

Many-body correlations, phase transitions, and clustering: how to identify and quantify them?

Organizers

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I. SCIENTIFIC ISSUE

The structure of atomic nuclei reflects a delicate interplay between single-particle motion and collective correlations. Phenomena such as pairing, shape coexistence and clustering exemplify how complex emergent behavior arises from fundamental nucleon–nucleon interactions.

In recent years, major progress has been achieved in *ab initio*, shell-model, and energy-density functional approaches, as well as through advanced experimental probes. However, the field still lacks unified diagnostics capable of quantifying the degree of collectivity, correlation, and condensation in a model-independent manner.

Information-theoretic and correlation measures, such as invariant correlation entropy, Shannon entanglement entropy, group-theoretic decompositions, and Yang’s criterion for off-diagonal long-range order, based on the eigenvalues of the density matrix, offer powerful tools to quantify correlations beyond conventional observables. Their systematic application to nuclear systems opens new opportunities to identify clustering and condensation in both ground and excited states, to trace signatures of pairing-to-clustering transitions, and to explore analogs of condensed-matter phenomena such as the Josephson effect in nuclei. Furthermore, these ideas can and do drive novel theoretical models, such as weak-entanglement between proton and neutron components suggesting a novel importance truncation method.

The topics we intend to discuss are:

- (a) *Clustering and α -like Correlations*: Identification of cluster structures and α -condensate components in ground and excited states; connections between cluster models, the shell model, and *ab initio* calculations; manifestations of clusterisation in light and medium-mass nuclei.
- (b) *Pairing and Condensation Phenomena*: Theoretical fingerprints of pair and α -condensation; observables in spectroscopy and reactions; analogies to superfluidity and Bose–Einstein condensation in finite systems.
- (c) *Josephson Effect in Nuclear Systems*: Recent theoretical and experimental studies of pair-transfer between superfluid nuclei; possible extension toward α -transfer in $N = Z$ systems; links to tunneling phenomena and coherence effects in nuclear reactions.
- (d) *Information-Theoretic and Correlation Measures*: Application of invariant correlation entropy, Shannon entanglement entropy, mutual information, and Yang’s criterion to characterize correlations and long-range order in nuclear models; benchmarking across theoretical frameworks.
- (e) *Emergent Symmetries and Quantum Phase Transitions*: Role of dynamical symmetries and symmetry-breaking transitions [$(SU(3)–U(5))$, pairing–quadrupole competition, shape coexistence] as organizing principles of nuclear collectivity.
- (f) *Entropy, Complexity, and Chaos in Finite Quantum Systems*: Using entanglement and information measures to quantify chaos, complexity, and mixing in nuclear spectra; connections with quantum thermalization and statistical behavior in finite nuclei.
- (g) *Interdisciplinary Perspectives*: Cross-fertilization with quantum information science, condensed-matter superfluidity, ultracold atomic gases, and quantum chemistry; identifying universal indicators of long-range order and condensation.
- (h) *Computational and Data-Driven Approaches*: Techniques for identifying correlated structures, dimensionality reduction of many-body wavefunctions.

II. GOALS OF THE WORKSHOP

- (i) To discuss how correlations and clusterisations are treated in various models and how they manifest in experimental data.
- (ii) To discuss how to identify and to quantify, theoretically and experimentally, the emergence of quantum phase transitions associated to pairing and α -like condensation.
- (iii) To explore the methods employed to describe correlations, phase transitions and condensation in condensed matter superfluidity, ultracold gases and quantum information, and to discuss how they can be applied to nuclear systems.

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- 10) C. White, A. Volya, D. Mulhall, and V. Zelevinsky, *Structured ground states of randomly interacting bosons*, Phys. Rev. Res. **5**, 013109 (2023).
- 11) N. Sandulescu, M. Sambataro and A Volya, *Proton-neutron pairing, quartet condensation and alpha transfer in N=Z nuclei*, EPJ Web of Conferences **292**, 01003 (2024)
- 12) M. Sambataro and N. Sandulescu, *Pairing correlations and eigenvalues of density matrix in atomic nuclei*, Annals of Physics **413** (2020) 168061
- 13) B. Le Crom, M. Assie, Y. Blumenfeld, J.Guillot, *Neutron-proton pairing in N=Z radioactive fp-shell nuclei ^{56}Ni and ^{52}Fe probed by pair transfer*, Phys. Lett.B **829** (2022) 136057
- 14) L. Corradi, *Sub-barrier transfer reactions and the nuclear Josephson effect*, EPJ Web Conf. **324** (2025) 00016
- 15) R. A. Broglia, F. Barranco, L. Corradi, G. Pottel, S. Szilner, *Nuclear Josephson-like gamma emission*, arXiv:2206.05351 (2022)
- 16) N. Gavrilov, A. Leviatan, F. Iachello, *Mixed configurations and intertwined quantum phase transitions in odd-mass nuclei*, Phys Rev. C **106**, L051304 (2022).
- 17) S. T. Guo, Y. X. Yu, C. W. Johnson, et al, “*Quantum phase transition in atomic nuclei driven by competition between subshell closure and collective motion*,” Phys. Rev. C **112**, L011301 (2025).
- 18) M. Sambataro, N. Sandulescu, C. W. Johnson, *Proton-neutron pairing in self-conjugate nuclei in a formalism of quartets*, Phys. Lett. B **740** (2015) 137

III. PROGRAM

List of speakers and talks

- M. Assié (IJCLab Orsay)
Probing neutron-proton pairing through pair transfer: the Anderson limit in nuclei
- F. Barranco (University of Sevilla) *Nuclear Josephson effect, theoretical aspects and predictions*
- D. Beaumel (IJCLab Orsay) *Approach to nuclear clustering in the ground-state of neutron-rich nuclei via direct reactions: first studies in inverse kinematics at RIKEN and GANIL*
- O. Bessidskaia-Bylund (IJCLab, Orsay) *Photoproduction of vector mesons at the LHC as a probe of nuclear geometry*
- B. Cederwall (KTH Royal Institute of Technology, Stockholm) *Probing pairing and its isospin modes at finite angular momentum*
- L. Corradi (INFN-LNL, Legnaro) *Sub barrier transfer reactions and the nuclear Josephson effect*
- D. Gambacurta (INFN Catania) *Coherence and Collectivity in nuclear excitations*
- N. Gavrielov (Hebrew University) *Shape-phase transitions and configuration crossing in the $A \sim 100$ region*
- V. Goldberg (Texas A&M) *Experimental Study of α -Cluster States in $N \neq Z$ Light Nuclei*
- L. Heitz (CEA DAM) *Localization/clustering from ab initio methods*
- N. Itagaki (Osaka Metropolitan University) *Exotic clustering of light nuclei*
- C. W. Johnson (SDSU, San Diego) *Can the ground state have a temperature? And other questions*
- D. Lee (Michigan State University)
Multimodal superfluidity of neutrons and neutron-rich nuclei
- H.-Z. Liang (U. Tokyo/RIKEN)
- E. Litvinova (Western Michigan University) *Spectral imprints of nuclear many-body correlations: constraining theory toward the spectroscopic accuracy frontier*
- P. Magierski (Warsaw University of Technology)
Stability and Dissipative Dynamics of Collective Modes in Ultracold Atomic Gases
- A. Nurmukhanbetova (Nazarbayev University)
The $^{12}\text{C} + ^{12}\text{C}$ Interaction in Astrophysics and Cluster Structure in ^{24}Mg
- T. Otsuka (University of Tokyo)
Dual rotational modes, compact-object and distant-object, in quantum many-body systems
- G. Rogachev (Texas A&M)
- N. Sandulescu (IFIN-HH, Bucharest) *Quartet correlations in $N=Z$ nuclei*
- P. Van Isacker (GANIL) *Counting pairs in the shell model*
- A. Volya (Florida State University) *Configuration-interaction studies of nuclear alpha clustering*

Schedule

	Monday 7 Sept.	Tuesday 8 Sept.	Wednesday 9 Sept.	Thursday 10 Sept.	Friday 11 Sept.
9h30	<i>Welcome</i>	<i>Discussions</i>	<i>Discussions</i>	<i>Discussions</i>	<i>Discussions</i>
9h40	M. Assié	P. Van Isacker	E. Litvinova	D. Beaumel	O. Bessidskaia-Bylund
10h30	<i>Break</i>	<i>Break</i>	<i>Break</i>	<i>Break</i>	<i>Break</i>
11h	B. Cederwall	D. Lee	P. Magierski	11h Seminar V. Goldberg	A. Nurmukhanbetova
11h50	<i>Discussions</i>	<i>Discussions</i>	<i>Discussions</i>	<i>Discussions</i>	<i>Discussions</i>
12h	<i>Lunch</i>	<i>Lunch</i>	<i>Lunch</i>	<i>Lunch</i>	<i>Lunch</i>
14h	F. Barranco	N. Sandulescu	D. Gambacurta	N. Itagaki	T. Otsuka
14h50	<i>Break</i>	<i>Break</i>	<i>Break</i>	<i>Break</i>	<i>Break</i>
15h20	L. Corradi	N. Gavrielov	L. Heitz	A. Volya	C. Johnson
16h	Discussions	Discussions	Discussions	Discussions	
17h	<i>End</i>	<i>End</i>	<i>End</i>	<i>End</i>	