Coulomb corrections in the extraction of the proton radius

John Arrington
Physics Division, Argonne National Laboratory, Argonne, IL 60439, USA

Abstract.

Multi-photon exchange contributions are important in extracting the proton charge radius from elastic electron–proton scattering. So far, only diagrams associated with the exchange of a second photon have been evaluated. At the low $Q^2$ values relevant to the radius extraction, and especially the very low $Q^2$ region to be probed by proposed measurements, higher order contributions may become important. We evaluate these corrections in the Effective Momentum Approximation, which includes the Coulomb interaction to all orders, and find small corrections with a strong $Q^2$ dependence at low $Q^2$ and large scattering angles. This suggests that the higher order terms may be important in the evaluation of the proton magnetic radius.

PACS numbers: 13.40.Gp,14.20.Dh,25.30.Bf
Coulomb corrections in the extraction of the proton radius

The proton RMS charge radius, $R_p$, has become a topic of great interest following recent Lamb shift measurements in muonic hydrogen [1, 2] which are extremely sensitive to $R_p$. These measurements yield $R_p=0.8409(4)$ fm, significantly smaller than recent extractions based on electron–proton interactions [3, 4, 5, 6, 7]. The extractions include both electron scattering and electron–proton interactions in the hydrogen atom, which yield a combined result of $R_p=0.8772(46)$ [6, 8], or $R_p=0.8775(51)$ according to the CODATA10 evaluation [9]. Significant efforts have gone into examining the current extractions and examining possible physics which could explain the discrepancy [10], but there is not yet a clear explanation.

In the atomic physics measurements, atomic transitions in hydrogen (or muonic hydrogen) are measured with high precision. Because the non-relativistic wavefunction for the electrons in S states have some overlap with the finite charge distribution of the proton, the Coulomb potential is modified at very short distances. This yields a very small correction to these energy levels and thus in transition such as the Lamb shift (2S-2P transition), which has been measured to to better than a part in $10^{14}$. Extraction of the radius from this measurement involves many corrections to the non-relativistic calculation, including uncertainty associated with the details of the spatial distribution of charge in the proton. Including these uncertainties, the radius extracted from such measurements is 0.8758(77) fm (Adjustment 6 of Ref. [9]).

In muonic hydrogen, the muon has significantly more overlap with the charge distribution of the proton because it is approximately 200 times more massive than the electron. Thus, the impact of the finite size of the proton yields a much greater correction to the energy levels, so a significantly less precise measurement of the Lamb shift in muonic hydrogen can determine the proton radius to much greater precision: $R_p = 0.84087(39)$ fm [2]. Again, there are significant corrections [11, 12, 13] to the simple non-relativistic calculations, which have been examined in great detail in light of the discrepancy [10].

In elastic electron-proton scattering, the finite size of the proton yields a deviation in the cross section from scattering off of a point-like charge. These are encoded in the charge and magnetic form factors, $G_E(Q^2)$ and $G_M(Q^2)$, where $-Q^2$ is the square of the four-momentum transfer between the electron and proton, and thus represents the momentum scale at which the proton structure is being probed. In the non-relativistic picture, the rest-frame RMS charge radius is directly related to the slope of the charge form factor at $Q^2=0$. However, relativistic boost corrections need to be applied, breaking the equivalence of these quantities. Because these boost corrections depend on the complicated sub-structure of the protons, the convention is to define the radius through the relation

$$R_p^2 = -6\frac{dG_E(Q^2)}{dQ^2}$$

in the limit $Q^2 \to 0$. Note that this is the equivalent to the definition of $R_p$ used in the extraction from the Lamb shift in hydrogen and atomic hydrogen.

Radiative corrections play an important role in the electron scattering measurements. While the largest corrections are well understood, the diagrams which depend on the proton structure, e.g. the two-photon exchange (TPE) diagrams, cannot be calculated exactly due to the hadronic structure uncertainty. In the past, these corrections were calculated in the 2nd Born approximation, assuming the exchange of a second soft photon with an unexcited intermediate state. Initial calculations were performed in the limit $Q^2 \to 0$ [14], and later at finite $Q^2$, which require a
Coulomb corrections in the extraction of the proton radius

3

parameterization of the proton charge and magnetic form factors, $G_E$ and $G_M$. The inclusion of these corrections was found to be important in the extraction of the proton radius [15, 3].

More recently, calculations going beyond the 2nd Born approximation have been performed [16, 17, 18, 19, 20, 21, 22], motivated by the discrepancy between Rosenbluth and polarization measurements at high $Q^2$ [23, 24, 25, 26, 27]. See recent reviews [28, 29] for further details on the different theoretical approaches. There have also been several phenomenological extractions of TPE contributions [30, 31, 32, 33, 34, 35, 36] and attempts to experimentally constrain TPE [37, 38, 39, 40, 41, 42, 43, 44], but essentially all of these works focus on $Q^2 > 2–3$ GeV$^2$, where there is a clear discrepancy between the Rosenbluth and polarization extractions of the form factors.

All of these calculations include only the effect of a second virtual photon exchange. Because the corrections are at the few percent level and this is an expansion in the fine structure constant, $\alpha \approx 1/137$, it is expected that two-photon terms should be sufficient. However, while higher order terms in the expansion are expected to be small, the approximations made in evaluating these contributions can yield a large range of results. The full TPE calculations include both the exchange of hard and soft photons, while evaluations in the 2nd Born approximation include only the exchange of a second soft photon. One can see that this has a significant impact even at low $Q^2$, and especially at low $\varepsilon$, by comparing the results in Figures 1 and 2. In some cases, e.g. Ref. [5], the correction calculated for a structureless proton, corresponding to the $Q^2 = 0$ limit of the 2nd Born calculation [29]. Note that this means that no $Q^2$ dependence is included for the exchange of the second photon, while the radius is determined entirely from the $Q^2$ dependence of the form factors. This also implies that the correction is of the wrong sign for $Q^2 > 0.3$ GeV$^2$, where the correction changes sign for both the soft-photon approximations and the full TPE calculations [29].

Figure 1. Range of results for several TPE calculations at low $Q^2$ [17, 45, 19, 46, 20, 47, 48]. Solid, long-dashed, short-dashed, and dotted lines show the range for $Q^2 = 0.01, 0.03, 0.1$, and $0.2$ GeV$^2$, respectively. Note that the low $Q^2$ expansion [46] is only valid up to $Q^2 = 0.1$ GeV$^2$, and so is excluded from the $Q^2 = 0.2$ GeV$^2$ range.

Focusing on the low $Q^2$ regime, relevant to the extraction of $R_p$, Figure 1 shows
the range of TPE corrections to the cross section based on a set of calculations which include both hard and soft TPE and which aim to be reliable at low \( Q^2 \). These include hadronic calculations with only protons in the intermediate state by Blunden, Melnitchouk, and Tjon \[17\] and by Borisyuk and Kobushkin \[19\], as well as calculations including intermediate \( \Delta \) \[15\] and \( \pi-N \) intermediate states \[18\]. Also shown are the Borisyuk and Kobushkin low-\( Q^2 \) TPE expansion \[16\] and their dispersion calculations excluding \[20\] and including \[47\] \( \Delta \) resonance contributions. While the correction decreases with increasing \( Q^2 \) for \( \varepsilon > 0.4 \), the TPE correction for \( \varepsilon < 0.3 \) first increases and then decreases. These corrections have been shown to have an important effect on the form factor extraction at low \( Q^2 \) values \[49\], as well as impacting the extracted charge and magnetization radii of the proton \[50, 6, 19, 51, 52\]. Given that present extractions from electron scattering measurements yield some inconsistency in the magnetic radius \[8, 6\], a detailed examination of all corrections at small \( Q^2 \) values is important in determining if there are any issues which could indicate issues with the extracted charge radii.

While calculations of TPE cross section corrections at higher \( Q^2 \) values tend to have greater range of results \[28, 29\], and for polarization observables yield an even larger range of predictions \[43\], the various approaches which are expected to be valid at low \( Q^2 \) indicate minimal model dependence. The results show a typical spread between calculations below 0.05%, suggesting that the TPE corrections are well known in this region. At these low \( Q^2 \) values, deviations from a linear correction in \( \varepsilon \) are small except for extreme \( \varepsilon \) values, making tests of the linearity of the Rosenbluth separation \[35, 32\] fairly insensitive to the low \( Q^2 \) contributions of these calculations. Note, however, that these TPE contributions are taken relative to the Mo & Tsai \[53\] prescription for radiative corrections. The IR-divergent contribution of the TPE contributions is included in all radiative correction procedures, to cancel the divergent term in the interference between electron and proton Bremsstrahlung. However, different prescriptions can have different finite residual contributions from TPE, which differ from that of Mo & Tsai. Almost all experiments have used the Mo & Tsai treatment of the TPE contributions, except for the recent Mainz measurement \[5, 7\], which applied the prescription of Maximon and Tjon \[16\]. Therefore, the TPE contributions in Fig 1 would have to be modified by the difference between the Mo & Tsai and the Maximon and Tjon TPE prescriptions, as shown in Figure 12 of Ref. \[29\]. However, at low \( Q^2 \) values this difference becomes very small and only weakly-dependent on \( Q^2 \), and so has little effect on the form factors in the region of interest for the radius extraction.

Extraction of the radius requires cross sections measured at low \( Q^2 \), meaning low electron energies, especially in the case of large-angle measurements needed to constrain \( G_M \) and the magnetization radius. At low energies, the change in the electron energy due to its interaction with the Coulomb potential of the nucleus may yield an important change in the kinematics at the scattering vertex. In quasi-elastic scattering this effect is sometimes estimated in the Effective Momentum Approximation (EMA) \[54\], where the acceleration due to the Coulomb field of a high-Z nucleus can have a significant impact on the e–p scattering kinematics by shifting the kinematics at the scattering vertex. This approach has the advantage of including the Coulomb interaction to all orders in a semi-classical picture, and can easily be applied to both high- and low-energy kinematics. In addition, the shift accounts for the fact that the hard photon can probe the proton at a different \( Q^2 \) value, which is not included in the evaluation of two-photon exchange in calculations which work in
Coulomb corrections in the extraction of the proton radius

the limit of \( q \to 0 \) for the second photon. More details of the EMA and comparisons to more complete approaches, where available, are given in Ref. [55, 56].

Figure 2. Coulomb corrections calculated in the 2nd Born approximation for e–p elastic scattering for \( Q^2 \) values from 0.01 GeV\(^2\) (top curve) to 1 GeV\(^2\) (bottom curve).

Figure 2 shows the fractional correction to the cross section in the 2nd Born approximation. One can make a crude estimate of the impact of these corrections on the radius. The RMS radius, \( R_p \), is defined in terms of the low \( Q^2 \) expansion of the form factor, \( G_E(Q^2) \approx 1 - Q^2 R_p^2 / 6 \), with a similar expression for the magnetic radius. A proton RMS radius of 0.85 fm yields \( G_E(Q^2) \approx 1 - 3 Q^2 \), with \( Q^2 \) in GeV\(^2\), or a fractional slope at \( Q^2 = 0 \) of roughly 300%/GeV\(^2\). The charge form factor contribution to the cross section goes like \( G_E(Q^2) \), for a slope of roughly 600%/GeV\(^2\) in the cross section. Coulomb corrections in the 2nd Born approximation change the cross section by about 0.2% between \( Q^2 = 0.01 \) and 0.03 GeV\(^2\) (Fig. 2), yielding a change in the slope of 0.2%/0.02 GeV\(^2\)=10%/GeV\(^2\). This is roughly 2% of the total slope introduced by the protons size, corresponding to a 1% change in the extracted radius, in good agreement with the observation of a roughly 0.01 fm change observed when the 2nd Born calculation is applied to the data [15]. Note that using this measure, the discrepancy between electron- and muon-based results yields a change in the slope of the reduced cross section of \( \approx 50% / \text{GeV}^2 \), or a 1% change in the cross section at \( Q^2 = 0.02 \) GeV\(^2\).

In this paper, we estimate the impact of higher-order Coulomb corrections by applying the EMA prescription of Ref. [57] to elastic e–p scattering at low \( Q^2 \). The key parameter in the calculation is the Coulomb potential at the point where the scattering occurs. When the EMA is used to evaluate scattering from a heavy nucleus, it is generally assumed that the scattering occurs uniformly within the nucleus, so the Coulomb potential is taken to be something between the surface and central potential. Averaging over the nuclear volume, assuming a uniform charge sphere, yields a potential that is 80% of the central potential, in good agreement with the result of Ref. [54] which adjusts the average potential in the EMA calculations to match distorted-wave Born approximation results [58, 59] which are more reliable but
Coulomb corrections in the extraction of the proton radius

can only be performed at lower $Q^2$ values.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{coulomb_correction.png}
\caption{Coulomb corrections calculated in the Effective Momentum Approximation (as described in the text) for $e^–p$ elastic scattering for $0.01 < Q^2 < 1 \text{ GeV}^2$.}
\end{figure}

At high energies, the EMA calculation yields a correction that is very similar to the 2nd Born approximation for $\varepsilon > 0.5$, as shown in Ref. [57], with small differences larger-angle scattering. Note that the EMA calculation applied in Ref. [57] used the central potential and did not include the flux factor of Ref. [54]. Inclusion of this correction yields somewhat improved agreement at low $\varepsilon$, but there are still clear differences remaining. For heavy nuclei and low energy scattering, there can be significant differences between the EMA result and more complete calculations [56], although the qualitative behavior is always reasonable.

For $e^–p$ elastic scattering at very low $Q^2$, one expects that the scattering will occur when the electron is outside of the proton, so using the average Coulomb potential in the proton would be an overestimate. We take the Coulomb potential corresponding to the case where the scattering occurs at a separation $\Delta x = 1/q$, where $q$ is the momentum of the exchanged virtual photon. This will suppress the impact of the energy shift for $Q^2$ values where the scattering occurs outside of the proton. This occurs for $Q^2 < 0.03 \text{ GeV}^2$ if we take the proton to be a uniform sphere of radius 1.15 fm to match the observed RMS radius. For $Q^2$ values where the scattering occurs inside of the proton, we limit the Coulomb potential to a maximum of the volume-averaged value of 1.5 MeV.

Figure 3 shows the Coulomb correction in the EMA. The behavior is qualitatively similar to the 2nd Born approximation result for $Q^2 = 1 \text{ GeV}^2$, as it is for larger $Q^2$ values [57]. The EMA result has a very different angular dependence at very low $Q^2$ values, with a sharp rise at low $\varepsilon$. As such, this correction could have an important impact on the low $Q^2$ extraction of the form factors and radius, especially for the extraction of $G_M$ and the magnetic radius. Note that the comparison of our EMA and the 2nd Born approximation (Figs. 2 and 3) show a much smaller correction in the EMA approach at very low $Q^2$ and large $\varepsilon$ (corresponding to larger electron energies), where the EMA should still be reasonably reliable. This suggests that taking
Δx = 1/q yields too much suppression of the correction at very low Q², and that the effects may be larger in this region. While the EMA is not expected to yield precise results in this region, it does allow for contributions that are not included in the 2nd Born approximation, and is therefore a reasonable tool for an initial investigation of such effects.

Figure 4. Q² dependence of the EMA correction at ε=0.02 (solid), 0.2 (long dash), and 0.5 (short dash).

Figure 4 shows the EMA result as a function of Q² for three ε values. At larger ε values, the effect is small, especially near Q²=0. As noted above, explaining the charge radius discrepancy would require a change in the slope of the reduced cross section at large ε of 50%/GeV², or a 1% change between Q² = 0.01 and 0.03 GeV², while the calculation yields a change of around 0.05%. So this suggests a negligible effect on the extraction of the charge radius.

For the magnetic radius, the low-ε results are more significant. At ε = 0.02, there is a very rapid rise with Q² (note that Q² is shown on a logarithmic scale). From the Q² dependence of the correction, it is straightforward to estimate what impact this would have on a direct extraction of the magnetic radius from very low Q² data at ε ≈ 0. The EMA yields a 1% change in the correction for a change in Q² of less than 0.01 GeV², or a change in the slope of 100%/Q². This would correspond to a very large correction to the magnetic radius.

However, existing measurements below Q²=0.1 GeV² are limited and there aren't measurements over this Q² and ε range. The kinematics of interest for existing data are at somewhat larger Q² or ε values. At ε=0.02, the correction decreases by 1.5% going from Q² = 0.03 GeV² to 0.2 GeV², while for ε = 0.2, it increases 0.3% in going from 0.01 to 0.03 GeV². These provide changes in the fractional slope of the cross section of ~8%/GeV² and +15%/GeV², respectively, corresponding to small but potentially significant corrections to the extracted magnetic proton radius. In addition, because the extraction of G_M comes from an extrapolation of the reduced cross section to ε = 0, where the cross section is very small, the fact that the different Q² dependence seen at low and high values of ε may yield a magnification of the impact on the magnetic radius.
While this rough estimate shows that these effects could have important contributions to the extraction of the magnetic radius, it is difficult to provide a more detailed estimate of the impact. First, because it is very sensitive to the exact kinematics of the data included in the extraction. The corrections would have to be applied to each measurement and then the radius extraction procedure, including fitting of normalization factors if they are allowed to vary, would have to be repeated. In addition, it is not clear how one would combine the results of the EMA at very low $Q^2$ with the TPE calculations, to include the full impact of the corrections without double counting. A more detailed calculation, e.g. in the distorted-wave Born approximation, would allow for a more reliable evaluation of the importance of the higher order contributions.

Two-photon exchange effects have been examined in the comparison of $e^- - p$ and $e^+ - p$ scattering, but existing data are limited in precision and are at $Q^2$ values that are too large to have a significant impact on the radius extraction \cite{60}. New $e^\pm - p$ measurements have made to examine two-photon exchange at Novosibirsk \cite{39, 61, 62}, Jefferson Lab \cite{63, 64, 65, 44}, and DESY \cite{66, 67, 68}, but will not extend below $Q^2 = 0.5$ GeV$^2$ except at very forward angles. However, these effects can be examined in future measurements at very low $Q^2$ in comparisons of $e^\pm - p$ and $\mu^\pm - p$ scattering in the MUSE experiment at PSI \cite{69}.

In conclusion, we find a clear qualitative difference between the 2nd Born approximation and the EMA evaluation of Coulomb corrections for $e^- - p$ elastic scattering at low $Q^2$. The difference is particularly important large angles, where the data are sensitive to $G_M(Q^2)$, suggesting that effects beyond two-photon exchange may be important in the extraction of the magnetic radius. A quantitative estimate of their impact would involve a more detailed calculation, with the impact of the correction evaluated using on the exact data set and fitting procedure used to extract the radius.

Acknowledgments

I thank M. K. Medina checking the calculations presented here, and A. Aste, P. Blunden and B. Kobushkin for providing calculations and useful discussion. This work was supported by the U.S. DOE through contract DE-AC02-06CH11357.

References

[1] Randolf Pohl et al. *Nature*, 466:213–216, 2010.
[2] Aldo Antognini, Francois Nez, Karsten Schuhmann, Fernando D. Amaro, FrancoisBiraben, et al. *Science*, 339:417–420, 2013.
[3] Ingo Sick. *Phys. Lett. B*, 576:62–67, 2003.
[4] Peter J. Mohr, Barry N. Taylor, and David B. Newell. *Rev. Mod. Phys.*, 80:633–730, 2008.
[5] J. C. Bernauer et al. *Phys. Rev. Lett.*, 105:242001, 2010.
[6] X. Zhan et al. *Phys. Lett.*, B705:59–64, 2011.
[7] J.C. Bernauer et al. *arXiv:1307.6227*, 2013.
[8] G. Ron et al. *Phys. Rev. C*, 84:055204, 2011.
[9] Peter J. Mohr, Barry N. Taylor, and David B. Newell. *Rev. Mod. Phys.*, 84:1527–1605, 2012.
[10] Randolf Pohl, Ronald Gilman, Gerald A. Miller, and Krzysztof Pachucki. *Ann. Rev. Nucl. Part. Sci.*, 63, 2013.
[11] Michael I. Eides, Howard Grotch, and Valery A. Shelyuto. *Phys. Rept.*, 342:63–261, 2001.
[12] Savely G. Karshenboim. *Phys. Rept.*, 422:1, 2005.
[13] Aldo Antognini et al. *Annals Phys.*, 331:127, 2013.
[14] W. A. McKinley and H. Feshbach. *Phys. Rev.*, 74:1759, 1948.
Coulomb corrections in the extraction of the proton radius

[15] R. Rosenfelder. Phys. Lett. B, 479:381, 2000.
[16] L. C. Maximon and J. A. Tjon. Phys. Rev. C, 62:054320, 2000.
[17] P. G. Blunden, W. Melnitchouk, and J. A. Tjon. Phys. Rev. C, 72:034612, 2005.
[18] Andrei V. Afanasev, Stanley J. Brodsky, Carl E. Carlson, Yu-Chun Chen, and Marc Vanderhaeghen. Phys. Rev. D, 72:013008, 2005.
[19] Dmitry Borisuyk and Alexander Kobushkin. Phys. Rev. C, 74:065203, 2006.
[20] Dmitry Borisuyk and Alexander Kobushkin. Phys. Rev. C, 78:025208, 2008.
[21] Nikolai Kivel and Marc Vanderhaeghen. Phys. Rev. Lett., 103:092004, 2009.
[22] Dmitry Borisuyk and Alexander Kobushkin. Phys. Rev. D, 79:034001, 2009.
[23] J. Arrington. Phys. Rev. C, 68:034325, 2003.
[24] P. A. M. Guichon and M. Vanderhaeghen. Phys. Rev. Lett., 91:142303, 2003.
[25] J. Arrington, C. D. Roberts, and J. M. Zanotti. J. Phys., G34:23, 2007.
[26] C. F. Perdrisat, V. Punjabi, and M. Vanderhaeghen. Prog. Part. Nucl. Phys., 59:694, 2007.
[27] John Arrington, Kees de Jager, and Charles F. Perdrisat. J. Phys. Conf. Ser., 299:012002, 2011.
[28] Carl E. Carlson and Marc Vanderhaeghen. Ann. Rev. Nucl. Part. Sci., 57:171, 2007.
[29] J. Arrington, P.G. Blunden, and W. Melnitchouk. Prog. Part. Nucl. Phys., 66:782–833, 2011.
[30] J. Arrington. Phys. Rev. C, 71:015202, 2005.
[31] Dmitry Borisyuk and Alexander Kobushkin. Phys. Rev. C, 76:022201, 2007.
[32] Yu-Chun Chen, Chung-Wen Kao, and Shin-Nan Yang. Phys. Lett., B652:269–274, 2007.
[33] M.A. Belushkin, H.-W. Hammer, and U.-G. Meissner. Phys. Rev. C, 84:034314, 2011.
[34] Krzysztof M. Graczyk. Phys. Rev. C, 84:034314, 2011.
[35] I. A. Qattan and A. Alsaad. Phys. Rev. C, 83:054307, 2011.
[36] I. A. Qattan, A. Alsaad, and J. Arrington. Phys. Rev. C, 84:054317, 2011.
[37] I. A. Qattan et al. Phys. Rev. Lett., 94:142301, 2005.
[38] V. Tvaskis et al. Phys. Rev. C, 73:025206, 2006.
[39] J. Arrington et al. arXiv:nucl-ex/0408020, 2004.
[40] John Arrington. AIP Conf. Proc., 1160:13–18, 2009.
[41] Dmitry Borisuyk and Alexander Kobushkin. Phys. Rev. C, 75:038202, 2007.
[42] J. Arrington, W. Melnitchouk, and J. A. Tjon. Phys. Rev. Lett., 107:119101, 2011.
[43] J.C. Bernauer et al. Phys. Rev. Lett., 107:119102, 2011.
[44] Luke W. Mo and Yun-Su Tsai. Rev. Mod. Phys., 41:205, 1969.
[45] Andreas Aste, Cyrill von Arx, and Dirk Trautmann. Eur. Phys. J., A26:191–215, 2008.
[46] Andreas W. Aste. Nucl.Phys., A806:191–215, 2008.
[47] J. Arrington and I. Sick. Phys. Rev. C, 70:025203, 2004.
[48] K.S. Kim, L.E. Wright, Yanhe Jin, and D.W. Kosik. Phys. Rev. C, 54:2515, 1996.
[49] J.M. Udias, P. Sarriguren, E. Moya de Guerra, E. Garrido, and J.A. Caballero. Phys. Rev. C, 48:2731–2739, 1993.
[50] J. Arrington. Phys. Rev. C, 69:032201(R), 2004.
[51] D. M. Nikolaenko et al. PoS, ICHEP2010:164, 2010.
[52] W. Brooks, A. Afanasev, J. Arrington, K. Joo, B. Raue, L. Weinstein, et al. Jefferson Lab experiment E07-005.
[53] L.B. Weinstein. AIP Conf. Proc., 1160:24–28, 2009.
[54] Robert Paul Bennett. AIP Conf. Proc., 1441:156–158, 2012.
[55] M. Kohl. AIP Conf. Proc., 1374:527–530, 2011.
[56] Richard G. Milner. AIP Conf. Proc., 1441:159–161, 2012.
[57] R. Gilman et al. arXiv:1303.2160, 2013.