Nucleon Form Factors '99*

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We review recent progress in the experimental knowledge of and theoretical speculations about nucleon form factors, with special emphasis on the large Q^2 region.

1. THEORETICAL BACKGROUND

There is now a long history of continuous progress in the understanding of electromagnetic form factors at large momentum transfer. After the pioneering works [1] leading to the celebrated quark counting rules, the understanding of hard scattering exclusive processes has been solidly founded [2]. A perturbative QCD subprocess is factorized from a wave function-like distribution amplitude $\varphi(x_i, Q^2)$ (x_i being the light cone fractions of momentum carried by valence quarks), the Q^2 dependence of which is analysed in the renormalization group approach. Although an asymptotic expression emerges from this analysis for the x dependence of the distribution, it was quickly understood that the evolution to the asymptotic Q^2 is very slow and that indeed some non pertubative input is required to get reliable estimates of this distribution amplitude at measurable Q^2.

The severe criticism [3] that most of the contributions to the form factor were coming from end-point regions in the x integration, especially when very asymmetric distribution amplitudes were used was answered by Li and Sterman [4] who proposed a modified factorization formula which takes into account Sudakov suppression of elastic scattering for soft gluon exchange. The resulting formula is, for the pion form factor:

$$F = 16\pi C_F \int dx dy \int b_1 db_1 \hat{\psi}(x, b_1) b_2 db_2 \hat{\psi}(y, b_2)\, \alpha_S\, T(b_1, b_2, x, y), \tag{1}$$

The integration range for the light-cone fractions of momentum x and y goes from 0 to 1. The functions $\hat{\psi}(x, b)$ contain a Sudakov form factor which suppresses contributions from large transverse distances b. This improvement leads to an enlargement of the domain of applicability of perturbative QCD calculations of exclusive processes. Whether accessible data may be understood within this formalism, is not yet clear and different strongly motivated conclusions have been stressed [5]. Let us briefly comment on this.

- Perturbative corrections are still unknown, and it would not be a great surprise if they give some enhancement factor; remember the K-factor of the Drell-Yan process.

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- The description of transverse size effects through Sudakov factors and through intrinsic k_T effects in the wave function may give rise to some double counting effects. The phenomenology of Sudakov suppression factors at moderate transfers is basically unknown.

- The Feynman 'soft' process may be a way to rephrase the perturbative calculation in some kinematical domain where this latter is not sound. It does however not seem logical to advocate Sudakov suppression of the perturbative process and not estimate the corresponding suppression factor in the soft case

- The concept of nuclear filtering [6] may turn to be very useful to the understanding of the free nucleon data. The relative contributions of short distance dominated versus soft processes should indeed be differentiated by the color transparency phenomenon. Selecting events where the outgoing hard scattered proton is not subject to final state interactions is indeed equivalent to selecting compact configurations which are characteristic of the short distance process.

In conclusion, it is fair to say that nobody now believes that form factors are sufficient to determine the proton distribution amplitude. A comprehensive analysis of many more data on different exclusive reactions at large transfers are needed. This in turn necessitates high luminosity high duty factor medium energy accelerators [7].

2. TIMELIKE REGION

The difference between the timelike and spacelike meson form factors has been analysed [8] in the framework of perturbative QCD with Sudakov effects included (but only in the simpler meson case).

In the timelike region, the amplitude for the hard process ruling $\gamma^* \to \pi^+\pi^-$ is simple to deduce from the spacelike formula:

$$T_H = 16\pi\alpha_S C_F \frac{xQ^2}{xQ^2 + \mathbf{k}^2 - i\varepsilon} \, \frac{1}{xyQ^2 + (\mathbf{k}-\mathbf{l})^2 - i\varepsilon}, \tag{2}$$

changing $Q^2 \to -W^2$. The new feature with respect to the spacelike form factor is that the contour of transverse momenta integration now goes near poles located at either: $\mathbf{k}^2 = xW^2 + i\varepsilon$ or: $(\mathbf{k}-\mathbf{l})^2 = xyW^2 + i\varepsilon$. Technically, these poles are, except in the end point regions $(x, y \to 0)$, far from the bounds of integration of the two independent variables $k = |\mathbf{k}|$ and $K = |\mathbf{k}-\mathbf{l}|$. Therefore, we may evaluate the integral by deforming the contour of integration in the complex plane of each of these variables.

The result of this analysis (for the meson case) is that the asymptotic behavior is the same in the timelike and spacelike regions but that the approach to asymptotia is quite slow and a rather constant enhancement of the timelike value is expected at measurable large Q^2. This study should be enlarged to the nucleon case where such an enhancement is clearly shown by experimental data [9].

3. EXPERIMENTAL PROGRESS

Up until only a few years ago, the quality of available data on nucleon form factors was quite limited, except for those on the magnetic form factor of the proton G_M^p, which had been accurately studied [10] up to over 30 (GeV/c)^2. Accurate measurements of the electric form factor of the proton G_E^p were restricted to Q^2-values below 1 (GeV/c)^2, because of the Q^2-weighting of the contribution from G_M^p in the Rosenbluth-separation technique. Studies of both neutron form factors had to use elastic or quasielastic scattering off a deuteron, whereby the subtraction of the contribution from the proton caused sizeable systematic uncertainties in the analysis.

It has been known for quite some time [11], that the quality of the data would be improved significantly by scattering polarized electrons either from a polarized target or from an unpolarized target while measuring the polarization of the recoiling or knocked-out nucleon. However, it has only been in the last few years that polarized beams became available with high polarization and intensity and the required polarized targets and recoil polarimeters were developed.

This has resulted in a first batch of new data with high precision. G_E^n has been measured at low Q^2 at Mainz [12] and NIKHEF [13] using polarized deuteron and ^3He targets and neutron polarimeters. All these experiments used large-acceptance detectors to compensate for the still limited luminosity, which required extensive Monte Carlo analysis techniques. Nuclear corrections, which for the deuteron turned out to be sizeable at very low Q^2-values, amounted [14] to $\approx 50\%$ for ^3He at $Q^2 \approx 0.35$ (GeV/c)^2, but now G_E^n-data are available with an accuracy of $\approx 15\%$ up to 0.65 (GeV/c)^2. G_E^p has been measured in Hall A [15] at JLab in a Q^2-range up to 3.5 (GeV/c)^2 using a focal-plane polarimeter to measure the polarization of the recoiling proton. The data with a statistical and systematic accuracy of less than 8% show that G_E^p decreases with Q^2 relative to G_M^p and the dipole prediction, indicating that the spatial distribution of the charge inside the proton extends further than that of the magnetization. G_M^n has been accurately measured up to 0.8 (GeV/c)^2 at Mainz [16] and Bonn[17] by measuring the ratio of neutron to proton knock-out from unpolarized deuterium. However, the two data sets do not overlap within their error bars and a new measurement of G_M^n in a similar Q^2-range has recently been performed at JLab [18], by studying quasi-elastic scattering of polarized electrons from a polarized ^3He target.

Further experiments have already been scheduled, or can be expected in a more distant future, to improve the accuracy and/or extend the Q^2-range of the existing data set. G_E^n will be measured at JLab up to $Q^2 \approx 2$ (GeV/c)^2 in two separate experiments [19], one using a neutron polarimeter, the other a polarized deuterium target. The BLAST detector [20] at the MIT-Bates facility will provide very accurate data in a lower Q^2-range, up to ≈ 0.8 (GeV/c)^2. The JLab G_E^p data set will be extended first to 6 (GeV/c)^2 with the same set-up as used in the first experiment [21], later to 10 (GeV/c)^2 using a lead-glass calorimeter for the detection of the scattered electron [22].

4. CONCLUSION

New data on nucleon form factors with an unprecedented precision have (and will continue to) become available in an increasing Q^2 domain. However, it is still difficult to make a precise statement on the applicability of improved perturbative calculations of the proton form factor at available momentum transfers. Future experience, to be gained from experiments at JLab at higher energies and at proposed dedicated machines [7], will provide essential information.

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