Gerdt V. P., Karimkhodzhaev A., Faustov R. N.

HADRONTIC VACUUM POLARIZATION
AND TEST OF QUANTUM ELECTRODYNAMICS
AT LOW ENERGIES

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V.P.GERDT, A.KARIMKHODZHAEV, R.N.FAUSTOV

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Hadronic Vacuum Polarization and Test of Quantum Electrodynamics at Low Energies

A hadronic vacuum polarization correction to the photon propagator is found by using the Dubnicka-Meshcheryakov parameterization of the pion electromagnetic form factor and new experimental data on the $e^+e^-$ hadrons annihilation cross section. Then, the contribution from the hadronic vacuum polarization to the muon anomalous magnetic moment and the Lamb shift in muonic atoms are calculated.

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1. INTRODUCTION

The test of quantum electrodynamics (QED) at the small distance is one of the important problems in the elementary particle physics. Many experimental and theoretical difficulties emerge in the region of small space interval. One of theoretical difficulties, for example, is the necessary of considering contributions of higher order in coupling constant \( \alpha = \frac{e^2}{4\pi} = \frac{1}{137} \). In order to evaluate the deviations from predictions of the "pure"QED, it is necessary to know corrections to observables due to strong and weak interactions. Particularly, it is necessary to consider the effect of the structure of hadrons. But this encounters serve difficulties, since we do not have any appropriate theory of strong interactions. The applicability of QED can be analyzed by two means: the first is to do experiments with large momentum transfer of high energy particles (experiments with colliding \( e^+e^- \)-beams, collision of leptons with nucleons). The second is to measure low energy observables such as the fine and superfine structures of atomic levels and anomalous magnetic moments of electron and muon. The influence of strong interactions on the observed quantities is manifested, in addition to taking into account the structure of hadrons, also through the hadronic vacuum polarization (HVP). In this note we will find the correction by HVP to the photon propagator, and with its help we will calculate the contribution HVP to the anomalous magnetic moment of the muon and Lamb shift of muonic atoms.

2. THE CONTRIBUTION OF HADRONIC VACUUM POLARIZATION INTO PHOTON GREEN FUNCTION

The photon Green’s function in the transverse gauge has the form

\[
D_{\mu\nu}(q^2) = -\left( g_{\mu\nu} - \frac{q^\mu q^\nu}{q^2} \right) D(q^2).
\]

(1)

Where the invariant function \( D(q^2) \) is expressed by using the HVP operator \( \Pi^h(q^2) \) in the \( e^2 \)-approximation as follows (Fig. 1):

\[
D(q^2) = \frac{1}{q^2}[1 - \Pi^h(q^2)].
\]

(2)

Fig.1

We write the invariant function \( \Pi^h(q^2) \) in the Callan-Lehmann representation with one supraction

\[
\Pi^h(q^2) = e^2 q^2 \int_{4m^2_\pi}^{\infty} \frac{\rho^h(s)ds}{s(s - q^2 - i0)},
\]

(3)

where the hadronic spectral function \( \rho^h \) is connected with the total \( e^+e^- \) annihilation cross section into hadrons by the following relation (Fig. 2)
\[ \sigma^h(q^2) = \frac{16\pi^3\alpha^2}{q^2}\rho^h(q^2) \]

As usual, it is convenient to introduce the ratio of cross section

\[ R = \frac{\sigma_h(e^+e^- \rightarrow \{\text{hadrons}\})}{\sigma_{\mu\mu}(e^+e^- \rightarrow \mu^+\mu^-)} \]

where

\[ \sigma_{\mu\mu} = \frac{4\pi\alpha^2}{3s}. \]

Then for the spectral function \( \rho^h \) we have

\[ \rho^h(q^2) = \frac{1}{12\pi^2} \frac{\sigma_h}{\sigma_{\mu\mu}} = \frac{1}{12\pi^2}R \]

As a result, the photon propagator \( D(q^2) \) taking into account the HVP correction in the \( e^2 \)-approximation, takes the following form /2/:

\[ D(q^2) = \frac{1}{q^2 + i0} \left[ 1 - \frac{\alpha}{3\pi q^2} \int_0^\infty \frac{R(s)ds}{s(s - q^2 - i0)} \right] \]

Since the integral in equation (6) converges quickly, it is clear that the essential contribution to the HVP comes from the region near the threshold, i.e. the two pion intermediate state. Our job is to find the parameterization of \( R \) by using the improved description of experimental data in the region of two pion creation [3] and by taking into account of new structures [4] in the \( \sigma_h(e^+e^- \rightarrow \text{hadrons}) \) cross section.

Cross section \( \sigma_h(e^+e^- \rightarrow \text{hadrons}) \) can be represented as the sum of several parts:

\[ \sigma_h = \sigma_{\text{background}} + \sigma_{\text{resonance}} + \sigma_{\text{heavylepton}} \]

First term- \( \sigma_{\text{background}} \) determined by fitting experimental [3]-[5] points after subtracting the resonance contribution. The second term \( \sigma_{\text{resonance}} \) is expressed by generalized vector dominance [6] model, by the following Breit-Wigner representation:

\[ \sigma_{\text{resonance}} = \frac{12\pi}{s} \sum_i \frac{m_i^2\Gamma_i\Gamma_i^\ell}{(s - m_i^2) + m_i^2\Gamma_i^2} \]

where \( i \) means both ”old” (\( \rho, \omega, \phi \), and ”new” (\( J/\psi, \psi', \psi'' \), . . . ) vector mesons having the quantum numbers of photon; \( m_i, \Gamma_i, \Gamma_i^\ell \) - respectively mass, total and leptonic width of vector mesons.

\[ ^1 \text{Sum rules for } \Pi(q^2) \text{ in theory with asymptotic freedom were considered in [21]} \]
Third term $\sigma_{\text{heavy lepton}}$ - heavy lepton contribution to the total cross section from decays into hadrons of a recently discovered $\tau$ with mass $m = 1.8$ GeV, which for $s \gg m_\tau^2$ has the form

$$\sigma_\tau \simeq \sigma_\mu = \frac{4\pi \alpha^2}{3s},$$

and correspondingly,

$$R = \frac{\sigma_\tau}{\sigma_\mu} \simeq 1.$$

At the threshold of heavy lepton production for $R_\tau$ the follow value is obtained [7]

$$R_\tau = 0.89 \pm 0.29 \pm 0.27,$$

where the first error is statistical and second is systematic. Since the main contribution to the integral (6) comes from $\rho$-meson and the two pion state, it is natural to use more precise expression in this area for $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$, than the formula (8). The cross section $\sigma(e^+e^- \rightarrow \pi^+\pi^-)$ is expressed by pion electromagnetic form factor $F_\pi(s)$ [3, 8]

$$\sigma(e^+e^- \rightarrow \pi^+\pi^-) = \frac{8\pi \alpha^2 q^2}{3s^{5/2}} |F_\pi(s)|^2,$$

where

$$q = \left(\frac{s}{4} - m_\pi^2\right)^{1/2}.$$

There are various parameterizations [9, 10] for form factor $F_\pi(s)$. In calculations we used the Dubnicka-Meshcheryakov parameterization [10], which describes experimental data in the wide range of energy $-2$ GeV$^2 \leq s \leq 4.4$ GeV$^2$, possessing an asymptotic behavior $1/s$, which is consistent with the results of the rules quark counting [11]. In this specified parameterization of the form factor, $F_\pi(s)$ is as follows:

$$F_\pi(s) = P_1(s) \frac{(q - q_1)}{(q + q_2)(q + q_3)(q + q_4)} \frac{(i + q_2)(i + q_3)(i + q_4)}{(i - q_1)},$$

where [3]

$$P_1 = 1 + A \cdot s,$$

$$A = 0.0027 \pm 0.0003,$$

$$q_1 = -i0.960504,$$

$$q_2 = -2.565913 + i0.289811,$$

$$q_3 = i1.048006,$$

$$q_4 = 2.565913 + i0.289811.$$

Interference $\rho \Pi \omega$ up to the production threshold $\omega\pi \rightarrow 0, 92$ GeV we took into account [3] by adding to $F_\pi(s)$ the expression

$$F_\pi^\omega = \frac{i0.014}{1 - \frac{s}{m_\omega^2} - i\frac{m_\omega}{m_\omega}}.$$

\[^2]\text{The numerical values of the parameters } A, q_i, \text{ correspond to unit mass of a pion (}m_\pi = 1\text{).}
For the rest of resonances we used representation Breit - Wigner [8]. To determine the contribution from the $\sigma_{background}$ to $R$, we have taking into account the fact that the experimental value of $R$ decreases slowly up to $\sqrt{s} = 3.0 \text{ GeV}$ and increases in the region $3.0 \text{GeV} \leq \sqrt{s} \leq 5.0 \text{GeV}$ due to the production of charm particles and starting from $\sqrt{s} = 5.0 \text{GeV}$ becomes approximately constant and equal to $4.5 - 5.5$. Fitting of experimental data [3]-[5] according to the formula $R = A \cdot s^\beta$ by the least squares method gives:

\[
R = (5, 4 \pm 1, 0) \cdot s^{-(0.5 \pm 0.1)} \quad \text{in the region } 1.2 \leq \sqrt{s} \leq 3.0 \text{ Gev},
\]

\[
R = (0, 4 \pm 0, 1) \cdot s^{(0.8 \pm 0.1)} \quad \text{in the region } 3.0 \leq \sqrt{s} \leq 5.0 \text{ GeV and}
\]

\[
R = (5, 3 \pm 0, 5) \quad \text{in the region } 5.0 \leq \sqrt{s} \leq 7.4 \text{ GeV}.
\]

For asymptotics $\sqrt{s} > 7.4 \text{ GeV}$ we can use the formula following from asymptotic freedom assumptions [12]

\[
R_{\infty} = (3 \sum_i Q_i^2)(1 + \frac{\delta}{\ln(s/\Lambda^2)}),
\]

where $Q_i$ is the quark charge , $\delta = \frac{12}{25}$ for the model with four colored quarks,

$$\Lambda = (5, 4 \pm 0, 6) \text{ GeV}. $$

Now let’s move on to specific applications in which the correction for the HVP to the photon propagator affects.

### 3. CONTRIBUTION OF HVP TO ANOMALOUS MAGNETIC MOMENT OF THE MUON

Recent measurements of anomalous magnetic moment $-a_\mu$ of the muon give the result [13]

$$a_\mu(\text{exp.}) = (1165922 \pm 9) \cdot 10^{-9}(8 \text{ ppm}).$$

Theoretical value $a_\mu$, including calculations up to the eighth order in $\alpha$ [13, 14], equals

$$a_\mu(QED) = (1165851, 8 \pm 2, 4) \cdot 10^{-9}.$$  

The difference between the theoretical value of $a_\mu(QED)$ from experimental

$$a_\mu(\text{exp.}) - a_\mu(QED) = (70, 2 \pm 11, 4) \cdot 10^{-9} \quad (17)$$

can be explained by the presence of HVP effects. можно объяснить наличием эффектов АПВ.

The hadronic contribution to $a_\mu$, which is manifested by the correction on HVP to the photon propagator (6), expressed through the well known integral [14, 15]/Fig. 3/

$$a_\mu(\text{эксп.}) = (\frac{m_\mu \alpha}{3\pi})^2 \int_{4m_\mu^2}^{\infty} \frac{R(s)K(s)}{s^2} ds, \quad (18)$$

where $m_\mu$ - mass of $\mu$ -meson. The kernel $K(s)$ has the form [15]

$$K(s) = \frac{3s}{m_\mu^2} \left\{ \frac{1}{2} x^2(2 - x^2) + \frac{(1 + x^2)(1 + x)^2}{x^2} \left[ \ln(1 + x) - x + \frac{x^2}{2} + \left( \frac{1 + x}{1 - x} \right) x^2 \ln(x) \right] \right\},$$
where

\[ x = \frac{s}{4m_\mu^2} (1 - \sqrt{1 - \frac{4m_\mu^2}{S}})^2. \]

Notice, that

\[ K(s \rightarrow \infty) = 1 \]

and

\[ K(s \equiv m_\rho^2) \equiv 0.877. \]

Calculation of the integral (18) using parameterization \( R \), given in Section 2 gives the result

\[ a_\mu(\text{hadrons}) = (72, 15 \pm 5, 96) \times 10^{-9}, \]

which is in good agreement with earlier calculations \[14, 16\] and experiment (Table.1.)

| Contributions to \( a_\mu(\text{hadrons}) \) | \( \times 10^{-9} \) |
|-----------------------------------------------|------------------|
| \( \rho, \omega \rightarrow 2\pi, \sqrt{s} < 0.92 \) | 47,3±0,70 |
| \( \omega \rightarrow 3\pi \) | 5,10±1,16 |
| \( \varphi \) | 4,10±0,32 |
| \( J/\Psi(3,095), \Psi'(3.684), \Psi''(3,772), \Psi(4,4) \) | 0,70±0,18 |
| background 1, 2 \( \leq \sqrt{s} \leq 3, 0 \) | 12,1±3,10 |
| background 3, 0 \( < \sqrt{s} \leq 5, 0 \) \( a_\mu(\tau) = 0.22 \pm 0.07 \) | 0,70±0,32 |
| background 5, 0 \( < \sqrt{s} \leq 7, 4 \) \( a_\mu(\tau) = 0.13 \pm 0.04 \) | 0,50±0,07 |
| Asymptotics \( \sqrt{s} \geq 7, 4 \) \( a_\mu(\tau) = 0.12 \) | 0,60±0,05 |
| (asymptotic freedom) | |
| Total | 72,15±5,96 |

Table.1

Note that the contribution to the \( a_\mu \) pion form factor for the parameterization of Dubnichka-Meshcheryakov slightly higher than for the Gunnaris-Sakurai parameterizations \[9, 16\], which is equal to 46,5 \( \times 10^{-9} \). Contribution from \( \sigma_{\text{background}} \), in the region 1, 2 \( < \sqrt{s} < 3, 0 \) GeV is
also slightly higher than others authors, but the difference is within the measurement error. Generally speaking, more than half of the error is in the value $a_\mu$ based on errors of experimental data in the region up to $\sqrt{s} = 3.0$ GeV, therefore it would be desirable to careful measurement of the cross section $\sigma_h$ up to $\sqrt{s} = 3.0$ Gev.

The contribution of heavy lepton to $a_\mu$(hadrons) is equal to

$$a_\mu(\text{heavylepton}) = (0.47 \pm 0.11) \cdot 10^{-9}$$

As shown in article [14], the contribution of higher-order HVP by $\alpha$ to $a_\mu$ is equal to

$$(-3.5 \pm 1.4) \cdot 10^{-9}.$$ 

Adding this contribution to the expression [19], we obtain

$$a_\mu(\text{hadrons}) = (68.65 \pm 7.36) \cdot 10^{-9},$$

which is in good agreement with the [17].

4. CONTRIBUTION OF HADRONS TO LAMB SHIFT IN MUONIC ATOMS

In the case when $q^2 \ll 4m^2_\tau$ the formula (6) may be rewritten as

$$D(q^2) \approx \frac{1}{q^2} \left[ 1 - \frac{\alpha}{3\pi} \frac{q^2}{m^2_h} \right],$$

where $m^2_h$ is the effective hadron mass defined as

$$m^2_h = \int_{4m^2_\tau/s^2}^{\infty} \frac{R(s)}{s^2} ds.$$  \hspace{1cm} (21)

Numerical integrations in (21) using the parameterization $R$ given in section 2 lead to the results collected in Table 2.

| Contributions to $a_\mu$(hadrons) | $\times 10^{-9}$ |
|----------------------------------|-----------------|
| $\rho, \omega \rightarrow 2\pi, \sqrt{s} < 0.92$ | 16.5$\pm$0.30 |
| $\omega \rightarrow 3\pi$ | 1.70$\pm$0.40 |
| $\varphi$ | 1.40$\pm$0.10 |
| $J/\Psi(3.095), \Psi'(3.684), \Psi''(3.772), \Psi'''(4.4)$ | 0.23$\pm$0.05 |
| background $1.2 \leq \sqrt{s} \leq 3.0$ | 4.70$\pm$1.05 |
| background $3.0 < \sqrt{s} \leq 5.0 (m^2_\tau = 0.06 \pm 0.02)$ | 0.24$\pm$0.10 |
| background $5.0 < \sqrt{s} \leq 7.4 (m^2_\tau = 0.04 \pm 0.01)$ | 0.20$\pm$0.02 |
| Asimptotics $\sqrt{s} > 7.4 (m^2_\tau = 0.03)$ (asymptotic freedom) | 0.15$\pm$0.01 |
| Total | 25.12$\pm$2.03 |

Table 2
Then:

$$m_h^{-2} = 0,25 \pm 0,02 \quad (22)$$

or $m_h^2 \approx 4m_\pi^2$.

Taking this value of $m_h^{-2}$ into account, the HVP contribution to the photon propagator is expressed by the formula:

$$D(q^2) \simeq \frac{1}{q^2}[1 - \frac{\alpha}{3\pi} \frac{q^2}{4m_h^2}] \quad (23)$$

For comparison, note that the contribution of only one $\pi$- meson loop (Fig. 4) with exact vertexes of one order lower is

$$D(q^2) \simeq \frac{1}{q^2} \left[ 1 - \frac{\alpha}{3\pi} \frac{q^2}{40m_\pi^2} \right], \quad (24)$$

e.g. $m_h^2 \approx 40m_\pi^2$.

The potential of interaction with the correction from HVP has the form

$$V(q^2) = -Ze^2 \frac{d(q^2)}{q^2}, \quad q^2 = -\tilde{q}^2 \quad (25)$$

where $Z$ - the charge of atomic nuclei and $d(q^2) = q^2D(q^2)$. Let us separate the pure Coulomb potential and write

$$V(q^2) = V_C(q^2) + \Delta V(q^2), \quad (26)$$

where $V_C(q^2) = -Ze^2/\tilde{q}^2$ - is the Coulomb potential, $\Delta V(q^2)$ is HVP correction to the potential. Consequently, it has the form

$$\Delta V(q^2) = -\frac{Ze^2}{\tilde{q}^2} [d(q^2) - 1] = -\frac{4\alpha \cdot Z\alpha}{3m_h^2}. \quad (27)$$

The corresponding shift of muon atom S-level in the first order of perturbation theory is

$$\Delta E_n = \langle \Psi_C | \Delta V(\vec{r}) | \Psi_C \rangle = -\frac{4\alpha (Z\alpha)}{3m_h^2} |\Psi_C(0)|^2. \quad (28)$$
The Coulomb wave functions $\Psi_C$ normalized at origin as follows

$$|\Psi_C(0)|^2 = \frac{(Z\alpha)^3 \mu^3}{\pi n^3 \delta_{00}},$$

where $n$ - principal quantum number, $\mu$-reduced mass.

Substituting the norm of (29) into (28), we get the final form of the S-level shift of muon atom:

$$\Delta E_n^h = \frac{-4\alpha(Z\alpha)\mu^3}{3n^3 m_h^2},$$

where $m_h^2 \approx 4m_e^2$.

Now we calculate numerical values of these corrections for $n = 2$ (i.e., the part of Lamb shift) in the following concrete cases:

a) heavy muon atom $M >> m_\mu$. The reduced mass is equal $\mu = \frac{Mm_\mu}{M+m_\mu} = m_\mu$, the shift is equal

$$\Delta E^h = -Z^4 \frac{\alpha^5 m_\mu^3}{6\pi(4m_e^2)} \approx -Z^4 \cdot 1.67 \cdot 10^{-5} \text{ eV.}$$

The total Lamb shift in the muon hydrogen is

$$\Delta E_L = (0.2108 \pm 0.0001) \text{ eV.}$$

b) $(\pi\mu)$-atom. In this case $\mu = m_e m_\mu/(m_e + m_\mu)$, $Z=1$ and

$$\Delta E^h = \frac{\alpha^5 \mu^3}{6\pi(4m_e^2)} \approx -0.31 \cdot 10^{-5} \text{ eV}$$

For comparison note that the total Lamb shift for $(\pi\mu)$-atom is equal [17]

$$\Delta E_L = -0.0795 \text{ eV.}$$

5. CONCLUSION

It is well known [18], that the contribution of the vacuum polarization in the Lamb shift of electronic atoms so small and is about $\sim 1\%$ of total shift. On the contrary, in the case of muonic atoms the contribution of the vacuum polarization dominates and constitutes $\sim 95\%$ to the total shift. Thus it is very important to increase the accuracy of corresponding experimental measurements in order to reveal the corrections by HVP. The suggested experiment of measuring Lamb shift on muonic atoms, particularly, in muonic hydrogen and $(\pi\mu)$-atom [19], will provide us a very valuable information on the influence of the effects of strong interactions upon QED at low energies. For example, in $(\pi\mu)$-atom the contribution of the size of pion to the total shift constitutes $\sim 1\%$, and the measurement of Lamb shift to $10^{-3}$ accuracy will lead to the more precise value of pion radius.

The contribution of HVP has been observed in the anomalous magnetic moment of muon and in the annihilation cross section [20] of $e^+e^-$ into $\mu^+\mu^-$. Increasing the accuracy of measurements and theoretical calculations of energy levels of muonic atoms should also reveal the effect of HVP.

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