Hoyle state in ^{12}C. The Tohsaki–Horiuchi–Schuck–Röpke (THSR) approach has been further developed (Zhou, Funaki, Yamada) and applied to light nuclei (Kanada-Enyo, Lyu, Kimura, Fujikawa, Schuck). New results have been obtained for such nuclei with additional nucleons (e.g., the ^{9}B and ^{9}Be–^{11}Be nuclei). Special attention was given to new experiments (Itoh, Kokalova, Santa Rito, Kawabata, Zarubin, Liu, Han, Barbui, Ito). Comparison with other ab initio approaches (Neff, Iachello, Shneydman, Lasseri, Dumitrescu, Baran, Shlomo, Vretenar, Samarin) has been discussed. The THSR ansatz seems to be very successful describing cluster formation in nuclei and is able to reproduce also complex structures of light nuclei. Generalizations of the simple THSR ansatz have been worked out which allow for deformation of the nucleus and different subdivisions into clusters so that a unified description of the excitations of light nuclei seems to be possible, which contains the shell-model

Peter Schuck passed away on 10. September 2022. He was influencing many of the collaborations reporting results in this Topical Collection and as an Editor was essential in bringing together the broad spectrum of research works on light clusters in nuclei and nuclear matter. A Topical Collection "The Nuclear Many-body Problem", devoted to the scientific legacy of Peter Schuck, is in preparation at EPJA.

[a] e-mail: david.blaschke@gmail.com (corresponding author)

Table 1 Contribution list of the talks presented at the Workshop, ordered according to discussion in the text. Presentations are found on the webpage of the Workshop [1]

Speaker	Talk title
Bo Zhou	Microscopic description of multi-clusters in light nuclei
Yasuro Funaki	Alpha cluster condensates and dynamics of cluster formation
Taiichi Yamada	Nuclear matter calculation with the tensor optimized Fermi sphere method
Yoshiko Kanada-En'yo	Cluster excited states probed by alpha and proton inelastic scattering
Mengjiao Lyu	Ab initio study of high-momentum physics in s-shell nuclei
Masaaki Kimura	Shape of light clustered nuclei
Yuki Fujikawa	Search for alpha-condensed state in 20Ne
Peter Schuck	GDR in alpha gas states; structure of family of Hoyle states
Masatoshi Itoh	Measurement of four-alpha decays near the four-alpha threshold energy in 16O
Tzany Kokalova	Theoretical challenges from an experimentalist's point of view
Pedro Santa Rita	Advances towards the measurement of gamma transitions in clustered states of 16O
Takahiro Kawabata	Gamma decay width of the 3-1 state in 12C, and recent activities of the Kyoto-Osaka group
Pavel Zarubin	Nuclear clustering studied inside fragmentation cone of relativistic nuclei
Irina Zarubina	Imaging of dissociation of relativistic nuclei in nuclear track emulsion
Yang Liu	Preliminary Experimental Results of the Molecular States in 16C
Jiaxing Han	Investigation of the 14C + α molecular configuration in 18O by means of transfer and sequential decay reaction
Marina Barbui	Experimental search for states analogous to the ^{12}C Hoyle state in heavier nuclei
Makoto Ito	Isoscalar transitions and alpha cluster structures
Thomas Neff	The role of clustering in structure and reactions of light nuclei
Francesco Iachello	Symmetry approach to clustering in nuclei
Timur Shneydman	Nuclear reflection-asymmetry in cluster approach
Raphael-David Lasseri	Quantum localisation and dilution effects on clusterisation
Alexandru Dumitrescu	Investigation of α-like Quasimolecules in Heavy Nuclei
Virgil Baran	Description of nuclei in terms of pairs and quartets
Shalom Shlomo	Sensitivity of giant resonances energies to nuclear matter properties and the equation of state
Dario Vretenar	Localization and clustering in atomic nuclei
Viacheslav Samarin	Application of Feynman's Path Integrals and Hyperspherical Functions to the Cluster Structure of Light Nuclei
Chang Xu	Alpha-cluster formation and decay in the quartetting wave function approach
Dong Bai	Some Progress on the New Double-Folding Potential and Alpha-Alpha Elastic Scattering
Zhongzhou Ren	Calculation on alpha-decay half-lives of heavy nuclei
Doru-Sabin Delion	Alpha decay versus alpha clustering
Mihail Mirea	Fine structure of alpha decay from the time dependent pairing equations
Hermann Wolter	Light cluster production in intermediate energy heavy-ion collisions
Joe Natowitz	Laboratory Studies of Dilute Nuclear Matter
Jerome Gauthier	A Nucleation Model Analysis of Neck emission yields in Heavy Ion-Reactions
Kai Gallmeister	Nucleosynthesis in heavy-ion collisions at the LHC via the Saha equation
Benjamin Doenigus	Cluster production in HIC at ALICE and STAR
Melanie Szala	Light nuclei formation in heavy ion collisions measured with HADES
Krzysztof Pysz	Production of H and He isotopes in pA collision at a few GeV beam energy
Stanislaw Mrowczynski	Thermal vs. coalescence model and production of light nuclei in relativistic heavy-ion collisions
Marina Kozhevnikova	Production of light clusters in generator THESEUS
David Blaschke	Production of hadrons and nuclei as quark clusters at chemical freezeout
Helena Pais	Light clusters and pasta phases in warm stellar matter
Niels-Uwe Bastian	From nuclear clusters to composite hadrons
Stefan Typel	Clusters in nuclear matter: from nuclei in the laboratory to stars in the cosmos
Tobias Fischer	Weak reactions with light clusters in simulations of core-collapse supernovae

approaches as well as a subdivision into smaller cluster structures.

Starting from a Green-function approach, in-medium Schrödinger equation for pairing and quartetting wave functions are derived and applied to clustering in heavy nuclei. Clustering is of relevance for radioactive decay, α preformation and the life-time of heavy nuclei. Different approaches (Xu, Bai, Ren, Delion, Mirea) and new calculations have been presented. The aim is to find a description like the well-known Cooper pairing for the two-nucleon states, which describes two-nucleon correlations in heavy nuclei, also for the important four-nucleon correlations. The self-consistent description of four-nucleon correlations is a challenge which is not completely solved at present, but the quartetting wave equation is a promising step to this goal.

Correlations and cluster formation is also an important issue in warm and dense nuclear matter. Theoretical approaches (Wolter) have been used to describe results of heavy ion collisions (Natowitz, Gauthier) at moderate energies as well as highest energies (Gallmeister, Doenigus, Szala, Pysz, Mrowczynski, Kozhevnikova, Blaschke). The role of medium effects has been intensely discussed. A new aspect is the non-equilibrium situation in heavy-ion collisions which needs new concepts, beyond the often used local thermodynamic equilibrium with time-dependent parameter values. Transport models based on kinetic equations for the single-nucleon distribution function are not able to describe quantum correlations like bound states, and semi-empirical approaches such as the coalescence model have been worked out to compensate this defect. Statistical models are able to introduce cluster formation, and it has been shown that medium modifications have to be implemented to improve the simple resonance-gas approximation, in particular the so-called nuclear statistical equilibrium (NSE) model. A systematic quantum statistical approach to nonequilibrium processes is one of the great challenges of recent theoretical physics.

Clustering in nuclear matter is also essential in astrophysics, for instance in the simulation of supernova explosions. As pointed out in several contributions (Pais, Bastian, Typel, Fischer), the inclusion of clustering is a necessary prerequisite to describe the structure and time evolution, for instance cooling by neutrino transport, of compact objects produced by supernova explosions of neutron star mergers. It was of interest to know recent progress and to discuss the implementation the experience of clustering in a dense medium. Whereas the formation of heavy nuclei in the outer crust of neutron stars is well described, the formation of light nuclei, of unstable clusters and correlations in the continuum is not well understood and leads to wrong results in the high-density region. The account of Pauli blocking and other in-medium effects has a strong influence on the formation of few-body correlations and, as a consequence, on the time evolution of the compact astrophysical objects, for instance the neutrino transport in supernova explosions.

The Workshop was a very useful opportunity to present and discuss new developments in the investigation of clustering in nuclear systems, in particular to bring together the leading groups in Japan and China with European and US physicists. A long-standing and very successful collaboration exploring the THSR approach used the Workshop to discuss future projects and collaboration. Of importance are the discussions with other groups and the comparison of different approaches. A main issue were the discussions with the experimentalists about the interpretation of new measurements and the identification of special nuclei which should be investigated in future experiments. The search for cluster effects in nuclei, which are not described by simple quasiparticle approaches like shell-model calculations, is a challenge to the theory but also to experiments, in particular working with beams of exotic nuclei.

Alpha decay of heavy nuclei is a long-standing problem in nuclear physics, in particular α preformation. The new approach based on the quartetting wave function will be worked out further. The local density (Thomas–Fermi) approach will be improved using shell-model wave functions. Recent results are promising but have to worked out more in detail within collaborations among the participants. It is expected that the systematic inclusion of few-body correlations may give an essential progress to calculate the α decay of heavy and superheavy nuclei.

A main puzzle in heavy ion collisions at highest energies is the description of the yield of light clusters by a simple chemical equilibrium picture. With respect to the preparing of experiments with new facilities now under construction, predictions about light cluster formation are of interest to characterize the state of hot and dense nuclear matter. At lower energies, results have been presented for light nuclei $A > 4$ to be explained within the collaboration by participants of the Workshop. At highest energies, the binding energies of the clusters are small compared to the observed temperatures, and the role of correlations in the continuum becomes more important to explain the formation of (anti-) nuclei and hypernuclei. More systematic many-particle approaches will be worked out to give a better approach to investigate these extreme matter processes.

There is emerging interest in the treatment of light clusters in connection with simulations of supernova explosions and related events. Simple approaches neglecting medium effects will be improved, first estimations have already been performed by the participants of the Workshop and will be completed next time. For instance, the large abundances of neutron-rich isotopes of H and He, predicted by simple NSE calculations, are spurious if Pauli blocking and other in-medium effects are taken into account.

Fig. 1 Group photo at the ECT* Trento Workshop on "Light clusters ...", Villa Tambosi, Trento (Italy), 2–6 September 2019. Top row: Benjamin Dönigus, Thomas Neff, Kai Gallmeister, Makoto Ito, Lassieri, ?, Masaaki Kimura, Masatoshi Ito, Yasuro Funaki, Melanie Szala, Helena Pais, Stanisław Mrowczyński, ?, Mihail Mirea, Jerôme Gauthier, Alexandru Dumitrescu,Virgil Baran, 5th row: Shalom Shlomo, Taiichi Yamada, Krzysztof Pysz, Stefan Typel, 4th row: Doru Delion, Yoshiko Kanada-En'yo, Bo Zhou, Dong Bai, Marina Kozhevnikova, 3rd row: Hermann Wolter, Takahiro Kawabata, Yuki Fujikawa, Dario Vretenar, Mengjiao Lyu, 2nd row: Niels-Uwe Bastian, Marina Zarubina, Tzany Kokalova, Pavel Zarubin, Marina Barbui, front row: Chang Xu, Elizaveta Nazarova, Gerd Röpke, David Blaschke, Joe Natowitz, Akihiro Tohsaki, Zhongzhou Ren, Peter Schuck

The Workshop did not only help to stimulate the discussion between different groups working on related projects, but initiated also common work and possible common publication if results have been obtained. In particular, the present Topical Collection of articles related to the field of research of the Workshop has been assembled. An overview is given by the following table of contents.

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   (i) Impurity lattice Monte Carlo for hypernuclei (Dillon Frame, Timo A. Lähde, Dean Lee, Ulf-G. Meißner) [10]

2. Reaction theory, α decay of heavy and superheavy nuclei

   (a) Validation of an optical potential for incident and emitted low-energy α-particles in the A $\sim$ 60 mass range I (V. Avrigeanu, M. Avrigeanu) [11]
   (b) Validation of an optical potential for incident and emitted low-energy α-particles in the A $\sim$ 60 mass range II: Neutron-induced reactions on Ni isotopes (V. Avrigeanu, M. Avrigeanu) [12]
   (c) Precision branching-ratio measurements in O (S. Pirrie, C. Wheldon, Tz. Kokalova, J. Bishop, Th. Faestermann, R. Hertenberger, H. F. Wirth, S. Bailey, N. Curtis, D. Dell'Aquila, D. Mengoni, R. Smith, D. Torresi, A. Turner) [13]
   (d) The identification of α-clustered doorway states in Ti using machine learning (Sam Bailey, Tzany Kokalova, Martin Freer, Carl Wheldon, Robin Smith, Joseph Walshe, Neven Soić, Lovro Prepolec, Vedrana Tokić, Francisco Miguel Marqués, Lynda Achouri, Franck Delaunay, Marian Parlog, Quentin Deshayes, Beatriz Fernández-Dominguez, Bertrand Jacquot) [14]
   (e) Isoscalar transitions and cluster structures in heavy nuclei (M. Ito, R. Nakamoto, M. Nakao, T. Okuno, S. Ebata) [15]
   (f) Unstable states in dissociation of relativistic nuclei – Recent findings and prospects of research (D. A. Artemenkov, V. Bradnova, M. M. Chernyavsky, E. Firu, M. Haiduc, N. K. Kornegrutsa, A. I. Malakhov, E. Mitsova, A. Neagu, N. G. Peresadko, V. V. Rusakova, R. Stanoeva, A. A. Zaitsev, P. I. Zarubin, I. G. Zarubina) [16]
   (g) Light element ($Z = 1, 2$) production from spontaneous ternary fission of Cf (G. Röpke, J. B. Natowitz, H. Pais) [17]
   (h) Fine structure of decay from the time-dependent pairing equations (M. Mirea) [18]

3. Clustering in nuclear matter and consequences for thermodynamic properties

   (a) Resolving the hyper-triton yield description puzzle in high energy nuclear collisions (O. V. Vitiuk, K. A. Bugaev, E. S. Zherebtsova, D. B. Blaschke, L. V. Bravina, E. E. Zabrodin, G. M. Zinovjev) [19]
   (b) A new formalism of nuclear matter: tensor-optimized Fermi sphere method – Power-series-type correlated wave function and linked-cluster expansion theorem (Taiichi Yamada) [20]
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   (d) Light clusters in dilute heavy-baryon admixed nuclear matter (Armen Sedrakian) [22]

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   (b) Thermal photons as a sensitive probe of α-cluster in C + Au collisions at the BNL Relativistic Heavy Ion Collider (Pingal Dasgupta, Guo-Liang Ma, Rupa Chatterjee, Li Yan, Song Zhang, Yu-Gang Ma) [24]
   (c) Production of light nuclei in heavy ion collisions via Hagedorn resonances (K. Gallmeister, C. Greiner) [25]
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   (e) Light-nuclei production and search for the QCD critical point (Edward Shuryak, Juan M. Torres-Rincon) [27]
   (f) Production of and correlation function in relativistic heavy-ion collisions (Sylwia Bazak, Stanisław Mrówczyński) [28]

(5.) Astrophysical consequences (neutron stars, supernova explosions, etc.)

   (a) Light clusters in warm stellar matter: calibrating the cluster couplings (Tiago Custódio, Alexandre Falcão, Helena Pais, Constança Providência, Francesca Gulminelli, Gerd Röpke) [29]

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