1495
UNIVERSITY
OF ABERDEEN

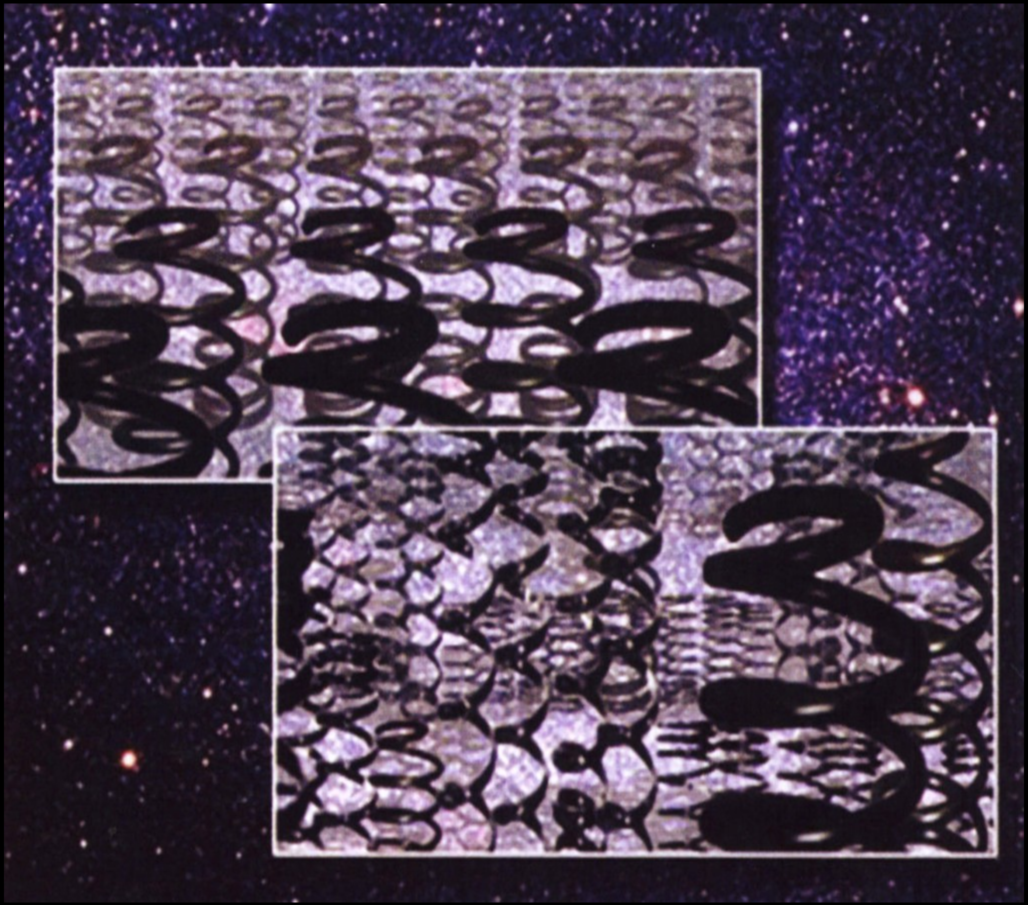
DETECTION OF ZERO POINT ENERGY, QUANTUM EQUIVALENCE PRINCIPLE, FROM "SCATTERING ATOM BEAMS"

Charles Wang

Department of Physics
University of Aberdeen
Scotland

CfFP/CL/FRAL-SPACE SCATTERING WORKSHOP, 4 March 2011

Vacuum fluctuations



Ambiguities in Quantum Gravity

PHYSICAL REVIEW D **72,** 087501 (2005)

Unambiguous spin-gauge formulation of canonical general relativity with conformorphism invariance

Charles H.-T. Wang
School of Engineering and Physical Sciences, University of Aberdeen, King's College, Aberdeen AB24 3UE, Scotland
Space Science and Technology Department, Rutherford Appleton Laboratory, Didcot, Oxon OX11 0QX, England
(Received 11 July 2005; published 6 October 2005)

We present a parameter-free gauge formulation of general relativity in terms of a new set of real spin connection variables. The theory is constructed by extending the phase space of the recently formulated conformal geometrodynamics to accommodate a spin-gauge description. This leads to a further enlarged set of first class gravitational constraints consisting of a reduced Hamiltonian constraint and the canonical generators for spin-gauge and conformorphism transformations. Owing to the incorporated conformal symmetry, the new theory is shown to be free from an ambiguity of the Barbero-Immirzi type.

DOI: 10.1103/PhysRevD.72.087501 PACS numbers: 04.20.Cv, 04.20.Fy, 04.60.Ds, 04.60.Pp

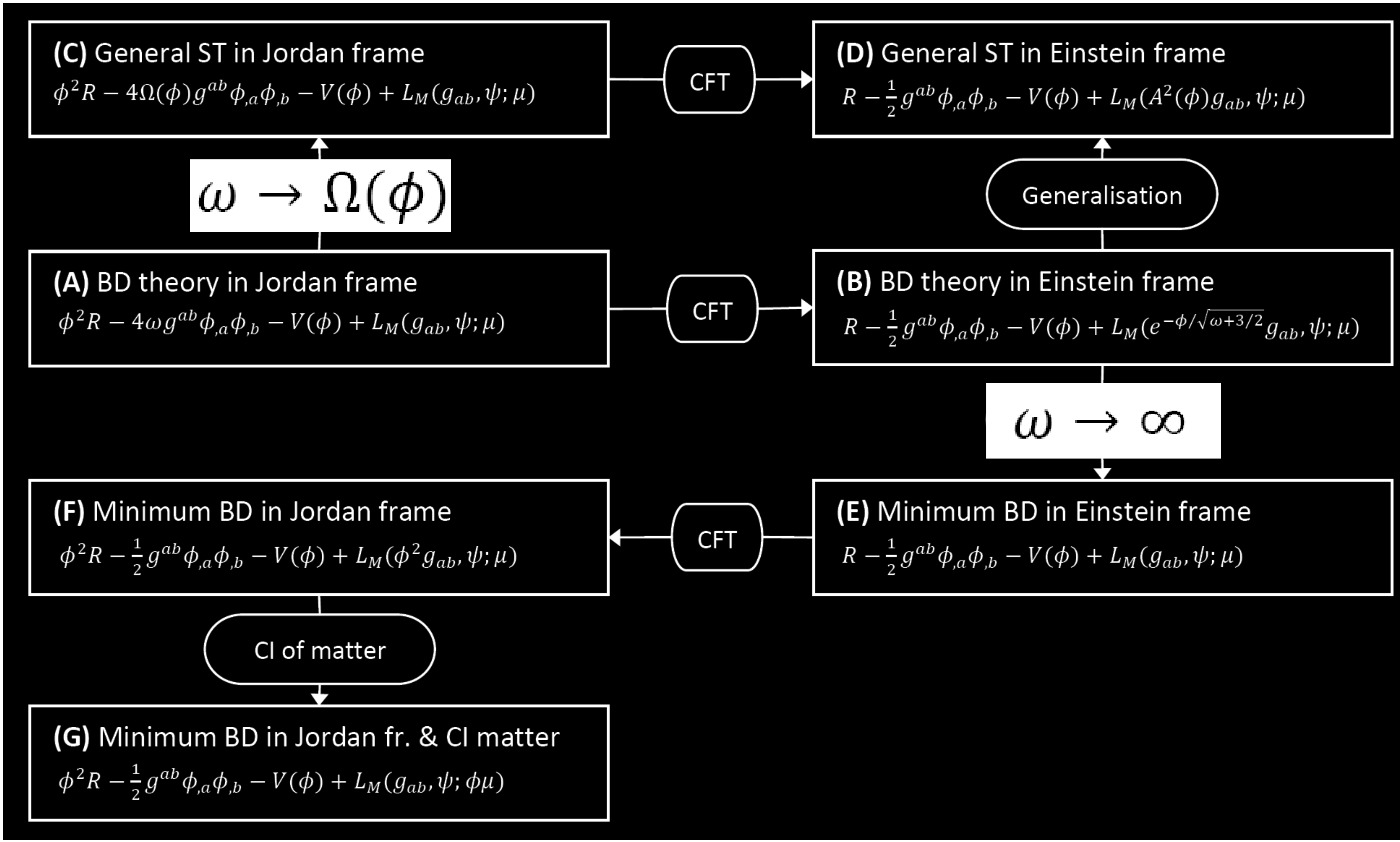
Conformal Structures, pre-Tractor Bundles and the Barbero-Immirzi Parameter

James Reid[1,2,*]
[1]*Perimeter Institute for Theoretical Physics,*
31 Caroline Street North, Waterloo,
ON, Canada, N2J 2W9, and
[2]*Department of Physics, University of Aberdeen,*
King's College, Scotland, AB24 3UE
(Dated: March 1, 2011)

The notion of *Superspace*, the true configuration space of General Relativity, has been constantly refined over the last fifty years. In Wheeler's Geometrodynamics, it is currently identified with the higher Teichmüller Space of conformal structures on a spatial hypersurface[1]. In Ashtekar's Connection-dynamics however, Superspace has considerably less geometric structure - being identified[3] with the space of suitably regular soldering forms modulo diffeomorphisms, $\{[\sigma]\}$. Under York's[5] assumption that the spatial hypersurface has the structure of a conformal 3-manifold, we use conformal spin geometry to prove that the soldering forms are naturally partitioned into conformal equivalence classes. This modifies the structure of Connection-dynamic Superspace, and the two configuration spaces are seen - as they were at the introduction of Ashtekar's new variables - to be 2-1 homomorphic. Lastly, we show that the enhanced structure on Connection-dynamic Superspace removes the (debatably unphysical) Barbero-Immirzi parameter of Loop Quantum Gravity at the expense of a non-dynamical scalar field: a geometric analogue of a result obtained by Wang[7].

arXiv:1102.5560v1 [gr-qc] 27 Feb 2011

Scalar Tensor Theory in Quantum Gravity

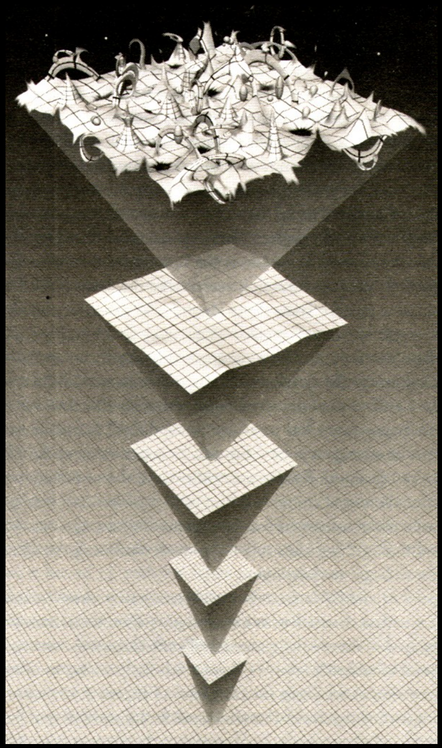


UNIVERSITY OF ABERDEEN

SCATTERING WORKSHOP

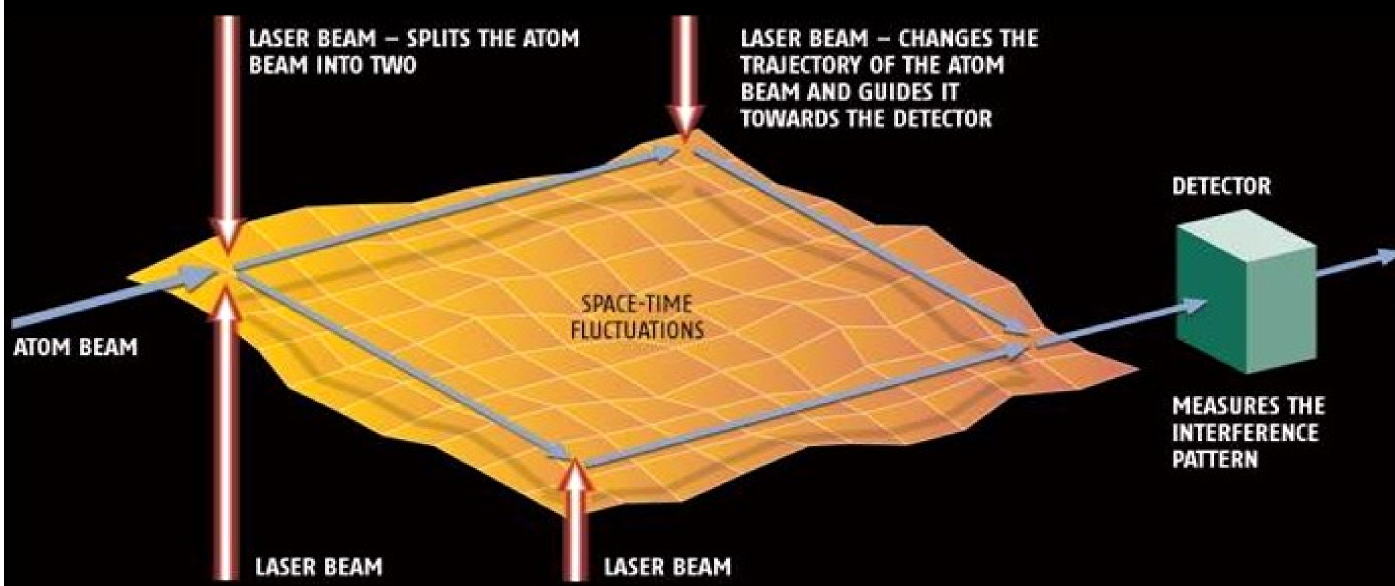
Quantum foam of spacetime

- Spacetime at the Planck scale could be topologically nontrivial, manifesting a granulated structure



Quantum decoherence due to space-time fluctuations

- Decoherence rate ~ mass^5 in "Planck scale" (BMW *CQG* 2006)
- E.g. a gold cluster of 10^{10} amu (~ 10^{-14} g) decoheres in 1 sec.



Blurring of fringe pattern may reflect decoherence due to space-time fluctuations. (*New Scientist* 2 Sept 2006 Wang *et al*)

Gravitational Lamb Shift of Bose-Einstein Condensates due to Spacetime Fluctuations

Charles H.-T. Wang,[1,2,*] Robert Bingham,[2,3,†] and J. Tito Mendonça[4,2,‡]

[1]*SUPA Department of Physics, University of Aberdeen, King's College, Aberdeen AB24 3UE, UK*
[2]*STFC Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK*
[3]*SUPA Department of Physics, University of Strathclyde, Glasgow G4 0NG, UK*
[4]*IPFN, Instituto Superior Técnico, 1049-001 Lisboa, Portugal*

We investigate the oscillation of the center of mass of trapped Bose-Einstein condensates coupled to the zero-point fluctuations of the gravitational field. A semiclassical analysis is performed that allows to calculate the mean square amplitude of the oscillation. In analogy with the Lamb shift in quantum electrodynamics, this gives rise to an upshift of the energy of the trapped condensates. We show that for an elongated trap, the energy shift scales quadratically with the length as well as cubically with the total number of atoms, leading to an energy increase of 1 % using a 5 cm long trap with 10^8 rubidium atoms. This could potentially lead to the first observable effect of low energy quantum gravity and provide a stringent test for any viable theory of quantum gravity.

The idea is to allow the wavefunction to extend to macroscopically large value of r^2 along the z-axis, where the gravitational fluctuations become much larger relative to the vicinity of center of the potential. The CM wavefunction in this case takes the form $\Psi(\boldsymbol{r}) = \Psi_{n_x,n_y}(x,y)\Psi_{n_z}(z)$ where $n_x, n_y = 0, 1, 2, \cdots$ are the quantum numbers for the effective 2D harmonic oscillator wavefunction $\Psi_{n_x,n_y}(x,y)$ in the (x,y)-plane, and $n_z = 0, 1, 2, \cdots$ is the quantum number for the effective boxed particle state $\Psi_{n_z}(z)$ in the z-direction.

The amount of shift is also calculated using (4) to be

$$\Delta E = \frac{4\sigma^2}{9\pi}\frac{m^3}{m_{\rm P}^2}\omega^2 \times \left\{(n_x+n_y+1)\frac{\hbar}{m\omega} + \frac{L^2}{12}\left[1 - \frac{6}{(n_z+1)^2\pi^2}\right]\right\}. \quad (11)$$

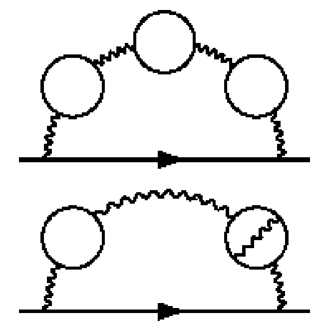
For example, assuming $\sigma \approx 1$, if $\omega = 2\pi$ kHz and N is the number of trapped rubidium atoms, then the ratio of the energy shift to the difference of transverse energy levels is

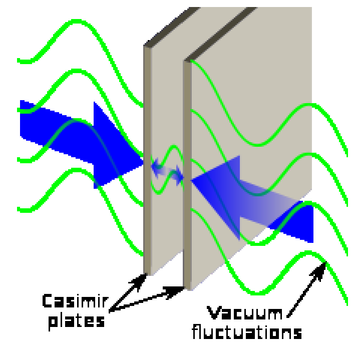
$$\frac{\Delta E}{\hbar\omega} \approx 4 \times 10^{-24} N^3 (L/\mathrm{m})^2. \quad (13)$$

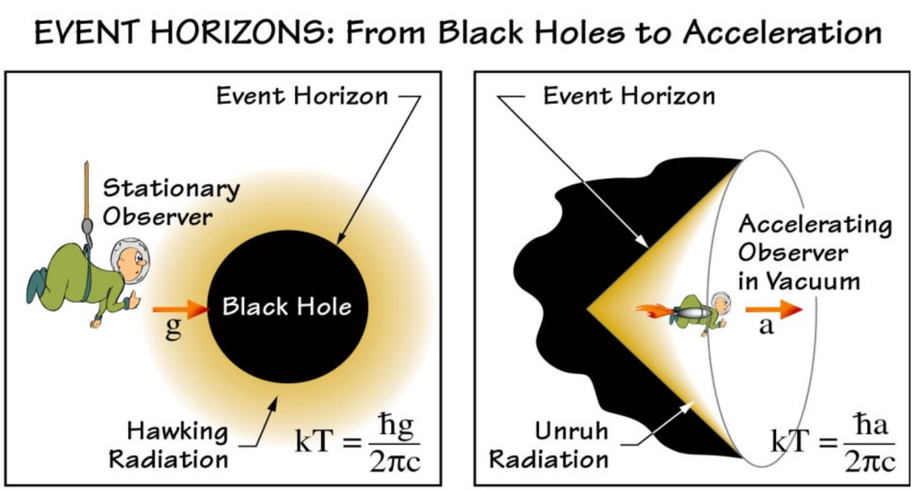
For $N = 10^6$ and $L = 1$ cm, the gravitational Lamb shift is vanishingly small, with $\Delta E/\hbar\omega \approx 4\times10^{-10}$. With a relatively moderate improvement of atom number to $N = 10^8$ while keeping $L = 1$ cm, the gravitational Lamb shift yields $\Delta E/\hbar\omega \approx 0.04\%$. For $N = 10^8$ and a further increase of the trap length to $L = 5$ cm, the gravitational Lamb shift has a potentially measurable value of $\Delta E/\hbar\omega \approx 1\%$.

Quantum Equivalence Principle

- Analogy between 2 quantum effects
  - Hawking radiation
  - Unruh radiation
- Duality between 2 classical limits
  - vacuum-fluctuation picture
  - radiation-reaction picture







A stationary observer outside the black hole would see the thermal Hawking radiation.

An accelerating observer in vacuum would see a similar Hawking-like radiation called Unruh radiation.

Is there a quantum equivalence principle?

P. Candelas
Center for Theoretical Physics, The University of Texas at Austin, Austin, Texas 78712,
Department of Astrophysics, Oxford University, England,
and International School for Advanced Studies, Trieste, Italy

D. W. Sciama
International School for Advanced Studies, Trieste, Italy,
International Center for Theoretical Physics, Trieste, Italy,
and Department of Astrophysics, Oxford University, England
(Received 12 October 1982)

The understanding that has been gained of accelerated vacua sheds new light on the classic issue of the self-force suffered by a uniformly accelerated charge. Moreover, the fact that, as a result of quantum theory, the radiative decay of an excited atom can be viewed equivalently as the result of the vacuum fluctuations of the electromagnetic field or as the result of the radiative self-force of the electron is shown to be nontrivially linked with the equivalence principle.

INTRODUCTION

The aim of this paper is to point out that the understanding that has been gained in recent years of accelerated vacuum states, motivated in large part by a desire to understand the phenomenon of black-hole radiance, sheds new light on the classic issue of the radiation reaction suffered by a uniformly accelerated charge and also on related questions regarding the radiation emitted by a charge that is either at rest in or freely falling through a static gravitational field. We begin with the case of uniform acceleration. The feature of this motion that has attracted so much attention over the years is the seemingly paradoxical relation between the radiation rate and the radiation-reaction force.

In order to avoid boundary effects that would otherwise obscure the issue, we shall consider only motions of the charge such that the agency produc- be considered as being effectively inertial for $t<0$, uniformly accelerated for $0<t<t_1$, and inertial again for $t>t_1$ though, as we shall see presently, the initial and final periods of nonuniform acceleration play a crucial role in the discussion.

UNIFORM ACCELERATION: THE NATURE OF THE PROBLEM

Following the detailed work of Bradbury[1] (see also the recent article by Boulware[2]) we note that the following facts are pertinent:

(i) By direct computation from the Lienard-Wiechart potentials it is straightforward to show that at each instant of retarded time the charge radiates energy at a rate P given by the Larmor formula

$$P=\frac{2}{3}\frac{e^2a^2}{c^3}$$

PHYSICAL REVIEW VOLUME 74, NUMBER 9 NOVEMBER 1, 1948

Some Observable Effects of the Quantum-Mechanical Fluctuations of the Electromagnetic Field

THEODORE A. WELTON*
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Received June 4, 1948)

An intuitive explanation is given for the electromagnetic shift of energy levels by calculating the mean square amplitude of oscillation of an electron coupled to the zero-point fluctuations of the electromagnetic field. The resulting disturbance of the charge and current density of the electron gives rise to various observable effects which can be estimated in a simple classical fashion. The effects treated are the Lamb shift, the correction to the g-factor for the orbital and spin angular momenta of the electron, and the correction to the Compton scattering cross section at low energies. A simple explanation is also given for the peculiar ultraviolet divergence noticed by Pauli and Fierz in their treatment of the infra-red paradox.

I. INTRODUCTION

IT has been pointed out by Bethe[1] that the displacement of the 2S level of hydrogen observed by Lamb and Retherford,[2] can be simply explained as a shift in the energy of the atom arising from its interaction with the radiation field. In order to obtain this result, it is necessary to subtract from the usual infinite result an infinite energy which is essentially the electromagnetic self-energy of the electron. The residual energy shift gives the experimental result, after the introduction of a plausible cut-off in the integral over quantum energies. It is the purpose of this note to point out the existence of a simple picture of the origin of this residual finite level shift which is capable of extension to other phe-

by these fluctuations. The most obvious effect is the spontaneous emission of radiation from atoms in excited states. This phenomenon can be thought of as forced emission taking place under the action of the fluctuating field. Another effect which is equally simple is the existence of a fluctuation in position of a free electron. This may be thought of as a Brownian motion of the electron in equilibrium with a hohlraum, which motion persists when the temperature is reduced to absolute zero. It may be expected that this fluctuation in position will disturb the charge and current distribution arising from an electron in an atom, and hence give rise to observable effects. Weisskopf[3] has pointed out that the interaction of this fluctuation with the field which cut-off occurring in the integral over quanta seems implausibly large from the arguments advanced thus far, but it will later be shown by a simple argument to be very reasonable.

It should be noted in passing that from the nature of the effect the sign of the energy shift is clear, it being obvious that the fluctuation in position must always act to weaken the effect of the potential energy.

We must now discuss the validity of the seemingly inadmissible omission of powers of the Laplacian higher than the first from the expansion (6). Suppose that the probability of finding the instantaneous fluctuation $\Delta\mathbf{q}$ in the volume element $d\Delta\mathbf{q}$ is

$$P(\Delta\mathbf{q})d\Delta\mathbf{q}. \tag{10}$$

IV. LOW ENERGY COMPTON SCATTERING

The general picture thus far developed can be used to give valuable insight into many interesting phenomena. We shall examine briefly several simple processes involving the interaction of electrons and radiation. In each case, the first non-vanishing approximation to the energy, or the second non-vanishing approximation to the transition probability will diverge if calculated on the usual theory. The preceding arguments concerning the Lamb shift strongly indicate that the physically real and finite parts of these divergences will always manifest themselves as a spreading out of the electronic charge and current by the fluctuation in position previously calculated.

As the simplest example of a phenomenon in which the position fluctuation modifies a transition probability, we consider the non-relativistic Compton scattering. For simplicity, we consider the effect to be completely classical, since this must give the correct non-relativistic answer. A free electron executes a steady forced oscillation under the action of the incident light wave and emits a scattered light wave of the same frequency. The effect of the position fluctuation is twofold. The electron behaves now like a distributed charge with a mean square radius $\langle(\Delta q)^2\rangle_{\text{Av}}$. It therefore interacts less strongly with the incident wave and radiates a weaker scattered wave. To find the magnitude of this reduction in the interaction between the electron and a

fluctuation higher than the frequency of the light wave will effectively spread out the scattering charge, while frequencies below this limit will only displace the scattering charge bodily in a random fashion. We therefore place $k_0=k$ and obtain

$$\frac{\Delta\sigma}{\sigma}=-\frac{4}{3\pi}\frac{e^2}{\hbar c}\left(\frac{\hbar k}{mc}\right)^2\log\frac{mc}{\hbar k}. \tag{18}$$

We see that the correction goes to zero strongly at low frequencies, and that for quanta of two-hundred kilovolts energy, where the formula (18) is probably still adequate, the fractional decrease becomes about one part in two thousand. The increase with energy indicated in (18) cannot be expected to continue much farther, so that an

Observing quantum gravity effects with high power lasers and fourth generation light sources

B. J. B. Crowley[1,2], R. Bingham[3], R. G. Evans[4], D. O. Gericke[5], C. D. Murphy[1], P. Norreys[4], S. J. Rose[4], Th. Tschentscher[6], J. S. Wark[1], C. H.-T. Wang[7], and G. Gregori[1,4,*]

[1]Department of Physics, University of Oxford, Oxford OX1 3PU, United Kingdom. [2]AWE plc, Reading RG7 4PR, United Kingdom. [3]Rutherford Appleton Laboratory, Chilton OX11 0QX, United Kingdom. [4]Department of Physics, Imperial College, London SW7 2BZ, United Kingdom. [5]Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom. [6]European XFEL GmbH, Albert-Einstein-Ring 19, 22671 Hamburg, Germany. [7]Department of Physics, University of Aberdeen, Aberdeen AB24 3UE, United Kingdom.

[*]Corresponding author: g.gregori1@physics.ox.ac.uk

We present a novel analysis of Thomson scattering of photons by uniformly accelerated electrons using the Newton-Schrödinger Hamiltonian formalism. We show that a scattering measurement in the laboratory frame can be used to detect quantum gravity processes arising from the Davies-Unruh (or Hawking radiation) effect. Finally, we suggest that currently available high power lasers and 4th generation light sources could be used directly to test these effects with measurable observables.

One of the grand challenges of contemporary physics is the development of an experimentally testable framework, which allows for a direct validation of theories unifying gravity and quantum mechanics. A common misperception of quantum gravity phenomenology is that it requires accessing energies up to the Planck scale of 10^{19} GeV, which is unattainable from any conceivable particle collider. However, quantum electro-dynamics, as a highly successful quantum field theory, has demonstrated how renormalization involving high energy states can influence low energy physical observables. The Casimir effect testifies to the observable nature of the modified renormalization of quantum vacuum through boundary conditions set by conducting plates at low energy. Similarly, the lowest energy quantum temperature - the Hawking temperature (7,8)

$$T_{BH} = \frac{\hbar\kappa}{2\pi k_B c}$$

where κ is the surface gravity (as usual, $\hbar$ is the Planck constant, k_B is the Boltzmann constant and c the speed of light in vacuum). This is a quite general fact, not confined to black holes. As shown by Davies, Unruh and Fulling (9-11), an observer in a uniformly accelerated frame experiences the surrounding vacuum as filled with thermal radiation with temperature

$$T_{DU} = \frac{\hbar g}{2\pi k_B c} \approx 4.05\times10^{-23} g\left[\mathrm{cm/s^2}\right] \quad \mathrm{K}$$

where g is the proper acceleration with respect to the laboratory frame. This is the Davies-Unruh temperature, and formally arises from replacing surface gravity by

Indeed, a direct test of the Hawking radiation and quantum gravity models still remains elusive. In this letter, we propose a novel approach that attempts to overcome these problems by probing the equilibrium state of an accelerated detector (electrons) by scattering of a beam of x ray photons. Such experiments are now becoming a possibility thanks to the recent development of 4th generation light sources (20) in combination with chirped pulse amplification (CPA) of optical laser light (21).

Suppose we have a non-relativistic electron gas illuminated by a high intensity (optical) laser beam – see Figure 1 for details. In the focal region the electrons can experience extreme accelerations due to the laser electric field:

$$g = \frac{eE}{m} \approx 3.4\times10^{16}\left(I\left[\mathrm{W/cm^2}\right]\right)^{1/2} \quad \mathrm{cm/s^2}$$

Scattering Experiment

(B. J. B. Crowley et al 2011)

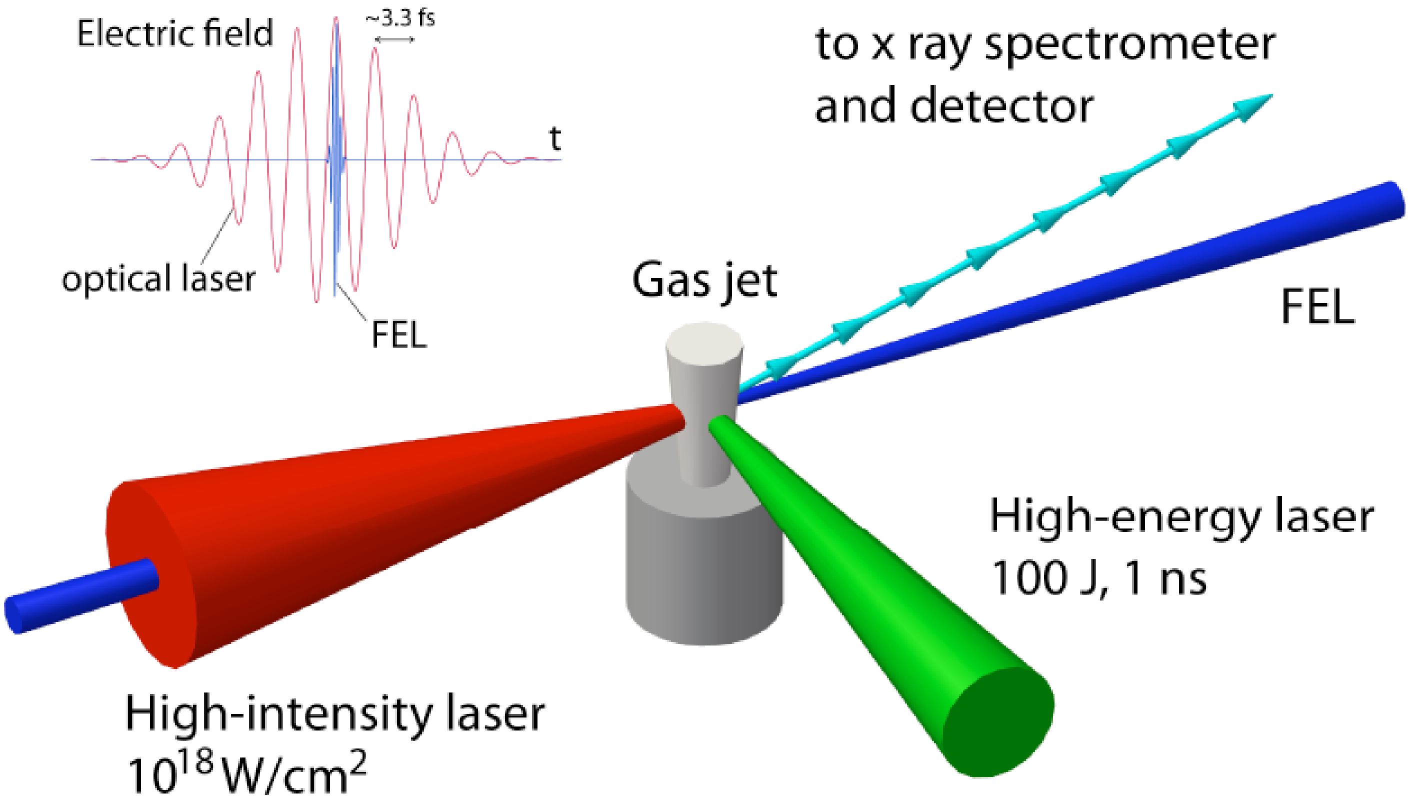


Figure 1: Proposed experimental setup. A high-energy laser excites a pulsed gas jet creating a plasma with electron density ~10^{19} cm^{-3}. A high-intensity CPA optical laser beam with focal spot ~1 µm then accelerates the electrons while the FEL probes them with synchronized x ray pulses in a collinear geometry. The inset shows the optical laser and FEL synchronization.

Any time for questions?