IL NUOVO CIMENTO Vol. 34 C, N. 6 Novembre-Dicembre 2011
DOI 10.1393/ncc/i2011-11081-x

Colloquia: IFAE 2011

The Jefferson Lab program at 12 GeV

P. Rossi
INFN, Laboratori Nazionali di Frascati - Frascati, Italy

(ricevuto il 29 Luglio 2011; pubblicato online il 7 Dicembre 2011)

Summary. — CEBAF at Jefferson Lab (USA) is an electron accelerator devoted to basic research in hadronic physics which will be upgraded in energy to 12 GeV by 2013. An overview of the experimental program is presented.

PACS `13.60.Le` – Meson production.
PACS `13.40.Gp` – Electromagnetic form factors.
PACS `14.20.Gk` – Baryon resonances ($S = C = B = 0$).

1. – The Jefferson Laboratory

CEBAF is a 5-pass, recirculating continuous-wave (cw) electron linac operating at 6 GeV. It is based on superconducting cavities and capable of delivering a "continuous" (pulses spaced of 2 ns), highly polarized beam of present maximum energy of 6 GeV to three experimental Halls A, B, C. The design features and excellent performance of the accelerator made it possible to plan an upgrade in energy without substantially altering the construction scheme of the accelerator. The scope of the upgrade project includes doubling the present energy of the accelerator, major enhancements to the equipment in the existing experimental areas, and the construction of a new experimental area (Hall D) with a new detector where the highest energy of 12 GeV will be delivered. The three existing areas will be able to use any multiple of 2.2 GeV (or a lower energy), up to 11 GeV. The project will be completed by the year 2013 and the commissioning of the experimental Halls will be extended until the end of 2015. The research program motivating the upgrade is focused on several hot topics in hadronic physics [1]: the study of the nucleon tomography and quark orbital momentum, accessible through the measurement of the Generalized Parton Distribution (GPDs) and the Transverse Momentum dependent parton Distribution functions (TMDs); the exploration of the high-Q^2 behavior of elastic and transition form factors which are sensitive to the high-momentum components of the valence quark wave functions; the study of the quark hadronization in the nuclear medium; the hadron spectroscopy and the study of hybrid mesons, which involve excited states of the glue, to explore the nature of quark confinement. Also precision tests of the Standard Model through parity-violating deep inelastic and Møller scattering experiments are included in the experimental program.

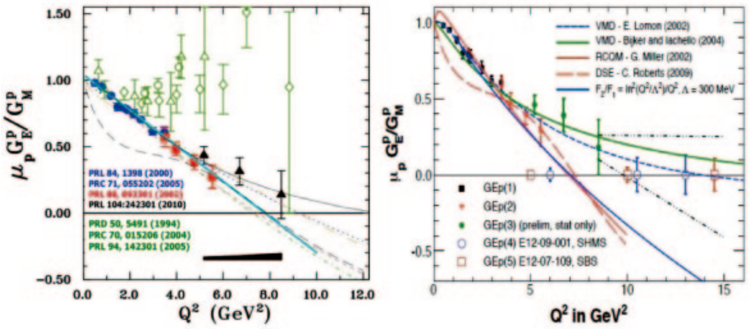

Fig. 1. – (Colour on-line) Left: the ratio $\mu_p G_E^p/G_M^p$ from polarization experiments [4] (blue full circles and triangles, red full squares, black full triangles) compararred with Rosenbluth results [3,5] (open green circles, diamonds and triangles). Right: the ratio $\mu_p G_E^p/G_M^p$ for the new approved polarization experiments at 12 GeV [6] (open red squares and open blue circles).

2. – A glance to the program at 12 GeV

2·1. *Nucleon form factors.* – The nucleon electromagnetic form factors encode information about its complex internal structure. They describe the spatial distributions of electric charge and current inside the nucleon and thus they are among the most basic observables of the nucleon. In spite of being under investigation by more than fifty years, nucleon form factors are far from being fully exploited. In fact, for more than thirty years it has been believed that the ratio of the electric to magnetic space-like form factor of the proton G_E^p/G_M^p, as obtained with the Rosenbluth technique, was constant and approximately equal to the magnetic moment of the proton μ_p [2,3]. The advent of electron beams with high luminosity and polarization, combined with new polarized targets, recoil polarimeters, and large-acceptance detectors, led to different results of nucleon form factors. At Jefferson Lab, measuremets of the proton electromagnetic form factors using the recoil polarization technique [4] have shown a dramatically different picture: the ratio G_E^p/G_M^p is monotonically decreasing with increasing Q^2 in disagreement with scaling. The results from polarization transfer and Rosenbluth extraction of G_E^p/G_M^p are compared in fig. 1 (left). The discrepancy between the two results is significant over a wide range of Q^2. Intensive discussion of various possible explanations followed and two-photon exchange (TPE) corrections received a great deal of attention as a possible explanation. There is an active program at JLab to determine if TPE corrections do in fact fully explain the discrepancy, and to map out their impact on both the cross section and polarization observables. The impact of these new experimental results was magnified by the parallel developments on the theory side, in particular several attempts to learn more about the internal sub-structure of the nucleon within the framework of GPDs. The increased electron energies available after the 12 GeV upgrade, coupled with further improvements in the experimental equipment, will enable a dramatic extension of the existing form factor measurements both for proton and neutron [6,7], doubling or tripling the Q^2 range of most of the available measurements (see fig. 1 (right) for the proton G_E^p/G_M^p future measurements). This will provide valuable constraints on GPDs at very high Q^2 values. In addition, also the study of transition region between the perturbative and non-perturbative QCD description will be possible making evaluation of nucleon models more reliable.

TABLE I. – *Leading-twist transverse-momentum–dependent parton distribution functions.*

N/q	U	L	T
U	$\mathbf{f_1}$		$h_1^\perp$
L		$\mathbf{g_1}$	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	$\mathbf{h_1}$ $h_{1T}^\perp$

2˙2. *Nucleon tomography.* – Having access to a 3-dimensional (3D) image of the nucleon opens up completely new insights into the complex structure of the nucleon. The 3D structure of the nucleon is encoded in the TMDs describing partonic distributions for different combinations of spins of partons and nucleons, and GPDs describing spatial distributions of partons. The role playing by correlations between partonic transverse momentum and spin is crucial for our understanding of the spin structure of the nucleon in terms of the quark and gluon degrees of freedom of QCD. Such spin-orbit correlations are described by transverse-momentum–dependent parton distribution and fragmentation functions, which are currently under intense investigation both from the experimental and theoretical side. These functions give rise to interesting single-spin phenomena in semi-inclusive lepton- and hadron-induced processes. TMDs are probability densities for finding a polarized/unpolarized parton with a longitudinal momentum fraction x and transverse momentum $\vec{k}_T$ in a polarized/unpolarized nucleon, see table I, where U, L, and T stand for transitions of unpolarized, longitudinally polarized, and transversely polarized nucleons (rows), and correspondingly for quarks (columns). The diagonal elements of the table (f_1, g_1, h_1) are the partonic momentum, longitudinal spin and transverse spin distribution functions. Similar quantities arise in the hadronization process. Two fundamental mechanisms have been identified leading to single spin asymmetries (SSAs) in hard processes: the Sivers mechanism [8-12], which generates an asymmetry in the distribution of quarks due to orbital motion of partons and the Collins mechanism [11, 13], which generates an asymmetry during the hadronization of quarks. In the area of deep inelastic semi-inclusive scattering (SIDIS) and hard exclusive scattering, the JLab 12 GeV program will be completely dominant for the foreseeable future. In particular, several proposals were approved by JLab PAC to study TMDs and GPDs in different processes involving semi-inclusive and exclusive pion and kaon production in Hall B with the CLAS12 detector using unpolarized and polarized hydrogen and deuteron targets.

For a longitudinally polarized target the only azimuthal asymmetry arising at leading order is the $\sin 2\phi$ moment [14-16], involving the Collins fragmentation function $H_1^\perp$ and the Ralston-Soper-Mulders-Tangerman (RSMT) distribution function $h_{1L}^\perp$ [17, 14], describing the transverse polarization of quarks in a longitudinally polarized proton.

Measurements of SSAs in SIDIS kinematics have been done at Jefferson Lab using a 5.7 GeV electron beam and the CEBAF Large Acceptance Spectrometer (CLAS). The $\sin 2\phi$ moment $A_{UL}^{\sin 2\phi}$ as a function of x is plotted in fig. 2 (empty triangles) [18]. The band shows the existing theory predictions with uncertainties due to the Collins function [20, 21]. The kinematic dependence of the SSA for π^+ from the CLAS data is roughly consistent with these predictions. The interpretation of the π^- data, which tends to have SSAs with a sign opposite to expectations, may require accounting for additional contributions. By the way, current statistical errors for π^-, and in particular

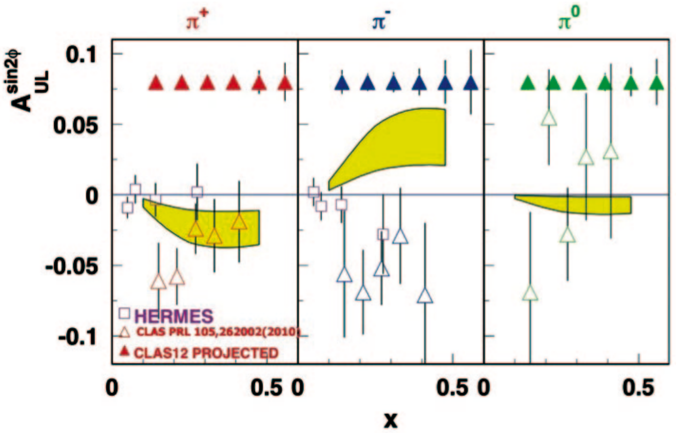

Fig. 2. – The CLAS measured x-dependence of the longitudinal target SSA $A_{UL}^{\sin 2\phi}$(empty triangles) [18]. The squares show the existing $A_{UL}^{\sin 2\phi}$ measurement from HERMES [19]. The band shows the existing theory predictions with uncertainties due to the Collins function [20,21]. The full triangles show the projected sensitivity of results for the 12 GeV experiment [22].

for π^0, are large and do not allow strong conclusions from the measured SSAs. Data at 6 GeV with ten times higher statistics have been collected in 2009 (experiment E05-133) and an experiment at 12 GeV has been approved (E12-07-107) [22] allowing statistically significant measurement of the $\sin 2\phi$ moment. The projected sensitivity of results for the experiment E12-07-107 are shown as full triangles in the upper part of fig. 2.

2˙3. *Meson spectroscopy and search for exotics.* – Understanding quark and gluon confinement in Quantum Chromodynamics is one of the main issues in hadronic physics. Theoretical conjectures, now strengthened by lattice QCD simulations, indicate that the most spectacular new prediction of QCD, quark confinement, occurs through the formation of a string-like flux tube between quarks. This conclusion can be tested by determining the spectrum of the gluonic excitations of mesons (referred to as hybrid mesons). Photon beams are expected to be particularly favorable for the production of the exotic hybrids. The reason is that the photon sometimes behaves as a virtual vector meson with total quark spin $S = 1$. When the flux tube in this $S = 1$ system is excited, both ordinary and exotic J^{PC} are possible. The interest lies in the mass range from $1.0\,\mathrm{GeV}/c^2$ up to about $2.7\,\mathrm{GeV}/c^2$, the region where light quark hybrids are expected to exist. Incident photon energies of 9 GeV are sufficient to access this mass range, and are achievable starting with 12 GeV electrons. The highest energy of 12 GeV will be available in a new experimental area, the Hall D. This area will be devoted to the photoproduction of exotic mesons using a linearly polarized photon beam, with an average degree of linear polarization in the peak of 40%, and the GlueX large-acceptance detector. An alternative possibility to measure photoproduction reactions at high energy is to use electro-production at very small electron scattering angles, of the order of few degrees or smaller. In this kinematics, the four-momentum transfer, Q^2, is very small and the virtual photon which is produced can be considered as quasi-real. The virtual photons associated with small-angle electrons have an intrinsic and sizeable degree of linear polarization that can be established on an event-by-event basis by measuring the electron energy and scattering plane. To exploit this possibility, a low-Q^2 tagging facility or *forward tagger* has been proposed for CLAS12 in Hall B and the related physics program has been approved by the PAC [23]. The facility will detect electrons scattered between 2.5 and 4.5 degrees and in the energy range between 0.5 GeV and 4.5 GeV. The corresponding virtual photons will be in the energy range 6.5–10.5 GeV with a degree of linear polarization varying between 10% and 65%. The forward tagger will consist of an electromagnetic calorimeter to identify the electrons and measure their energy, a veto counter to distinguish electrons from photons and a tracker to measure the electron angles precisely, therefore determine the linear polarization of the photon.

3. – Conclusions

The JLab Upgrade at 12 GeV has well-defined physics goals of fundamental importance for the future of hadron physics. Accelerator and equipment upgrades are underway and the accelerator commissioning is scheduled for 2013.

REFERENCES

[1] `http://hallaweb.jlab.org/12GeV`; `http://www.jlab.org/Hall-B/clas12_tdr.pdf`; `http://www.jlab.org/Hall-C/upgrade`; `http://www.jlab.org/Hall-D`.

[2] Walker R. C. *et al.*, *Phys. Rev. D*, **49** (1994) 5671.

[3] Andivahis R. C. *et al.*, *Phys. Rev. D*, **50** (1994) 5491.

[4] Jones M. K. *et al.*, *Phys. Rev. Lett.*, **84** (2000) 1398; Gayou O. *et al.*, *Phys. Rev. C*, **64** (2001) 038202; *Phys. Rev. Lett.*, **88** (2002) 092301; Punjabi V. *et al.*, *Phys. Rev. C*, **71** (2005) 055202; Puckett A. J. R. *et al.*, *Phys. Rev. Lett.*, **104** (2010) 242301.

[5] Christy M. E. *et al.*, *Phys. Rev. C*, **70** (2004) 15206; Quattan I. A. *et al.*, *Phys. Rev. Lett.*, **94** (2005) 142301.

[6] *Proton form factor measurements:* `http://hallaweb.jlab.org/collab/PAC/PAC32/PR12-07-108-GMP.pdf`; `http://hallaweb.jlab.org/collab/PAC/PAC32/PR12-07-109-Ratio.pdf`.

[7] *Neutron form factor measurements:* `http://www.jlab.org/exp_prog/proposals/07/PR12-07-104.pdf`; `http://www.jlab.org/exp_prog/proposals/09/PR12-09-006.pdf`; `http://hallaweb.jlab.org/collab/PAC/PAC34/PR-09-019-gmn.pdf`; `http://hallaweb.jlab.org/collab/PAC/PAC34/PR-09-016-gen.pdf`.

[8] Sivers D. W., *Phys. Rev. D*, **43** (1991) 261.

[9] Anselmino M. and Murgia F., *Phys. Lett. B*, **442** (1998) 470.

[10] Brodsky S. J. and Hwang D. S., *Phys. Lett. B*, **530** (2002) 99.

[11] Collins J. C., *Phys. Lett. B*, **536** (2002) 43.

[12] Ji X. D. and Yuan F., *Phys. Lett. B*, **543** (2002) 66.

[13] Mulders P. J. and Tangerman R. D., *Phys. Lett. B*, **461** (1996) 197.

[14] Mulders P. J. and Tangerman R. D., *Nucl. Phys. B*, **461** (1996) 197.

[15] Kotzinian A., *Nucl. Phys. B*, **441** (1995) 234.

[16] Kotzinian A. and Mulders P. J., *Phys. Rev. D*, **54** (1996) 1229.

[17] Ralston J. P. and Soper D. E., *Nucl. Phys. B*, **152** (1979) 109.

[18] Avakian H. *et al.*, *Phys. Rev. Lett.*, **105** (2010) 262002.

[19] Airapetian A. *et al.*, *Phys. Rev. Lett.*, **94** (2005) 012002.

[20] Avakian H. *et al.*, *Phys. Rev. D*, **77** (2008) 014023.

[21] Efremov A. V., Goeke K. and Schweitzer P., *Phys. Rev. D*, **67** (2003) 114014.

[22] `http://www.jlab.org/exp_prog/proposals/07/PR12-07-107.pdf`.

[23] `http://www.jlab.org/exp_prog/proposals/11/PR12-11-005.pdf`.