Title: Acceleration Radiation: The Prophet and the Heretics

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Abstract: I review the contentious question, "Does a uniformly accelerated detector radiate?" As Audretsch and Muller pointed out long ago, this is partly a semantic dispute. The talk draws on recent discussions with Alex Calogeracos and George Matsas.

Acceleration Radiation: The Prophet and the Heretics

Stephen A. Fulling

Happy Birthyear, Bill!

Rambling and curmudgeonly remarks

Casimir (1948): Neutral conductors attract.
(finite size; discrete spectrum; periodic classical paths)
This is a unique, and uniquely important, effect.
Doesn't require a boundary (a compact manifold will do).

Then, e.g., Deutsch and Candelas (1979): Boundary energy in quantum field theory
(boundary conditions; short nonperiodic closed classical paths) **This is something different from the true Casimir effect** (although related.)

Pair creation by time-dependent external fields

Parker (1966): cosmological gravitational field

Narozhny and Nikishov (1970), Schroer et al. (1970): electromagnetic field

Moore (1970): moving mirrors

Then there was a boom in moving mirrors:

Moore (1970); DeWitt (1975); Fulling and Davies (1976)

The subject of pair creation by moving mirrors is now called **the dynamical Casimir effect**, apparently because of the role of the boundary.

How far afield may we use the holy name of Casimir in vain?

Experimental verifications of the dynamical Casimir effect (proposed and actual [Wilson et al. (2011)]) do not actually involve sharp boundaries. They are instances of particle creation by time-dependent external fields.

The original (mirror) effect is particle creation by time-dependent geometry. Perhaps it would better be called "the boundary-localized Parker effect"?

"Cosmological particle creation in the early universe (studied by Parker and Zel'dovich in the 1960s–1970s) is a form of the dynamical Casimir effect since it arises from the parametric amplification of vacuum fluctuations by the expansion of the universe."

Galley, Behunin, and Hu (2013)

Surrender

So, nowadays **Casimir effect** $\equiv$ any topic in **quantum field theory under the influence of external conditions**.

M. Bordag, ed. (. . . , 1995, 1998, . . . 2007, . . .)

Acceleration Radiation: The Prophet and the Heretics

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Passive hyperbolic Casimir effect: Unruh (1976)
An accelerated detector detects a thermal gas in the vacuum.

Active hyperbolic Casimir effect: Unruh and Wald (1984)
An accelerated detector emits quanta into the vacuum.

On the Existence of the Active Hyperbolic Casimir Effect

Stephen A. Fulling

Happy Birthyear, Bill!

Outline

1. What the critics actually say, and what Unruh and Wald actually said.
2. The Unruh–Wald effect in second-order perturbation theory, following Audretsch and Müller (1994).
3. Experiments taking place over finite time.

I won't discuss heretics who are obviously wrong

- Those who deny even the passive Unruh effect.
- Those who accept it but deny that it is properly characterized by a nonzero temperature.

But there are heretics who do have a point:

Does an accelerated detector really radiate?

- Grove et al. (1986, 1991) [then Unruh (1992)]
- Massar et al. (1993); Hinterleitner (1993)
  [then Audretsch and Müller (1994)]
- Hu and Raval (2001); Ford and O'Connell (2006)
- Lin and Hu (2006, 2007) (in 4D)

The curmudgeon says: This is a dialogue of the deaf that has been going on in the literature for 30 years. Both sides are right, but both sides are guilty of confusing the issue by sloppy language.

What Hu–Raval and Ford–O'Connell assert and prove is that *if the detector is in equilibrium with the Rindler thermal gas*, then there is no net radiation from it.

"This result, which took some doing to obtain, should have been expected from the beginning. After all, in equilibrium the mean energy of the oscillator is constant, so the mean energy flux radiated into the field by the oscillator must be balanced by a mean energy flux from the field into the oscillator."

Ford and O'Connell

"Under *nonequilibrium* conditions which can prevail for non-uniformly accelerated trajectories or before the atom or oscillator reaches equilbrium, there is conceivably radiation emitted, but that is not what Unruh effect entails."

Hu and Raval

But what question did Unruh and Wald ask?

Most of these papers make the stronger statement that the entire $\langle T_{\mu\nu} \rangle$ is identically zero, not just $\langle T_{\tau\rho} \rangle$ (Rindler coordinates). Unruh (1992) largely agreed but introduced two caveats:

- There may be radiation right on the past horizon.
- Around the detector there is a nontrivial $\langle \phi^2 \rangle$ ("polarization cloud") with zero energy.

It may still seem strange that the equilibrated detector is not emitting from the *inertial* observer's point of view. There clearly is a connection with the vexed classical problem of a uniformly accelerated charge.

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Hu and Raval

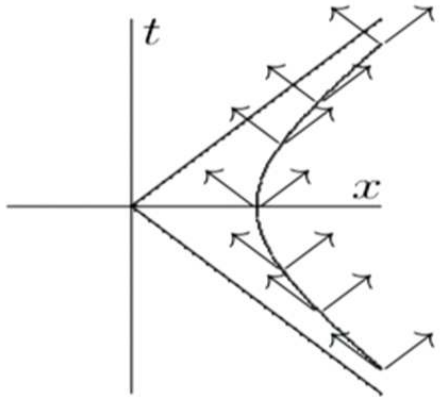
But what question did Unruh and Wald ask?

The Unruh–Wald question

The detector *starts* in its ground state, and the field in its Minkowski vacuum. The detector has some probability of absorbing a quantum from the Rindler bath. *How is this possible from the point of view of an inertial observer, who has no quanta to absorb?* Answer: A Minkowski quantum must be emitted.

They never said that the detector goes on radiating forever like a light bulb, nor that first-order perturbation theory is a definitive treatment of the system.

What is wrong with this picture?



(a) for 2-state detector?

(b) for classical charge?

"[N]o such processes like 'recoil' are taking place. . . . [T]he two-level system does not emit or absorb energy like an antenna. Instead the reduction effects accompanying the measurements play the essential role."

Audretsch and Müller (1994)

Remark: The orthodox usually study a two-level detector in the interaction picture by perturbation theory. The heretics almost always study a harmonic-oscillator detector in the Heisenberg picture by an exact solution. I don't think the detector model is a crucial point.

The Audretsch–Müller picture

The most illuminating paper on the subject is more than 20 years old:

Audretsch and Müller, *Phys. Rev. D* **49** (1994) 6566–6575 (also ibid. 4056–4065)

But I think it contains at least one significant error. Also, most of their insights are already stated in Unruh–Wald, but Audretsch–Müller isolate and emphasize the facts most relevant to this controversy.

They extend the Unruh–Wald calculation to second-order perturbation theory. For the two-state detector with initial state $|\phi, \downarrow\rangle$ they find a final state of the structure

$$[|\phi, \downarrow\rangle - \lambda^2(\cdots)a^\dagger a|\phi, \downarrow\rangle] - i\lambda(\cdots)a^\dagger|\phi, \uparrow\rangle,$$

where the creation operators are for Rindler modes in the right wedge. Thus $\langle T_{\mu\nu}\rangle$ is $O(\lambda)$ and consists of $\langle 1, 1\rangle$ and $\langle 0, 2\rangle$ terms. (In general, $\uparrow$-states have an odd number of extra particles, $\downarrow$-states an even number.)

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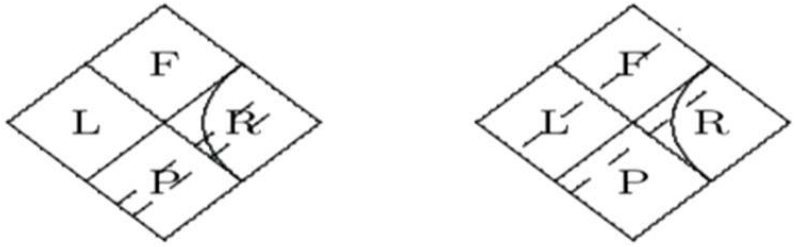
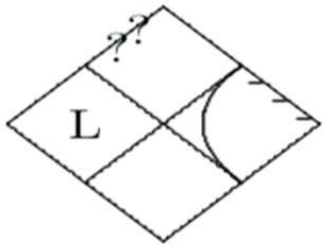


right Rindler mode left Mink. mode

Minkowski modes slop over to the other side; Rindler modes do not. There are also left-moving modes of each type (8 types of modes in all). For massive or 4-dimensional fields the pictures are muddier because wave packets diffuse.

The properly normalized sum of these two terms is the expected energy if no measurement is made, *or* if Alice never hears from Bob what the result was, and hence can't divide her data into two sets.



This total energy expectation can be expressed entirely in terms of right Rindler modes — which is why it *must* vanish in L by causality, and does.

Audretsch–Müller say that these modes "vanish outside R" (rather than just "vanish in L"). But that is wrong: they propagate into F (if left-moving) or P (if right-moving). In the left-moving case they reach the $\mathcal{I}^+$ of F and should make the nonzero contribution I labeled "?".

The bigger problem: Finite-order perturbation theory is not trustworthy for an interaction that lasts forever at the same strength. That is the legitimate point of the heretics. The equilibrium should be reached.

Finite-time detectors

- Svaiter and Svaiter, *PRD* **46** (1992) 5267; erratum **47** (1993) 4802
- Higuchi, Matsas, and Peres, *PRD* **48** (1993) 3731
- Satz, *CQG* **24** (2007) 1719, building on Schlicht (2004) and Louko and Satz (2006)
- Barton and Calogeracos (2005, 2008); Calogeracos (submitted) (realistic atom as detector)

A measurement (or state preparation) is made at proper (or Rindler) time τ_i that shows the field to be in (say) its Minkowski ground state, $|0\rangle$, and the detector in its unexcited state, $|\downarrow\rangle$. At time τ_f the detector is observed again.

"[A] quantum-mechanical two-level system on its own is not a (simple) detector. It needs in addition a macroscopic device which performs an energy measurement on it to obtain ['down' or 'up']."

Audretsch and Müller

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Audretsch and Müller

Quantum theory should make the same prediction whether τ_i is the time when the coupling is turned on, when the acceleration begins, or merely when a measurement is made showing that the state is $|0\rangle \otimes |\downarrow\rangle$.

"The assumption that the interaction starts at τ_i is not necessary; it is enough to suppose that in τ_i the detector is in the ground state, the field is in the vacuum state, and that the interaction [has begun]. It is also not necessary to assume anything about the interaction after τ_f ."

Svaiter and Svaiter

Aside: The accelerated charge is different

"[A] more mathematical approach clear[s] the cobwebs considerably, eliminating the nonsense of adiabatic switching. . . . One can't help picturing a pair of experimenters in the lab, one shouting to the other, 'I have the beam ready, turn on the target but do it very slowly!'"

B. Simon (1971)

Here equilibration is not an issue, since the charge has no internal degree of freedom and can radiate eternally.

For the detector, complications ensue

Despite what I just said, the initial state preparation cannot be made instantaneously. Schlicht, Louko, and Satz found that sensible, Lorentz-invariant results require that the detector be "smeared" in either space or time, the latter being simpler. Thus there are two time scales in the problem: the duration of each measurement (or of switching on or off), and the duration of the experiment.

Let $\Delta\tau = \tau_f - \tau_i$. If F is the transition probability, the transition *rate* R could be defined as $F/\Delta\tau$ or as $dF/d\Delta\tau$; the latter is better behaved, so it's adopted.

Let δ be the time scale of the switching (taken fairly small), E be the level splitting in the detector, $(\Delta x(s))^2$ the squared geodesic distance between the detector's position at $\tau = s$ and its starting point.

Combine formulas from Satz and Louko–Satz:

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Combine formulas from Satz and Louko–Satz:

$$
\begin{aligned}
R = & \frac{1}{2\pi^2}\int_0^{\Delta\tau} ds \left(\frac{1}{(\Delta x)^2}+\frac{1}{s^2}\right)\cos(Es) \\
& - \frac{E}{2\pi}\,\theta(-E) \\
& + \frac{1}{2\pi^2\Delta\tau} \\
& + \frac{1}{2\pi^2}\left[\frac{\cos(E\Delta\tau)-1}{\Delta\tau} + |E|\,\mathrm{si}(|E|\Delta\tau)\right] .
\end{aligned}
$$

Remark: This formula already appears in the Svaiter–Svaiter erratum (1992), although not so convincingly argued.

The first term, $\frac{1}{2\pi^2}\int_0^{\Delta\tau} ds \left(\frac{1}{(\Delta x)^2}+\frac{1}{s^2}\right)\cos(Es)$, vanishes for an inertial detector, because then $(\Delta x)^2 = -s^2$. All other terms are independent of the path. So this first term precisely captures the effect of acceleration.

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The second term, $-\frac{E}{2\pi}\,\theta(-E)$, is the expected response of an inertial detector.

The remaining terms go to 0 when $\Delta\tau \to \infty$, but in general they are nonzero. Therefore, the inertial detector clicks even in the vacuum state!

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Furthermore, the third term, $R = 1/2\pi^2\Delta\tau$, goes to infinity as $\Delta\tau \to 0$, while the others remain bounded. Over very short times the detector gives nonsense.

Also, when $E = 0$ this term survives while the second and fourth vanish. So the detector in some sense operates even when it has no level spacing.

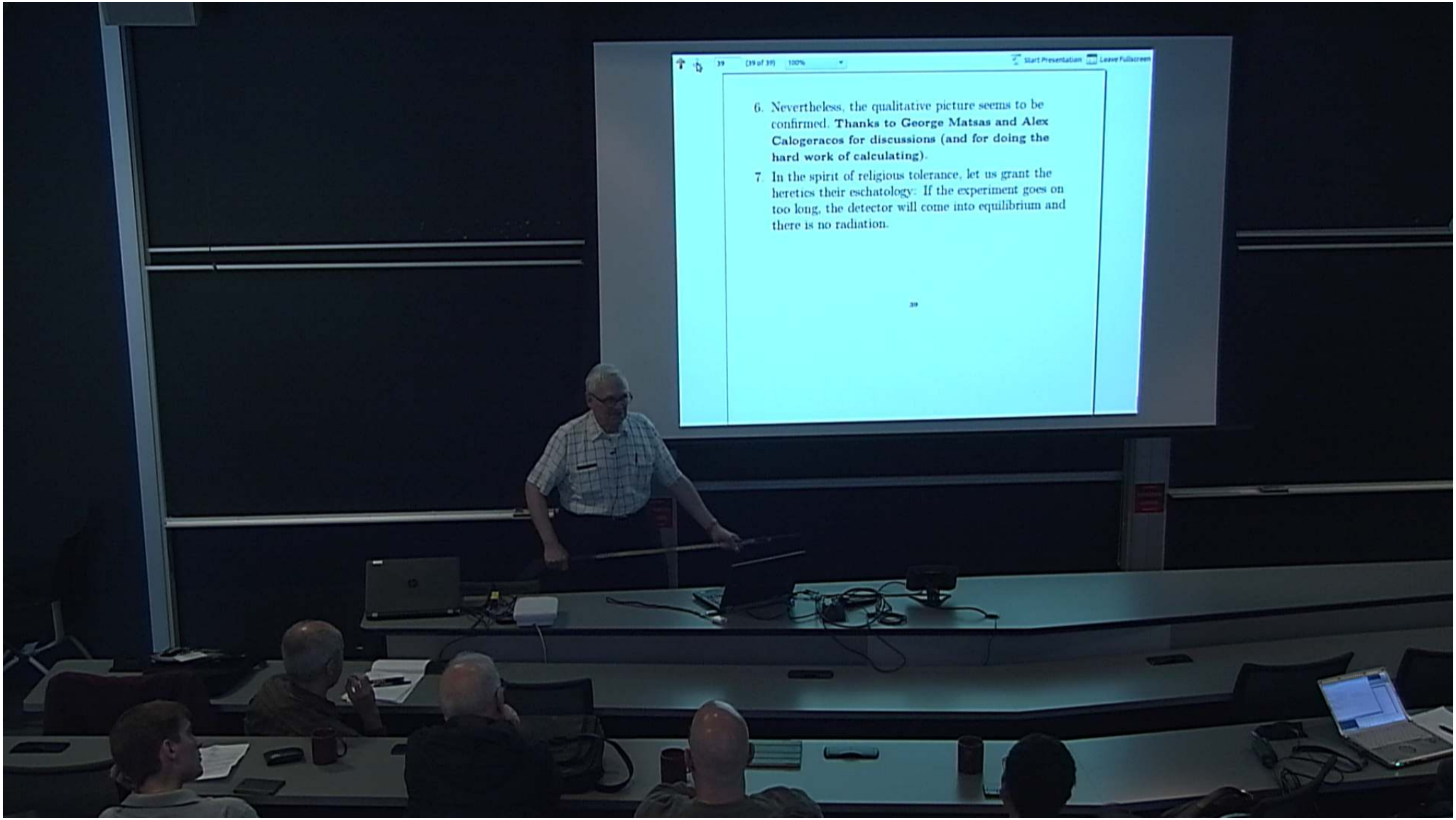
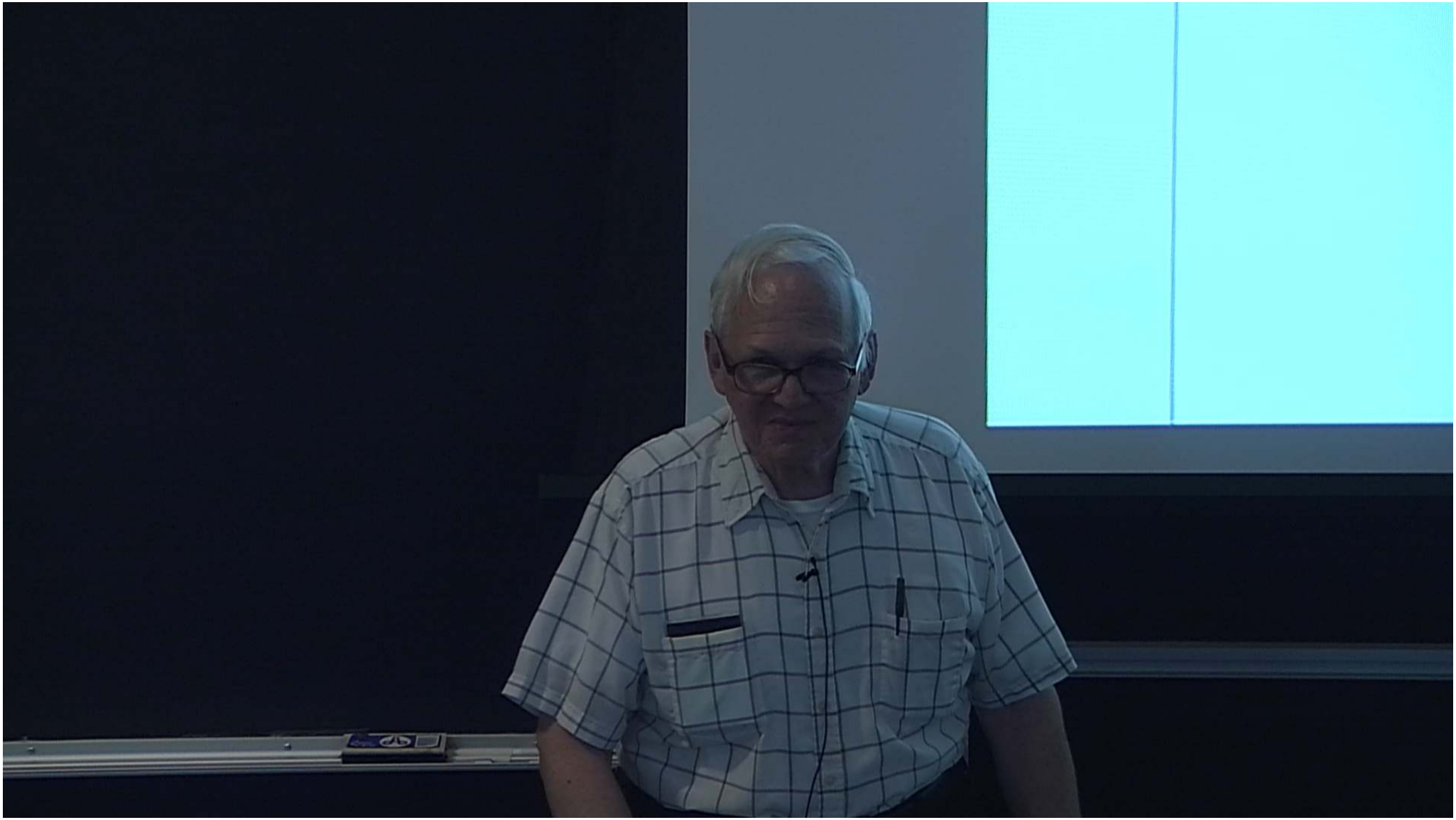
Conclusion: $\Delta\tau$ must not be too short, lest the experiment be poisoned by this static. But it also must not be too long, lest perturbation theory become inapplicable.

Summary

1. There is very little new in this talk.
2. But the experts have been talking past each other for 30 years, and undoubtedly the nonexperts are grossly confused as a result.
3. Unruh–Wald and Audretsch–Müller gave a correct qualitative analysis of an experiment in which an initial tensor-product state of (field vacuum) $\otimes$ (accelerated detector) is evolved for a time and then the detector is (perhaps) observed.

4. But quantitatively their calculations assume that the duration of the experiment is essentially infinite, and perturbation theory is physically untrustworthy in that regime. (It's OK for scattering!)
5. For a finite-time experiment, the calculations are mathematically cumbersome and their interpretation is clouded by the time-energy uncertainty relation, which causes many spurious counts if the time is too short.

6. Nevertheless, the qualitative picture seems to be confirmed. **Thanks to George Matsas and Alex Calogeracos for discussions (and for doing the hard work of calculating).**
7. In the spirit of religious tolerance, let us grant the heretics their eschatology: If the experiment goes on too long, the detector will come into equilibrium and there is no radiation.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