Transverse Nuclear Polarization in Hydrogen-Like Heavy Ions

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Recent progress in precise spectroscopic measurements for highly charged heavy ions stimulates higher-order calculations of quantum electrodynamics (QED) effects for the Lamb shift (see Ref. [1]). Comparison between the precise experiment and the calculation provides a critical test in a strong Coulomb field. In heavy ions, however, nuclear effects are also important for the comparison. Among them is the nuclear polarization (NP) effect, which is a shift of an atomic energy level due to virtual nuclear excitations.

In the previous studies of the NP effect[2, 3, 4, 5], it has been assumed that a nucleus is polarized by a bound electron only through the Coulomb interaction; the transverse interaction has been ignored. In the present work, we demonstrate that the transverse interaction is essential to the NP effect in heavy ions (see Refs. [6, 7] for preliminary studies).

The lowest order NP correction is formulated for the ground state of a hydrogen-like ion with the ladder and crossed diagrams of two-photon exchange in terms of the bound-state QED formalism, where a whole of the Coulomb and and transverse interactions is incorporated. The NP effect due to the transverse interaction (TNP) is given as the difference between the NP effect due to the Coulomb interaction (CNP) and that due to the whole interaction.

To examine the TNP effect without going into details of nuclear structure, we consider the hydrogen-like ${}^{238}_{92}$U ion, taking into account the lowest electric-quadrupole (E2) excitation and the electric-dipole (E1) giant resonance. Note that the two modes are responsible for more than 80% of the CNP correction according to a previous calculation[5]. Intrinsic nuclear dynamics is described by the transition charge and current densities of the collective model.

Table 1 shows results of the NP corrections. The present result of the CNP is in good agreement with the previous calculation[5]. A small discrepancy of several meV is attributed to the wave functions used; those for the point charge are used in the present work and those for an extended nucleus in Ref. [5]. For the lowest E2 excitation, the whole NP correction almost coincides with the CNP; the effect of the transverse interaction is negligible. For the E1 giant resonance, however, the whole NP correction is about three times larger than the CNP; the TNP dominates the NP effect.

These results indicate a striking contrast between the two nuclear excitation modes as to the relative contribution of the transverse and Coulomb interactions. To understand this point, we consider two electronic radial form factors, $F_{\lambda,\lambda-1}$ and F_λ, for excitation of multipolarity λ. The modulus squared of the ratio $F_{\lambda,\lambda-1}/F_\lambda$ approximately scales the relative magnitude of the TNP to CNP effects. The ratio is roughly written as

$$\frac{F_{\lambda,\lambda-1}(r,\omega)}{F_\lambda(r,\omega)} \approx \frac{\omega_{\rm n} h^{(1)}_{\lambda-1}(\omega r)}{\lambda \omega h^{(1)}_\lambda(\omega r)}, \tag{1}$$

with the photon energy ω and the nuclear excitation energy $\omega_{\rm n}$, $h^{(1)}_\lambda$ denoting the spherical Hankel function of the first kind. It is seen from this equation that the higher is the $\omega_{\rm n}$, the more important is the TNP effect. Furthermore, we can take $\omega \approx \omega_{\rm e}$ with the electronic transition energy $\omega_{\rm e}$ between the intermediate and the groud states, and $r \approx \langle r \rangle$ with the electronic mean radius $\langle r \rangle \sim 1$ r.u. in the ground state. Thus, the ratio (1) is reduced to $\omega_{\rm n}\langle r \rangle$ when $\omega_{\rm e}\langle r \rangle < 1$, while to $\omega_{\rm n}/\omega_{\rm e}$ when $\omega_{\rm e}\langle r \rangle > 1$. Hence, the TNP is negligible when $\omega_{\rm n} \ll 1/\langle r \rangle$, while it is crucial when $\omega_{\rm n} \gg 1/\langle r \rangle$ and a contribution from $\omega_{\rm e} < \omega_{\rm n}$ is important. This is the case with the present results for the lowest E2 excitation ($\omega_{\rm n} \ll 1$ r.u.) and the E1 giant resonance ($\omega_{\rm n} \gg 1$ r.u.).

We conclude from the present result for the specific $^{238}_{92}$U ion that, in general, the contribution of the transverse interaction to the NP effect in a heavy ion is comparable to, or even larger than, that of the Coulomb interaction, unless the nucleus has a dominant excitation mode with $\omega_{\rm n} \ll 1/\langle r \rangle$. The transverse interaction, induced by the nuclear current, is often ignored with a statement that "velocities associated with collective nuclear dynamics are essentially nonrelativistic"[5]. However, this argument is incorrect because the NP effect is associated with fluctuation of the nuclear current, and not with the average.

Table 1: Nuclear polarization correction [meV] for the ground state of the hydrogen-like $^{238}_{92}$U ion; NP denotes the correction due to a whole of the Coulomb and transverse interactions, CNP being due to the Coulomb interaction.

mode	$\omega_{\rm n}$ [MeV]	present work NP	present work CNP	Ref. [5] CNP
E2	0.0449	−131.9	−131.4	−125.2
E1	12.856	−154.3	−49.3	−42.4

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