Flavor Decomposition of Nucleon Form Factors

Bogdan Wojtsekhowski¹

¹Thomas Jefferson National Accelerator Facility
Newport News, Virginia 23606 USA
(Dated: January 8, 2020)

The nucleon form factors provide fundamental knowledge about the strong interaction. We review the flavor composition of the nucleon form factors and focus on an analysis of the possible impact of the $s$-quark contribution. A future experiment is presented to measure the strange form factor at large momentum transfer.

PACS numbers: 14.20.Dh, 13.40.Gp

High $Q^2$ nucleon form factor experiments

Nucleon structure investigation using high energy electron scattering has been a successful field where many discoveries have been made since the 1955 observation of the proton size [1]. The status of current knowledge of the nucleon electromagnetic form factors is reviewed in Ref. [2]. To a large extent, this success is due to the dominance of the one-photon exchange mechanism of electron scattering as proposed in the original theory [3].

The most decisive studies of the partonic structure of the nucleon could be performed when the dominant part of the wave function is a 3-quark Fock state. This requires large momentum transfer. By the early 90s, the data sets at large $Q^2$ for the proton and the neutron have been found to be in agreement in the Dipole fit, $G_{Dipole} = (1 + Q^2/0.71[GeV^2])^{-2}$, see Ref. [4]. The SLAC experimental data [5] on the proton Dirac form factor $F^p_1$ at $Q^2$ above 10 GeV$^2$ have been found to be in fair agreement with the scaling prediction [6] based on perturbative QCD: $F^p_1 \propto Q^{-4}$, where $Q^2$ is the negative four-momentum transfer squared.

New development began with a precision experiment [7] which made a very productive realization of a double polarization method suggested in Refs. [8]. The double polarization method has large sensitivity to the typically small electric form factor due to the interference nature of the double polarization asymmetry. It is also less insensitive to the two-photon exchange contributions, which complicates the Rosenbluth method.

The experimental results from Jefferson Laboratory [9] are shown in Fig.1 (left). The ratio of the proton Pauli form factor $F^p_2$ and the Dirac form factor $F^p_1$ have been found to be in disagreement with the scaling law $F^p_2/F^p_1 \propto 1/Q^2$ (which requires the $G^p_E$ to be proportional to $G^p_M$ for large momentum transfer, $\tau >> 1$) suggested in Ref. [6].

The data for $\mu_p G^p_E/G^p_M$ revealed an unexpected reduction with $Q^2$, which also means that $F^p_1$ and $Q^2 F^p_2$ for the proton have different $Q^2$ dependencies. The origin of the scaling prediction violation has been attributed to an effect of the quark orbital momentum (so-called “logarithmic scaling”) which provides a very efficient fit of the data for a proton in a wide range of the momentum transfer above 1 GeV$^2$ [10].
The measurement of the proton to the neutron cross section ratio in the quasi-elastic nucleon knockout from the deuteron was used in JLab’s precision experiment of the neutron magnetic form factor for $Q^2$ up to 4 GeV$^2$ [11]. With the latest JLab experiment on the neutron electric form factor [12], the data on all four nucleon form factors have become available in the $Q^2$ region of 3-quark dominance.

The first analysis of these new data for the flavor contributions to the nucleon form factors was reported in Ref. [13]. The $Q^2 F_2/F_1$ for individual flavors as a function of $Q^2$ shown in Fig. 2 (left) does not have any sign of the saturation expected in the case of approaching the pQCD regime. Analysis shows a large unexpected reduction in the relative size of the $d$-quark contribution to the $F_p^2$ form factor, which drops by a factor of 3 when $Q^2$ increases from 1 to 3.4 GeV$^2$. A similar result was found in an advanced analysis [14] with the GPD-based fits of the form factors, see Fig. 2 (right).

The observed reduction of the $d$-quark contribution to $F_p^2$ naturally explains the JLab result for the momentum dependence of $F_p^2/F_1$ without the effect of the quark orbital momentum (at least at $Q^2$ below 3.4 GeV$^2$). The origin of the observed $F_d^1/F_u^1$ reduction with the increase of $Q^2$ is a subject of significant interest as it could be the most direct evidence of the di-quark correlations in a nucleon as proposed in Ref. [20].

The flavor decomposition leads to two simple conclusions:

- The contributions of the $u$-quarks and $d$-quark to the magnetic and electric form factors of the proton all have different $Q^2$ dependencies.
- The contribution of the $d$-quark to the $F_p^1$ form factor at $Q^2=3.4$ GeV$^2$ is three times less than the contribution of the $u$-quarks (corrected for the number of quarks and their charge).

The second observation suggests that the probability of proton survival after the absorption of a massive virtual photon is much higher when the photon interacts with a $u$-quark, which is doubly represented in the proton. This may be interpreted as an indication of an important role of the $u$-$u$ correlation. It is well known that the correlation usually enhances the high momentum component and the interaction cross section. The relatively weak $d$-quark contribution to the $F_p^1$ indicates a suppression of the $u$-$d$ correlation or a mutual cancellation of different types of $u$-$d$ correlations.

The SBS nucleon form factor program

A set of experiments was proposed with the Super BigBite Spectrometer whose large angular acceptance allows us to advance very significantly the measurements of the $G_p^E$, $G_n^M$, and $G_n^E$ (see Table I).

The first measurement for the neutron magnetic form factor ($G_n^m$) is under preparation for data taking in 2021. Fig. 1 (right) shows the projected accuracy for the ratio $F_1^u/F_1^d$ obtained from $G_n^m/G_p^p$ with systematic uncertainties dominated by the uncertainty of the $G_p^E/G_p^p$ ratio.
Table I: Upcoming measurements of the nucleon form factors in JLab Hall A with SBS (approved experiments). Projected range of $Q^2$ and accuracy relative to the Dipole form factor at max. value of $Q^2$.

| Form factor Reference | $Q^2$ range, GeV$^2$ | $\Delta G/G_{\text{Dipole}} \,(\text{stat/syst})$ at max $Q^2$ |
|-----------------------|----------------------|-------------------------------------------------|
| $G^p_n$ | $23$ | 5-12 0.08 / 0.02 |
| $G^E_n$ | $25$ | 1.5-10.2 0.23 / 0.07 |
| $G^E_M$ | $24$ | 3.5-13.5 0.06 / 0.03 |

New experiment for measurement of the strangeness form factor at high $Q^2$

In this section we present the physics motivation and specific ideas for a new experiment for the measurement of the $F^p_s$ by using SBS equipment. In the original flavor decomposition study [13] we decided to omit the heavier quark contribution motivated by the fact that all experimental data on the strangeness form factor of a proton $F^p_s$ are consistent with zero [15, 17] (in agreement with the lattice calculations). However, all known experiments were performed for $Q^2$ below 1 GeV$^2$. At the same time, the relative role of the $s\bar{s}$ in the elastic electron-nucleon scattering could be higher at the momentum transfer of 3 GeV$^2$ [18]. The recent analysis of the possible value for the strange form factor performed by T. Hobbs, M. Alberg, and J. Miller suggests that $F^p_s$ could be as high as a $G_{\text{Dipole}}$ (which is 0.03 at $Q^2=3.4$ GeV$^2$) or even larger, see Fig. 3 from Refs. [18, 19].

![Figure 3](image_url)  
**FIG. 3:** The strange form factor vs. momentum transfer data and projections per Refs. [18, 19].

In the one-photon exchange approximation, the amplitude for electron-nucleon elastic scattering can be written as $M^{\text{vac}} = -(4\pi\alpha/Q^2)\bar{v}\mu J_{\mu}^{\text{vac}}$, where $\alpha$ is the fine structure constant, $\bar{v} = \overline{\tau}\gamma^\mu e$ is the leptonic vector current, and

$$J_{\mu}^{\text{vac}} = \langle p(n)|((\frac{2}{3}\tau_\mu\gamma_\mu u + \frac{1}{3}\tau_\mu\gamma_\mu d) + \frac{1}{3}\bar{s}\gamma_\mu s)|p(n)\rangle$$  \hspace{1cm} (1)

is the hadronic matrix element of the electromagnetic current operators for the proton (neutron).

The corresponding nucleon form factors for the virtual photon have three contributions:

$$G^{\gamma}_{E,M} = \frac{2}{3}G^n_{E,M} + \frac{1}{3}G^d_{E,M} + \frac{1}{3}G^s_{E,M}$$  \hspace{1cm} (2)

The $Z$ boson exchange between an electron and a nucleon leads to a similar structure of the current. The contribution of $G^{\gamma}_{E,M}$ could be observed thanks to the significant interference term in the matrix element of the scattering. The measurement of the asymmetry of the longitudinally polarized electrons scattering from a proton (left vs. right) allows us to find $G^s_{E,M}$, see Refs. [15, 16] and complete flavor decomposition of the nucleon form factors (assuming isospin symmetry).

It is easy to see that the uncertainty in $G^s_{E,M}$ (and $F_{1,2}$) contributes linearly to the uncertainty of $u$- and $d$-quark contributions. At $Q^2=3.4$ GeV$^2$ for the $\Delta G^n_s = G^n_{\text{Dipole}}$, the corresponding uncertainty $\Delta(Q^4F^4_s) \sim 0.35$, which is much larger than the contribution from the uncertainty of the $G^n_{E}$ [12], see Fig. 2.
The interest in high \(Q^2\) measurement of \(F_p^s\) is also motivated by the expectation that \(F_p^s\) has a maximum at a momentum transfer much larger than the location of the \(G_E^n\) maximum due to the heavier mass of the \(s\)-quark. Such an expectation is supported by the small radius of a \(\phi\) meson which could be obtained from the form factor in the \(\phi\) decay to \(\pi^0\varepsilon^+\varepsilon^-\).[27]

There are two experimental difficulties in doing the \(F_p^s\) measurement at large \(Q^2\): the reduced counting rate and large background from inelastic electron-proton scattering. The reduction of the counting rate, which is due to reduction of the \(\sigma_{\text{Mott}} G^2_{\text{Dipole}}\), is partly compensated for by a linear increase of the asymmetry for high \(Q^2\). For suppression of the inelastic events we proposed to use the tight time and the angular correlations between the scattered electron and recoiled proton (as well as the energy deposited in the detectors), as it was considered in Ref. [28].

The solid angle of the apparatus should cover a suitable range of the momentum transfer \(\Delta Q^2/Q^2 \sim 0.1\) for which the event rate variation over the acceptance is limited (we selected a factor of 4). The equipment needed for such an experiment could be obtained from the SBS where a highly segmented hadron calorimeter and electromagnetic calorimeters are under preparation for the GEp experiment. Figure 4 shows the proposed configuration of the detectors.

![Diagram of the apparatus](image)

**FIG. 4**: Left: Side view of the apparatus. The electron beam goes from right to left. The proton detector is shown in green and the electron detector in purple; the liquid hydrogen target is shown in blue. Right: Front view of the apparatus. The blocks in orange get signals from the electron and the proton whose directions are shown in red.

The proposed detector configuration has an electron arm with a solid angle of 0.1 sr at a scattering angle of 18±1.5 degrees. Within 30 days of data taking with a 6.6 GeV beam the PV asymmetry will be measured to 3% relative accuracy which corresponds to an uncertainty of \(F_p^s\) of 0.002. Such a measurement will provide the first experimental limit on \(F_p^s\) at large momentum transfer of 3 GeV\(^2\) (or discover its non-zero value) and reduce the current uncertainty from the strangeness contribution in the flavor separated proton form factors such as \(F_d^2\) by six times.

**Acknowledgments**

This work was supported by Department of Energy (DOE) contract number DE-AC05-06OR23177, under which the Jefferson Science Associates operates the Thomas Jefferson National Accelerator Facility.

---

[1] R. Hofstadter, R.W. McAllister, Phys. Rev. 98, 217 (1955).
[2] V. Punjabi, C.F. Perdrisat, M.K. Jones, E.J. Brash, and C.E. Carlson, Eur. Phys. J. A 51, 79 (2015).
[3] M.N. Rosenbluth, Phys. Rev. 79, 615 (1950).
[4] P. Bosted, Phys. Rev. C 51, 409 (1995).
[5] R.G. Arnold et al., Phys. Rev. Lett. 57, 174 (1986); A.F. Sill et al., Phys. Rev. D 48, 29 (1993).
[6] G.P. Lepage and S.J. Brodsky, Phys. Rev. Lett. 43, 545 (1979); 43, 1625(E) (1979).
[7] “Measurement of the Electric Form Factor of the Proton by Recoil Polarization”, Spokespersons Ch. Perdrisat and V. Punjabi, JLab proposal 89-014, 1989.
[8] A.I. Akhiezer, L.N. Rosenzweig and I.M. Shmushkevich, Sov. Phys. JETP 6, 588 (1958); J.H. Scofield, Phys. Rev. 113, 1599 (1959); N. Dombey, Rev. Mod. Phys. 41, 236 (1969); A.I. Akhiezer and M.P. Rekalo. Sov. J. Part. Nucl., 3:277, 1974; R.G. Arnold, C.E. Carlson, and F. Gross, Phys. Rev. C 23, 363 (1981).
[9] M.K. Jones et al., Phys. Rev. Lett. 84, 1398 (2000); O. Gayou et al., Phys. Rev. C 64, 038202 (2001); O. Gayou et al., Phys. Rev. Lett. 88, 092301 (2002); V. Punjabi et al., Phys. Rev. C 71, 055202 (2005); A. Puckett et al., Phys. Rev. Lett. 104, 242301 (2010); A. Puckett et al., Phys. Rev. C 96, 055203 (2017).
[10] A.V. Belitsky, Xiangdong Ji, and Feng Yuan, Phys. Rev. Lett. 91, 092003 (2003).
[11] J. Lachniet et al., Phys. Rev. Lett. 102, 192001 (2009).
[12] S. Riordan et al., Phys. Rev. Lett. 105, 262302 (2010).
[13] G. Cates, K. deJager, S. Riordan, and B. Wojtsekhowski, Phys. Rev. Lett. 106, 252003 (2011).
[14] M. Diehl and P. Kroll, Eur.Phys.J. C 73, 2397 (2013).
[15] D.H. Beck and R.D. McKeown, Annu. Rev. Nucl. Part. Sci. 51, 189 (2001);
[16] B. Beise, M. Pitt and D. Spayde, Prog. Part. Nucl. Phys. 54, 289 (2005).
[17] D.S. Armstrong and R.D. McKeown, Annu. Rev. Nucl. Part. Sci. 62, 337 (2012).
[18] T.J. Hobbs, M. Alberg, and G.A. Miller, Phys. Rev. C 91, 035205 (2015).
[19] T.J. Hobbs and G.A. Miller, private communication, 2019.
[20] C.D. Roberts et al., Eur. Phys. J. ST 140, 53 (2007); I.C. Cloët et al., Few-Body Systems 46, 1(2009).
[21] Thomas Jefferson National Accelerator Laboratory, https://www.jlab.org
[22] Super Bigbite Spectrometer, http://hallaweb.jlab.org/12GeV/SuperBigBite/
[23] JLab experiment E12-07-109, Spokespeople E. Cisbani, M. Jones, N. Liyanage, A. Puckett, L. Pentchev, and B. Wojtsekhowski, https://misportal.jlab.org/mis/physics/experiments/searchProposals.cfm?paramHall=A&paramExperimentStatusList=A&paramExperimentEnergy=12GeV&paramExperimentStatusList=A
[24] JLab experiment E12-09-019, Spokespeople D. Hamilton, B. Quinn, and B. Wojtsekhowski, Ibid.
[25] JLab experiment E12-09-016, Spokespeople T. Averett, G. Cates, S. Riordan, and B. Wojtsekhowski, Ibid.
[26] M. Diehl and P. Kroll, Eur.Phys.J. C 73 (2013) 2397; arXiv:1302.4604
[27] A. Anastasi et al., Phys. Lett. B 757 362 (2016).
[28] “Strangeness form factor of the proton at 2 (GeV/c )”²”, Spokesperson B. Wojtsekhowski, JLab proposal PR-06-004, 2005.