QUANTUM MÜNCHHAUSEN EFFECT IN TUNNELING

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Any charged object interacts with the electromagnetic radiation field which invariably accompanies motion of the object. This interaction is responsible for two type of effects. In an external potential, the acceleration of the charge causes emission of real photons (the radiation field is torn away from the system). This effect is present in classical electrodynamics. Another, pure quantum effect, is related to virtual emission and absorption of quanta. These processes contribute to self-energy of the object and usually are called radiation corrections. A typical example of the second type effect is the Lamb shift of atomic levels.

Recently a great interest arose to the bremstrahlung during a tunneling process. A charged particle tunneling through a potential barrier radiates not only in the classical motion beyond the barrier but under the barrier as well. Strictly speaking, the emitted photon is formed by the entire wave function including classically forbidden regions, and the resulting radiation characteristics, as intensity, frequency spectrum and angular distribution, are determined by the complicated interference of radiation coming from different parts of the quantum cloud. As easy to figure out, in the processes like alpha-decay or nuclear fission the interference of radiation from under the barrier and from the final Coulomb acceleration is mostly destructive. This was observed in the measurement of the radiation during alpha-decay [*J. Kasagi et al.*, Phys. Rev. Lett. **79** (1997) 371] and triggered a number of theoretical works.

We considered the self-energy $\hat{\Sigma}$ for a charged particle in an external potential $U(\mathbf{r})$. In the one-photon approximation it is a complex, nonlocal and energy-dependent operator, expressed as a sum over photon modes with the wave vector **k**, frequency $\omega_{\mathbf{k}}$ and polarization λ, and over stationary states $|n\rangle$ of the particle with energy E_n,

$$\Sigma(\mathbf{r},\mathbf{r}',E)=\sum_{\mathbf{k},\lambda}|g_{\mathbf{k}}|^2\sum_n\frac{\langle\mathbf{r}|(\hat{\mathbf{p}}\cdot\mathbf{e}_{\mathbf{k}\lambda})e^{i\mathbf{k}\cdot\hat{\mathbf{r}}}|n\rangle\langle n|(\hat{\mathbf{p}}\cdot\mathbf{e}^*_{\mathbf{k}\lambda})e^{-i\mathbf{k}\cdot\hat{\mathbf{r}}}|\mathbf{r}'\rangle}{E-E_n-\omega_{\mathbf{k}}-i0}. \qquad (1)$$

Here the polarization vectors $\mathbf{e}_{\mathbf{k}\lambda}$ are transverse with respect to **k**, and the normalization factors are included into $g_{\mathbf{k}}\propto\omega_k^{-1/2}$. The antihermitian part Γ of the operator $\Sigma=M-(i/2)\Gamma$ comes from the on-shell emission at $E=E_n+\omega_{\mathbf{k}}$ and determines the radiation intensity.

The hermitian part M leads to the renormalization of the original external potential. In a good approximation, it can be represented by a local operator

$$M(\mathbf{r},\mathbf{r}',E)\simeq\frac{Z^2\alpha}{3\pi m^2}L\nabla^2U(\mathbf{r})\delta(\mathbf{r}-\mathbf{r}'), \qquad (2)$$

where Ze is the particle charge, m its mass (reduced mass for alpha-decay), α fine structure constant, and the logarithmic factor L, similarly to the Lamb shift calculation, depends on details of the particle spectrum. In the semiclassical case for the s-wave tunneling under the barrier of spherical symmetry, this factor, not very close to the turning points, can be found as

$$L(r,E)=\ln\frac{m}{|U_p(r)-E|} \qquad (3)$$

where $U_p(r)$ is the potential including the centrifugal part for the virtual p-wave states appearing as intermediate states in the sum (1).

The Laplacian of the potential in eq. (2) near the top of the barrier is negative which leads to the increase of the tunneling probability. According to the Poisson equation, it is always negative for the Coulomb barrier in the region of a non-zero charge density. For the alpha-decay, the correction to the potential is small, ~ 1 keV, but it should be more important for fission. It can be noticeable in some cases due to the exponential sensitivity to the height of the barrier (recall the notorious cold fusion problem). Also, there exist theories like QCD where the radiation corrections are not small.

Similar effects as tunneling assisted by wave-like excitations are known in condensed matter and nuclear reactions (subbarier fission and fusion). They represent a part of the problem of energy exchange between a tunneling particle and environment [*A.O. Caldeira and A.J. Leggett*, Ann. Phys. **149** (1983) 374; *A.B. Balantekin and N. Takigawa*, Rev. Mod. Phys. **70** (1998) 77]. However, in our case, the environment cannot be removed being a inalienable attribute of particle's existence and always has to be taken into account as one of "small" QED effects. In fact, the effect of self-accelerated tunneling reminds the feat of famous baron von Munchhausen who was able to save himself from a swamp pulling his hairs by the hand of his own. Here the particle uses the virtual photon hand to enhance the tunneling probability.

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