Virtual Photons From Unruh Radiation and the Lamb Shift to Dicke’s Superradiance

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One of the most intriguing results of modern quantum field theory is the proof by Davies et al., and others, that ground-state atoms, accelerated through vacuum, are promoted to an excited state just as if they were in contact with a blackbody thermal field. These studies predict that a (two-level) ground-state atom, having transition frequency \( \omega \), and experiencing a constant acceleration \( a \), will be excited to its upper level with a probability governed by the Boltzmann factor \( \exp(-2\pi \omega/\alpha) \), where \( \alpha = a/c \), \( c \) is the speed of light in vacuum. Unfortunately, even for large acceleration frequency \( \alpha \approx 10^8 \) Hz, and microwave frequency \( \omega \approx 10^{10} \) Hz, this factor is exponentially small, \( \sim 10^{-200} \), and is not of experimental interest.

Thus we were motivated to study a simple gedanken experiment based on a model consisting of a high \( Q \) “single mode” cavity through which we pass accelerated two-level atoms, as in Fig. 1. We find that the radiation is thermal (in the typical case) and the effective Boltzmann factor is now given by \( \alpha/2\pi \omega \). For the above example, \( \alpha/2\pi \omega \sim 10^{-3} \); hence, it is many orders of magnitude larger than that for the usual Unruh effect and is potentially observable. The reason for such a strong enhancement is a fast nonadiabatic switch of the interaction of atoms with the field at the boundaries of the cavity. Moreover, this nonadiabatic boundary contribution, in most cases, prevails over the standard Unruh effect.

The Lamb shift and Dicke’s superradiance are two of the most intriguing effects in atomic physics and quantum optics. Lamb measured the electromagnetic level shift in hydrogen and provided the stimulus for renormalized quantum field theory. Dicke gave us a simple formalism for calculating the collective spontaneous emission from a small cloud of \( N \) atoms yielding fascinating results; e.g., one symmetric excitation of such a cloud will decay \( N \) times faster than a single isolated atom. We call this “single photon superradiance.”

The focus of the present talk is a toy model yielding the dynamical evolution of the atomic system described by \( \left| B_0 \right> \), associated with real (decay) and virtual (level shift) photon emission. Specifically we find to a good approximation that the probability amplitude \( B_0 \) for the large sample state \( \left| B_0 \right> \) obeys the simple small sample superradiance type equation

\[
\dot{\beta}_0 = -i [\Gamma + \Gamma_N + i \mathcal{L}_N] \beta_0,
\]

(1a)

where \( \Gamma \) is the single atom decay rate and the collective decay rate of the atomic cloud containing \( N \) atoms in a volume \( V \) of radius \( R \) is given by \( \Gamma_N = \frac{\Gamma}{4\pi} \frac{N^2}{V} \lambda^2 R \),

while the \( N \) atom Lamb shift \([3,4]\) of \( \left| B_0 \right> \) is given by

\[
\mathcal{L}_N = -\frac{\Gamma}{\pi} \left( \ln \frac{K^2 - k_0^2}{k_0^2} - N \ln \frac{K + k_0}{k_0} \right) + \frac{\Gamma_N \lambda \lambda}{4\pi 4R} S,
\]

(1b)

where \( K \) is the Bethe cutoff, \( k_0 = \omega/c \), and \( S \) is an uninteresting shape factor of order one. The first term in Eq. (1b) is the usual single (two level) atom level shift; the second term is a collective shift common to the ground state. The last term is the interesting one.
