Letter-of-Intent to PAC46

Physics with Positron Beams at Jefferson Lab 12 GeV

John Arrington[1], Marco Battaglieri[2], Jan Bernauer[3],
Volker Burkert[4], Volker Burkert[4], Pierre Chatagnon[6],
Latifa Elouadrhiri[4], François-Xavier Girod[4], Joseph Grames[4],
Luca Marsicano[2], Carlos Muñoz Camacho[6], Silvia Niccolai[6],
Axel Schmidt[3], Mike Tiefenback[4], Eric Voutier[6], Rong Wang[6],
Shenying Zhao[6]

[1] *Argonne National Laboratory*
9700 S. Cass Avenue, Argonne, Illinois 60439, USA

[2] *Istituto Nazionale di Fisica Nucleare*
Sezione di Genova
Via Dodecaneso, 33 - 16146 Genova, Italia

[3] *Laboratory for Nuclear Science*
Massachusetts Institute of Technology
77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA

[4] *Thomas Jefferson National Accelerator Facility*
12000 Jefferson Avenue, Newport News, Virginia 23606, USA

[5] *Institut de Recherche sur les Lois Fondamentales de l'Univers*
Commissariat à l'Energie Atomique, Université Paris-Saclay
91191 Gif-sur-Yvette, France

[6] *Institut de Physique Nucléaire*
Université Paris-Sud & Paris-Saclay
15 rue Georges Clémenceau, 91406 Orsay cedex, France

Letter-of-Intent as of 18 May 2018

Contact persons: grames@jlab.org, voutier@ipno.in2p3.fr

Abstract

Table of contents

1 Introduction

Quantum Electrodynamics (QED) is one of the most powerful quantum physics theories. The highly accurate predictive power of this theory allows not only to investigate numerous physics phenomena at the macroscopic, atomic, nuclear, and partonic scales, but also to test the validity of the Standard Model. Therefore, QED promotes electrons and positrons as unique physics probes, as demonstrated worldwide over decades of scientific research at different laboratories.

Both from the projectile and target point of views, spin appears nowadays as the finest tool for the study of the intimate structure of matter. Recent examples from the experimental physics program developed at the Thomas Jefferson National Accelerator Facility (JLab) include: the measurement of polarization observables in elastic electron scattering off the nucleon [Jon00,Gay02,Puc10], that established the unexpected magnitude and behaviour of the proton electric form factor at high momentum transfer (see [Pun15] for a review); the experimental evidence, in the production of real photons from a polarized electron beam interacting with unpolarized protons, of a strong sensitivity to the orientation of the longitudinal polarization of the electron beam [Ste01], that opened the investigation of the 3-dimensional partonic structure of nucleons and nuclei via the generalized parton distributions [Mul94] measured through the deeply virtual Compton scattering [Ji97,Rad97]; the achievement of a unique parity violation experimental program [Arm05,Ani06,And13] accessing the smallest ever measured polarized beam asymmetries ($\sim 10^{-7}$), which provided the first determination of the weak charge of the proton [And13] and allowed for stringent tests of the Standard Model at the TeV mass-scale [You06]; etc. Undoubtably, polarization became an important capability and a mandatory property of the current and next accelerator generation.

The combination of the QED predictive power and the fineness of the spin probe led to a large but yet limited variety of impressive physics results. Adding to this tool-kit charge symmetry properties in terms of polarized positron beams will provide a more complete and accurate picture of the physics at play, independently of the size of the scale involved. In the context of the experimental study of the structure of hadronic matter worked-out at JLab, the electromagnetic interaction dominates lepton-hadron reactions and there is no stringent difference between the physics information obtained from the scattering of electrons or positrons off an hadronic target. However, every time a reaction process is a conspiracy of more than one elementary mechanism, the comparison between electron and positron scatterings allows us to isolate the quantum interference between these mechanisms. This is of particular interest for studying limitations of the one-photon exchange Born approximation in elastic and inelastic scatterings [Gui03]. It is also essential for the experimental determination of the generalized parton distributions where the interference between the known Bethe-Heitler process and the unknown deeply virtual Compton scattering requires polarized and unpolarized electron and positron beams for a model independent extraction [Vou14]. Such polarized lepton beams also provide the ability to test the existence of a new physics beyond the frontiers of the Standard Model. ... More text about C_{3q}

(?) and dark matter search.

The production of high-quality polarized positron beams relevant to these many applications remains however a highly difficult task that, until recently, was feasible only at large scale accelerator facilities. Relying on the most recent advances in high polarization and high intensity electron sources [Add10], the PEPPo (Polarized Electrons for Polarized Positrons) technique [Abb16], demonstrated at the injector of the Continuous Electron Beam Accelerator Facility (CEBAF), provides a novel and widely accessible approach based on the production, within a tungsten target, of polarized e^+e^- pairs from the circularly polarized bremsstrahlung radiation of a low energy highly polarized electron beam. As opposed to other schemes operating at GeV lepton beam energies [Sok64,Omo06,Ale08], the operation of the PEPPo technique requires only energies above the pair-production threshold and is teherefore ideally suited for a polarized positron beam at CEBAF.

This document...

2 Physics motivations

2.1 Elastic lepton scattering

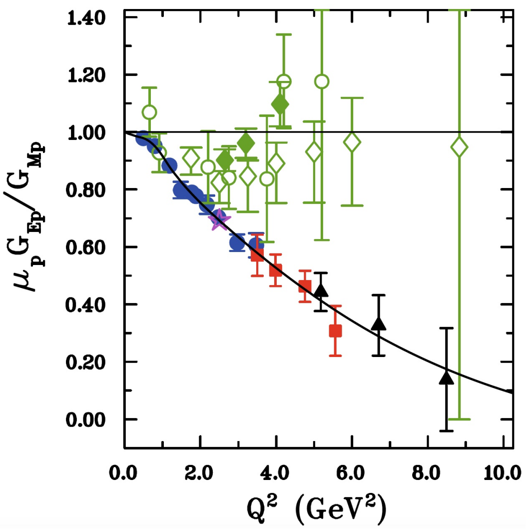

Figure 1. Rosenbluth (green symbols) and polarization transfer (blue, red, and black symbols) experimental data about the ratio between the electric and magnetic form factor of the proton, together with an empirical fit of polarization data [Pun15].

The measurement of the electric form factor of the nucleon (G_E) at high momentum transfer, in the perspective of the experimental assessment of perturbative Quantum Chromodynamics (QCD) scaling laws [Bro81], motivated an intense experimental effort targeted by the advent of high energy continuous polarized electron beams. Indeed, the polarization observables technique [Akh74,Arn81] is expected to be more sensitive to G_E than the cross section method relying on a Rosenbluth separation [Ros50]. However, the strong disagreement between the results of these two experimental methods (Fig. 1) came as a real surprise. Following the very first measurements of polarization transfer observables in the $^1\mathrm{H}(\vec{e},e\vec{p})$ reaction [Jon00], the validity of the Born approximation for the description of the elastic scattering of electrons off protons was questionned. The eventual importance of higher orders in the α-development of the electromagnetic interaction was suggested [Gui03] as an hypothesis to reconciliate cross section and polarization transfer experimental data, while making impossible a model-independent experimental determination of the nucleon electromagnetic form factors via solely electron scattering.

Considering the possible existence of second order contributions to the electromagnetic current, the so-called 2γ-exchange, the eN-interaction is no longer characterized by 2 real form factors but by 3 generalized complex form factors

$$\widetilde{G}_M = e\,G_M + \delta\widetilde{G}_M\,, \quad \widetilde{G}_E = e\,G_E + \delta\widetilde{G}_E\,, \quad \widetilde{F}_3 = \delta\widetilde{F}_3\,, \tag{1}$$

where e represents the lepton beam charge. These expressions involve up to 8 unknown real quantities that should be recovered from experiments [Rek04]. Considering unpolarized leptons, the non point-like structure of the nucleon can be expressed by the reduced cross section

$$\begin{aligned}\sigma_R^e = \tau G_M^2 + \epsilon G_E^2 + 2e\,\tau G_M\,\Re e\left[\delta\widetilde{G}_M\right] \\ + 2e\,\epsilon\,G_E\,\Re e\left[\delta\widetilde{G}_E\right] + e\,\sqrt{\tau(1-\epsilon^2)(1+\tau)}G_M\,\Re e\left[\delta\widetilde{F}_3\right]\end{aligned} \tag{2}$$

where the charge dependent contributions denote the additional contributions from the 2γ-exchange mechanisms. The variable ϵ characterizing, in the 1γ-exchange approximation, the virtual photon polarization writes

$$\epsilon = \left[1 - 2\frac{\vec{q}\cdot\vec{q}}{Q^2}\tan^2\left(\frac{\theta_e}{2}\right)\right]^{-1} \tag{3}$$

where θ_e is the electron scattering angle, $q \equiv (\vec{q},\omega)$ is the virtual photon with four-mometum transfer $Q^2{=}-q\cdot q$, and $\tau{=}Q^2/4M^2$ with M representing the nucleon mass. In absence of lepton beams of opposite charge, the Rosenbluth method, consisting in the measurement of the reduced cross section at different ϵ-values while keeping constant Q^2, allows the determination of a combination of 1γ and 2γ electromagnetic form factors and requires consequently some model-dependent input to separate further the electric and magnetic form factors.

The transfer of the longitudinal polarization of a lepton beam via the elastic scattering off a nucleon provides 2 additionnal and different linear combinations of the same physics quantities in the form of the transverse (P_t^e) and longitudinal (P_l^e) polarization components of the nucleon

$$
\begin{aligned}
\sigma_R^e P_t^e =& -\lambda\sqrt{2\epsilon\tau(1-\epsilon)}\left(G_E G_M + e\, G_E \Re e\left[\delta\widetilde{G}_M\right]\right. \qquad (4)\\
& \left. + e\, G_M \Re e\left[\delta\widetilde{G}_E\right] + e\sqrt{\frac{1+\epsilon}{1-\epsilon}}G_E \Re e\left[\delta\widetilde{F}_3\right]\right)\\
\sigma_R^e P_l^e =& \,\lambda\,\tau\sqrt{1-\epsilon^2}\left(G_M^2 + e\left[2+\sqrt{\frac{1+\tau}{\tau(1-\epsilon)}}\right]G_M \Re e\left[\delta\widetilde{F}_3\right]\right). \qquad (5)
\end{aligned}
$$

where λ is the lepton beam polarization. The combination of polarized and unpolarized beam observables of elastic electron scattering involve up to 6 unknown real quantities, requiring at least 6 independent experimental observables. Therefore, taking into account 2γ-exchange mechanisms electron beams only can no longer provide an experimental alone determination of the electromagnetic form factors of the nucleon. However, comparing polarized electron and positron beams, one can separate the charge dependent and independent contributions of experimental observables i.e. separate the 1γ and 2γ form factors. For instance,

$$
\begin{aligned}
\frac{\sigma_R^+ + \sigma_R^-}{2} =& \,\tau G_M^2 + \epsilon G_E^2 \qquad (6)\\
\frac{\sigma_R^+ - \sigma_R^-}{2} =& \,2\tau G_M \,\Re e\left[\delta\widetilde{G}_M\right] \qquad (7)\\
& + 2\,\epsilon\, G_E\, \Re e\left[\delta\widetilde{G}_E\right] + \sqrt{\tau(1-\epsilon^2)(1+\tau)}G_M\, \Re e\left[\delta\widetilde{F}_3\right]
\end{aligned}
$$

and similarly for polarized observables. Consequently, the measurement of polarized and unpolarized elastic scattering of both electrons and positrons provide the necessary data for a model independent determination of the nucleon electromagnetic form factors.

2.2 Deep inelastic lepton scattering

The understanding of the partonic structure and dynamics of hadronic matter is the major goal of modern Nuclear Physics. The availability of high intensity continuous polarized electron beams with high energy together with performant detector systems at different facilities is providing today an unprecedented but still limited insight into this problem. Similarly to the elastic scattering case, the combination of measurements with polarized electrons and polarized positrons in the deep inelastic regime will allow to obtain unique experimental observables enabling a strict model-independent interpretation.

The generalized parton distribution (GPD) framework [Mul94] constitutes the most appealling and advanced parameterization of the hadron structure. It encodes the intimate structure of matter in terms of quarks and gluons and unifies within the same framework electromagnetic form factors, parton distributions, and the description of the nucleon spin (see [Die03,Bel05] for a review). GPDs can be interpreted as the probability to find at a given trans-

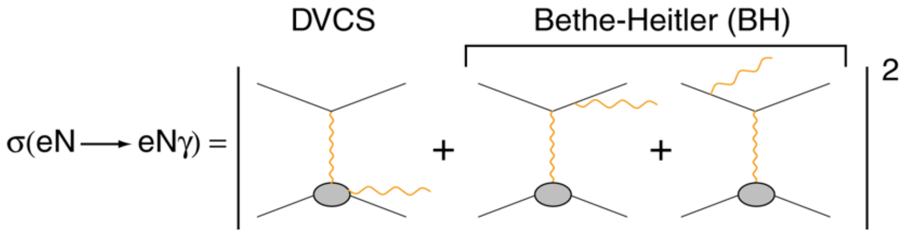

Figure 2. Lowest order QED amplitude of the electroproduction of real photons off nucleons(nuclei).

verse position a parton carrying a certain fraction of the longitudinal momentum of the nucleon. The combination of longitudinal and transverse degrees of freedom is responsible for the richness of this universal framework.

GPDs are involved in any deep process and are preferentially accessed in hard lepto-production of real photons i.e. deeply virtual Compton scattering (DVCS). This process competes with the known Bethe-Heitler (BH) reaction [Bet34] where real photons are emitted from initial or final leptons instead of the probed hadronic state (Fig. 2). The lepton beam charge and polarization dependence of the $eN(A)\gamma$ cross section off nucleons(nuclei) writes [Die09]

$$\sigma^{e}_{\lambda 0} = \sigma_{BH} + \sigma_{DVCS} + \lambda\,\widetilde{\sigma}_{DVCS} + e\,\sigma_{INT} + e\lambda\,\widetilde{\sigma}_{INT} \qquad (8)$$

where the index INT denotes the interference contribution to the cross section originating from the quantum interference of the BH and DVCS processes. Polarized electron scattering provide the experimental observables

$$\sigma^{-}_{00} = \frac{\sigma^{-}_{+0} + \sigma^{-}_{-0}}{2} = \sigma_{BH} + \sigma_{DVCS} - \sigma_{INT}\,, \qquad (9)$$

$$^{1}\Delta^{-}_{\lambda 0} = \frac{\sigma^{-}_{+0} - \sigma^{-}_{-0}}{2} = \lambda\,\left[\widetilde{\sigma}_{DVCS} - \widetilde{\sigma}_{INT}\right] \qquad (10)$$

involving unseparated combinations of the unknwon INT and $DVCS$ reaction amplitudes. The comparison between polarized electron and polarized positron reactions provides the additional observables

$$\Delta\sigma_{00} = \frac{\sigma^{+}_{00} - \sigma^{-}_{00}}{2} = \sigma_{INT} \qquad (11)$$

$$^{2}\Delta_{\lambda 0} = \frac{^{1}\Delta^{+}_{\lambda 0} - {}^{1}\Delta^{-}_{\lambda 0}}{2} = \lambda\,\widetilde{\sigma}_{INT} \qquad (12)$$

which isolate the interference amplitude. Consequently, measuring real photon lepto-production off nucleons(nuclei) with opposite charge polarized leptons allows to separate the four unknown contributions to the $eN(A)\gamma$ cross section.
For a spin s hadron, one can define $(2s+1)^2$ parton helicity conserving and chiral even elementary GPDs that can be accessed through DVCS. They appear within the reaction amplitudes in the form of unseparated linear and bi-linear

expresssion. Their separation requires additional observables that can be obtained considering polarized targets (S) [Bel02]. The full lepton beam charge and polarizations dependence of the $eN(A)\gamma$ cross section can be written generically [Die09]

$$\begin{aligned} \sigma^e_{\lambda S} =& \, \sigma^e_{\lambda 0} \\ & + S \left[\lambda \, \Delta\sigma_{BH} + \lambda \, \Delta\sigma_{DVCS} + \Delta\widetilde{\sigma}_{DVCS} + e\lambda \, \Delta\sigma_{INT} + e \, \Delta\widetilde{\sigma}_{INT} \right] . \end{aligned} \tag{13}$$

where $\Delta\sigma_{BH}$ is the known sensitivity of the BH process to the target polarization and the remaining terms feature four new combinations of the nucleon GPDs to be isolated. Polarized electron scattering provides the combinations

$${}^1\Delta\sigma^-_{0S} = \frac{\sigma^-_{0+} - \sigma^-_{0-}}{2} = S \, \left[\Delta\widetilde{\sigma}_{DVCS} - \Delta\widetilde{\sigma}_{INT} \right] \tag{14}$$

$${}^2\Delta^-_{\lambda S} = \frac{{}^1\Delta^-_{\lambda +} - {}^1\Delta^-_{\lambda -}}{2} = S \, \lambda \, \left[\Delta\sigma_{BH} + \Delta\sigma_{DVCS} - \Delta\sigma_{INT} \right] \tag{15}$$

and the comparison between polarized electrons and positrons yields

$${}^2\Delta\sigma_{0S} = \frac{{}^1\Delta\sigma^+_{0S} - {}^1\Delta\sigma^-_{0S}}{2} = S \, \Delta\widetilde{\sigma}_{INT} \tag{16}$$

$${}^3\Delta_{\lambda S} = \frac{{}^2\Delta^+_{\lambda S} - {}^2\Delta^-_{\lambda S}}{2} = S \, \lambda \, \Delta\sigma_{INT} \tag{17}$$

which once again isolates the interference contribution and allows to separate the four reaction amplitudes of interest.
Polarized positron beams then appear as a mandatory complement to polarized electron beams for a model independent determination of nucleons and nuclei GPDs.

2.3 Test of the Standard Model

3 Polarized positron beam at CEBAF

4 TPE-CLAS12

Spokesperons:

5 TPE-SBS

Spokesperons:

6 pDVCS-CLAS12

Spokesperons:

7 nDVCS-CLAS12

Spokesperons:

8 pDVCS-SHMS

Spokesperons:

9 Dark photon search

Spokesperons:

10 Conclusions

References

[Abb16] (PEPPo Collaboration) D. Abbott *et al.* Phys. Rev. Lett. **116** (2016) 214801.

[Add10] P. Adderley *et al.* Phys. Rev. Acc. Beams **13** (2010) 010101.

[Akh74] A.I. Akhiezer, M.P. Rekalo, Sov. J. Part. Nucl. **4** (1974) 277.

[Ale08] G. Alexander *et al.* Phys. Rev. Lett. **108** (2008) 210801.

[And13] (Q_{weak} Collaboration) D. Androić *et al.* Phys. Rev. Lett. **111** (2013) 141803.

[Ani06] (HAPPEX Collaboration) K.A. Aniol *et al.* Phys. Rev. Lett. **96** (2006) 022003;
(HAPPEX Collaboration) K.A. Aniol *et al.* Phys. Lett. B **635** (2006) 275;
(HAPPEX Collaboration) A. Acha *et al.* Phys. Rev. Lett. **98** (2007) 032301.

[Arn81] R. Arnold, C. Carlson, F. Gross, Phys. Rev. C **23** (1981) 363.

[Arm05] (G0 Collaboration) D.S Amstrong *et al.* Phys. Rev. Lett. **95** (2005) 092001;
(G0 Collaboration) D. Androić *et al.* Phys. Rev. Lett. **104** (2010) 012001;
(G0 Collaboration) D. Androić *et al.* Phys. Rev. Lett. **107** (2011) 022501;
(G0 Collaboration) D. Androić *et al.* Phys. Rev. Lett. **108** (2012) 122002.

[Bel02] A.V. Belitsky, D. Müller, A. Kirchner, Nucl. Phys.B **629** (2002) 323.

[Bel05] A.V. Belitsky, A.V. Radyushkin, Phys. Rep. **418** (2005) 1.

[Bet34] H.A. Bethe, W. Heitler, Proc. Roy. Soc. London A **146** (1934) 83.

[Bro81] S.J. Brodsky, G.P. Lepage, Phys. Rev. D **22** (1981) 2157.

[Die03] M. Diehl, Phys. Rep. **388** (2003) 41.

[Die09] M. Diehl, *Cont. to the CLAS12 European Workshop* (Genova (Italy), 2009).

[Gay02] (Hall A Collaboration) O. Gayou *et al.* Phys. Rev. Lett. **88** (2002) 092301.

[Gui03] P.A.M. Guichon and M. Vanderhaeghen, Phys. Rev. Lett. **91** (2003) 142303.

[Ji97] X. Ji, Phys. Rev. Lett. **78** (1997) 610.

[Jon00] (Hall A Collaboration) M.K. Jones *et al.* Phys. Rev. Lett. **84** (2000) 1398.

[Mul94] D. Müller, D. Robaschick, B. Geyer, F.M. Dittes, J. Hořejši, Fortschr. Phys. **42** (1994) 101.

[Omo06] T. Omori et al., Phys. Rev. Lett. **96** (2006) 114801.

[Puc10] (Hall A Collaboration) A.J.R. Puckett *et al.* Phys. Rev. Lett. **104** (2010) 242301.

[Pun15] V. Punjabi, C.F. Perdrisat, M.K. Jones, E.J. Brash and C.E. Carlson, Eur. Phys. J. A **51** (2015) 79.

[Rad97] A.V. Radyushkin, Phys. Rev. **D 56** (1997) 5524.

[Rek04] M.P. Rekalo, E. Tomasi-Gustafsson, Nucl. Phys. A **742** (2004) 322.

[Ros50] M.N. Rosenbluth, Phys. Rev. **79** (1950) 615.

[Sok64] A.A. Sokolov and I.M. Ternov, Sov. Phys. Dokl. **8** (1964) 1203.

[Ste01] (CLAS Collaboration) S. Stepanyan *et al.* Phys. Rev. Lett. **87** (2001) 182002.

[Vou14] E. Voutier, Nuclear Theory **33** (Heron Press, Sofia) (2014) 142; arXiv:1412.1249.

[You06] R.D. Young, J. Roche, R.D. Carlini, A.W. Thomas, Phys. Rev. Lett. **97** (2006) 102002.