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Precision Measurement of $\mu G_E^p / G_M^p$ at Low Q^2

Received: 22 November 2010 / Accepted: 26 November 2010
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Abstract Precision measurements are presented of the proton electric to magnetic form-factors ratios at $Q^2 = 0.3 - 0.8 (GeV/c)^2$, obtained by polarization-transfer in Hall A of the Jefferson Laboratory. The measured ratios are significantly lower than published values. New global fits to the individual form factors indicate a lower electric form factor and a slightly higher magnetic form factor. The proton charge radius extracted from the new results is somewhat smaller but consistent with previous values obtained from electron–proton scattering, and is in significant disagreement with the recent value obtained from muonic hydrogen. The effects of the new results on other quantities are briefly discussed.

The elastic electromagnetic (EM) form factors (FFs), $G_E(Q^2)$ and $G_M(Q^2)$, of nucleons are fundamental quantities for nucleons' structure. Their intuitive interpretation is that of the Fourier transforms of the nucleon's charge and magnetization densities, but this interpretation only holds for the Breit frame in the non-relativistic limit. In the infinite-momentum frame, the FFs are related in a model-independent way to the nucleon's two-dimensional charge and magnetization distributions in the plane transverse to the nucleon's motion.

$G_E(Q^2)$ and $G_M(Q^2)$ have been measured for many years utilizing the “Rosenbluth separation”. However, this method does not allow the precise extractions of G_E at large Q^2 and of G_M at small Q^2 (except for electron scattering angles very close to 90°). In the last decade, intense high quality polarized electron beams, highly polarized targets, and nucleon polarimeters at the Jefferson Laboratory (JLAB), MIT-Bates and MAMI have allowed the use of polarization observables for the precision measurement of the elastic EM FFs ratios, $\mu G_E / G_M(Q^2)$, at both high and low Q^2 . At high Q^2 , the elastic EM FFs are sensitive to the short-distance structure of nucleons and parton degrees of freedoms, while at low Q^2 they are sensitive to the large-distance structure, including the pion cloud and nucleon size. These new precise experimental results have been accompanied by a flurry of new theoretical activities.

New measurements of the proton FFs ratios at $Q^2 = 0.3 - 0.8 (GeV/c)^2$ are presented here. These measurements were performed in Hall A of JLAB using the polarization-transfer reaction $p(\vec{e}, e' \vec{p})$ and yielded the most precise data to date. The preliminary new results, as well as previously published data from polarization observables at $Q^2 < 1 (GeV/c)^2$ are displayed in Fig. 1. The new data consist of the results of two independent measurements and analyses [1]. The data from these two new measurements are consistent with each other, but are significantly lower than and not consistent with previously published results from JLAB [2, 3] and BATES [4]. We note that the data by Ron et al. (Ledex) [3] have recently been re-analyzed. The new Ledex results are in excellent agreement with our new data, and will be submitted for publication shortly. Our

Presented at the 21st European Conference on Few-Body Problems in Physics, Salamanca, Spain, 30 August–3 September 2010.

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Fig. 1 World data of $\mu_p G_E^p / G_M^p(Q^2)$ for $Q^2 < 1(\text{GeV}/c)^2$. The new results are the blue solid dots and black solid square [1]. The updated global fit (dashed-red) is the only one that includes the new data. The dashed-black curve is the previous global fit [6], and the dashed-blue curve is an older fit [7]

new results are also in good agreement with new measurements from MAMI [5]. The disagreements between our new results and the BATES [4] and the JLAB results by Punjabi et al. [2] are yet to be resolved.

The new FFs ratios decrease slowly with Q^2 in this Q^2 range, and their pattern suggests that the ratio is smaller than unity even at very low Q^2 . This implies that at large distances the charge distribution in the proton is larger than the magnetization distribution.

Also shown in Fig. 1 are several fits to the world data at $Q^2 < 1$. The updated global fit by J. Arrington takes into account two-photon corrections. It is the only fit that includes our new preliminary results. The fit by Arrington, Melnitchouk, and Tjon (AMT) [6] is the previous global fit. It takes 2-photon corrections into account but does not include our new data. It is evident that the new data significantly affect the global fit of the ratios.

The updated global fit that includes the new data yields individual FFs at this Q^2 range that are $\sim 2\%$ lower for G_E^p and $\sim 0.5\%$ higher for G_M^p than previously determined. This, in turn, affects the Dirac (F_1^p) and Pauli (F_2^p) FFs that are linear combinations of G_E^p and G_M^p . It also affects the values of the isoscalar and isovector FFs that are linear combinations of the Dirac and Pauli FFs of the proton and neutron and are important for lattice QCD calculations.

Other quantities rely on the EM FFs for their determination. The strange FFs of nucleons as measured by parity violating elastic electron scattering rely on the values of the EM FFs. The new values of G_E^p and G_M^p change the values of the strange FFs in this Q^2 range by about 0.5σ .

At $Q^2 < 1(\text{GeV}/c)^2$, the e-d elastic cross sections depend mainly on $(G_E^p)^2$. In this Q^2 range, there is also a long-standing discrepancy between model calculations of the e-d elastic cross sections and the data - the calculated cross sections over estimate the experimental data by a few percent. Using the updated (smaller) value for G_E^p in the calculations will result in a better agreement with the data.

The hyperfine splitting of the hydrogen ground state is calculated in QED to a very high precision. The difference between the QED and the experimentally-determined values is due to several correction related to the proton's structure. The largest uncertainty in these corrections is the uncertainty in the Zemach radius, which depends on the EM elastic FFs. Because of the form of the Zemach radius, about 70% of its uncertainty is determined by the uncertainty in the EM form factors at $Q^2 < 1(\text{GeV}/c)^2$. Our precise determinations of the EM FFs reduces the uncertainty of the Zemach radius from ~ 1 to $\sim 0.5\%$.

Finally, the charge and magnetization radii of the proton were determined from the new global fits of the FFs and their slopes at $Q^2 = 0$. They yield a charge radius of $0.870(10)$ fm, lower than but consistent with the CODATA value of $0.877(7)$ fm, the global-fit value by Sick of $0.897(18)$ fm [8] and the new value from the MAMI measurement of $0.879(8)$ fm [5]. It is much higher than the very precise charge radius of 0.840 fm recently determined from muonic hydrogen data [9]. The discrepancy between the values from elastic e-p scattering and that from the muonic hydrogen data is not well understood. We determine the magnetization

radius of the proton to be smaller than the charge radius, 0.850(30) fm, but the uncertainty in this value is relatively large.

A new measurement scheduled for late 2012 in Hall A at JLAB will employ elastically scattered polarized electrons from a polarized proton target to measure $\mu G_E^p / G_M^p$ for $Q^2 = 0.015 - 0.4(\text{GeV}/c)^2$. It will allow much smaller extrapolation of the FFs to $Q^2 = 0$, and hence a much more precise extraction of the proton charge and magnetization radii.

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