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Isotope-shift factors with quantum electrodynamics effects for many-electron systems: A study of the nuclear charge radius of ^{26m}Al

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Accurate determination of nuclear charge radii serves as a sensitive test of various aspects of nuclear structure and provides an important benchmark for the development of nuclear models~[1]. Precise charge radius measurements can also constrain the parameters of the nuclear matter equation of state. The knowledge of nuclear charge radii for certain isotopes is crucial for testing fundamental particle physics models. The Cabibbo-Kobayashi-Maskawa (CKM) matrix plays a central role in describing quark-flavour mixing via the weak interaction within the Standard Model (SM). According to the SM, the CKM matrix must be unitary, but this property requires experimental verification. Any deviation from unitarity could signal new physics beyond the SM. Significant efforts are underway to test this unitarity~[2]. The deviation from unitarity in the top row of the CKM matrix can be quantified by the parameter $\Delta_{\mathrm{CKM}} = 1 - (|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2)$, which should be zero if the matrix is unitary. The largest V_{ud} element can be extracted from a global analysis of superallowed $0^+ \to 0^+$ nuclear β decays of certain isotopes~[2]. Among these, the superallowed β decay of the isomer ^{26m}Al is of particular importance, as it exhibits the smallest nuclear-structure-dependent corrections~[2]. Several corrections must be calculated to relate the experimentally measured ft value (which characterizes the superallowed β decay) to the V_{ud}. One of these corrections is the isospin-symmetry-breaking term, which depends on the nuclear mean-square (ms) charge radius. This radius can be extracted from isotope shift (IS) measurements, which in turn require accurate knowledge of atomic parameters known as the field and mass shifts—a challenge for modern many-body atomic theory.

A method for calculating the field shift contribution to isotope shifts in many-electron atoms, including quantum electrodynamics (QED) effects, has been introduced~[3]. We also implement a model QED approach to incorporate QED corrections to the nuclear recoil effect proposed in Ref.~[4]. The developed computational scheme utilizes advanced methods such as coupled cluster with single, double, triple and perturbative quadruple excitations, CCSDT(Q), to accurately account for electron correlation effects beyond the 6 order of perturbation theory. For the first time for a many-electron atom, achieved theoretical uncertainty required consideration of the QED effects.

By combining our calculated atomic factors with the recently measured isotope shift of the $3s^2 3p\ ^2P_{3/2} \to 3s^2 4s\ ^2S_{1/2}$ transition in Al, we obtain a difference in ms charge radii between ^{27}Al and ^{26m}Al of $0.443(44)(19)$ fm^2, where the first and second uncertainties are experimental and theoretical, respectively. The theoretical uncertainty has been reduced by a factor of four compared to previous works. Using this result and the known charge radius of ^{27}Al, we derive $R_c(^{26m}\mathrm{Al}) = 3.132(10)$ fm. With the improved accuracy of the calculated IS factors, the uncertainty in $R_c(^{26m}\mathrm{Al})$ is now dominated by experimental error. We also revise charge radii of ^{28}Al, ^{29}Al, ^{30}Al, ^{31}Al, and ^{32}Al using existing IS data. Additionally, we compute atomic factors for the $3s^2 3p\ ^2P_{3/2} \to 3s^2 4s\ ^2S_{1/2}$, $3s^2 3p\ ^2P_{1/2} \to 3s^2 5s\ ^2S_{1/2}$, and $3s^2 3p\ ^2P_{3/2} \to 3s^2 5s\ ^2S_{1/2}$ transitions in Al, which can be used in future experiments.
The improved rms charge radius of ^{26m}Al directly affects the evaluation of the V_{ud} element of the CKM matrix and, consequently, has important implications for testing the unitarity of the CKM matrix.

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