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What are the physical processes behind the evolution of spatial coherence out of incoherent light and particle beams?

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Abstract: This paper raises the fundamental questions to explore the possible physical models behind the evolution of spatial coherence during the propagation of an incoherent EM wave beam or a particle beam.

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1. van Cittert-Zernike theorem for an extended incoherent optical beam

We express the Superposition Principle (SP) as a simple (linear) summation of more than one complex amplitudes representing the harmonic oscillations of EM or matter waves. This is true for both the classical and quantum physics. In classical optics, we use the expression $a\exp[-i2\pi\nu t]$ to represent a generic complex amplitude, where a is the amplitude and ν is frequency of oscillation of the electric vector, determined by the emitting source. For EM waves, the core mathematical formulation for the evolution of spatial coherence is the Huygens Postulate of non-interacting secondary wavelets out of every point on every wavefront [1, 2]. Huygens book). This key concept has been mathematically co-opted by Fresnel, which has been further developed in several forms to incorporate the key mathematical self-consistency [3]. Since minuscule atoms or molecules emit optical radiations, they represent ideal point sources. The radiation then propagates out as diffractively divergent wave fronts. However, every point on the wavefront has the same phase (Fig.1). They are now spatially extent coherent wave fronts. Each point source now covers a broad spatial area with the same phase value. This is clearly the physical origin of enhanced spatial coherence through propagation in the forward field. The X-plane now displays partial coherence through double-slit visibility measurement [4], even though the double-slit is placed in the far field of an extended incoherent source. This partial coherence can be expressed as (the curve "a" in Fig.1):

$$\gamma_{12} = 2J_1(u)/u \qquad (1)$$

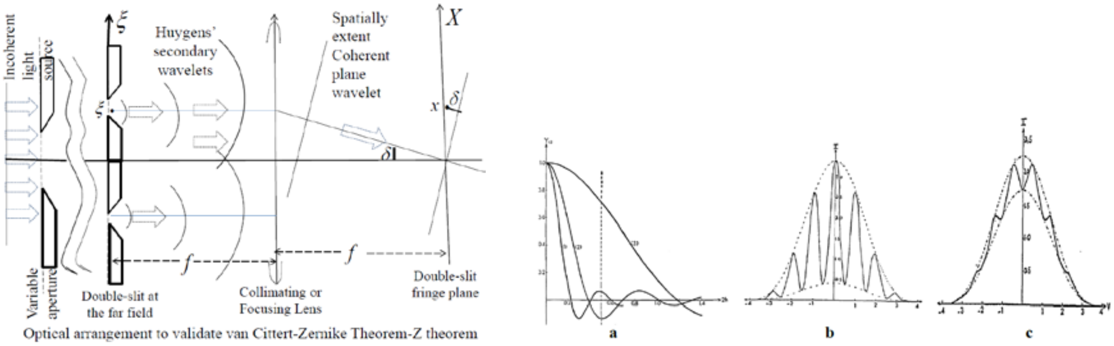

Figure 1. Experimental setup to quantify the evolution of far field degree of coherence out of an extended thermal optical source. The plot of the complex degree of coherence, as in (a), fior three different sizes of the incoherent source. The double-slit fringes show a central bright fringe, as in (b), for narrow source such (the curve "1" in "a""; note the dotted vertical line). But, the central fringe is dark and the visibility is poorer, as in (c), for a narrower source (curve "2" in "a"). The slit spacing now falls in the negative lobe as in (a); note the vertical line. This is the physical meaning of the negative degree of partial coherence [3,4].

2. Non-Interaction of optical waves and out-of-phase waves passing through the dark fringe locations

The wave propagation sketch in Fig.1, emulates Huygens-Fresnel diffraction integral. They implicate optical wavelets evolve through each other without any mutual interaction and without any re-organization of mutual energy until they collectively illuminate a detector array, which then absorbs energy from all the waves proportional to the square modulus of the sum total amplitude stimulation induced on the detector array. This non-interaction of waves (NIW) is a critical property of all waves while propagating through any linear medium (including vacuum).

NIW has been formally articulated by Huygens in his book [1] and its physical significance has been elaborated in a recent book by Roychoudhuri [2]. It is then obvious that dark fringe locations on the detector are also receiving the EM waves, but no energy is registered because the resultant sum total E-vector being zero, the un-stimulated detecting dipoles cannot absorb any energy. The waves just pass through these locations.

3. van Cittert-Zernike theorem for an extended incoherent particle beam

We will now try to reconcile the above wave picture for particle beams, while recognizing that particles definitely do not diffract out like Huygens wavelets. Atoms always preserve their size of ~1A for all velocities. The general double-slit diffraction can be expressed as the superposition of two beams emerging from the two slits. ***This is a causal mathematical formulation valid for both the optical and the particle beams:***

$$\left|\psi_{1,2}\right|^2 = \left|\chi a_1 e^{-i2\pi ft} + \chi a_2 e^{-i2\pi f(t+\tau)}\right|^2, \text{ where } hf = (1/2)m\mathrm{v}^2 = E \qquad (2)$$

For light f is the optical frequency of the radiation, and for particles f is kinetic-frequency of oscillation for a given velocity. One can call it the de Broglie frequency. The traditional de Broglie wavelength $\lambda = h/p = h/m\mathrm{v}$ goes to infinity for $\mathrm{v} = 0$, which is a non-causal result. In Eq.2 each of the two incident signals stimulates the same detecting element, and the strengths of the individually induced dipolar amplitude stimulations are χa_1 and χa_2. The sum total stimulation would be zero ***only when*** $\chi a_1 = \chi a_2$ and $2\pi f\tau$ is an odd multiple of π.

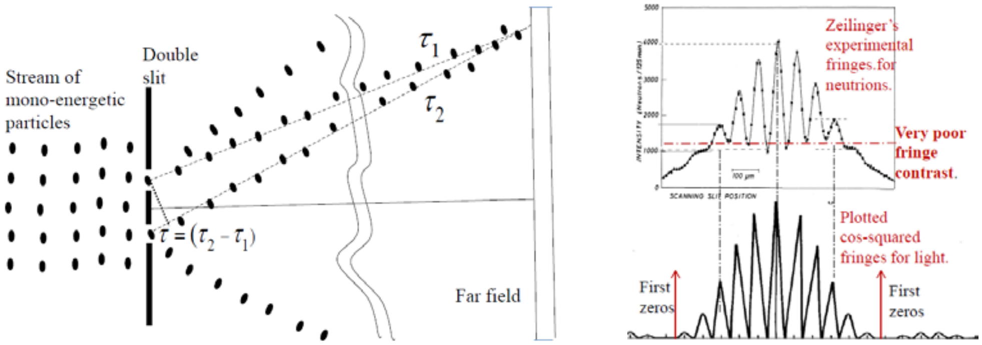

Figure 1. ***Left****: Sketch for a double-slit particle diffraction.* ***Righ****t; Comparison of double-slit fringe contrast for particle beam (right-top) and for optical beam (right-bottom).*

In other words, for both particle and optical beams, the dark fringe locations are not due to *non-arrival* of the signals. The two signals just cancel each other's stimulation capability of the detecting dipole. For particle diffraction, this would require that pairs of oppositely phased particles arrive simultaneously at these locations. Individually arrived particle will stimulate the detecting element and reduce the fringe contrast. This prediction appears to be systematically correct for particle diffraction patterns reported in literature [5]. One example is reproduced in Fig.2, where for particle diffraction curve (top right) is compared with that for light (right bottom). Hence, we believe that quantitative reproduction of negative partial coherence ("c" in Fig.1) for particle beams, as predicted by vC-Z theorem, would be a very instructive experiment. Since individual particle do not spread out like Huygens wavelets, after selection of same velocity particles, they must co-propagate in the proximity of each other for some distance to evolve into a same-phase beam. This phase entanglement would likely degrade as the width of the oven-slit is broadened. Such experiments should be carried out using Rb-atom beam coming out of a precisely adjustable wide slit and a thick holographic plate as a detector. The developed plate, observed in white light, should show the traditional double-slit fringes. However, when the plate is observed using resonant florescence red light (780nm), the spatial variation of the fluorescent light will be proportional to the number distribution of the lodged Rb-atoms.

4. References

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