ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА 2013. Т. 44. ВЫП. 6

SPIN EFFECTS, QCD, AND JEFFERSON LABORATORY WITH 12 GeV ELECTRONS* *A. Prokudin***

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QCD and spin physics are playing important role in our understanding of hadron structure. I will give a short overview of the origin of the hadron structure in QCD and highlight modern understanding of the subject. Jefferson Laboratory is undergoing an upgrade that will increase the energy of electron beam up to 12 GeV. JLab is one of the leading facilities in nuclear-physics studies, and once operational in 2015 JLab 12 will be crucial for future of nuclear physics. I will briefly discuss future studies in four experimental halls of Jefferson Lab.

PACS: 12.38.-t; 13.60.-r; 01.52.+r

INTRODUCTION

With the advent of quark parton model and Bjorken scaling in the 1960s, the theoretical and experimental studies of the hadron structure became an important part of nuclear physics agenda throughout the world.

Indeed, by studying the proton we understand the underlying nature of Quantum Chromodynamics (QCD) — the theory that describes the hadron as bound system of quarks and gluons. Asymptotic freedom of QCD allows one to study the structure of the proton at small distances by varying, for example, the virtuality Q^2 of the incident photon in deep inelastic scattering.

Protons are used as a discovery tool in several facilities including Large Hadron Collider, and precise knowledge of its structure becomes an essential ingredient of the discovery potential of such facilities.

A number of experimental facilities study hadron structure. In particular, experimental studies including spin degrees of freedom are important. HERMES (DESY), COMPASS (CERN), RHIC (BNL), JLAB pioneered these studies. Fragmentation of quarks into colorless hadrons is being studied at BELLE (KEK) and BaBar (SLAC).

^{*}Summary of two plenary talks at 20th International Symposium on Spin Physics (SPIN2012), JINR, Dubna, September 17–22, 2012.

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Jefferson Lab is accomplishing the 12 GeV upgrade project [1] which is due to be operational in 2015 and will enable us to look with an unprecedented precision at the nucleon structure in the region where valence quarks are dominant in the nucleon's wave function. Such a precision is needed for better understanding of the nature of the nucleon as a many body relativistic system in terms of internal dynamics.

Looking forward in future, one would like to study the dynamical origin of quarks and gluons in the region where sea quarks and gluons start the dominating nucleon's wave function. This can be achieved by constructing a new facility — polarized Electron Ion Collider (EIC) [1–3] with variable center-of-mass energy $\sqrt{s} \sim 20-70$ GeV and luminosity $\sim 10^{34}$ cm⁻² · s⁻¹ that would be uniquely suited to address several outstanding questions of quantum chromodynamics (QCD) and the microscopic structure of hadrons and nuclei. In Fig. 1*, kinematical ranges of JLab and EIC are compared as functions of Bjorken-*x* and Q^2 .



Fig. 1. a) Kinematic coverage in x and Q^2 in ep-scattering experiments with JLab 12 GeV and a medium-energy EIC of CM energy $\sqrt{s} = 20$ and 70 GeV. The minimum momentum transfer here was chosen as $Q_{\min}^2 = 2 \text{ GeV}^2$. b) Components of the nucleon wave function probed in scattering experiments at different x

^{*}The plot is from [2]. See [2] for details on nuclear physics opportunities at a mediumenergy EIC.

Spin and polarization measurements have been playing a crucial role in our understanding of the nucleon's properties throughout many decades. Since famous «spin crisis» [4,5] of the 1980s, we learned that quark spins do not account for the full spin of the nucleon. Given the later observation that the contribution of the gluon spin to that of the nucleon could be rather small [6], one concludes that a static picture of the nucleon with quarks in s states does not account for the complexity of the parton dynamics. Orbital motion of quarks and gluons must play an important role in our understanding of the nucleon's structure.

In recent years, the description of the nucleon's spin and momentum structure given in terms of partonic substructure has led to rapid development of QCD theory. In hard semi-inclusive processes involving noncollinear dynamics these



Fig. 2. Wigner distribution and relation to Generalized Parton Distributions (GPDs) and Transverse Momentum-Dependent Distributions (TMDs). Parton distributions and form factors can be related to GPDs and TMDs

structures are described by transverse momentum parton (TMD) distributions and fragmentation functions (TMD-PDFs and TMD-FFs, or jointly TMDs). TMDs depend both on Bjorken-x and transverse motion of partons k_T thus making them sensitive to orbital angular momentum of quarks and gluons. The transverse degrees of freedom also play a crucial role in high-energy collider experiments through the so-called Efremov–Teryaev–Qiu–Sterman matrix elements [7–9], i.e., multiparton correlations.

In more exclusive processes such as deep virtual Compton scattering or exclusive vector meson electroproduction one encounters the so-called generalized parton distributions (GPDs) that, by Fourier transform over transferred momentum t, depend, additionally to the usual Bjorken-x, on the position of partons in coordinate space.

There is a general belief that QCD is the underlying theory that describes nucleon structure by quark and gluon degrees of freedom, yet we lack a detailed understanding of these objects from first principles. Nevertheless, a new framework has emerged in the past ten years which is suitable for a comprehensive and quantitative approach to the description of nucleon structure [10–12]. In this framework, our knowledge of nucleon structure is encoded in the Wigner distributions of the constituents, a quantum mechanical concept, introduced in 1932 [13]. From the Wigner distributions, see Fig. 2 (the plot is from [1]), a natural interpretation of measured observables is provided through the construction of its integrated «slices» or projections which are in fact generalized parton distributions and transverse momentum-dependent distributions.

1. QCD EVOLUTION AND SPIN EFFECTS

The nucleon in QCD represents a dynamical system of fascinating complexity. In the rest frame, it may be viewed as an ensemble of interacting color fields, coupled in an intricate way to the vacuum fluctuations that govern the effective dynamics at distances ~ 1 fm. A complementary description emerges when one considers a nucleon that moves fast, with a momentum much larger than that of the typical vacuum fluctuations. In this limit, the nucleon's color fields can be projected on elementary quanta with point-particle characteristics (partons), and the nucleon becomes a many-body system of quarks and gluons. As such, it can be described by a wave function, in much the same way as many-body systems, in QCD the number of point-like constituents is not fixed, as they constantly undergo creation/annihilation processes mediated by QCD interactions, reflecting the essentially relativistic nature of the dynamics.

Accordingly, the QCD evolution that governs content of the nucleon is interpreted differently in different frames. If one considers evolution of parton densities with energy, then the appropriate frame is the so-called dipole frame in which virtual photon fluctuates into a color dipole (quark-antiquark pair), and this dipole interacts with target nucleon. Corresponding evolution is governed by Balitsky–Fadin–Kuraev–Lipatov (BFKL) evolution equation [14, 15]. The nonlinear regime of this evolution is described via Balitsky equation [16], Balitsky–Kovchegov equation in large N_c limit (BK) [16–18], and JIMWLK evolution equations [19–21]. Subsequently, the system will pass from dilute to dense regime of QCD and to predicted but yet to be observed regime of saturation of gluon densities. Geometrical scaling of structure functions at low-x observed at HERA (DESY) [22] is an indication of this regime to take place. Note that the resolution scale that is defined by the virtuality of the photon Q^2 is fixed in this case.

DGLAP equation describes the evolution of densities as a function of Q^2 at the given energy scale or rapidity y. Infinite momentum frame (the frame in which the target nucleon moves with infinite momentum and thus along light-cone) is suitable for interpretation in this case. Fluctuations of incident photon into quark-antiquark pairs are suppressed, and the photon probes «frozen» partonic states inside of the nucleon. Gluon radiation in the available phase space produces multiple quark, antiquark, and gluon states that are responsible for the growth of parton densities in low-x region. Note that the resolution scale Q^2 increases, and thus, the distance at which the states are probed and the «effective size» of partons diminishes. See Fig. 3 for representation of different evolutions.

Evolution of transverse momentum-dependent distributions is an emerging subject of nuclear theory. The details of TMD factorization were derived in [23]



Fig. 3. Evolution of parton densities can be considered either in energy/rapidity y (BFKL, BK, and JIMWLK equations) or in virtuality of the photon Q^2 (DGLAP equation). The system will go from dilute towards dense regime and undergo transition to saturation region which is characterized by saturation scale $Q_s^2(y)$

and successfully implemented in [24, 25]. It was demonstrated that TMD evolution [26, 27] appropriately takes into account the behavior of experimental data. One of the particularities of the TMD evolution consists in the fact that unlike usual collinear distributions, where only collinear singularities are present, TMDs exhibit rapidity divergences along with collinear ones. Thus evolution is more intricate and describes not only how the form of distribution changes in terms of Bjorken-*x*, but also how the width is changed in momentum space k_T . It was shown in [23] that TMD formalism in fact corresponds to the well-known Collins–Soper–Sterman (CSS) resummation [28, 29].

Evolution of twist-3 matrix elements was also recently worked out in [30–33] and the obtained results by three groups employing different methods agree with each other [34]. The CSS resummation was also applied to spin-dependent quantities in [35]. Along with advances in TMD evolution implementation, these results will lead to complete NLO knowledge of TMDs and twist-3 matrix elements which are sources of spin asymmetries observed in different experiments in SIDIS, DY, and e^+e^- annihilation.

Many new formulations of TMD factorization [36], in particular, in the framework of Soft Collinear Effective Theory (SCET), have emerged recently [37–39]. General relations between those different formulations and comparison of resulting evolution equations will be particularly interesting in future.

2. PUZZLES OF SPIN

The «spin crisis» [4,5] of the 1980s was not the last one to challenge our theoretical understanding of hadron structure and QCD. There existed a simple and intuitive prediction [40] for the so-called A_N asymmetry in $pp^{\uparrow} \leftarrow \pi X$ to be negligible. Famous measurement of FNAL-E704 [41] proved this prediction to be wrong. Not only the asymmetry was large at relatively low energy $\sqrt{s} = 19.4$ GeV [41], but it remained so at much higher energies at RHIC up to $\sqrt{s} = 200$ GeV [42,43].

For processes such as single inclusive hadron production in proton-proton collisions, $p^{\uparrow}p \rightarrow hX$, which exhibits only one characteristic hard scale, the transverse momentum $P_{h\perp}^2 \gg \Lambda_{\rm QCD}^2$ of the produced hadron, one could describe the SSAs in terms of twist-three quark-gluon correlation functions [7–9,44–46]. One of the well-known examples is the so-called Efremov-Teryaev-Qiu-Sterman (ETQS) function. Phenomenological extractions were performed in different papers [47,48].

On the other hand, for the process such as SemiInclusive Deep Inelastic Scattering (SIDIS) which possesses two characteristic scales, the photon's virtuality Q and $P_{h\perp}$ of the produced hadron, one can use a TMD factorization formalism [23,49,50] in the region $\Lambda^2_{\rm QCD} < P^2_{h\perp} \ll Q^2$ and describe asymmetries with TMD functions. Extractions of TMDs have been performed using experimental data at fixed scales [51–57].

These two formalisms are closely related to each other, and have been shown to be equivalent in the overlap region where both can be applied [58–60].

Recently it has been found that there exists «sign puzzle» or «sign mismatch» between these two mechanisms [61]. Yet another puzzle is to challenge our understanding of QCD. Some preliminary explanations are already available [62], however, in order to achieve the complete coherent picture we will have to work for more years to come.

3. JEFFERSON LAB WITH 12 GeV ELECTRONS

The continuous Electron Beam Accelerator Facility (CEBAF) of Jefferson Lab is being upgraded and will provide electron beam of 11 GeV to three experimental Halls A, B, and C and 12 GeV electron beam to Hall D (Fig. 4). CEBAF will also maintain capability of providing lower energy beam to the Halls.



Fig. 4. CEBAF of Jefferson Lab and four experimental Halls

Jefferson Lab itself is a multipurpose laboratory for nuclear studies. Its scientific activity spans from material studies, lasers, medical imaging, accelerator research and development to a vast fundamental experimental and theoretical research in nuclear physics and searches beyond the Standard Model.

The 6 GeV scientific program of Jefferson Lab successfully finished in 2012. Upgrade is designed to build on existing facility: vast majority of accelerator

and experimental equipment have continued use. The completion of the 12 GeV upgrade of CEBAF was ranked the highest priority in the 2007 NSAC Long Range Plan. The scope of the project includes doubling the accelerator beam energy, construction of a new experimental Hall (D) and beamline, an upgrading to existing experimental Halls (A, B, C).

The main goals of Jefferson Lab experimental program are

— the physical origins of quark confinement (meson and baryon spectroscopy);

— the spin and flavor structure of the proton and neutron (PDFs, GPDs, TMDs);

— the quark structure of nuclei;

- probe potential new physics through high precision tests of the Standard Model.

In order to define the scientific program, Jefferson Lab Program Advisory Committee gathered 8 times for a period 2006–2011, and, as a result, 52 experiments were approved and 15 experiments were conditionally approved. White Paper [1] was submitted for NSAC subcommittee.

Hall D will be exploring the origin of confinement by studying exotic mesons. In order to study mesonic system, the photon beam of energy up to 9 GeV will be produced. GlueX experiment being constructed in Hall D will reach the mass range up to 3.5 GeV and will offer insight into the role of gluon self-interactions and the nature of confinement. Detailed spectroscopic information from experiment, coupled with the guidance of new Lattice QCD results, offers an exciting and unique opportunity to explore mechanisms of confinement.

HERMES and COMPASS, together with the 6 GeV Jefferson Lab have demonstrated the feasibility of studying transverse momentum-dependent distributions (TMDs) as well as Deeply Virtual Compton Scattering (DVCS) measurements that offer access to generalized parton distributions (GPDs). The extended kinematic range and new experimental hardware associated with the Jefferson Lab 12 GeV. Upgrade will provide access to these fundamental underlying distributions and reveal new aspects of nucleon structure. It is quite possible that much of the remaining nucleon spin will be found in the orbital motion of the valence quarks. Halls A, B, and C have 18 approved experiments dedicated to studies of TMDs and GPDs. Hall B CLAS detector will have hermetic design which is important for exclusive reaction measurements. Future data from the corresponding experiments in Hall B with CLAS 12, in Hall A with Super-BigBite and with SoLID complemented with precision SIDIS experiments in Hall C will allow a far more precise determination of TMDs, GPDs and ordinary PDFs to a much greater precision if compared to modern knowledge of these distributions.

The electric and magnetic form factors of the nucleon describe the distribution of charge and currents, and are probed in elastic electron–nucleon scattering.

JLab 12 will continue studying form factors and reach much higher values of Q^2 up to 10–11 GeV².

Eleven experiments in Halls A, B, and C are dedicated to studies of hadrons and cold nuclear matter. One of the outstanding questions is whether the nuclear medium alters the structure of bound nucleons and, if it does, how.

It is believed that the Standard Model as a theory of fundamental interactions is incomplete. Thus it is important to pursue precision tests and searches beyond the Standard Model. JLab 12 with its high luminosity and accuracy is certainly one of the key payers in this search. A very precise SM prediction of running of $\sin^2 \theta_W$, where θ_W is the weak mixing angle, allows for a precision test of the Standard Model. High luminosity of JLab 12 up to 10^{38} cm⁻² · s⁻¹ is certainly one of the key ingredients for successful high precision measurement.

The Qweak experiment has completed data collection to measure $A_{\rm PV}$ in elastic electron-proton scattering at low $Q^2 \ 0.021 \ {\rm GeV}^2$ in Hall C [63]. The weak charge of the proton $Q_W^p = 1-4\sin^2\theta_W$ is suppressed, which allows for search of beyond the Standard Model contributions. This suppression and the expected precision of the Qweak measurement of Q_W^p of 4%, gives a sensitivity to new parity-violating physics up to 2 TeV. Parity violation experiments require polarized electrons, which are routinely produced already at CEBAF, and many of the electroproduction experiments planned, e.g., DVCS experiments, also require polarized electrons. MOLLER experiment and SoLID will continue PV measurements at JLab 12.

Heavy photons, called A's, are new hypothesized massive vector bosons that have a small coupling to electrically charged matter, including electrons. The existence of A' can explain discrepancy between measured and predicted value of anomalous magnetic moment of the muon [64]. Moreover, signals of astrophysical positron excess [65] suggest a massive neutral vector boson A' with low mass ($M_{A'} < 1$ GeV). APEX (Hall A), HPS (Hall B), and Dark Light (FEL) will search for A' in MeV–GeV mass range.

Concluding, we might say that JLab 12 will provide decades of extremely interesting reseach and measurements in nuclear physics and beyond. In no way, the information presented here accounts completely for all plans of JLab 12, interested reader is referred to the White paper [1] for more information.

Acknowledgements. The author thanks Hugh Montgomery for careful reading of the manuscript and Anatoly Radyushkin for useful discussions. Authored by a Jefferson Science Associate, LLC under U.S. DOE Contract No. DE-AC05-06OR23177.

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