Nucleon Electromagnetic Form Factors and Quark Content

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The status of measurements of the ground-state electromagnetic form factors will be presented, with particular emphasis on recent measurements from both Mainz and JLab and some of their surprising implications. Also covered will be the exciting potential of future measurements.

At high Q^2, a series of recoil polarization experiments at JLab have provided accurate measurements of the ratio of the electric and magnetic form factors of the proton, G_E^p/G_M^p, up to $8.5\,\mathrm{GeV}^2$. The striking decrease of this ratio with increasing Q^2 has received considerable attention, including its implications for the importance of the effects of quark orbital angular momentum, as well as the importance of two-photon effects in traditional Rosenbluth separations. Recent measurements of the ratio of the electric and magnetic form factors of the neutron, G_E^n/G_M^n, have been made up to $Q^2 = 3.4\,\mathrm{GeV}^2$. When taken together with the proton results, it is now possible to extract the individual u- and d-quark contributions to the elastic nucleon form factors into a Q^2-regime that has proven to be quite interesting. The flavor-decomposed form factors exhibit several surprising behaviors. For example, The Dirac form-factor contribution from the down quark, F_1^d, appears to scale like $1/Q^4$ at the surprisingly low Q^2 of about $1\,\mathrm{GeV}^2$. In sharp contrast, the up-quark contribution F_1^u has a very different behavior, and if anything, scales more like $1/Q^2$. Based both on naive expectations from constituent counting rules as well as calculations based on QCD's Dyson-Schwinger equations, the behavior of F_1^d and F_1^u can be interpreted as providing strong evidence for the importance of diquark degrees of freedom.

At low Q^2, precise new cross-section data from Mainz as well as new polarization-transfer data from JLab provide significantly improved knowledge of the charge radius of the proton. These new data from Mainz and JLab agree with one another as well as with charge-radius determinations extracted from Lamb Shift measurements on hydrogen. A new and very accurate measurement of the Lamb Shift in muonic hydrogen, however, is in sharp disagreement with these other determinations, a discrepancy that is as yet unresolved.

Much progress has also been made on the time-like form factors which are intimately related to the space-like form factors through dispersion relations. Data from BABAR as well as LEAR have greatly extended the Q^2 range over which measurements exist. Interestingly, there is significant disagreement between these two data sets. It is also notable that recent observations of the time-like transition form factor of the pion by BABAR show a strong violation of the scaling predicted by perturbative QCD.

Looking forward, the JLab 12 GeV upgrade will roughly double the Q^2 range over which the space-like ground-state electromagnetic form factors are known, and will enable the extraction of flavor-separated form factors up $10\,\mathrm{GeV}^2$. Such measurements remain a unique probe of the transverse structure of the nucleon at short distance scales. Given the unanticipated behaviors that have been observed in recent years, these measurements are of great importance. Knowledge of time-like form factors will also be greatly improved at high Q^2 with future measurements at BES-III in Beijing and PANDA in Darmstadt. At low Q^2, precise measurements will be key to understanding the puzzle presented by the recent measurement of the Lamb Shift in muonic hydrogen. New low-Q^2 experiments are planned at both Mainz and JLab. In summary, in a diverse set of measurements, the electromagnetic nucleon form factors are continuing to provide new insight into nucleon structure and moving us toward a solution of QCD in the non-perturbative regime.