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## Is the Coulomb sum rule violated in nuclei?

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### Abstract

Guided by the experimental confirmation of the validity of the Effective Momentum Approximation (EMA) in quasi-elastic scattering off nuclei, we have re-examined the extraction of the longitudinal and transverse response functions in medium-weight and heavy nuclei. In the EMA we have performed a Rosenbluth separation of the available world data on <sup>40</sup>Ca, <sup>48</sup>Ca, <sup>56</sup>Fe, <sup>197</sup>Au, <sup>208</sup>Pb and <sup>238</sup>U. We find that the longitudinal response function for these nuclei is “quenched” and that the Coulomb sum is not saturated, at odds with claims in the literature.

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One of the important questions in nuclear physics is how nucleon properties are affected by the nuclear medium, since it might form a bridge between the strong interaction between nucleons and the underlying theory of Quantum Chromodynamics (QCD). A good example is the partial restoration of chiral symmetry in nuclear matter and its consequence for nucleon properties in the nuclear medium (for comprehensive reviews see [1,2]). Since elastic scattering from a free nucleon has been well measured, quasi-elastic electron scattering off nuclei is considered a promising tool to investigate the properties of nucleons in nuclei. In particular, it was proposed [3] that a Rosenbluth separation of the electric and magnetic responses of a nucleus ( $R_L$  and  $R_T$ , respectively) could test a model-independent property known as the Coulomb sum rule (CSR). This sum rule states that when integrating the quasi-elastic  $R_L(q, \omega)$  over the full range of energy loss  $\omega$  at large enough three-

momentum transfer  $|\mathbf{q}| = q$  (greater than twice the Fermi momentum,  $q \gtrsim 500$  MeV/c), one should count the number of protons ( $Z$ ) in a nucleus. More explicitly the quantity  $S_L(q)$  defined by

$$S_L(q) = \frac{1}{Z} \int_{0^+}^{\infty} \frac{R_L(q, \omega)}{\tilde{G}_E^2} d\omega \quad (1)$$

is predicted to be unity in the limit of large  $q$ . Here  $\tilde{G}_E = (G_E^p + N/Z G_E^n)\zeta$  takes into account the nucleon charge form factor inside the nucleus (which is usually taken to be equal to that of a free nucleon) as well as a relativistic correction ( $\zeta$ ) suggested by de Forest [4]. The lower limit of integration  $0^+$  excludes the elastic peak.

This simple picture can be polluted by the modification of the free nucleon electromagnetic properties by the nuclear medium and the presence of nucleon–nucleon short-range correlations. There is general agreement that around  $q$  of 500 MeV/c,  $S_L$  should not deviate more than a few percent from unity due

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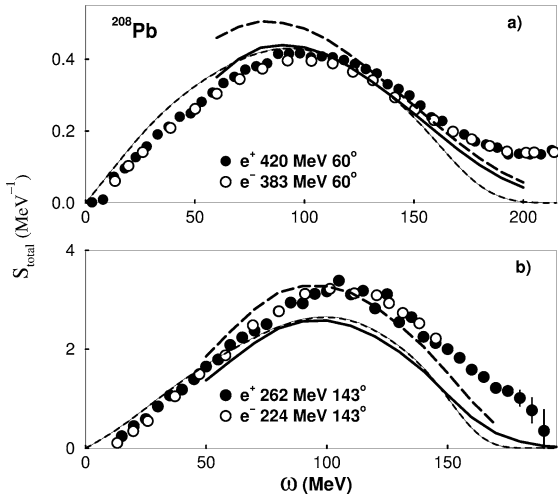


Fig. 1.  $e^+$  (filled circles) and  $e^-$  (open circles) total response functions at the same effective incident energies along with the Ohio group calculations ( $e^+$  thick solid lines,  $e^-$  thick dashed lines) and the Trento group calculations ( $e^+$  thin solid lines,  $e^-$  thin dashed lines).

to nucleon–nucleon correlations, and reach unity at higher  $q$ -values, independent of the nucleon–nucleon force chosen (see the review paper [5]). Thus, a result of  $S_L$  far from unity might indicate a modification of the nucleon electric properties in the nuclear medium.

In the last twenty years a large experimental program has been carried out at Bates [6–14], Saclay [15–19] and SLAC [20–22] aimed at the extraction of  $R_L$  and  $R_T$  for a variety of nuclei. Unfortunately, in the case of medium-weight and heavy nuclei conclusions reached by different experiments ranged from a full saturation of the CSR to its violation by 30%. As a result a spectrum of explanations has emerged ranging from questioning the validity of the experiments (i.e., experimental backgrounds), inadequate Coulomb corrections (especially for heavy nuclei) to suggesting picture of a “swollen nucleon” in the nuclear medium due to a partial deconfinement [23–27].

Up to now the Coulomb corrections for inclusive experiments have been evaluated theoretically by two independent groups, one from Trento University [28–30] and the other from Ohio University [31]. The Trento group found that the Effective Momentum Approximation (EMA) works with an accuracy better than 1%, while the Ohio group derived significant corrections beyond EMA. All useful quantities

for the EMA are defined in [28,29,32,33]. A detailed discussion of the different theoretical approaches can be found in [30]. Previous extractions of  $R_L$  and  $R_T$  were performed either without Coulomb corrections in [16,17] or by applying the Trento group calculations [19], or the Ohio group calculations [14,34]. This led to questionable results even when Coulomb corrections from either groups were applied, particularly in the region beyond the quasielastic peak known as the “dip region” since meson exchange currents and pion production while significant, but were not included in any of the nuclear models used.

Recently and for the first time the Coulomb corrections have been studied in a direct comparison of quasielastic electron and positron scattering off  $^{12}\text{C}$  and  $^{208}\text{Pb}$  at forward (Fig. 1(a)) and backward (Fig. 1(b)) angles [33]. It has been found experimentally that the EMA can adequately describe the electron and positron scattering over the entire quasielastic and dip regions. For the quasielastic region were theoretical calculations have been performed, this comparison is in agreement with Traini and collaborators’ result [28–30] and in disagreement with the Ohio group’s result as shown in Fig. 1. Recent full DWBA calculations of the Ohio group [35] are presented here instead of the LEMA calculations presented in [33], nevertheless, the disagreement with the experimental comparison persists. Values of the effective Coulomb potential  $\tilde{V}_C$ , equal to half the difference between the electrons and positrons incident energies, were extracted from this comparison allowing us to separate  $R_L$  and  $R_T$  with the EMA independently from any theoretical calculations of the Coulomb corrections. The values of  $\tilde{V}_C$  were found to be very close to the average Coulomb potential of the nucleus and not to the value  $V_C(0)$  at the center of the nucleus (see Table 2 of Ref. [33]) as used previously by several authors including ourselves [10,14,19,34].

We present here the results of a reanalysis of the Saclay data only using the Coulomb corrections based on the EMA to extract  $R_L$  and  $R_T$  and evaluate  $S_L(q)$ . Our goal was to first determine the change in our previously reported results which either had no Coulomb corrections applied, for  $^{40}\text{Ca}$ ,  $^{48}\text{Ca}$  and  $^{56}\text{Fe}$  [16] or for  $^{208}\text{Pb}$  [19], had Coulomb corrections applied following a procedure described by Traini et al. [28] with  $V_C(0)$  instead of  $\tilde{V}_C$  and a too crude nuclear model which generated spurious higher order

corrections. Next, it was important to test whether the data from SLAC and Bates analyzed within the EMA would influence our original results as quoted in [34] for the case of  $^{56}\text{Fe}$ . For that purpose, we present the results obtained with the EMA by combining data from Saclay, Bates and SLAC on  $^{40}\text{Ca}$ ,  $^{48}\text{Ca}$ ,  $^{56}\text{Fe}$ ,  $^{197}\text{Au}$ ,  $^{208}\text{Pb}$  and  $^{238}\text{U}$  [8,9,14,16,19,20,36]. In order to combine different nuclei at the same kinematics, we normalized each nucleus with the factor

$$\mathbf{K} = Z[(\epsilon\sigma_{ep}^L + \sigma_{ep}^T) + N(\epsilon\sigma_{en}^L + \sigma_{en}^T)],$$

where  $\epsilon$  is the virtual photon polarization and  $\sigma_{ep(n)}^{L(T)}$  is the longitudinal (transverse) virtual photon–proton (–neutron) cross section. We conclude by evaluating  $S_L$  and testing the Coulomb sum rule.

In Fig. 2 we present the results of the Rosenbluth separation at  $q_{\text{eff}} = 570 \text{ MeV}/c$ , the same  $q_{\text{eff}}$  as used in Jourdan’s analysis. In our original publication the highest  $q$ -value chosen was  $550 \text{ MeV}/c$  to avoid regions of high  $\omega$  where systematic errors are large and difficult to estimate. There is a clear disagreement between the results in [34] and the present analysis above  $\omega = 150 \text{ MeV}$  for  $R_T$  and  $\omega = 230 \text{ MeV}$  for  $R_L$ . The difference between these results is significant for both  $R_L$  and  $R_T$  and we attribute it to the Coulomb corrections used in [34] following the Ohio group calculations [31] since, as shown in Fig. 1, these corrections do not reproduce the EMA behavior observed in the comparison of electron and positron quasielastic cross section [33]. Within the EMA, the same nominal momentum is obtained by adding at each incident energy a constant negative value  $\tilde{V}_C$ . Therefore, larger cross sections are used to perform the Rosenbluth separation of  $R_L$  and  $R_T$  because the new incident energies are lower at all angles. However, due to the lower value of the incident energy required at backward-angles for the same  $q_{\text{eff}}$ , the relative increase in the cross section is more sizeable at backward-angles than at forward angles. Consequently, within EMA,  $R_T$  is increased and  $R_L$  decreased. This effect was previously seen in the results of SLAC experiment NE9 [21] at  $q_{\text{eff}} = 1 \text{ GeV}/c$ . However, as shown in Fig. 2, the Coulomb corrections applied in [34] following the prescription described in [31] have the opposite effect, namely, to decrease  $R_T$  and to enhance  $R_L$ . We note that the results of the present analysis are only slightly changed

when we combine the forward-angle SLAC NE3 [36] and the Saclay data.

The situation for the Bates measurements on  $^{40}\text{Ca}$  [14] and  $^{238}\text{U}$  [10] requires further clarification. Backward-angle cross sections were measured in an early stage of the experiment, where secondary scattering background was present. This background was estimated in part by performing some experimental tests and corrected using a simulation code. Forward-angle cross sections,  $^{238}\text{U}$  at  $60^\circ$  and  $^{40}\text{Ca}$  at  $45.5^\circ$ , have been measured with a modified experimental setup. Cross sections of  $^{56}\text{Fe}$  at  $180^\circ$  [8] have been also measured at Bates with another setup. In Fig. 3 we have compared backward-angle data by comparing the transverse responses. The  $^{56}\text{Fe}$   $180^\circ$  data is purely transverse, and transverse responses obtained after separation from  $^{56}\text{Fe}$  measurements at  $140^\circ$ ,  $143^\circ$ ,  $160^\circ$ , depend very little on the uncertainties of the forward-angle measurements. We can observe a good agreement between Saclay and the  $180^\circ$   $^{56}\text{Fe}$  measurements from Bates. However, discrepancies between the  $^{40}\text{Ca}$  backward-angles data from Bates and Saclay (Fig. 3(a)), and  $^{238}\text{U}$  from Bates and  $^{208}\text{Pb}$  from Saclay (Fig. 3(b)) are observed. Part of these discrepancies are due to the Coulomb corrections, but there remain experimental differences in spite of the background corrections performed in the Bates experiments. Fig. 3(c) shows the total responses at  $60^\circ$  of  $^{238}\text{U}$  from Bates with the new setup and of  $^{208}\text{Pb}$  from Saclay in fairly good agreement. Also, longitudinal and transverse responses of  $^4\text{He}$  and  $^3\text{He}$  obtained in a Rosenbluth separation from forward- and backward-angle measurements using the new experimental setup at Bates [11,12] are also in good agreement with the Saclay response functions [18,19] as shown in Fig. 4.

In Fig. 5 we show results for  $R_L$  (a) and  $R_T$  (b) at  $q_{\text{eff}} = 550 \text{ MeV}/c$  and for  $R_L$  (c) at  $500 \text{ MeV}/c$  obtained with a reanalysis of  $^{208}\text{Pb}$  in the EMA [33]. The data are compared to the previously published work of Zghiche et al. [19]. Furthermore, for a consistency check of our analysis, we present in Fig. 5 results obtained by combining the Saclay data, the  $^{197}\text{Au}$  SLAC data [36] and the  $^{238}\text{U}$  Bates data [10]. Both data sets were renormalized to  $^{208}\text{Pb}$  with the factor  $\mathbf{K}$ , equal to 1.05 for  $^{197}\text{Au}$  and 0.88 for  $^{238}\text{U}$ . For  $^{238}\text{U}$  we have used only the  $60^\circ$  data taken with the new experimental setup but not data at backward angle taken with the earlier setup [37]. While there is a clear

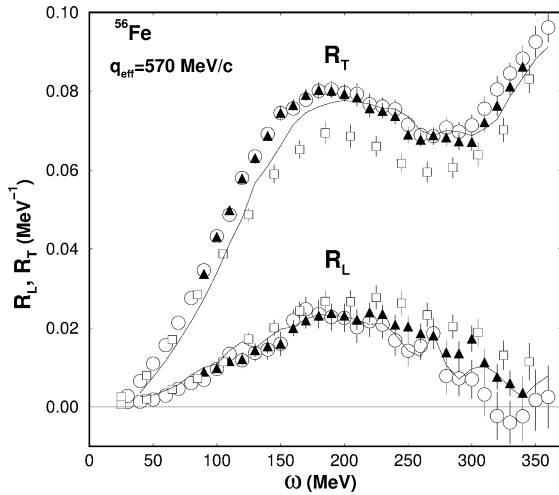


Fig. 2.  $R_L$  and  $R_T$  response functions of  $^{56}\text{Fe}$  extracted at  $q_{\text{eff}} = 570 \text{ MeV}/c$  in the present analysis using the Saclay data only (circles), then with adding the SLAC data from NE3 [36] (triangles) and from Jourdan's analysis [34] (squares). The result of the original Saclay analysis without Coulomb corrections [16,17] is indicated by the solid line.

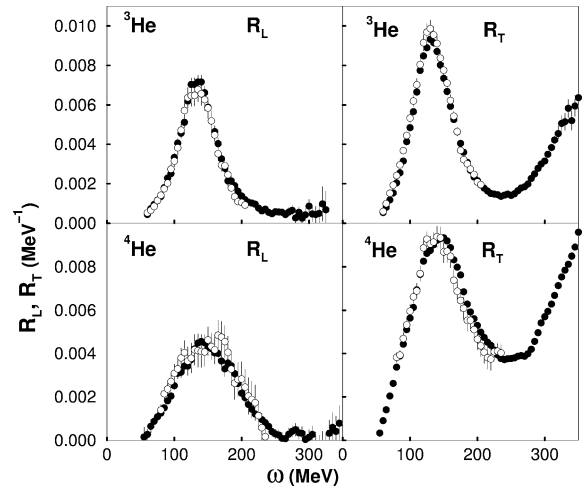


Fig. 4. Longitudinal and transverse response functions of  $^3\text{He}$  and  $^4\text{He}$  at  $q = 500 \text{ MeV}/c$ . Bates data [11,12] are the open circles and Saclay data [18,19] are the filled circles.

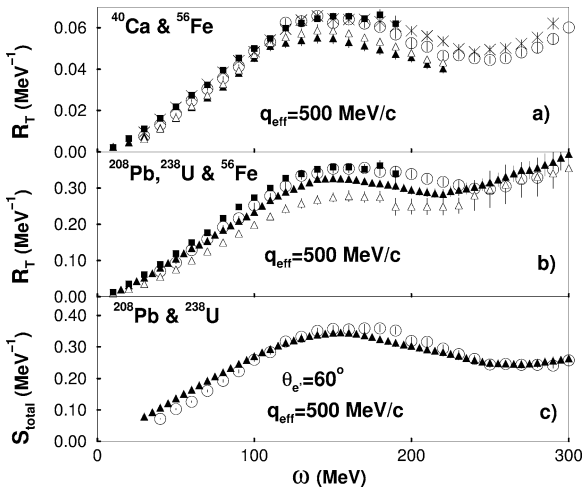


Fig. 3. (a) Transverse response functions of  $^{40}\text{Ca}$ : Saclay data (open circles), Bates results [14] (filled triangles), our analysis of Bates data using EMA (open triangles) and  $^{56}\text{Fe}$  Saclay data (crosses), Bates data at  $180^\circ$  (filled squares); (b) Transverse response functions of  $^{208}\text{Pb}$ : Saclay data (open circles),  $^{238}\text{U}$  Bates results (filled triangles), our analysis of Bates results using EMA (open triangles) and  $^{56}\text{Fe}$  Bates data at  $180^\circ$  for comparison (filled squares); (c) Total response function at  $60^\circ$  of  $^{208}\text{Pb}$  (open circles) and  $^{238}\text{U}$  (filled triangles).

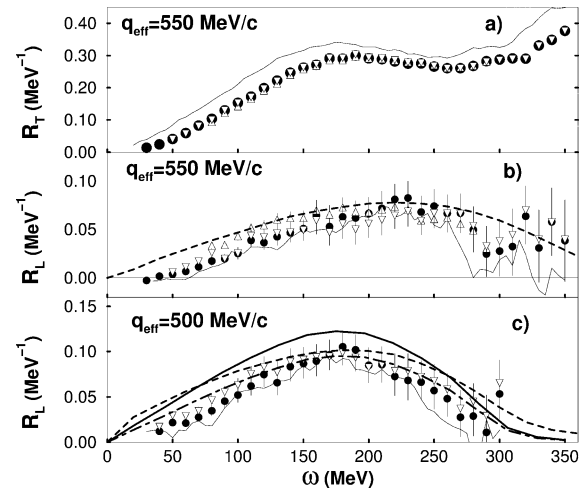


Fig. 5. Longitudinal (a) and transverse (b) response functions of  $^{208}\text{Pb}$  at  $q_{\text{eff}} = 550 \text{ MeV}/c$  extracted in the EMA. Saclay data only (filled circles), combined with  $^{197}\text{Au}$ - $15^\circ$  SLAC data (triangles up), combined with Bates  $^{238}\text{U}$ - $60^\circ$  data (triangles down); previous Saclay results with Coulomb corrections [19]: thin solid lines. (c) Longitudinal response function at  $q_{\text{eff}} = 500 \text{ MeV}/c$  (same experimental symbols). Nuclear matter calculations [38]: dashed line, Hartree Fock calculations including short range correlations and final state interactions [39] with free nucleon form factors (solid line), with modified nucleon form factors (dotted-dashed line).

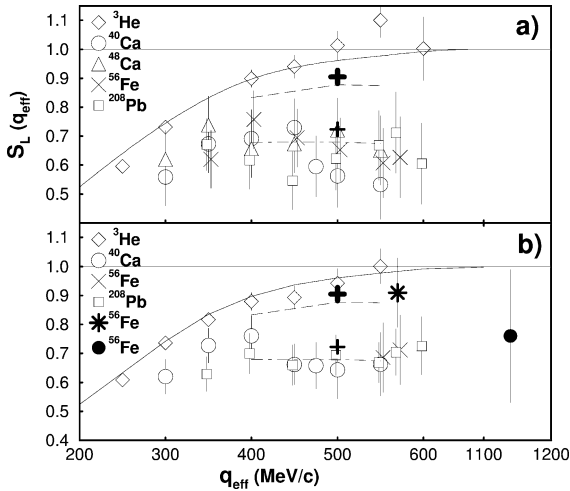


Fig. 6.  $S_L$  obtained in the EMA as a function of  $q_{\text{eff}}$  using only Saclay data (a) and using Saclay data combined with SLAC NE3 and Bates data with the new experimental setup (b). N–M calculations [38] (solid line), N–M calculations integrated within the experimental limits: dashed line, same with modified form factors (dotted-dashed line),  $^{208}\text{Pb}$  H–F calculations [39] integrated within the experimental limits (thick right cross), same with modified form factors (thin right cross).  $^{56}\text{Fe}$  SLAC NE9 [21] (filled circle) and Jourdan analysis of  $^{56}\text{Fe}$  Saclay data (thick star) are shown in (b).

difference in  $R_T$  between the previously published work [19] and this analysis the conclusions regarding the quenching of  $R_L$  have not changed qualitatively. Fig. 5 also shows that combining the SLAC, Bates and Saclay data to extract  $R_L$  and  $R_T$  does not change the results significantly. We also present in Fig. 5 ((b) and (c) panels) microscopic Nuclear Matter calculations (NM) of  $R_L$  at 550 and 500 MeV/c [38] (dashed lines) and Hartree–Fock calculations (HF) of  $R_L$  at 500 MeV/c including short-range correlations and final-state interaction [39] (solid line). If the integrated strengths of  $R_L$  within the experimental limits are quite close (5% more strength for HF; see Fig. 6, compared to NM), the shapes are different. The large energy excitation tail of  $R_L$  is much less important in the HF than in the NM calculation. Finally, we plotted in Fig. 5(c) the HF calculation with a modified form factor [40,41] (dotted-dashed curve) (discussed later in the text) and find a fairly good agreement with the combined Saclay and Bates-60° data (triangles down).

We now turn to the results of the experimental Coulomb sum but first discuss the quantitative difference between the EMA analysis and that of Ref. [34]

as summarized in Table 1. A comparison between the present result of  $S_L$  for  $^{56}\text{Fe}$  and that of Ref. [34] identifies two possible sources for the difference; (a) the Coulomb corrections and (b) the use of the total error in the Saclay data but only the statistical error in the SLAC data. For (a), we believe that the Coulomb corrections used in [34] following the prescription of [31], at variance with the experimental confirmation of the EMA [33], have the wrong sign; they increase the longitudinal response instead of decreasing it. The Coulomb corrections within the EMA reduce  $S_L$  by 10% while it is increased by 5% in [34]. For (b), more weight was given to the SLAC NE3 data by neglecting the 3.5% systematic error quoted by the authors [36], leading to an artificial enhancement of  $R_L$  by 4%.

Fig. 6 shows the results obtained in the present analysis for  $S_L$  of  $^{40}\text{Ca}$ ,  $^{48}\text{Ca}$ ,  $^{56}\text{Fe}$  and  $^{208}\text{Pb}$ . In Fig. 6(a) the data shown were obtained using only cross section measured at Saclay, whereas in Fig. 6(b) the results by combining data from at least two different laboratories among Bates, Saclay and SLAC except for the data point from SLAC experiment NE9 at  $q_{\text{eff}} = 1.14$  GeV/c. Among the Bates cross section data of  $^{40}\text{Ca}$  and  $^{238}\text{U}$  we chose to use only those measured at forward-angles with the modified experimental setup. In order to evaluate  $S_L$  we used the Simon [42] parametrization of the proton charge form factor, while for the neutron charge form factor we have taken into account the data by Herberg et al. [43]. We note that for  $^{208}\text{Pb}$  the total error in the experimental determination of  $\tilde{V}_C$  is 1.5 MeV leading to a relative uncertainty of 2% on  $S_L$  at  $q_{\text{eff}} = 500$  MeV/c. We have plotted the total NM Coulomb sum [44] (solid line), a partial NM Coulomb sum integrated only within the experimental limits at  $400 \leq q_{\text{eff}} \leq 550$  MeV/c [38] (dashed curve) and a partial HF Coulomb sum in  $^{208}\text{Pb}$  integrated within the experimental limits at  $q_{\text{eff}} = 500$  MeV/c [39] (thick right cross). The experimental results are to be compared with the partial sum and not the total sum values. We observe a quenching between 20% and 30% in all medium and heavy nuclei.

The observed quenching is similar to the quenching of the ratio  $R_L/R_T$  observed in a  $^{40}\text{Ca}$  ( $e e' p$ )  $^{39}\text{K}$  experiment [45] which was performed at energy transfers  $\omega$  near or below the maximum of the quasi-elastic peak ( $\omega \lesssim \omega_{\text{max}}$ ) where the quasi-elastic process is dominant. The observed quenching of  $R_L/R_T$  implies

Table 1

Comparison of the Coulomb sum results in  $^{56}\text{Fe}$  between Jourdan's work and the present analysis. Total refers to the statistical and systematic uncertainties added in quadrature. Jourdan's Coulomb corrections are described in [34] following the Ohio group prescription [31]. This work Coulomb corrections when applied are performed following the EMA [33]

Analysis	Saclay uncertainty	SLAC data	SLAC uncertainty	Coulomb corrections	$S_L$
Jourdan	Total	Included	Statistical	No	$0.86 \pm 0.12$
	Total	Included	Statistical	Yes	$0.91 \pm 0.12$
Present work	Total	Not included	–	No	$0.72 \pm 0.23$
	Total	Not included	–	Yes	$0.63 \pm 0.20$
	Total	Included	Total	No	$0.82 \pm 0.12$
	Total	Included	Total	Yes	$0.73 \pm 0.12$

that  $R_T$  is little affected by the medium while  $R_L$  is reduced. On the other hand, when analyzing the SLAC data [36,46], it has been observed that the un-separated cross sections scale at momentum transfers  $q \gtrsim 2 \text{ GeV}/c$  for  $\omega \lesssim \omega_{\text{max}}$ . It was pointed out in [46] that this scaling is destroyed if one introduces medium effects in the nucleon form factors. However, at these momentum transfers the longitudinal component represents only 20% or less of the total cross section; a quenching of the longitudinal response ranging from 20% to 30% produces a quenching between 4% and 6% for the un-separated cross sections, which clearly remains within the experimental band of the scaling representation [47]. Consequently, the conclusion that no medium effects are observed applies essentially to the transverse response, in agreement with what we obtain from the Saclay ( $e, e'$ ) and ( $e, e'p$ ) experiments.

Several authors have proposed models for medium effects to explain this quenching [23–25], but found it difficult to explain why only  $R_L$  was affected by the medium. A later model based on chiral-symmetry restoration in nuclei [27,40] predicted a decrease of vector-meson masses (and consequently a decrease of the nucleon form factor) inside nuclei. In this model only  $R_L$  is affected while  $R_T$  changes very little because the magnetic operator is changed by about the same amount as the magnetic form factor due to the change of the nucleon free mass into the effective mass. The dot-dashed curve and the thin right cross are from similar calculations to those of the dashed curve and the thick right cross except that we have replaced the free nucleon form factor by a modified form factor

in  $^{208}\text{Pb}$  calculated in Ref. [40]. We can see that there is a good agreement with the data. A quenching of about 20% of  $R_L$  with a small change of  $R_T$  has also been predicted in calculations based on an improved Walecka model [48] using density dependent coupling constants and relativistic RPA correlations [49,50].

In conclusion, there is a good agreement between the data from Saclay, SLAC, Bates 180° experiments and Bates data taken with the new setup. We believe that we have established experimentally the existence of a quenching of  $S_L$  in medium and heavy nuclei as shown in Fig. 6. This quenching is not observed in low-density nuclei such as  $^3\text{He}$  and  $^2\text{D}$  [11,18] and short-range correlations are not able to explain this effect. We interpret this as an indication for a change of the nucleon properties inside the nuclear medium. If we assume the dipole expression for the charge form factor, the observed quenching of the CSR would correspond to a relative change of the proton charge radius of  $13 \pm 4\%$  in a heavy nucleus. The accuracy of the CSR could be improved and the  $q$  region extended up to  $1 \text{ GeV}/c$  with the new generation of electron accelerators. Such a proposal has been approved recently at Jefferson Lab [51].

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