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The Controversy on Photons and the Hanbury Brown & Twiss Experiment

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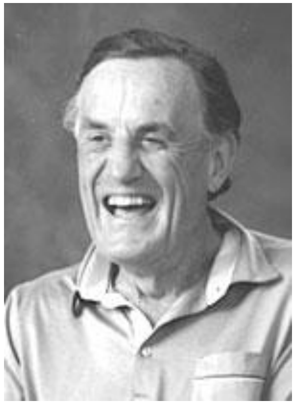
Outline of my talk

- Introduction
- The Hanbury Brown & Twiss (HBT) experiment
- The early reception of the HBT experimental result
- The answer from Hanbury Brown and Twiss to the criticisms
- Some concluding remarks

Introduction

• Robert Hanbury Brown (1916-2002) and Richard Quentin Twiss (1920-2005) were born in India then a part of the Britain Empire.



R. Hanbury Brown
(1916-2002)

• Hanbury Brown got a B.Sc. in electrical engineering;
• Doctorate in radio engineering;

R. Q. Twiss
(1920-2005)

• Mathematical Tripos;
• Doctorate in theory of magnetrons from MIT;

Introduction

Hanbury Brown (1991, p. 120)

"Our work really put the cat among the pigeons."

Alain Aspect

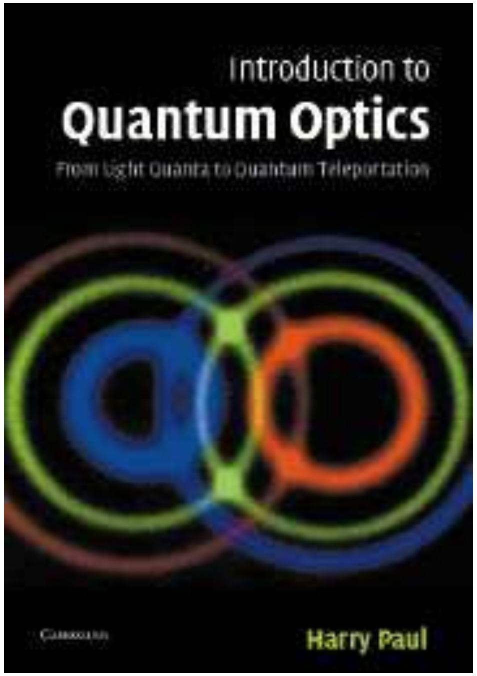
Correspondence from Alain Aspect to Olival Freire and Indianara Silva (December 21st, 2009)

"[…] In my opinion **HBT is more a precursor of the quantum optics** effects involving photon correlation […]." (emphases are mine)

Introduction

Paul (2004, p. 127)

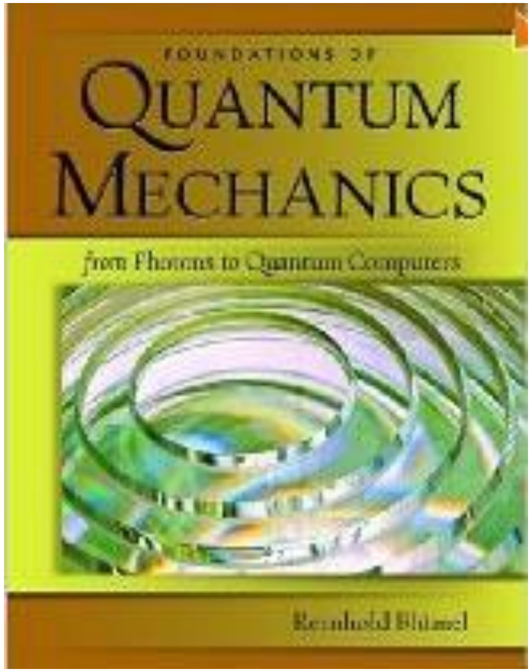
> “The credit for developing the basic technique for intensity fluctuation measurements goes to **the British scientists R. Hanbury Brown and R. Q. Twiss, who became the fathers of a new optical discipline** which investigates statistical laws valid for photocounting under various physical situations. When we talk of studies of "photon statistics" it is these investigations that we are referring to.” (emphases are mine)



Introduction

Blümel (2010, p. 14)

> “This experiment showed a strong coincidence signal, thus **favoring the wave theory of light**. At the time this result was puzzling and seemed to contradict the photon theory of light.” (emphases are mine)



The Michelson's Interferometer

- In the final of 1940's, the radio astronomers used the Michelson's interferometer to calculate the angular diameter of radio stars.

- With this device, it was possible to determine the shape of the distribution of intensity across the source.

- This Michelson-type interferometer had two major problems.

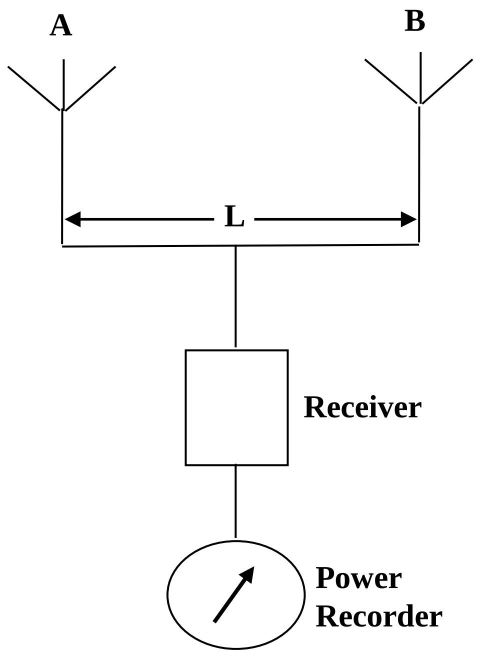
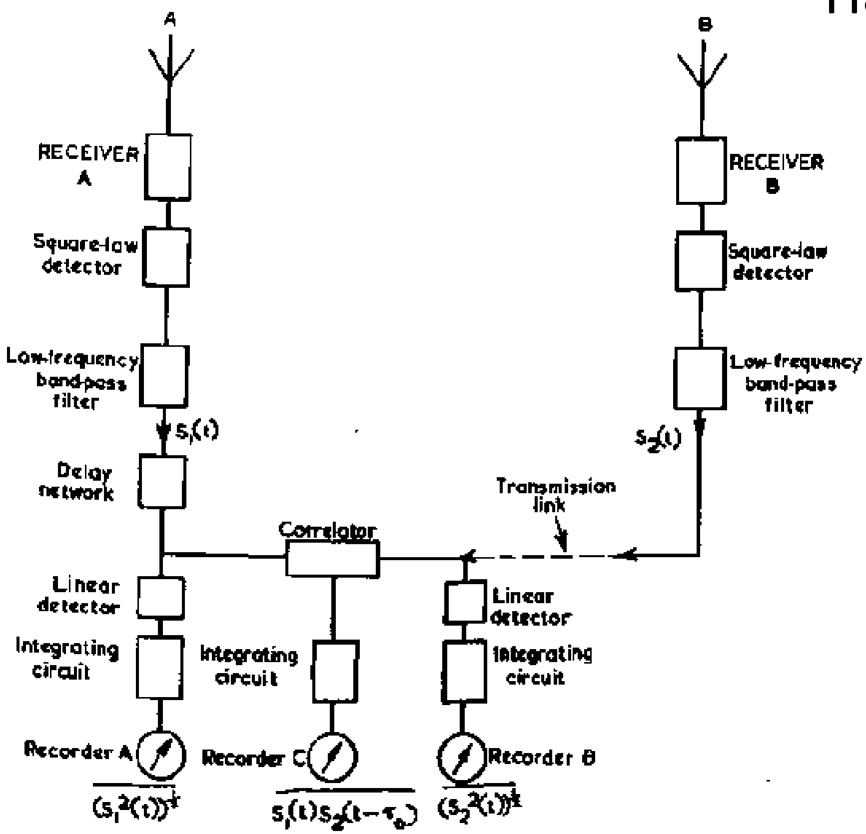


Fig. 1

A new type of interferometer for use in radio astronomy with long baseline and without the ionosphere effect :

The HBT interferometer

The Hanbury Brown & Twiss (HBT) Interferometer



Block diagram of new type of interferometer.

Fig. 2

Hanbury Brown & Twiss (1954, p. 668)

"two aerials, A and B, feed two independent receivers tuned to the same frequency with identical band-pass characteristics. The output of each receiver is rectified in a square-law detector and is fed to a low-frequency band-pass filter. The outputs of these filters are combined in a correlator the output is passed, via an integrating circuit of bandwidth to a pen recording the time-dependent signal."

From the radio astronomy to the optical domain.

The HBT Experiment

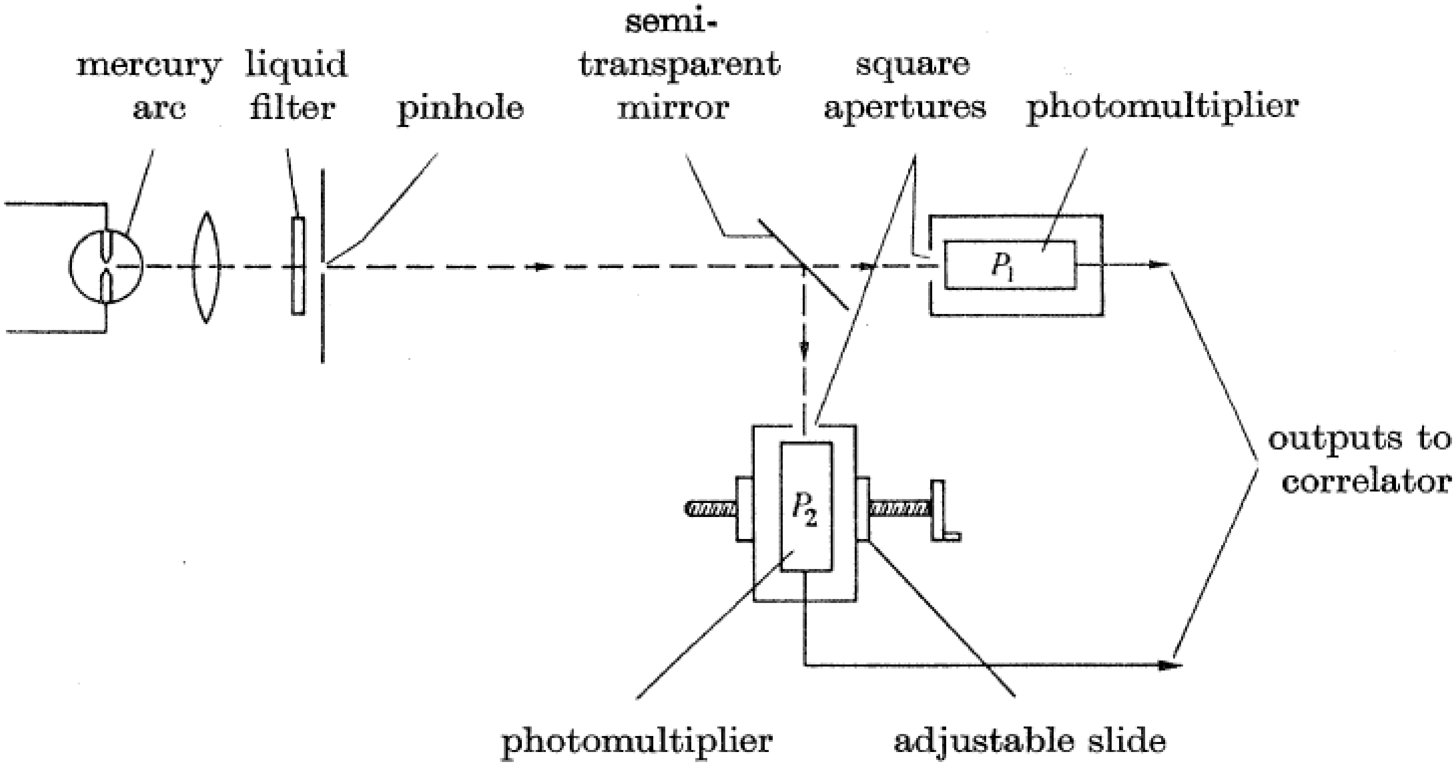


Fig. 3: The optical system set up by Hanbury Brown and Twiss. Source: Hanbury Brown & Twiss, 1958, p. 299).

The HBT Experiment

Hanbury Brown & Twiss (1956a, p. 27)

> In this optical systemfundamental that "**the time of arrival of photons** at the two photocathodes should be **correlated** when **the light beams** incident upon the two mirrors are **coherent**. However, so far as we know, this fundamental effect has never been directly observed with light, and **indeed its very existence has been questioned.**" (emphases are mine)

The HBT Experiment and its results

TABLE 2. THE EXPERIMENTAL AND THEORETICAL VALUES FOR THE NORMALIZED CORRELATION FACTOR FOR DIFFERENT CATHODE SPACINGS

run no.	cathode separation (mm) d	observed correlation (r.m.s. signal to noise ratio) (S/N)	theoretical correlation assuming cathodes superimposed (r.m.s. signal to noise ratio) $(S/N)'$	experimental value of normalized correlation factor $\Gamma^2(\nu_0, d) = \frac{(S/N)}{(S/N)'}$	theoretical value of the normalized correlation factor $\Gamma^2(\nu_0, d)$
1	0	+17·55	+17·10	1·03 ± 0·04 (p.e.)	1·00
2	1·25	+ 8·25	+ 9·27	0·89 ± 0·07	0·928
3	2·50	+ 5·75	+ 8·85	0·65 ± 0·08	0·713
4	3·75	+ 3·59	+ 8·99	0·40 ± 0·07	0·461
5	5·00	+ 2·97	+ 9·00	0·33 ± 0·07	0·244
6	10·00	+ 0·90	+ 8·17	0·11 ± 0·08	0·015

- The HBT model: a semi-classical approach.

The HBT Experiment and its results

Hanbury Brown and Twiss (1958, p. 308)

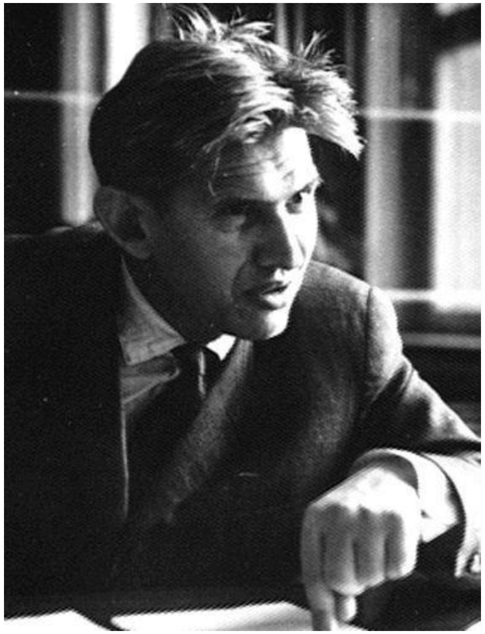
"**The fluctuations of intensity in two coherent beams of light are correlated**" when the photocathodes were superimposed (emphases are mine).

The early reception of the HBT experimental result

Hanbury Brown (1991, p. 119)

Our original theory had been accepted by radio engineers without a murmur because to them radio waves were simply waves and it was easy to prove by fairly simple mathematics that our interferometer would work. However, **when it came to proving that it would work with light we had to worry about photons, and there were some lingering doubts in our own minds and several well entrenched doubts in the minds of the physicists whom we consulted.**" (emphases are mine)

The early reception of the HBT experimental result



Lajos Jánossy

Eric Brannen

They found ***no correlation*** between the current outputs from two photomultipliers when they were illuminated by coherent light rays.

The early reception of the HBT experimental result

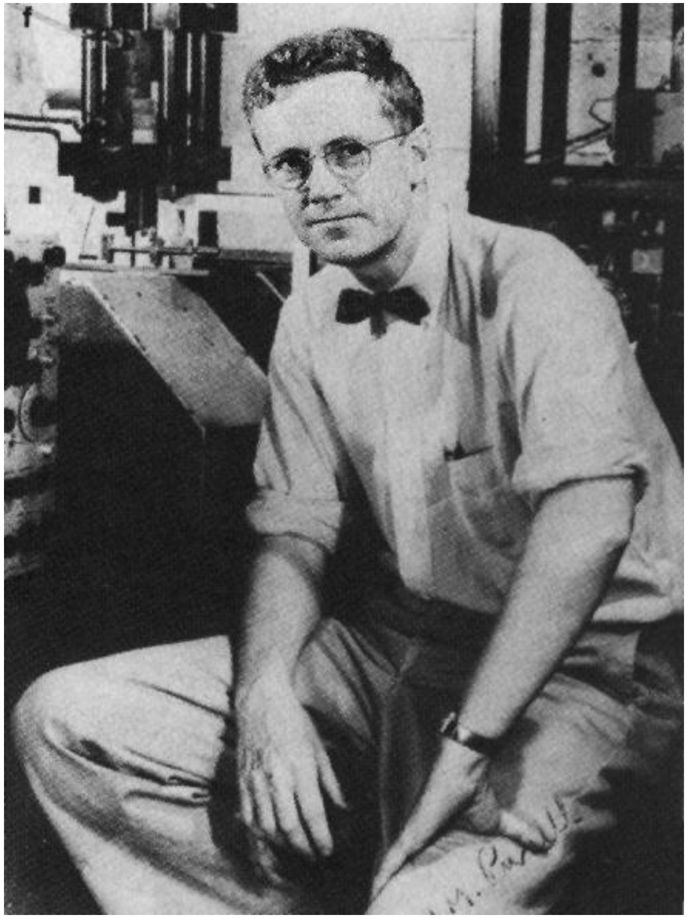
Brannen and Ferguson's experiment

- The coherent source was the high-pressure mercury arc
- The electronic detection

Hanbury Brown and Twiss' experiment

- The coherent source was the high-pressure mercury arc
- A linear photomultiplier

The early reception of the HBT experimental result



Edward Millis Purcell

Nobel laureate in 1952 for his work on new methods for measurement of nuclear magnetism.

The early reception of the HBT experimental result

Correspondence from Eric Brannen and Harry I. Ferguson to Edward M. Purcell (November 29th, 1956)

> "Our interpretation of the effect that Brown and Twiss were advocating was not this ['photons overlap'] but rather that they expected an effect similar to the division of amplitude of a classical wave, half energy going to one photomultiplier and half detected at the two photomultipliers. We thought then that they expected this correlation even at low light intensities to the limit of only one photon being in the system at a time (to speak loosely). **This is the effect which we said would call for a revision of some of the concepts of quantum theory**." (Harvard University Archives, p. 1, the second emphases are mine)

The early reception of the HBT experimental result

Correspondence from E. Brannen and H. I. S. Ferguson to E. M. Purcell (November 29th, 1956)

> "He offered no suggestion of 'photon overlap' or indeed any clarification of the physical principles involved but only stated that he thought their experiments were more accurate" (Harvard University Archives, author's emphasis)

The early reception of the HBT experimental result

Correspondence from Eric Brannen and Harry Ferguson to E. M. Purcell (November 29th, 1956)

> "Perhaps the principal criticism we make of Brown and Twiss is that their article was ambiguous to some readers and that their suggested optical astronomical device would be extremely difficult to use with anything but brightest star. […] **it would seem that their high pressure mercury arc source intensity would have to be quite constant to ensure that the 'photon overlap' correlation not be swamped by rapid intensity fluctuations** […]. In conclusion, we <u>purposely</u> kept our intensity low enough that we could say roughly that 'only one photon was in the system at a time', in order to keep away from any effects due to 'photon bunching'." (Harvard University Archives, the first emphases are mine)

The early reception of the HBT experimental result

Correspondence from E. M. Purcell to E. Brannen (December 17th, 1956)

> "I want to say, too, that talking about **<u>interference</u> of <u>photons</u> is the easiest way to go astray in such matters.** To try to represent <u>a</u> photon by <u>a</u> wave-packet is asking for trouble. **On the other hand the classical calculations, a la Brown and Twiss, of the fluctuations in P is a perfectly sound and rigorous procedure**. The electromagnetic field is a classical field after all, which is why the Brown-Twiss effect only appears odd if one looks at it from a particle point of view; its oddness being simply the peculiarity of bosons. One might turn it around and say that this is a nice example of the fact that classical field <u>must</u> have bosons for its quanta." (Harvard University Archives, author's the first and third emphases and the second is mine)

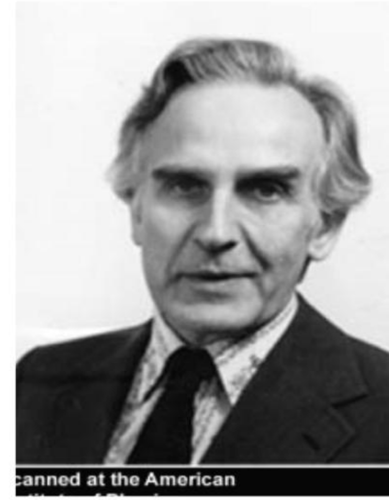
The early reception of the HBT experimental result

Correspondence from E. M. Purcell to E. Brannen (December 17th, 1956)

> "In regard to your comment about fluctuations in the source in the original Brown-Twiss experiment, I gathered from their paper that they had checked this by displacing one photocell enough to destroy the coherence, thus doing in the space domain what you did in the time domain by your insertion of the delay. There is a slight loop-hole in either procedure, it seems to me, which might be described in your case by saying that source fluctuations of period shorter than your smallest delay would still produce an effect." (Harvard University Archives)


Robert Pound

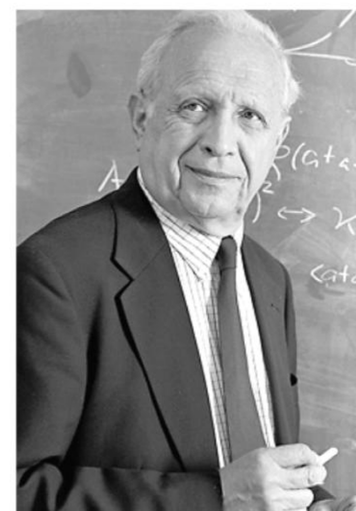

Glen Rebka



Peter Fellgett


Leonard Mandell


Emil Wolf


Roy J. Glauber

The early reception of the HBT experimental result

Fellgett (1957,p. 956)

"[…] belongs to the class in which an effect dependent on the **'wave' proprieties of light is observed in circumstances where the 'particle' proprieties predominate**, and therefore a refined experimental method is necessary to detect the effect sought for."

"**Semi-classical ideas, in fact, do not include the totality of our knowledge about the properties of radiation**, and there is precedent for a more subtle theory being needed to predict fluctuations than suffices for mean values." (emphases are mine)

The early reception of the HBT experimental result

Sillito (1957, p. 1127)

"It is presumably some such interference in the probability amplitude that explains the 'abnormal' fluctuations detected in the experiments of Brown and Twiss. On this point of view the effect is to be ascribed essentially to the operation of quantum statistics, as is suggested by Purcell. […] This does not imply, as has sometimes been suggested, that the interference between two photons may give rise to, say, four or none. The photon is not a particle, it does not survive a counting process uncharged, and it detectable only through its interaction with matter. […] **the interference between photons produces a distortion of the distribution in time of the events by which photons are detected**." (emphases are mine)

The answer from Hanbury Brown and Twiss to the criticisms

Hanbury Brown and Twiss (1957, p. 300-301)

"As Bohr has pointed out, in his Principle of Complementarity, a particular experiment can exemplify the wave or the particle aspect of light but not both; thus the interpretation is greatly simplified, and indeed is much more likely to be correct, if one confines oneself rigidly to the use of the appropriate language and talks photons when the energy behaves like a classical particle but otherwise talks only waves. […] we are dealing essentially **with an interference phenomena** which can be interpreted, on the **classical wave picture**, as a correlation between intensity fluctuations due to beats between waves of different frequency; **the concept of a photon need only be introduced at the stage where the energy is extracted from the light beam in the process of photoemission**." (emphases are mine)

The answer from Hanbury Brown and Twiss to the criticisms

Hanbury Brown and Twiss (1958, p. 291-292)

> "The first techniques, which may conveniently be regarded as illustrating the wave picture, consists in finding the correlation between the fluctuations in the anode currents of the light detectors by means of a linear multiplier which takes the time average of their cross-product. The second techniques, which illustrates the corpuscular nature of light, makes a use of a coincidence counter to detect individual events in which photoelectrons are emitted simultaneously from the cathodes of two light detectors."

The answer from Hanbury Brown and Twiss to the criticisms

Hanbury Brown (1991, p. 121)

> “To me the most interesting thing about all this fuss was that so **many physicists had failed to grasp how profoundly mysterious light really is**, and were reluctant to accept the practical consequences of the fact that **modern physics doesn’t claim to tell us what things are like ‘in themselves’ but only how they ‘behave’**. […] **If our system was really going to work, one would have to imagine photons hanging about waiting for each other in space**!” (emphases are mine)

Some concluding remarks

- Was the HBT experimental result wrong? Was the time of arrival of photons correlated when a coherent beam light was used as Hanbury Brown and Twiss had pointed out? If their results were correct, what would the fate of the concept of photon be?

- Hanbury Brown and Twiss observed, in fact, a real effect when they showed that the time of arrival of photons was correlated because they did not use a completely coherent light beam. But, we know it in hindsight. However, they thought, like Brannen and Ferguson, that an arc mercury source was a coherent beam. A completely coherent source only became possible with the laser in 1960.

Some concluding remarks

- Though Purcell (1956, p. 1449) claimed that “the [Hanbury] Brown-Twiss effect, far from requiring a revision of quantum mechanics, is an instructive illustration of its elementary principle”, the HBT experiment provoked a heated debate about the concept of the photon.

- As we know, this *imbroglio* was later solved by Glauber, in a work awarded the 2005 Physics Nobel Prize, through the theoretical development of “the coherent states of the electromagnetic field, often called Glauber states” (Paul, 2004, 39).

Some concluding remarks

Glauber (2005)

> “The late 50's proved to be an exciting time for many reasons. A radically new light source, the laser, was being developed and there were questions in the air regarding the quantum structure of its output. **That was particularly so in view of the surprising discovery of quantum correlations in ordinary light by Hanbury Brown and Twiss**. **[…] That was the period in which I began to work on quantum optics with a surmise that the Hanbury Brown-Twiss correlation would be found absent from a stable laser beam**, and then followed it with a sequence of more general papers on photon statistics and the meaning of coherence.” (Nobel Prize Speech, emphases are mine)

Acknowledgements

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Vielen Dank!