Quantum Radiation

from an **atom** interacting with a Quantum **Field**

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Vacuum fluctuations, Quantum dissipation
Quantum radiation, Radiation reaction

Bei - Lok Hu 胡悲樂

Maryland Center for Fundamental Physics and
Joint Quantum Institute, University of Maryland, USA

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Ongoing work with **Jen - Tsung Hsiang** 项人宗 (NCU)

J. T. Hsiang and B. L. Hu, Special issue on "the quantum vacuum" in *Physics* *1*(3), 430-444; 2019 doi:10.3390/physics1030031 arXiv:1910.11527

--- slides courtesy of **Dr. Jen-Tsung Hsiang,** who has presented this work at Tufts University Nov 2019, Fudan University Dec 2019

Classical Radiation & Rad Reaction

- Uniformly accelerated charge (UAC) emits classical radiation, but there is no radiation reaction

- So when people say that vacuum fluctuations and radiation reaction produce the same effect, or are two sides of the same coin (e.g., Milonni, 1993 *The Quantum Vacuum*)

  it generates unnecessary confusion

- Vacuum Fluctuation is of a quantum origin and ubiquitous, but radiation reaction is classical.

Radiation reaction and vacuum fluctuations – confusion in terminology or in contents?

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Fluctuation-Dissipation Relation (FDR)

- This relation is what people use to equate the effects of radiation reaction with vacuum fluctuation. But,

- These quantities operate at two different levels:

  Vacuum Fluctuation is Quantum and ubiquitous.

  Radiation reaction is Classical but non-ubiquitous.

  E.g., in the case of a uniformly accelerated charge there is no radiation reaction.

The correct entity which enters in the FDR is

Not radiation reaction (classical) but Quantum Dissipation.

Quantum Dissipation: Origin

- The backreaction of the field (environment) affects the motion of the charge (system).

- Governed by the fluctuation-dissipation relation.

- Both are of quantum origin. NOT radiation reaction which exists at the classical level.

- This was emphasized by Johnson, P.R.; Hu, B.L. (2002) *Stochastic theory of relativistic particles moving in a quantum field: Scalar Abraham-Lorentz-Dirac-Langevin equation, radiation reaction, and vacuum fluctuations*. Phys. Rev. D 2002, 65, 065015

Quantum Radiation: Origin

- Vacuum fluctuations in the field add on a stochastic component in the motion of the charge
- this nonuniform motion generates quantum radiation

- Because it is due to vacuum fluctuations, this radiation is of quantum origin.
- Since vacuum fluctuations are small, this quantum radiation is very weak.

- Thus quantum radiation can exist even for a stationary atom interacting with a quantum field.

Unruh Effect: Quantum Radiance

- Refers to a uniformly accelerated (UA) “detector”. We shall call it an atom (at the origin O) to avoid confusion with a detector located at the reception point (R).

- Of foremost importance -- Distinguish between:

  a UA atom getting hot with thermal radiance of T_u at O

  vs an atom emitting radiation detected at R.

- Both are of quantum origin. How does this relate to the quantum radiation from the stochastic motion of an atom due to the vacuum fluctuations of the q field?

Features of Q. Radiation from UA atom.

For an Unruh-DeWitt detector, or Harmonic Atom

- in 1+1D, there is no radiation: Tmn=0 everywhere

  (Grove 86, Raine Sciama & Grove 91, Unruh 92, Hinterleitner 93, Massar, Parentani and Brout 93, Raval, Hu & Anglin, 1996, Hu & Raval 2001, Ford & O'Connell 2006)

- in 1+3D there is net emitted radiation albeit very weak

  S. Y. Lin and B. L. Hu, **Accelerated Detector - Quantum Field Correlations: From Vacuum Fluctuations to Radiation Flux** Phys. Rev. D73 (2006) 124018 [quant-ph/0507054]

  Iso, Oshita, Tatsukawa, Yamamoto, Zhang 2017, Higuchi, Iso, Ueda, Yamamoto 2017: Entanglement induced quantum radiation

- Why such a difference? What is the source of this emitted energy? Is quantum entanglement involved?

- We would like get a better understanding of these issues by examining the energy – q radiation flowing out from the atom at O, and that associated with the vacuum fluctuations of the field at the point of observation R.

First, Stationary Atom: This Work.

Then, Uniformly Accelerated Atom & Unruh effect

What should we expect?

- For a stationary atom, we expect no emitted radiation. But then earlier we mentioned the existence of quantum radiation from the stochastic motion of the atom owing to vacuum fluctuations.

- Let's sort out all the factors involved, item by item, at the receiver point R. They should add up to zero.

- This is by no means a trivial problem. It reveals the complex physics involved and provides a stringent test.

Atom-field interaction: A simple model

- Unruh-DeWitt detector/harmonic atom

  Its internal degree of freedom (idf) is modeled by a simple harmonic oscillator (SHO). The atom's external degree of freedom (edf) follows a prescribed trajectory (no backreaction).

- Massless scalar field in 1+3 Minkowski space

  can be straightforwardly generalized to the EM field

- Coupling strength between the atom and the field can be arbitrarily strong --- Strong coupling physics is an emergent field, already of great interest in AMO physics (cavity QED, circuit QED)

  This atom-field setup, being Gaussian, is exactly solvable, so no need to worry about the errors introduced by using approximation schemes, as is often done.

  No nonlinearity, no high field in the current case. Can solve for complete time evolution, relaxation, dissipative dynamics, etc.

Equations of motion

- For Gaussian systems the Heisenberg equations of motion have the same form as the classical:

$$\frac{d^2}{dt^2}\hat{Q}(t) + \omega_0^2\,\hat{Q}(t) = \frac{e}{m}\,\hat{\phi}(\mathbf{z}, t)\,,$$
$$\left(\frac{\partial^2}{\partial t^2} - \nabla^2\right)\hat{\phi}(\mathbf{x}, t) = e\,\hat{Q}(t)\,\delta^{(3)}(\mathbf{x} - \mathbf{z})\,,$$

where ω_0 is the bare frequency of the internal degree of freedom (idf) of the oscillator (atom), $\mathbf{z}$ is its prescribed trajectory (the external dof), e is the coupling strength between the oscillator and the field.

- The formal solution of the field is:

$$\hat{\phi}(\mathbf{x},t) = \hat{\phi}_{0,h}(\mathbf{x},t) + e\int d^4x'\; G^{(\phi)}_{0,R}(x,x')\,\hat{Q}(t')\,\delta^{(3)}(\mathbf{x}'-\mathbf{z}')\,,$$

  - The first term describes the quantum fluctuations of the free field,
  - The 2nd term is the radiation field from the atom if the motion of the idf is nonuniform.

- Substituting this into the equation for $\hat{Q}$ gives

$$\frac{d^2}{dt^2}\hat{Q}(t) + \omega_0^2\,\hat{Q}(t) = \boxed{\frac{e}{m}\,\hat{\phi}_{0,h}(\mathbf{z},t)} + \frac{e^2}{m}\int dt'\; G^{(\phi)}_{0,R}(\mathbf{z},t;\mathbf{z}',t')\,\hat{Q}(t')$$

  - This is in the form of a Quantum Langevin Equation
  - The idf is driven by the quantum fluctuations of the free field at the location of the atom.

- The reaction from this radiation introduces a local damping force

(self-force) $$\ddot{\hat{Q}}(t) + 2\gamma\,\dot{\hat{Q}}(t) + \omega^2\,\hat{Q}(t) = \frac{e}{m}\,\hat{\phi}_{0,h}(\mathbf{z},t)$$

  - This is of quantum origin, although it resembles its classical counterpart; that is where the earlier confusion arises.

- If there are more than one atom, then

$$\ddot{\hat{Q}}_i(t) + 2\gamma\,\dot{\hat{Q}}_i(t) + \omega^2\,\hat{Q}_i(t) - \frac{e^2}{m}\int_0^t dt'\; G^{(\phi)}_{0,R}(\mathbf{z}_i,t;\mathbf{z}_j,t')\,\hat{Q}_j(t') = \frac{e}{m}\,\hat{\phi}_{0,h}(\mathbf{z}_i,t)$$

  - The additional term expresses the non-Markovian influences of all other atoms on the ith atom

- The idf behaves like a driven, damped, non-Markovian (linear) oscillator

  - These three types of back actions due to the field are different and play different roles.

Dynamics of a stationary detector

- The idf evolves according to (assuming the source is fixed at $\mathbf{z}_s$)

$$\hat{Q}(t) = \hat{Q}_h(t) + \frac{e}{m}\int_0^t ds\, G_R^{(Q)}(t-s)\,\hat{\phi}_{0,h}(\mathbf{z}_s, s)$$

  - The 1st term, the "intrinsic" quantum fluctuations of the atom, is determined by the initial conditions, and will decay with time
  - The 2nd term involves the driving quantum field:

$G_R^{(Q)}(t-s)$ is the retarded Green's function for the idf, whose Fourier transform is given by

$$\overline{G}_R^{(Q)}(\omega) = \frac{1}{-\omega^2 + \omega - i\,2\gamma\,\omega} = \frac{1}{-\omega^2 + \omega_0^2 - \frac{e^2}{m}\,\overline{G}_{0,R}^{(\phi)}(\mathbf{0};\omega)}$$

  - At late times, the dynamics of the idf is governed by the field,

- The damping will relax the dynamics of the idf to an equilibrium state, independent of the initial states of the idf

- During the relaxation, the correlation function of the idf is given by

$$G_H^{(Q)}(t,t') \simeq \frac{e^2}{m^2}\int_0^t ds \int_0^{t'} ds'\, G_R^{(Q)}(t-s)\, G_R^{(Q)}(t'-s')\, G_H^{(\phi)}(\mathbf{0}, s-s')$$

  - In general it is not stationary, but at late times ($t, t' \gg \gamma^{-1}$), it will approach

$$G_H^{(Q)}(t-t') \simeq \int_{-\infty}^{\infty} \frac{d\kappa}{2\pi}\, \coth\frac{\beta\kappa}{2}\left\{\mathrm{Im}\,\overline{G}_R^{(Q)}(\kappa)\right\} e^{-i\kappa(t-t')}$$

    if the field is initially in a thermal state at the temp β^{-1}

  - We have used the FDR of the free field

$$\overline{G}_{0,H}^{(\phi)}(\kappa) = \coth\frac{\beta\kappa}{2}\,\mathrm{Im}\,\overline{G}_{0,R}^{(\phi)}(\kappa)$$

  - It induces a FDR of the detector $\overline{G}_H^{(Q)}(\kappa) = \coth\frac{\beta\kappa}{2}\,\mathrm{Im}\,\overline{G}_R^{(Q)}(\kappa)$

Fluctuation-Dissipation Relations

$$\overline{G}_H^{(Q)}(\kappa) = \coth\frac{\beta\kappa}{2}\,\mathrm{Im}\,\overline{G}_R^{(Q)}(\kappa)$$

- This FDR is derived for an arbitrary coupling strength, in contrast to FDR derived in linear response theory (LRT)
  - In LRT, 1) the system-bath coupling is vanishingly weak 2) the system temperature is the same as the bath's 3) the system is perturbed off equilibrium for a short time and let go.
  - In NEq theory, 1) the initial state of the system can be far from equilibrium, 2) the FDR is derived in the final equilibrium state, 3) this state does not take on the Gibbs form, and 4) the "effective" temp extracted from the equilibrium state is not universal. It is not equal to the bath temp, except in the vanishing coupling limit
    - Thus, in NEq theory, β^{-1} is not the system temperature. Instead, it is the initial temp of the bath

    ∵ The late-time dynamics of the system is governed by the bath, so it will inherit the bath's statistical and causal properties.

FDR in the context of NEq dynamics of the atom

Consider $$\ddot{\hat{Q}}(t) + 2\gamma\,\dot{\hat{Q}}(t) + \omega^2\,\hat{Q}(t) = \frac{e}{m}\,\hat{\phi}_{0,h}(\mathbf{z},t)$$

- The power delivered by the field fluctuations, or noise:

$$P_\xi(t) = \frac{e}{2}\,\langle\{\hat{\phi}_{0,h}(\mathbf{z},t),\dot{\hat{Q}}(t)\}\rangle_{\rho_s}$$

- The power delivered by quantum dissipation (damping self- force, `radiation reaction')

$$P_\gamma(t) = \frac{1}{2}\langle\{-2m\gamma\,\dot{\hat{Q}}(t),\dot{\hat{Q}}(t)\}\rangle_{\rho_s}$$

- At late times,

$$P_\gamma(\infty) = -e^2\int_{-\infty}^{\infty}\frac{d\kappa}{2\pi}\;\kappa\;\mathrm{Im}\,\overline{G}_{0,R}^{(\phi)}(\kappa)\,\overline{G}_{H}^{(Q)}(\kappa) = -P_\xi(\infty)$$

- The equal signs are possible only if the FDRs become valid. It says that the energy flow into and out of the detector is balanced once the system has fully relaxed.

- If there are more than one atom the off-diagonal elements account for the energy flow between the atoms. The role of cross-correlation becomes important —They obey a correlation-propagation relation (CPR):

  -- first discovered by Raval, Hu, Anglin 1996 PRD

- The energy flow from the field fluctuations is distributed among the atoms and then dissipated back to the field from each atom.

- The combined FDR-CPR takes on a matrix form.

Hsiang, J.-T.; Hu, B.L.; Lin, S.-Y. Fluctuation-dissipation and correlation-propagation relations from the nonequilibrium dynamics of detector-quantum field systems. Phys. Rev. D 2019, 100, 025019.

Hsiang, J.-T.; Hu, B.L.; Lin, S.-Y.; Yamamoto, K. Fluctuation-dissipation and correlation-propagation relations in (1+3)D moving detector-quantum field systems. Phys. Lett. B 2019, 795, 694.

From the Quantum Field's Perspective

- From the perspective of the atom, the energy flow is balanced, but does the field think the same way?
  - Based on energy conservation, it must be so. But how does it actually work out?
  - More importantly, does a uniformly accelerating atom radiate (~~classically~~/quantum mechanically) when it is excited by fluctuations, quantum or thermal, at its location?

Quantum Field Dynamics

- Here we consider the field dynamics, when it couples to a static atom (still working on the uniformly accelerating case)

$$\hat{\phi}(\mathbf{x},t) = \hat{\phi}_{0,h}(\mathbf{x},t) + e\int d^4x'\, G^{(\phi)}_{0,R}(x,x')\,\hat{Q}(t')\,\delta^{(3)}(\mathbf{x}'-\mathbf{z}')$$

$$= \hat{\phi}_{0,h}(\mathbf{x},t) + \frac{e^2}{m}\int dt'\, G^{(\phi)}_{0,R}(\mathbf{x},t;\mathbf{z}',t')\int_0^{t'} ds\, G^{(Q)}_R(t'-s)\,\hat{\phi}_{0,h}(\mathbf{z}_s,s)$$

$$+\, e\int_0^t dt'\, G^{(\phi)}_{0,R}(\mathbf{x},t;\mathbf{z}',t')\,\hat{Q}_h(t')$$

- The 1st term is the local free field at R the observation/receiver point.
- The 3rd term is a transient radiation field coming from the intrinsic quantum fluctuations of the atom at O, the position of the atom.
- The 2nd term is the radiation field resulting from the induced quantum fluctuations on the atom due to the field fluctuations at O,

$$\hat{Q}(t) = \hat{Q}_h(t) + \frac{e}{m}\int_0^t ds\, G^{(Q)}_R(t-s)\,\hat{\phi}_{0,h}(\mathbf{z}_s,s)$$

- Q: 1) does the atom radiate?, 2) is there a net energy flux propagating outward to null infinity?
- A: It does radiate b/c the idf undergoes stochastic motion, driven by the field fluctuations

-- If it radiates it will carry some energy to afar.

> But where does this energy come from? in particular, if the free field is initially in the vacuum state.

- Let us first consider the more familiar case of

  a uniformly accelerating classical charge:

  - No classical field around, except for the radiation field from the charge
  - The far-field component of the radiation field survives at null infinity and delivers a power $\propto \dot{v}^2$,
  - The damping force is $\propto \ddot{v}$
  - Thus, it radiates energy out, but no radiation damping!
  - Where does the energy come from?

- The energy flow from the charge has two components
    - The radiated energy: purely from the far field (only this part goes to null infinity)
    - The Schott energy: interference between the near field and the far field (it can go back to the charge)

- The forces associated with each component (neither of them corresponds to the radiation reaction) cancel one another in the limit of uniform acceleration.

- In our model example, the additional field component in

$$\hat{\phi}(\mathbf{x},t) = \hat{\phi}_{0,h}(\mathbf{x},t) + \boxed{\frac{e^2}{m}\int dt'\, G^{(\phi)}_{0,R}(\mathbf{x},t;\mathbf{z}',t') \int_0^{t'} ds\, G^{(Q)}_R(t'-s)\, \hat{\phi}_{0,h}(\mathbf{z}_s,s)}$$

$$+\, e\int_0^t dt'\, G^{(\phi)}_{0,R}(\mathbf{x},t;\mathbf{z}',t')\, \hat{Q}_h(t')$$

$$= \hat{\phi}_{0,h}(\mathbf{x},t) + \hat{\phi}_{\mathrm{R}}(\mathbf{x},t) + \cdots$$

is of quantum origin, and will be correlated to the original quantum field $\hat{\phi}_{0,h}(\mathbf{x},t)$ at the observation point R (obs. Pt.) $\mathbf{x}$

- This can be seen from the correlation function of the full field

$$\{\hat{\phi}(x),\hat{\phi}(x')\} = \{\hat{\phi}_{0,h}(x),\hat{\phi}_{0,h}(x')\} + \boxed{\{\hat{\phi}_{0,h}(x),\hat{\phi}_{\mathrm{R}}(x')\} + \{\hat{\phi}_{\mathrm{R}}(x),\hat{\phi}_{0,h}(x')\}} + \{\hat{\phi}_{\mathrm{R}}(x),\hat{\phi}_{\mathrm{R}}(x')\} + \cdots$$

- An interference term exists between the radiated field and the local free field at the obs. pt.

- The FDR of the free field has a role to play.

- Similar to the atomic case, this correlation is not stationary, but will become so at late times

- With the help of the FDR of the atom, we may reduce

$$\frac{1}{2}\{\hat{\phi}_{\rm R}(x),\hat{\phi}_{\rm R}(x')\}=\frac{e^4}{m^2}\int_0^t ds_1\int_0^{t'} ds_1'\;G^{(\phi)}_{0,R}(\mathbf{x},t;\mathbf{z}_1,s_1)G^{(\phi)}_{0,R}(\mathbf{x}',t';\mathbf{z}_1',s_1')$$

$$\times\int_0^{s_1} ds_2\int_0^{s_1'} ds_2'\;G^{(Q)}_R(s_1-s_2)G^{(Q)}_R(s_1'-s_2')\,G^{(\phi)}_{0,H}(\mathbf{z}_2,s_2;\mathbf{z}_2',s_2')$$

$$=\frac{e^2}{m}\int_{-\infty}^{\infty}\frac{d\kappa}{2\pi}\;\coth\frac{\beta\kappa}{2}\;\mathrm{Im}\,\overline{G}^{(Q)}_R(\kappa)\,\overline{G}^{(\phi)}_{0,R}(\mathbf{r}_2;\kappa)\,\overline{G}^{(\phi)*}_{0,R}(\mathbf{r}_1;\kappa)\,e^{-i\kappa(t-t')}+\cdots$$

$$\mathbf{r}_1=\mathbf{x}'-\mathbf{z}$$

$$\mathbf{r}_2=\mathbf{x}-\mathbf{z}$$

- This looks very similar to the contribution from the interference terms

$$\frac{e^2}{m}\int_{-\infty}^{\infty}\frac{d\kappa}{2\pi}\;\overline{G}^{(\phi)}_{0,H}(\mathbf{r}_2;\kappa)\,\overline{G}^{(\phi)*}_{0,R}(\mathbf{r}_1;\kappa)\,\overline{G}^{(Q)*}_R(\kappa)\,e^{-i\kappa(t-t')}$$

$$+\frac{e^2}{m}\int_{-\infty}^{\infty}\frac{d\kappa}{2\pi}\;\overline{G}^{(\phi)}_{0,H}(\mathbf{r}_1;\kappa)\,\overline{G}^{(\phi)}_{0,R}(\mathbf{r}_2;\kappa)\,\overline{G}^{(Q)}_R(\kappa)\,e^{-i\kappa(t-t')}$$

Energy Flow: Power Balance

- The expectation value of the normal-ordered stress-energy tensor operator $\hat{T}_{\mu\nu}(x)$ wrt the "in-state" is

$$\langle : \hat{T}_{\mu\nu}(x) : \rangle = \lim_{x' \to x} \left\{ \frac{\partial^2}{\partial x^\mu \partial x'^\nu} - \frac{1}{2} g_{\mu\nu} g^{\alpha\beta} \frac{\partial^2}{\partial x^\alpha \partial x'^\beta} \right\} \left[G_H^{(\phi)}(x,x') - G_{0,H}^{(\phi)}(x,x') \right]$$

where

$$G_H^{(\phi)}(x,x') = \frac{1}{2} \langle \{ \hat{\phi}(x), \hat{\phi}(x') \} \rangle$$

- The energy flow (power) received at the obs. pt. is

$$P = -\int d\Omega \, r^2 n^\mu \langle : \hat{T}_{\mu\nu}(x) : \rangle \, v^\nu(\tau_-) = P_\times + P_{\mathrm{R}}$$

  - P_R is the power due solely to the radiation field (its far field component)
  - $P_\times$ is the power due to the interference term

- Applying the FDR of the detector again, we find

$$P_{\mathrm{R}} = +\frac{e^2}{m}\int_{-\infty}^{\infty}\frac{d\kappa}{2\pi}\,\frac{\kappa^2}{4\pi}\,\coth\frac{\beta\kappa}{2}\,\operatorname{Im}\overline{G}_R^{(Q)}(\kappa)$$

it gives an outward energy flow (power) to null infinity; however,

$$P_{\times} = -\frac{e^2}{m}\int_{-\infty}^{\infty}\frac{d\kappa}{2\pi}\,\frac{\kappa^2}{4\pi}\,\coth\frac{\beta\kappa}{2}\,\operatorname{Im}\overline{G}_R^{(Q)}(\kappa)$$

the interference term produces an inward energy flow (power) of exactly the same magnitude!

The net power becomes zero and the conservation of energy is enforced by the interference between the local free field and the field radiated from the atom.

- Repeated application of the FDRs tells that nonlocal correlation (CPR) of the field will “control” the correlations of the atom, which in turn correlate with the radiated field from the atom and the free field at the faraway observation point.

- Without this interference term we would see a net quantum radiation, which contradicts our intuition, particularly if the field is initially in a vacuum state.

- Compare with the dissipated power from the atom, we have
  - $P_{\rm R} = P_\gamma$: the dissipated power gets radiated away to null infinity
  - $P_{\rm R} = -P_\times$: the inward power due to interference is balanced by the radiated power
  - $P_\times = P_\xi$: this inflow replenishes the power from the stochastic force assoc. with field fluctuations at the atom
  - $P_\xi = -P_\gamma$: this stochastic driving power when balanced by the dissipated power => the detector's idf reaches equilibrium
- We clearly see how energy flows between the atom and the field and how each component by itself reaches equilibration.

Now, an intriguing point

- This feature is not restricted to the vacuum field. Same conclusion of no net quantum radiation if the detector is coupled with an ambient thermal field.
- Now, we know a uniformly accelerating atom feels hot at a (Unruh) temperature proportional to the proper acceleration. This thermal radiance is different from the emitted quantum radiation (Lin & Hu, 2006 in 3+1D).
- Does there exist any relation btw these two forms of quantum radiation? Can we explain all this from the vacuum fluctuations of the quantum field and the excitations in the idf of the atom as is done here for a stationary atom? How does the "quantum" energy transfer between the detector and the field? (We're working on this Paper 2)
- In this set up one can inquire whether a Quantum Equivalence Principle exists – Does a uniformly accelerated atom experience the same effect as in a gravitational field. But then classical Equivalence Principle may not hold for quantum systems. [Candelas & Sciama 1981, Anastopoulos & Hu 2018]

Summary

- A better understanding of the FDR from the vantage point of nonequilibrium dynamics with arbitrary coupling strength beyond LRT
- In an open system perspective: relation between quantum fluctuations of the environment (field) and quantum dissipation in the system (atom).
- The FDR takes on a dynamical meaning in the context of relaxation.
  - It ensures the balance of the energy flow between the atom and the field
  - Examples from both perspectives, of the detector and the field, are provided.
- We also show there is no quantum radiation for a stationary detector in the vacuum or in a thermal field, highlighting the role of the interference term and the importance of the FDRs for both the field and the atom.

Thank you!

Open questions:

- how the energy balance is broken-- if it radiates -- when the atom undergoes uniform acceleration. Why?
- the difference between this case and a static atom subjected to quantum or thermal field fluctuations?
- if different, how does it impact on the equivalence principle? A quantum equivalence principle?
- Back to the basics: Show how the classical theory of radiation (*Jackson*) can be derived from the quantum theory of radiation, fluctuations & dissipation.