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Nothing really matters - Proposals for laser experiments on vacuum fluctuations

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Abstract.
Usually the number density of photons in light beams is many orders of magnitude less than the number density of vacuum fluctuations. Therefore, if a vacuum fluctuation interacts with a photon, it almost never interacts with a second photon before the single-photon-excited vacuum fluctuation decays and emits a photon. With developing laser technology, short, intense laser pulses have photon number densities in the focus approaching the high number density required to create a sufficient number density of two-photon-excited vacuum fluctuations that the vacuum permittivity will be increased and the speed of light will be decreased. Particle colliders create high energies and these laser experiments will create high photon number densities as they appeared at the beginning of the big bang. In this publication ideas for laser experiments on vacuum fluctuations will be presented: If two photons in the laser focus create two-photon-excited vacuum fluctuations, they will be delayed relative to single-photon-excited vacuum fluctuation, and this could be measured with a diode, or an auto-correlator, or in interference. Additionally, in a pump-probe geometry this intense laser focus (pump) could be measured with a second laser pulse (probe) in reflection. After passing the intense focus, perhaps even the spectrum and duration of the laser pulse could be influenced, all of which can be measured by standard optical techniques.

1 Introduction

In the beginning the universe was in a hot, dense state. Then the expansion of space itself started, not an expansion in space, which is often misunderstood. Introductions about the big bang theory can be found in [1, 2, 3]. Since space itself is expanding, light from galaxies that are farther from us are more red-shifted than galaxies that are closer. Thus, the corresponding velocity of separation v is increasing linearly with increasing distance D as described by the Hubble-Lemaître law $v = H_0 \cdot D$. Here H_0 is the Hubble constant, and its value is about 72 (km/s)/Mpc [2]. While space is expanding, the photon and particle number density together with the temperature of the universe are decreasing.

But what is this space that is expanding? Space or vacuum is not just nothing, because nothing would have exactly zero energy, and an exact energy value of zero would violate the Heisenberg uncertainty principle. The vacuum consists of vacuum fluctuations (VFs) that appear and disappear subject to the constraints of the Heisenberg uncertainty principle that are valid at any time and everywhere. Already in 1934 Furry and Oppenheimer wrote that the polarizability of the charged particles and anti-particles of the VFs would affect the value of the dielectric constant of the vacuum [4]. Consequently, the dielectric constant of empty space differs from that of "truly empty space". In 1957 Dicke wrote that vacuum can be treated as a dielectric medium [5]. In recent theoretical works [6, 7, 8] the vacuum permittivity ϵ_0, the speed c of light in the vacuum, and the fine-structure constant α were calculated from the interaction of photons with VFs. To minimize the violation of conservation of energy and conserve angular momentum, VFs of charged particle-antiparticle pairs appear as bound states in the lowest energy level that has zero angular momentum. VFs interact with single photons somewhat similarly to the way that ordinary matter interacts with single photons. The theoretical calculated values for ϵ_0, c, and α agree within a few percent with the accepted values. In [9] the value calculated for c predicts that there must be three lepton families.

The number density of electron-positron VFs, which appear in the vacuum as parapositronium, was also estimated in [6, 7, 8]: Starting with the Heisenberg uncertainty principle $\Delta E \cdot \Delta t \geq \hbar/2$ and using $\Delta E = 2m_e c^2$, where m_e is the mass of the electron or positron, $\Delta t = \hbar/(4m_e c^2) = 3.2 \cdot 10^{-22}$ s. Multiplying Δt by c, the maximal possible extent L of a parapositronium VF is $L = c \cdot \Delta t = \hbar/(4m_e c) = 9.7 \cdot 10^{-14}$ m. Postulating that there is only one VF in the volume L^3, the number density of parapositronium VFs is $1/L^3 = 1.1 \cdot 10^{39}$ VFs/m^3. The Ansatz in [6, 7, 8] that there is only one VF in the volume L^3 is reasonable and it is justified by the fact that the speed of light is calculated very well. However, since there are no direct measurements so far to confirm this, nature might still have surprises at the very small length scales of VFs. Future experiments, as described below, will hopefully be able to measure or at least estimate the VF number density.

Comparing the size of a parapositronium VF with the size of an atom, which in surface science is the ultimate resolution for a microscope, makes clear how small these dimensions are: The Bohr diameter of hydrogen $1.06 \cdot 10^{-10}$ m is a factor of 1093 larger than the maximal extension of a parapositronium VF. The volume of a parapositronium VF fits within the hydrogen Bohr volume $6.83 \cdot 10^8$ times. Even within an atom with a few protons, neutrons, and electrons the number density of parapositronium alone is many orders of magnitudes greater. A real electron can annihilate with a positron from a VF and the electron that was part of the VF then becomes a real electron [8]. This leads to the so-called Zitterbewegung (trembling motion), which gives a particle its size. The Zitterbewegung frequency corresponds to twice the mass of the particle. Since $E = hf$, for an electron $f = E/h = 2m_e c^2/h = 2.48 \cdot 10^{20}$ Hz or a period $T = 4.03 \cdot 10^{-21}$ s. In comparison, the period of the Bohr orbit of an electron in the ground state of a hydrogen atom is 152 as $= 1.52 \cdot 10^{-16}$ s, a time range in laser physics that is called ultra-fast science. Thus, for hydrogen in its ground state, during one Bohr orbit the electron interacts $3.8 \cdot 10^4$ times with the VFs. Note that the number density of VFs depends on the particle and anti-particle species. Here only parapositronium VFs are considered. For muons and tauons, which are much heavier than electrons, Δt and L are much smaller, and, consequently, the VF number density is much higher, namely, $9.8 \cdot 10^{45}$ VFs/m^3 and $4.7 \cdot 10^{49}$ VFs/m^3, respectively.

In [6, 7, 8] the authors considered the case that only one photon interacts with one VF at a time. In our expanded universe this is certainly correct, since the number density of photons is many orders of magnitude less than the number density of VFs. But, in the very young universe, where less space was available, the number density of photons was higher than the number density of VFs. The photon number density in the universe can be deduced from Plancks black body radiation to $N[\text{Photons/cm}^3] = 20.28 \cdot (T[\text{K}])^3$ [1]. If we set the parapositronium number density deduced above equal to N, we get a temperature of $T = 3.8 \cdot 10^{10}\ K$. At that temperature the universe had a photon number density that was equal to the parapositronium number density. In the radiation dominated era of the universe the relation between age t and temperature T is $t[\text{sec}] = (2 \cdot 10^{10}\ \text{K} \ /\ T[\text{K}])^2$ [2]. Thus, the photon number density was equal to the parapositronium VF number density at 0.28 sec after the big bang, before it was even higher. At this universe age and temperature the four fundamental interactions already became distinct. The average photon energy can be calculated with $E_{ph}[\text{J}] = 3.73 \cdot 10^{-23} \cdot T[\text{K}]$ [1]. Therefore, at $3.8 \cdot 10^{10}$ K this leads to an average photon energy of 8.9 MeV. Note that photon energies around 8.9 MeV are much higher than the usual 1.55 eV from the high power lasers and pair production was possible for electrons and positrons ($2\times$ 0.51 MeV) but not any more for protons and anti-protons ($2\times$ 938.3 MeV) and neutrons and anti-neutrons ($2\times$ 939.6 MeV). Due to the expansion of the universe, these photons represent today the cosmic microwave background, they are red shifted to 2.7 K, and have a number density of $4 \cdot 10^8$ photons/m^3 [2]. At that young age of the universe and moreover when it was younger, elementary particles, which also interact with VFs, have to share VFs with the photons, which already saturate the VFs. Additionally, the photons could make pair production and these electrons and positrons also interact with the VFs. Could it happen that elementary particles and photons interact with a single VF? Could it happen that at the same time or sequentially two or more photons interact with a single VF? This would be a

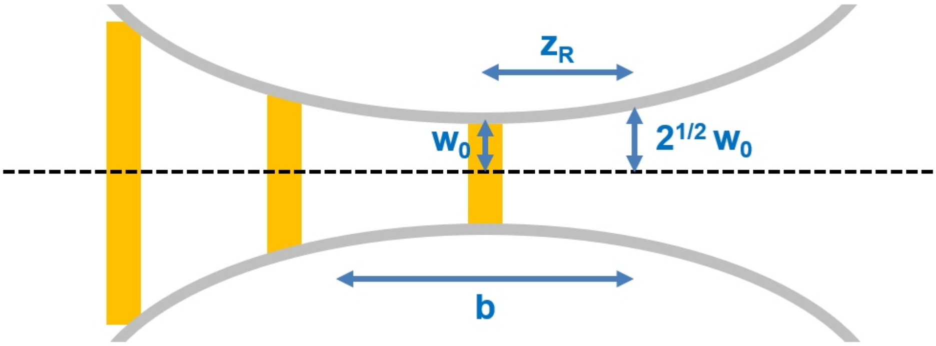

Figure 1: Schematic laser pulse (in orange) traveling from left to right through the focus. Rayleigh length z_R, confocal parameter $b = 2z_R$, and the radius w_0 of the beam in the focus are marked.

similar situation to two-photon or multi-photon excitation of an atom or molecule. But how much is the speed of light reduced and the vacuum permittivity increased by two-photon-excited VFs? This question is currently under theoretical research by the same authors [6, 7, 8].

An indirect proof of the existence of VFs is the Lamb shift. Direct experiments with space itself are challenging: If a photon interacts with a VF, a photon with the same photon energy and direction is emitted. If a photon with a higher photon energy is absorbed, a photon with a higher photon energy is emitted. The vacuum speed of light does not depend on the photon energy. There are no resonances, there are no losses, and there is no dispersion. The vacuum is fully transparent, isotropic, and homogeneous. Light can travel through billions of lightyears of space without any loss. VFs come from nothing and they return to nothing within the time uncertainty Δt. VFs are always and everywhere present, they interact continuously with particles (Zitterbewegung) and photons, but they do not take energy or momentum and they do not give energy or momentum to ordinary matter; otherwise, the energy and momentum conservation laws would be violated.

In this paper I will propose experiments with short and intense laser pulses, which approach the number density of parapositronium VFs and which could measure directly properties of the vacuum. In section 2 focussing of short laser pulses will be introduced. I will discuss the photon number densities in laser foci which can be achieved today by commercial lasers and laser facilities and give an outlook for the near future. Different scenarios for photons in the strong laser focus will be presented. In section 3 I will present ideas for laser experiments which could measure the influence of two or more photons interacting with a single VF. Finally, in Section 4 a short summary will conclude this paper.

2 Photon number densities in a short pulse laser focus

A short laser pulse is a thin disk of light propagating at the speed of light. This is shown schematically as an orange rectangle in Fig. 1. The front and tail of the short pulse are weak while the center has the strongest field and highest photon number density. For example, a 1 ps or 1 fs short laser pulse corresponds to 300 μm or 300 nm thin light disks, respectively.

The commercial short-pulse laser Pulsar 250 from the company Amplitude [10], for example, has short laser pulses with a pulse energy above 6 J, a pulse duration τ below 25 fs, at a central wavelength of 800 nm. A 20 fs pulse duration multiplied with the speed of light corresponds to a 6 μm thin light disk. A short laser pulse can be additionally focused in space, as shown schematically in Fig. 1. Usually reflective focussing mirrors are used to avoid pulse distortions through the material of a focussing lens. The Rayleigh length z_R, confocal parameter b, beam quality factor M^2, radius of the beam in the focus w_0, wavelength λ, beam diameter D, focal length f, and refractive index of the medium n have these relations: $b = 2 \cdot z_R = 2 \cdot 1/M^2 \cdot n\pi w_0^2/\lambda$ with $w_0 = 2\lambda f/(\pi D)$. For example, if $D = 7$ cm, $\lambda = 800$ nm, and $f = 41$ cm the radius of the beam in the focus is $w_0 = 3$ μm. For the vacuum n is equal to 1. For a good adjusted laser the beam quality factor M^2 is also equal or close to 1. Note that high power lasers usually have slightly higher M^2 value, but here it is assumed for simplicity to be 1. For a real laser experiment the actual M^2 values has to be used for designing the experiment. For the example above, this lead to a confocal parameter $b = 71\ \mu$m. The volume of the laser pulse at the focus is $c \cdot \tau \cdot \pi w_0^2 = 1.7 \cdot 10^{-16}$ m^3. The entire pulse has 6 J and each photon at 800 nm has an energy of 1.55 eV (spectral width of the pulse is neglected). Consequently, there are $2.4 \cdot 10^{19}$ photons in the pulse. Overall, this example leads in the focus to $1.4 \cdot 10^{35}$ photons/m^3. Compared to the VFs number density of $1.1 \cdot 10^{39}$ VF/m^3 this is "only" 4 orders of magnitude less. Note that laser facilities such as the Extreme Laser Infrastructure (ELI) [11] can make equally short pulses with energies up to 250 J. There are already plans to build laser facilities which exceed the 1000 J level such as the eXawatt Center for Extreme Light Studies (XCELS) [12] and the Station of Extreme Light (SEL) [13, 14]. At the Shanghai Superintense Ultrafast Laser Facility (SULF) a laser pulse of 30 fs pulse duration and 72 J pulse energy was already successfully focussed onto a 6 μm FWHM diameter [15]. A new laser system in Shanghai will produce 1500 J pulse energies in 15 fs long pulses, reaching a design intensity of higher than 10^{23} W/cm^2 [16]. Additionally, one could try to focus harder, but this would also decrease the confocal parameter b, which is the region where we get the signal for our measurement. The idea of, the so called, loose-focussing is adapted from high-harmonic generation, where the interaction between the focussed laser and the gas target is increased in order to increase the conversion efficiency [17]. Free-electron lasers (FELs) also deliver short, high energetic pulses. The advantage of FELs is that the shorter wavelengths can be focussed down to even a few nm [18]. The disadvantage is that the total pulse energies are much smaller than for optical lasers and, additionally, the higher photon energies lead to a smaller number of photons per pulse. For example, in [18] FEL pulses at 9.124 keV photon energy and a pulse duration of 7 fs were focused down to 7 nm $\times$ 7 nm. Directly at the focus there was 49.9 μJ pulse energy (losses of X-ray mirrors with the KirkpatrickBaez geometry included). This leads in the focus to $3.3 \cdot 10^{32}$ photons/m^3, which is three orders of magnitudes less than the example above. Additionally, this nm-size focus has a very small confocal parameter of around 0.6 μm.

Ideas for different types of photon propagations in a short pulse laser focus are shown as a simple two dimensional model in Fig. 2. The squares indicate the random appearing and disappearing VFs which can absorb photons (red dots) and emit photons (yellow arrows). Note that VFs do not have any periodicity, since this would lead to distinguished directions like the periodic grating in solid state physics, which do not exist for empty space where all directions are equal. This is just a photo of the university campus floor for illustration and any periodicity is just incidental and not deliberate. If the photon number density is much smaller than the VF number density as in (a), only single photons are absorbed and emitted by the VFs which leads to the standard speed c of light. If the photon number density in the center of the pulse approach the VF number density as in (b), then also two-photon-excited VFs could appear (purple dots). This region has a reduced speed $c^\star$ of light and an increased permittivity $\epsilon_0^\star$. The photons in the weaker front of the pulse will still propagate with c into the free space in front of the laser pulse while they interact via the usual single photon absorption and emission. The photons in the weak tail of the pulse will also propagate with c, until they catch up the central region of the pulse where two-photon-excited VFs have not decayed yet because of their longer decay time: Will they overtake this region in space which is occupied by slower decaying two-photon-excited VFs? But how should this happen? Or will this lead to three-photon-excited VFs which in turn will have an even longer decay time? Another idea is reflection, since the photons move from a region with the usual vacuum permittivity ϵ_0 into a region with a different $\epsilon_0^\star$. This is similar to the situation where light travels between two media with different relative permittivities such as from air into glass. In a laser pump-probe experiment, if a second, synchronized probe pulse consisting of single-photon-excited VFs (red dots) crosses a region with two-photon-excited VFs (purple dots) as in Fig. 2(c), will there be reflection? What would happen if a two-photon-excited VF (purple dots) decays as depicted in Fig. 2(d) while the neighboring two-photon-excited VFs did not decay? Would this lead to reflection or to four-photon-excited VFs? If a single-photon-excited VF decays it must emit a photon at the original photon energy, because of energy conservation. Would it be possible for a two-photon-excited VF, where both photons originally had the same photon energy, to decay into two photons with unequal photon energies? This would be similar to a nonlinear optical process in a crystal.

A strong short pulse laser focus does not only have a high photon number density but also strong electromagnetic fields. In addition to the above described scenarios also other effects due to the high fields could happen. The usual upper limit of the laser field strength in a perfect vacuum, which is called Schwinger field, is 10^{29} W/cm^2 [19]. This can be further reduced as a function of the residual electron density in the vacuum chamber, because the residual electrons can trigger an avalanche of a quantum

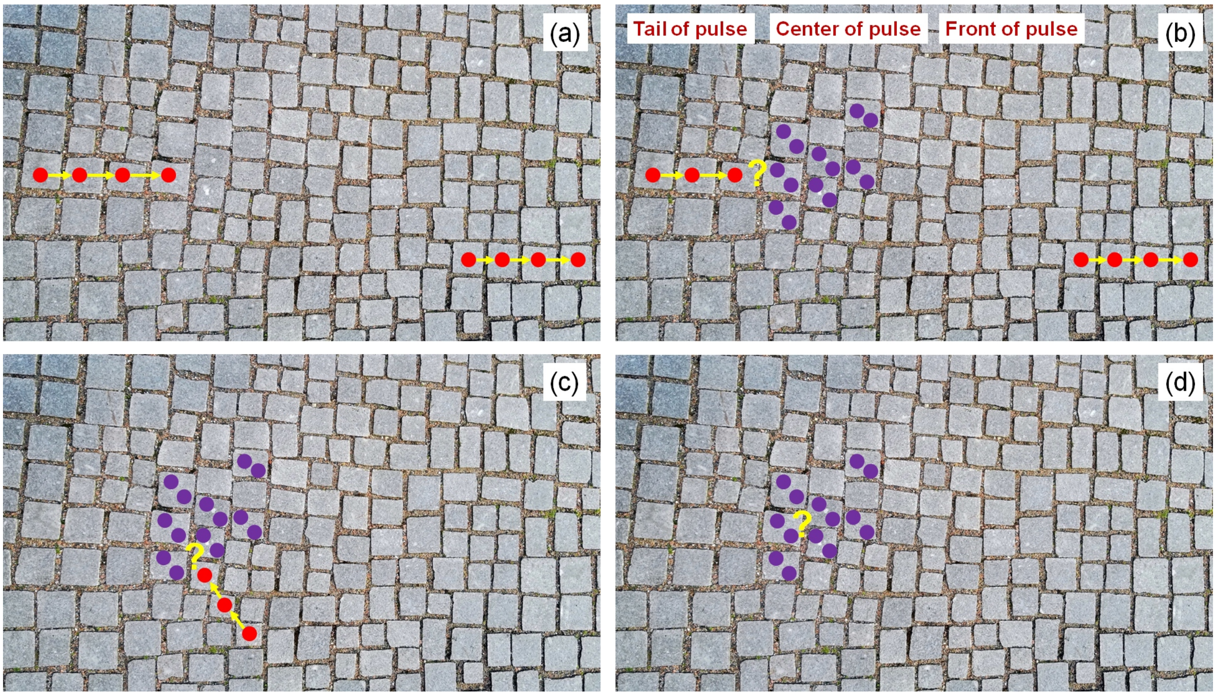

Figure 2: Schematics of different photon propagations in a short laser focus. The squares indicate random appearing and disappearing VFs that can absorb photons (red dots) and emit photons (yellow arrows). (a) If the photon number density is much smaller than the VF number density, only single photons are absorbed and emitted by the VFs that leads to the standard speed c of light. (b) If the photon number density approaches the VF number density, then two-photon-excited VFs could also appear in the strong center of the pulse (purple dots), which have a reduced speed $c^\star$ of light. The photons in the weaker front of the pulse will propagate with c into free space. The photons in the weak tail of the pulse will also propagate with c, until they catch up the central region of the pulse where two-photon-excited VFs have not decayed yet because of their longer decay time: Since photons move from a region with the usual permittivity ϵ_0 into a region with a different permittivity $\epsilon_0^\star$, will there be reflection? (c) Will photons from a synchronized probe pulse (red dots) which cross this region (purple dots) be reflected? (d) What will happen if a two-photon-excited VF decays, while the neighboring did not? Will we get any non-linear decay?

electrodynamics cascade which could create more and more electron and positron pairs as described in [19]. For comparison, the example above with the commercial laser at a 3 μm focus has $1.1 \cdot 10^{21}\ W/\text{cm}^2$ which is many orders of magnitude smaller than the Schwinger limit. There are other experimental approaches which try to measure photon-photon elastic scattering in the X-ray region [20]. This was predicted by Halpern in 1933 as a non-linear effect of the quantum vacuum [21]. In the theoretical paper [22] the authors discuss detection schemes for quantum vacuum diffraction and birefringence between optical (1.5 eV) and FEL (6 keV) pulses, including difference in propagation direction and polarization change. Note that up to now, there is no experimental evidence for these effects.

3 Proposals for laser experiments

Figures 3 and 4 show schematically experimental setups which could measure properties of VFs as described in section 2. Both experiments could be integrated in the same vacuum chamber: If for the right hand, x is the direction of the incoming laser pulse, then the setup of Fig. 3 could be oriented to the y and the setup of Fig. 4 to the z axis.

In Fig. 3 the short laser pulse (orange) moves from left to right. It is focussed with a spherical mirror and thereafter it moves from right to left through the focus. The left diode measures the arrival time of the incoming beam. This signal could be used as the trigger for an analog-to-digital converter (ADC), marked as channel 0 (CH0). The right diode measures the arrival time of the reflected beam after it propagated through the focus. This signal could be measured on CH1 of the same ADC. For a beam where the photon number density in the focus is much smaller than the VF number density, the delay between the CH0 and CH1 peaks will correspond to the normal speed c of light. If the photons, or part of the photons, are delayed due to two-photon-excited VFs, than they will arrive later on the diode. This additional delay could be measured, if it is bigger than the resolution of the diodes, together with cables and ADC. For the example above with the confocal parameter $b = 71$ μm, light needs through usual vacuum, where only single photons interact with VFs, 237 fs. If one assumes that the speed of light decreases due to two-photon-excited VFs by one over the fine-structure constant $c^\star = c/\alpha = c/137$, the pulse would be delayed from 237 fs to 32.5 ps, which maybe can be directly measured with the fast laser diodes. Smaller delays, which would slightly increase the pulse duration of the laser after it passed through the focus, could be measured with conventional laser auto-correlator techniques like frequency-resolved optical gating (FROG) [23]. FROG has a resolution of 1 fs, which could measure down to a speed of light decrease of $c^\star = c \cdot 237$ fs/238 fs $= c/1.004$. If the speed of light is reduced even less due to two-photon-excited VFs, one could use interference, where part of the incoming beam is interfered with the beam after the focus.

If photons are reflected from the focus region, they will move from left-to-right back to the focusing mirror and than from right-to-left to the CH1 diode. Such a huge delay could be very easily detected with the diodes.

In case particles and antiparticles are released from the vacuum by the laser, the positive and negative high-voltage meshes will separate and accelerate them towards the multi-channel plates (MCPs). Besides, only charge particles and antiparticles can be separated and collected by the MCPs. MCPs can amplify even single charged particles up to a detectable level. The MCP signal could be additionally amplified with fast electronic amplifiers, which separate and protect the ADCs from the MCP high-voltage and these signals could be read out in coincidence on the same ADC, marked as CH2 for positive and CH3 for negative particles. If this is successful, one could use instead of this simple MCPs with meshes more advanced time-of-flight detectors and analyse the charge over mass of the created particles.

In Fig. 4 the short laser pulse (here grey) also moves from left to right and is focussed with a spherical mirror and thereafter it moves from right to left through the focus. A short and synchronized pulse (red) arrives at the same time at the focus area when the high-power pulse is there. In the usual naming of laser physics, the strong laser pulse (grey) is called pump and the weak pulse (red) is called probe. At usual photon number densities far below the VFs number density both pulses percolate each other without any interaction. If the photon number density of the pump pulse in the focus is approaching the VFs number density, the vacuum permittivity will change from ϵ_0 to $\epsilon_0^\star$. Thus, the weak probe pulse will propagate between regions with different vacuum permittivities. Will the weak probe pulse be partly reflected? In this crossed geometry the right part of the probe pulse arrives earlier at the focus region than the left part. This leads to a time-to-space mapping, which will probe regions of different photon number densities. This is a similar experiment as the arrival-time tool used for FELs [24]. In that experiment the reflectivity change of a semiconductor is used for the time-to-space mapping. Here the vacuum itself will be the target. Note, as the pump pulse propagates into the focus the photon number density is increasing. This is similar to the big bang theory backwards in time, where less space lead to higher photon number densities. The probe pulse will measure the reflection at different photon number densities before (and after) the focus like probing space at different stages of the big bang.

Additionally, one could measure and compare the spectra of the original incoming pulse and the reflected pulse after it passed the focus region. If a two-photon-excited VF decays non-linearly into two photons with different photon energies, this should be directly measurable with a standard spectrometer.

In the following the demands on the technical vacuum levels will be discussed. Using the ideal gas equation, ambient air at 1 bar and 300 K has 2.4 $\cdot 10^{25}$ particles/m^3. High vacuum of 10^{-4} mbar which can be typically achieved with scroll pumps has at room temperature 2.4 $\cdot 10^{18}$ particles/m^3. Turbo pumps can reach down to 10^{-10} mbar (ultra-high vacuum), which corresponds to 2.4 $\cdot 10^{12}$ particles/m^3. Finally, ion-getter pumps, chamber backing above 100°C, and cold traps can reach a vacuum of 10^{-12} mbar, which corresponds to 2.4 $\cdot 10^{10}$ particles/m^3. Note that even the best technically achievable

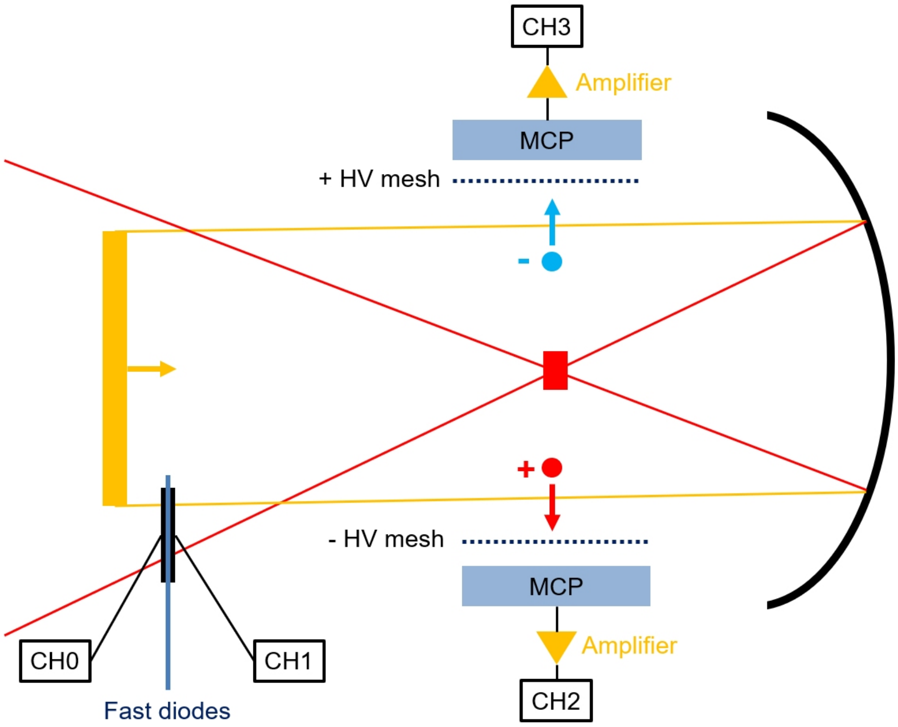

Figure 3: Schematic of laser experiments on VFs, part 1: A short laser pulse (orange) moves from left to right, is focussed with a spherical mirror, and moves then from right to left through the focus. The left diode (CH0) measures the arrival time of the incoming beam and could be used as the trigger for the analog-to-digital converter (ADC). The right diode measures the arrival time of the reflected beam after it propagated through the focus (CH1 of same ADC). If the photons or part of the photons are delayed due to two-photon-excited VFs more than the resolution of the diodes this could be measured directly. If photons are reflected from the focus region, they will move from left-to-right back to the focusing mirror and then from right-to-left to the CH1 diode with a huge and easily detectable delay. If any charged particles and antiparticles are released from the vacuum by the strong electric field of the laser, the positive and negative, high-voltage meshes will separate and accelerate them towards the multi-channel plates (MCPs), and these signals could be amplified and read out in coincidence in CH2 and CH3 of the same ADC.

vacuum still has 24 billion particles in one cubic meter. Additionally, neutrinos from the universe, mostly from the sun, will pass unperturbed through the vacuum chamber and the photons from the black body radiation of the chamber itself are also present, but their number densities are many orders of magnitudes smaller compared to the VFs. Fortunately, for the experiment we do not need one cubic meter free of particle, but only the interaction volume, where the laser pulse is focussed, should be free of atoms and molecules. If we roughly assume for the interaction volume $\pi w_0^2 \cdot b$ and use the values from section 2, we get $2 \cdot 10^{-15}$ m^3. The gas pressure which has on average 1 particle in this volume at 300 K corresponds according to the ideal gas equation to a pressure of $2.1 \cdot 10^{-8}$ mbar. Since 10^{-10} mbar (and even 10^{-12} mbar) can be technically reached, every 100 (or 10000) pulse could maybe hit a remaining atom or molecule in the focus. In such a strong laser field tunnel ionization and multi-photon absorption will ionize any atom or molecule. The transition between both regimes is described by the Keldysh parameter [25]. If any ionization should happen, the charged fragments will also be separated by the electric field of the HV meshes and amplified with the MCP plates and this will lead to a large background compared with any effect from the VFs. Laser shots where an atom or molecule is hit in the focus will create a coincident signal on CH2 (positive photo-ions) and CH3 (negative photoelectrons) and can be excluded from the data sets. In case Schwinger pairs are also created, a procedure has to be developed in order to distinguish between these two pulse shapes on the ADCs. In order to avoid window flanges between air and the vacuum chamber, which will disturb the short and

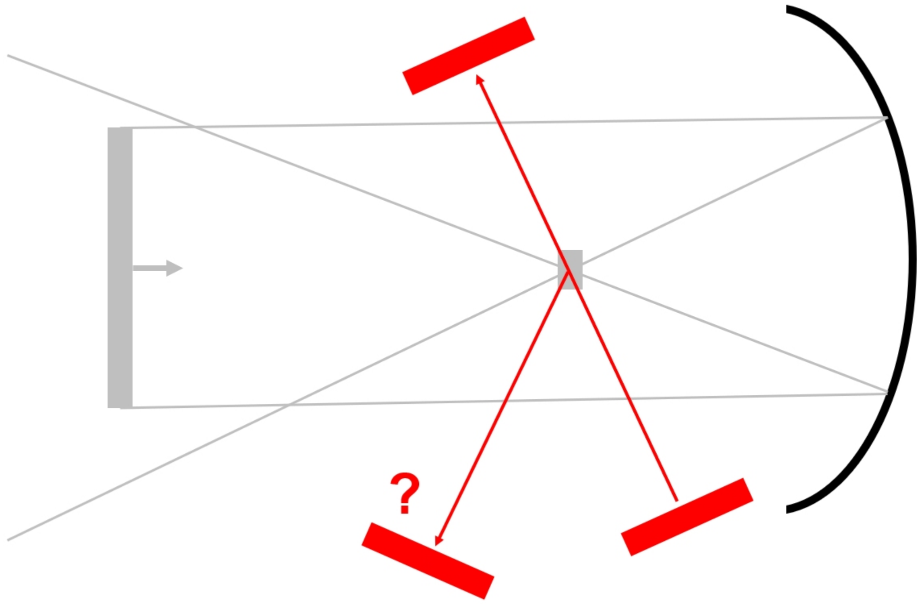

Figure 4: Schematic of laser experiments on VFs, part 2: A short and synchronized probe pulse (red) arrives at the same time at the focus of the high-power pump pulse (here in grey). At photon number densities far below the VFs number density both pulses pass through each other without interaction. If the photon number density in the focus is approaching the VFs number density, will the weak probe pulse be partly reflected? In this crossed geometry the right part of the probe pulse arrives earlier at the interaction region than the left part, leading to a time-to-space mapping, which will probe regions of different photon number densities.

strong laser pulse, the last laser compressor stage should be build already in vacuum. Maybe a differential pumping system between the laser and experimental vacuum chamber is needed to reach a pressure at the interaction region below 10^{-10} mbar.

4 Summary

In this publication several proposals for laser experiments on VFs are presented, which become accessible in the near future. With developing laser technology, the focus of short laser pulses reach photon number densities that approach the parapositronium VF number density. Effects are discussed that could happen if two-photon-excited VFs should appear and how they could be measured. An increase of the vacuum permittivity from ϵ_0 to $\epsilon_0^\star$ or, consequently, a decrease of the speed of light from c to $c^\star$ could temporally delay or stretch a pulse and maybe even reflection of photons could happen between spaces with different vacuum permittivities. Temporal delays could be measured with a diode, or an auto-correlator, or in interference. Additionally, the possibility of non-linear decay of doubly excited VFs is discussed, which could be measured with a spectrometer. If the Schwinger effect should appear, charged particles and anti-particles could be separated with meshes under high-voltage and amplified with MCPs. In this paper, space itself is the final frontier. The majority of the entire universe is space, even within an atom the majority are VFs. Theoretical and experimental understanding of VFs can increase the fundamental understanding of the universe at the beginning of space and time itself, where the photon and particle number density were equal or even higher than the VFs number density.

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