5.25: Holography Involves Single Photon Interference

Recently I was reading an encyclopedia article [McMillan Encyclopedia of Physics, John Rigden, Editor, page 716] about holography...

The word "holography" is derived from Greek roots that literally mean "entire picture." The act of doing holograhpy is to make holograms. There are many different types of holograms, but they all share one common distinguishing feature, they recreate truly three-dimensional imgages of original objects.

The field of holography was originally discovered by Dennis Gabor in 1947. He was awarded the Nobel Prize for physics in 1971. In the early 1960s, Emmett N. Leith and Juris Upatinieks of the United States and Yu. Denisyuk of Russia independently discovered additional methods in using laser light to make holograms.

What is a hologram? A hologram is a recording on a lightsensitive medium (e.g. photographic emulsion) of interference patterns formed between two or more beams of light derived from the same laser.

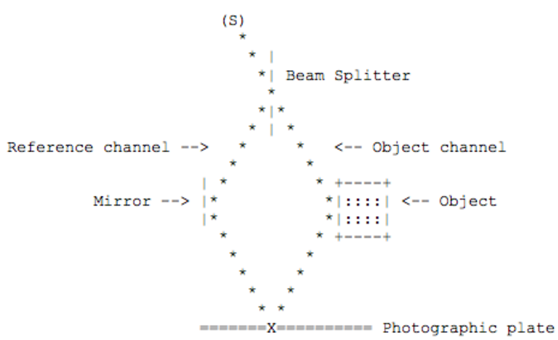
In holography, as the figure below shows, a laser beam is split by a beam splitter with one arm going to the object and the other going to a mirror. The beam arms recombine at the detector, in this case a photographic plate, and constructive or destructive interference occurs.

Although it isn't stated explicitly above, I assume that holography is an example of single-photon interference, and that the same can be said about any diffraction phenomenon - X-ray, electron, neutron, etc. To support this assumption I quote the celebrated remark by Dirac, "Each photon then interferes only with itself. Interference between two different photons never occurs." [I am aware of Roy Glauber's cautionary remarks about the second sentence - American Journal of Physics 63, 12 (1995). For example, two-photon interference can be observed if the photons are created in an entangled state.]

According to this single-particle mechanism, after the beam splitter each photon is considered to be in a linear superposition of being transmitted (toward object) and reflected (toward mirror). At the detector the probability amplitudes for these paths interfere (constructively or destructively) giving an interference pattern characteristic of the object. In Dirac notation, the probability of detection at some point x on the photographic film is,

$$P(x) = |\langle \text{Detector(x)} \mid \text{Mirror} \rangle \langle \text{Mirror}|\text{Source} \rangle + \langle \text{Detector(x)}|\text{Object} \rangle \langle \text{Object}|\text{Source} \rangle|^2$$

This is a clear example of quantum mechanical wave-particle duality; the photon is created by the source as a particle, behaves like a wave, and is detected at the photographic plate as a particle.



I would like to add further support the underlying assumption of this tutorial that holography is an example of single-particle interference with the following excerpt from Volume 23 of the *Encyclopedia Britannica*, 15^{th} Edition, pages 20- 21.

It was at one time suggested that interference and diffraction phenomena are caused by collisions between photons considered as small particles, or at least to some kind of complex interaction between photons. A simple experiment performed by a British physicist, Geoffrey Ingram Taylor, in 1908 excludes this possibility. He photographed the diffraction pattern of a needle and reduced the illumination until long exposures were needed to obtain an image. When the chance of two or more energy quanta passing through the apparatus simultaneously was made extremely small, the diffraction pattern was exactly the same as that obtained with a strong source of light.

This experiment is supported by many later experiments, showing that interference and diffraction are to be associated with single photons. The discussion in the section on coherence above implies that when ordinary sources of light are used each photon can interfere only with itself and not with any other photon. An interference pattern can, of course, be photographed only by recording the effects of many photons because one photon can activate only one grain on the photographic plate, but it does not matter whether the photons all arrive over a time span of a microsecond or of several weeks.

The photograph of an interference pattern is both a wave phenomenon because it shows the characteristic spatial periodicity and a quantum phenomenon because the whole energy of a photon can be used to activate a single grain. It is not possible to trace the path of one photon (regarded as a particle) through the apparatus and, at the same time, obtain the interference pattern. In Young's experiment there is no way of finding out through which slit a given photon passes--except by covering one slit and thus losing the interference fringes.

For a discussion of the related double-slit experiment see the related tutorial: Calculating the Double-Slit Interference Pattern. To learn about contemporary applications of holographic techniques at the atomic level see "Optics: Holograms of Atoms," *Nature* **410**, 1037-1040 (2001) and references cited therein.