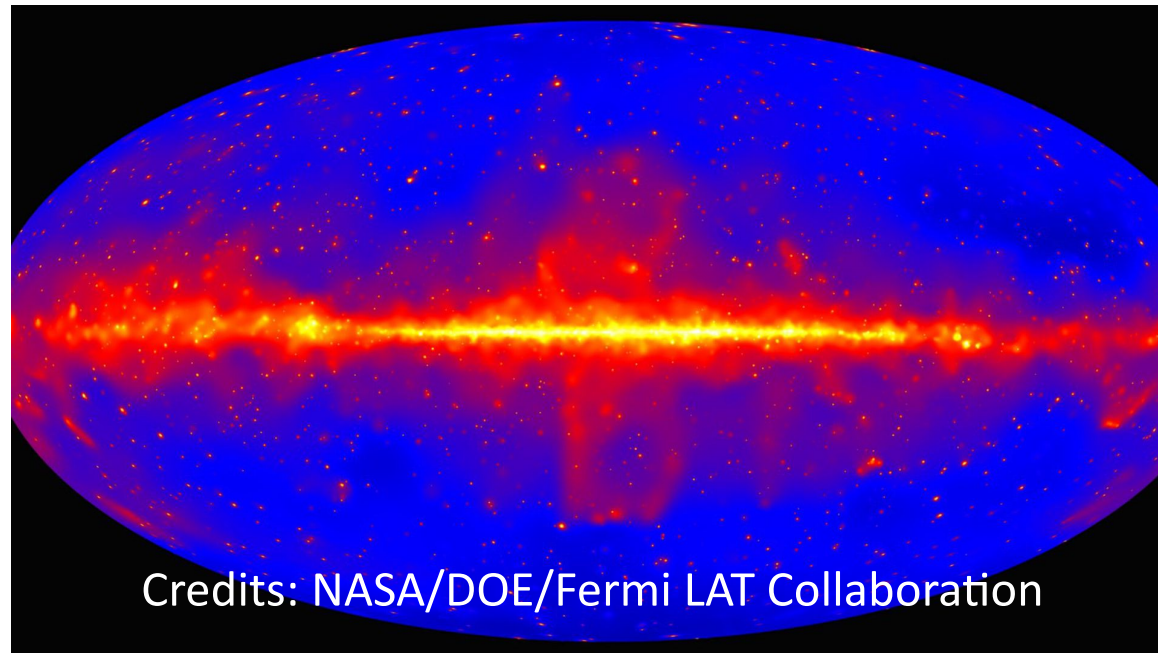


A SHORT HISTORY OF THE PHOTON

Fulvio Parmigiani



" John A. Wheeler: "the photon — a smoky dragon". "...no elementary quantum phenomenon is a phenomenon until it is a recorded phenomenon"

Roy Glauber: "A photon is what a photodetector detects."

"A photon is *where* the photodetector detects it."

THE MOMENTUM OF A MASSLESS PARTICLE

MOMENTUM TRANSFER (RADIATION PRESSURE) BY LIGHT ONTO MATTER

In 1608, Johannes Kepler (1571–1630) wrote the about the effects of the sunlight on a comet flying past the Sun:

“ The Sun’s rays pass through the corpus of the comet and instantly take some of its material along on its way out, away from the Sun; that is how, I think, the tail of the comet comes about, which always stretches away from the Sun. “

Kepler, Johannes. 1608. Ausführlicher Bericht von dem .. 1607 erschienenen Haarstern oder Cometen vnd seinen Bedeutungen

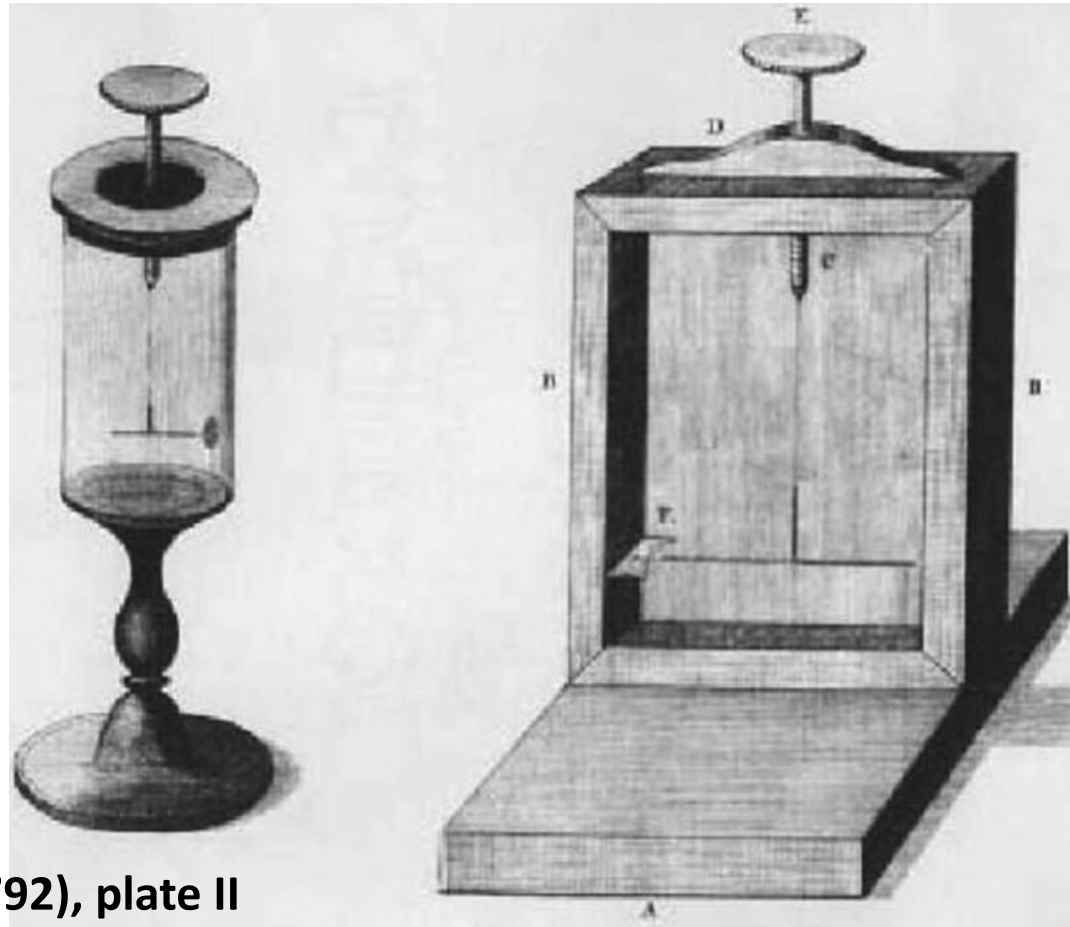
Wilhelm Homberg (1652–1715) in 1708 set an experiment where he flipped around an asbestos fiber placed at the focus a Tschirnhaus burning mirror concluding *“que les rayons de soleil eussent la force de presser et de pousser, même quand ils sont renis par le Miroir ardent...»*

However, later on (mid of the 18th century) it was clear to the scholar studying the nature of the light that the heating effects at the focus of a large lens or mirror, could be the cause of the mechanical effects attributed to the light.



Johannes Kepler (1571–1630)

MOMENTUM TRANSFER (RADIATION PRESSURE) NOT SO EASY TO MEASURE



Source Bennet (1792), plate II

Reverend **Abraham Bennet (1749–1799)** gave the first scientific observation of a freely swinging needle in a partially evacuated glass vessel (1792). But he commented: “*I could not perceive any motion distinguishable from the effects of heat.*”

He wondered about the model of light particles: “*Perhaps sensible heat and light may not be caused by the influx or rectilinear projections of fine particles: but by the vibrations made in the universally diffused caloric or matter of heat, or fluid of light.*”

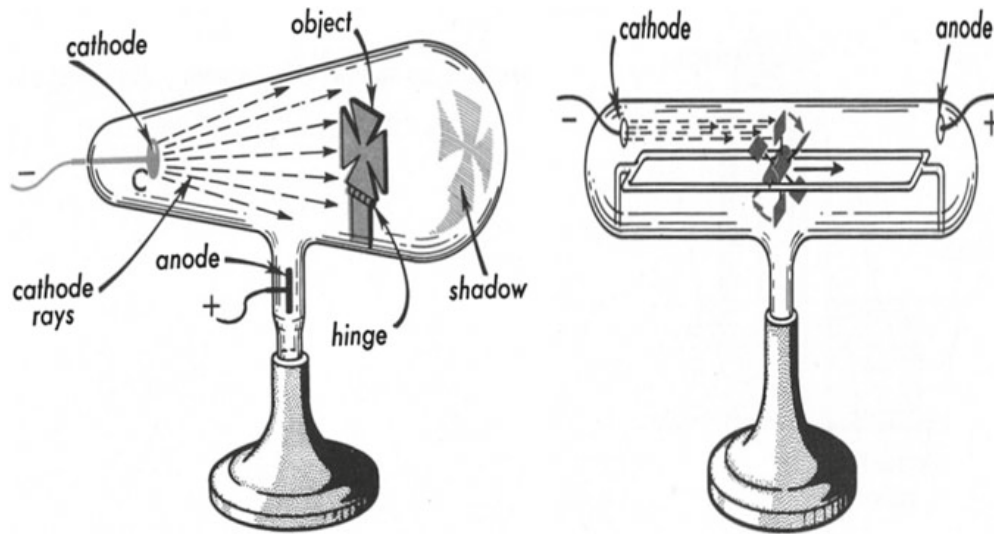
EXPERIMENTAL PROOF OF LIGHT PRESSURE

In 1876 the Italian physicist **Adolfo Bartoli (1851–1896)** produced an elegant thermodynamical argument, based on a thought experiment where a suspended surface within a partially evacuated glass container exerts “light pressure” on that surface for why the light pressure must exist, otherwise the second law of thermodynamics, when applied to a cyclical process with thermal radiation, would be violated.

Experimental proof of light pressure finally arrived in 1901. **Pyotr Nikolaevich Lebedev (1866–1912)** at the *Lomonosov State University* in Moscow **succeeded in producing the first laboratory proof of radiation pressure, but with a high margin of systematic error (greater than 10%).** In 1903 **Ernest Fox Nichols (1869–1924)** and **Gordon Ferrie Hull (1870–1956)** at *Dartmouth College* in the U.S.A. managed to reduce this error to just 1%.

[See Maxwell (1873) §792–793, Poynting (1884); in addition Poincaré (1900), who also calculated the recoil of a system emitting or reflecting light]

CATHODIC RAYS AND LIGHT PRESSURE



Source of both images: Wikimedia, in the public domain

James Clerk Maxwell (1831–1879) and John Henry Poynting (1852–1914).

The energy density of the electromagnetic field results from Maxwell's equations for the electric and magnetic fields \mathbf{E} and \mathbf{B} proportional to $(E^2 + B^2)$. The so-called Poynting vector

$\mathbf{S} = \mathbf{E} \times \mathbf{B}$ describes the magnitude and direction of flow of electromagnetic energy and was first computed by this English physicist in 1884. In his words : **“It follows at once that the energy flows perpendicularly to the lines of electric force, and so along the equipotential surfaces where these exist. It also flows perpendicularly to the lines of magnetic force, and so along the magnetic equipotential surfaces where these exist. If both sets of surfaces exist their lines of intersection are the lines of flow of energy.”**

CATHODIC RAYS AND LIGHT PRESSURE: A CAREFULL ANALYSIS

The Dutch physicist Hendrik **Antoon Lorentz (1853–1928)** carefully distinguished in his book, *The Theory of Electrons* (1909), between the transfer of energy and momentum by massive particles (electrons) versus electromagnetic waves :

«The flow of energy can, in my opinion, never have quite the same distinct meaning as a flow of material particles. [...] It might even be questioned whether, in electromagnetic phenomena, the transfer of energy really takes place in the way indicated by Poynting's law, whether, for example, the heat developed in the wire of an incandescent lamp is really due to energy which it receives from the surrounding medium, as the theorem teaches us, and not to a flow of energy along the wire itself. In fact, all depends upon the hypotheses which we make concerning the internal forces in the system, and it may very well be that a change in these hypotheses would materially alter our ideas about the path along which the energy is carried from one part of the system to another. It must be observed however that there is no longer room for any doubt, so soon as we admit that the phenomena going on in some part of the ether are entirely determined by the electric and magnetic force existing in that part. Therefore, if all depends on the electric and magnetic force, there must also be one near the surface of a wire carrying a current, because here, as well as in a beam of light, the two forces exist at the same time and are perpendicular to each other.»

[Lorentz, Hendrik Antoon. 1909. *The Theory of Electrons and Its Applications to the Phenomena of Light and Radiant Heat. A Course of Lectures delivered in Columbia University, New York, in March and April 1906*, (a) New York: Columbia University Press, 1909; (b) 2nd ed., 1915; (c) Leipzig: Teubner, 1916.

]

AN UNEXPECTED HELP

For many physicists, it seemed self-contradictory that a 'massless' light quantum should transfer momentum like a material particle in collision processes. However, an important outcome from the special theory of relativity came by considering the square of the momentum four-vector $p^\mu (E/c, \mathbf{p})$

$$E^2 = (pc)^2 + (mc^2)^2$$

where evidently a massless particle ($m=0$) still have a momentum

$$E = pc \Rightarrow p = E/c$$

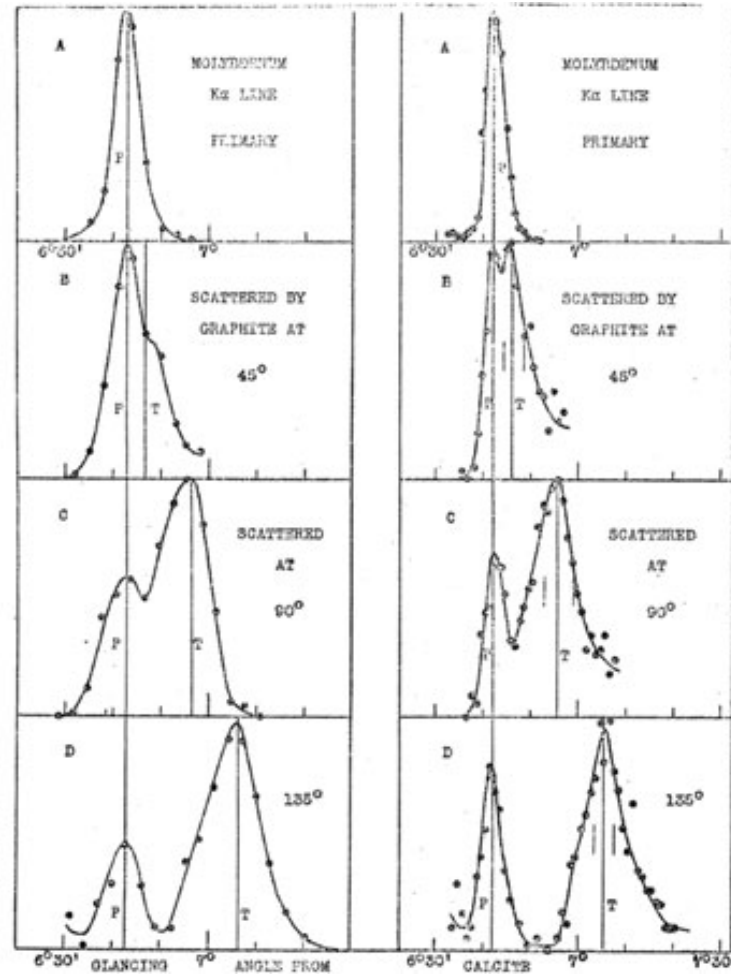
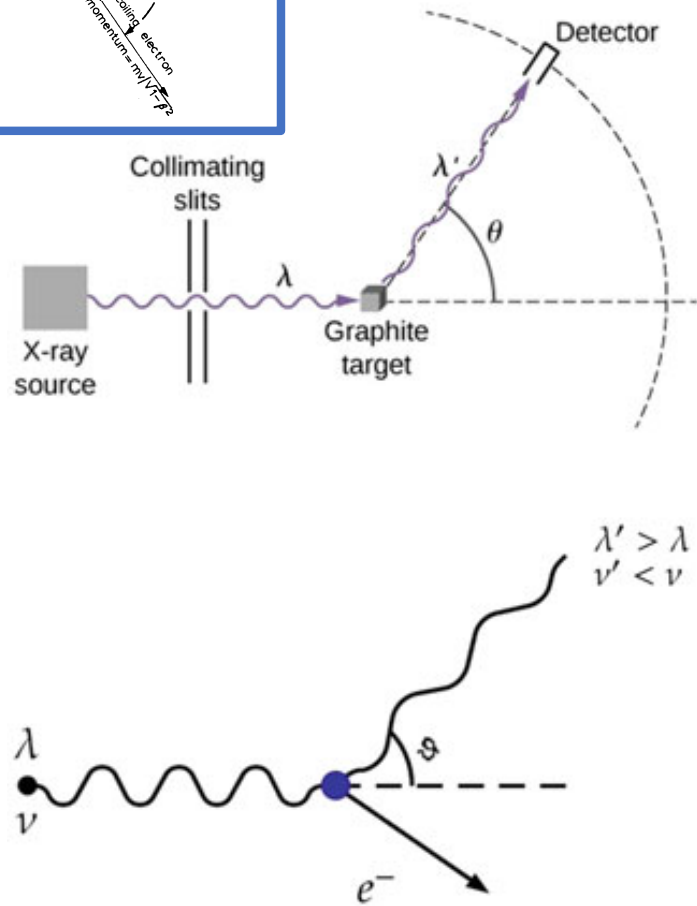
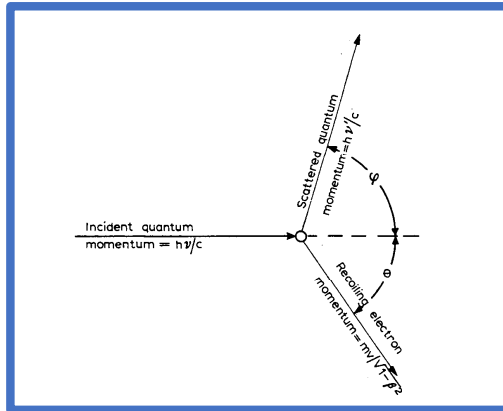
This ultra-relativistic limit inheres a strict proportionality between energy and momentum $p = E/c = hv/c$. This is what was used to interpret Compton experiments. As **Max Planck** and **Louis de Broglie** showed, the radiation pressure of light and other electromagnetic waves could be brought quantitatively into agreement with the increasingly precise measurements when Einstein's postulate $p = hv/c$ is adopted. **Conversely whereas Newtonian dynamics or semiclassical electrodynamics only lead to half the measured value.**

REMINDING THE COMPTON EXPERIMENT

ARTHUR H. COMPTON

X-rays as a branch of optics

Nobel Lecture, December 12, 1927



AN UNCOMFORTABLE SITUATION

THE MATTER WAVES

The next major step toward such an integrative clarification of wave-particle duality was taken by **Louis de Broglie (1892–1987)**.

In 1924 Louis de Broglie completed his studies with a dissertation on *Recherches sur la Théorie des Quanta*. Starting from Einstein's $E = mc^2$ and $E = hv$ de Broglie drew the consistent conclusion that to any mass m there must also be a corresponding frequency $\nu = mc^2/h$. Thus, a frequency and also wavelength $\lambda = h/p$ must be assigned to each particle as well, where $p = mv$ is the momentum of a particle of mass m and velocity v , and the frequency ν and velocity of light c must be attached to the wavelength λ as $\lambda = c/\nu$.

In 1922, it was not yet clear to de Broglie that the rest mass of a light quantum is exactly zero. In a paper for *Journal de Physique et Le Radium*, he wagered that these **“atoms of light (presumed to be of the same very small mass) seem to move at speeds varying with their energy (frequency), but all at extremely close to c .”**

«This is an astonishing parallel with Isaac Newton's projectile theory of light 250 years before. As we have already seen, Newton had drawn a very similar dependence between the velocity of light and the presumed mass of his light globuli, but rejected it again when he saw that there was no empirical evidence of any existing speed discrepancies in light from different regions of the optical spectrum.» [Klaus Hentschel: *Photons The History and Mental Models of Light Quanta*, Springer 2018]

UNDULATORY AND CORPUSCULAR PROPERTIES OF LIGHT

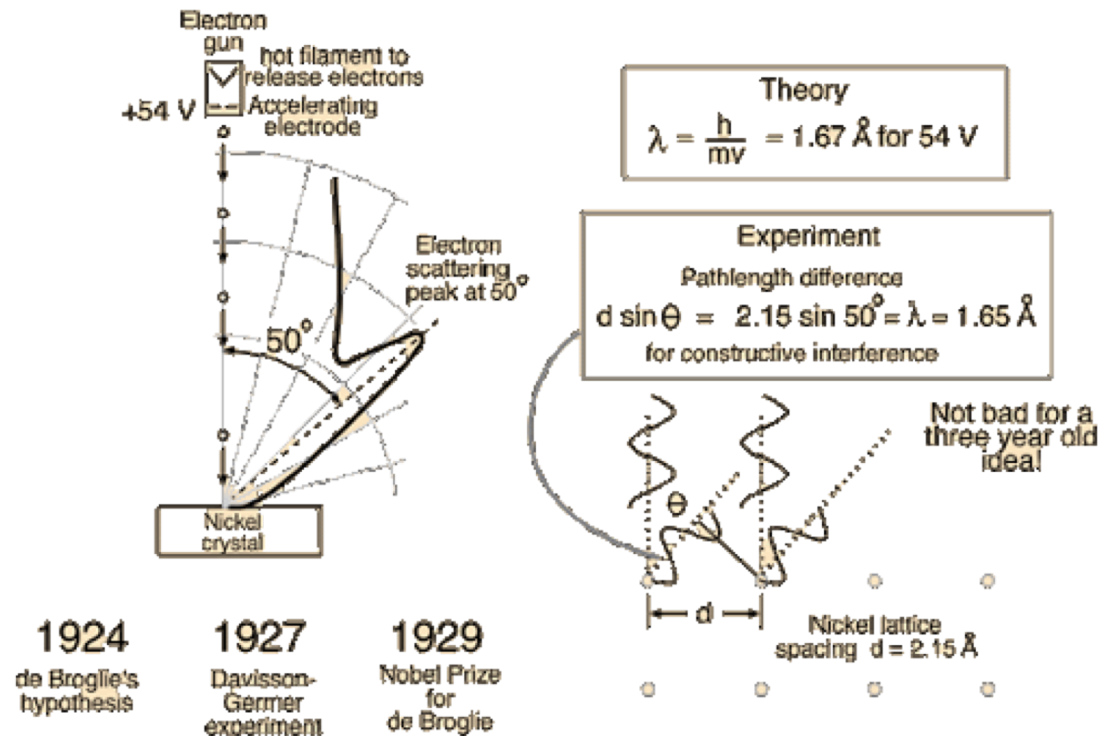
Einstein enthusiastically wrote to de Broglie's doctoral advisor, **Paul Langevin (1872–1946)**, at the end of 1924: “He has lifted one corner of the great veil.” De Broglie received awards in 1926 and 1927 from the *Institut de France*, and two years later the highly regarded *Medaille Henri Poincaré* conferred by the Parisian *Académie des Sciences* as well as the Nobel prize in physics.¹⁰²

In a speech at the University of Berlin on 23 February 1927, Albert Einstein described with these words the complicated constant vacillation **between undulatory and corpuscular properties of light**, and now also of matter, as a hopelessly overtaxed the “intellectual powers of physicists” —including his own: ***The problem that we presently have, which is of a principal nature in the area of luminous phenomena, comes down to showing either that the corpuscular theory grasps the true essence of light, or that the undulatory theory is right and the quantum-like aspects are merely apparent, or, finally, that both interpretations correspond to the true nature of light and that light has characteristics that are both quantum-like and undulatory.*** [1927 This is a report about Einstein's talk before the *Mathematisch- Physikalische Arbeitsgemeinschaft an der Universität Berlin*, with passages occasionally quoted almost verbatim.]

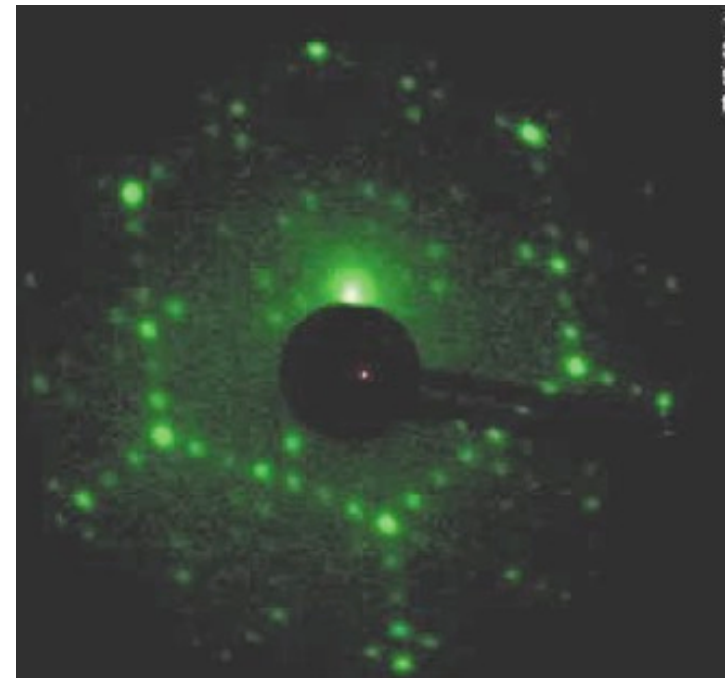
AN INDISPUTABLE DEMONSTRATION

In 1927 **Clinton J. Davisson (1881–1958)** and **Lester H. Germer (1896–1971)** succeeded in verifying de Broglie's bold predictions.

Their experiment made the matter waves associated with electrons interfere with each other—a clear characteristic of wave-like entities!



LEED pattern obtained from Si(111)7x7 reconstructed surface



HOW EMPTY IS THE PHYSICAL VACUUM?

P.M. DIRAC AND E.FERMI: QUANTUM THEORY OF RADIATION

The beginning of quantum electrodynamics as a modern theory of interaction of light with matter was made by **Paul Dirac** in 1927 in his fundamental paper on '*Quantum theory of emission and absorption of radiation,*' *communicated to the Proceedings of the Royal Society (London).*

*The Quantum Theory of the Emission and Absorption of
Radiation.*

By P. A. M. DIRAC, St. John's College, Cambridge, and Institute for
Theoretical Physics, Copenhagen.

(Communicated by N. Bohr, For. Mem. R.S.—Received February 2, 1927.)

Independently **Enrico Fermi (1901-1954)** developed his own approach towards the quantum theory of radiation. Fermi applies the quantum theory of radiation to many physical situations. For example, he treats Lippmann fringes and shows that the radiation emitted by one atom and absorbed by another travels with the speed of light.

JANUARY, 1932

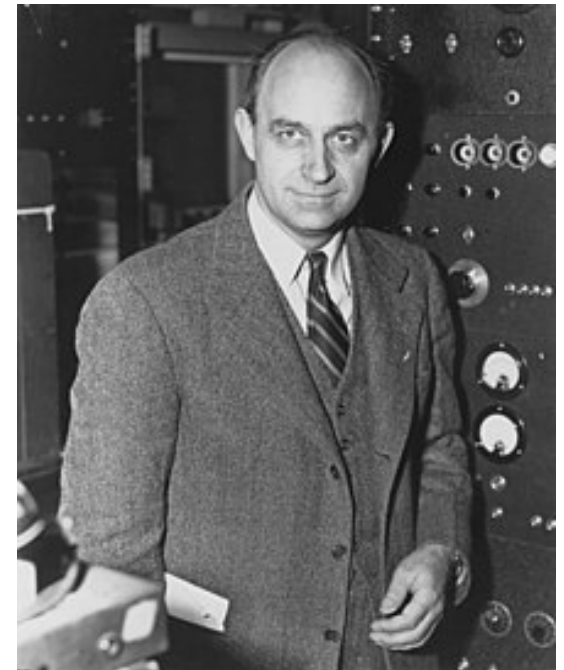
REVIEWS OF MODERN PHYSICS

VOLUME 4

QUANTUM THEORY OF RADIATION*

BY ENRICO FERMI

UNIVERSITY OF ROME, ITALY



Enrico Fermi (1901-1954)

THE ZERO FIELD ENERGY

Dirac's idea was to apply quantum mechanics not only to the particles in atoms but also, by making use of the ideas of Paul Ehrenfest and Peter Debye, to consider the radiation field in empty space as a system of quantized oscillators which interact with atoms. The difficulties involved were so great that Dirac found it worthwhile to look into an approximation which was not relativistic. As a total system, he considered an atom in interaction with a radiation field. In order to have a discrete number of degrees of freedom for the latter, he enclosed the system in a finite box, and decomposed the radiation into its Fourier components. (See Appendix 1).

The resulting quantization of the EM led to an Hamiltonian (the total energy of the e.m. mode) given by

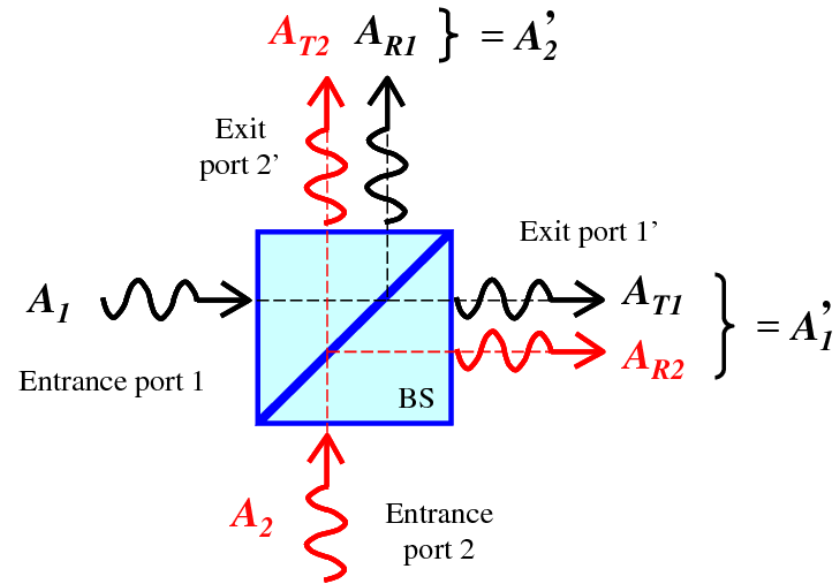
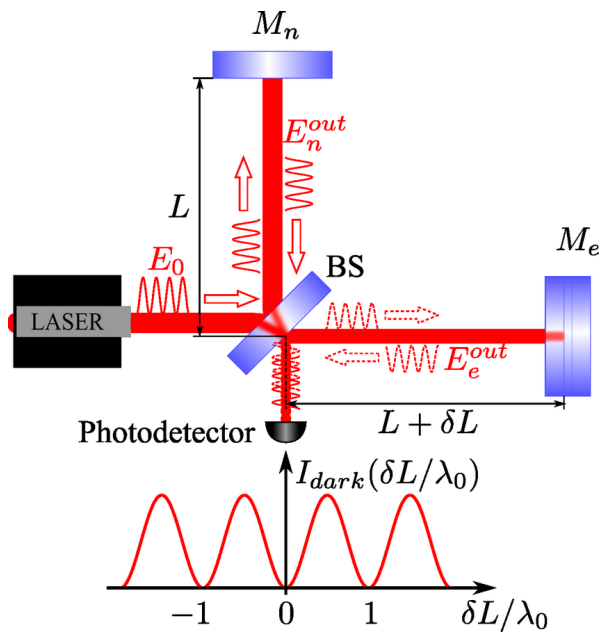
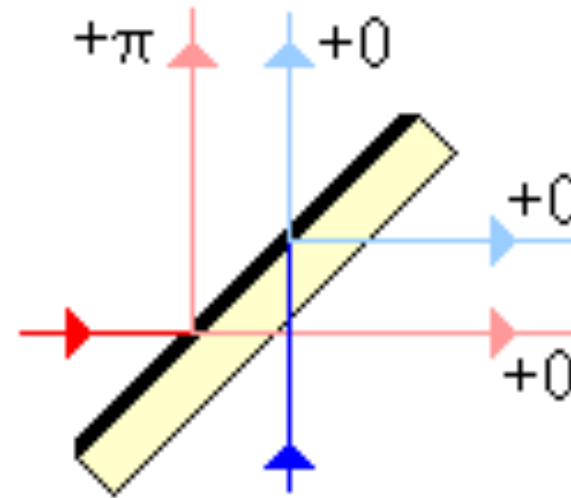
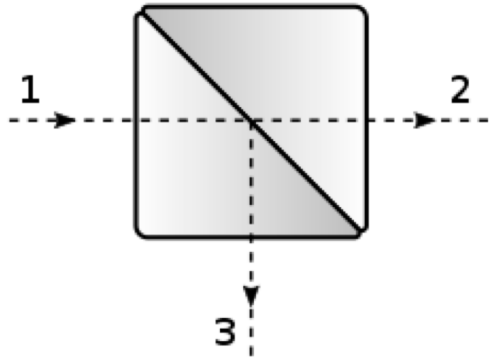
$$E = \langle \mathcal{H} \rangle = 2 \sum_{k=1}^{k_c} \hbar \omega_k \left\langle a_k^\dagger a_k + \frac{1}{2} \right\rangle$$

and the zero-point energy

$$E_0 = \frac{2}{V} \sum_{k=1}^{k_c} \frac{1}{2} \hbar \omega_k$$

SEE APPENDIX 1

OBSERVING THE VACUUM STATE



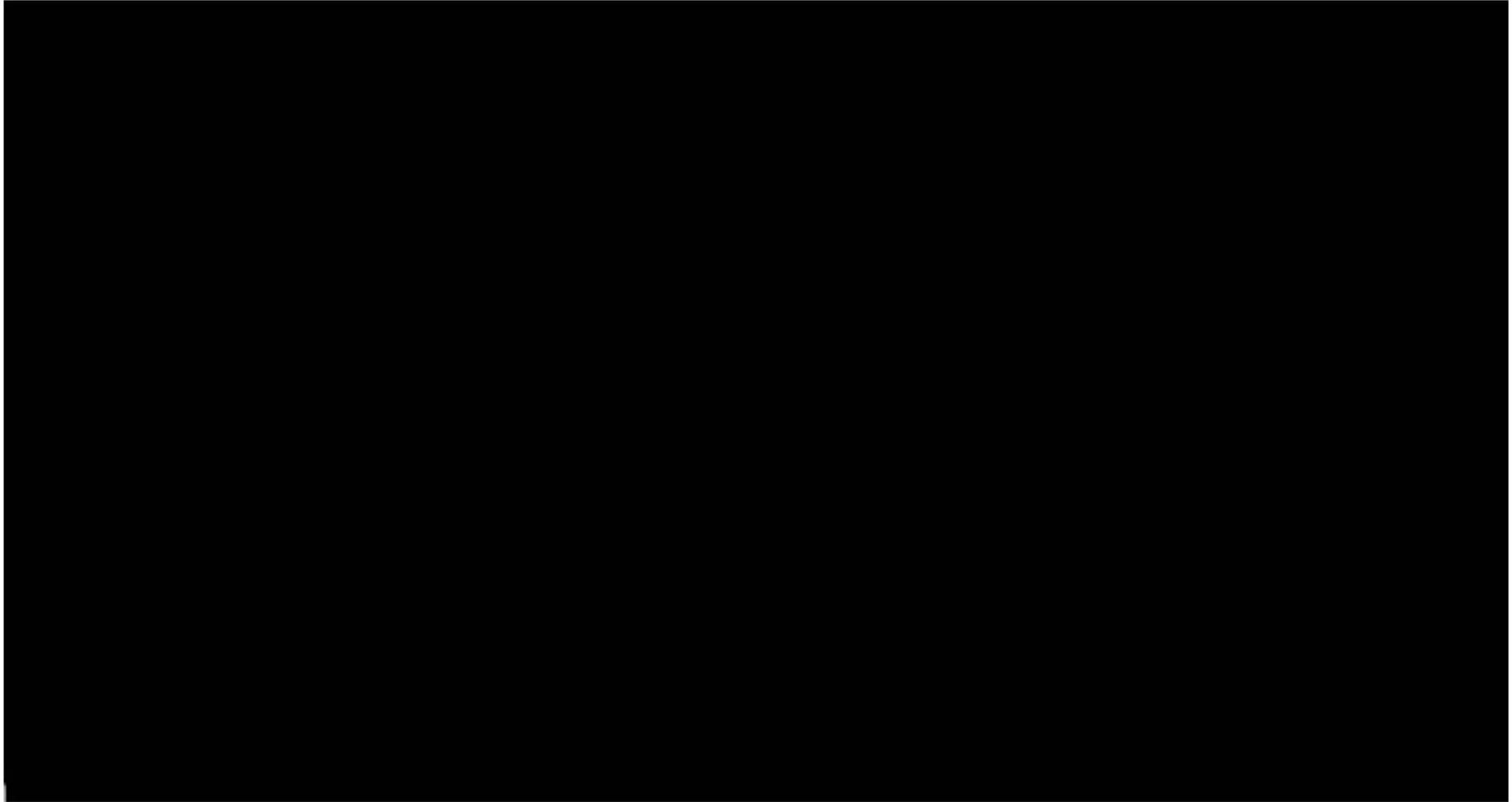
SINGLE PHOTON YOUNG INTERFEROMETER



Universiteit Leiden

0,025 msec

SINGLE ELECTRON YOUNG INTERFEROMETER



QM COPENAGHEN INTERPRETATION IN A NUTSHELL

- A system is completely described by a **wave function Ψ** , which represents an observer's knowledge of the system. (Heisenberg).
- The description of nature is **probabilistic**. The probability of an event is the mag squared of the wave function related to it. (Max Born).
- **Heisenberg's Uncertainty Principle** says it's impossible to know the values of all of the properties of the system at the same time; properties not known with precision are described by probabilities.
- **Complementarily Principle**: matter exhibits a **wave-particle duality**. An experiment can show the particle-like properties of matter, or wave-like properties, but not both at the same time. (Bohr).
- Measuring devices are essentially **classical devices**, and they **measure classical properties such as position and momentum**.
- The correspondence principle of Bohr and Heisenberg: **the quantum mechanical description of large systems should closely approximate the classical description**.

**“I, AT ANY RATE, AM CONVINCED
THAT GOD DOES NOT PLAY DICE.”**

Einstein to Born

EPR PARADOX



A. Einstein

B. Podolsky

N. Rosen

The **Einstein–Podolsky–Rosen paradox** (EPR paradox) is a [thought experiment](#) proposed by physicists [Albert Einstein](#), [Boris Podolsky](#) and [Nathan Rosen](#) (EPR), with which they argued that the description of physical reality provided by [quantum mechanics](#) was incomplete. In a 1935 paper titled "Can Quantum-Mechanical Description of Physical Reality be Considered Complete?»

They argued that no action taken on the first particle could instantaneously affect the other, since this would involve information being transmitted faster than light, which is forbidden by the [theory of relativity](#). They invoked a principle, later known as the "EPR criterion of reality", positing that, "If, without in any way disturbing a system, we can predict with certainty (i.e., with [probability](#) equal to unity) the value of a physical quantity, then there exists an element of reality corresponding to that quantity".

The EPR paper ends by saying:

«While we have thus shown that the wave function does not provide a complete description of the physical reality, we left open the question of whether or not such a description exists. We believe, however, that such a theory is possible.»

"STOP TELLING GOD WHAT TO DO"

Neils Bohr

BOHM'S HIDDEN VARIABLES AND BELL'S THEOREM

Bohm's variant

In 1951, **David Bohm** proposed a variant of the EPR thought experiment in which the measurements have discrete ranges of possible outcomes, unlike the position and momentum measurements considered by EPR.

In 1964, **John Bell (John Stewart Bell 1928 –1990)** published a paper investigating the puzzling situation at that time: on one hand, the EPR paradox purportedly showed that quantum mechanics was nonlocal, and suggested that a hidden-variable theory could heal this nonlocality.

Bell set out to investigate whether it was indeed possible to solve the nonlocality problem with hidden variables, and found out that first, the correlations shown in both EPR's and Bohm's versions of the paradox could indeed be explained in a local way with hidden variables, and second, that the correlations shown in his own variant of the paradox couldn't be explained by *any* local hidden-variable theory. This second result became known as the Bell theorem.

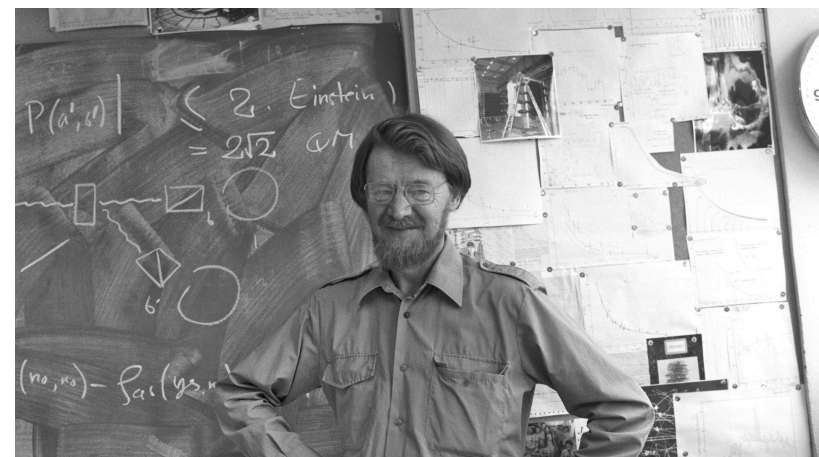
Physics Vol. 1, No. 3, pp. 195–200, 1964 Physics Publishing Co. Printed in the United States

ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

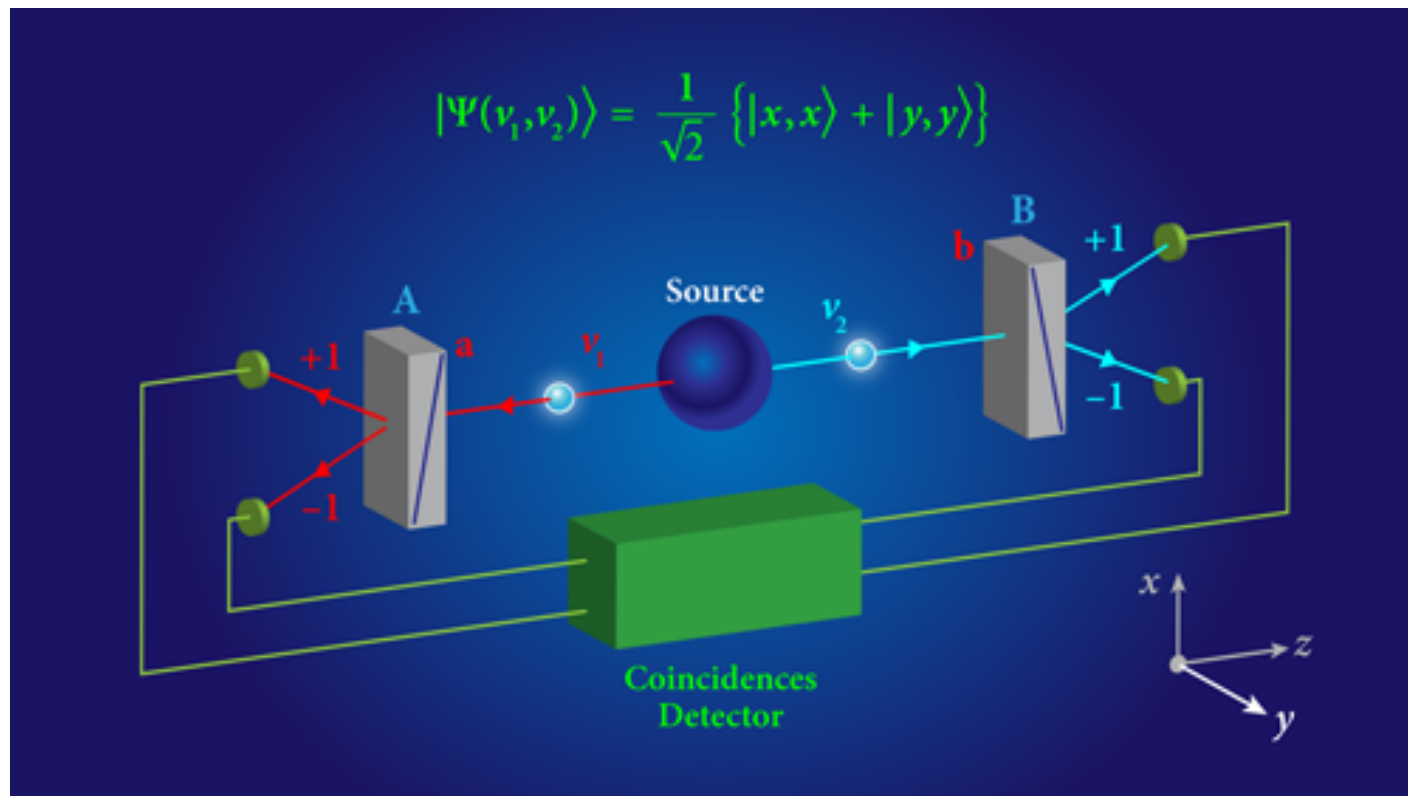
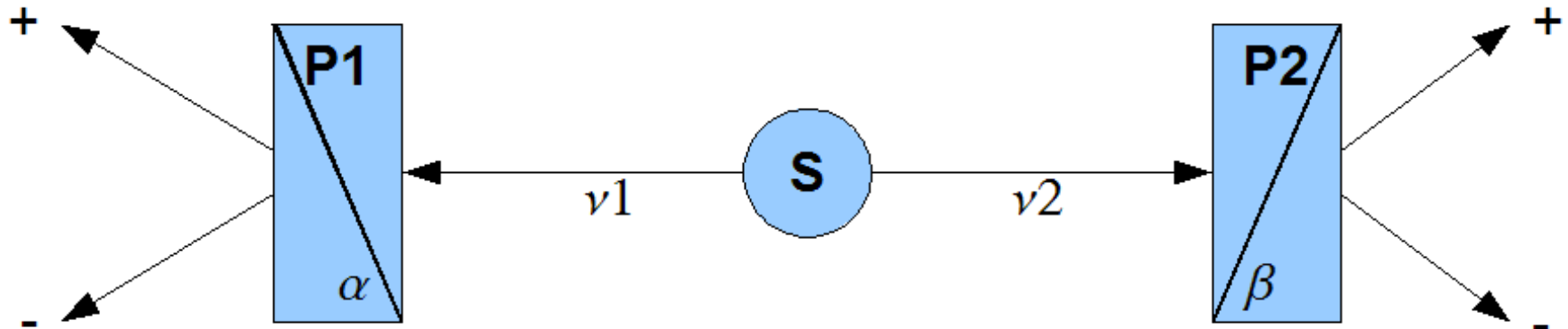
J. S. BELL†

Department of Physics, University of Wisconsin, Madison, Wisconsin

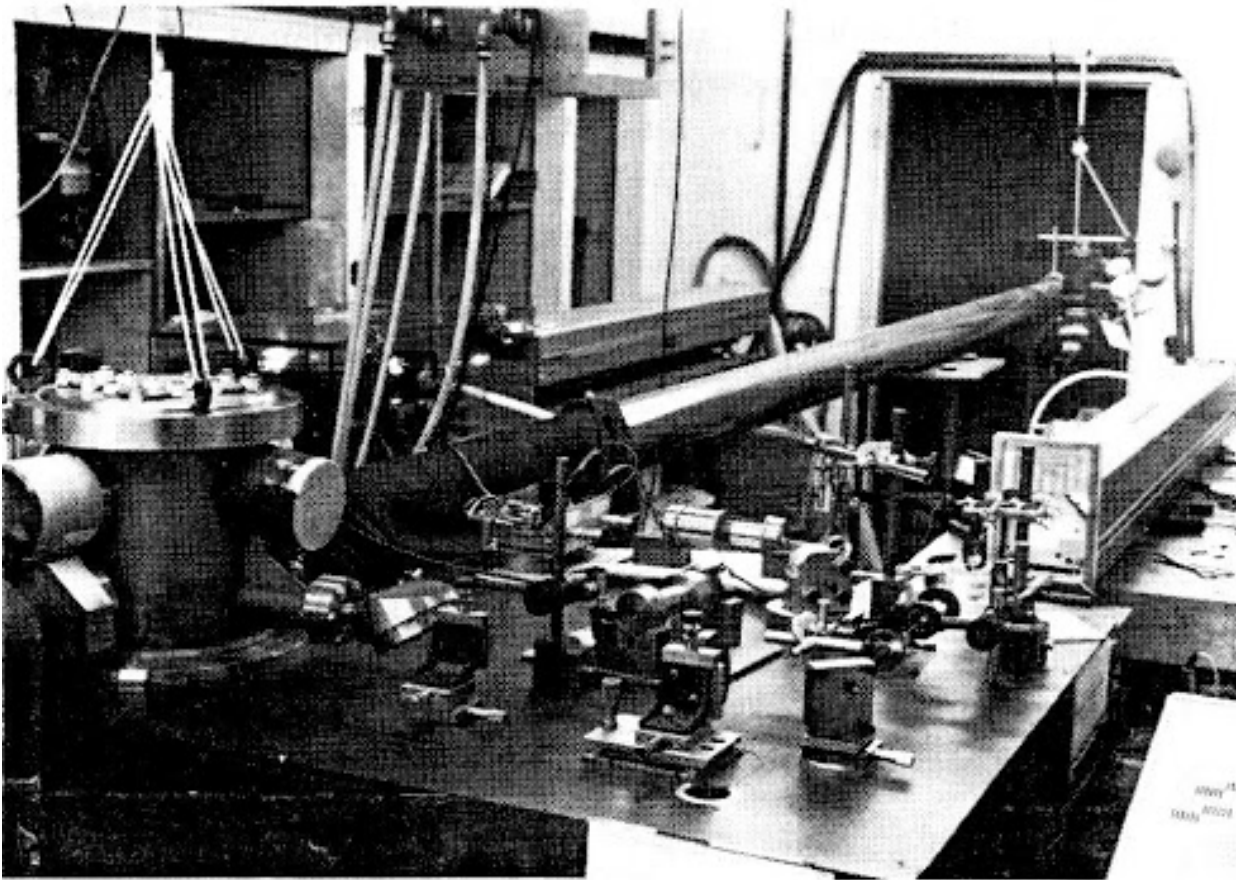
(Received 4 November 1964)



ENTANGLED PHOTONS



THE ALAN ASPECT EXPERIMENT



*Optique de focalisation du laser à
Krypton ionisé dans l'enceinte à vide
(cf. Fig. VI-8, page 197).*

CONCLUSIONS

After a great number of experiments it has been proved that entangled states of quantum particles exhibit the non separability and nonlocality of quantum mechanics.

Nowadays the generation of entangled states of photons, particularly for use in tests of Bell's inequalities is at the hand of many laboratories.

More and more this matter is becoming the play ground of potentially useful technological applications ranging from
quantum communication, including cryptography
transfer of two bits of information in one photon
quantum teleportation
quantum computation

However, accordingly to many physicists we still don't know what a photon is.

" John A. Wheeler: "the photon — a smoky dragon". "...no elementary quantum phenomenon is a phenomenon until it is a recorded phenomenon"

Roy Glauber: "A photon is what a photodetector detects."

"A photon is *where* the photodetector detects it."

APPENDIX 1a

A new picture of forces between particles appears in quantum field theory. We can understand the interaction between two charged particles at a distance as an exchange of virtual photons, which continuously pass from one charged particle to another. These exchanged virtual particles are not directly observed as particles because of the conservation of energy, but, according to Niels Bohr's extension of Heisenberg's uncertainty principle, $\Delta E \Delta t \geq \hbar$, such an exchange is possible for short enough time intervals. Hence the virtual particles can be created for a very short time in the intermediate states of the physical processes, but they must be absorbed quickly enough. As a result, the charged particle is surrounded by a cloud of virtual photons. The latter can produce other virtual particles, such as electrons and positrons, by means of pair creation in the vacuum, and then the electrons and positrons thus created must annihilate each other very quickly to preserve energy conservation within the limits of the uncertainty principle. Thus the cloud around the charged particle consists of photons, electrons, and positrons.

Pauli's response was scathing. In a letter to Dirac he said, 'Your recently published remarks in the Proceedings of the Royal Society concerning Quantum electrodynamics were ... certainly no masterpiece. After a confused introduction, that consisted of only half understandable, because only half understood, sentences, you come finally to results in a simplified one dimensional example that are identical with those that the formalism of Heisenberg and I gives for that example. (This identity is immediately recognizable and has since been calculated in much too complicated a fashion by Rosenfeld.) This conclusion of your work stands in contrast to your more or less unambiguous assertion in the introduction that somehow you can construct a better quantum electrodynamics than Heisenberg and I.

APPENDIX 1 continue

As an indirect consequence of his theory, Dirac arrived at a completely new picture for the vacuum. But in quantum mechanics, because of Heisenberg's uncertainty principle, the electromagnetic field oscillators cannot be strictly at rest. As a consequence, even in the ground state with the lowest possible energy, there still exist the so-called zero-point oscillations of quantum oscillators of frequency ω , having the energy $1/2\hbar\omega$. Hence the oscillatory nature of the electromagnetic field of radiation leads to the zero-point oscillations of this field in the vacuum state (the state of lowest possible energy). The physical vacuum is not an empty space, but is 'populated' with zero-point oscillations, which are the cause of the spontaneous emission of radiation from atoms.

Thus Dirac's theory provided the explanation for all results regarding the emission and absorption of radiation by atoms.

This quantum field theory could be used to model important processes such as the emission of a [photon](#) by an electron dropping into a [quantum state](#) of lower energy, a process in which the *number of particles changes*—one atom in the initial state becomes an atom plus a [photon](#) in the final state. It is now understood that the ability to describe such processes is one of the most important features of quantum field theory.

APPENDIX 2

By the 1920s, it had become clear to most physicists that classical mechanics could not fully describe the world of atoms, especially the notion of “quanta of light”

Thus, Quantum Mechanics which was born in the 1900s, marked a revolution in Physics. Werner Heisenberg, Niels Bohr and others helped to create the theory, called Copenhagen interpretation of quantum mechanics .

- This is the most general interpretation of quantum mechanics.

The Copenhagen Interpretation is an interpretation of quantum mechanics. It arose out of discussions between **Bohr** and **Heisenberg** in 1927 and was strongly supported by Max Born and Wolfgang Pauli, having in the work of P. Dirac Principles of **Quantum Mechanics** (1930) and in particular in the ***Mathematical Foundations of Quantum Mechanics*** (1932) by John von Neumann a solid mathematical base for the future development of quantum theory and experiments.

APPENDIX 3

Quantum entanglement is a physical phenomenon that occurs when pairs or groups of particles are generated or interact in ways such that the quantum state of each particle cannot be described independently of the others.

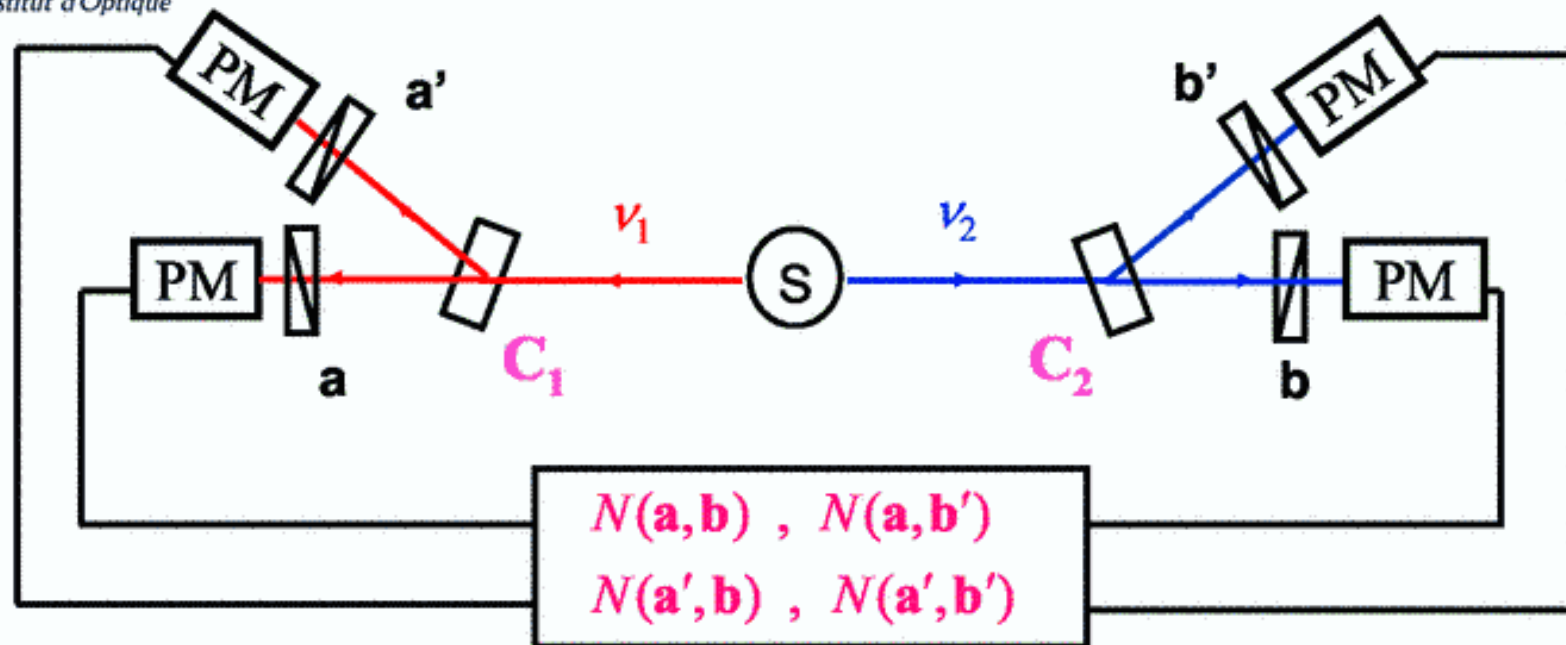
The basic idea of quantum entanglement is that two particles can be intimately linked to each other even if separated by billions of light-years of space; a change induced in one will affect the other.

Measurements of physical properties such position, appropriately momentum, correlated. as performed on entangled particles are found to be spin, and polarization, performed on entangled particles are found to be correlated in ways such that the quantum state of each particle cannot be described independently of the others, even when the particles are separated by a large distance – instead, a quantum state must be described for the system as a whole. even if separated by billions of light-years of space; a change induced in one will affect the other.

There are two entangled state A with wave function Y_1 and Y_2 and state B with wave function X_1 and X_2 . then,

Superposed state: $Y_1X_1+Y_1X_2+Y_2X_1+Y_2X_2$ Entangled state: $(Y_1+Y_2)(X_1+X_2)$

Experiment with optical switches



In the 1982 Orsay experiment, each switch C_1 and C_2 worked in a quasi-periodic way, not truly random.

But the two switches were driven by two different generators, drifting independently.