Correlations in Partonic and Hadronic Interactions

P. Achenbach (JLab), H. Avakian (JLab), A. Bacchetta (Pavia U.), M. Battaglieri (INFN), L. El Fassi (MSState), L. Gan (UNCW), L. Gamberg (Penn State Berks), A. Gasparian (NCAT U), K. Joo (UCONN), B. Parsamyan (AANL, INFN Section of Turin and CERN), M. Sargsian (FIU), S. Stepanyan (JLab), A. Vossen (Duke U), E. Voutier (IJCLab)

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Executive Summary

The essential quest of modern nuclear and hadronic physics is the comprehensive understanding of the nucleon and nuclear structure and dynamics in terms of the elementary bricks of matter, the quarks and the gluons or, more generally, the partons. It explores the emergence of collective behaviors, and the correlations between the constituents, within the hadrons and nuclei, shedding light on fundamental aspects of the matter. With a wide array of methodologies and approaches, ranging from state-of-the-art low-energy accelerators to the 12-GeV JLab, and high-energy colliders, the study of hadrons and nuclei unfolds across diverse explorations. This physics program motivates the JLab upgrade to higher energies providing a critical bridge between the 12-GeV JLab and the Electron-Ion Collider (EIC), exploring fascinating and essential aspects of the emergence of hadrons that are needed for complete understanding and yet not covered by either JLab12 or the EIC.

The theoretical and experimental studies offer insights into the dynamics of strongly interacting matter, investigations into transverse partonic structures, hadronization processes, correlations within nuclear mediums, and the spectroscopy of exotic states. The study also encompasses the strong force's binding limits, nuclear shapes, and cosmic implications. A vast array of observables are necessary for harnessing the 12 GeV JLab's capabilities and advancing the potential of the forthcoming EIC. These observables probe the uncharted territory of non-perturbative strong interactions, unraveling intricate relationships among various components within the nuclear framework. Furthermore, the quest to explore physics beyond the standard model is also in the mix through precision measurements using the available nuclear physics facilities.

In this context, we present a proposal for a workshop aimed at addressing these enigmas and forging connections across diverse energy regimes within nuclei. This interdisciplinary endeavor seeks to unravel the role of partonic correlations in shaping hadronic observables, investigating phenomena like short-range correlations in deep inelastic scattering from nuclear targets, understanding the interplay between short-range nuclear structures and medium modifications, and deciphering the intricate forces governing multi-nucleon correlations and emergent collective behaviors. This workshop, embracing the theme of Correlations in Nucleons and Nuclei, will also explore the latest advancements in three-dimensional imaging techniques, revolutionizing our understanding of the nuclear landscape with unprecedented depth and clarity. Moreover, the workshop will delve into the uncharted territories of physics beyond the Standard Model. Leveraging enhanced experimental techniques and high-precision, high-luminosity detectors in the realm of nuclear physics, these endeavors hold the potential to illuminate the mysteries of dark matter and dark force carriers.

Scheduled for September 30 to October 4 in 2024 at the Alikhanyan National Laboratory of Armenia (Formerly the Yerevan Physics Institute), this week-long workshop promises to serve as a melting pot of intellectual exchange and collaboration. Bringing together leading researchers and experts from diverse corners of nuclear physics, it bridges the realms of low-energy and medium-energy nuclear physics communities. Through this collective effort, the workshop aims to amplify international engagement and support, fostering a vibrant atmosphere of innovation that will drive nuclear physics forward into new frontiers.

The Science Motivation

Significant progress has been made in the last couple of decades in understanding the partonic structure of hadrons and nuclei encoded in Generalized Parton Distributions (GPDs) and Transverse Momentum-dependent Distributions (TMDs). The three-dimensional (3-D) imaging of nucleons and nuclei is relevant for studies on fixed target facilities and colliders, such as Large Hadron Collider (LHC) through Drell-Yan-like processes and the forthcoming EIC. The TMD and GPD formalisms provide a framework for 3-D imaging, but various challenges remain in extracting the information from the experimental data. Factorization breakdown, process dependence, operator definitions, and gauge invariance of parton densities add complexity.

Incorporating TMD evolution and combining TMD information with Parton Distribution Functions (PDFs) require addressing uncertainties in non-perturbative parameters and intricate correlations. The multiplicity of GPD components involving quarks and gluons and model-dependent assumptions about GPD functional forms introduce uncertainties, hindering accurate extraction. It is also essential to identify outstanding issues in the calculations of radiative corrections and their integration into data analysis procedures. Examples include treatment of bremsstrahlung beyond peaking approximation, resummation of multiphoton emission, two-photon exchange effects for TMD and GPD measurements, and Coulomb corrections for SIDIS on heavy nuclei. Collaborative efforts between experimentalists and theorists are necessary to address these challenges and extract meaningful insights from experimental data.

In addition to experimental efforts in semi-inclusive DIS (SIDIS), significant progress has been made in recent years to calculate TMD-PDFs inside a nucleon from lattice QCD. One direction is the computation of ratios of TMD x-moments in the transverse space, and the other is a large-momentum effective theory (LaMET) that allows for the extraction of the critical non-perturbative objects as well as the full kinematic dependencies of the 3-D PDFs.

A lot has to be done for a global analysis. Several software frameworks have been developed covering different aspects of TMD and GPD analysis and using different sets of models. But various assumptions in various extraction frameworks require strict procedures for validation. The development of MC event generators is another prerequisite for a global analysis.

Another aspect of current research involves QCD studies in the nuclear medium. Many aspects of research envisioned for the 12 GeV JLab program has direct relevance for LHC physics. Such as the detailed extraction of nuclear PDFs, including $x > 1$ region, understanding the dynamics of nuclear medium modifications of QCD observables, and using tagged processes to study the space-time evolution of quarks to observed hadrons. Recent advanced nuclear SRCs studies at JLab opened new venues for QCD studies that the short-range structure of nuclei may influence. These are the dominance of the proton-neutron SRCs that can result in the flavor dependence of medium modifications of partonic distributions. Understanding such phenomena may be crucial for analyzing the neutrino-nuclei DIS processes aimed at extracting the standard model parameters. The emerging subject of nuclear QCD research is studies of medium modifications of GPDs and TMDs that can exhibit strong sensitivity to the nuclear structure at short distances. Finally, another critical part of the program will be studies of hadronization processes in tagged nuclear SIDIS. The experimental advanced made in recent years in detecting slow hadrons in nuclear fragmentation regions created new opportunities for probing DIS processes at different stages of hadronization at varying kinematics of tagged hadrons. On the other hand, low-energy nuclear physics is focused on the origin of matter and its evolution in the universe. The question addresses the self-organization of nucleons and the emergence of new phenomena. The science is also about the nuclear force, the limits of binding of nucleons to nuclei as you go to the extremes of neutron or proton richness on the chart of nuclides. Studies of nuclear structure in low-energy nuclear physics study the low-lying excited states of nuclei and trace the evolution of nuclear shapes as one goes from stable exotic nuclei either on the proton-rich or the neutron-rich side.

The proton charge radius studies uniquely connect three primary domains in modern physics: nuclear, particle, and atomic physics. This quantity's precise knowledge is central to advancing our understanding of how QCD works in the non-perturbative region. It is also a crucial input to high-precision tests of quantum electrodynamics (QED) based on hydrogen Lamb shift measurements. The discrepancy between determination of proton charge radius using electron scattering and hydrogen Lamb shift measurements and measurements using muonic hydrogen Lamb shift is known as the "proton radius puzzle". It led to intense theoretical efforts to explain this disagreement and triggered the development of new experimental programs worldwide.

The overwhelming evidence for dark matter (DM) in cosmological observations, manifested by its gravitational interactions, has inspired a major experimental effort to uncover its particle nature. Scenarios involving a light, hidden sector dark matter with masses in the MeV-GeV range have garnered much attention. Models with hidden U(1) gauge symmetry are particularly attractive as they can be tested experimentally. Experiments at Jefferson Lab and elsewhere use the expected signatures to search for heavy photons or light dark matter particles in the MeV to GeV mass range. The workshop will discuss the state of the field, the status of the ongoing, planned experiments, and future opportunities.

An essential application of low-energy nuclear physics is in Nuclear Astrophysics, and the attempt to understand the synthesis of the elements in the cosmos and the life-span and energy generation of stars. Nuclear Astrophysics studies involve measurements of reaction cross sections with protons and/or alphas to study energy generation in the evolution of a star's life. Solar temperatures correspond to very low energies in the laboratory and nuclear reactions, and their cross-sections yield important information regarding the likelihood of stars of varying masses and lifetimes producing elements. Nuclear Reactions and cross-sections can also give important information about Coulomb tunneling. These low-lying resonances affect the cross-sections and are crucial in nucleosynthesis simulations in various stellar and cosmic processes. There are also measurements of nuclear-level lifetimes that can be applied to fundamental symmetries, Charge-Parity-Time violation studies, etc. Another application of low-energy nuclear science is the production of isotopes of medical interest. Isotope production is a valuable societal contribution of nuclear science.

This workshop addresses the challenges above, bringing together theorists, phenomenologists, and experimentalists from different sub-fields of the nuclear physics community.

The following list represents several critical questions about the nuclear structure to be addressed by proposed workshop.

1) **3-D structure and QCD**:

- **QCD Factorization issues in hadron production**;
- **Phenomenology of 3-D parton distributions (TMDs and GPDs)**;
- **Study of the QCD evolution of 3-D PDFs**;
- **Gluonic form factors**;
- **Unintegrated and Generalized TMDs**.

2) **Extraction of 3-D PDFs from experimental observables**:

- **Evolution properties of cross sections and azimuthal moments in exclusive and semi-inclusive processes**;
- **Understanding of multiplicities in hard scattering processes and the role of longitudinally polarized photons**;
- **Frameworks for global analysis of 3-D PDFs**;
- **Radiative corrections to hard scattering in exclusive and semi-inclusive processes**.

3) **Partonic structure beyond simple densities**:

- **Medium modifications of distribution and fragmentation functions**;
- **Tagged processes off nuclear targets**;
- **Hard nuclear QCD processes**;
- **PDF medium modifications and short-range nucleon correlations**;
- **Target fragmentation and conditional probabilities**;
- **Higher twist asymmetries in semi-inclusive and hard exclusive processes**;
- **New insights on 3-D PDFs from non-perturbative models**.

4) **Experimental efforts**:

- **Electroproduction with fixed target facilities and the EIC**;
- **Drell-Yan processes, including jets**;
- **Heavy flavor production**;
- **Soft particle production and multi-parton interactions**;

5) **Confinement QCD and fundamental symmetries**:

- **QCD symmetries at low-energy and properties of light pseudoscalar mesons**;
- **Fundamental questions in the Standard Model and beyond**;
- **Experimental study of proton's charge and mass radii**.
- **The ongoing experimental program and future opportunities for the search for dark matter and dark forces**.

6) **Software tools for nuclear physics data analysis**:

- **AI for acquisition. Data reduction, monitoring, reconstruction, and physics reaction identification**;
- **AI for detector data reconstruction, charge particle track identification, particle identification**;
- **AI for data Monte-Carlo simulation. Efficient detector simulations using machine learning methods**.

7) **Physics with low-energy beams of protons and neutrons**:

- **Studies of neutron-rich nuclei from the nuclear fission**;
- **Neutron capture reactions**;
- **New tools to test neutron capture rates and separation of low-energy neutrons and gammas**;
- **Studies of beta decay and gamma-ray spectroscopy**;
- **Medicine intended isotopes production technology creation and development**;
- **Using low-energy proton and neutron beams in field of applied physics**.

Workshop Outcomes

The workshop will explore fundamental interactions underpinning the structure and evolution of matter, collective behaviors, and the correlations between the constituents within the hadrons and nuclei. Additionally, it will delve into various investigative methods available at different facilities.

The primary objectives of the workshop encompass fostering the exchange of ideas across multiple physics communities. This exchange aims to cultivate new collaborative partnerships and facilitate the synchronization of endeavors related to the study of the partonic structure of matter on a global scale. In doing so, the workshop will provide essential support to the physics initiatives undertaken by different facilities, including JLab, low-energy accelerator laboratories, and the potential contributions to the EIC and the upgraded JLab projects.

Furthermore, the workshop will delve into the latest advancements in experimental techniques, both for high-energy and low-energy nuclear physics. This will encompass in-depth discussions not only about the technical aspects but also about the societal impacts and the beneficial applications that arise.