Light nuclei between single-particle and clustering features

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I. SCIENTIFIC ISSUE

Light nuclei represent an ideal laboratory for testing nuclear forces and investigating how interacting nucleons organise themselves in the nuclear medium. In particular, nucleon correlations in terms of pairs, quartets or more general clusters constitute essential properties that have far-reaching implications both on a fundamental level and for several applications of nuclear structure, e.g. in the astrophysical context.

Nuclear structure models that can tackle light nuclei display a large variety, ranging from macroscopic approaches where clusters may appear as explicit degrees of freedom to microscopic techniques that start from nucleons and the interactions among them. Examples from the former category are geometric or algebraic models, which are traditionally based on α-cluster constituents [1]. In the past 20 years, such models have been successfully applied to the study of α-conjugate nuclei, in particular searching for evidence of point-group symmetries in their spectrum. In addition, extensions such as the cluster shell model allow one to address $N = Z \pm 1$ and $Z \pm 2$ systems, thus considerably extending their reach. Furthermore, beside the α-particle other groupings of nucleons, from the deuteron to light nuclei such as ^{6}He, have been considered as clusters, enriching the possible domain of applications. In recent years, approaches based on the concept of effective field theory (EFT) have also been proposed, namely in the form of cluster or halo EFT [2], providing a systematic and complementary viewpoint.

How do clusters emerge in nuclei and nuclear matter? What is the interplay between a cluster structure and a single-particle or *mean-field* picture? What regulates the equilibrium between them? Preferred tools to address these questions are microscopic approaches that do not impose cluster degrees of freedom from the start, e.g. anti-symmetrized molecular dynamics [3, 4], the resonating group method [5] or energy-density-functional (EDF) based formalisms such as the generator coordinate method (GCM). Recently, for instance, EDF calculations succeeded in describing the onset of cluster structures in light nuclei [6], eventually interpreted as a Mott phase transition in which nuclear deformation plays the role of control parameter [7].

In the past few years the GCM approach has been extended to an *ab initio* formulation [8, 9]. This new development enables the investigation of deformed intrinsic densities as emerging from inter-nucleon interactions, including transition densities involving excited states of the nucleus.

Last but not least, more traditional *ab initio* techniques like the no-core shell model [10], Quantum Monte Carlo [11] or Nuclear Lattice EFT [12] are able, as of today, to deliver precise predictions of a large pool of observables in light nuclei. In particular, energies, electromagnetic and reaction properties of typical *clusters* and halo nuclei can be computed within these techniques and confronted with those from more phenomenological or macroscopic models.

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The many existing complementary ways to investigate light nuclei make this sector of the Segrè chart a rich and unique setting to advance our knowledge on nuclear forces and the structure of atomic nuclei. In particular, the formation and role of nucleonic clusters might prove instrumental in shedding light on fundamental nuclear properties. Recent advances in *ab initio* methods, new findings from EDF calculations, the revived interest in algebraic models as well as new experimental achievements indicate that it is timely to bring together practitioners from all these fields to discuss the state of the art of theory and experiment, bridge between the different approaches and delineate future perspectives.

II. GOALS OF THE PROJECT

The workshop foresees the meeting between the *ab-initio*, the *phenomenological microscopic* and the *macroscopic* communities of nuclear theory, as well as the participation of experimentalists in the field of light nuclei. Exchanges and discussions on the prediction of structure observables, with particular attention to cluster properties, are expected to take place. On the whole, the goals of the workshops are

- to define the current state of the field;
- to bridge results of phenomenological and macroscopic approaches with ones achievable by ab-initio methods;
- to weigh the role of α-clustering and assessing perks and limits of macroscopic approaches;
- to provide a comprehensive understanding of the subject for all participants;
- to initiate possible new collaborations.

III. LIST OF TALKS

The workshop aims at involving nuclear theoreticians and experimentalists, whose recent or ongoing works are focused on structure properties of light nuclei, with a preference for cluster properties. We envisage 6 presentations per day for a total of 3 days, followed by one day with four presentations and an ample conclusion or discussion session. In the spirit of the workshop, it is ensured that quite ample time is allocated for discussions in the coffee breaks and in the afternoon after 16h45. The list of confirmed speakers is presented below.

A. Structure properties and symmetries of light nuclei from phenomenological cluster approaches

- Roelof Bijker, "*Discrete symmetries in the cluster shell model*", *Departamento de Estructura de la Materia, Universidad Nacional Autónoma de Mexico* (Mexico), bijker@nucleares.unam.mx;
- David G. Jenkins, "*Spectrum, clustering and Hoyle-state candidates in the* ^{24}Mg *nucleus*", *School of Physics, Engineering and Technology, University of York* (UK), david.jenkins@york.ac.uk;
- Masaaki Kimura, "*Structure of carbon isotopes*", *RIKEN Nishina Center* (Japan), masaaki.kimura@ribf.riken.jp;
- Gianluca Stellin, "*Spectrum and electromagnetic properties in the macroscopic α-cluster model of* ^{24}Mg*: evidence of $\mathcal{D}_{4h}$ symmetry*", *ESNT, Irfu/DPhN, CEA Saclay* (France), gianluca.stellin@cea.fr;

B. Clustering as a quantum phase transition and nuclear shape evolution from microscopic viewpoints

- Jean-Paul Ebran, "*Nuclear clustering within the Energy Density Functional approach*", *DAM, CEA Brulyères-le-Châtel* (France), jean-paul.ebran@cea.fr;
- Elias Khan, "*Clustering in nuclei at finite temperature*", *Université Paris-Saclay, CNRS/IN2P3, IJCLab, Orsay* (France), elias.khan@ijclab.in2p3.fr;
- Marek Płoszajczak, "*Threshold states and clustering as the emerging phenomenon in open quantum system*", *GANIL* (France), marek.ploszajczak@ganil.fr;

C. Pairing correlations and halos from microscopic approaches

- Jaume Carbonell, "*Heavy boron istopoes as multineutron halos*", *Irène Joliot-Curie Laboratory*, *CNRS & Université Paris-Saclay* (France), jaume.carbonell@ijclab.in2p3.fr;
- Live-Palm Kubushishi, "*Structure and reactions of ^{10,11}Be and ^{15,19}C nuclei through halo effective field theory*", *Department of Physics and Astronomy*, *Ohio University*, *Athens* (USA), lkubushi@ohio.edu;
- Jagjit Singh, "*Studying the Low-Z coast of the Island of Inversion: Exploring Two-Neutron Halos in $N = 20$ and $N = 28$ Isotones*", *Department of Physics and Astronomy University of Manchester* (UK), jagjit.singh@manchester.ac.uk;
- Pieter Van Isacker, "*Neutron-proton spin-spin correlations in the ground states of N=Z nuclei*", *Grand Accélérateur National d'Ions Lourds*, *GANIL* (France), pieter.vanisacker@cea.fr;

D. Cluster correlations in light nuclei from ab-initio approaches

- Lukas Bovermann, "*Nuclear lattice EFT with wave function matching for light nuclei*", *Institut für theoretische Physik II: Physik der Hadronen und Kerne*, *Ruhr-Universität Bochum* (Germany), lukas.bovermann@ruhr-uni-bochum.de;
- Bryce Fore, "*Light nuclei with neural-network quantum states*", *Argonne National Laboratory*, *Lemont* (USA), bfore@anl.gov;
- Timo Arvid Lähde, "*Emergent geometry and duality in the carbon nucleus*", *Institute of Advanced Simulation* (IAS-4), *Forschungszentrum Jülich* (Germany), t.laehde@fz-juelich.de;
- Anna E. McCoy, "*Intruder band mixing in an ab initio description of* ^{12}Be", *Physics Division*, *Argonne National Laboratory*, *Lemont* (USA), amccoy@anl.gov;
- Osama Yaghi, "*Resonances properties in light nuclei from structure methods: NCSM with complex-scaling*", *Irène Joliot-Curie Laboratory*, *CNRS & Université Paris-Saclay* (France), yaghi@ijclab.in2p3.fr;

E. Experimental investigations on light nuclei

- Anna Corsi, "*Searching for dineutron correlations in Borromean halo nuclei*", *CEA Saclay* (France), anna.corsi@cea.fr;
- Valérie Lapoux, "*A comparative analysis of nuclear models using benchmark observables: Borromean structures of the exotic ^{6,8}He nuclei via direct reactions on proton*", *CEA Saclay* (France), valerie.lapoux@cea.fr;
- Juan Lois-Fuentes, "*Spectroscopy of neutron orbitals in ^{15}C: A test for p-sd interactions*", *Facility for Rare Isotope Beams*, *Michigan State University*, *East Lansing* (USA), loisfuen@frib.msu.edu;
- Robin Smith, "*The Hoyle Family: modern experiments to probe the cluster structure of ^{12}C*", *Department of Engineering and Mathematics*, *Sheffield Hallam University* (UK), robin.smith@shu.ac.uk;
- Irene Zanon, "*High-precision spectroscopy of ^{20}O benchmarking ab-initio calculations in light nuclei*", *Department of Physics*, *Stockholms Universitet*, *Stockholm*, (Sweden), irene.zanon@fysik.su.se;

IV. TIMETABLE

The workshop will be opened by a 15' introductory talk, briefly recapitulating the motivation, the topics of the presentations and practical information. The other contributions consist of a $35'$ *presentation* followed by a $10'$ *discussion* each. The distribution of the talks permits to touch all the four thematic threads A-E in which contributions are grouped in the same day, with the exception of Friday. For the conclusion, a free discussion time after a short thanksgiving speech by the organizers is envisaged. The discussions may be centered on technical nuances, specific phenomena or new collaborations.

	Tuesday 03/12		Wednesday 04/12		Thursday 05/12		Friday 06/12
9h15	Welcome	9h30	**P. van Isacker**	9h30	**M. Kimura**	9h30	**L. Bovermann**
9h30	**R. Bijker**	10h15	Break	10h15	Break	10h15	Break
10h15	Break	10h45	**L.-P. Kubushishi**	10h45	**J.-P. Ebran**	10h45	**A. Corsi**
10h45	**A. McCoy**	11h30	**J. Singh**	11h30	**D. Jenkins**	11h30	**E. Khan**
11h30	**V. Lapoux**	12h15	Lunch	12h15	Lunch	12h15	Lunch
12h15	Lunch	14h00	**R. Smith**	14h00	**O. Yaghi**	14h00	**J. Carbonell**
14h00	**M. Płoszajczak**	14h45	Break	14h45	**I. Zanon**	14h45	Conclusion
14h45	**B. Fore**	15h15	**T.A. Lähde**	15h30	Break		
15h30	Break			16h00	**G. Stellin**		
16h00	**J. Lois-Fuentes**						

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