Electroweak Radiative Effects in Deep Inelastic Interaction of Polarized Leptons and Nucleons

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Abstract

The results for one-loop correction to deep inelastic scattering of longitudinal polarized leptons on longitudinal polarized hadrons are obtained within the framework of the standard theory of electroweak interactions and ordinary quark-parton model. The on-shell renormalization scheme in t’Hooft-Feynman gauge is applied.

The numerical analysis is carried out under conditions of modern particle physics experiments. Particular emphasis is laid on contributions usually ignored at RC procedure – electroweak corrections to electromagnetic asymmetry and RC to hadronic current. The structure of RC contribution to polarized asymmetries within the framework of QED and electroweak theory is also discussed.

1 Introduction

Main sources of an information about spin properties of nucleons are experiments on deep inelastic scattering (DIS) of polarized lepton by polarized targets [1]-[4]. Results of the last ones [2]-[4] form an inconsistent picture of nature of nucleon spin (see [5] and reference therein). This stimulates realization of new experiments [3, 7] on measurement of proton and neutron spin-dependent SF $g_1^{p,n}$ and $g_2^{p,n}$ and on testing of Bjorken [8], Ellis-Jaffe [9] and Burkhardt-Cottingham [10] sum rules.

An interpretation of experimental data requires an adequate calculation of background radiative effects (RE). The one-loop contribution to cross section of DIS of non-polarized particles within the framework of quantum electrodynamics (QED) was widely discussed in literature (see, for example, [11]-[13]). Results of model-independent part of the one-loop QED contribution and model-dependent RE in hadronic current (hadronic RE) in DIS of polarized particles can be found in [14, 15].

In the present report the results for one-loop radiative correction (RC) to DIS of polarized lepton on polarized proton are obtained within the framework of the standard theory of electroweak interaction and ordinary parton model. We follow to the on-mass renormalization scheme in t’Hooft-Feynman gauge [16] (see also the reviews [17]-[20]) and use the results of calculation for the case of non-polarized particles [21, 22]. We note, that the problem of infrared divergence cancellation

$^{1}$Some estimates of the one-loop contribution in DIS of polarized particles can be found in article [23]
has been resolved within covariant approach been proposed in [12]: the RC is to be finally free from dependence of any unphysical parameter like ”photon softness”.

In section 2 we discuss one-loop RC to DIS of polarized particles. It is shown, that RC can be separated by leading-log contribution and contribution independent of particle masses. In this report we give the explicit form only for leading log contribution. In section 3 infrared free one-loop RC is studied numerically. We study the structure of contributions in polarization asymmetry, calculate the magnitudes of effects normally missed at RC procedure of experimental data and analyse RC to SF $g_1(x, Q^2)$ and to sum rules.

2 One-loop RC

We consider DIS of longitudinally polarized leptons on longitudinally polarized nucleons

$$\ell(k_1, \xi) + N(p, \eta) \to \ell(k_2) + X$$

(1)

with taking into account the one-loop RE within parton model. The vectors in brackets designate a momentum and polarization of appropriate particles ($k_1^2 = k_2^2 = m^2$, $p^2 = M^2$). A complete set of Feynman graphs is presented in figure 1. The result can be written in a form of sum of the Born contribution, R- and V-contributions (the first line of graphs in figure 1 and the last ones)

$$\sigma = \sigma_0 + \sigma_v + \sigma_r,$$

(2)

where $\sigma_0, v, r \equiv d^2 \sigma_{0, v, r}/dxdy$, and $x, y$ are scaling variables.

The on-shell renormalization scheme of electroweak theory is submitted in the reviews [16, 17] and is advanced in [18]-[20]. This scheme uses an electrical charge and masses of particles as physical parameters. Both self-energies together with a complete set of renormalization constants and vertex functions of fermions were calculated in [16]. Renormalization formulae for self-energies of vector bosons, vertex functions and graphs of two boson exchange were also presented. All results of [16] are given in a form convenient for further applications to RC calculation for fermion processes, including DIS. We use these results for calculation of V-contribution.

V-contribution can be written as a sum of the contributions of self-energies of vector boson and quark ($\sigma_{s}^B, \sigma_{s}^q$), vertex functions of lepton and hadron ($\sigma_{vl}, \sigma_{vq}$) and contributions of two boson exchange ($\sigma_{box}$):

$$\sigma_v = \sigma_{s}^B + \sigma_{s}^q + \sigma_{vl} + \sigma_{vq} + \sigma_{box}.$$  

(3)

As usual we keep the leading contributions (containing mass singularity — $\ln m^2$) and next-to-leading ones (without any mass dependence). In this report we give the explicit form only for leading contributions (for more details see [24]).
Figure 1: A complete set of electroweak graphs, contributed to lepton-quark scattering within quark-parton model. The double line corresponds to the contribution of \( \gamma \)- or \( Z \)-exchange. All possible graphs, which give the contribution to vacuum polarization, are designated by symbol \( \bullet \).
The mass singularity in the V-contribution due to smallness of mass of particles participating in a scattering, is contained only in the correction to vertex:

\[
\sigma_V = \frac{\alpha}{2\pi} \Lambda_1(Q^2, m^2) \sigma_0, \\
\sigma_{Vq} = \frac{\alpha}{2\pi} \sum_q e_q^2 \Lambda_1(Q^2, m_q^2) \sigma_0^q.
\]

(4)

Here \(e_q\) is quark charge, and \(\sigma_0 = \sum_q \sigma_0^q = \sum_{ij=\gamma Z} \sigma^{ij}\). The function \(\Lambda_1(Q^2, m^2)\) is given by the formula (B.3) of [16]. In our case it has the form

\[
\Lambda_1(Q^2, m^2) = \ln \frac{Q^2}{m^2} \left(1 + \ln \frac{Q^2}{m^2}\right).
\]

(5)

Self-energies of vector bosons

\[
\sigma_B = -2\Pi^\gamma \sigma_0^{\gamma Z} - 2(\Pi^\gamma + \Pi^Z) \left(\sigma_0^{\gamma Z} + \sigma_0^{Z\gamma}\right) - 2\Pi^Z \sigma_0^{ZZ} - 2\Pi^{Z\gamma} \sigma_0^{Z\gamma}
\]

(6)

have mass singularity due to smallness of particle mass appearing in loops of vacuum polarization. The quantities \(\Pi^{\gamma, Z, \gamma Z}\) are polarization operators and \(\sigma_0^{\gamma Z}\) was found in [24]. For simplicity we give expressions for vacuum polarization by leptons only. For the various polarization operators (6) we have

\[
\Pi^\gamma = -\frac{\alpha}{3\pi} \sum_{l=e,\mu,\tau} (v_l^\gamma)^2 \ln \frac{Q^2}{m_l^2}, \\
\Pi^{Z\gamma} = -\frac{\alpha}{3\pi} \sum_{l=e,\mu,\tau} \left(v_l^\gamma v_l^Z - \frac{s_w}{c_w} ((v_l^Z)^2 + 3(a_l^Z)^2 - (a_l^W)^2)\right) \ln \frac{Q^2}{m_l^2}, \\
\Pi^Z = -\frac{\alpha}{3\pi} \sum_{l=e,\mu,\tau} \left(c_w^2 ((v_l^Z)^2 + 3(a_l^Z)^2) - \frac{s_w^2}{c_w^2} ((v_l^W)^2 + (a_l^W)^2)\right) \ln \frac{Q^2}{m_l^2},
\]

(7)

where \(v_l\) and \(a_l\) are vector and axial coupling constants of leptons, and \(c_w\) and \(s_w\) are cosine and sine of Weinberg angle.

Result for the contribution of process with radiation of real photon

\[
\ell(k_1, \xi) + (p, \eta) \to \ell(k_2) + \gamma(k) + X
\]

(8)

to observed cross section of DIS can be written in the form

\[
\sigma_R = \frac{\alpha}{2\pi} \ln \frac{Q^2}{\lambda^2} \sum_q J(Q^2, 0) \sigma_0^q + \frac{\alpha}{\pi} \sum_q \delta_q \sigma_0^q + \sum_q \sigma_R^q,
\]

(9)

where

\[
\sigma_R^q = \sum_{ij=\gamma, Z} \left\{ \sigma_{ij}^{l} + \hat{\delta}_{ij}^{l} + e_q \sigma_{lh}^{ij} + e_q^2 \left(\sigma_{ih}^{ij} + \hat{\delta}_{h}^{ij}\right) \right\}.
\]

(10)
Low index \((b = l, h, lh)\) of cross sections in right side of the equation corresponds to contributions of radiation by leptons, by hadrons and their interference. Only \(\sigma_{ij}^l\) and \(\sigma_{ij}^h\) content leading contributions.

The infrared divergence is extracted by the method of Bardin and Shumeiko \[12\]. It is completely contained in the first term of expression \(9\) and is cancelled with an appropriate term of \(V\)-contribution.

We distinguish three kinds of mass singularities: leptonic \((\ln Q^2/m^2)\), quark \((\ln Q^2/m_q^2)\) and nucleon \((\ln Q^2/M^2)\). Such singularities are contained in quantity \(\delta_q:\)

\[
\delta_q = -\frac{1}{2}l_m^2 + l_m(2l_v + l_{sx} + 1) + e_q^2(l_q(2l_v - \frac{1}{4})),
\]  

where \(l_m = \ln \frac{Q^2}{m^2}, \quad l_q = \ln \frac{Q^2}{m_q^2}, \quad l_v = \ln \frac{1-x}{x}, \quad l_{sx} = \ln \frac{y^2}{1-y} \),

and in \(\sigma_{ij}^l,\) which are considered below.

Firstly we consider dependence on leptonic mass \(m\), which is contained only in the contribution of radiation by leptons \(\sigma_{ij}^l\). Result in standard leading log form is obtained by splitting the cross section by the contributions appearing from \(k_1\)- and \(k_2\)-peaks \[25\]:

\[
\sum_{ij} \sum_q \sigma_{ij}^l = \sigma_{k_1}^l + \sigma_{k_2}^l,
\]

and

\[
\sigma_{k_1}^l = \frac{\alpha}{2\pi} l_m \int_{z_1^l}^{1} \frac{ydz_1}{z_1 - 1 + y} \left\{ \frac{1 + z_1^2}{1 - z_1} \sigma_{k_1}^0 - \frac{2}{1 - z_1} \sigma_0 \right\},
\]

\[
\sigma_{k_2}^l = \frac{\alpha}{2\pi} l_m \int_{z_2^l}^{1} \frac{ydz_2}{z_2 - 1 + y} \left\{ \frac{1 + z_2^2}{z_2(1 - z_2)} \sigma_{k_2}^0 - \frac{2}{1 - z_2} \sigma_0 \right\}.
\]

Here the cross sections \(\sigma_{0, k_1, k_2}^l\) are obtained from born one

\[
\sigma_0 \equiv \sigma_0(S, x, y)
\]

by replacements

\[
\sigma_{0, k_1}^l = \sigma_0 \left( z_1 S, \frac{xyz_1}{z_1 - 1 + y}, \frac{z_1 - 1 + y}{z_1} \right), \quad \sigma_{0, k_2}^l = \sigma_0 \left( S, \frac{xy}{z_2 - 1 + y}, \frac{z_2 - 1 + y}{z_2} \right).
\]

The low limits of integration are equal to

\[
z_1^l = (1-y)/(1-xy), \quad z_2^l = 1 - y + xy.
\]

The dependence on quark mass is retained only in the contributions of radiation by hadrons and in the leptonic QED correction. For the contribution of hadronic radiation \(\sigma_{ij}^h\) we obtain

\[
\sum_q e_q^2 \sigma_{ij}^h = \sigma_{ij}^0 \left( f^\pm_q(x) \rightarrow f^\pm_{q rad}(x) \right),
\]
where
\[
f_q^{\pm \text{rad}}(x) = e_q^2 \frac{\alpha}{2\pi} l_q \left\{ -f_q^{\pm}(x)(l_q + 2l_v) + \int_x^1 \frac{dz}{z} \left\{ \frac{1 + z^2}{1 - z} f_q^{\pm}(x/z) - \frac{2}{1 - z} f_q^{\pm}(x) \right\} \right\}. \tag{19}
\]

In the case of leptonic electromagnetic radiation the appearing of quark mass has a purely kinematic origin, and it can be replaced with proton mass in accord with the rule of parton model: \( m_q = \xi M \). It follows from comparison of results for electromagnetic radiation in parton model and ones obtained by a model independent way. In this case we have

\[
\sigma_{\gamma \gamma} = \frac{\alpha^3 y}{4} \ln \frac{Q^2}{M^2} \int_x^1 \frac{d\xi}{\xi} \left\{ T_{\pm M} R_{V}^{\gamma \gamma} F_{V}^{\gamma \gamma}(\xi) + T_{-M} R_{A}^{\gamma \gamma} F_{A}^{\gamma \gamma}(\xi) \right\}, \tag{20}
\]

where
\[
T_{\pm M} = -\frac{1 \pm (1 - y)^2}{S y(1 - y)} \frac{1 \pm (1 - x/\xi)^2}{x^2}. \tag{21}
\]

Thus, self-energies, vertex functions and the contributions of radiation by leptons and by hadrons have a mass singularity and therefore are significant. Neither the lepton-hadron interference in bremsstrahlung nor the contributions of two boson exchange contain any mass singularities. In this sense we speak, that the leptonic and hadronic corrections are separated. Radiation by leptons contains both leptonic and nucleon mass singularity. Extraction of contribution containing the leptonic mass in a separate term leads to peaking and leading log approximation. The contribution of a nucleon mass singularity corresponds to t-peak when a real photon is radiated parallel to virtual one. This contribution is not extracted by methods of the leading logarithms. The quark mass singularity in purely hadronic radiation is reduced to the correction to parton distributions \([19]\). In the leading log approximation this result for unpolarization and polarization cases was received in refs. \([26, 27]\).

3 Numerical analysis

In this section complete one-loop RC to various observables in DIS of polarized particles is analyzed numerically in a wide range kinematic variables. The special attention is paid to the contributions, which are usually neglected at the data analysis in modern polarization experiments: to the electroweak corrections to electromagnetic asymmetry and effects of radiation by hadrons. Important question on the structure of the contributions in polarization asymmetry in QED and electroweak theory is discussed as well.
3.1 Structure of contribution to polarization asymmetry

The cross section of DIS $\sigma$ both at a born level and at a level of the radiative corrections can be written as follows:

$$\sigma = \sigma^a + P_L \sigma^\xi + P_N \sigma^\eta + P_L P_N \sigma^{\xi\eta}. \quad (22)$$

Here $\sigma^a$ is unpolarization cross section, and three other terms give polarization contributions. $P_L$ and $P_N$ are polarization degrees of lepton and hadron.

Let us define the following quantities:

$$A_\xi = \frac{\sigma_\xi}{\sigma^a}, \quad A_\eta = \frac{\sigma_\eta}{\sigma^a}, \quad A_{\xi\eta} = \frac{\sigma_{\xi\eta}}{\sigma^a}, \quad (23)$$

and consider polarization asymmetry

$$A = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} = \frac{A_\eta + A_{\xi\eta}}{1 + A_\xi}. \quad (24)$$

We note, that $A$ equals to $A_{\xi\eta}$ in electrodynamics. By using as an example $A_{\xi\eta}$ we analyse magnitudes of the various one-loop contributions in asymmetry. Such analysis is convenient to conduct by expansion $A_{\xi\eta}$ with the account RC in a series over coupling constants:

$$A_{\xi\eta} = \frac{\sigma^0_{\xi\eta} + \sum_i \sigma^a_{i,\xi\eta}}{\sigma^a_0 + \sum_i \sigma^a_i} = A^0_{\xi\eta} + \frac{1}{\sigma^a_0} \sum_i (\sigma^a_{i,\xi\eta,0} - \sigma^a_{i,\xi\eta,0}) + O(\alpha^2), \quad (25)$$

where quantities with an index "0" are the born contributions. The sum on $i$ corresponds to separating of the one-loop correction into the contributions: effects of vacuum polarization, corrections to vertex, two boson exchange and bremsstrahlung of photon $\gamma$. \textit{From (25) we see if for any cross section $\sigma^{a,\xi\eta}_i$ a quantity}

$$\sigma^{\xi\eta}_i \sigma^a_0 - \sigma^{a,\xi\eta}_i \sigma^a_0 \quad (26)$$

is equal to zero, then it does not give the contribution to polarization asymmetry.

In QED the spin average and spin dependent parts of one-loop cross section can be written as

$$\sigma^{a,\xi\eta} = \sigma^{a,\xi\eta}_0 + (-2\Pi_\gamma^{\text{QED}} + \delta F_V^{\text{QED}} + \delta a^{a,\xi\eta}_2) \sigma^{a,\xi\eta}_0 + \delta a^{a,\xi\eta}_R. \quad (27)$$

The quantities $\delta a^{a,\xi\eta}_2$ describe the contribution of two-photon exchange and are agreed with ones considered in [13, 15]. A symbol "QED" indicates that only QED effects are retained in corresponding quantities. Expansion (23) in this case gives

$$A = A_0 (1 - \delta^{a}_{2,\gamma} + \delta^{\xi\eta}_{2,\gamma}) + (\sigma^{\xi\eta}_R \sigma^a_0 - \sigma^{a,\xi\eta}_R \sigma^a_0) / \sigma^a_0^2 + O(\alpha^2). \quad (28)$$
Among all terms of V-contribution only small (without mass singularity terms) effects of two-photon exchange contribute to polarization asymmetry. R-contribution has a leading log term and dominates in (28). The logarithmic correction to polarization asymmetry has been calculated in [27].

In the electroweak theory the contributions of vertex functions and self-energies are not factorized in front of born section and do not vanish in combination (26). That is valid for leading log contributions of polarization operators (7) and next-to-leading terms of vertex functions. Thus, in contrast to QED, where only bremsstrahlung contributes to polarization asymmetry, in electroweak theory V-contribution is also significant.

3.2 Electroweak effects and radiation by hadrons

Cross section of DIS with taking into account the complete one-loop correction can be presented by

$$\sigma = \sum_b \sum_B \sigma^{bB}. \quad (29)$$

The index $B = \gamma, I, Z$ corresponds to the contributions $\gamma$, $Z$-exchange and their interference, and $b = 0, l, h, i$ — to born contribution, leptonic, hadronic correction and lepton - hadronic interference. We note, that in modern polarization experiments the procedure RC takes into account only contribution $\sigma^{l\gamma}$, and the systematic error due to RC includes only an error of calculation of the leptonic QED correction.

Below we consider the electroweak effects at born and one-loop levels and contributions of radiation by hadrons. For convenience of the numerical analysis we define the next cross sections:

$$\sigma^{0} = \sum_{B=\gamma, I, Z} \sigma^{0B}, \quad \sigma^{had} = \sigma^{0\gamma} + \sum_{b=0,l,h} \sigma^{b\gamma},$$

$$\sigma^{lep}_{z} = \sigma^{0\gamma} + \sum_{B=\gamma,I,Z} \sigma^{IB}, \quad \sigma^{had}_{z} = \sigma^{0\gamma} + \sum_{b=0,l,h,B=\gamma,I,Z} \sum_{B=\gamma,I,Z} \sigma^{bB}. \quad (30)$$

In each of them in addition to the contributions $\sigma^{l\gamma}$ and/or $\sigma^{0\gamma}$ one of the following effects are added: QED radiation by hadrons ($\sigma^{had}$) and Z-exchange: at a born level ($\sigma^{0}$), at bremsstrahlung by lepton ($\sigma_{z}^{lep}$) and hadron ($\sigma_{z}^{had}$). Using (30), we construct of asymmetry (24) — $A_0$, $A_{z}^{had}$, $A_{z}^{lep}$ and $A_{z}^{had}$. In the range of small $x$ the basis contribution at an one-loop level is given by the QED correction, including correction to hadronic current. The contribution of the graphs with Z-exchange is insignificant both at a born level ($A_{z}^{0\gamma}$) and on a level of RC ($A_{z}^{\gamma\gamma}$, $A_{z}^{lep}$ and $A_{z}^{had}$). In the range of high $x$ electroweak effects dominate and the complete correction to asymmetry is defined basically by an electroweak interference ($A \approx A_{z}^{had} \approx A_{z}^{had}$). The influence of RE decreases with growth $x$: so, for example, the part of RE becomes smaller 10% for $E_1 = 100$ at $x \geq 0.8$, and for $E_1 = 1000\text{GeV}$ already at $x \geq 0.15$. 

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We also study numerically the next relative corrections:

\[ \Delta_B = \frac{A_0 - A_0^{\gamma\gamma}}{A_0^{\gamma\gamma}}, \quad \Delta_h = \frac{A^{had} - A^{\gamma\gamma}}{A^{\gamma\gamma}}, \]

\[ \Delta_{ew} = \frac{A^{lep} - A^{\gamma\gamma}}{A^{\gamma\gamma}}, \quad \Delta_{hz} = \frac{A^{had} - A^{\gamma\gamma}}{A^{\gamma\gamma}}. \]

(31)

\(\Delta_B\) is constructed from born asymmetries and gives the correction due to electroweak interference to purely electromagnetic born contribution. The other quantities are investigated in comparison with an one-loop model independent part of correction. Thus, the corrections (31) (tab. 1) give insight on values of effects, not included by the usual QED procedure RC. The table also illustrates a dependence of discussed quantities on energy of scattering lepton. We note, that if at existing energies of the correction (31) does not exceed 3-5 %, these effects can not be ignored in future experiments with energies up to 1 TeV.

3.3 QED correction to \(g_1(x, Q^2)\) and sum rules

RC procedure based on model independent exact formulae for the lowest order RE and described in [28] gives as a result SF \(g_1(x, Q^2)\) with taking into account only model independent effects. Model dependent effects (electroweak effects, radiation by hadrons) are ignored. In this case the effects should be taking into account for subsequent analysing of the SF in parton model:

\[ g_1(x, Q^2) = g_1^0(x) + g_1^{QCD}(x, Q^2) + g_1^{QED}(x, Q^2), \]

(32)

where

\[ g_1^0(x) = \frac{1}{2} \sum_q e_q^2 f_q^{(-)}(x), \]

(33)

and \(g_1^{QCD}(x, Q^2)\) and \(g_1^{QED}(x, Q^2)\) are QCD and QED correction to it. In the report we discuss the QED effects which arise from real photon radiation by hadrons and quark vertex function. Analogously we obtain for each quark flavour \(j\)

\[ \Delta q_j = \Delta q_j^0 + \Delta q_j^{QCD} + \Delta q_j^{QED}, \]

(34)
where each $\Delta q_j = \int_0^1 dx (f_j^{(-)}(x) + \bar{f}_j^{(-)}(x))$. We have to take into account the RC to the observables $g_1(x, Q^2)$, $\Delta q_j$ and to obtain the quantities $g_1^0(x)$, $\Delta q_j^0$ as a experimental results. By consideration of leading and next-to-leading contribution we have for $g_1^{QED}(x, Q^2)$

$$g_1^{QED}(x, Q^2) = \frac{\alpha}{4\pi} \sum_q e_q^4 \left\{ \left( \frac{3}{2} l_q + 2 l_q l_v - l_v^2 - \frac{7}{2} l_v - \frac{5}{2} - \pi^2/3 \right) f_q^{(-)}(x) \right. \right.$$

$$+ \left. \left. \frac{1}{z(1-z)} \left[ \left( (1+z^2)(l_q - \ln z(1-z) - 4) + 5z - \frac{1}{2} \right) f_q^{(-)}(\frac{x}{z}) \right. \right.$$

$$\left. \left. - 2 \left( l_q + \ln \frac{z}{1-z} - \frac{7}{4} \right) f_q^{(-)}(x) \right] \right\}$$

(35)

and for $\Delta q_j^{QED}$

$$\Delta q_j^{QED} = -\frac{9e_q^2\alpha}{4\pi} \Delta q_j^0.$$  (36)

The correction does not contain a leading contribution and is small. By applying this result to EMC results [2]

$$\Delta u = 0.782, \quad \Delta d = -0.472, \quad \Delta s = -0.190$$  (37)

obtained for $Q^2 = 10.7\text{GeV}^2$ and recalculated with taking into account $\Delta q_j^{QCD}$ we find

$$\Delta u^0 = 0.780, \quad \Delta d^0 = -0.472, \quad \Delta s^0 = -0.190.$$  (38)

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