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Calculating the many-potential vacuum polarization density of the Dirac equation in the finite-basis approximation

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Contrary to the muonic atoms case, it is well known that the self-energy correction to the solutions of the Dirac equation dominates vacuum-polarization in electronic atoms. However, having precise results for the latter contribution is crucial to obtaining accurate numerical results on the first-order QED corrections to the Dirac equation. Accounting for the vacuum polarization effect is standardly done through the inclusion of the Uehling potential [1] $\alpha(Z\alpha)$, and its finite nuclear size correction can be easily incorporated [2]. With an increasing nuclear charge Z, or (and) for heavier bound fermions (muons and tauons), it becomes more demanding to include higher-order $\alpha(Z\alpha)^{n\geq 3}$ corrections to the Uehling process, with their corresponding finite nuclear size effects.

In the current work [3], we propose an efficient and accurate method to compute the $\alpha(Z\alpha)^{n\geq 3}$ vacuum polarization density, within the finite basis approximation of the Dirac equation. To prove the functionality of our computational method, we choose to work with the one-electron uranium atom and employ relativistic Gaussian basis functions. In summary, we find that compliance with charge conjugation symmetry is necessary to obtain physical results that are in line with our knowledge of the analytical (exact) problem, as indicated by Salman in [4], in addition to Grant and Quiney in [5]. We also note that the final results are in excellent agreement with previous formal analytical (and numerical) evaluations, done by Soff, Mohr, and Plunien in [6, 7]. Our technique can be easily and efficiently implemented in codes that solve the radial Dirac equation in the finite basis set framework and could be employed for atomic problems with arbitrary (radial) nuclear charge distribution. The obtained numerical results of the non-linear vacuum polarization density are, therefore, automatically accounting for the extended nuclear size effect. This method is hence of special importance for atomic problems with nuclear distributions whose analytical expressions of their associated Dirac Green's functions are not in hand or have relatively complicated analytical forms.

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