Time-resolved diffraction and interference: Young´s interference with photons of different energy as revealed by time resolution

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We present time-resolved diffraction and two-slit interference experiments using a streak camera as a detector for femtosecond pulses of photons. These experiments show how the diffraction pattern is built by adding frames of a few photons each frame. It is estimated that after 300 photons the diffraction pattern emerges. With time resolution we can check the speed of light and put an upper limit of 2ps at our resolution to the time for wave function collapse in the quantum measurement process. We then produce interference experiments with photons of different energies impinging the slits; *i.e.* we know which photon impinges each slit. We show that for poor time resolution no interference is observed but for high time resolution we have interference which is revealed as beats of 100 GHz frequency. The condition for interference is that the two pulses should overlap spatially at the detector, even if the pulses have different energies, but are generated from the same pulse of the laser. The interference seems to be in agreement with classical theory at first sight, however closer study and analysis of the data show deviations in the visibility of the interference fringes and of their phase. These experiments are discussed in connection with quantum mechanics and it may be concluded that the time resolution provides new data for understanding the long standing and continuing arguments on wave-particle duality initiated by Newton, Young, Fresnel, Planck and others. A thought experiment is presented in the appendix to try to distinguish the photons at the detector by making it sensitive to colour.

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1. Introduction

The concept of light as a particle or a wave has been a controversial topic during the centuries in which optics developed. The magnificent authority of Newton led to the rejection of the wave theory throughout the eighteenth century. However at the beginning of the nineteenth century decisive discoveries were made that put forward the wave theory once more. The very first and important discovery was the enunciation of the principle of interference (Young, 1802, 1804) for which the 200th anniversary is at hand. Even if this discovery established ground for the wave theory with further support from the remarkable experiments of Fresnel (1816), some time was required for it to be generally accepted and a revival of the corpuscular theory occurred with the discovery of quanta (Planck 1900). Nowadays it seems to be generally accepted that wave-particle duality is intrinsic to the nature of light but we believe that time-resolved measurements may have something more to say. This could be important in quantum physics where the time is not treated as an observable operator but is just considered as a parameter. Although we are happy to use the Fourier transform relation between time and energy, there is no associated probability function and therefore the times we are measuring are times of flight of photons and not expectation values that satisfy an uncertainty principle.

Quantum physics is described by a probability theory in which the physical quantities are given by mean values provided by a probability function. Therefore quantum physics necessarily refers to a system in terms of an ensemble of events. This requirement is met by measuring a large number of similar systems or by repeatedly measuring a single particle many times with the condition that each measurement is done under the same conditions. Unquestionably these ideas have provided us with an understanding of the atomic and micro world and have lead to the development of a tremendous number of new technological devices and gadgets (Feynman 1966,1985; Ballantine 1990; Cohen-Tannoudji 1977). QM seems to work very well for an ensemble of particles, but when describing single-particle behaviour it raises fundamental questions and controversies which have been familiar for many years (Shrödinger 1926; Einstein 1935, 1949; Margenau 1936) and are still unresolved. QM postulates wave-particle duality, which for light reawakens the great controversy existing before and after Newton and certainly not yet closed. The state of a particle is described by a wave function $|\Phi(r,t)\rangle$, where r and t are the position and the time, and behaves as a wave (linear superposition of eigenfunctions $|\Psi(r,t)\rangle$). However when a measurement of this state is made then it behaves as a particle at the position of the detector and the coefficients of the linear combinations are projected onto one of these eigenfunctions. This process is also known as the collapse or reduction of the wave function but raises the questions should there therefore be a collapsing time and how is it defined? Furthermore the state of the particle can only be determined after the measurement is done, but not before.

Here we present diffraction and interference experiments with picosecond (ps) time resolution. Section 2 deals with the formation of the diffraction pattern by counting photon by photon as they arrive at the detector (a streak camera). Although the concept of wave function collapse, taken as one of the postulates of quantum mechanics (QM) remains a mystery to us, we are able to estimate that the collapse time is less than 2 ps. Also, by measuring time delay, we can check the speed of light or better the group velocity of light propagation. Alternatively, assuming that the speed of light is $c=3.10^{10}$cm/s, we can use the data obtained for the calibration of the streak camera.

In a section 3 we present interference experiments with photons of different energies going through different slits. We know at which slit the blue and red, high and low energy, photons arrived although we cannot distinguish these photons when they reach the screen. This observation may indicate that some modification is needed in the books which state that interference is produced only if we do not know to through which slit each photon goes. In our experiments the indeterminacy is after the slits. Furthermore we find interference beats of 100GHz and show that, on a closer analysis, the data do not follow classical wave physics. It maybe argued that this is because there are external decoherence processes but then the decoherence should not be independent of the time of flight of photons or of the surrounding media. Different experimental configurations were always found to give data deviating from classical wave theory in the same way. These results will be discussed in terms of internal decoherence theory, which if used in the way proposed in QM shows agreement with the data. Through this discussion on decoherence it is clear that the data presented here with time resolution, open possible new views on how to treat time in the wave- particle duality problem.

Finally, in section 4, conclusions are presented and, in Appendix A, an experiment is suggested to try to distinguish the photons of different colour.

2. Diffraction experiments

We try to study, using femtosecond pulses of photons the wave function collapse time in QM by measuring patterns of photons diffracted by a slit. These patterns are obtained by accumulating many few-photon events (we have no reason to claim one photon events) in order to know how many photons are needed to describe the typical diffraction pattern. Here we introduce a new ingredient by using a streak camera to measure the time of flight of pulses from the slit to detectors located at different positions. As our streak camera has a 2ps resolution we can establish that this is an upper limit of the collapsing time because we do not find any sign of a collapsing time. We can operate with many photons or a few photons in a pulse and therefore in the last case using the photon counting mode we can measure the time of flight of each photon that has a signature of a brilliant spot at the streak camera.

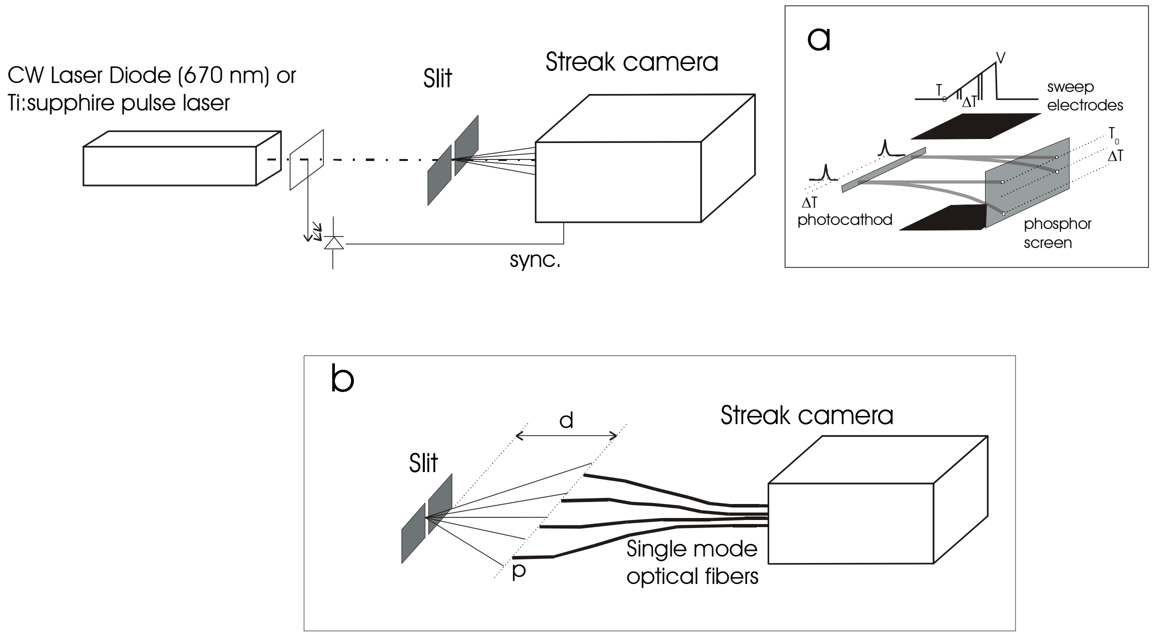

Figure 1 *Experimental arrangement. A sketch of the way the diffraction experiments are performed. A CW diode-laser (670nm) or Ti:sapphire femtosecond pulsed laser was used as a source of light.*

a) *Schematic diagram of the streak camera.*
b) *Arrangement for time of flight experiments.*

The diffraction experiment is shown in Fig.1. A slit of width150 μm was illuminated by a CW diode laser (λ=670 nm) or by a Tsunami Mode-locked Ti:sapphire Laser producing light pulses of 150 fs duration, frequency 82 MHz and 800 nm wavelength. The diffraction pattern goes into the entrance slit of the streak camera (Hamamatsu C5680). The photocathode of the streak camera collects light and produces a number of electrons that is proportional to the intensity of the incident light and these electrons are directed towards a phosphor screen by means of accelerating electrodes. In the counting mode, each photon gives a brilliant spot that can be assigned a position (horizontal axis) and a time of flight (vertical axis). A high-speed, high-level voltage synchronised to the incident light is applied to the sweep electrodes, so that the advancing electrons are swept in the direction from top to bottom. The rapidly increasing electric sweeping field of the streak camera will also generate a magnetic field that additionally deflects the electrons. When the electric field increases linearly with time, as indicated in fig. 1(a), this magnetic field is independent of time and may therefore be neglected. The synchronising signal is provided by each incident pulse and at least one photon is absorbed from the pulse in this process. The optical image produced on the phosphor screen is called the "streak image", and has an intensity distribution which appears

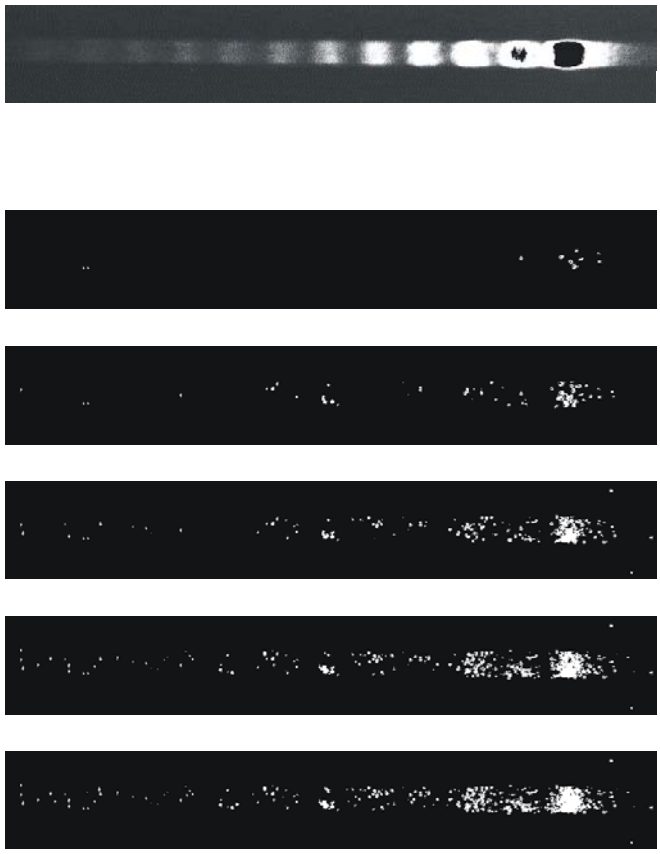

Figure 2 *Diffraction pattern taken from a slit (150 μm width) with zero-order maximum left out (because of extremely high intensity, i.e. saturation). No sweep voltage was applied to the streak camera electrodes, so the frames are just images of the streak camera input window. Top frame was taken in analogue mode. Others frames were taken in photon counting mode and correspond to 10, 50, 120, 240, 300 photoelectrons.*

at the appropriate position in the vertical direction as time passes. With no voltage applied to the sweep electrodes (focus mode) the streak image is nothing but the spatial intensity distribution of light. The top panel of Fig. 2 shows a typical many-photon diffraction pattern, obtained by illuminating the slit for 5 sec by an intense light. These patterns agree with Fraunhofer diffraction from a slit at normal incidence and are described by the Fourier transform of the slit (Goodman 1968). When we build up the diffraction pattern by adding the spots produced by a few photons at a time (generated by reducing the beam's intensity), we find that the signal of each photon corresponds to a pixel at the screen of the streak camera. The second up to the sixth panel of Fig.2 show the intensity for 10, 50, 120, 240 and 300 events respectively (taken in frames of about 10 photons each after 200 ms). The similarity between the upper frame of Fig. 2 and the lower one (300 photons) is clear. These experimental results show how the diffraction pattern, i.e. the signature of wave behaviour, of the slit results from impacts of single photons which, according to the wave-particle duality and the wave-function collapse postulate, produce one impact each. In other words the diffraction pattern appears as an statistical addition of many photons collected in time.

Single photon experiments of this type have been performed before to show the build-up of interference. However, by using pulses of several photons, we can explore further the wave-particle duality and measure the time-of-flight of the photons from the slit to the detectors, i.e. the time differences between photons arriving at two different diffraction spots. With our streak camera we can achieve a 2 ps time resolution for detection points that are sufficiently separated in space. The difference in light path between the zero-order maximum and any other point of the diffraction pattern is determined by the distance between the slit and the point on the screen where we measure the diffraction pattern (see Fig.3). This path difference Δl is thus given by $\Delta l = \sqrt{d^2 + x^2} - d$, where d is distance from slit to screen and x is the position of measurement relative to the zero-order maximum. In our case the photocathode of the streak camera is the screen at which we measure diffraction pattern. At d=50 mm and x=2.5 mm (half the size of the photocathode) Δl is equal to 0.06 mm, corresponding to a 0.2 ps time delay which is much below the resolution of our streak camera (2 ps). To increase the accuracy of our measurements we collected light with single-mode optical fibres, which were placed at the positions near to maxima in the diffraction pattern.

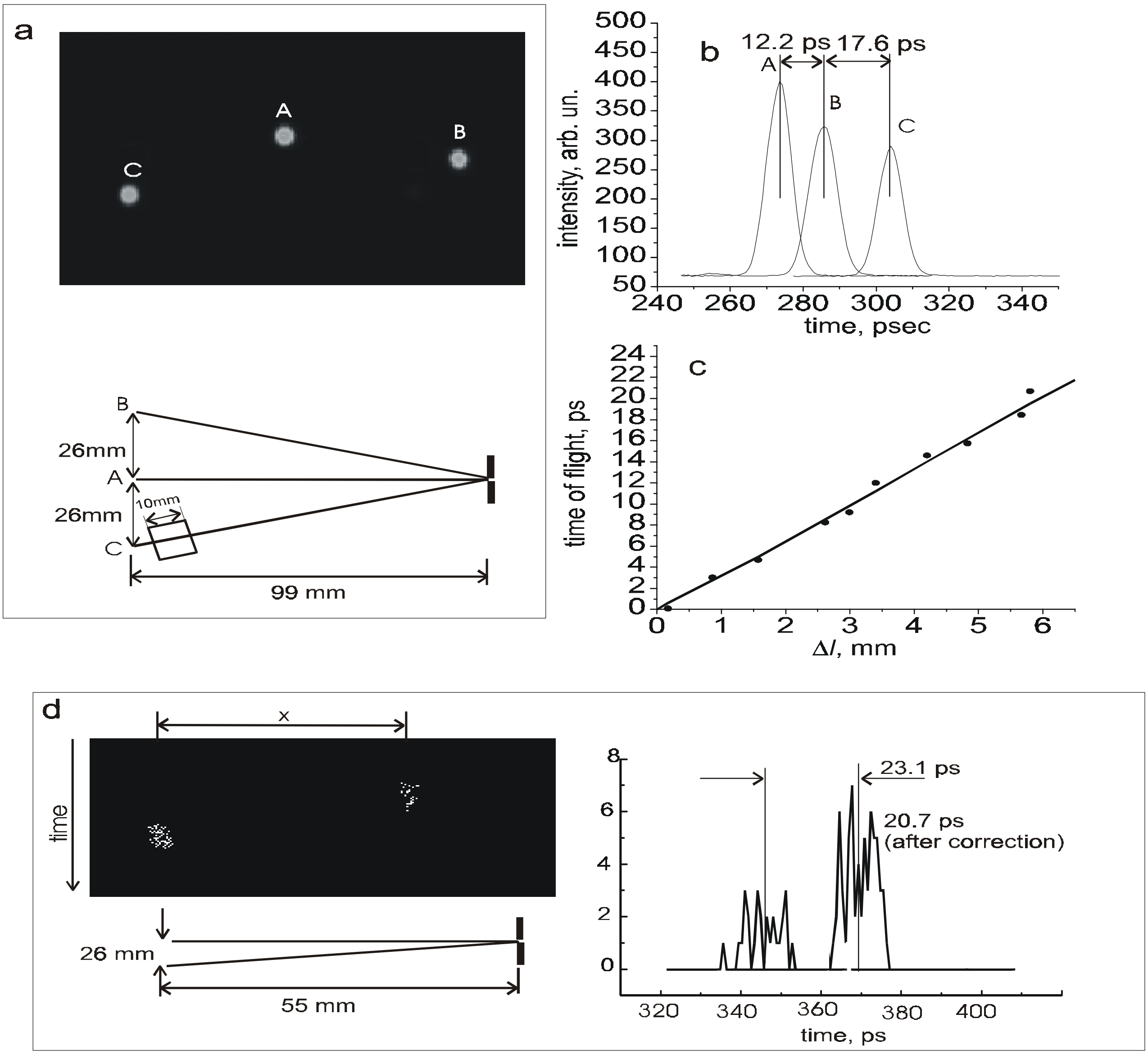

Figure3 *Results of the time of flight experiments.*

Streak images of three fibres. The experimental scheme is presented in the lower part of figure.
a) The diffraction pattern illuminates the input ends of the fibres. The central spot (A) corresponds to the position of the zero-order maximum and the right-hand spot (B) corresponds to the diffraction maximum separated by 26 mm from the zero-order maximum.
The left-hand spot (C) corresponds to the same separation from zero-order maximum as (B) but a glass plate (thickness is 1cm , n=1.54) is inserted in the optical path.

b)Profiles of the spots demonstrating the time delay between them.
c)Time of flight of photons vs distance. Dots represent experimental data and lines are calculated assuming velocity of photons equal to velocity of light.
d)The same as in (a) but the images are taken in single counting mode so that the time of flight of single photons can be measured. In these experiments the arrival time should be related to the centre of gravity of the spots indicated by bars.

The distances between these positions could be changed within 30 mm. The collected light was then directed into the streak camera. Constant temporal shifts due to the slightly different lengths of the fibres (within the accuracy of their preparation) were measured by illuminating the fibres with a telescope. These shifts were then compensated for by subtracting them from the times measured by the streak camera.

Fig. 3 a) shows the streak images corresponding to the zero-order diffraction maximum (spot A on the figure) and to maxima separated by 26 mm from zero-order maximum (spots B and C). The time delays between these spots are presented in the Fig. 3b). The time difference between spots B and C arises from additional delay in the 1cm glass plate (refraction index n=1.54) inserted in the optical path to point C (see the lower part of the Fig.3a)). The glass chosen had a non-dispersive dielectric response so that the phase and group velocity are both given by c/n. All the measurements of time of flight *vs*. difference in optical path (distance) are summarised in Fig.3c. The experiments can also be done in the single counting mode, where the time of flight for single photons is measured, by using a small number of photons in the pulse by filtering or reducing the pulse intensity. In Fig.3d we show data in single photon counting mode for d=5.5cm and x=2.6 cm. The correct centre of gravity of the groups of streaked photons is at 20.7ps while the calculated one is at 19.4ps, again in excellent agreement with the straight –line trajectories from the slit to the detector.

All these experiments showed within the 2 ps accuracy of our streak camera resolution that the time delays measured correspond to straight line "bullet" (impact of a wave packet) trajectories from the slit to the detectors. These experiments permit us to check the refractive index of glass and the speed of light. More usefully, if we assume c to be 3.10^{10}cm/s we can calibrate our streak camera very precisely. The straight line (Fig. 3c) is the fitting of different spots of our experiments using the above speed of light. We find it difficult to explain these experiments, if we cannot know the photon trajectory and if before wave collapse on the detector the diffraction picture is one wave. We believe that this is a manifestation of the particle character of the photons during their flight from source to detector describing straight lines.

Our high -speed time resolved experiments lead to a new question: when does collapse of the wave function occur? We do not know because we see nothing related to a collapse, but any time required must be smaller than our 2ps time resolution. By constructing a faster detector, this measured time will go down and down but it is simply a mystery for us. The wavefront is not plane and contacts the detector (screen) at different times but, if the collapse is to take place across the whole detector area in less than 2ps, velocities in excess of 4c are implied.

3. Interference experiments

The description of particle interference phenomena in QM is based on the probability of the particle being in one of several different indistinguishable alternatives inside the experiment. Dirac (1958) said: "*Each photon then interferes only with itself. Interference between two different photons never occurs*." Experiments were done with two different lasers used as sources of light (Dirac 1958; Magyar and Mandel 1963; Mandel and Wolf 1965; Endo and Toyoshima 1992). These experiments have been explained quantum mechanically (Mandel and Wolf 1965; Endo and Toyoshima 1992) on the grounds that photons were indistinguishable. Other works have been devoted to two-photon interferometry in which pairs of photons are generated by spontaneous parametric down-conversion in a nonlinear crystal (Hong 1987; Kwiat 1992; Strekalov 1995; Putman 1996). These pairs of photons are not independent (they are in an "entangled" state) and the concept of a bi-photon is helpful (Kwiat1992). Once more the bi-photon (two-photon entity) interferes with itself (Strekalov 1995). Here however we present Young's double slit experiments that show interference between different photons of different energies as measured by the output of a spectrometer *and knowing which photon colour goes to each slit*. Fringe patterns are taken in both space and time using the fast streak camera. "beats" in the interference pattern are observed for different energy photons by having high enough temporal resolution.

In the experiment we prepare two sources of light with different frequencies using a femtosecond pulsed laser. Such a short pulse has a spectrum of frequencies depending on its duration $\Delta\tau$ in accordance with relation:

$$\Delta\nu\Delta\tau \approx 1 \qquad (1)$$

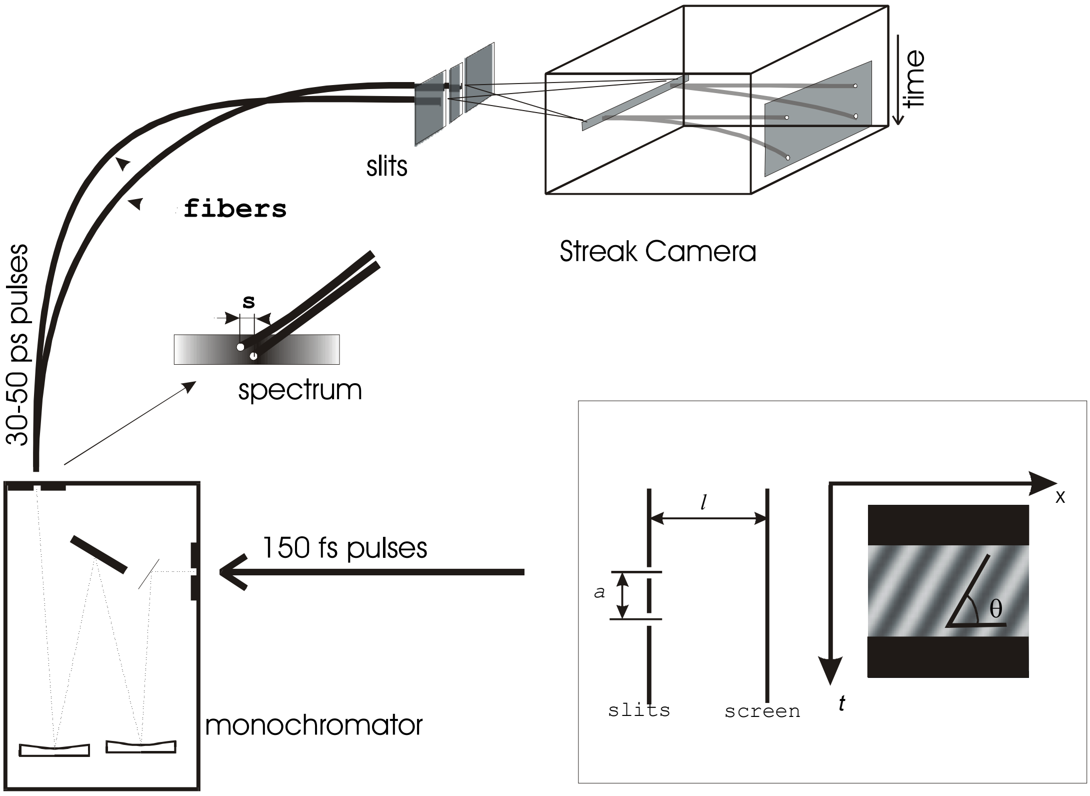

Figure 4 *Arrangement for the interference experiments.*

Inset: Schematic description of the experiment with a estimated picture of the interference fringes, obtained by adding together two plane waves with slightly different frequency, $\Delta\nu = K_m{*}s$ *as determined by the fibre position near the output of the monochromator. The widths of the pulses coming out of the spectrometer into the fibres are of 20-50ps.*

where Δν is the halfwidth of the spectrum. Therefore with a spectrometer different spectral regions with different frequencies of light can be chosen. Then, the idea is to select different photon frequencies and measure, as in the previous diffraction experiments, the time-resolved interference pattern with the streak camera. That is to say we can spread the 150ps pulse and select within the pulse, as described below, 20-50ps pulses.

The experimental arrangement is shown in Fig. 4. 150 fs pulses from a Ti:sapphire (Tsunami) laser with a central wavelength of 800 nm were directed to a spectrometer and at the output the optical spectrum of laser pulses was obtained. Two optical fibres (of the same length) with core diameter 100 μm were placed close to each other vertically at the spectrometer output slit which was completely open. By varying the horizontal distance *s* between the two fibres we can adjust the difference in energy of the two components of the pulse of the photons chosen from the spectrum. The cromex monochromator used yielded an output with linear dispersion over a large aberration-free area 10x22 mm. In our experiment s<0.2 mm, therefore we can assume that the difference in light frequency $\Delta\nu$ is a linear function of the fibre separation $\Delta\nu=K_m*s$ (K_m=8 10^8 $s^{-1}\mu m^{-1}$). The different frequency pulses so selected have a duration of 20-50ps determined by the diameters of the fibres.

The output end of each fibre illuminated one of the slits. A slit width of 125 μm and slit separation of 1 mm was used. The interference pattern obtained at the entrance slit of streak camera could then be analysed dynamically when the image of the entrance slit was swept in time. The temporal resolution was determined mainly by the width of the entrance slit and was varied from 4 to 15 ps. The same results have been obtained when slits were discarded and interference of the two beams emerging from the fibres occurred. That is to say instead of sending the light to the slits we just produce the interferences by substituting the slits by the opening of the fibres. This point is important in the discussion of the experiments, because the classical wave theory cannot explain them completely. Arguing in terms of decoherence by the surrounding medium maybe problematic because the decoherence we observe is the same whether we have slits or not.

The frames in Fig. 5 show streak images of interference patterns corresponding to different positions of one of the fibres located at s. The other fibre is always located at s = 0. The value of s corresponding to each of the frames is indicated. One can see interference fringes, with an inclination in space-time coordinates representing the interference "beats" between two waves with different frequencies. These waves are distinguishable and travel in two different fibres placed at two different slits, so that a well-known frequency goes to a well-known slit. The argument given in books (eg Feynman 1985; Tonomura 1998) that interference occurs because it is not known by which slit the photon goes is not applicable here. The slope of the fringes increases with increasing *s; i.e* with increasing the frequency difference between the photons in the fibres.

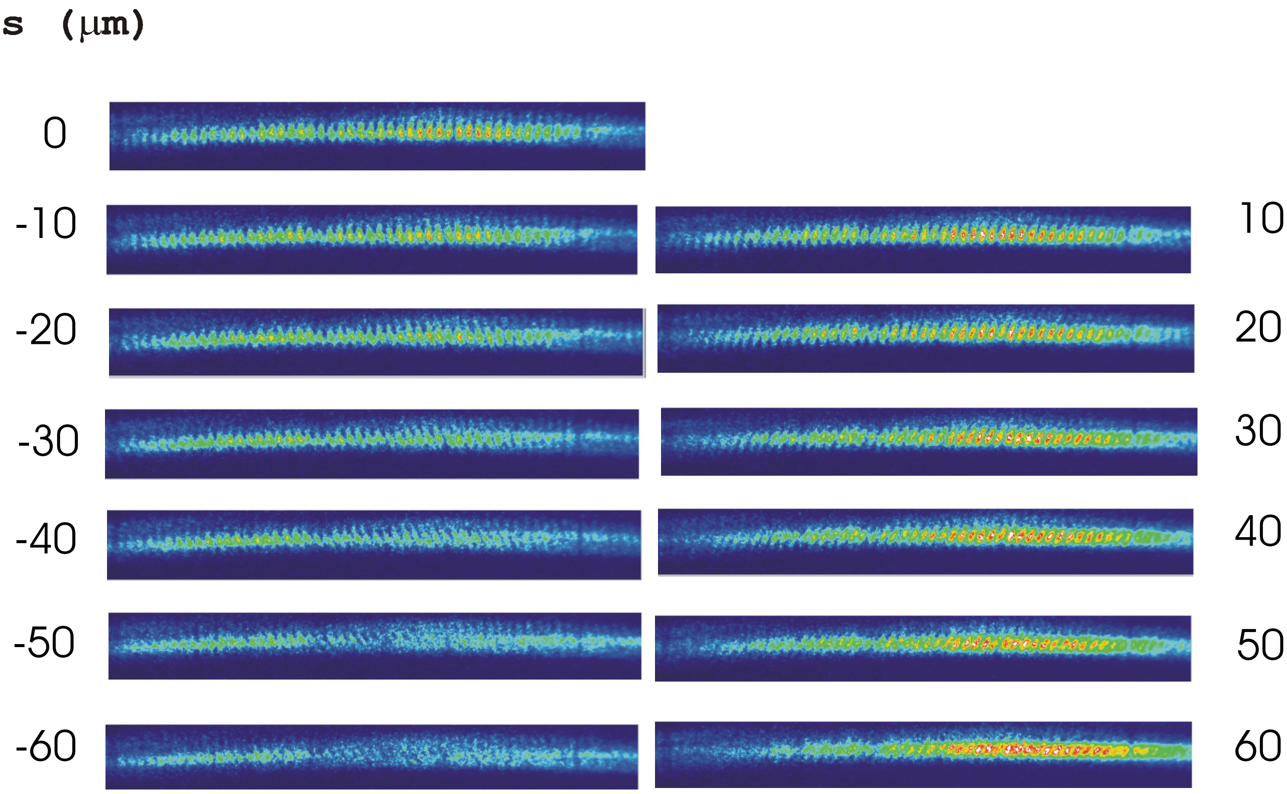

Figure 5 *Different frames showing streak images of interference patterns. Numbers near the frames correspond to differences s (in μm) between the position of the fibres near the output slit of monochromator. Interference fringes with an inclination in space-time coordinates are visible when s≠0. This inclination represents interference "beats" between two waves with different frequencies, which are distinguishable, and travelling in two different fibres. Each fibre carries photons of different colour. However at the screen we do not know which photon is which because the path between the fibres or the slits to the screen (streak camera) is not known.*

To explain these results one can use the classical interpretation of the interference of linear waves. Let's make a classical addition of two waves with slightly different frequencies ν and $\nu+\Delta\nu$, where $\Delta\nu<<\nu$. If we assume that the intensities of the waves are the same I_0 and that the slit separation a is much smaller than distance l from the slits to the streak camera as in our experiments (see inset in Fig.4) then we obtain the intensity distribution $I(x,t)$ on the screen (*i.e.* the entrance slit of the streak camera in our case):

$$I(x,t) = 2I_0\left[1+\cos\left(2\pi\Delta\nu t + \frac{2\pi a\nu}{cl}x\right)\right] \qquad (2)$$

where x is a coordinate along entrance slit and t is time. The calculated light distribution on the x-t plane is presented in the inset to Fig.4. Interference fringes correspond to lines with constant phase and their inclination can be derived from (2):

$$\frac{\Delta x}{\Delta t} = \frac{cl\Delta\nu}{a\nu} \qquad (3)$$

To allow for the finite time resolution of the streak camera we have to average Eq. (2)

$$I(x,t) = \frac{1}{\tau_{res}} \int_{t}^{t+\tau_{res}} I(x,t')dt' = 2I_0\left[1 + A_r \cos\left(2\pi\Delta\nu t + \frac{2\pi a\nu}{cl}x\right)\right] \qquad (4)$$

Here A_r is a visibility parameter for interference fringes depending on $\Delta\nu$ and on the resolution time τ_{res} and given by the expression

$$A_r = \left|\frac{\sin(\pi \cdot \Delta\nu \cdot \tau_{res})}{\pi \cdot \Delta\nu \cdot \tau_{res}}\right| \qquad (5)$$

For $\Delta\nu*\tau_{res}$ <<1 the visibility is 1 and but quickly decreases with increasing frequency difference. There should also be an integration over the frequency distribution of the 20-50ps pulses in the fibres. We have done this operation but for simplicity the expression is not quoted since the resulting corrections are smaller than 1%.

The classical wave interpretation can qualitatively describe the phenomena observed but a closer study (see below) shows difficulties in the understanding the results. These experiments clearly show that different photons (with different energies) produce interference fringes and the patterns depend strongly on the magnitude of the energy differences between the photons. We believe that each slit is illuminated by definitely different photons and there is no alternative for the photons to be either in one way or another. Although is also true that we do not know which photon is which after the slits, **we do know them before the slits!** In this case we cannot apply the QM explanation (Mandel 1965; Hanbury-Brown 1956) similar to the one given for the Hanbury-Brown and Twiss experiments by Purcell (1956) in which interference between different

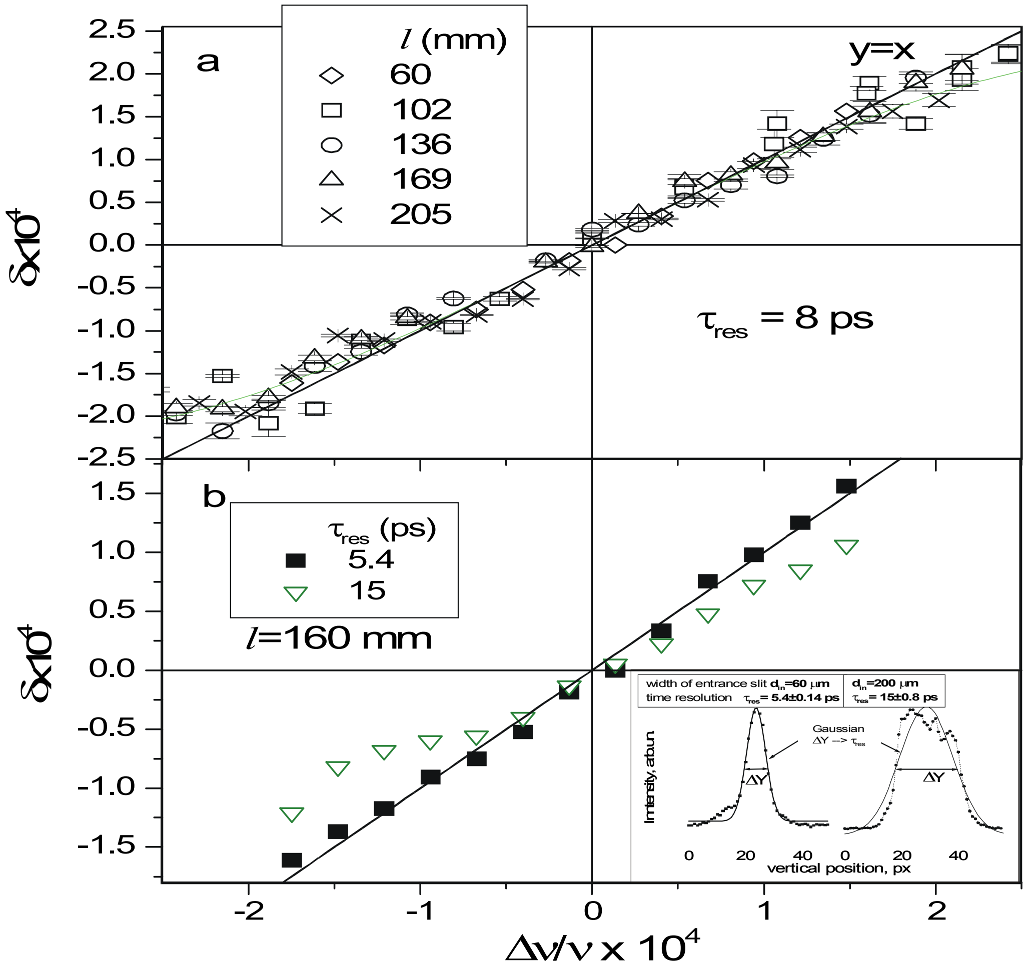

Figure 6 *Dependence of the normalized slope of the interference fringes on the relative difference of frequency of light in the fibres. Points are experimental data, lines are calculated using classical theory for addition of two waves Eq.(3).*

a) Experimental data have been obtained for different distances between sources of light and streak camera.

b) Experimental data have been obtained for different values of the streak camera time reolution τ_{res}. *Notice the deviation from the classical theory line for* τ_{res}*=15 ps.*

The inset shows the spot width in the focus mode of the pulses and how the time resolution is obtained by fitting the experimental curves.

photons can occur due to the fact that it cannot be told which source has emitted individual photons. On the other hand photons are not in an "entangled state" as occurs in interference experiments with photons created by down-conversion in a nonlinear crystal (Puttman 1996; Hanbury-Brown 1956; Purcell 1956; Cramer 1986). In our experiment we can provide "which-path" information (at least we know that different energy photons, as measured from the spectrometer, are impinging each one of the slits (Fig.1)) using both space and time-resolved measurements. In our interference experiments the time resolution brings up new points that should be discussed.

Lets us now make a closer quantitative comparison of the experimental results with the classical wave theory Eq.(2-5). We will study the dimensionless experimental slope of interference fringes $\delta \equiv \frac{\Delta x}{\Delta t}\frac{a}{l}\frac{1}{c}$ as a function of the normalized frequency difference $\frac{\Delta\nu}{\nu} \equiv K_m \frac{s}{\nu}$. From theoretical equations Eq.(2-5) it is clear that parameter δ should be equal to Δν/ν under all any experimental conditions. These experimental dependencies are presented in Fig.6 for $\frac{\Delta\nu}{\nu}$ running from –2.5 10^{-4} to 2.5 10^{-4}. The different types of points in Fig.6a correspond to different distances l between the slits or output ends of fibres and the screen (entrance slit of streak camera). Then over a wide range of $\frac{\Delta\nu}{\nu}$ all experimental data fall on a straight line with slope equal to 1 in agreement with theory. Small deviations from the line can be observed only for $\left|\frac{\Delta\nu}{\nu}\right| \geq 1.7\cdot10^{-4}$. All the data in Fig.6a data were obtained at the same resolution of the streak camera τ_{res}=8 ps. The

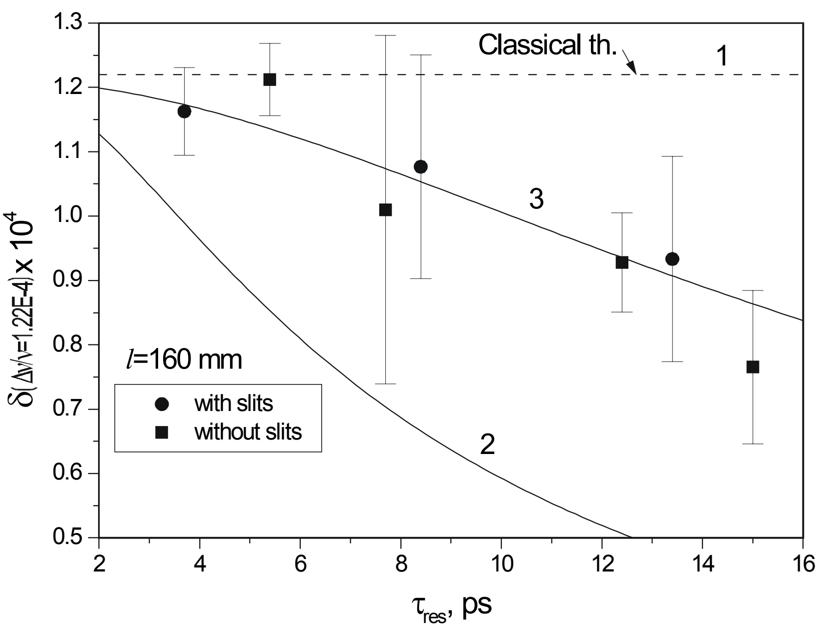

Figure 7 *Normalized slope of interference fringes at fixed Δν/ν=1.2 10^{-4} vs. resolution time τ_{res} of the streak camera. Points are experimental data: cycles - experiments with slits, squares – experiments without slits giving direct interference of the light beams from fibres. Curve 1 is calculated using classical theory Eq.(3); curve 2 is calculated using nondissipativve decoherence theory Eq.(9) accepting $\tau=\tau_{res}$; curve 3 is a best fit of experimental data using Eq.(9) with $\tau=0.35\tau_{res}$.*

resolution time is experimentally determined as the width of the light spot at the streak image in focus mode of the camera (see inset in Fig. 6b). This can be varied by changing the entrance slit width of the streak camera. Experimental dependencies $\delta = f\left(\frac{\Delta\nu}{\nu}\right)$ obtained at two different values of the streak camera resolution are shown in Fig.6b. The data obtained at τ_{res}=5.4 ps (filled points) are well described by theoretical line for the complete experimental range. Quite a different pictures is observed when τ_{res}=15 ps (triangles). Noticeable deviations from the theoretical line are observed at $\left|\frac{\Delta\nu}{\nu}\right| \geq 5\cdot10^{-5}$. In Fig.7 we display experimental values of the dimensionless slope of the fringes at the constant frequency difference δ ($\left|\frac{\Delta\nu}{\nu}\right| = 1.2\cdot10^{-4}$), which were measured for different values of the resolution time. One can see that the deviations from the classical horizontal line (the dotted line in Fig.7) monotonically increase with increasing of τ_{res}.

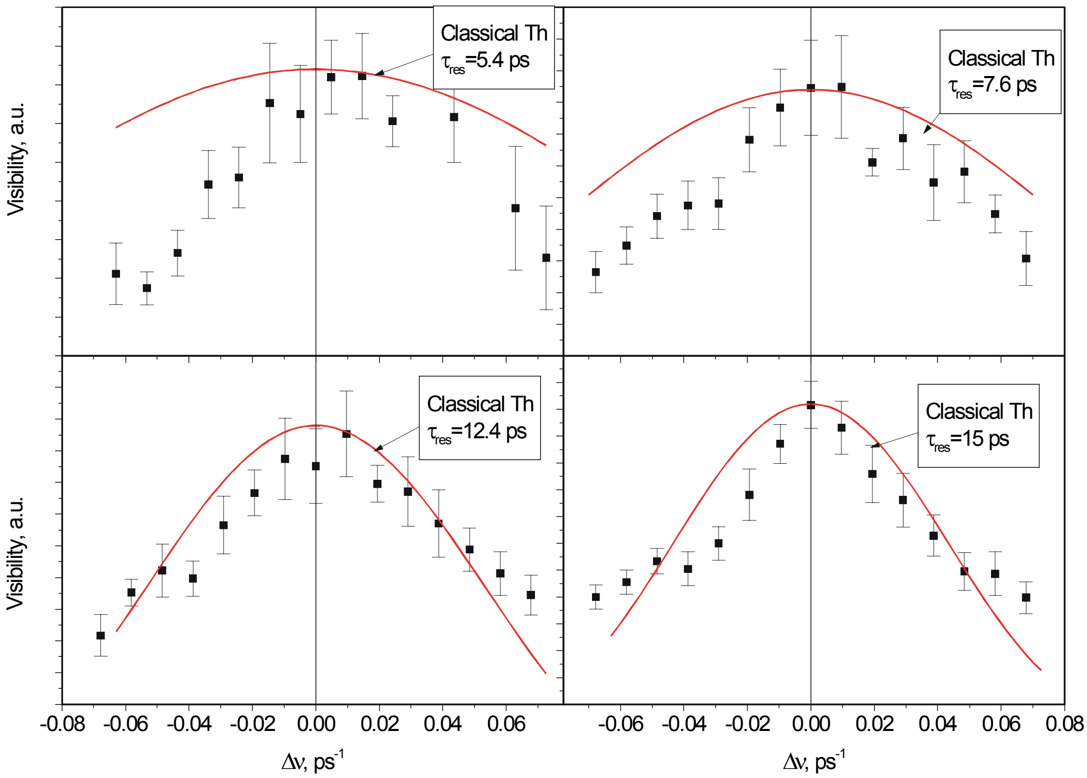

Figure 8 *Visibility of interference fringes vs. frequency differences of light beams. Experimental data (points), and calculated curves correspond to different time resolution values* τ_{res} *of the streak camera.*

We can also analyse the fringe visibility from the profile of the interference pictures presented in Fig.5, which yield the average amplitude of the intensity fluctuations corresponding to interference fringes. The amplitude is normalized to 1 at $\Delta\nu=0$ and with this normalization factor we multiply the experimental amplitudes to obtain the normalized visibilities at different frequencies. These are presented in Fig.8 for different resolution times. Dotted lines on the figures are calculated using the classical equation (5). The classical theory describes well the experimental dependence at low resolution *i.e.* high values of τ_{res} (see the two lower panels fig.8c and 8d). At high resolution we see deviations of the visibility of the interference fringes at large $\Delta\nu$. It should be said that in order not to complicate the expression for δ we have neglected path difference terms quadratic in x. These introduce corrections of 10^{-4} in *1* and cannot therefore account for the observed deviations.

At this point it could be argued that the deviations obtained between the data and the classical wave theory may be due to miscalibration of the equipment. In this sense we have to say: i) one possible source of error is the linearity between s and the $\Delta\nu$. This can be discarded because it has been measured from the spectrometer; ii) another source of error may be the setting of the streak camera, however this has been calibrated with the speed of light for the propagation of photons in vacuum and in a crystal of known refraction index; iii) also the deviation in the slopes (Fig.6, 7 and 9) occurred for large values of τ_{res}>8ps (low resolutions) where the precision of the streak camera should be better, its resolution limit being 2ps. In contrast, the deviations in the visibilities happens at low values of τ_{res} <8ps (high resolution). These considerations prove that is not likely that the equipment is the responsible for the deviation from classical wave physics.

We cannot definitely identify the source of the deviations from classical wave superposition: nor can we build a theory to explain the data. As a possible explanation of the unexpected influence of the resolution time on the interference patterns, we may take into account the predictions of non-dissipative decoherence theory (Bonifacio 1999; Bonifacio et al. 2000). This theory implies that time is quantized with quantum τ and yields a probability function for t, at the cost of dropping the unitarity property in the time evolution operator. One of the interesting things that comes out of this theory (for more details see Bonifacio *et al* 2000) is that the interference fringe slopes depend on the time uncertainty parameter τ, according to

$$\frac{\Delta x}{\Delta t} = \frac{cl}{a}\frac{\arctan(2\pi \cdot \Delta\nu \cdot \tau)}{2\pi \cdot \Delta\nu \cdot \tau} \qquad (6)$$

When $(2\pi \cdot \Delta\nu \cdot \tau) << 1$ Eq.(6) transforms into the classical Eq.(3).

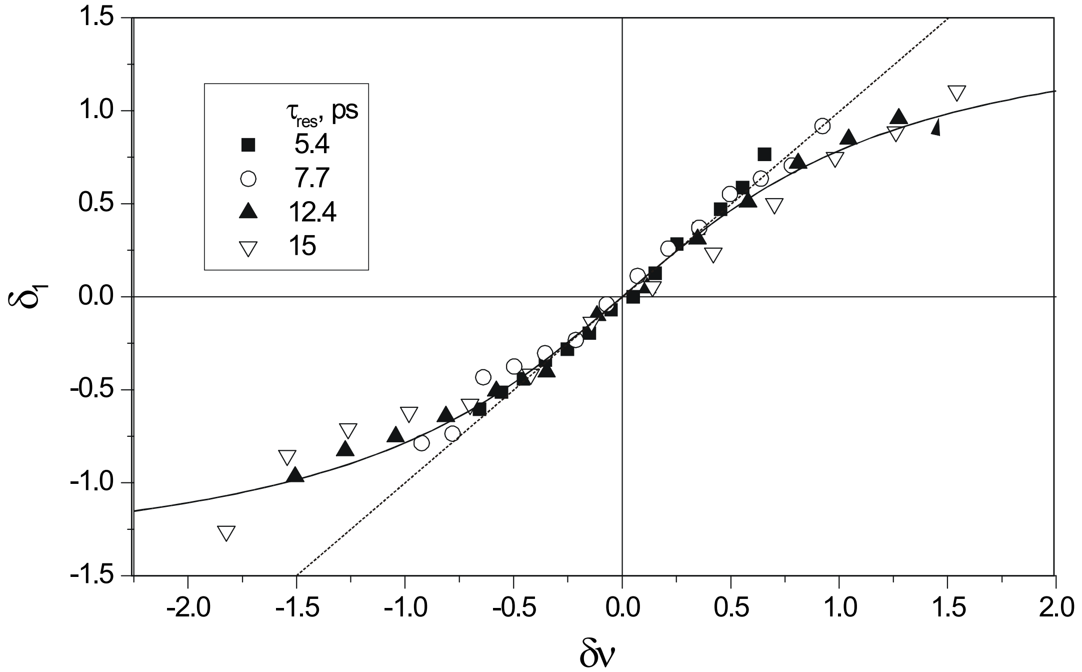

Figure 9 *Complete experimental dependence of interference fringe slopes on frequency variation presented in coordinates* $\delta_1 \equiv \frac{\Delta x}{\Delta t}\frac{a}{l}\frac{1}{c} \cdot 2\pi\nu\tau$ *vs.* $\delta\nu \equiv 2\pi \cdot \Delta\nu \cdot \tau$ *. The curve is calculated using Eq.(10) . The straight line is the classical theory with no decoherence.*

Let us suppose that uncertainty parameter τ of this theory corresponds to a resolution time of streak camera. It is easy to see that if $\tau \sim \tau_{res}$ Eq.(6) can qualitatively follow the classical wave prediction (see Fig.6, 7 and 9). Line 2 in Fig.7 is calculated using eqn. (6) supposing that $\tau = \tau_{res}$. To get quantitative agreement with the experimental data we have to assume $\tau = 0.35\tau_{res}$ (see line 3 in Fig.7). We now normalize all experimental data in accordance with Eq.(6): $\delta_1 \equiv \frac{\Delta x}{\Delta t}\frac{a}{l}\frac{1}{c}\cdot 2\pi\nu\tau$ and $\delta\nu \equiv 2\pi\cdot\Delta\nu\cdot\tau$. As a result eqn. (6) can be rewritten as a simple equation without any parameters:

$$\delta_1 = \arctan(\delta\nu) \qquad (7)$$

All the experimental dependence of the fringe slope on frequency variation are presented in Fig. 9 using these new coordinates: δ_1 vs. $\delta\nu$ with $\tau=0.35\tau_{res}$. The line calculated according to eqn. (7) well describes all the experimental data independently of the resolution time and any other parameters of the experiment. It is really surprising that the theory of Bonifacio *et al* (2000) can describe all the data independently of the resolution time and $\Delta\nu$ simply by adjusting the parameter $\tau=0.35\tau_{res}$. In consequence, if this theory is applicable to photons, it could be a basis for understanding the data. However regarding the fringe visibility we cannot make a comparison with the same theory because it seems to depend on the time t.

To explore further the dependence of the interference on other parameters, we have performed pulse interference experiments where the time resolution and the optical paths (distance from the slits to the detector) have been combined. Fig. 10 is an illustration of these experiments. The pulses used came from the monochromator with a duration of 20 – 50 ps . Two fibres with an end output length difference Δl were used for the interference experiments. This Δl could be varied as indicated at the left-hand side of each interference pattern. The right-hand side gives the corresponding Δt. It can be seen that for 0 to 5ps time difference we have interference but with a larger inclination of the fringes for the larger time differences. At larger values of the time/length difference the fringes start to disappear. At 8ps (2.5 mm) difference there are no fringes. The main reason for that is, that in order to have interference, we need to have good resolution and overlap of the pulses at the detector photocathode of the streak camera. The increasing inclination of the interference fringes as the overlap is reduced indicates that the overlapping components in the two pulses are increasingly different in frequency. Eventually the corresponding movement of the fringes may be too fast for the steak camera to resolve. For example when Δt=8ps there is still overlap in space but for frequencies that are too different for the operating resolution time of about 8ps.

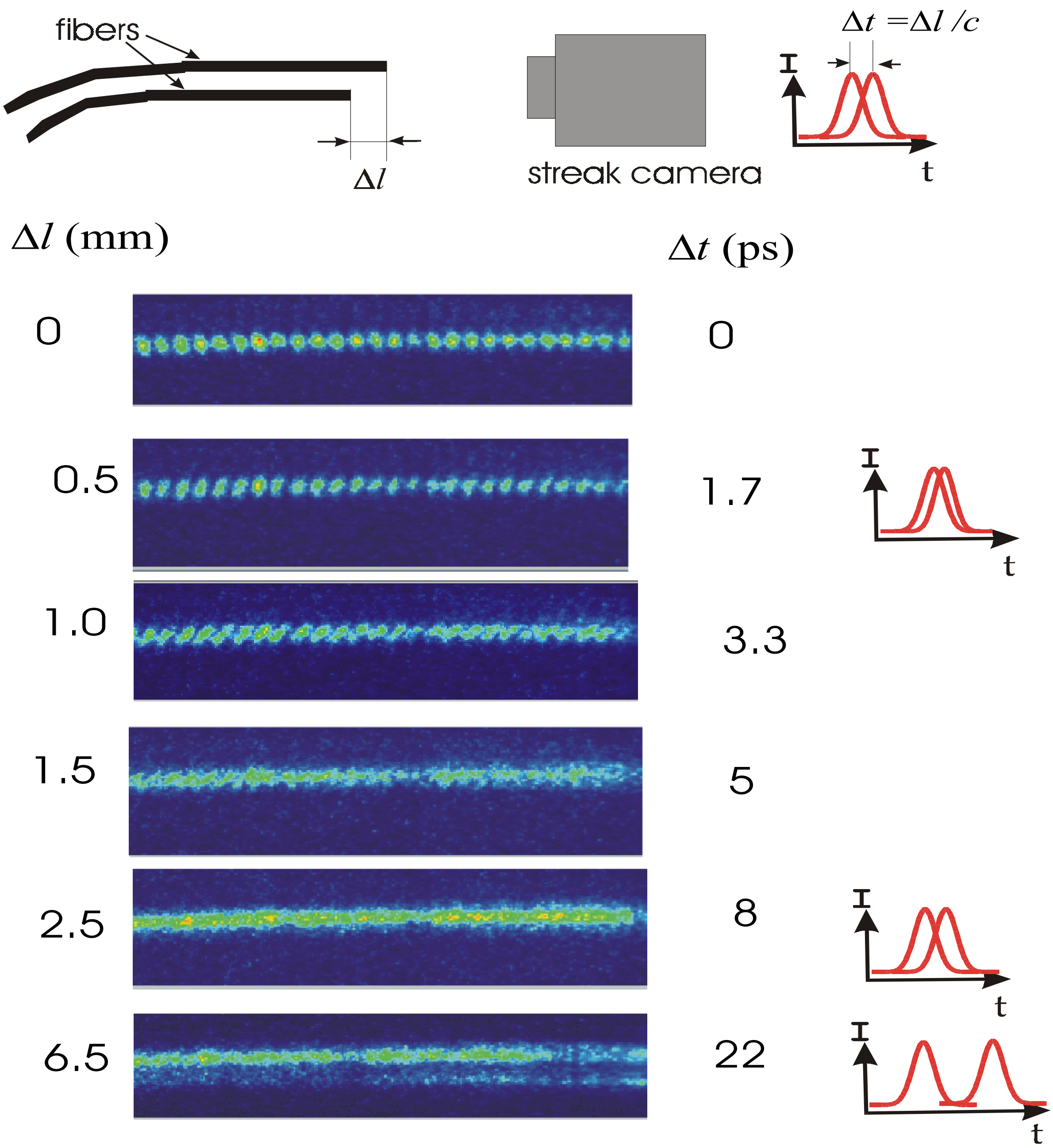

Figure 10 *Results of varying the distance between one of the fibres and the streak camera. The upper part of the figure presents the experimental arrangement. The frames are streak camera images corresponding to the same position of fibre ends near the spectrum (s=0 and Δν=0) but to different distance between ends of the fibre and streak camera. Beside the frames we give (at left) the values of fibre shift Δl in mm and (at right) the corresponding time difference between centre of light pulses Δt in ps. The inclination of the interference fringes at small time separation of pulses 0<Δt<5ps can be seen. We can compensate this inclination by shifting one of the fibres near the spectrum creating frequency difference between pulses Δν. Note that at Δt=8 ps there is some overlapping of the pulses but interference has vanished*

This is a very important point: with no overlap of the pulses no interference can be observed no matter how good resolution we have, be the photons of the same energy or different. The fact that the overlap is needed may indicate that indistinguishability of the photons is necessary at the detector but certainly not at the slits. In appendix A we present a thought experiment that may get rid of the indistinguishability of the photons and still give interference.

Summarizing, time resolved interference patterns of photons with different energies arriving from different paths are observed. Noticeable deviations of the experimental results from the classical predictions are found. A non-classical de-phasing factor occurs and increases with increasing time uncertainty *i.e.* with decreasing of the time resolution of the detector. The visibility of the interference fringes is not well described by classical theory, the deviation being most noticeable at high time resolution. Theory of the non-dissipative de-coherence may be applicable and can qualitatively describe part of these observed features. Also, as Fig.10 indicates, the key requirement for interference is to have overlap of the pulses impinging the photo-cathode of the streak camera. Also to have interference with photons of different energy we need adequate time resolution to freeze the fringes.

4. Discussion and Conclusions

Time resolved diffraction and interference experiments have been performed. From the data and its analysis we can draw the following tentative conclusions:

1. The diffraction patterns obtained by adding many few photon events show that the wave character of the diffraction pattern begins to be observable after approximately 300 events (photons) have been counted. Each photon is manifest as an impact (bullet) at the photo-cathode of the streak camera.

2. The pulses arrival times match those of bullets propagating along straight line trajectories from the slits to the appropriate point on the screen at velocity c. Across the area of the detector there is no sign of wavefront collapse during the resolution time of 2ps. This implies a wavefront collapse velocity exceeding 4c.

3. Interference beats with photons of different energies, generated by the laser pulsed photons, can be observed only if the resolution in time is good enough to freeze the beats. At lower resolution the interference disappears.

4. The interferences appear even with knowledge of what photon goes to each slit (see Fig.A in the Appendix). The spectrometer measurements show that red photons go through slit A and blue through B, thus identifying what photons are in each slit. The fact that we identify the photons entering the slits may raise difficulties for the discussion in the book of Feynman (1985) and Tonomura (1998). Although we cannot identify the photons in the path from the slits to the streak camera an experiment is devised in the Appendix which may be able to do this.

5. The interference patterns seem to be in agreement with classical superposition of waves. However closer study and analysis of the experiments (Fig.6 to 9) show that there are significant deviations from the classical theory. These deviations, as discussed, do not seem to be due to the functioning of the equipment. Decoherence could provide a possible explanation but not, we believe, decoherence due to the surroundings because under very different experimental conditions of the phase shift responsible for the slope of the interference fringes always follows the same curve (eqn. (7) and Fig.9).

6. We have tried to understand the experiments applying a theory by Bonifacio et al (2000) of non-dissipative decoherence. By adjusting a single parameter, this theory well describes the phase shift (eqn.(7) and Fig.9); however there are difficulties with the visibility of the interference fringes.

7. A *sine qua non* condition for interference, checked here in several ways, is that the pulse of the red and blue photons overlap at the photo-cathode. For example no interference occurs, at any resolution, for fibres with optical path lengths sufficiently different to ensure that the red and blue photons arrive at very different times, with no overlap, at the photocathode. Therefore photon by

photon, say first red, then blue, blue, blue, red and so on, without overlap, will not show interferences (see Fig.10).

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Appendix

Here we propose a thought experiment.

In Fig.A (a and b) is sketched the experimental arrangement showing the photocathode and the streak camera with the sweep potential working. We have hν and h(ν+Δν) red and blue photons. In our current arrangement electrons are emitted indiscriminately at the photocathode by blue and red photons and there is no method to distinguish them. Now we know that when the two pulses overlap there are interference fringes. This overlap is very important and Fig. 10 shows an experiment confirming the overlap for having interference. We cannot know which path the photons took between the slits and the phothocathode because it fails to distinguish between and blue and red.

Since for interference we need overlap and an adequate time resolution for a given Δν we could imagine building a phothocathode consisting of two plates (Fig.Ac) separated by a distance much smaller than the wavelength λ of the photons but now one plate is sensitive to blue and the other to red. Because the distance between plates is much smaller than λ the overlap will take place as in the case of Fig.Ab with just one plate. Now however, as indicated by the circles and the squares, one plate will sign blue and the other red - perhaps by the spins of the electrons emitted. Thus we may know from which slit are coming blue and red and we will have identified the complete photon paths . It should be noticed that one of the cathodes should be transparent (invisible) to

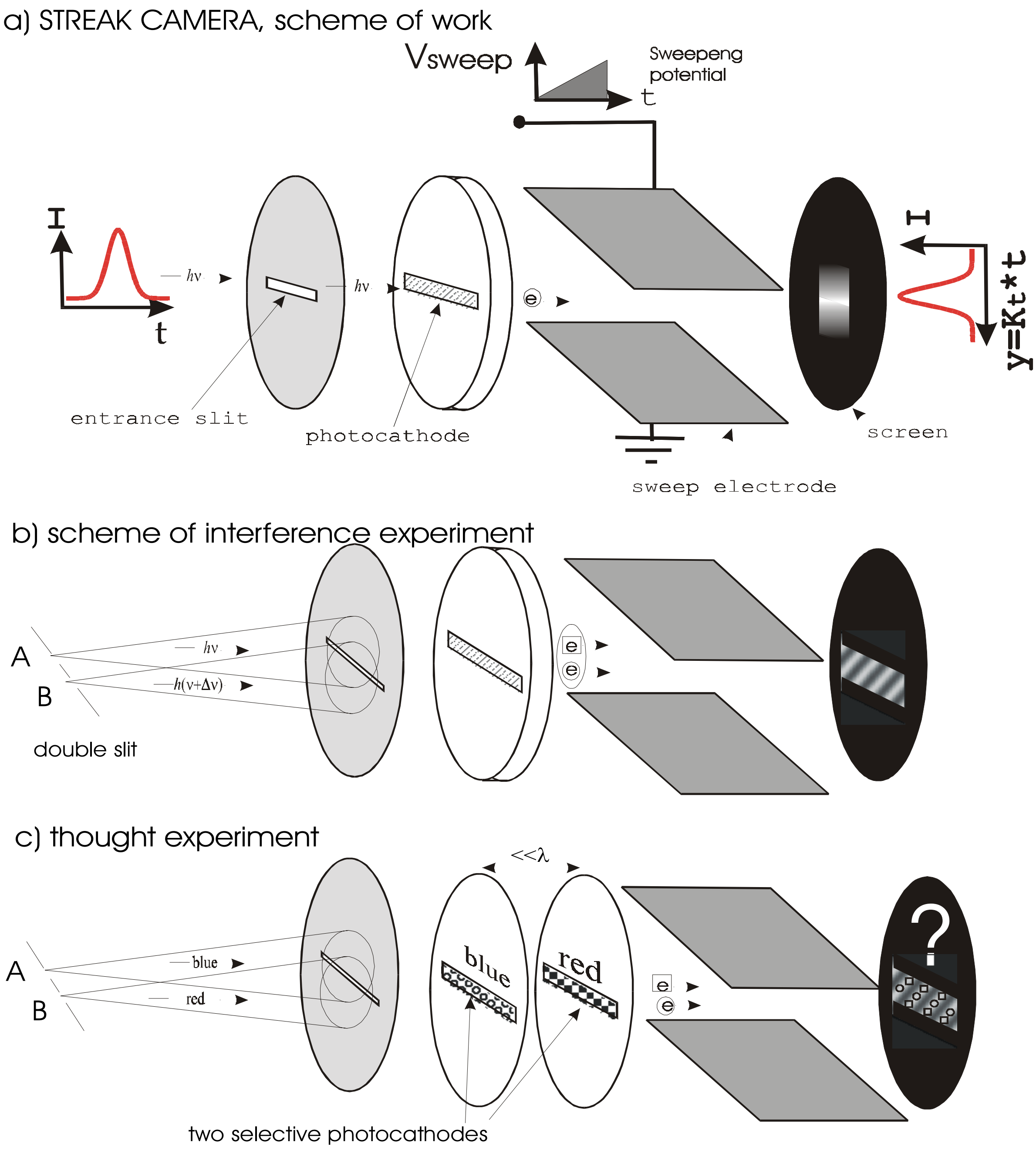

Figure A *a) Sketch of the streak camera arrangement; b) arrangement for the interference experiments shown in this work. The cathode cannot distinguish the colour being insensitive to small frequency differences. In this case we see fringes. c) The new photocathode design for a thought experiment. We have two photocathode plates separated by a distance much smaller than λ in such a way that the pulses overlap but now one plate signs blue and the other red.*

the blue photons and the other to the red ones. Also the second cathode has to be transparent to the electrons emitted by the first one. **The question is would interference fringes appear?** The opinion of one the authors (NG) is why not?. The other author (IGS) opinion is: never.

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