The Vacuum in modern quantum field theory: nothing’s plenty

... an experimental point of view

Experimental demonstrations of the QF of the EM field:

- **static** scenario
  - Casimir force, Lamb shift, spontaneous emission and liquid He

- **dynamical** scenario
  - DCE (cavity/waveguide), Unruh and Hawking radiation,
    the dynamical Casimir-Polder force
Physics of the vacuum as presently understood by Relativistic Quantum Field theory

The distinction between quantum fluctuations and thermal fluctuations is not invariant but depends on the observer motion.

A harmonic oscillator in acceleration gains energy from the fluctuations of the ZP of the EM field in the vacuum. For a uniformly accelerating oscillator, the distribution of energy is thermal.

velocity is constant $\rightarrow$ Lorentz invariance

$\quad a = \text{const} \rightarrow \text{Unruh effect}$ (detectors)

non-uniform $a \rightarrow \text{Dynamical Casimir effect}$ (mirrors)
Part of Feynman’s blackboard at California Institute of Technology at the time of his death in 1988.

At the right-hand side one can find “accel. temp.” as one of the issues to learn.
Physics of the vacuum as presently understood by Relativistic Quantum Field theory

Framework

STATE of a SYSTEM := system of fields

Energy of the states of a system of fields?
Energy of the states of a system of fields?

**GROUND STATE**
state of MIN energy
stability state

**EXCITED STATES**
containing
elementary quanta
of excitation

Essential point of view:
the Vacuum is not a substance, but a STATE,
precisely the ground state of the many field system.

VACUUM:= No excitation quanta – No particles

The excited states are the PARTICLE ASPECT of a field
- Casimir effect (PRL 88, 041804 (2002) in Padova)
  \[ \frac{\Delta E_0(d)}{L^2} = -\frac{\pi^2 \hbar c}{720 d^3} \]

- failure of liquid \(^4\text{He}\) to solidify at normal pressures as \(T \to \text{absolute 0}\)

- spontaneous emission

- Lamb shift (Lamb, Retherford 1947) measurement; (Bethe 1947) calculation
- failure of liquid $^4\text{He}$ to solidify at normal pressures as $T \to$ absolute 0
The Vacuum in modern quantum field theory: nothing’s plenty
... an experimental point of view

Experimental demonstrations of the QF of the EM field:
- **static** scenario
  *Casimir force, Lamb shift, spontaneous emission and LHe…*

- **dynamical** scenario
  *DCE, Unruh and Hawking radiation, Schwinger process*

- A new QED effect possibly to be explored…
  *the dynamical Casimir-Polder effect*
Main mechanisms by which vacuum fluctuations are *amplified* into photons:

- Dynamical Casimir effect
- Hawking radiation
- Unruh effect

They become appreciable under *extreme conditions*
Main mechanisms by which vacuum fluctuations are *amplified* into photons:

- **Dynamical Casimir effect** rapidly modulating the boundary conditions of the EM field, with peak velocities close to the speed of light

- **Hawking radiation** not only a black hole!

- **Unruh effect** an observer accelerated to $10^{20}g$

They become appreciable under *extreme conditions*

How to detect them in the laboratory?
An apparently innocent, “einsteinian” question:

how are the QF perceived by an observer in acceleration?

oscillator (particle detector) → its QF noise power is the same
… BUT
this is no more true for the noise power of the field, to be calculated for the oscillator universe line (geodetic).

A QUBIT

In Minkowsky coordinates (ct,x) the paths of observers with constant acceleration are hyperbolas in spacetime
In order to describe the Minkovski vacuum as seen by the accelerating observer, the mode functions and their associated vacuum states are found for a scalar and quantum field in both the Minkovski and Rindler spacetimes.

Bogoliubov transformations linking the M and R creation and annihilation operators are found, and the quantum state seen by a RRW observer is described.

Unruh (Phys. Rev. D14, 870 (1976))

\[ T_U = \frac{\hbar}{2\pi c k_B} a \]

An observer would measure a nonzero temperature \( T_U \) with respect to a zero temperature vacuum in the laboratory frame.
Unruh effect

“accel. radiation” is exceedingly small!

\[
T_U = \frac{\hbar}{2\pi ck_B} a \approx 4 \cdot 10^{23} a
\]

\[\Rightarrow a \geq 10^{20} g, \ g \text{ mean gravity acceleration on Earth}\]

is required in order to have a heat bath quantum vacuum at the level of only one Kelvin!

An experimental proposal to study the acceleration temperature
Rogers, Phys Rev. Lett. 61, 2118 (1988)

the electron accelerates centripetally in the trap's magnetic field, the vacuum radiation excites its motion along the trap axis (\(\omega_a\))

- detector:= relativistic \(e^-\) confined into a Penning trap (“Geonium atom”)
- \(e^-\) path is a combination of three components: \(\omega_m, \omega_c\) and \(\omega_a\)
- \(B = 150 \text{ kG} \Rightarrow a \approx 10^{22} \text{ cm/s}^2\) corresponding to \(T_U=2.4 \text{ K}\)
- cavity surrounding the Penning trap
Hawking radiation

Hawking (Nature 248, 30-31 (1974))

\[ T_H = \frac{\hbar}{2\pi c k_B} g \]

\[ T_U = \frac{\hbar}{2\pi c k_B} a \]
DCE: a definition

Single-mirror DCE

Broadband photons generation

IN THE MATTER

Cavity DCE

Basic mechanism is parametric amplification
\[ \nu_{\text{excitation}} = 2\nu_0 \]
C. Braggio et al. EPL 70, pp. 754–760 (2005)

IN THE VACUUM
**Single-mirror DCE**

Broadband photons generation

**Cavity DCE**

Basic mechanism is parametric amplification
\[ \nu_{\text{excitation}} = 2\nu_0 \]

A representative example: a child standing on a swing

The amplification is driven by changing the center of mass, and thus effective length, of the pendulum at twice the frequency of the unperturbed swing.

\[ \theta(t) = \theta(0) \cos(\omega_s t) + \frac{L(0)}{m\omega_s l} \sin(\omega_s t), \quad \omega_s(t) = \omega_s(0) + \epsilon \sin(\omega_{cm} t), \]

\[ \omega_{cm} = 2\omega_s, \quad \theta(t) = \theta(0) e^{\epsilon t/2} \cos(\omega_s t) + \frac{L(0)}{m\omega_s l} e^{-\epsilon t/2} \sin(\omega_s t). \]

Parametrically excited resonant circuit
DCE: Casimir radiation stored in the cavity mode

The dynamical Casimir effect
- the moving mirror generates photons that accumulate inside the cavity...
How to perform the required wall oscillation?

Cavity DCE

\[ E = \frac{1}{2} \rho V \omega^2 \delta x^2 \]

\[ \omega / 2 \pi = 10 \text{ GHz} \]

\[ \delta x = 1 \text{ nm} \]

Required mechanical power
P ~ kW - MW
With Q factor = 100
P = 10 W – 10 KW
i) Acoustic waves in solids
In the 60’s Bömmel-Dransfeld produced GHz acoustic waves in quartz using piezo excitation, but exciting all modes.
- Motion of a single mode $dx \ll 1$ nm.
- Large microwave power.

ii) Acoustic microscopes
Excitation of resonant modes in sapphire blocks (typical frequency 3 GHz)

High Q reduces power requests, in fact for sapphire $Qf \sim 10^{12}$, i.e. for $f \sim 10^9$ follows $Q \sim 10^3$.
Same amplitude with $P/1000$.
But again $dx \sim 10^{-10}$ m and small area.
Modulation of the surface CONDUCTIVITY of a semiconductor slab inside a microwave cavity


Accelerating reference frame for electromagnetic waves in a rapidly growing plasma: Unruh-Davies-De Witt radiation and the nonadiabatic Casimir effect


Parametric excitation of vacuum by use of femtosecond pulses


Quantum phenomena in nonstationary media

Single-mirror DCE

Correlation at sideband frequencies

Photons are produced in pairs such that their frequencies sum to the drive frequency

\[ \omega_d = \omega_+ + \omega_- \]
Alternative approaches

The key requirement is to modulate the boundaries to the EM field

- **Modulation of the conductivity**
  - Excitation source: laser

- **Modulation of the cavity gap capacitance**
  - By means of a VARICAP
  - Excitation source: a radiofrequency generator

- **Modulation of the index of refraction**
  - In a NONLINEAR CRYSTAL
  - Excitation Source: laser
**Nb superconducting cavity**  
(80 x 90 x 9) mm$^3$

**Cylindrical reentrant cavity**  
($\Phi_{\text{cav}} = 42$ mm, $h = 34$ mm, $\Phi_{\text{GaAs}} = 8$ mm, $d = 10$ mm)

1. Smaller amount of $E_{\text{pulse}}$
2. Simplified optical scheme for uniform illumination of the semiconductor
parametrically excited photons could initially be seeded by thermal fluctuations instead of vacuum fluctuations…

80 l LHe vessel, \( T = (0.8 \div 9) \) K

30 l

cryogenic environment
$E_{\text{pulse}} \approx 10 \mu\text{J};$
since the average power of a CW mode-locked laser having this value of energy per pulse would be too high, we developed a laser delivering a macropulse up to of $\Delta T = 450 \text{ ns}$ duration ($\sim$ 2000 pulses).

Total macropulse energy is a few millijoules.

**FINAL SPECS**
- high frequency repetition rate ($f_{\text{rep}} \approx 5 \text{ GHz}$, stability better than the cavity BW 1 kHz),
- tunable $f_{\text{rep}}$,
- 10 ps pulses duration,
- $E_{\text{pulse}} \approx$ few microjoules,
- 780 – 820 nm output wavelength.

*Optics Express* 13, 5302 (2005)
*Optics Express* 14, 9244 (2006)
*Optics Express* 16, 15811 (2008)
LASER repetition rate stability and tuning

Active control of the Master Oscillator length: the feedback system locks the repetition frequency of the laser to a reference microwave generator.

**SHORT TERM STABILITY**


greater than ~1 kHz

**LONG TERM STABILITY**

Starting frequency ≈ 4.589 GHz
Requirements: high mobility (1 m²/Vs)
short recombination time (a few picoseconds)

R&D on a new material, starting from semi-insulating (SI) GaAs

SI GaAs irradiated with thermal neutrons (Italy, USA)
SI GaAs irradiated with Au, Br ions (Tandem accel. in LNL)
SI GaAs irradiated with 1-5 MeV protons (CN accel. in LNL)

Measurement of the recombination time and mobility of the irradiated samples

Optical-pump terahertz-probe setup

1. Same concentration of free carriers produced as in the plasma mirror ($n \approx 10^{17}$ cm⁻³);
2. Measurements are conducted at different temperatures in the range 300 – 10 K in a cryocooler

Foulon et al. 2000, J. Appl. Phys. 88, 3634
Mangeney et al. 2002, Appl. Phys. Lett. 80, 4711
Mangeney et al. 2000, Appl. Phys. Lett. 76, 40
1. exponential growth at the parametric resonance; decaying oscillations when detuned
2. higher order maxima in the gain vs. $\delta f$ plot are observed
3. the maximum of the amplification is found at $f_{\text{rep}} = 2f_0 + \delta f$ (in our experiment the excitation is not a pure harmonic signal);
4. If the phase between the excitation and the field in the cavity varies, at each laser shot a different gain is observed;
a pre-charged field (external generator) is used to study of the parametric response (detuning curve)
make sure that the modulator is not the source of the searched photons
compare results from NG Spice simulations and theory (V. Dodonov)
thermal field
DCE field at cryogenic temperatures

The DCE with the ‘semiconductor approach’ is not detectable due to inherent dissipative phenomena in the parametric amplification process.
Alternative approaches

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- Modulation of the cavity gap capacitance by means of a VARICAP
  - Excitation source: a radiofrequency generator

- Modulation of the index of refraction in a NONLINEAR CRYSTAL
  - Excitation Source: laser
Study of a single-mode thermal field

modulation of the cavity gap capacitance by means of a VARICAP

Excitation source: a radiofrequency generator


\[ P_v(n) = \frac{1}{\bar{n} + 1} \left( \frac{\bar{n}}{\bar{n} + 1} \right)^n \]

\[ \bar{n} = [\exp(h\nu_r / kT) - 1]^{-1} \]

It is a parametric amplifier

\[ P_{\text{out}}(t) = P_{\text{out}}(0)e^{2(\gamma - \lambda)t}g(\theta) \]

\[ t_T = \tau_p \left[ \ln \frac{P_T}{P_{\text{out}}(0)} - \ln g(\theta) \right] \]

exponential growth of the signal seeded by external/thermal photons at T=300 K
\[ P_{\text{out}}(t) \approx P_{\text{out}}(0)e^{2(s-\lambda)t}g(\theta) \]

\[ t_T = \tau_p \left[ \ln \frac{P_T}{P_{\text{out}}(0)} - \ln g(\theta) \right] \]

The time constant of the amplification process is measured and plotted as a function of the pre-charged field.

There is a source that cannot be switched off.

MC- simulation of the parametric process: generate values of the time delays assuming that the energy present in the cavity at the starting trigger follows a B-E probability distribution.
Calibration of the apparatus with a **pre-charged field** or with **thermal photons**

\[ E_0 \text{ thermal or external field} \]

\[ N_{ph}(n) \propto E_0 e^{2|\chi_{max}|F(A_0)n} \]

\[ n \text{ number of pulses} \]

\[ F(A_0) \text{ gain coefficient} \]

\[ |\chi_{max}| \text{ increases with stationary frequency shift } \Delta f = f_{ill} - f_0 \]

To run this test we arranged a simplified experimental condition:

1. the cavity is pre-charged
2. the radiofrequency at \( f_0 \) is switched off (EM field starts to decay with decay time \( \tau_0 \): free oscillations);
3. \(~100 \text{ ns after switching off the external generator, the laser train of pulses impinges on the semiconductor surface}\)