Letter of intent for pac 25

Measurement of the Q^2 dependence of the axial-vector and pseudoscalar nucleon form factors from $Q^2 = 1$ to 3 (GeV/c)^2

A. Deur, University of Virginia.

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Abstract

We discuss here the feasibility of a weak charged current experiment. The first goal is to measure in a yet unreached domain the Q^2 dependence of the axial-vector form factor g_A. If g_A follows a dipole form the axial mass can be extracted with an accuracy at least at the level of the compiled world data. The measured g_A together with data from a back detector necessary to reduce the electromagnetic background may allow for a measurement of the pseudoscalar form factor g_P. This would be of extreme importance since no data exist beside a few points at very low Q^2. Finally, the completion of this experiment would be a proof of principle for a new program of exploration of the nucleon using a charged weak probe.

1 Motivation

We discuss here the possibility of measuring the axial and pseudoscalar form factors of the nucleon and study their Q^2-dependence. To do so, we propose a pioneering measurement using the weak charged current reaction $e+p \rightarrow \nu+n$. In this section, we discuss the different motivations for such an experiment.

1.1 The proton axial-vector form factor

The axial-vector form factor g_A is a fundamental quantity characterizing the nucleon. Since its measurement is more delicate than electromagnetic form factors, it is less known. Hence, precise data in an unmeasured region would be a major contribution to our understanding of the nucleon.

So far, two techniques have been used to measure g_A as a function of Q^2: elastic neutrino scattering with both charged and neutral currents, and pion electroproduction. While neutrino experiments are very delicate to carry out and rely on Monte Carlo simulations, pion data need theoretical corrections to be interpreted. Until recently, the neutrino and pion data disagreed. New corrections based on baryon chiral perturbation theory seems to bring the data to agreement [1]. However, it is desirable to provide a third, more robust, way to measure the axial form factor. We study here such possibility. In addition to providing a third and, we believe, better way, this would extend our knowledge of g_A to a Q^2-domain unmeasured yet.

The axial-vector form factor can be fit by a dipole form:

$$g_A(Q^2) = \frac{g_a}{(1+Q^2/M_A^2)^2}$$

where g_a is the well measured axial coupling constant, $g_a = 1.2673 \pm 0.0035$ [2] and M_A is the so-called “axial mass”.

World data on $g_A(Q^2)$ are shown in the figure below. We can clearly see that the data precision is not as good as for the electromagnetic form factors. A straight line describes the data as well as the dipole fit, which shows the importance of studying the Q^2-dependence of g_A. With measurements from 1 to 3 $(\mathrm{GeV/c})^2$ we will have a large lever arm to validate or not the dipole dependence.

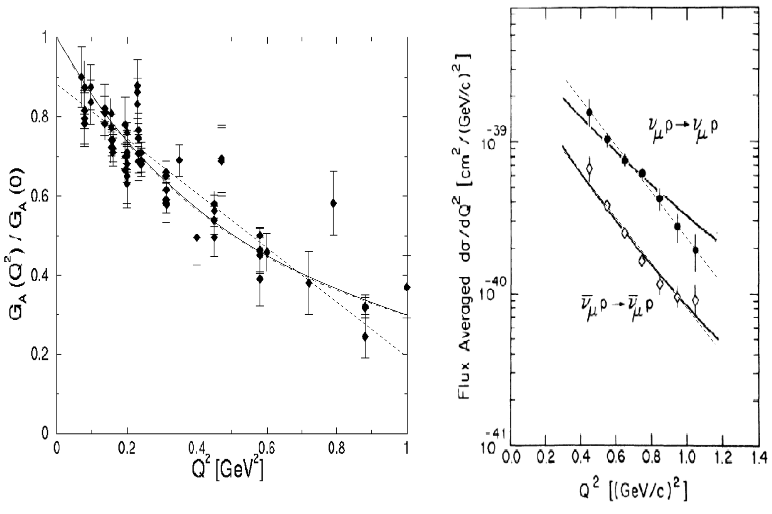

Fig. 1. The world data on $g_A(Q^2)$. The left plot, from the review [1], shows the data obtained from pion electroproduction experiments. The axial mass used for the fit is $M_A = 1.1$ GeV. This mass does not include the corrections based on baryon chiral perturbation theory. The right plot shows the cross

sections obtained from neutrino and anti-neutrino scatterings [3]. The solid lines are from the best dipole fit to the data ($M_A = 1.06$ GeV). The dashed lines are linear fits.

1.2 The induced pseudoscalar form factor

The induced pseudoscalar form factor g_P is of the same importance as g_A and other form factors for our understanding of the nucleon, yet it is almost unknown. g_P as been interpreted so far in terms of the nucleon pion cloud picture. Accessing g_P at larger Q^2 will help to understand it in term of quark-gluon degrees of freedom. Because it is difficult to measure, very few data exist, none of them at large Q^2. Muon capture experiments have provided points at extremely low Q^2 (0.01 GeV^2) [4] but the different results disagree. The only data existing at larger Q^2 are from Saclay and range from 0.07 to 0.18 GeV^2 [5]. They were obtained from a Rosenbluth separation of g_P and g_A on the e(p,eπ^+)n reaction. The pion momentum in the center of mass, P_{cm}, has to be small in order to apply Chiral Perturbation Theory, which requires to detect very low kinetic energy pions. The condition is $P_{cm} + M_\pi \ll M_N$. From the 3 sets of data at $P_{cm} = 40$ MeV, 68 MeV and 98 MeV, only the 40 MeV data could be used to extract reliably g_P and g_A.

Using hadronic degrees of freedom, the pseudoscalar term can be described as arising from electrons scattering off the meson cloud made dominantly of pions. This is the so-called pion pole dominance hypothesis which explains well the low Q^2 data, see the figure below.

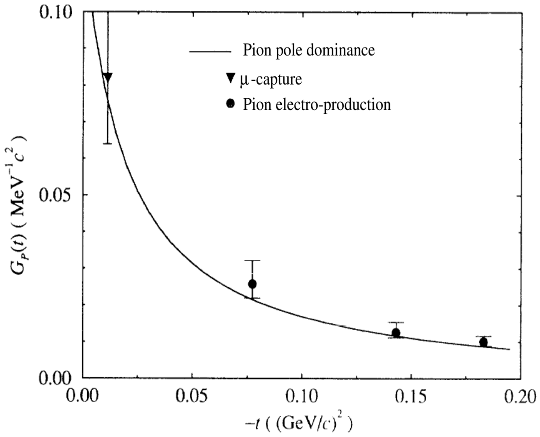

Fig. 2. World data on g_P and pion pole dominance calculation.

In the experiment we are investigating, we will have to measure the reaction e(p,e'n)π^+ in the same time as the e(p,n)ν reaction in order to remove backgrounds. We can extract from the e(p,e'n)π^+ reaction the linear combination of g_A and g_P, while g_A is independently extracted from the e(p,n)ν reaction.

Hence, no delicate Rosenbluth technique needs to be used here, which is an unique advantage of our proposal.

The kinematics for the e(p,e'n)π^+ reaction are given in section 3.1.2. As we can see there, the pion stays at very small c.m. momentum. Therefore, this yields a measurement as clean as possibly achievable in term of chiral limit requirement.

To conclude, we may have the possibility of measuring g_P in an unmeasured range and without the issues of the previous measurement. This would extend the world data dramatically. Such data, together with the independent g_A data, would allow to check if the pion pole dominance hypothesis remains valid at large Q^2, which could help understanding the pseudoscalar form factor in terms of the fundamental partonic degrees of freedom.

1.3 Other motivations

Successful running of such an experiment would serve as a proof of principle for weak interaction experiments and would be key to further develop techniques using the charged weak probe. This would open a new way of exploring the nucleon, the free neutron, the nuclei, and possibly to study effects beyond the standard model.

2 Cross section for charged current "quasi-elastic" [1] scattering of electron off proton.

The reaction considered in this letter is represented in Fig. 3.

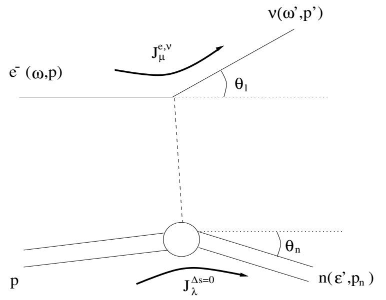

Fig. 3. Charged current "quasi-elastic" scattering of electron off proton

The cross section for such process is:

$$\frac{d\sigma}{d\omega'} = M\frac{G^2\cos^2\theta_c}{\pi}\frac{\omega'}{\omega}\left[\cos^2(\theta_l/2)f_2 + \left(2f_1 + \frac{\omega+\omega'}{M}f_3\right)\sin^2(\theta_l/2)\right]$$

[1] In neutrino elastic scattering, charged currents ($W^{+/-}$ exchange) flip the isospin of the target. To distinguish it from non-isospin-flip (Z^0 exchange), it is called "quasi-elastic scattering". This is not to be confused with the nuclear quasi-elastic scattering which corresponds to electron elastic scattering on a nucleon within a nucleus.

Where G is the Fermi coupling constant, θ_c the Cabibbo mixing angle and the form factors f_i are combinations of g_A, G_M^n, G_E^n, G_M^p and G_E^p.

The cross-section depends essentially on the axial form factor g_A and to a lower extend on the difference between proton and neutron magnetic form factors $g_M = G_M^p$ - G_M^n. We have very small sensitivity to the electric form factors G_E^p and G_E^n [6]. The good knowledge of electromagnetic form factors allows to use them as an input to extract g_A.

3 Experimental aspects

In this section we summarize a possible experiment. Details on the experimental apparatus and the background study can be found in [6]. Work on a full Monte Carlo is presently ongoing in order to establish firmly the feasibility of the experiment.

Studying $p(e,n)\nu$ implies the following:

- Only the neutron can be detected. We need a device to detect with high efficiency and good angular/energy resolutions high-energy neutrons at about 10^o. Such neutron forward angle is desirable to minimize the electromagnetic backgrounds.
- We will be measuring cross-sections at typically a few 10^{-39} cm^{-2}/Sr. We need the highest possible luminosity. With a 20 cm long cryotarget and 100 μA we reach a luminosity of $6.\times 10^{38}$ cm^{-2} s^{-1}. With a reasonable size neutron detector ($\Delta\Omega = 0.1$ Sr) we see that we are considering rates of the order of a tenth of a Hz.

The principal challenge here is to reduce backgrounds that are many orders of magnitude higher than our signal of interest. To do so we will have the following:

- A 63 MHz pulsed beam will allow time-of-flight (TOF) measurement. This will remove the prompt background: photons, electrons and the π^0 decay products.
- A sweeping dipole with a $\int Bdl$ of 0.6 T.m will stand between the target and the neutron detector to sweep away the charged particles (electrons from elastic at small Q^2 and protons from elastic at large Q^2). It will have a large acceptance but no strong requirement on the field homogeneity. A warm dipole will be enough to meet such requirement. Its acceptance has to be defined by non-magnetic collimators to avoid pole-tip scattering of polarized electrons.
- The TOF measurement on the neutron together with the detector segmentation will allow to resolve a region around the elastic reaction.

- A detector at back angle will measure electrons to remove the backgrounds coming from: 1) pion electroproduction e+p $\rightarrow$ e+n+π^+, 2) quasi-elastic scattering off nuclei e+Be $\rightarrow$ e+n+X and 3) charge exchange process occurring after the elastic e+p $\rightarrow$ e+p where the outgoing proton is transformed into a neutron. The measurement on e+p $\rightarrow$ e+n+π^+ may be also used to extract g_P. The back detector is also necessary to measure the pions photoproduction γ+ p $\rightarrow$ n+π^+. We need another smaller sweeping magnet to reduce the single rate background.

- The neutron detector will be shielded to cut the low energy backgrounds. Veto planes will remove the charged background and cosmics.

- The beam polarization together with a setup symmetric with respect to the beam line will clean-up the remaining of the backgrounds. This is possible due to the 100% physics asymmetry of the weak charged current. By using a polarized beam we measure the raw asymmetry and hence the dilution factor. Since the dilution factor is directly related to the background, we can do online a precise background monitoring. The measurement of the remaining background is inclusive, which cancels out any azimuthal-dependent asymmetry. Residual asymmetry, if any, will be canceled by the symmetric setup.

Half of the experimental set-up is shown in the following figure. The other part is symmetric with respect to the beam line and is not shown for clarity.

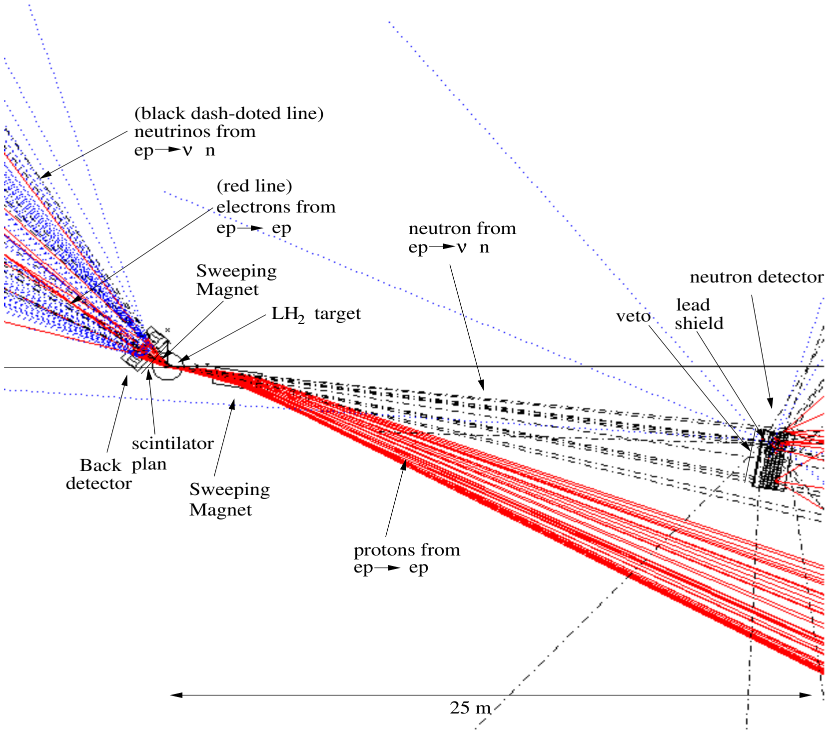

Fig. 4. Experimental set-up with simulated elastic electromagnetic scattering e+p→e+p and weak scattering e+p→ν+n. The amount of electromagnetic ep has been largely decreased for clarity. Not shown on the figure are the forward electrons and back protons from e+p→e+p.

3.1 Kinematics

3.1.1 Charged current reaction

Kinematics variables, cross sections and rates for e+p→n+ν are given in the table below. The energies are in GeV

E	θ_n	P_n	θ_l	P	Q^2	Xs	R
0.85	7.7^o-12.3^o	1.11-1.14	135^o-151^o	0.315-0.334	0.97-1.00	7.2×10^{-9}	0.017
1.00	7.7^o-12.3^o	1.27-1.30	131^o-149^o	0.336-0.361	1.20-1.25	4.6×10^{-9}	0.014
1.70	7.7^o-12.3^o	1.96-2.02	117^o-138^o	0.408-0.467	2.31-2.42	8.6×10^{-10}	0.007
2.00	7.7^o-12.3^o	2.23-2.32	111^o-134^o	0.434-0.511	2.79-2.94	5.0×10^{-10}	0.005

- E is the beam energy
- θ_n is the range of the neutron detection angle
- P_n is the neutron momentum
- θ_l is the neutrino scattering angle corresponding to the neutron detection angle

- P is the neutrino momentum corresponding to the neutron detection angle
- Xs is the cross section within the neutron detector solid angle, in μb/GeV
- R is the counting rate with a 100 μA beam current.

3.1.2 Pion electroproduction

The following table gives the kinematics for the pion electroproduction e+p→n+e+π^+ near threshold (W=1.079 GeV) for neutrons detected at -10^o.

E	Q^2	P_{el}	θ_{el}	P_π	θ_π	$P_{\pi cm}$	P_n
0.85	0.80	0.272	137^o	0.144	-10.4^o	0.004	0.920
1	1.03	0.302	134^o	0.166	-10.4^o	0.004	1.063
1.7	2.14	0.408	123^o	0.259	-11^o	0.004	1.692
2	2.63	0.447	118^o	0.297	-10.8^o	0.004	1.947

We can see that in all cases, the pions are produced with low $P_{\pi cm}$, which allows to extract the pseudoscalar form factor g_P.

3.2 Backgrounds

The backgrounds are described and estimated in [6]. We summarize them here:

- Inelastic production of neutron (e+p→n+e+π^+ and γ+p→n+π^+): assuming a 10^{-3} back detector inefficiency, the background/signal ratio should be below 1.
- The window background from Be+e→e+n+X is mainly removed by the back detector. It can be corrected to a negligible level using either calculations or empty cell runs.
- Photons and π^0 decay products are part of the prompt electromagnetic flash and should be negligible after their subtraction using TOF.
- The background from deuterium contamination within the LH_2 cell will be at the 20% level. It will be decreased to negligible level by detecting the recoiling electrons.
- The neutrons from the protons that undergo charge exchange at the cell wall. The uncertainty on this background is negligible.
- Cosmic background will be removed using a veto on the top of the neutron detector.
- The uncertainty due to neutrons produced at the Be window and rescattered by the LH_2 is negligible.
- The background due to the electrons scattered at the Be window and knocking out neutrons from the cell wall is negligible.

3.3 Uncertainties

The systematic uncertainties on the backgrounds will not enter directly into the final systematic error since the beam helicity reversal will measure them on line. Rather, only the magnitude of the background is important. It will determine how long we need to run and how much the systematics arising for a polarized experiment will be important. If, for example, the background dilutes the asymmetry by a factor 5 and the beam polarization is 80%, then we are measuring a 16% raw asymmetry and the only significant systematic errors will come from the beam polarimetry and the absolute cross section measurement.

The uncertainty budget is detailed in [6]. All in all we expect a total uncertainty on the cross section of 4%. This gives a 4-5% error on $g_A(Q^2)$. The uncertainty on $g_P(Q^2)$ has not been estimated yet.

3.4 Expected results

3.4.1 Axial mass

If our data have a the Q^2-dependence following a dipole form, then the axial mass is a meaningful quantity to extract. We can extract it with a 3% accuracy, to compare to 4% accuracy of the compiled world data for the neutrino experiments and to 3% for the pion experiments. The figure below compares the expected result to the world data.

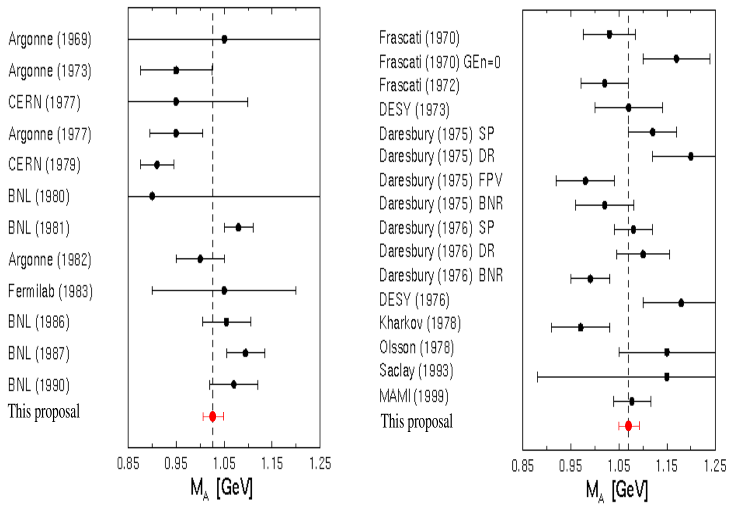

Fig. 5. World data on M_A from neutrino scattering (left plot) and pion electroproduction (right) [1]. The expected results (3% accuracy) have been added to the figure. The chiral perturbation theory based correction has not been applied to the pion data.

3.4.2 Q^2-dependence of g_A and g_P

In the figure below is shown the results we could expect on $g_A(Q^2)$ in our Q^2 range. We have assumed a 4% statistical error.

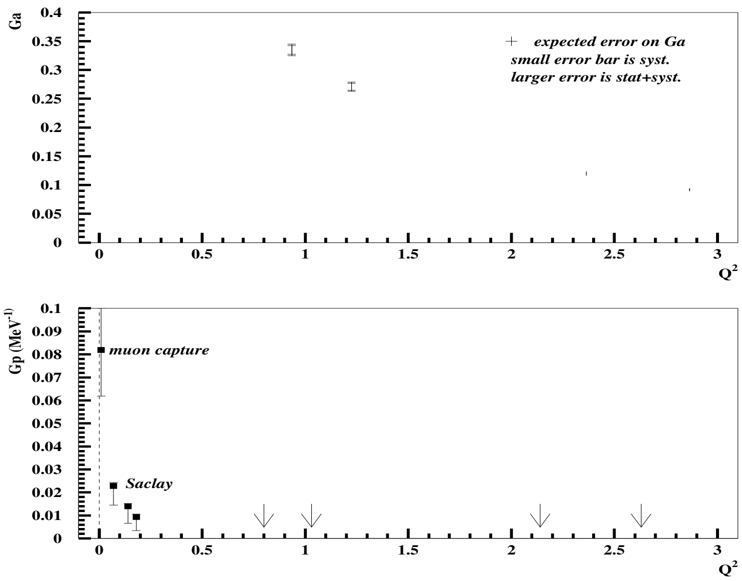

Fig. 6. Results on $g_A(Q^2)$ and $g_P(Q^2)$. For g_A (top plot), the smaller error bars correspond to the systematic error. The larger are the systematic errors with the 4% statistical added in quadrature. No uncertainty estimate has been done on the pseudoscalar form factor g_P. We give the available world data together with the position where our points would be.

4 Time estimate

In the table below we give an example of what can be achieved in a month of beam time. We assume that we use 2 symmetric neutron detectors and 100 μA of 80% polarized beam. We make the assumption that the background/signal is 7 before the clean-up with the beam helicity reversal. We believe this assumption to be conservative.

E	Beam time	R	$\Delta\sigma_{stat}$
0.85 GeV	160 h	0.017	4%
1.70 GeV	420 h	0.007	4%
1 GeV	200 h	0.014	4%
2 GeV	600 h	0.005	4%

We need to point out again that this amount of time is depending on the assumption on the background/signal ratio. We have assumed a factor 7 which we think to be conservative but this factor may change after more detailed simulation work is done.

5 Summary

We propose a pioneering experiment to measure precisely and in a robust way the proton axial form factor and the pseudoscalar form factor in an unmeasured domain. A dipole form dependence would lead to a determination of the axial mass at least as accurate as the world data taken altogether. Such an experiment may be possible because the photon propagator suppresses the recoil of high energy nucleon at forward angle and the asymmetry of the weak process is maximal. To carry out the experiment we need neutron detectors, back angle detectors and large acceptance sweeping magnets. It would also required slight modifications of the cryotarget: 100 μm Be windows and a high purity LH_2 content.

We stress that this experiment, beside providing quantities of fundamental importance, would establish a new way to explore the nucleon structure and possibly physics beyond the standard model. Its completion would be a proof of principle for such a program.

Finally, it should be noticed that JLab is an ideal place to carry out such an experiment because at lower beam energy, the reaction is buried under electromagnetic backgrounds while at higher energy, the resolution of the neutron detector does not allow to cleanly extract the reaction from inelastic process. Furthermore, the experiment requires the unique luminosity of Jefferson Lab.

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