Vacuum Fluctuations Detection:
A Pedagogic Overview of the University of Konstanz Experiment

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Abstract

The recent University of Konstanz experiment by Riek et al[1] purporting to detect vacuum fluctuations directly is ingenious, was executed masterfully, and may be of considerable importance. Yet, it can, for those not well versed in nonlinear optics, be challenging to fully fathom. This article 1) attempts to provide a pedagogic, simplified introduction to that experiment suitable for students and non-specialists, and 2) poses questions related to the theoretical interpretation of, and possible alternative explanations for, the results.

1 Components of the Monitored Signal

Riek et al consider the electric field (1) of an electromagnetic signal (in the mid-infrared region), which originates in a pump and then passes through a nonlinear polarizing crystal (labeled GX),

$$\hat{E}_{MIR} = E_{MIR} + \delta\hat{E}_{MIR} \qquad \big(\text{Pump signal that traverses GX crystal}\big), \tag{1}$$

where E_{MIR} is considered to be the underlying base wave that has zero random variation, and $\delta\hat{E}_{MIR}$ is the random variation from that signal.

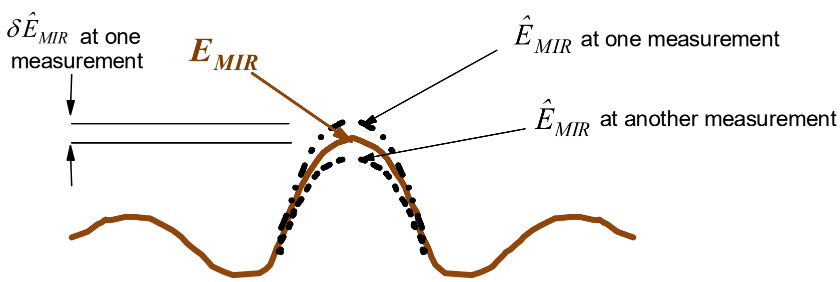

Figure 1. Variations in Pump/MIR Signal $\hat{E}_{MIR}$

The authors trigger monitoring of that pump signal with a narrow wave pulse probe signal $\hat{E}_{probe}$, as in Figure 2. The peak point of the probe signal triggers the measurement of $\hat{E}_{MIR}$, and that peak can be moved relative to the pump wave $\hat{E}_{MIR}$ by delaying the probe signal by time t_D, such that any single signal detection can be carried out at any desired point along the wave, i.e. at $\hat{E}_{MIR}\left(t_D\right)$.

In practice, in physical space, the probe signal $\hat{E}_{probe}$ is aligned perpendicular to the pump signal $\hat{E}_{MIR}$, as this facilitates measurement with the particular sensing apparatus employed. Figure 2 seems to suggest

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they are aligned, but the two signals are presented as they are in that figure because it is easier to do so graphically, and easier to represent the concept of detecting at the probe peak for a given delay time.

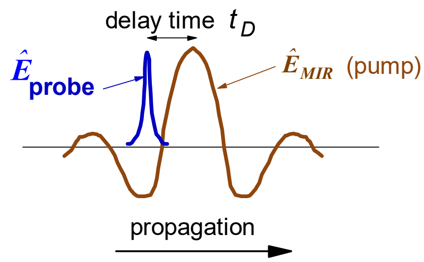

Figure 2. Detection at Peak of Probe

2 Components of the Probe Signal

In practice, the probe signal also has a variation from its mean similar to that of (1). That is,

$$\hat{E}_{probe} = E_{probe} + E_{SN} \qquad \big(\text{Probe signal that does not traverse GX}\big), \tag{2}$$

where E_{probe} is considered to be the underlying wave that has zero random variation and E_{SN} is the (shot noise) random variation from that signal (parallel to $\delta\hat{E}_{MIR}$ for the pump/MIR signal). Pictorially,

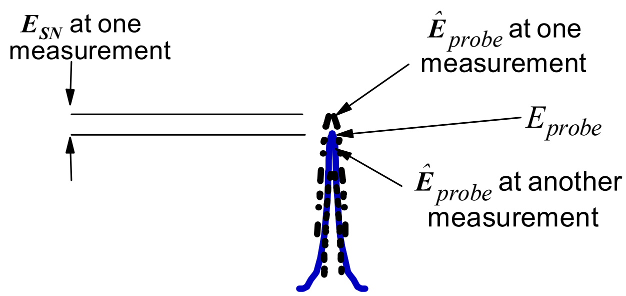

Figure 3. Variations in the Probe Signal $\hat{E}_{probe}$

3 Experimental Setup

A complete schematic of the test configuration can be found in Ref. [1]. (See Fig. 1 of the Extended Data section.) Figure 4 herein shows it in very oversimplified form.

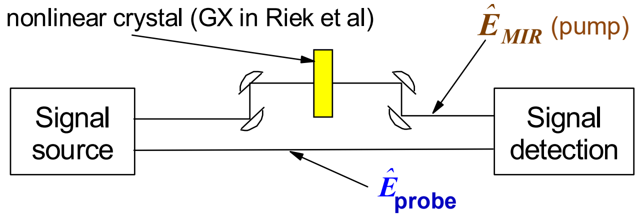

Figure 4. Over Simplified Schematic of Experimental Setup

4 The Measured Signal

The experimental apparatus does not actually detect the pump signal directly, but detects the difference between the pump $\hat{E}_{MIR}$ and the probe $\hat{E}_{probe}$, i.e., between (1) and (2), at the peak point of $\hat{E}_{probe}$.

Data at a given delay time was taken for repeated $\hat{E}_{MIR}$ waves, so averages and standard deviations of the detected signal were obtained for each of many different delay times (each of many different points along the wave). The same data generation was also carried out with the pump off, i.e., with E_{MIR} of (1) equal zero.

Note that, in an attempt to present the analysis in as transparent a manner as possible, more descriptive (subscripts primarily) notation than that of Riek et al is employed herein. After an initial introduction in Sections 5 to 7 of the analysis method using the more descriptive notation, said notation is displayed alongside that of Riek et al in Section 8 for ready comparison of the two.

For any single signal sampling, with the pump on or off, one has (with (1) and (2))

$$\begin{array}{c}\text{measured quantity}\\ \text{with pump signal on}\end{array} = \hat{E}_{\substack{meas \\ w\,pump}} = \hat{E}_{MIR} - \hat{E}_{probe} = E_{MIR} + \delta\hat{E}_{\substack{MIR \\ w\,pump}} - E_{probe} - E_{SN} \tag{3}$$

$$\begin{array}{c}\text{measured quantity}\\ \text{with pump signal off}\end{array} = \hat{E}_{\substack{meas \\ no\,pump}} = \hat{E}_{MIR} - \hat{E}_{probe} = \delta\hat{E}_{\substack{MIR \\ no\,pump}} - E_{probe} - E_{SN} \ . \tag{4}$$

5 Assumptions on What is Being Measured

5.1 Composition of the Pump Signal Variations

Riek et al consider $\delta\hat{E}_{\substack{MIR \\ w\,pump}}$ and $\delta\hat{E}_{\substack{MIR \\ no\,pump}}$ to be due purely to vacuum fluctuations, i.e.,

$$\delta\hat{E}_{\substack{MIR \\ w\,pump}} = \delta\hat{E}_{\substack{vac \\ w\,pump}} \qquad \delta\hat{E}_{\substack{MIR \\ no\,pump}} = \delta\hat{E}_{\substack{vac \\ no\,pump}} \qquad \big(\text{Riek et al assumption}\big). \tag{5}$$

However, if there are variations in the signal due to other causes, such as thermal oscillations in the GX crystal, mirrors, polarizers, etc. or non-vacuum induced deviations originating in the pump, then one would have

$$\delta\hat{E}_{\substack{MIR \\ w\,pump}} = \delta\hat{E}_{\substack{other \\ w\,pump}} + \delta\hat{E}_{\substack{vac \\ w\,pump}} \qquad \delta\hat{E}_{\substack{MIR \\ no\,pump}} = \delta\hat{E}_{\substack{other \\ no\,pump}} + \delta\hat{E}_{\substack{vac \\ no\,pump}} \qquad \big(\text{More general assumption}\big) \ .(6)$$

5.2 Type and Path of Travel of Vacuum Fluctuations

The authors consider the vacuum fluctuations measured to be zero-point energy (ZPE) fluctuations arising with energy ½ $h\nu$ for each component wave of frequency ν. Further, they consider these ZPE fluctuations to be detectable with their instrumentation. Still further, they consider the vacuum fluctuations to travel the same path through their experimental apparatus, both with the pump on and the pump off.

6 The Effect of the GX Crystal

The pump signal passes through a crystal (GX) with nonlinear polarization properties, i.e., the dielectric "constant" is not actually constant, but depends on the electric field intensity. The greater the signal level E_{MIR}, the greater the dielectric "constant" ε, the greater the decrease in e/m wave speed inside the crystal (since wave speed $v_{e/m} = c / \sqrt{\varepsilon\mu}$). Thus, higher points on the $\hat{E}_{MIR}$ waves of Figure 1 and Figure 2 travel slower than the lower points, and the wave disperses (changes shape). A smaller amplitude wave (lower maximum height in the figures) would disperse into a different shape than a higher amplitude wave.

Said another way, since the source field is greater with the pump on than off, the dielectric is higher with the pump on than off. This effects the degree to which the dielectric affects the vacuum fluctuations. If the crystal were linear (dielectric the same at any level of the E field), then one would not expect the vacuum fluctuations to change their statistical behavior as the source field is turned on vs off. It is thus important the GX crystal is nonlinear.

See Klauber[2], particularly Fig. 7, pg. 14, for more detail on the effect of the GX crystal.

7 Comparing Pump-On to Pump-Off Signals

With the pump on, E_{MIR} in (3) is substantial, and that causes the GX dielectric property to change significantly. So, $\delta\hat{E}_{\substack{MIR \\ w\,pump}}$ changes significantly as it passes through the crystal. With the pump off (E_{MIR}=0, as in (4)), the dielectric changes very little, and $\delta\hat{E}_{\substack{MIR \\ no\,pump}}$ is virtually unchanged by the crystal.

If, as in assumption (5), this variation in the signal is due to vacuum fluctuations, then a comparison of the two cases should reveal a change in the vacuum fluctuations caused by the GX crystal. This is what the authors consider to be detected.

8 Comparison of Standard Deviations for Pump On and Pump Off

8.1 Differential Noise (*DN*)

With many measurements at each point on the $\hat{E}_{MIR}$ wave of (3), one can determine the standard deviation of that signal at each such point. From statistics theory (see Klauber[2] for details), we know that variances for independent signals add (both when the signals are added, and when they are subtracted), and it is reasonable to consider the component signals of (3) to be independent. Thus, with (6) in (3), where represents rms standard deviation of many signal measurements, and the standard deviations of E_{MIR} and E_{probe} are, by definition, zero,

$$\text{variance of measured quantity with pump signal on} = \overbrace{\left(\Delta E_{\substack{MIR \\ w\,pump}}\right)^2 + \left(\Delta\delta\hat{E}_{\substack{other \\ w\,pump}}\right)^2 + \left(\Delta\delta\hat{E}_{\substack{vac \\ w\,pump}}\right)^2 + \left(\Delta E_{probe}\right)^2 + \left(\Delta E_{SN}\right)^2}^{\text{Notation of this article}} =$$

$$= 0 + \underbrace{\left(\Delta\delta\hat{E}_{\substack{other \\ w\,pump}}\right)^2}_{\text{Not in Riek et al}} + \underbrace{\left(\Delta E_{rms}\right)^2 + 0 + \left(\Delta E_{SN}\right)^2}_{\text{Riek et al notation}}. \tag{7}$$

Similarly, with the pump off, using (4) and (6), we have

$$\begin{array}{c}\text{variance of measured quantity}\\ \text{with pump signal off}\end{array} = \overbrace{\Big(\Delta\delta\hat{E}_{\substack{other\\ no\,pump}}\Big)^2 + \Big(\Delta\delta\hat{E}_{\substack{vac\\ no\,pump}}\Big)^2 + \big(\Delta E_{probe}\big)^2 + \big(\Delta E_{SN}\big)^2}^{\text{Notation of this article}} =$$
$$= \underbrace{\Big(\Delta\delta\hat{E}_{\substack{other\\ no\,pump}}\Big)^2}_{\text{Not in Riek et al}} + \underbrace{\big(\Delta E_{vac}\big)^2 \quad + \quad 0 \quad + \big(\Delta E_{SN}\big)^2}_{\text{Riek et al notation}} \quad . \tag{8}$$

We can reasonably assume $\delta\hat{E}_{\substack{other\\ no\,pump}} = 0$ with zero standard deviation, as there is no signal coming from the pump at all in this case to be distorted. Thus, the difference in the two standard deviations [which are the square roots of (7) and (8)] is deemed the differential noise (DN) and is

$$\begin{aligned} DN &= \sqrt{\Big(\Delta\delta\hat{E}_{\substack{other\\ w\,pump}}\Big)^2 + \Big(\Delta\delta\hat{E}_{\substack{vac\\ w\,pump}}\Big)^2 + \big(\Delta E_{SN}\big)^2} - \sqrt{\Big(\Delta\delta\hat{E}_{\substack{vac\\ no\,pump}}\Big)^2 + \big(\Delta E_{SN}\big)^2} \quad \text{notation of this article} \\ &= \sqrt{\underbrace{\Big(\Delta\delta\hat{E}_{\substack{other\\ w\,pump}}\Big)^2}_{\text{Not in Riek et al}} + \big(\Delta E_{rms}\big)^2 + \big(\Delta E_{SN}\big)^2} - \sqrt{\big(\Delta E_{vac}\big)^2 + \big(\Delta E_{SN}\big)^2} \quad \text{Riek et al notation.} \end{aligned} \tag{9}$$

Riek et al define a unitless relative differential noise (RDN) to be (9) divided by $\sqrt{\Big(\Delta\delta\hat{E}_{\substack{vac\\ no\,pump}}\Big)^2 + \big(\Delta E_{SN}\big)^2}$ (notation of this article).

$$\begin{aligned} RDN &= \frac{DN}{\sqrt{\Big(\Delta\delta\hat{E}_{\substack{vac\\ no\,pump}}\Big)^2 + \big(\Delta E_{SN}\big)^2}} \\ &= \frac{\sqrt{\Big(\Delta\delta\hat{E}_{\substack{other\\ w\,pump}}\Big)^2 + \Big(\Delta\delta\hat{E}_{\substack{vac\\ w\,pump}}\Big)^2 + \big(\Delta E_{SN}\big)^2} - \sqrt{\Big(\Delta\delta\hat{E}_{\substack{vac\\ no\,pump}}\Big)^2 + \big(\Delta E_{SN}\big)^2}}{\sqrt{\Big(\Delta\delta\hat{E}_{\substack{vac\\ no\,pump}}\Big)^2 + \big(\Delta E_{SN}\big)^2}} \quad \begin{array}{c}\text{notation of}\\ \text{this article.}\end{array} \end{aligned} \tag{10}$$

As noted in Section 5.1, Riek et al assume there are no fluctuations in the signal other than from the vacuum, i.e.,

$$\Delta E_{\substack{other\\ w\,pump}} = 0 \qquad\qquad \text{Riek et al assumption.} \tag{11}$$

They also assume

$$\big(\Delta E_{SN}\big)^2 \gg \Big(\Delta E_{\substack{vac\\ no\,pump}}\Big)^2 \approx \Big(\Delta E_{\substack{vac\\ w\,pump}}\Big)^2 \qquad \text{Riek et al assumption.} \tag{12}$$

The rational to justify (12) is fairly extensive, and understanding it requires study of refs. [1], [2] (pgs. 10-11 and Appendix B), [3], and [4]. One might question why, for example, the variance of vacuum fluctuations in the probe signal (SN subscript) would be substantially greater than that of the pump signal, but the authors feel they have support for this assumption.

Using (11) in (10), we get

$$RDN = \frac{\sqrt{\left(\Delta\delta E_{\substack{vac\\ w\,pump}}\right)^2 + \left(\Delta E_{SN}\right)^2} - \sqrt{\left(\Delta\delta E_{\substack{vac\\ no\,pump}}\right)^2 + \left(\Delta E_{SN}\right)^2}}{\sqrt{\Delta E^2_{\substack{vac\\ no\,pump}} + \left(\Delta E_{SN}\right)^2}}$$

$$= \frac{\Delta E_{SN}\sqrt{1 + \left(\Delta\delta E_{\substack{vac\\ w\,pump}}\right)^2 / \left(\Delta E_{SN}\right)^2} - \Delta E_{SN}\sqrt{1 + \left(\Delta\delta E_{\substack{vac\\ no\,pump}}\right)^2 / \left(\Delta E_{SN}\right)^2}}{\Delta E_{SN}\sqrt{1 + \left(\Delta\delta E_{\substack{vac\\ no\,pump}}\right)^2 / \left(\Delta E_{SN}\right)^2}} . \tag{13}$$

Riek et al then use the first part of (12) to approximate (13), i.e.,

$$RDN \approx \frac{\Delta E_{SN}\left(1 + \frac{1}{2}\left(\Delta\delta E_{\substack{vac\\ w\,pump}}\right)^2 / \left(\Delta E_{SN}\right)^2\right) - \Delta E_{SN}\left(1 + \frac{1}{2}\left(\Delta\delta E_{\substack{vac\\ no\,pump}}\right)^2 / \left(\Delta E_{SN}\right)^2\right)}{\Delta E_{SN}}$$

$$= \frac{1}{2}\left(\Delta\delta E_{\substack{vac\\ w\,pump}}\right)^2 / \left(\Delta E_{SN}\right)^2 - \frac{1}{2}\left(\Delta\delta E_{\substack{vac\\ no\,pump}}\right)^2 / \left(\Delta E_{SN}\right)^2 = \frac{1}{2}\frac{\left(\Delta\delta E_{\substack{vac\\ w\,pump}}\right)^2 - \left(\Delta\delta E_{\substack{vac\\ no\,pump}}\right)^2}{\left(\Delta E_{SN}\right)^2} . \tag{14}$$

They then use the second part of (12) in (14) to get

$$RDN \approx \frac{1}{2}\left(\Delta\delta E_{\substack{vac\\ w\,pump}} - \Delta\delta E_{\substack{vac\\ no\,pump}}\right)\frac{\Delta\delta E_{\substack{vac\\ no\,pump}}}{\left(\Delta E_{SN}\right)^2} \qquad \text{notation of this article}$$

$$= \frac{1}{2}\left(\Delta E_{rms} - \Delta E_{vac}\right)\frac{\Delta E_{vac}}{\left(\Delta E_{SN}\right)^2} \qquad \text{Riek et al notation} . \tag{15}$$

Note that Riek et al drop the ½ factor in (15) for their definition of RDN.

8.2 Relevance of *RDN*

As the authors assume $\Delta\delta\hat{E}_{\substack{other\\ w\,pump}} = 0$, they consider a negative value for (15) to indicate detection of vacuum fluctuations, since in that case $\Delta\delta E_{\substack{vac\\ w\,pump}} < \Delta\delta E_{\substack{vac\\ no\,pump}}$ ($\Delta E_{rms} < \Delta E_{vac}$ in Riek et al notation). For that to occur, the reasoning is, vacuum fluctuations must have been "squeezed" (reduced standard deviation) as a result of having passed through the GX crystal. Similarly, for "antisqueezing" (increased standard deviation), vacuum fluctuations would be affected in an opposite manner.

8.3 Vacuum Fluctuations Deviation for No Pump Signal is Calculated, Not Measured

Note that in (9) to (15) $\Delta\delta E_{\substack{vac\\ no\,pump}}$ (ΔE_{vac} in Riek et al notation) is determined theoretically. (See Riek et al (2015)[3][4] and for more details, Klauber[2].) The total signal deviation with the pump on,

$\sqrt{\underbrace{\left(\Delta\delta\hat{E}_{\substack{other \\ w\,pump}}\right)^2}_{\text{Not in Riek et al}} + \left(\Delta\delta\hat{E}_{\substack{vac \\ w\,pump}}\right)^2}$ $(\Delta\delta E_{\substack{vac \\ w\,pump}} = \Delta E_{rms}$ in Riek et al notation where it is assumed that $\Delta\delta\hat{E}_{\substack{other \\ w\,pump}} = 0)$ is experimentally determined.

$$\begin{array}{lll} \Delta\delta E_{\substack{vac \\ w\,pump}} & \left(\Delta E_{rms} \text{ Riek et al notation}\right) & \text{is empirically determined} \\ \Delta\delta E_{\substack{vac \\ no\,pump}} & \left(\Delta E_{vac} \text{ Riek et al notation}\right) & \text{is calculated .} \end{array} \tag{16}$$

9 Test Results

Results of testing are displayed in Figure 5, where the top part of the figure shows the $\hat{E}_{MIR}$ wave shape and the bottom the RDN along the wave. Note that standard deviation of the vacuum fluctuations is considered to have been reduced by the GX crystal in some places, and increased in others.

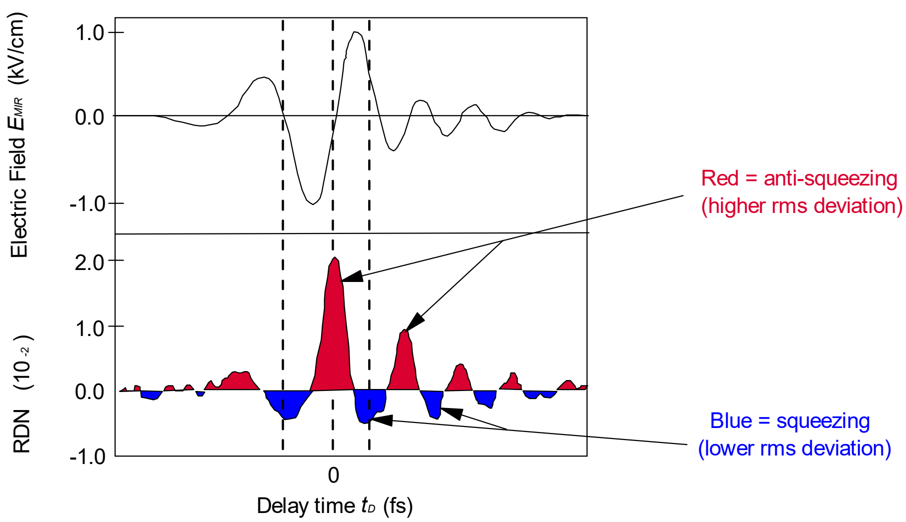

Figure 5. Squeezing vs Anti-Squeezing at Different Points in the Pump/MIR Wavepacket

(Abridged version of Riek et al[1] Fig. 2, here showing only one pump/MIR signal.)

Why the amplitudes vary with time delay (location along the wave) as shown in Figure 5, and why squeezing occurs in some locations, and anti-squeezing in others, are fairly complex issues in nonlinear optics theory. A summary of the analyses behind these results is presented in Riek et al[1], and with more extensive explanation in Klauber[2].

10 Interpretation

Figure 5 is considered to imply that the standard deviation of the vacuum fluctuations is altered (to different degrees at different locations along the wave) by the GX crystal, and this effect is measured by the experiment. Thus, the result is interpreted to be a direct measurement of vacuum fluctuations.

11 Considerations

11.1 Summary of Assumptions

Riek et al assume the following.

1) ZPE fluctuations can be measured.
2) ZPE fluctuations travel the same path through the test apparatus with the pump on or off.
3) There are no variations from causes other than vacuum fluctuations ($\Delta\delta\hat{E}_{\substack{other\\w\,pump}} = 0$). See (11).
4) The vacuum fluctuations deviation with the pump off $\Delta\delta\hat{E}_{\substack{vac\\no\,pump}}$ (ΔE_{vac} in Riek et al notation) can be calculated and used in determining *RDN*.
5) As shown in (12), the variance of the probe signal $\left(\Delta E_{SN}\right)^2$ is much greater than the variances of the pump signals $\left(\Delta E_{\substack{vac\\no\,pump}}\right)^2$ and $\left(\Delta E_{\substack{vac\\w\,pump}}\right)^2$ [$(\Delta E_{vac})^2$ and $(\Delta E_{rms})^2$ respectively, in Riek et al], and the latter two are approximately equal.

11.2 Assumption 1

There has been a marked inability to detect vacuum fluctuations in other experiments. If they really impact the physical world, we should be able to detect them. But, a detector picks up the non-vacuum contribution, but nothing from the vacuum.

> *It seems to me that, if you say radiation is "real," you ought to mean by that, that it can be detected by a real detector. But an optical pyrometer sees only the Planck term, and not the zero-point term, in black body-radiation.*
>
> Edwin T. Jaynes[5]

Historically, neither real-world sensors, nor other means, have been able to detect vacuum fluctuations.

> *It is a supple ontology which supposes that vacuum fluctuations are just real enough to shift the hydrogen 2s level by 4 microvolts; but not real enough to be seen by our eyes, although in the optical band they correspond to a flux of over 100 kilowatts/cm^2. Nevertheless, the dark-adapted eye, looking for example at a faint star, can see real radiation of the order of 10^{-15} watts/cm^2."*
>
> Edwin T. Jaynes[5]

In other words, if we can measure vacuum fluctuations in an experiment like that of Riek et al, then should we not be able to simply measure them directly with an appropriate instrument, or even observe them ourselves? But, no one else seems to have done so[6][7][8][9][10].

Further, if the vacuum fluctuations bounce off mirrors and get polarized by polarizers, they must interact via QED interactions with those mirrors and polarizers. If they can do that, they should also activate electromagnetic field detectors of all types, and be directly measurable in the simplest experiments. But, as noted above, they are not.

11.3 Assumption 2

It would seem reasonable that the vacuum fluctuations measured at the detector would come from all directions, and the particular ones that traveled through the entire apparatus on the same route as the pump signal (see Figure 4) would represent a vanishingly small percentage of the total signal. And thus, any change measured with the pump on or off would be expected to be vanishingly small.

In this context, a common analogy portrays vacuum fluctuations much like boiling of water, i.e., random, with no direction involved. In the analogy, a propagating particle/field is like a wave on the water. It is not intuitive to think of the bubbles (vacuum fluctuations) traveling a particular route along with a given wave (e/m wave).

11.4 Assumption 3

Instead of the assumption 3 of (11) where $\underset{w\,pump}{\Delta\delta\hat{E}_{other}} = 0$ in (10), consider the case where, in the real world, that value is not zero and vacuum fluctuations are undetectable, i.e.,

$$\underset{w\,pump}{\Delta\delta\hat{E}_{vac}} = \underset{no\,pump}{\Delta\delta\hat{E}_{vac}} = 0 \qquad \underset{w\,pump}{\Delta\delta\hat{E}_{other}} \neq 0 \qquad \big(\text{Alternative possibility for real world}\big). \tag{17}$$

Then using (17) in (10), we would get similar results as in Figure 5. The only difference would be in interpretation. $\underset{w\,pump}{\Delta\delta\hat{E}_{vac}}$ (ΔE_{rms} in Riek et al) would be replaced in (15) with $\underset{w\,pump}{\Delta\delta\hat{E}_{other}}$ (not in Riek et al), with the same *calculated* value originally used for $\underset{no\,pump}{\Delta\delta\hat{E}_{vac}}$ (ΔE_{vac} in Riek et al). The *RDN* variation would then come from changes induced by the GX crystal on other types of random signal variation, rather than on vacuum fluctuations.

Of course, it is possible that both types of signal are present, i.e., both $\underset{w\,pump}{\delta\hat{E}_{vac}}$ (ΔE_{rms} in Riek et al) and $\underset{w\,pump}{\delta\hat{E}_{other}}$ (not in Riek et al), are non-zero.

11.5 Assumption 4

The numerical RDN result depends on a theoretically calculated value $\underset{no\,pump}{\Delta\delta\hat{E}_{vac}}$ (ΔE_{vac} in Riek et al notation). RDN is obtained by subtracting this value from the experimentally determined value $\underset{w\,pump}{\Delta\delta\hat{E}_{vac}}$ (ΔE_{rms} in Riek et al notation). Thus, RDN is not purely an experimental result. If the theoretical analysis were not correct, the RDN would not be. If $\underset{no\,pump}{\Delta\delta\hat{E}_{vac}}$ (ΔE_{vac} in Riek et al notation) were, for instance, actually zero, then RDN would never be negative, since standard deviation is never negative.

However, for any theoretical value for $\underset{no\,pump}{\Delta\delta\hat{E}_{vac}}$ (E_{vac} in Riek et al notation), one would still see a variation in RDN at different locations along the wave, similar to, though perhaps not the same as, that of Figure 5. So, qualitative conclusions that fluctuations in the pump signal are affected by the GX crystal and measured by the experiment remain valid in any case.

11.6 Assumption 5

The assumptions on relative amplitudes of variances of the different signals shown in (12) has a quantitative effect on the RDN approximation of (15). However, qualitatively, if the exact value of the RDN (10) is negative, then so should be the approximation; and if the exact value is positive, again, so should the approximation.

Thus, assumption 5 should have no consequence on the reasoning that Figure 5 is indicative of vacuum fluctuation detection.

11.7 Why Not Measure $\Delta\delta\hat{E}_{\substack{vac \\ no\,pump}}$ $(= \Delta E_{vac})$ Directly?

One could ask why not simply measure the vacuum fluctuations signal with the pump off $\Delta\delta\hat{E}_{\substack{vac \\ no\,pump}}$ (=ΔE_{vac} in Riek et al notation), directly? That is, use (4) and (8), simply turn off the probe signal $\hat{E}_{probe}$, and measure $\Delta\delta\hat{E}_{\substack{MIR \\ no\,pump}}$ directly with the pump also off. Would that not be a simple, unequivocal measurement of vacuum fluctuations (provided the source of the variations is, indeed, due to the vacuum and not some other cause)?

12 Suggestion for Future Experiment

Possible sources for fluctuations from sources other than the vacuum, as in (17), include thermally induced fluctuations. This potential influence on the results could be quantified by repeating the experiment at different temperatures and measuring the degree, if any, to which RDN is affected.

13 Summary and Conclusions

This article is intended as a simplified, pedagogic introduction to the experiment by Riek et al[1], which was exquisitely executed, may have detected vacuum fluctuations, and thus could be of considerable importance. It also considers alternative interpretations of the data for which vacuum fluctuations might not be the source of the results.

14 Response by the Experimenters

A response by the authors of Riek et al to some of the issues raised herein has been requested and may be found at www.quantumfieldtheory.info/Konstanz_response.htm .

Acknowledgements

I thank Luc Longtin and Christian Maennel for reviewing the manuscript, finding errata, and offering valuable insights and suggestions.

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[6] S. de Clark, The Scharnhorst Effect: Superluminality and Causality in Effective Field Theories, PhD dissertation at University of Arizona 2016 http://arizona.openrepository.com/arizona/handle/10150/622964. Section 5.1.2 and Appendix A provide an excellent overview of arguments for and against the reality of vacuum fluctuations.

[7] R. D. Klauber, *Student Friendly Quantum Field Theory*, 2nd edition (2nd revision), Sandtrove Press (July 2015) Chap 10. Experiments such as those done with Casimir plates are often cited as experimental proof of vacuum fluctuations, but as noted in this reference, such results can be explained theoretically without recourse to the vacuum.

[8] R. L. Jaffe, "Casimir Effect and the Quantum Vacuum", *Phys. Rev. D*72 021301(R) (2005) https://arxiv.org/abs/hep-th/0503158 . Jaffe shows that experimental effects previously attributed to vacuum fluctuations can be derived theoretically without recourse to the vacuum. He states "No known phenomenon, including the Casimir effect, demonstrates that zero-point energies are "real"".

[9] H. Nikolić, "Proof that Casimir forces do not originate from vacuum energy", *Phys. Lett. B* **761** (2016) 197-202 https://arxiv.org/abs/1605.04143 . The author notes that typical analyses of the Casimir effect use a Hamiltonian that has implicit dependence on matter fields and illegitimately treat it as if the dependence were explicit. In alignment with Ref. 8, he contends the true origin of the Casimir force is the van der Waals force.

[10] R. J. Nemiroff, R. Connolly,J. Holmes, A. B. Kostinski1, "Bounds on Spectral Dispersion from Fermi-detected Gamma Ray Bursts" *Physical Review Letters.* 108 (23): 231103 (2012). https://arxiv.org/abs/1109.5191 18 Apr 2012. This study of photon propagation over billions of light-years implies spacetime is not "foamy" at the Planck scale, where vacuum fluctuations should be paramount, and thus lends support to the notion that such fluctuations do not exist. For popular accounts, see R. Cowen, "Cosmic race ends in a tie". *Nature.* (10 January 2012). http://www.nature.com/news/cosmic-race-ends-in-a-tie-1.9768, and "Spacetime: A smoother brew than we knew" (January 2013) https://phys.org/news/2013-01-spacetime-smoother-brew-knew.html .