Nuclear QED effect in atoms

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Photons propagating in an atom give rise to $e\bar{e}$ vacuum polarization [1]. Likewise mesons propagating in a nucleus excite nucleon-antinucleon ($N\bar{N}$) vacuum polarization. An $e\bar{e}$ pair produced in an atom couples with a proton-antiproton ($p\bar{p}$) pair in the nucleus through a photon exchange. In this paper we will discuss the effect on atomic properties of these vacuum polarizations.

The motion of nucleons in a nucleus is supposed to be nonrelativistic. However relativistic effect might be significant, since mesons propagating in a nucleus could excite negative energy nucleons (Dirac sea) to make $N\bar{N}$ vacuum polarization. In the previous paper [2], to solve the problem if negative enegy nucleons affect properties of nuclei, we have performed the Hartree calculations for a nucleus in two ways, one only in positive energy nucleon sector and the other in full sector taking into account not only positive energy nuleons but also negative energy nucleons for the Slater determinant Hartree wave function. In the relativistic Hartree approximation, σ and ω mesons contribute to spin $S = 0$ and isospin $I = 0$ nuclei. The result of the Hartree calculation is summerized as follows. The full sector calculation predicts 1) smaller binding energies of antinucleons and 2) wider nuclear radius and smaller nuclear total energy. The smaller binding energies of nucleons and antinucleons obtained in the full sector calculation are understandable from the minimum total energy principle of Hartree calculation.

To elucidate more the result of the above relarivistic Hartree calculation in the previous paper, we took the picture of a nucleus as a system composed only of positive energy nucleons, which are affected by negative energy nucleons. The attractive σ meson exchange interaction between positive energy nucleons in momentum representation,

$$V_\sigma(k) = -\frac{g_\sigma^2}{m_\sigma^2 + k^2}, \tag{1}$$

with coupling constant g_σ, meson mass m_σ and momentum k, is affected by negative energy nucleons: The meson exchaged between positive energy nucleons excites $N\bar{N}$ vacuum polarizations so that the meson exchange interaction is modified to be

$$V_\sigma(k) = -\frac{g_\sigma^2}{m_\sigma^2 + k^2 + \Pi_\sigma(k)} \tag{2}$$

with $N\bar{N}$ vacuum polarization function $\Pi_\sigma(k)$. In a same way the repulsive ω meson exchange interaction is modified to be

$$V_\omega(k) = \frac{g_\omega^2}{m_\omega^2 + k^2 + \Pi_\omega(k)} \tag{3}$$

in terms of the polarization function $\Pi_\omega(k)$.

The $N\bar{N}$ vacuum polarization functions $\Pi(k)$ are renormalized so that they vanish in vacuum. Then they become to be proportional to the density of the medium, which makes the meson exchange interactions $V(k)$ be effective many-body interactions in the nucleus. Three body interaction, which is believed to exist in nuclei, must be originated from the relativistic nuclear dynamics under present consideration.

The σ meson couples with the ω meson through $N\bar{N}$ vacuum polarization $\Pi^0_{\sigma\omega}(k)$. This coupling of the mesons makes the polarization functions $\Pi_\sigma(k)$ and $\Pi_\omega(k)$ in Eq's. (2)-(3) be modified: For example, the polarization function $\Pi_\sigma(k)$ is modified to be

$$\Pi_\sigma(k) = \Pi^0_\sigma(k) + \frac{\Pi^0_{\sigma\omega}(k)\Pi^0_{\omega\sigma}(k)}{m_\omega^2 + k^2 + \Pi_\omega(k)} \tag{4}$$

in terms of the fundamental polarization function $\Pi^0_\sigma(k)$. The polarization functions $\Pi(k)$ have been evaluated to make an observable effect on the meson exchange interactions in Eq's. (2)-(3).

Likewise to the coupling of σ meson with ω meson, a photon couples with these mesons in nuclei. In this paper we will discuss the problem how photons couple with mesons through vacuum polarizations in atomic systems. In muonic atoms this effect might be clearly observed.

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