Axial and Pseudoscalar Nucleon Form Factors from Low Energy Pion Electroproduction

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The cross section for exclusive π^+ electroproduction on the proton has been measured near threshold for the first time at two different values of the virtual photon polarization ($\varepsilon \sim 0.2$ and $\varepsilon \sim 0.7$). Using the low energy theorem for this reaction we deduce the axial and pseudoscalar weak form factors G_A and G_P at $|t| = 0.073$, 0.139, and 0.179 $(\mathrm{GeV}/c)^2$. The slope of G_A agrees with the value obtained in neutrino experiments. G_P satisfies the pion pole dominance hypothesis, which is thus verified for the first time in this range of transfer.

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The electroweak form factors provide a significant test of our understanding of the nucleon structure. Continuous efforts are devoted to their experimental determination but, as compared to the electromagnetic form factors of the nucleon $(F_1^{p,n}, F_2^{p,n})$, the axial (G_A) and pseudoscalar (G_P) weak form factors are still poorly known. In particular, very little is known about G_P which is very sensitive to the pion cloud of the nucleon. This Letter reports the first determination of both G_A and G_P at $t = -0.073$, -0.139, and -0.179 $(\mathrm{GeV}/c)^2$, using near threshold π^+ electroproduction on the proton with detection of the pion and electron in coincidence.

To fix our conventions we write the matrix element of the axial current between nucleon states of momenta p_1 and p_2 $[t = (p_1 - p_2)^2]$:

$$\langle p_1 | A^\mu | p_2 \rangle = \bar{u}(p_1)[G_A(t)\gamma^\mu + G_P(t)(p_1 - p_2)^\mu]\gamma_5 u(p_1) . \tag{1}$$

From β decay and muon capture one can determine the weak form factors in the range $|t| \sim 0$–0.01 $(\mathrm{GeV}/c)^2$, but at larger t the only direct information comes from neutrino scattering on nuclei. From these experiments, only the mass parameter M_A of the dipole parametrization of G_A can be obtained, assuming that the vector and magnetic weak form factors can be taken from electron scattering using the isotriplet hypothesis and that G_P is given by pion pole dominance [1], which we write in the form $G_P(t) = -2MG_A(t)/(t - m_\pi^2)$.

The well established approximate chiral symmetry of strong interactions allows us to write a low energy theorem [1,2] which relates the low energy pion electroproduction amplitude to G_A, G_P, $F_1^{p,n}$, and $F_2^{p,n}$, up to corrections which vanish in the chiral limit (pion mass going to zero). For our purpose, $F_1^{p,n}$ and $F_2^{p,n}$ are known with sufficient accuracy. Therefore, a measurement at the same t for two values of the virtual photon polarization ε allows a simultaneous determination of G_A and G_P. Previous experiments (see Ref. [3] for a list of references) performed the measurement only at a single value of ε except in Ref. [4] where the neutral pions were not separated from the charged ones. Therefore the determination of G_A relied either on the pion pole dominance hypothesis for G_P or on a model for the estimation of the neutral pion contribution. Our experiment is the first exclusive experiment which uses two values of ε ($\varepsilon \sim 0.2$ and $\varepsilon \sim 0.7$) different enough to allow an independent determination of G_A and G_P. Up to now, the latter is known only at the muon point [5]: $G_P = 0.082 \pm 0.018$ $\mathrm{MeV}^{-1} c^2$ at $t = -0.0112$ $(\mathrm{GeV}/c)^2$.

In the following, p_1, p_2, q, and k are, respectively, the four-momenta of the proton, neutron, pion, and virtual photon in the pion-neutron center of mass (c.m.) frame. The pion c.m. polar angle with respect to the virtual photon and its azimuthal angle with respect to the electron plane are noted, respectively, (θ, φ). Our convention is that the azimuthal angle of the scattered electron is 180°. We have measured the electroproduction cross section for three values of k^2 and two values of ε. For each set (k^2, ε), the cross section was measured for three values of $|\mathbf{q}|$ close to threshold and at $\varphi = 0°$. The pion momentum was not parallel to the virtual direction (see Table I).

The experiment was carried on with the electron beam ($E_{\max} = 700$ MeV) of the Saclay Linear Accelerator (ALS). For the detection of the scattered electron, the 600 spectrometer of the experimental hall HE1 was used with its conventional detectors [6]: four wire chambers, three scintillator hodoscopes, and one gas Cerenkov counter. To detect the low energy pions (kinetic energy $T_\pi = 10$–65 MeV), a "clamshell" shaped magnetic dipole spectrometer with short trajectory length (1.5 m) and large deviation angle was constructed [7]. Its solid angle and relative momentum acceptance are 25.8 msr and $\pm 17\%$, respectively. The detection system of this spectrometer is made of six planes of drift chambers and three planes of scintillators. Protons from elastic scattering were stopped by a CH_2 absorber in front of the first

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TABLE I. Differential cross sections (last column) measured at 18 kinematical conditions. Rows 3 to 8 (respectively, 10 to 15 and 17 to 22) correspond to $k^2=-0.0701$ (GeV/c)^2, $\theta=70°$ [respectively, $k^2=-0.136$ (GeV/c)^2, $\theta=90°$ and $k^2=-0.195$ (GeV/c)^2, $\theta=73°$]. Columns 1 to 5 are, in increasing order, the transfer to the nucleon, the beam energy, the electron scattering angle, the polarization parameter of the virtual photon, and the pion c.m. momentum. The units are, respectively (GeV/c)^2 for t and k^2, MeV/c for $|\mathbf{q}|$, and degrees for θ. The last column is $\sigma=d^5\sigma/dE'd\Omega_e d\Omega_\pi^{\text{c.m.}}$ in pb MeV^{-1}sr^{-2}.

$-t$ [(GeV/c)^2]	E_{beam} (GeV)	θ^e_{scatt} (deg)	ε	$\lvert\mathbf{q}\rvert$ (MeV/c)	$\frac{d^5\sigma}{dE'd\Omega_e d\Omega_\pi^{\text{c.m.}}}$ (pb MeV^{-1}sr^{-2})
		$k^2=-0.0701$ (GeV/c)^2, $\theta=70°$			
0.0732	299.9	97.3	0.20	40.1	1.59 ± 0.07
0.0732	312.8	95.8	0.20	69.1	3.05 ± 0.13
0.0759	332.1	93.5	0.20	99.0	4.13 ± 0.17
0.0732	490.4	40.8	0.70	40.2	9.22 ± 0.44
0.0732	508.5	39.8	0.70	68.8	15.5 ± 0.60
0.0755	535.7	38.4	0.70	98.4	25.9 ± 1.0
		$k^2=-0.136$ (GeV/c)^2, $\theta=90°$			
0.139	366.6	112.1	0.14	40.4	0.607 ± 0.032
0.144	378.6	111.1	0.14	69.3	1.22 ± 0.05
0.152	396.5	109.6	0.14	98.6	1.70 ± 0.08
0.139	634.4	42.8	0.70	40.6	3.95 ± 0.28
0.144	651.4	42.1	0.70	69.5	7.09 ± 0.39
0.152	676.8	41.1	0.70	98.8	10.8 ± 0.7
		$k^2=-0.195$ (GeV/c)^2, $\theta=73°$			
0.179	430.0	110.7	0.15	40.0	0.382 ± 0.021
0.176	441.8	109.9	0.15	68.9	0.698 ± 0.036
0.175	459.5	108.7	0.15	98.1	0.969 ± 0.051
0.179	644.8	52.8	0.60	40.2	1.53 ± 0.10
0.176	659.9	52.1	0.60	68.8	2.76 ± 0.16
0.175	682.5	51.1	0.60	98.4	3.97 ± 0.24

drift chamber. During data acquisition, only loose triggering conditions were imposed. The coincidence time window was as large as 100 ns to allow subsequent subtraction of the accidental coincidence events. We used a 5 cm long liquid hydrogen target at 20.4 K with a geometry such that the pion path in the target was never larger than 1 cm. Because of the cryogenic capability of the target and accidental coincidences rate limitations, the average beam intensity was limited to 1–5 μA. To control the variations of the beam current and target density, the integrated luminosity was determined by the single electron counting rate in the 600 spectrometer during data acquisition. The absolute calibration of the single electron rate was determined by the extrapolation to zero of several measurements at decreasing intensities. Three cuts were applied in the off-line analysis:

First, a rough selection of the π^+ electroproduction events was performed by applying a cut on the energy loss in the scintillators.

Second, real coincidence events were identified by measuring the time difference between the arrivals of the electron and the pion. After correcting the spread in the time of flight (dispersion of particle velocities and of trajectory lengths, residual delays in the electronics), a coincidence peak of 2 ns (FWHM) was obtained for each kinematics. The coincidence events were selected by applying cuts at ±2.5 ns away from the peak center. After these cuts, the true-to-accidental events ratio was between 0.5 and 1.5.

The final selection of the π^+ electroproduction events was performed using the mass spectrum of the undetected neutron. This missing mass was calculated for each event from the electron and pion momenta measured by the spectrometers. The energy losses of the pion and electron in the target were taken into account. Peak resolutions of 2–3 MeV/c^2 (FWHM) for each kinematics were obtained. Lower and upper cuts of 935.4 and 944.7 MeV/c^2, respectively, were applied to select the π^+ electroproduction events.

The number of events, after the application of these cuts, was obtained by subtraction of the accidentals. The rate of the latter was measured on the edges of the coincidence time distribution. The coincidence acceptances (FWHM) for the pion c.m. momentum and angles were, respectively, $\Delta q\simeq13$ MeV/c, $\Delta\theta\simeq14°$, and $\Delta\varphi\simeq20°$.

The acceptance in coincidence of the detection system was estimated by a Monte Carlo simulation. For the electron arm, a fit in phase space of the limits of the spectrometer acceptance was used [8]. The loss of events due to the inefficiency of the detectors and tracking was

1%–2% and it was applied as a corrective factor to the cross section. The acceptance of the pion arm was computed from a full simulation of particle trajectories from the interaction point up to the last detector [9]. The trajectory was reconstructed by Runge-Kutta integration in the measured field map of the spectrometer. The energy loss and angular deviation due to multiple Coulomb scattering were taken into account as well as particle reflection on the spectrometer poles, in-flight pion decay, and nuclear pion absorption. The inefficiency of the tracks reconstruction was evaluated from the real data. It was included in the simulation as a drift chamber intrinsic inefficiency ($\sim$3%) and by the generation of parasite tracks producing ambiguities in the reconstruction algorithm, leading to the loss of good tracks. The loss of event due to the electronics dead time was measured using a random pulse generator for each spectrometer ($\sim$3.5% effect).

The effects of radiative processes were divided into two parts: one, mainly due to real photon emission, which depends on the detector and missing mass cuts, and the other one, mainly due to virtual photon exchange, which is independent of these cuts [10]. The former was taken into account by including the real photon emission processes in the simulation. The latter depends only on k^2 and was computed numerically for each kinematics (5.6%–6.1% effect).

The resulting cross sections including all the corrections are given in Table I. The quoted errors are only statistical ones. The systematic errors were estimated to be 2%–3%. The effect of averaging over the pion acceptance has been found to be negligible. As explained below, only the lowest value of $|\mathbf{q}|$ has been retained for the determination of G_A and G_P but, for completeness, Table I displays all the cross sections measured in this experiment.

At threshold the cross section is proportional to

$$|E_0^+|^2 - \epsilon |L_0^+|^2 k^2/k_0^2 \,, \tag{2}$$

with E_0^+, L_0^+ the usual multipoles which can be related to G_A and G_P through a low energy theorem (LET) [2]. The original idea was to extrapolate the cross section to threshold for two values of ϵ so as to extract E_0^+ and L_0^+. This is why the cross section was measured at three values of $|\mathbf{q}|$. It turns out that the statistical accuracies of our data are not sufficient to perform this extrapolation with confidence. Therefore we propose another analysis which does not rely on the determination of the threshold multipoles but which allows the determination of G_A and G_P from the cross section measured at $|\mathbf{q}| = 40$ MeV/c.

To avoid any confusion, we first remind the reader that, even at threshold, the LET is not exact. There are corrections to the chiral limit which originate from S-wave rescattering of the pion, heavy mesons exchanges in the t channel, and higher commutators not specified by current algebra [11]. When the pion is emitted with small but nonzero momentum, these corrections have about the same magnitude. This is due to the large mass of the heavy mesons as well as the large excitation energy of the first S-wave pion-nucleon resonance. In the following, we make the usual assumption that these types of corrections can be neglected. Their evaluation is a theoretical problem *per se* (see for instance Refs. [11,12]), and is beyond the scope of this Letter.

In order to interpret our data we need a LET for a moving pion. We derive it by following the same steps as for the LET at threshold [2]. The only difference is that one works in the Lorentz frame where the pion is at rest. After a boost to the c.m. frame where the pion has momentum $|\mathbf{q}|$ one gets the following amplitude, where terms which vanish after contraction with the lepton current have been omitted ($f_\pi = 93$ MeV):

$$\begin{aligned}(-i\sqrt{2}f_\pi)T_\mu^{\pi^+} &= \bar{u}(p_2)\{G_A(t)\gamma_\mu - [G_P(t)+D(t)]q_\mu\}\gamma_5 u(p_1)\\ &\quad - G_A(0)\bar{u}(p_2)\left[q\cdot\gamma\gamma_5 \frac{p_2\cdot\gamma + M}{2p_2\cdot q}V_\mu^p + V_\mu^n \frac{p_1\cdot\gamma+M}{2p_1\cdot q} q\cdot\gamma\gamma_5\right]u(p_1) + \delta T_\mu^{\pi^+} \,,\end{aligned} \tag{3}$$

with

$$V_\mu^{p,n} = [F_1^{p,n}(t) + F_2^{p,n}(t)]\gamma_\mu - F_2^{p,n}(t)\frac{(p_2+p_1)_\mu}{2M} \tag{4}$$

and $D(t) = [2MG_A(t) + tG_P(t)]/m_\pi^2$. This amplitude has the same structure as the one obtained from the pseudovector model [13] but, in the latter case, the form factors must be added by hand and pion pole dominance is assumed from the beginning. We stress that pion pole dominance is *not* used in the derivative of Eq. (3).

The term $\delta T_\mu^{\pi^+}$ is the correction to the chiral limit. It contains new contributions with respect to the threshold case since P waves now contribute. At low c.m. energy they are dominated by the $\Delta(1232)$ and, due to the proximity of this resonance, the corresponding corrections increase rapidly with the c.m. pion momentum. To minimize their effect we have retained only the data at $|\mathbf{q}| = 40$ MeV/c (that is a c.m. energy of 6.47 MeV above threshold). To control their size, we have estimated these corrections using the cloudy bag model [14] with parameters fitted to pion photoproduction in the Δ region. For $|\mathbf{q}| = 40$ MeV/c, the effect on the cross section is always smaller than 8% and has no significant influence on the determination of $G_A(t)$ and $G_P(t)$.

Using Eq. (3), including the correction due to Δ excitation, one can write the cross section as a second-order polynomial in $G_A(t)$ and $G_P(t)$ where the coefficients are known for each kinematics. Since the pion is not emitted in the direction of the virtual photon, there are interfer-

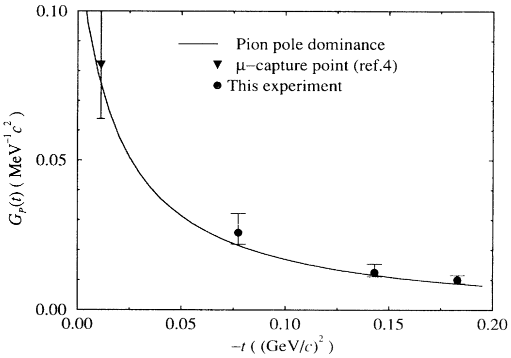

FIG. 1. Pseudoscalar form factor versus t. The curve is the pion pole dominance prediction as specified in the text.

ences between the longitudinal and transverse polarizations but this is not a problem since we are not interested in the multipoles. The only thing that matters is that, from the cross sections measured at two different values of ε and the same t one gets a system of quadratic equations which determines $G_A(t)$ and $G_P(t)$.

This system always has two pairs of solutions which are distinguished by the sign of $D(t)$. We have used this difference of sign to select the physical solution. The quantity $D(t)$, which is proportional to the divergence of the nucleon axial current, does not vanish in the range of t that we are considering. Otherwise the pion nucleon form factor $g_{\pi NN}(t)$, which is proportional to $D(t)$, would also vanish [15], implying a very rapid variation of the latter from its pole value $g_{\pi NN}(-m_\pi^2)\sim 13.5$. This would be inconsistent with the general success of the PCAC (partial conservation of axial-vector current) hypothesis [15] which states the contrary. Moreover, a zero of $g_{\pi NN}(t)$ for such a small value of t would manifest itself in the long range part of the nucleon-nucleon (NN) interaction. This is ruled out by the phenomenology of NN scattering and by the properties of the deuteron [16]. We conclude that $D(t)$ cannot change sign between the β decay or muon capture transfer, for which it is positive, and the transfers of this experiment. Therefore we have considered as physical the solution for which $D(t)>0$. With the uncertainties quoted in Table I, this criterion turns out to be unambiguous for the three values of t.

The solution for $G_A(t)$ has been parametrized as $G_A(t)=G_A(0)(1-t/M_A^2)^{-2}$. A least-squares fit leads to $G_A(0)=1.35\pm 0.11$, which is compatible with the β-decay value (1.257 ± 0.003 [17]), and $M_A=1.15\pm 0.27$ GeV/c^2 which is compatible both with the last neutrino result [18] ($M_A=1.09\pm 0.03\pm 0.02$ GeV/c^2) and with the most recent electroproduction experiment [4,19] ($M_A=0.96\pm 0.03$ GeV/c^2 and $M_A=0.97\pm 0.06$ GeV/c^2, respectively). A general discussion about the determination of M_A will be given in a forthcoming publication [20].

Our result for G_P is shown in Fig. 1, together with the muon capture point. The agreement with the pion pole dominance prediction is striking. It is the first time that this prediction is verified explicitly in this range of transfer. This, together with our result for $G_A(t)$, indicates a global consistency of both the experimental data and the theoretical analysis. Apparently the corrections due to S-wave rescattering, heavy mesons exchanges, and higher commutators have a negligible effect in the range of transfer of this experiment. This certainly deserves further theoretical investigations.

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