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Experimental physics at JLab: Where confinement meets asymptotic freedom

E. Cisbani

INFN Rome, Sanità group and Italian National Institute of Health - Rome, Italy

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Summary. — Physics and technological highlights of the current and near future activities of the Italian JLab12 collaboration working at the Jefferson National Accelerator Facility are shortly summarized.

PACS 12.38.-t – Quantum chromodynamics.
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1. – Introduction

The Thomas Jefferson National Accelerator Facility (JLAB) is one of the most important nuclear physics laboratory in the world, where QCD is extensively investigated by means of a high-intensity, longitudinally polarized, 6 GeV electron beam of the Continuous Electron Beam Accelerator Facility (CEBAF); the beam is delivered simultaneously in 3 experimental halls. Within the next two years, the beam energy will be doubled, a new hall will be available for real photon physics and the equipments of the existing halls will be upgraded or renewed.

With this update JLAB will enter the 12 GeV era and will offer substantial opportunities to improve our understanding of the nature of the strong interaction in the hadrons, nucleus and sub-nucleon (quark and gluon) scales, at low energies as well as small distances, where QCD shows its remarkable peculiarities of confinement and asymptotic freedom, respectively. Moreover, the high luminosity achievable in the JLAB experiments and the excellent control of the beam parameters give access to the measurement of the parity-violating processes of the electroweak interaction, and therefore they permit the test of the Standard Model, at low energies, with high accuracy.

In this scientific context operates the Italian JLab12 Collaboration; it involves 50 Italian researchers, funded primarily by the third INFN Scientific Commission. The collaboration activities cover large part of the JLAB scientific program; they are mainly devoted to the experimental studies on the structure and dynamics of the nucleon, the origin of the confinement and the role of the gluon in the hadronic spectrum, the inner behavior of (hyper)nuclei and the measurement of the nuclear/nucleon properties by the electron scattering, both electromagnetic and the parity violating weak interaction.

2. – Physics

2˙1. *Nucleon structure*. – The current picture of the nucleon structure consists of three quantities [1]: the nucleon form factors, the parton distribution functions (PDF), and the generalized parton distribution functions (GPD). All of them can be derived from the phase-space parton distribution Wigner functions reviewed in [2]; according to the present understanding the Wigner functions cannot be measured directly.

Form factors, PDFs and GPDs express fundamental properties of the nucleon and its internal dynamics, such as the origin of the spin and the orbital angular momentum (OAM) of its constituents, and therefore of the complex aspects of Quantum Chromodynamics (QCD).

New data from elastic electron-proton scattering experiments performed at JLAB around 2000, clearly demonstrated, for the first time, a firm negative slope of the proton electric to magnetic form factor ratio *versus* the momentum transfer Q^2 [3], in contrast to the existing results obtained by the traditional Rosenbluth separation method; a possible explanation of this discrepancy is the inadequacy of the single-photon exchange mechanism in describing the elastic scattering. New experiments at JLAB have been approved to measure, by different techniques, the neutron and proton electromagnetic form factors at high Q^2, up to $\sim 15\,\text{GeV}^2$ where quark OAM (unknown and expected to provide a significant contribution to the total spin of the nucleon), may play a noticeable role, perturbative QCD can provide reliable predictions [4] and different models have quite different behaviors.

PDFs are mainly accessed by the measurement of the cross section asymmetries on polarized beam and/or target, in DIS (inclusive and semi inclusive, SIDIS) and, in Drell-Yan processes (assuming some sort of PDF universality is valid). Of the 8 leading twist PDFs, five are transverse-momentum–dependent (TMD) distribution functions accounting for the probability of the quark with transverse momentum (k_T) and a given polarization in a nucleon with defined polarization relative to the direction of the nucleon. Most of them are related, rather directly, to the quark OAM. The remaining 3 PDFs are the well-known unpolarized distribution $f_1(x;Q)$, the rather known helicity $g_1(x;Q)$ and the recently measured transversity $h_1(x;Q)$ being x the momentum fraction of the quark relative to the momentum of the nucleon and Q the energy scale (momentum transfer in DIS). Investigation of the spin related PDF and TMDs will greatly improve with the new JLAB beam in terms of larger statistics, flavor decomposition and extended phase space, especially toward the high-x valence region (unique feature offered by JLAB), where sea partons effects are marginal and lattice QCD may be predictable. In this direction a pretty large program on nucleon PDF, both on neutron and proton, will interest the JLAB activities [5].

The most recent advance in the theoretical description of the nucleon structure, that gathered considerable experimental attention, are the GPDs, which somehow connect form factors and PDFs and are measurable in hard exclusive processes. Experimental knowledge of GPD's is still modest; the Deep Virtual Compton Scattering (DVCS) process is the main tools of investigation and will be largely used also at JLAB [6].

2˙2. *Hadron spectroscopy*. – The gluon role in the determination of the hadron spectrum is of fundamental importance in the understanding of the QCD. The interaction of quarks in terms of gluon flux tube (string) implies the possibility of existence of mesons with *exotic* quantum numbers due to the excitation of the force mediators; in these cases the gluonic degree of freedom seems to contribute explicitly to the color singlet. Lattice QCD predicts the lowest exotics states (hybrids) in the range of 1.4–3.0 GeV [7], which optimally matches the energy range that will be available at JLab in 2014. Search of exotics meson states is going on in different laboratories especially by hadron probes with spin 0 like pions and kaons; the use of photon beam is expected to favor the creation of exotic states due to the higher possible number of final states related to the spin 1 of the probe. A comprehensive study of the meson spectrum will be carried on in Hall B [8] using the CLAS12 detector extended by a Forward Tagger (mentioned later) that will permit to run experiments with quasi-real photons.

The hadron spectroscopy in general is the primary source of information in questions like: the origin of the quark and gluon confinement and therefore the origin of the hadron formation, the origin of the hadron masses, the effective degrees of freedom when asymptotic freedom is not applicable.

2˙3. *Parity violation.* – The longitudinally polarized, very stable, and intense CEBAF electron beam permits accurate and precise measurements of the parity violating electron scattering (PVES) asymmetry of the weak interaction, directly related to the Weinberg mixing angle θ_W, as well as the weak currents in the nucleons and nuclei; while the latter gives access to properties of the hadrons largely suppressed in electromagnetic interaction, the measurement of θ_W probes the validity of the Standard Model.

The most precise determination of the quark s contribution to the nucleon form factors has been obtained by a series of PVES experiments at JLAB [9]; in 2012 the first direct determination of the neutron skin (difference of the radii of the neutron and proton distributions) in Lead has been published by the PREX experiment [10], probably one of the most challenging experiment at JLAB. New, more precise, PVES measurements are scheduled to run after the 12 GeV upgrade.

2˙4. *Nuclear structure and dynamics by electron scattering.* – The above studies covers a large part of the JLAB physics program; however investigation on *traditional* nuclear and hypernuclear physics aspects will continue after the 12 GeV upgrade: relativistic effects and short range correlation in nuclei, electrodisintegration of the deuteron, color transparency, as well as the reaction mechanism in electron scattering off nucleons and nuclei [11].

3. – Technological development

This extended physics program requires new detectors and equipment able to permit the full exploitation of the high energy beam (up to 11 GeV), its intense current (up to 100 μA) and large longitudinal polarization (up to $\sim 90\%$). The JLab12 collaboration, is therefore promoting quite a few new devices, covering basically all main component of a scattering experiment: beam, target and detectors; they are shorty introduced in this section.

3˙1. *Forward photon tagger.* – The new Hall D with its GlueX [12] detector will be dedicated to real photon physics and therefore the JLAB laboratory of election for hadron spectroscopy. However limited resolution and particle identification will be complemented by a new photon forward tagger that is under development to extend the CLAS12 detector capability in HallB. The device, shown in the left of fig. 1 will consist of a calorimeter, a scintillator hodoscope and a MicroMegas tracker that will detects position (angle)

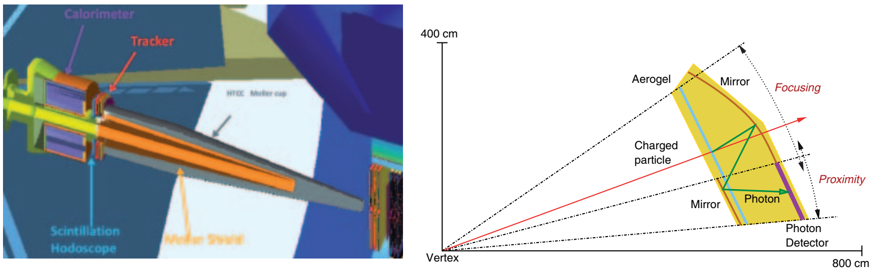

Fig. 1. – Left: 3D view of the forward photon tagger. Right: conceptual side view of the CLAS12 aerogel RICH with two overlapping focusing and proximity optics that minimize the photon detector size; only one Cherenkov photon is shown.

and energy of the forward scattered electrons thus providing energy and polarization of the quasi-real radiated photon. High-intensity quasi-real photon beam will be therefore available for the comprehensive physics program on meson spectroscopy mentioned above.

3˙2. *Hydrogen-deuteride polarized target*. – One of the most interesting, and challenging, polarized target proposed for the next generation experiments at JLAB is the solid, frozen spin, hydrogen-deuteride neutron and proton target previously used at LEGS on photon beam [13], which may provide longitudinal and transverse polarization up to 75% on H and 40% on D, with extremely long relaxation time. Signal to background ratio of the HD target is largely superior to conventional polarized target, however stability of the target under relatively intense electron beam has still to be demonstrated.

3˙3. *RICH for CLAS12*. – The baseline CLAS12 detector lacks for an effective π/K/p identification in the $\sim$ 3–8 GeV/c; to overcome this limitation and permit a extensive program of TMDs measurements toward a flavor decomposition, a challenging large area RICH detector is under development [14]. The new RICH is based on high-quality aerogel radiator and an hybrid optics (proximity and focusing, see the right drawing of fig. 1) with double-crossing of the aerogel by part of the Cherenkov photons; this complex geometrical configuration will minimize the expensive photon detector area which will likely consist of a regular array of multianode photomultipliers or silicon photomultipliers. Intense R&D study is in progress to prove the feasibility of the detector at acceptable cost.

3˙4. *GEM/SiD trackers*. – Relevant part of the physics program on form factors at high Q^2 and neutron PDF's measurement in Hall A needs a new spectrometer able to operate in high luminosity environment and with moderately high acceptance at forward angles. Such a spectrometer is under development and will include a large area tracker based on gas chambers in GEM technology sitting behind a 2 T·m dipole magnet. Two small silicon detector planes upstream to the dipole, will significantly extend the effective length of the measured trajectory, thus improving remarkably the track reconstruction accuracy.

The GEM tracker [15] is in advanced development and will provide a hit spatial resolution at the level of 70 μm, capability to support large background flux (up to 250 MHz/cm^2 photons and 160 kHz/cm^2 charged particles), transverse active area of $\sim 40 \times 150$ cm^2. The tracker will consist of up to 6 GEM chambers, each chamber made by three adjacent triple GEM 40×50 cm^2 modules, with minimal dead area.

4. – Conclusion

The above-presented physics and technological programs are a partial excerpt of the activities carried on at JLAB by the JLab12 collaboration with the purpose of improving our understanding of the strong interaction and its currently accepted theory: the QCD. The approaches are diversified and reflect the great complexity of the QCD interaction and its consequences on hadrons. JLAB, with the 12 GeV upgrade, its high-intensity, longitudinally polarized and stable beam, combined to new complementary equipments and dedicated detectors, is going to be one of the most advanced facilities to carry on extensively and comprehensively the QCD investigation and other relevant studies on testing the standard model and the existence of dark matter.

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