HIGHER ORDER CORRECTIONS AND SPIN CONNECTIONS OF THE LAMB SHIFT

by

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ABSTRACT

Higher order corrections are calculated for the Lamb shift using an accurate theory that does not depend on quantum electrodynamics, and which is based on the tensor Taylor expansion of immediately preceding papers. Higher order corrections are inversely proportional to powers of the radiation volume and could become the dominant terms if the radiation volume is small, for example for nuclear physics. ECE2 spin connections are computed for the Lamb shift.

Keywords: ECE2 theory, higher order corrections and spin connections, Lamb shift.

4FT 398

1. INTRODUCTION

In immediately preceding papers of this series {1 - 41} the tensor Taylor expansion has been developed and applied to ECE2 theory. In Section 2 the method is applied to calculate higher order corrections and spin connections of the Lamb shift, using a theory that does not rely on quantum electrodynamics. It is shown that higher order corrections are inversely proportional to powers of the radiation volume V. The latter does not appear in the usual expression for the Lamb shift, which is produced by the same theory as used here for higher order corrections, and which is very accurate.

This paper is a short synopsis of detailed calculations found in notes accompanying UFT398 on www.aias.us. Note 398(1) describes the computation of the vector spin connection in ECE2 theory, Notes 398(2) and 398(3) describe the calculation of the higher order corrections of the Lamb shift using higher order terms of the tensor Taylor series. Note 398(4) gives components of the spin connection vector for the Lamb shift, and Note 398(5) calculates higher order fluctuation terms.

2. HIGHER ORDER TERMS

In general, it was shown in the preceding paper UFT397 of this series {1 - 41} that the isotropically averaged change in any scalar function f due to the vacuum fluctuation $\delta \underline{r}$ is:

$$\langle \Delta f \rangle = \langle \Delta f \rangle^{(2)} + \langle \Delta f \rangle^{(4)} + \langle \Delta f \rangle^{(6)} + \dots \quad -(1)$$

where, in Cartesian coordinates:

$$\langle \Delta f \rangle^{(2)} = \frac{1}{6} \langle \delta \underline{r} \cdot \delta \underline{r} \rangle \nabla^2 f , \quad -(2)$$

$$\langle \Delta f \rangle^{(4)} = \frac{1}{216} \langle (\delta \underline{r} \cdot \delta \underline{r})^2 \rangle \left(\frac{\partial^4 f}{\partial X^4} + \frac{\partial^4 f}{\partial Y^4} + \frac{\partial^4 f}{\partial Z^4} + 6 \left(\frac{\partial^4 f}{\partial Y^2 \partial Z^2} + \frac{\partial^4 f}{\partial X^2 \partial Z^2} + \frac{\partial^4 f}{\partial X^2 \partial Y^2} \right) \right) \quad -(3)$$

$$\langle \Delta f \rangle^{(6)} = \frac{1}{19440} \langle (\delta \underline{r} \cdot \delta \underline{r})^3 \rangle \left(\frac{\partial^6 f}{\partial X^6} + \frac{\partial^6 f}{\partial Y^6} + \frac{\partial^6 f}{\partial Z^6} + 15 \left(\frac{\partial^6 f}{\partial Y^4 \partial Z^2} + \frac{\partial^6 f}{\partial Y^2 \partial Z^4} + \frac{\partial^6 f}{\partial X^4 \partial Z^2} + \frac{\partial^6 f}{\partial X^4 \partial Y^2} + \frac{\partial^6 f}{\partial X^2 \partial Z^4} + \frac{\partial^6 f}{\partial X^2 \partial Y^4} \right) + \frac{90 \, \partial^6 f}{\partial X^2 \partial Y^2 \partial Z^2} \right) \quad -(4)$$

When f is the Coulomb potential between the electron and proton of an H atom:

$$f := \phi_0 = \frac{-e^2}{4\pi \epsilon_0 r} \quad -(5)$$

Eq. (1) produces higher order corrections to the well known Lamb shift. Here e is the charge on the proton, ϵ_0 is the vacuum permittivity and r the distance between the electron and proton.

The spin connection vector $\underline{\omega}$ in ECE2 is defined by:

$$\underline{E} = -\underline{\nabla} \phi_0 + \underline{\omega} \phi_0 \quad -(6)$$

where $\underline{E}$ is the total electric field strength and E_0 the Coulombic electric field strength:

$$\underline{E}_0 = -\underline{\nabla} \phi_0 \quad -(7)$$

Therefore:

$$\langle \Delta \underline{E}_0 \rangle = \underline{E}(\mathrm{vac}) = \langle \Delta E_{X0} \rangle \underline{i} + \langle \Delta E_{Y0} \rangle \underline{j} + \langle \Delta E_{Z0} \rangle \underline{k} \quad -(8)$$

is the vacuum electric field strength and can be calculated with the tensor Taylor sereis method. So:

$$\langle \Delta E_{X0} \rangle = \langle \Delta E_{X0} \rangle^{(2)} + \langle \Delta E_{X0} \rangle^{(4)} + \langle \Delta E_{X0} \rangle^{(6)} \quad -(9)$$

where

$$\underline{E}_0 = -\frac{e^2}{4\pi \epsilon_0} \frac{\underline{r}}{r^3} \quad -(10)$$

and similarly for Y and Z.

Similarly, the magnetic spin connection vector can be computed from:

$$\langle \Delta \underline{B}_0 \rangle = \underline{B}(\mathrm{vac}) = -\underline{\omega} \times \underline{A}_0 \quad -(11)$$

For example $\underline{A}_0$ is the dipole vector potential:

$$\underline{A}_0 = \frac{\mu_0}{4\pi} \frac{\underline{m} \times \underline{r}}{r^3} \quad -(12)$$

and:

$$\underline{B}_0 = \underline{\nabla} \times \underline{A}_0 = \frac{\mu_0}{4\pi} \left[\frac{3\underline{m} \cdot \underline{r}\,\underline{r}}{r^5} - \frac{\underline{m}}{r^3} \left(\underline{1} + r^3 \nabla^2 \left(\frac{1}{r} \right) \right) \right] \quad -(13)$$

This expression simplifies if vector analysis is used on the classical level:

$$\nabla^2 \left(\frac{1}{r} \right) = 0 \quad -(14)$$

However, in the calculation of the Lamb shift on the quantum level, it is assumed that:

$$\nabla^2 \left(\frac{1}{r} \right) = -4\pi\, \delta_D(r) \quad -(15)$$

where δ_D is the Dirac delta function.

The Lamb shift can be calculated accurately from the force equation:

$$m \frac{d^2 \delta \underline{r}}{dt^2} = -e\underline{E} \quad -(16)$$

where $\underline{E}$ is the vacuum electric field strength and -e is the charge on the electron. If it is assumed that:

$$\delta r = \delta r(0)\, e^{-i\omega t} \quad -(17)$$

then:

$$\frac{d^2 \delta r}{dt^2} = -\omega^2 \delta r \quad -(18)$$

and

$$\delta r = \frac{eE}{m\omega^2} = \frac{eE}{mc^2 \kappa^2}. \quad -(19)$$

The vacuum field is assumed to be:

$$\underline{E} = \underline{E}(0) \left(a_\kappa \exp\left(-i\left(\omega t - \underline{\kappa} \cdot \underline{r}\right)\right) + a_\kappa^{+} \exp\left(i\left(\omega t - \underline{\kappa} \cdot \underline{r}\right)\right)\right) \quad -(20)$$

so that the fluctuation is:

$$\langle \delta \underline{r} \cdot \delta \underline{r} \rangle = \sum_\kappa \left(\frac{e}{mc^2 \kappa^2} \right)^2 \langle 0 | E^2 | 0 \rangle \quad -(21)$$

and is calculated by a summation over all κ. From mode theory:

$$\langle 0 | E^2 | 0 \rangle = \frac{\hbar c \kappa}{2 \epsilon_0 V} \quad -(22)$$

where V is the radiation volume. So:

$$\langle \delta \underline{r} \cdot \delta \underline{r} \rangle = \frac{2\pi}{V} \alpha \lambda^2 \sum_{\kappa} \frac{1}{\kappa^3} \quad -(23)$$

where α is the fine structure constant:

$$\alpha = \frac{e^2}{4\pi \hbar c \epsilon_0} \quad -(24)$$

and

$$\lambda = \frac{\hbar}{mc} \,. \quad -(25)$$

Similarly:

$$\langle (\delta \underline{r} \cdot \delta \underline{r})^2 \rangle = \left(\frac{2\pi}{V} \alpha \lambda^2 \right)^2 \sum_{\kappa} \frac{1}{\kappa^6} \quad -(26)$$

and

$$\langle (\delta \underline{r} \cdot \delta \underline{r})^3 \rangle = \left(\frac{2\pi}{V} \alpha \lambda^2 \right)^3 \sum_{\kappa} \frac{1}{\kappa^9} \,. \quad -(27)$$

In the theory of the Lamb shift, the summation in Eq. (23) is replaced by an integral as follows:

$$\sum_{\kappa} \rightarrow \frac{2V}{(2\pi)^3} \int d^3\kappa = \frac{2V}{(2\pi)^3} \cdot 4\pi \int \kappa^2 d\kappa \quad -(28)$$

From Eqs. (23) and (28):

$$\langle \delta \underline{r} \cdot \delta \underline{r} \rangle = \frac{2}{\pi} \alpha \lambda^2 \int \frac{d\kappa}{\kappa} \quad -(29)$$

The lower bound of κ is:

$$\kappa_l = \frac{\pi}{a_0} = 5.936 \times 10^{10}\ m^{-1} \quad -(30)$$

and the upper bound is:

$$\kappa_u = \frac{mc}{\hbar} = 6.570 \times 10^{10}\ m^{-1} \quad -(31)$$

where a_0 is the Bohr radius. Therefore:

$$\langle \delta \underline{r} \cdot \delta \underline{r} \rangle = \frac{2}{\pi} \alpha \lambda^2 \int_{\pi/a_0}^{mc/\hbar} \frac{d\kappa}{\kappa} = \frac{2}{\pi} \alpha \lambda^2 \log_e \frac{1}{\pi \alpha} \quad -(32)$$

$$= 2.616 \times 10^{-27}\ m^2.$$

This result gives the Lamb shift accurately to first order in $\langle \delta \underline{r} \cdot \delta \underline{r} \rangle$.

However there are higher order terms of the Taylor series (1):

$$\langle \Delta \phi_0 \rangle = \langle \Delta \phi_0 \rangle^{(2)} + \langle \Delta \phi_0 \rangle^{(4)} + \langle \Delta \phi_0 \rangle^{(6)} + \cdots \quad -(33)$$

to be considered, with

$$f = \phi_0. \quad -(34)$$

The series uses the results from the above calculation:

$$\langle \Delta \phi_0 \rangle = \frac{1}{6} \langle \delta \underline{r} \cdot \delta \underline{r} \rangle \nabla^2 \phi_0 + \cdots \quad -(34)$$

The usual theory of the Lamb shift uses only:

$$\langle \Delta \phi_0 \rangle = \frac{\hbar c}{6 \pi a_0} \log_e \frac{1}{\pi \alpha} \quad -(35)$$

(See Note 398(3)), but the complete calculation leads to:

$$\langle \Delta \phi_0 \rangle = \frac{\hbar c}{6 \pi a_0} \log_e \frac{1}{\pi \alpha} + \langle \Delta \phi_0 \rangle^{(4)} + \langle \Delta \phi_0 \rangle^{(6)} + \cdots \quad -(36)$$

using the tensor Taylor series (1). As shown in Note 398(5):

$$\langle \delta\underline{r} \cdot \delta\underline{r} \rangle = \frac{2}{\pi} \alpha \lambda^2 \log_e \frac{1}{\pi \alpha} = 2.616 \times 10^{-27} m^2 \quad -(37)$$

with:

$$\langle (\delta\underline{r} \cdot \delta\underline{r})^2 \rangle = \frac{4}{3V} (\alpha\lambda^2)^2 \left(\left(\frac{a_0}{\pi}\right)^3 - \left(\frac{\hbar}{mc}\right)^3 \right) = \frac{1.5788 \times 10^{-81} m^4}{V} \quad -(38)$$

and:

$$\langle (\delta\underline{r} \cdot \delta\underline{r})^3 \rangle = \frac{8\pi\lambda^6\alpha^3}{6V^2} \left(\left(\frac{a_0}{\pi}\right)^6 - \left(\frac{\hbar}{mc}\right)^6 \right) \quad -(39)$$

A suitable expression for the radiation volume must be used. For example if it is assumed that:

$$V = \frac{4}{3}\pi a_0^3 = 6.207 \times 10^{-31} m^3 \quad -(40)$$

then:

$$\langle (\delta\underline{r} \cdot \delta\underline{r})^2 \rangle = 2.544 \times 10^{-51} m^4 \quad -(41)$$

If non relativistic orbitals of the H atom are considered, then the expectation values of r can be used to calculate the radiation volume:

$$\langle r \rangle (1s) = \int \phi^* r \phi \, d\tau = \frac{3}{2} a_0 \quad -(42)$$

$$\langle r \rangle (2s) = \int \phi^* r \phi \, d\tau = 6 a_0 \quad -(43)$$

$$\vdots$$

and so on. It is also possible to use the expectation values of the classical spherical volume (40):

$$\langle V \rangle = \frac{4}{3}\pi \int \phi^* r^3 \phi \, d\tau \quad -(44)$$

for a given wave function. The normalization condition is:

$$\int \psi^* \psi \, d\tau = 1 \quad -(45)$$

Finally the vector spin connection components are computed from:

$$\langle \Delta \underline{E} \rangle = \langle \Delta E_X \rangle \underline{i} + \langle \Delta E_Y \rangle \underline{j} + \langle \Delta E_Z \rangle \underline{k} = \underline{\omega} \phi_0 \quad -(46)$$

At second order in the Taylor series:

$$\langle \Delta E_X \rangle^{(2)} = \frac{1}{6} \langle \delta \underline{r} \cdot \delta \underline{r} \rangle \nabla^2 E_X = \omega_X \phi_0 \quad -(47)$$

where:

$$E_X = -e^2 \frac{X}{(X^2+Y^2+Z^2)^{3/2}} \quad -(48)$$

and similarly for the Y and Z components. On the classical level:

$$\langle \Delta E_X \rangle^{(2)} = \langle \Delta E_Y \rangle^{(2)} = \langle \Delta E_Z \rangle^{(2)} = 0 \quad -(49)$$

as in UFT397. So:

$$-\frac{e^2}{4\pi\epsilon_0 r} \omega_X = \langle \Delta E_X \rangle^{(4)} + \langle \Delta E_X \rangle^{(6)} + \cdots \quad -(50)$$

$$-\frac{e^2}{4\pi\epsilon_0 r} \omega_Y = \langle \Delta E_Y \rangle^{(4)} + \langle \Delta E_Y \rangle^{(6)} + \cdots \quad (51)$$

$$-\frac{e^2}{4\pi\epsilon_0 r} \omega_Z = \langle \Delta E_Z \rangle^{(4)} + \langle \Delta E_Z \rangle^{(6)} + \cdots \quad (52)$$

These spin connection components are computed and graphed in Section 3.

3. NUMERICAL AND GRAPHICAL ANALYSIS.

Section by co author Horst Eckardt.

Higher order corrections and spin connections of the Lamb shift

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3 Numerical and graphical analysis

The fluctuation averages of higher order are analyzed numerically. In the preceding section the formulas (37-39) were derived for fluctuation radius δr averages of second, fourth and sixth order. The latter two depend on the radiation valume V. For our example we assume

$$V = \frac{4}{3}\pi \langle r \rangle^3 \tag{53}$$

where $\langle r \rangle$ is the mean radius of atomic s states of the Hydrogen atom. The results are listed in Table 1 for the first three s states. The radii are known from wave function averages, see Eqs. (42,43). The volumes increase with the radius. The averages $\langle \delta\mathbf{r} \cdot \delta\mathbf{r} \rangle$ do not depend on radius and are the same for all states. Higher-order averages are at least 30 order of magnitude smaller. Interestingly, for the values of the $1s$ state, the sixth-order term is larger than the fourt-order term. Normally higher orders should give smaller average values. This is the case for the $2s$ and $3s$ states.

state	$\langle r \rangle$	V	$\langle \delta\mathbf{r} \cdot \delta\mathbf{r} \rangle$	$\left\langle (\delta\mathbf{r} \cdot \delta\mathbf{r})^2 \right\rangle$	$\left\langle (\delta\mathbf{r} \cdot \delta\mathbf{r})^3 \right\rangle$
1s	$\frac{3}{2}a_0$	$2.095 \cdot 10^{-30}$	$2.616 \cdot 10^{-27}$	$3.602 \cdot 10^{-57}$	$1.341 \cdot 10^{-56}$
2s	$6a_0$	$1.341 \cdot 10^{-28}$	$2.616 \cdot 10^{-27}$	$5.628 \cdot 10^{-59}$	$5.115 \cdot 10^{-62}$
3s	$\frac{27}{2}a_0$	$1.527 \cdot 10^{-27}$	$2.616 \cdot 10^{-27}$	$4.941 \cdot 10^{-60}$	$3.461 \cdot 10^{-65}$

Table 1: δr fluctuation averages for s states of Hydrogen in SI units.

On the classical level, the X component of the (normalized) electric Coulomb field is

$$E_X = -\frac{X}{(X^2 + Y^2 + Z^2)^{3/2}}. \tag{54}$$

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Using the isotropic averaging method as in previous papers, we obtain the values of fluctuation contributions $\langle \Delta E_X \rangle^{(4)}$ and $\langle \Delta E_X \rangle^{(6)}$. Inserting these into Eq. (50), the contributions for the vector spin connection are

$$\omega_X^{(4)} = \frac{35X\left(3Z^4 - 3Y^2 Z^2 - 5X^2 Z^2 + 3Y^4 - 5X^2 Y^2 + X^4\right)}{18(Z^2+Y^2+X^2)^5} \cdot \left\langle (\delta\mathbf{r}\cdot\delta\mathbf{r})^2 \right\rangle , \tag{55}$$

$$\begin{aligned}\omega_X^{(6)} = &\frac{7X}{9(Z^2+Y^2+X^2)^7} \cdot \big(8Z^6 - 75Y^2 Z^4 - 15X^2 Z^4 - 75Y^4 Z^2 + \\ &300X^2 Y^2 Z^2 - 21X^4 Z^2 + 8Y^6 - 15X^2 Y^4 - 21X^4 Y^2 + 2X^6\big) \\ &\cdot \left\langle (\delta\mathbf{r}\cdot\delta\mathbf{r})^3 \right\rangle .\end{aligned} \tag{56}$$

These contributions to the spin connection, together with their sum ω_X, are graphed in Fig. 1 with setting $\delta r = 0.2$ as used in graphs of preceding papers. The spin connection terms are positive, while the Coulomb field E_X is negative. The spin connection is more concentrated to the charge centre due to its higher exponents in the denominator.

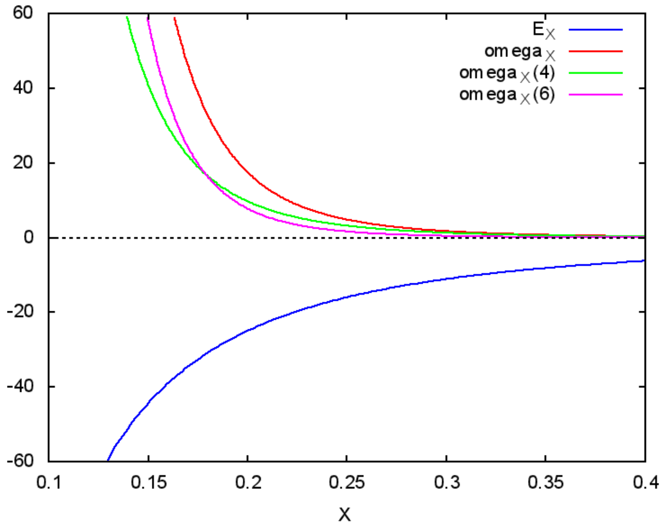

Figure 1: X component of Coulomb field and spin connection terms of 4th and 6th order.

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