# Atomic theory and test of the Standard Model

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Atomic measurements of the weak charge characterising the strength of the electron-nucleon weak interaction provide tests of the Standard Model and a way of searching for new physics beyond the Standard Model. Atomic experiments give the best limits on the extra Z-boson ($Z_x$), leptoquarks, composite fermions; they are sensitive to the parameter S which characterises the oblique radiative corrections.

The latest analysis [1] of the most precise measurements of parity non-conservation (PNC) in cesium [4] suggests that the value of the weak charge of $^{133}$Cs nucleus differs from the prediction of the Standard Model by $2.5\sigma$. In that experiment [4] the ratio of the PNC $E1$ amplitude to the tensor polarizability $\beta$ for the $7s_{1/2} - 6s_{1/2}$ transition was measured with 0.35% accuracy. The measured value can be written in a form

$$\frac{k_{PNC}}{\beta}\frac{Q_W}{N}, \tag{1}$$

where $k_{PNC}$ is the electron matrix element of the electric dipole transition induced by weak interaction between $7s_{1/2}$ and $6s_{1/2}$ states of $^{133}$Cs, $Q_W$ is the weak nuclear charge and $N$ is the number of neutrons. To interpret the measurements in terms of the weak nuclear charge one needs to know $k_{PNC}$ and $\beta$. $k_{PNC}$ can be obtained from atomic calculations only. Bennet and Wieman [1] used the value $k_{\rm PNC} = 0.9065(36)iea_0$ which is the average of our result $k_{\rm PNC} = 0.908(91)iea_0$ [2] obtained in 1989 and the result of the Notre-Dame group $k_{\rm PNC} = 0.905(91)iea_0$ [3] obtained a year later. Note that Bennett and Wieman assumed 0.4% accuracy of the calculations contrary to the 1% accuracy claimed in both calculations. This assumption was based on the comparison of the calculated atomic quantities relevant to the PNC amplitude with the latest very accurate measurements which resolved major discrepancies between theory and experiment in favour of theory.

The most precise value of $\beta, \beta = 27.024(43)(67)a_0^3$ was obtained in Ref. [1] from the measurements of the ratio $M_{hfs}/\beta$ of the off-diagonal hyperfine amplitude for the $6s-7s$ transition to $\beta$. Semiempirical formula for the $M_{hfs}$ amplitude derived in Ref. [5] was used in the analysis:

$$M_{hfs} = -\left|\frac{\mu_B}{c}\right| \frac{\sqrt{A_{6s}A_{7s}}}{E_{7s}-E_{6s}}\frac{1}{2}(g_S - g_I)1.0024 \tag{2}$$

Here $A_{6s}$ and $A_{7s}$ are the hyperfine structure (hfs) constants of the $6s$ and $7s$ states of Cs, $g_S = 2.0025, g_I = -0.0004$ and the coefficient 1.0024 is introduced to account for the many-body effects. The values $\beta = 27.024(43)(67)a_0^3$ and $k_{PNC} = 0.9065(36)iea_0$ and measurements

of (1) [4] lead to the value of the weak charge of $^{133}$Cs $Q_W = -72.06(28)(34)$ which differs from the prediction of the Standard Model $Q_W = -73.20(13)$ [6] by $2.5\sigma$.

In the present work we analyse formula (2) performing relativistic many-body calculations of the diagonal and off-diagonal hfs matrix elements of the $6s$ and $7s$ states of Cs. The method of calculation is based on all-orders summation of the dominating diagrams of the many- body perturbation theory in the residual Coulomb interaction [2]. Zero-approximation energy levels, wave functions and Green's functions have been calculated using the relativistic Hartree-Fock method. Then the polarisation of the atomic electron core by the nuclear magnetic field has been calculated (summation of the "RPA with exchange" chain of diagrams). Finally, we calculated all second order correlation corrections and three series of dominating higher-order diagrams: screening of the electron-electron interaction, hole-particle interaction, and iterations of the self-energy operator. The results show that introduction of the many-body corrections leaves the square-root formula $\langle 6s|H_{hfs}|7s\rangle = \sqrt{\langle 6s|H_{hfs}|6s\rangle\langle 7s|H_{hfs}|7s\rangle}$ valid to an accuracy of better than $5 \times 10^{-4}$. This means that the role of the many-body effects in Ref. [5] has been overestimated and the coefficient 1.0024 should be removed from the formula (2). This leads to the new values of $M_{hfs}, \beta$ and $Q_W$:

$$\begin{aligned} M_{hfs} &= |\frac{\mu_B}{c}|0.8074(8) \times 10^{-5}, \\ \beta &= 26.957(43)(27)a_0^3, \\ Q_W &= -71.88(28)(29). \end{aligned} \tag{3}$$

Note that the deviation from the Standard Model increases from $2.5\sigma$ to $3.1\sigma$. If the theoretical uncertainty is 1% as it has been assumed in Refs. [2, 3] then there is still a $1.5\sigma$ deviation from the Standard Model. New calculations of the $k_{PNC}$ matrix element with careful analysis of accuracy is needed to shed some light on the problem.

Meanwhile we have performed calculations of the $k_{PNC}$ matrix element for the $s - d$ transitions in Cs, Fr, $Ba^+$ and $Ra^+$. These transitions are considered for new PNC measurements in atoms.


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