The tower of effective (field) theories and the emergence of nuclear phenomena

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Workshop of the *Laboratoire de Recherche sur les Sciences de la Matière*
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I. OBJECTIVES

The objectives of the workshop series co-organized by the Laboratoire de Recherche sur les Sciences de la Matière (LARSIM) and the Espace de Structure et réactions Nucléaire Théorique (ESNT) is to conduct a long-term reflection on the epistemological undertaking and the practice of scientific research.

This year, the program momentarily distance itself from the trend of traditional workshops by focusing on epistemological aspects of state-of-the-art research in fundamental nuclear science. The objective is to discuss the building of nuclear theories and the epistemological tools appropriate to the understanding and the description of emerging nuclear phenomena.

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II. CONTEXT AND RATIONALE

Throughout the XX$^{\text{th}}$ century, the astonishingly rich phenomenology nuclear systems display at low energy has lead theorists to develop a large mosaic of nuclear models. This variety of models makes however difficult to elucidate the deeper ambitions of this research activity given that epistemological tools have been rather elaborated to account for a unified and stabilized theory than to apprehend a plurality of models. Indeed, the scientific value of a theory is typically evaluated in terms of the precision of its prediction, of its range of applicability and of the intelligibility of its principles. Ideally, a theory is thus meant to be reductionist, unifying and fundamentalist. In view of the intrinsic limited precision of their prediction and of the difficulty to assess *a priori* their range of applicability, as well as of their specific and disconnected character, traditional models of inter-nucleon interactions and of nuclear structure and reactions are necessarily deficient when analyzed by means of standard epistemological interpretative frameworks. In this context, the main benefit of the notions of emergence and effectiveness is to offer the possibility of a more pertinent reformulation of the key questions at play.

The notion of emergence first arose in connection with a philosophical reflection on the relationship a material substrate entertains with properties of an organism that seem to be irreducible to this substrate: for example, how life emerges from matter (in a vitalist perspective) or how conscience emerges from brain's activity (in an idealist perspective). Later on, the notion disseminated into intra-disciplinary debates on the modeling of complex physical or biological systems: emergence steps in whenever properties observed at a certain scale are inexplicable or unpredictable starting from an underlying scale. As such, it challenges the understanding and the articulation of the various organizational levels of complex systems. The emergence problem reactivates the ancient debate between partisans of reductionism and holism, the latter considering after Aristotle that properties of an organism as a whole cannot be identified to those resulting from the aggregation of its parts.

The notion of effective reality, which distinguishes an actuality from the vague notion of "reality", was also first elaborated by the philosophical reflection. In *Science of Logic*, Hegel instituted the effective reality *(Wirklichkeit)* as a primordial category to underline the fact that only "what is effective can act": effective reality is a law that first imposes itself onto reality as an arbitrary necessity whose justification can only be captured *a posteriori* by human's mind in that its activity is precisely what reveals the most significant aspects of reality. Independently of this elaboration, scientific language seized this notion to designate theories relying on a deliberate rejection of the explicative factors originating from the underlying scales. It constitutes a strategy that opposes the reductionist ambition when the knowledge of the explicative factors from the underlying scales defaults or when their complexity makes predictions impractical. Even more so, the use of an effective theory can be justified when the reductionist view is at reach but unnecessarily complicated to apprehend the phenomena of interest.

Emergence and effectiveness embody two symmetric ruptures with respect to the standard set by reductionist, unifying and fundamentalist theories: while emergence signals the occurrence of phenomena that challenge the ambition to explain everything starting from a fundamental scale, effectiveness notifies that it might actually be preferable to escape such a demand. Furthermore, emergence and effectiveness define two alternative viewpoints regarding what a theory must be. The former institutes a tension with the reductionist explanation that encourage scientific rationalism to deepen its comprehension of the relative character of the various levels of organization whereas effective theories arrogate a pragmatic justification.

Following a revision of the meaning of renormalization procedures in particle physics, Steven Weinberg rehabilitated and promoted the notion of effective field theories, before initiating chiral effective field theory that has been paving the way for a reconfiguration of low-energy nuclear physics. The development of effective theories (and their interlocking) represents a considerable transformation compared to the situation embodied by the plurality of models: a new exigence of systematicity implying the necessity

1. to state *a priori* the range of applicability of the theory and to specify the pertinent degrees of freedom, along with the symmetries originating from the underlying scales,

2. to motivate (often on the basis of "naturalness") an organization (a "power counting") of *all* interaction operators allowed by symmetries,

3. to determine the low-energy constants associated with the unresolved physics, either deductively from the underlying effective theory or inductively from experiment.

While the portfolio of nuclear models constitutes a compromise between the necessity to account for emerging phenomena and the demand for a reductionist explanation, compromise whose status remains the one of a norm by default, effective theories break away from the inferiority complex with respect to the "grand theory". They incarnate themselves through the coherence of the boundaries they assess to their own applicability and through the selection of the underlying factors they explicitly retain. The intriguing zoology of nuclear models now extends into the research,

yet labyrinthine, of a hierarchy or a tree view of nuclear effective theories paving the composite rationality of the nuclear domain. However, it would be presumptuous to believe having solved, or even anticipated, all the obstacles by the sole transitioning from the perspective of models to the perspective of effective theories. Contrarily, an entire range of new thorny questions arises and indicates, paradoxically, the fact that it is impossible to give neither the surprises of emergence nor the frustration of rationalism their final notice.

Indeed, the first successes of effective theories in the context of low-energy nuclear science unavoidably question the frontiers of complexity, the naturalness of scales separation between effective theories and the limit of a theoretical construct via a bottom-up strategy. The issue associated with the articulation of a potential arborescence of nuclear effective theories is accompanied by the uncertainty of the criteria supposed to order each of them: should one invoke systematicity, naturalness or commodity? Besides, unexpected emerging phenomena/scales can indicate that the power counting organizing the hierarchy of operators in such or such effective theory may not be optimal anymore. In this context, epistemological issues are not as massive and abstract as metaphysical questions are, i.e. "does nature display a bottom?" or "do our theories possess a double-bottom?", but rather relate to fine-tuning procedures. The fact remains that it is by maintaining the fertile tension between the rationalist ambition to make the range of applicability intelligible and the pragmatist adjustment of the theoretical tools that one can hope to clarify the unanswered questions at play in low-energy nuclear physics.

The present ESNT workshop aims at addressing and clarifying some of the points elaborated on above with the ambition to help articulating a penetrating path forward for low-energy nuclear physics. The workshop is organized in two complementary parts. The first two days will be dedicated to discussing the philosophical, historical and sociological background pertinent to the challenges for low-energy nuclear science that interest us here. In particular, the notions of reductionism, emergence, holism and effectiveness will be scrutinized. This will be followed by a set of talks that will introduce how these notions come into play in cognitive science, in biological and gravitation systems, before turning to nuclear systems at low energy. After discussing the current situation of effective theories within the frame of low-energy nuclear physics by mainly reviewing the status of existing chiral effective field theory, pionless effective field theory and halo effective field theory, the reformulation of a nuclear model into a proper effective theory will be examplified. The next three days of the workshop will focus on state-of-the art developments in nuclear theory. The objective is to discuss recent advances in view of their epistemological undertaking and try to systematically address the thorny questions that have or may arise. Throughout the five days of the workshop, discussion sessions will be organized to further address the key discussions that will have come up during the talks.

III. OBJECTIVES OF THE WORKSHOP

In summary, the objectives are

1. to nurture the research activity of nuclear scientists by discussing its philosophical undertaking,
2. to expose scientists at large to state-of-large developments in fundamental nuclear science via the prism of associated epistemological challenges,
3. to discuss the paths forward in state-of-the-art research in low-energy nuclear theory.

IV. PROGRAM

- **I. Reductionism, emergence and effective theories**
  1. Historical and philosophical introductions to emergence, effectiveness and explanation
     (V. Bontems, philosopher)
  2. Reductionism, holism and emergence
     (R. Fjelland, philosopher)
  3. Effective theories and conceptual questions in high-energy physics
     (A. Grinbaum, philosopher)
  4. Reductionism, emergence and the renormalization group
     (A. Franklin, philosopher)
  5. Effective field theory for gravity and emerging phenomena
     (J. Donoghue, physicist)

6. Tower of nuclear effective field theories: current status and perspectives
   (U. van Kolck, physicist)
7. Turning a model into a proper effective theory: the example of emergent symmetry breaking in deformed atomic nuclei
   (H. A. Weidenmueller, physicist)
8. Emergent phenomena and partonic structure in hadrons
   (C. Roberts, physicist)

- **II. From the era of nuclear models to the era of nuclear effective (field) theories?**

1. Can we reliably predict nuclear forces and/or nuclei from QCD?
   (Z. Davoudi, physicist)
2. Effective field theory for lattice nuclei: the matching of EFTs
   (N. Barnea, physicist)
3. Effective field theory for halo nuclei
   (C. Ji, physicist)
4. Appropriate degrees of freedom and higher-order operators
   (D. Gazit, physicist)
5. Pragmatic versus rigorist view on chiral EFT(-based) inter-nucleon interactions
   (C. Forssen, physicist)
6. Error quantification and falsification of chiral-EFT interactions
   (R. Navarro Pérez, physicist)
7. Are the fundamental physics constants fine tuned from an EFT perspective?
   (U.-G. Meissner, physicist)
8. Is something wrong with chiral EFT?
   (H. W. Griesshammer, physicist)
9. Experimental signatures of the emergence of shell structures and of the mean field: from macroscopic systems to the atomic nucleus
   (R. Garcia-Ruiz, physicist)
10. Emergence of magic numbers from inter-nucleon interactions: necessary ingredients
    (C. Barbieri, physicist)
11. Can the shell-model be truly ab-initio?
    (R. S. Stroberg, physicist)
12. Connecting nuclear forces with properties of nuclei and neutron stars
    (S. Gandolfi, physicist)
13. Threshold phenomena and the emergence of nuclear clustering
    (M. Ploszajczak, physicist)
14. Chaotic systems and emerging phenomena
    (H. A. Weidenmueller, physicist)

V. DETAILED PROGRAM

Monday jan. 16	**Tuesday jan. 17**	**Wednesday jan. 18**	**Thursday jan. 19**	**Friday jan. 20**
09h15 Welcome				
09h30 Bontems	09h30 Donoghue	09h30 Weidenmueller	09h30 Griesshammer	09h30 Meissner
10h30 **Coffee**	10h30 **Coffee**	10h30 **Coffee**	10h30 **Coffee**	10h30 **Coffee**
11h00 Grinbaum	11h00 van Kolck	11h00 Davoudi	11h00 Navarro Pérez	11h00 Gandolfi
12h00 **Lunch**	12h00 **Lunch**	12h00 **Lunch**	12h00 **Lunch**	12h00 **Lunch**
13h30 Bontems	13h30 Roberts	13h30 Ji	13h30 Garcia-Ruiz	13h30 Stroberg
14h30 **Coffee**	14h30 **Coffee**	14h30 **Coffee**	14h30 **Coffee**	14h30 **Coffee**
15h00 Fjelland	15h00 Barbieri	15h00 Forssen	15h00 Gazit	15h00 Ploszajczak
16h00 Franklin	16h00 Discussion	16h00 Barnea	16h00 Discussion	16h00 Weidenmueller
17h00 **End**	17h00 **End**	17h00 **End**	17h00 **End**	17h00 **End**
			19h00 **Workshop dinner**	