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Our Evolving View of the Nature of X-Rays

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The advent of x-ray free electron lasers (X-FELs) necessitates a re-evaluation of the adequacy of our description of x-rays and their interactions with matter. I will review the concepts used during the first 100 years of x-ray science and how they need to be modified by use of the full quantum theory of light that extends beyond a first order description of coherence.

My talk explores and challenges some fundamental concepts, like the existence of spherical light waves underlying the magical Huygens-Fresnel principle, Dirac's bold statement that photons never interfere with each other, and the absolute validity of Heisenberg's uncertainty principle. I will show how these concepts naturally emerged historically and why they need to be revised based on present-day knowledge.

I will outline how the historical description of light increasingly incorporated a hidden hierarchical order that exists in its complicated coherence properties. In *zeroth order*, light behaves as "rays", leading to real space images through particle-like trajectories. In *first order*, light behaves as "waves'', leading to reciprocal or Fourier space "diffraction images''. At the size of the wavelength, i.e. the minimum size required for the birth of radiation, the ray and wave concepts merge into the quantum mechanical uncertainty principle. It establishes lower limits for the products between corresponding real and conjugate variables, leading to the so-called *diffraction* (real-reciprocal space) and *transform* (time-energy) limits. The product of the diffraction and transform limits defines the total minimum space-time uncertainty or maximum source brightness $\sim \lambda^3$.

The uncertainty principle and the so-defined brightness, however, are only first order concepts due to the linearity of quantum mechanics, and they are therefore incomplete. They do not properly describe photon-photon interactions which arise only in *second order* coherence theory, where photon-photon interference becomes allowed. This opens the door for spatial resolution below the diffraction limit. To prove this point, I will review experiments where two correlated photons ("biphotons") that are created simultaneously in space-time though non-linear photon "*fission*" (spontaneous parametric down conversion) or "*fusion*" (stimulated emission) processes in a solid clearly reveal photon-photon interference through the narrowing of the far-field diffraction pattern.

Remarkably, the extension of quantum coherence theory from 2^{nd} to n^{th} order, corresponding to the emission of a large number n of indistinguishable (cloned) photons, will be shown to lead to a far field "image" that is no longer a reciprocal space diffraction pattern but a real space replica of the source itself. With increasing order n of coherence, the particle-like behavior of light with vanishing uncertainty amazingly re-emerges.

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