Deciphering nuclear phenomenology across energy scales

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I. SCIENTIFIC ISSUE

Over the past two decades, a successful program of high-energy nuclear collisions has been conducted in the world's largest accelerator facilities, namely, the BNL Relativistic Heavy-Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC). The main purpose of these experiments is the creation and the study of the hot and dense state of strong-interaction matter, named the quark-gluon plasma (QGP). The QGP was discovered nearly 20 years ago in ^{197}Au+^{197}Au collisions following the beginning of operation of the RHIC facility. About ten years later, production of QGP droplets by means of relativistic ^{208}Pb+^{208}Pb collisions also started at the LHC.
In the past 5 years or so, with the advent of ^{238}U+^{238}U collisions at RHIC, and ^{129}Xe+^{129}Xe collisions at LHC, it has been realized that experimental data in high-energy nuclear collisions contains evidence of unprecedented phenomenological manifestations of the collective structure of the colliding ions, notably, their deformations and radial profiles. The simplest example is that of the nucleus ^{238}U, which has a well-known strongly-prolate shape. Observables measured at RHIC in collisions of ^{238}U nuclei are qualitatively different from the same observables measured in collisions of ^{197}Au nuclei. In the state-of-the-art modeling of high-energy nuclear collisions, these findings are immediately explained by the fact that uranium nuclei are much more deformed in their ground state.

A plethora of such findings have further clarified that it is quite easy to "see" the deformation of nuclei in high-energy collisions. The notion of nuclear *shapes*, in particular, has been straightforwardly borrowed from low-energy physics in the modeling of heavy-ion collisions. One simply assumes a deformed Woods-Saxon geometry for the nucleon density of a given ion in the ground state, and that the nucleons are positioned randomly and independently according to such density in each collision event. The deformed configuration of nucleons is then assumed to possess a random orientation in space at the time of scattering. Classical concepts such as the relative orientation between two colliding ions acquire physical significance, and can be used to perform quantitative predictions. Such predictions have been confirmed experimentally in a highly spectacular manner.

This triggers a number of fundamental questions. Should one really interpret the observations made in high-energy experiments in terms of the same theoretical concepts used in the low-energy phenomenology of nuclei ? Is a semi-classical picture of rotating deformed nucleon configurations justified at high energy, and why does it work so well there ? What is the effect of a strong Lorentz boost on the pattern of correlations that characterize the ground state of nuclei ? These new questions, triggered by recent collider data, open a new direction of research in nuclear physics. The community of high-energy physicists is showing a growing interest in the manifestations of nuclear

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structure at colliders. However, guidance from the low-energy community is needed. Establishing a collaboration between high-energy heavy-ion physics and low-energy nuclear structure physics, would, therefore, help maximize the output of nuclear collision campaigns, and eventually improve our understanding of nuclei across energy scales.

Addressing these questions is also very timely, as they could inspire new high-energy experiments in the near future. The running plans for the heavy-ion programs at both RHIC and LHC have never fully considered the possibility of performing collisions by scanning over a wide variety of stable isotopes. No science case has been put forward to motivate such an endeavour. The RHIC accelerator, while designed to collide essentially all nuclear species, has only collided a handful of them (only 5) over the past 20 years. The LHC accelerator, which is mainly used as a proton collider, has limitations on the type of nuclei it can collide. In over one decade of nuclear experiments, it has only collided ^{208}Pb, with the exception of a short one-day run of ^{129}Xe+^{129}Xe collisions. Clarifying the connection between high-energy observations and low-energy theory may lead to the formulation of questions of fundamental importance in nuclear physics that may be addressed by dedicated collision runs. This would give a strong motivation to collide more nuclei. At RHIC, this may be possible before its shutdown around 2026, while the plan for nuclear collisions at the LHC beyond 2030 has still to be defined, such that this is the right time to gather experts and discuss about these new potential goals.

II. GOALS OF THE PROJECT

We plan to have 4 days of intense discussions among experts (both theorists and experimentalists) from the high- and low-energy nuclear communities to achieve the following goals :

1. Reviewing the variety of deformation effects (static deformation versus shape fluctuations, shape coexistence, shape changes when exciting nuclei, . . .) observed in low-energy experiments, their imprint on observable phenomena in low-energy nuclear structure and reactions, and the types of deformation that are deduced from the data (axial, non-axial, octupolarity, hexadecapolarity, . . .).
2. Reviewing the status of the manifestations of nuclear structure at high-energy colliders, what phenomena are deduced from such data (e.g. deformations, neutron skin, . . .), and how nuclear structure effects are modeled in theoretical calculations.
3. Pointing out important conceptual issues centred around the question : are high-energy and low-energy experiments observing the manifestation of the same thing ?
4. Identifying information from potential new low-energy experiments that may help explain high-energy data (e.g. recent evidence of deformation in collisions of ^{96}Zr and ^{96}Ru nuclei), and, conversely, assessing whether the great flexibility of high-energy experiments may be used to probe phenomena difficult to access via spectroscopic experiments (e.g. the deformations of any stable odd-mass nucleus, imprint of octupole deformations, . . .).
5. Identifying optimal choices of nuclei that, if collided at high energy, would help make progress in our understanding of nuclear phenomenology across energy scales.

List of references

1. STAR Collaboration, *“Azimuthal anisotropy in U+U and Au+Au collisions at RHIC”*, https ://arxiv.org/abs/1505.07812
2. ALICE Collaboration, *“Anisotropic flow in Xe-Xe collisions at* $\sqrt{s_{\rm NN}} = 5.44$ *TeV”*, https ://arxiv.org/abs/1805.01832
3. G. Giacalone, *"A matter of shape : seeing the deformation of atomic nuclei at high-energy colliders"*, https ://tel.archives-ouvertes.fr/tel-03185076
4. G. Giacalone, J. Jia, C. Zhang, *“The impact of nuclear deformation on relativistic heavy-ion collisions : assessing consistency in nuclear physics across energy scales”*, https ://arxiv.org/abs/2105.01638
5. J. Jia, *“Shape of atomic nuclei in heavy ion collisions”*, https ://arxiv.org/abs/2106.08768
6. B. Bally, M. Bender, G. Giacalone, V. Somà, *“Evidence of the triaxial structure of* ^{129}*Xe at the Large Hadron Collider”*, https ://arxiv.org/abs/2108.09578
7. J. Jia, C. Zhang, *“Evidence of quadrupole and octupole deformations in* ^{96}*Zr+*^{96}*Zr and* ^{96}*Ru+*^{96}*Ru collisions at ultra-relativistic energies”*, https ://arxiv.org/abs/2109.01631
8. G. Nijs, W. van der Schee, *“Inferring nuclear structure from heavy isobar collisions using Trajectum”*, https ://arxiv.org/abs/2112.13771

III. PROGRAM

Day 1 – **Tue 20/09/2022** – **Topic :** *Nuclear deformation across energy scales*

09h00 – *Nuclear deformation and energy density functional method*
speaker : Benjamin Bally (ESNT, DPhN, IRFU, CEA Saclay) – `benjamin.bally@cea.fr`

10h45 – *Evidence of nuclear deformation in low-energy experiments : methods, limitations, interpretation*
speaker : David Verney (IJCLab, Orsay) – `david.verney@ijclab.in2p3.fr`

12h15 – 13h30 **Lunch**

13h30 – *Evidence of nuclear deformation in high-energy experiments*
speaker : Giuliano Giacalone (ITP, Heidelberg) – `giacalone@thphys.uni-heidelberg.de`

15h15 – **Discussion :** Are we observing the same things ?

16h30 – **End**

Day 2 – **Wed 21/09/2022** – **Topic :** *Relativistic collisions of isobars : the 2021 breakthrough*

09h00 – *Overview of nuclear deformation and shape coexistence around* ^{96}Zr *and* ^{96}Ru
speaker : Magda Zielinska (DPhN, IRFU, CEA Saclay) – `magda.zielinska@cea.fr`

10h45 – *The isobar collision run at RHIC : a tool for precision studies*
speaker : Jiangyong Jia (Stony Brook & BNL, New York) – `jiangyong.jia@stonybrook.edu`

12h15 – 13h30 **Lunch**

13h30 – *Precision phenomenology of nuclear structure in high-energy isobar collisions*
speaker : Wilke van der Schee (CERN TH) – `wilke.van.der.schee@cern.ch`

15h15 – **Discussion :** The unreasonable effectiveness of intrinsic nuclear shapes in high-energy collisions

16h30 – **End**

Day 3 – Thu 22/09/2022 – Topic : *Nuclear models across energy scales*
09h00 – *The quantum-number projection technique* speaker : Benjamin Bally (ESNT, DPhN, IRFU) – `benjamin.bally@cea.fr` 10h45 – *Effective theories of QCD for nuclei at low energy* speaker : Sören Schlichting (Universität Bielefeld, Bielefeld) – `sschlichting@physik.uni-bielefeld.de`
12h15 – 13h30 **Lunch**
13h30 – *Effective theories of QCD for nuclei at high energy* speaker : François Gelis (IPhT, Saclay) – `francois.gelis@ipht.fr` 15h15 – **Discussion :** Towards a unified description 16h30 – **End**

Day 4 – Fri 23/09/2022 – Topic : *Future perspectives on nuclear studies at high energy*
09h00 – *Opportunities for QGP studies from Bayesian analyses with several ions* speaker : Matthew Luzum (Universidade de São Paulo, São Paulo) – `mluzum@usp.br` 10h45 – *Overview of nuclear parton distribution functions from LHC to EIC* speaker : Petja Paakkinen (University of Jyväskylä) – `petja.k.m.paakkinen@jyu.fi`
12h15 – 13h30 **Lunch**
13h30 – *The nuclear program beyond LHC Run4* speaker : Alexander Kalweit (CERN) – `alexander.philipp.kalweit@cern.ch` 15h15 – **Discussion :** High-energy experiments with several nuclear species 16h30 – **End**