Ab initio many-body calculations: where has the nuclear pairing gone?

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I. SCIENTIFIC ISSUE

Among the rich phenomenology displayed by quantum many-body systems, observable effects associated with correlations between particles that are strong enough to induce a superfluid phase of Cooper pairs have attracted a lot of attention over the years. In nuclear physics, while the odd-even staggering of masses is considered to be the paradigmatic fingerprint of spin-singlet proton-proton and neutron-neutron pairing correlations [1], other observable patterns are believed to reflect them as well, i.e. the predominance of $J = 0$ even-even ground states, the distinct low-energy excitation spectra of successive even and odd isotopes (isotones), the increase of moment of inertia along ground-state rotational bands and the backbending phenomenon, the enhancement of two-particle transfer cross sections or the odd-even staggering of charge radii. Furthermore, pairing correlations are also thought to impact many properties of extended nuclear matter in neutron stars, e.g. the attribution of pulsar glitches to neutron superfluidity which initiated a branch of nuclear astrophysics [2].

While the phenomenology associated with like-particle pairing correlations is well established, the situation is less clear for the spin-singlet and spin-triplet neutron-proton pairing phases whose existence and impact have remained elusive so far. While two-particle transfer reactions have signed the presence of strong neutron-proton correlations in light and medium-mass nuclei [3–5], these experiments are hindered in heavy heavier systems by low cross-sections, the low intensity of the available radioactive beams, and the density of states of the residual odd-odd nuclei. So far, only less direct fingerprints based on, e.g., rotational bands have been targeted in heavy nuclei [6, 7]. Nevertheless, a new empirical evidence pointed towards the existence of the exotic spin-triplet neutron-proton pairing phase in heavy nuclei and extended matter [8, 9]. Along the way, alternative probes, such as knock-out reactions, which are expected to be soon feasible in fragmentation facilities [7], have been proposed. Ultimately, a clear-cut fingerprint of the existence of the spin-triplet neutron-proton superfluid phase in nuclei, which both experiment and theory could focus on, is still to be found.

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From a theoretical perspective, the existence of the spin-singlet and spin-triplet superfluid phases is expected from the strong attractive character of the nucleon-nucleon interaction in its spin-singlet and spin-triplet S-wave channels, respectively. While the elusive character of neutron-proton pairing in nuclei is challenging this naive expectation from the outset, the recent extension of ab initio many-body methods to open-shell nuclei up to mass $A \approx 200$ poses novel questions regarding the actual processes building up neutron-neutron and proton-proton pairing in nuclei and extended matter. Polynomially-scaling methods such as many-body perturbation theory (MBPT), coupled-cluster (CC) theory, in-medium similarity renormalization group (IMSRG) approach or self-consistent Green's functions (SCGF), offer the best pathway to heavy nuclei but must typically rely on the breaking (and further restoration) of symmetries by the employed reference state to capture static, i.e. long-range, correlations [10, 11]. This way, superfluidity and/or deformation physics are meant to be grasped from the outset by employing a reference state spontaneously breaking U(1) and/or SU(2) symmetries, respectively. While deformation physics seems to be well-captured from the start by using a deformed reference state [12], the use of a Bogoliubov reference state typically delivers little spin-singlet pairing correlations in mid-mass nuclei [12, 13], in spite of the strong attractive character of the nucleon-nucleon interaction in the spin-singlet S-wave channel. This deficiency is not overcome by adding dynamical correlations on top of the reference state based on state-of-the-art truncation schemes currently employed in Bogoliubov MBPT, Bogoliubov CC, Gorkov SCGF or multi-reference calculations [12, 13]. While resorting to non-polynomial methods such as valence-space IMSRG, which does not rely on the explicit breaking of U(1) symmetry, offers a way out [14] and demonstrates that Chiral Hamiltonians are not the primer suspect, the way to capture pairing correlations at low computational cost within polynomially-scaling methods is presently put into question. Indeed, it is likely to be necessary to explicitly account for the exchange of *collective* fluctuations by members of the Cooper pair to capture the missing pairing correlations [15, 16]. Addressing this challenge is key to envision a quantitative description of nuclear superfluidity in heavy nuclei and extended matter.

Similarly, the relevance of neutron-proton pairing to build efficient and accurate ab initio descriptions of finite and infinite nuclear systems is attracting growing interest and its inclusion in state-of-the-art methods raises further theoretical challenges. While a robust neutron-proton pairing phase is expected to be more likely to appear in large nuclei and infinite matter, its importance in the description of lighter systems has been recently explored. For example, building explicitly neutron-proton pairing into the reference state has been shown to improve the description of mid-mass nuclei [18] and to be critical for an exact description of the deuteron at mean-field cost [19]. In extended matter, the ab initio description of neutron-proton pairs requires a reference state incorporating pairing in multiple isospin and angular momentum channels. Furthermore, this must be done while accounting for the dominant and costly to incorporate quartetting (alpha-particle) correlations [20], making the general ab initio description of neutron-proton mixtures at the thermodynamic limit challenging. These recent developments raise important questions regarding the relevance of neutron-proton pairing correlations in the ab initio description of nuclear systems: their answers could lead to more efficient ab initio methods paving the way to heavier nuclei and exotic nuclear systems.

In view of the above, it is timely to gather the relevant community of nuclear experimentalists and theorists during a one week and half workshop program to explore the following fundamental questions: when do we consider a finite nuclear many-body system to have neutron-proton pairing? What experimentally observable signature should we search to identify neutron-proton pairing in nuclei? What is the best way to incorporate pairing correlations in ab initio many-body calculations scalable to heavy nuclei? How critical is neutron-proton pairing in the design of efficient ab initio methods?

II. GOALS OF THE PROJECT

In summary, the goals of the project are

1. Review the status of the theoretical description of spin-singlet and spin-triplet pairing phases in nuclear systems and of their standard experimental markers.
2. Identify signatures of neutron-proton pairing that could be measured experimentally in the future.
3. Address the theoretical challenges related to an efficient and accurate ab initio description of the phenomenology related to pairing correlations in both finite and infinite nuclear systems.

III. LIST OF SPEAKERS

1. Introductory lectures

   - G. Palkanoglou (TRIUMF, gpalkanoglou@triumf.ca)
     Ab initio calculations of spin-singlet and spin-triplet pairing gaps in infinite nuclear matter
   - T. Duguet (CEA-Saclay, thomas.duguet@cea.fr)
     Ab initio description of neutron-neutron and proton-proton pairing in finite nuclei
   - S. Frauendorf (ND, sfrauend@nd.edu)
     *Phenomenology and theoretical description of neutron-proton pairing in finite nuclei**
   - M. Urban (IJCLab, michael.urban@ijclab.in2p3.fr)
     Nuclear superfluidity: from cold atoms to neutron stars

2. Experimental talks

   - H. Jacob (IJCLab, hugo.jacob@ijclab.in2p3.fr)
     Neutron-proton pairing through transfer reactions with stable and radioactive beams
   - B. Cederwall (KTH, bc@kth.se)
     Searching for np pairing by studying rotational bands, case of ^{88}Ru
   - A. Kwiatkowski (TRIUMF, aniak@triumf.ca)
     Pairing studies via precision mass measurements
   - T. Uesaka (RIKEN, uesaka@riken.jp)
     Search for deuteron clusters at ONOKORO and relation to the neutron-proton pairing search
   - D. Thisse (CEA-Saclay, damien.thisse@cea.fr)
     Investigation of the GMR along the Ni isotopic chain

3. Theoretical talks

   - T. Miyagi (University of Tsukuba, miyagi@nucl.ph.tsukuba.ac.jp)
     Valence-space in-medium similarity renormalization group description of calcium isotopes
   - C. W. Johnson (San Diego State University, cjohnson@sdsu.edu)
     The predominance of J=0 even-even ground-state: is it a fingerprint of pairing correlations?
   - P. Demol (KU Leuven, pepijn.demol@ulb.be)
     Role of pairing in semi-magic nuclear ground states based on Bogoliubov coupled cluster calculations
   - H. Hergert (Michigan State University, hergert@frib.msu.edu)
     Odd-even mass staggering in multi-reference in-medium similarity renormalization group calculations
   - A. Ekström (Chalmers university of Technology, andreas.ekstrom@chalmers.se)
     Correlation between chiral EFT interaction contributions and pairing properties in nuclei
   - E. Vigezzi (INFN, enrico.vigezzi@mi.infn.it)
     To which extent pairing originates from the exchange of collective fluctuations?
   - F. Barranco (University of Seville, barranco@us.es)
     *Fragmentation of the giant pairing vibration induced by many-body processes**
   - G. Hagen (ORNL, hageng@ornl.gov)
     Momentum of inertia of ground-state rotational bands in mid-mass nuclei: can one account for its increase with spin without explicitly breaking $U(1)$ *symmetry?*
   - E. Khan (IJCLab, khan@ipno.in2p3.fr)
     Fingerprint of superfluidity in EDF calculations on giant monopole resonances of mid-mass open-shell nuclei
   - A. Porro (TU Darmstadt, aporro@theorie.ikp.physik.tu-darmstadt.de)
     Evolution of multipole giant resonance energies in mid-mass open-shell nuclei
   - V. Somà (CEA-Saclay, vittorio.soma@cea.fr)
     Odd-even staggering of masses and charge radii in semi-magic nuclei from Gorkov Self-consistent Green's function calculations

- A. Rios (ICCUB, arnau.rios@icc.ub.edu)
  Impact of correlations on the phase diagram of nuclear matter
- Y. Fujimoto (UCB, yfujimoto@berkeley.edu)
  Kohn-Luttinger effects for superfluid nuclear matter
- B. Bally (CEA-Saclay, benja.bally@gmail.fr)
  Role of neutron-proton pairing in the exact description of the deuteron at mean-field cost
- A. Gezerlis (University of Guelph, gezerlis@uoguelph.ca)
  Coexistence of spin-singlet and spin-triplet pairing phases in nuclei
- D. Lee (Michigan State University, leed@frib.msu.edu)
  Inter-species pairing and clustering in fermionic matter
- P. van Isacker (GANIL, isacker@ganil.fr)
  Alternative signatures of neutron-proton pairing

IV. PROGRAM

	Tuesday 13/05		Wednesday 14/05		Thursday 15/05		Friday 16/05
9h15	Welcome	9h30	**A. Kwiatkowski**	9h30	**G. Hagen**	9h30	**E. Vigezzi**
9h30	**G. Palkanoglou**	10h20	**H. Hergert**	10h20	**B. Cederwall***	10h20	**C. W. Johnson**
10h30	Break	11h10	Break	11h10	Break	11h10	Break
11h00	**T. Duguet**	11h30	**T. Miyagi**	11h30	**H. Jacob**	11h30	**P. van Isacker**
12h00	Lunch	12h20	Lunch	12h20	Lunch	12h20	Lunch
13h30	**S. Frauendorf***	14h00	**A. Ekström**	14h00	**T. Uesaka**	14h00	**Discussion 3**
14h30	**M. Urban**	14h50	Break	14h50	Break	15h30	End
15h30	End	15h00	**Discussion 1**	15h00	**Discussion 2**		
17h00		17h00	End	17h00	End		

	Monday 19/05		Tuesday 20/05		Wednesday 21/05**
9h30	**E. Khan**	9h30	**V. Somà**	9h30	**A. Rios**
10h20	**D. Thisse**	10h20	**P. Demol**	10h20	**D. Lee**
11h10	Break	11h10	Break	11h10	Break
11h30	**A. Porro**	11h30	**A. Gezerlis**	11h30	**Y. Fujimoto**
12h20	Lunch	12h20	Lunch	12h20	Lunch
14h00	**F. Barranco***	14h00	**B. Bally**	14h00	End
14h50	Break	14h50	Break	14h50	
15h00	**Discussion 4**	15h00	**Discussion 5**	15h00	
17h00	End	17h00	End	17h00	

* The talk will be given remotely.
** On Wednesday May 21^{st} the workshop will take place in room 102 of building 713.

A. Talk schedule

TUESDAY 13/05: *Introductory Lectures*

09:30 **G. Palkanoglou** *Ab initio calculations of singlet and triplet pairing gaps in infinite nuclear matter*

11:00 **T. Duguet** *Ab initio description of neutron-neutron and proton-proton pairing in finite nuclei*

13:30 **S. Frauendorf** *Theoretical description of neutron-proton pairing in finite nuclei*

14:30 **M. Urban** *Nuclear superfluidity: from cold atoms to neutron stars*

WEDNESDAY 14/05: *Masses, Radii, and Nuclear Interactions*

09:30 **A. Kwiatkowski** *Pairing studies via precision mass measurements*

10:20 **H. Hergert** *Odd-even mass staggering in multi-reference IMSRG calculations*

11:30 **T. Miyagi** *Valence-space in-medium similarity renormalization group description of calcium isotopes*

14:00 **A. Ekström** *Correlation between chiral EFT interaction contributions and pairing properties in nuclei*

THURSDAY 15/05: *Rotational Properties*

09:30 **G. Hagen** *Moment of inertia of ground-state rotational bands in mid-mass nuclei: can one account for its increase with spin without explicitly breaking* $U(1)$ *symmetry?*

10:20 **B. Cederwall** *Searching for neutron-proton pairing by studying rotational bands, the case of* ^{88}Ru

11:30 **H. Jacob** *Neutron-proton pairing through transfer reactions with stable and radioactive beams*

14:00 **T. Uesaka** *Search for deuteron clusters at ONOKORO and relation to the neutron-proton pairing search*

FRIDAY 16/05: *Alternative Effects and Signatures*

09:30 **E. Vigezzi** *To which extent pairing originates from the exchange of collective fluctuations?*

10:20 **C. W. Johnson** *The predominance of* $J = 0$ *even-even ground-state: is it a fingerprint of pairing correlations?*

11:30 **P. van Isacker** *Alternative signatures of neutron-proton pairing*

MONDAY 19/05: *Giant Monopole Resonances and Giant Pairing Vibrations*

09:30 **E. Khan** *Fingerprint of superfluidity in EDF calculations on giant monopole resonances of mid-mass open-shell nuclei*

10:20 **D. Thisse** *Investigation of the GMR along the Ni isotopic chain*

11:30 **A. Porro** *Evolution of multipole giant resonance energies in mid-mass open-shell nuclei*

14:00 **F. Barranco** *Fragmentation of the giant pairing vibration induced by many-body processes*

TUESDAY 20/05: *Masses, Radii, and Nuclear Interactions (cont'd)*

09:30 **V. Somà** *Odd-even staggering of masses and charge radii in semi-magic nuclei from Gorkov Self-Consistent Green's function calculations*

10:20 **P. Demol** *Role of pairing in semi-magic nuclear ground states based on Bogoliubov coupled cluster calculations*

11:30 **A. Gezerlis** *Coexistence of spin-singlet and spin-triplet pairing phases in nuclei*

14:00 **B. Bally** *Role of neutron-proton pairing in the exact description of the deuteron at mean-field cost*

WEDNESDAY 21/05: *Infinite Matter*

09:30 **A. Rios** *Impact of correlations on the phase diagram of nuclear matter*

10:20 **D. Lee** *Inter-species pairing and clustering in fermionic matter*

11:30 **Y. Fujimoto** *Kohn-Luttinger effects for superfluid nuclear matter*

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