Topical issue on the 3-D structure of the nucleon

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Understanding the structural complexity of protons and neutrons in terms of quarks and gluons is one of the most important challenges facing physics today, a challenge that motivates the newest generation of experimental facilities. In understanding the microscopic structure of the nucleon, for a long time we have relied mainly on two types of physical quantities: its spatial distribution of charge and current probed through elastic lepton-nucleon scattering and described by the elastic form factors (FFs), and its longitudinal-momentum distributions described by the parton distribution functions (PDFs) and probed through deep inelastic scattering experiments (DIS) in which high-energy leptons scatter off individual quarks.

Although FFs and PDFs have provided much information to shape our physical picture of the nucleon, they have similar deficiencies. The FFs contain no dynamical information on the constituents, such as their linear and angular momenta, and the PDFs provide no knowledge of their spatial locations and transverse motion. To address one of the key questions for understanding the structure of the nucleon, namely how its spin is apportioned between the spin of its constituents and their orbital angular momentum we need a new representation able to describe the correlation between their momentum and spatial coordinates. The Wigner distributions, the quantum-mechanical version of the classical phase space distributions, provide this new framework. They inspire a three-dimensional description of the nucleon through the construction of measurable quantities known as generalised parton distributions (GPDs) and transverse-momentum-dependent parton distribution functions (TMD-PDFs). The Wigner distributions are related, via a Fourier transform, to equivalent distributions denoted as generalised transverse-momentum-dependent partonic distributions (GTMDs).

The Wigner distributions depend on the parton longitudinal-momentum fraction x , transverse position $\mathbf{b}_\perp$ and transverse momentum $\mathbf{k}_\perp$. Upon integration over the transverse momentum they give distributions which encode the correlation between the quark/gluon transverse position in the nucleon and its longitudinal momentum, *i.e.* hold information on how the transverse spatial shape of the nucleon changes when probing quarks with different longitudinal momenta. The measurable GPDs are related to these distributions by a simple Fourier transform. Due to the space-momentum correlation information encoded in the GPDs it is possible, through the so-called Ji sum rule, to link a certain combination of GPDs to the total angular momentum of a parton in the nucleon.

The TMD-PDFs directly arise by integrating the Wigner distributions over the transverse spatial position $\mathbf{b}_\perp$ of the partons and are functions of both the longitudinal-momentum fraction x and transverse motion $\mathbf{k}_\perp$ of partons. They offer a momentum tomography of the nucleon complementary to the spatial tomography of GPDs. When adding the spin degree of freedom, TMDs may link the parton spin to the parent proton spin and to the transverse motion, and also the parton transverse momentum to the nucleon spin.

The GPDs are off-diagonal matrix elements of quark and gluon operators between nucleon states and can be accessed in hard exclusive processes such as the lepto-production of a photon or of a meson or in photo-production of a lepton pair. The measured quantities are convolutions of GPDs with hard scattering amplitudes. Taking into account the spin degrees of freedom there are eight leading-order-independent nucleon GPDs. In the diagonal limit the GPDs coincide with the PDFs, while their integration over x gives the nucleon form factors.

The TMD-PDFs can be accessed in semi-inclusive DIS processes (SIDIS, lepton + nucleon $\rightarrow$ lepton + hadron + X) or in Drell-Yan processes (hadron + nucleon $\rightarrow$ lepton pair + X). In SIDIS experimental observables they are combined with transverse-momentum-dependent fragmentation functions (TMD-FFs). When integrated over transverse momentum, these quantities reduce to the standard collinear PDFs and FFs. In all cases, a detailed knowledge of the TMDs must include their dependence on hadronic and parton spin. At leading order in $1/Q$ there are eight

TMD-PDFs and, for spinless or unpolarised final hadrons, two TMD-FFs. Independent information on the TMD-FFs can be obtained from other processes, like the annihilation of e^+ and e^- into pairs of hadrons.

In the last 10–15 years the first measurements of azimuthal asymmetries in SIDIS processes by the HERMES, COMPASS and JLab Collaborations, together with the related theoretical analyses, have definitely revealed the role of the TMDs and allowed the first extraction of some of them. Similarly for the GPDs. Recent results by the Belle and BaBar Collaborations in $e^+e^- \rightarrow h_1 h_2 X$ processes have shown the role of TMD-FFs. Important data are expected soon in the hadron physics community from the Drell-Yan processes at COMPASS2 and RHIC, and from the 12 GeV upgrade of JLab. Great expectations are linked to the planned future Electron Ion Collider (EIC) in USA, which has been included in the recommendations of the 2015 Long Range Plan of the Nuclear Science Advisory Committee. In China an EIC at the HIAF facility has been proposed. In Europe the LHeC project and the AFTER experiment at CERN and the ENC at FAIR are also under discussion.

The QCD framework to analyse data and eventually extract GPDs was laid out in a rigorous way from the very beginning. The QCD properties of the TMDs, in particular their evolution, have been studied more recently, and now a sound and consistent factorisation scheme for TMDs has been developed and the very first applications have been made. We are now in an important time of transition from an exploration phase, which has established the basic experimental evidence and the theoretical framework, to a precision phase for the exploration of the nucleon 3-D structure.

This Topical Issue of *EPJ A* is dedicated to the 3-dimensional structure of the nucleon and addresses all the points outlined above. It presents a logical sequence of contributions, meant to introduce the field from its origin, in all its different aspects, describing its progresses up to the most recent results and the near future plans and expectations.

It starts with a first theoretical contribution on the formal introduction, definition and physical interpretation of TMDs and GPDs, followed by the related experimental investigations and results on TMD-PDFs (from SIDIS processes), GPDs (from $\gamma^* p \rightarrow \gamma p$ exclusive processes) and TMD-FFs (from $e^+e^- \rightarrow h_1 h_2 X$ processes). Two contributions then address the QCD phenomenological study of TMDs with their evolution, factorisation properties, universality and extraction from experimental data. An alternative way of accessing TMDs, through a di-hadron FF is also described. The possible role of TMDs in explaining intriguing spin asymmetries observed since a long time in proton-proton inclusive processes has a dedicated contribution. The GPD phenomenology and extraction, both in exclusive photon and meson production in ep interactions is then reviewed. Nuclear effects in the phenomenological study of GPDs and TMDs are also considered.

The last articles refer to the goal of reconstructing the 3-dimensional structure of the nucleon and to the planning of future investigations. The intrinsic motion of quarks and gluons inside a nucleon is related to the parton orbital angular momentum, which has to be fully formalised and understood. Modelling and imaging of the nucleon structure, possibly combining experimental information into models for the generalised TMDs or the Wigner functions, have to be attempted and pursued. The huge effort which is being dedicated to the proposal and planning of a future Electron Ion Collider in USA, devoted to the study of the nucleon structure, is reviewed. A final contribution summarises, with a wide perspective, the state-of-the-art and the open problems in the study of the 3-dimensional nucleon structure.

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Guest Editors