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Wave-particle duality: The mystery keeps unfolding

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Abstract. The current status of wave particle duality using single photon sources is briefly reviewed.

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1. The double-slit experiment

The double-slit experiment with single particles passing through the apparatus one at a time, lies at the heart of all debates regarding interpretations of quantum mechanics and the measurement problem. The only way to determine which path a particle takes is to close one of the two holes, in which case the interference pattern necessarily disappears. In other words, interference (wave-like information) and a knowledge of "which path" a particle takes all the way from the aperture to the final screen (particle-like information) are *mutually exclusive*. This is the essential content of Bohr's "complementarity principle" as applied to wave-particle duality. Phrased differently, it states that a consistent description of the double-slit experiment in terms of classical pictures (waves *or* particles) is possible provided the condition of the apparatus is specified (both the holes open or one of them shut).

Although the simultaneous observation of wave and particle behaviour is thus usually believed to be prohibited (the complementarity principle) by the position-momentum uncertainty relation, one can show that it is possible in practice to obtain "which path" or particle-like information without scattering or otherwise introducing large uncontrolled phase factors into the interfering beams by using recent advances in quantum optics, namely the micro-maser and laser cooling [2]. However, the interference fringes disappear once this path information is obtained. *This is because complementarity in interference experiments is guaranteed by the formalism of quantum mechanics.*

It has long been known that the interference produced by two light beams is related to their mutual coherence. We have just learnt that in quantum mechanics it is also related to the intrinsic indistinguishability of the particle paths. It can be shown that there is a precise mathematical relation between these two features – the degree of indistinguishability of the paths equals the degree of coherence [3].

These considerations show that the words "wave" and "particle" are divested of their absolute and objective classical meaning in standard quantum theory in which they retain only a *contextual* significance. It is possible to rephrase the concept of wave-particle complementarity in purely *quantitative* terms as the expression of the mutual exclusiveness of coherence and path distinguishability [4]. It is, in fact, not necessary at all to use the words "wave" and "particle" which are borrowed from classical physics and are therefore of limited applicability in purely quantum mechanical situations. Nevertheless, one can, for convenience, also continue to use the words "wave" and "particle" consistently in the context of wave-particle complementarity provided they are used purely as *mnemonics* for "mutual coherence" and "path distinguishability" respectively.

A number of experiments have been done to test wave-particle complementarity using neutron and electron interferometry [1], [5], [6]. The interesting thing from the point of view of interpretations is that *causal* explanations of the observed self-interference effects can be given in terms of well defined particle *trajectories* and the quantum potential [7], which shows that the standard Copenhagen interpretation of quantum mechanics and its variants are derived from philosophical assumptions that are not necessarily implied by the mathematical formalism and empirical success of quantum mechanics.

2. Single photon states and complementarity

Finally, let us turn to wave-particle duality of single photon states. For such states unambiguous evidence of complementarity between interference and "which path" information had to wait until technological advances made it possible to produce such states and detect them. The first experiment of this kind was performed by Aspect, Grangier and Roger around 1986–1987 [8]. A number of experiments had been done earlier since 1909 [9] to demonstrate interference with highly attenuated pulses of quasi-monochromatic light of frequency ν whose energies were so low that it was believed they could not contain more than one photon of the same frequency and whose flux was so low that no more than one pulse could pass through the interferometer at a time. Each pulse produced a single spot on the photographic plate, and it took about six months of exposure time for Taylor to develop the fringe pattern in 1909. It was argued that these experiments demonstrated the wave-particle duality of light, the particle aspect manifesting itself in the discrete spots and the wave aspect in the interference fringes. However, clearly there was no "which path" information in these spots and there was no arrangement in any of these experiments to demonstrate the mutual incompatibility between the fringe pattern and "which path" information that lies at the heart of the Einstein–Bohr debate and complementarity. This is exactly what Aspect and his collaborators provided, and in the process also demonstrated that it was impossible to get "which path" information with the kind of low flux weak pulses that had been used earlier – one needs to use a low flux of genuine single photon pulses that were not available earlier.

There was another feature of these experiments that Aspect *et al* pointed out which is often not appreciated. And it is this : although the discreteness of the spots (photodetection) can be explained if one accepts the existence of photons, *they can also be attributed to the quantization of the detector alone.* There is therefore *no logical necessity to intro-*

duce the concept of the photon to describe the interference of weak light. Thus, *Einstein's interpretation of the photoelectric effect by no means implies the necessity of describing light as composed of photons.* Indeed, there were many stalwarts like Planck, Nernst, Warburg and Bohr who refused to take Einstein's light-quantum hypothesis seriously for a long time [10]. It is only now that the truly quantum nature of light is beginning to be observed definitively through the production of special states of light like single photon states and squeezed states [23] that the light-quantum hypothesis has been convincingly vindicated.

The strategy followed by Aspect *et al* was to use anti-correlation or anti-coincidence on a beam splitter to obtain "which path" information. The quantum theory of light predicts perfect anti-correlation for singles detections on the two sides of a beam splitter, whereas a classical light pulse, however weak, would be divided on a beam splitter and therefore produce a minimum degree of correlated or coincident counts. It is possible to make these considerations more quantitative. Let a source of light pulses impinge on a beam splitter (figure 1). A triggering system produces gates of duration T, synchronized with the light pulses. The detections are authorized only during the gates. A coincidence is counted when both the photomultiplers PM_r and PM_t register a detection during the *same* gate. If the probabilities for transmission, reflection and coincidence count during a gate are given respectively by P_t, P_r and P_c, and the singles probabilities are small compared to one, one obtains for classical light

$$P_c \geq P_r P_t \,, \tag{1}$$

by using the standard Cauchy–Schwartz inequality, or equivalently

$$\alpha \geq 1 \,, \quad \alpha = \frac{P_c}{P_r P_t} . \tag{2}$$

This result states that there is a *minimum* rate of coincidences count, corresponding to "accidental coincidences", for a *classical* wave divided on the beam splitter. On the other hand, $\alpha = 0$ for a single photon state. This therefore provides an empirical or operational criterion characterizing single particle behaviour of light – the violation of the inequality (2) would indicate that the light pulses cannot be described as wave packets that divide on the beam splitter but rather as single photons that cannot be so divided and detected simultaneously on both sides of the beam splitter.

When Aspect *et al* used light from a pulsed photodiode that was attenuated to a level corresponding to one detection per 1000 emitted pulses with a detector quantum efficiency of about 10 per cent, the average energy per pulse was estimated to be about 0.01 photon. Such a source would certainly have been considered a source of single photons. Nevertheless, the quantity α was consistently found to be equal to one, i.e., no anticorrelation was observed. This showed that light emitted by an attenuated classical source does not exhibit single photon behaviour, and one cannot get "which path" information using such a source. It is therefore impossible to demonstrate the complementarity between interference and "which path" information using such a source.

Although an excited atom emits a single photon, many atoms of a classical source are 'in view' of the detectors, and the number of excited atoms fluctuates. Consequently, the emitted light can be described by a density matrix reflecting these fluctuations. For a Poissonian fluctuation of the number of emitting atoms, one can show that the statistical properties of light cannot be distinguished from those of classical light.

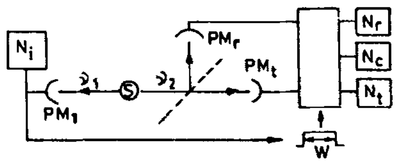

Figure 1. Study of detection correlations after a beam splitter.

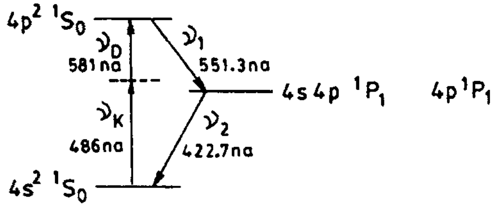

Figure 2. Two photon radiative cascade of calcium used to generate single photon wave packets.

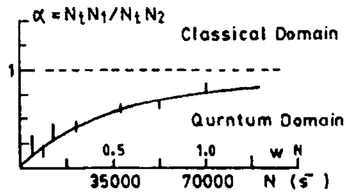

Figure 3. The anti-correlation parameter α as a function of ωN (the number of cascades excited during a gate) and the trigger rate N_1.

In order to observe non-classical features of light, it is therefore necessary to isolate single atom emissions. This was achieved by Aspect *et al* using the two-photon radiative cascades from a calcium source (figure 2). The atoms were excited by two-photon absorption from stabilized cw lasers to an upper level which then de-excited in two succesive steps, emitting two photons at different frequencies ν_1 and ν_2. The intermediate level was metastable and had a life-time $\tau_s = 4.7$ ns. By choosing the rate of excitation of the cascades such that $N << \tau_s^{-1}$, they achieved cascades well separated in time. They used the detection of the first photon ν_1 as a trigger for a gate of duration $T \approx 2\tau_s$. During a gate the probability of a photon ν_2 coming from the *same* atom that emitted ν_1 was much larger than that from a *different* atom in the source. They were therefore in a situation close to an ideal single photon source.

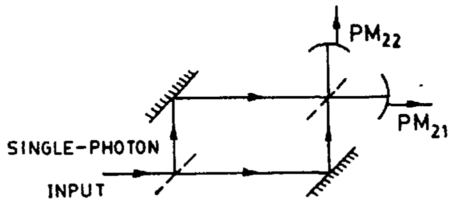

Figure 4. The Mach–Zehnder interferometer.

The quantum mechanical prediction for α is

$$\alpha_{QM} = \frac{2f(T)\,NT + (NT)^2}{[f(T) + NT]^2} \tag{3}$$

where $f(T)$ is a quantity very close to unity in the experiment, being the product of the factor $[1 - \exp(-T/\tau_s)]$ (the overlap between the gate and the exponential decay) and a factor somewhat greater than unity related to the angular correlation between ν_1 and ν_2 [12]. The smaller NT is compared to $f(T)$, the stronger will be the anti-correlation ($\alpha << 1$). The results are shown in figure 3 which shows a plot of α as a function of NT. It is clear that the violation of the inequality (2) increases as NT decreases. The maximum violation of more than 13 standard deviations was obtained for a counting time of five hours. The value of α was 0.18 ± 0.06, corresponding to a total number 9 of coincidences instead of a minimum of 50 coincidences expected for a classical model of light. This was characteristic of single photons as predicted by quantum theory, and the anti-correlated counts on the two sides of the beam splitter gave "which path" information. With such a source available, Aspect *et al* could turn to a study of single photon interference.

They constructed a Mach–Zehnder interferometer in which the two detectors were removed and placed behind a second beam splitter on which the two beams were recombined with the help of two mirrors, as shown in figure 4. The detectors were gated as in the previous experiment and once again their counts were found to be anti-correlated, but this time they did not contain any "which path" information which was lost after the second beam splitter. When the path difference between the two beams was varied with the help of a phase shifter, the probabilities of single photon detection by each detector varied sinusoidally. The fringe visibility was close to unity. This completed the demonstration of complementarity between "which path" information and interference.

3. The double prism experiment

We have seen that the degree of mutual coherence of two beams depends on their intrinsic path indistinguishability, and even the mere possibility of obtaining "which path" information is sufficient to destroy this coherence. This is the basis of the complementarity in the sense of *mutual exclusiveness* of the wave and particle descriptions in quantum theory. *According to Bohr this mutual exclusiveness also extends to the classical concepts of waves and particles.* He presumably arrived at this view point from (a) his insistence on the use of common language, suitably refined by classical physics, for the unambiguous communication of every experimental result and (b) the assumption that interference is 'the only means of defining the concepts of frequency and wavelength of a photon' [13]. The question arises as to whether Bohr's extension of complementarity to the classical concepts of waves and particles holds in *every situation.* A little reflection shows that it does *not,* because Bohr's assumption (b) is not true. There are characteristic features of wave-like propagation like tunneling and birefringence of single photon states in which *the interference of the alternative amplitudes* (for the reflected and transmitted rays in tunneling and for the ordinary and extraordinary rays in birefringence) *plays no pertinent role,* and yet these phenomena can just as well be used to define and measure wavelengths and frequencies as interference. For example, tunneling occurs only when the tunneling gap is less than the wavelength of the incident photons and can, therefore, be used to measure their wavelengths, and birefringence is the result of dispersion in the refracting medium. *There is, however, nothing in the mathematical structure of quantum mechanics that rules out simultaneous path distinguishability and tunneling or simultaneous path distinguishability and birefringence.* If the concept of a 'wave' in quantum theory is extended to include tunneling and birefringence in addition to coherence, as in classical physics, it follows that quantum mechanics does not rule out the possibility of observing wave and particle-like behaviours *at the same space-time point* (the point of incidence of a photon on the boundary between two media). The classical concepts of waves and particles cannot obviously be consistently applied to such situations. We will now discuss an actual experiment of this kind proposed by Ghose, Home and Agarwal [14].

The classical analogue of the experiment was done by J C Bose way back in 1897 as reported in Sommerfeld's *Optics* [15]. A beam of microwaves directed at a 45° asphalt prism was totally internally reflected by the 45° face. When a second similar prism was placed face to face in contact with the first prism, the beam passed straight through. However, when the gap between the prism faces was increased but kept significantly smaller than the wavelength of the beam, a portion of the beam was internally reflected and the rest tunneled across the gap. This was a striking confirmation of the wave nature of the radiation Bose was experimenting with. A similar experiment can also be done with visible light. Only in this case the gap between the prism faces must be controlled and kept at about several tens of a nanometer.

Ghose, Home and Agarwal pointed out that if this experiment was performed with "single photon states" of light, the interpretation of the results in terms of classical wave and particle pictures would acquire a new significance. Should the photon behave like a classical wave, a part of it must be reflected and at the same time the rest of it must tunnel across the gap. On the other hand, should the photon behave strictly like a classical particle, it should not be able to tunnel across the gap because tunneling is a purely wave phenomenon. Quantum optics, however, predicts that a photon will be either reflected by or tunnel across the gap, but *not at the same time.* Thus, a photon will reveal itself as a wave when it tunnels across the gap, and *at the same time* as a particle because it is indivisible and follows a path. Thus *both wave and particle behaviours of light should be observable simultaneously.*

Mizobuchi and Ohtaké [16] performed the experiment. They used a pulsed laser diode to measure the coincidence counts (figure 5), and reduced the light intensity with the help of neutral density filters to as low as 10^4 photons per second. With an apparatus size of less than one metre, this ensured that there was never more than one photon in the apparatus at any given instant. Yet, the measured ratio of coincidences to singles counts was found to

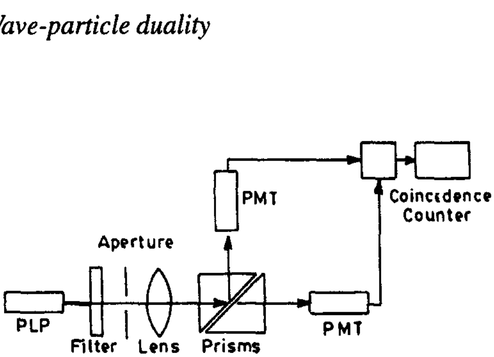

Figure 5. The coincidence experiment.

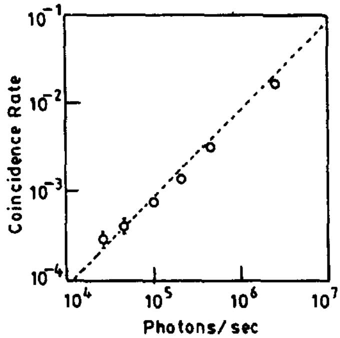

Figure 6. Coincidences as a function of singles counts per second.

be nearly proportional to the singles counts (figure 6). Thus, no non-classical wave-like or single particle-like behaviour was observed with semi-classical light, as in the experiment of Aspect *et al.*

To do the anti-coincidence experiment (figure 7) proposed by Ghose, Home and Agarwal, they used the parametric down-conversion technique [17] to produce correlated photon pairs. One of the photons served as the single photon source. The advantage of the down-conversion technique over the atomic cascades is that the former is more controllable and gives higher gain because the down-converted photons strictly satisfy the momentum conservation law. They used the third harmonic of a pulsed Nd:YAG laser which has a typical wavelength of 355 nm, and the beam was injected on a BBO crystal in which the down-converted photon pairs of wavelength 710 nm were generated. The intensity of the light was again reduced with the help of neutral density filters to the single photon intensity level before it was incident on the prism. The gap between the prism faces was controlled by putting Langmuir-Blodgett films between the prisms, leaving the passage of the light untouched. The relation between tunneling and reflection was measured as the gap width was varied. It was found that as the gap decreased, tunneling increased (figure 8), showing the classical wave nature of the light. The reflected and transmitted light were detected by avalanche photodiode (APD) single photon detectors with an efficiency of 38 per cent. The resolving time of anti-coincidence was determined by the input rectangular pulse duration of 600 ns. The counter units were gated on for $20\mu s$ synchronized with each laser pulse to minimize the dark counts. The results are shown in figure 9 in which the ratio of

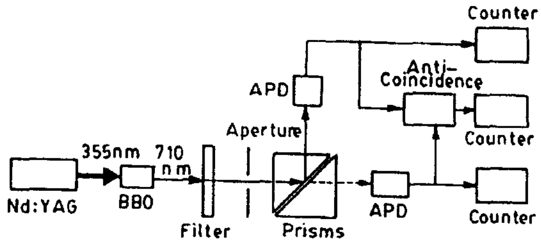

Figure 7. The anti-coincidence experiment.

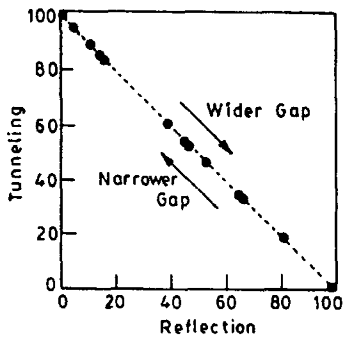

Figure 8. The relation between reflection and tunneling as the gap between the prisms is varied.

anti-coincidence counts to the number of signal counts from either the reflected or the transmitted light is plotted against the detected signal counts per second at each detector. This ratio should be unity if there is complete anti-coincidence. The experimental results tend to show that this is the case. The uncertainties arise from the lack of long time stability of the Nd:YAG laser used and the consequent lack of statistical accuracy.

Unnikrishnan and Murthy [18] have made a systematic error analysis of this experiment and shown that although the observed anti-coincidence rate is smaller than the classical prediction, it implies a larger coincidence rate than the classical prediction because of the large intensity fluctuations produced by the Nd:YAG laser. They suggest that the use of a relatively more stable cw laser for the down-conversion would be preferable as the intensity fluctuations would be smaller and the count rates orders of magnitude higher. Such an experiment is in progress.

4. Birefringence and complementarity

Refraction is yet another phenomenon which conclusively established the wave nature of classical light. Any corpuscular classical theory of light, like that of Newton, implies that

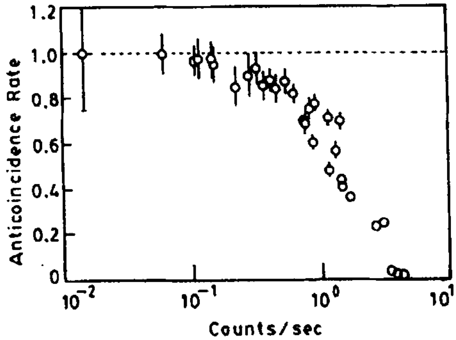

Figure 9. The anti-coincidence rate plotted against signal counts per second.

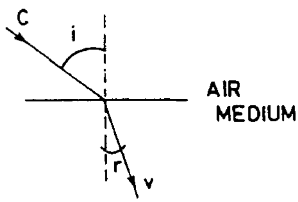

Figure 10. Principle of the single photon birefringence experiment.

light must travel faster in an optically denser medium than in vacuum in order to be consistent with the observed law of refraction (Snell's law). This follows if one makes use of the condition that the transverse component of the velocity must be continuous across the boundary between the two media (figure 10) :

$$c \sin i = v \sin r \tag{4}$$

where i and r are the angles of incidence and refraction ($i > r$) and c and v are the velocities of light in vacuum and the optically denser medium respectively. Then, the refractive index μ is given by

$$\mu = \frac{\sin i}{\sin r} = \frac{v}{c} > 1. \tag{5}$$

The classical electromagnetic theory of light, on the other hand, implies the opposite, namely

$$\mu = \frac{\sin i}{\sin r} = \frac{c}{v} > 1. \tag{6}$$

Fizeau's experiment [19] on the speed of light in water conclusively showed that $v < c$, ruling out any classical particle theory of light.

There are birefringent crystals in which the incident light is split into two beams, the ordinary and the extra-ordinary rays, both of which have refractive indices larger than unity and therefore propagate as waves. If a single photon state is incident on such a crystal, it will be in a superposition of the two possible paths (corresponding to the ordinary and extra-ordinary rays). If two detectors are placed in these two paths, their counts will be anti-correlated, giving us "which path" (or particle-like) information. Yet, the very fact that the refractive indices for both the paths are greater than unity can only be explained in terms of wave-like propagation. Here again Bohr's extension of complementarity to the classical concepts of waves and particles fails. An experiment is being carried out to test this prediction at TIFR.

5. Conclusion and summary

We therefore conclude that although the complementarity principle holds in every situation in which non-commuting observables are involved, in the case of wave-particle duality, Bohr's extension of the principle to the *classical* concepts of waves and particles holds only in interference experiments because of the quantitative relationship between intrinsic path distinguishability and mutual coherence in quantum mechanics, but not generally as in tunneling and birefringence where coherence of the component waves plays no pertinent role. Bohr's extension cannot therefore be given the status of a general *principle*. However, all experiments are quite consistent with the Einstein–de Broglie–Bohm version of wave-particle duality [20] in which the position of the particle which is present all the time is guided by the quantum potential determined by the total wave function, as well as with the causal model for the behaviour of light in terms of a quantum field theory where the hidden variable representing the field is not the photon position but the coordinates of the field modes [21]. Recently a causal model of massive and massless spin-0 and spin-1 bosons (below the threshold of particle production and annihilation) in which the boson position is used as the hidden variable has been developed [22]. In this interpretation photons travel as particles along the lines of energy flow which are modified by boundary conditions (as in a double-slit configuration), resulting in a redistribution corresponding exactly to interference and diffraction patterns as already demonstrated by Prosser [23].

These considerations show that the debate concerning the precise nature of wave-particle duality (waves *and* particles versus waves *or* particles) is not purely metaphysical – it is open to experimental scrutiny and has important bearings on the measurement problem.

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