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François Frémont

Young-Type Interferences with Electrons

Basics and Theoretical Challenges in Molecular Collision Systems

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With 206 Figures

Springer

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Preface

We know that light has fascinated philosophers, physicists, theologians, and engineers for a long time. The nature of light, especially, has been the subject of many controversies and discussed in detail since the seventeenth century. This is essentially due to the fact that light in itself is not visible. From simple considerations, Isaac Newton put forward the idea that light was composed of little balls. This truly innovative idea was quickly countered with the emergence of the wave theory of light. For two centuries, this theory was proven in all areas of wave frequencies. However, at the beginning of the twentieth century, this ingrained idea was challenged through the decisive contribution of Albert Einstein, who showed that the photoelectric effect could be easily explained when light was considered to be composed of small particles, or "quanta."

Then, in 1924, Louis de Broglie formulated his well-known hypothesis that waves could be associated with any massive particle. Thus was born the concept of wave-particle duality. This duality particularly manifests itself in the interference phenomenon, first discovered for light by Thomas Young in 1801. Since the de Broglie hypothesis, many interference experiments using massive particles, such as electrons, protons, and atoms, have confirmed both the wave and particle theories.

Despite experimental and theoretical efforts, the nature of light and, consequently, the nature of massive particles remain mysterious. The very issue of duality means that we do not know how to define these particles. With the advent of new technologies, we could imagine that the nature of light would be revealed. But despite these efforts, the question remains. The only thing we can characterize is the behavior of these particles or waves, depending on their action on the interacting medium. Both aspects are nevertheless mixed: when wave behavior is revealed, the particle aspect is not lost, and vice versa.

Centuries of research, heated discussions, and controversies force us to make a detailed analysis of the past and the present situation. To the best of our knowledge, no book has dealt with the interference phenomenon, including light and massive particles. Consequently, analogies between photon interferences and massive particle interferences are rare. However, over the past decade, new approaches have been developed through the detailed analysis of interference figures produced by electrons emitted during fast or slow ion collisions with molecules.

To explain these analogies, this book is divided into five parts. The first and second chapters are devoted to interferences with light and massive particles, respectively. In the third chapter, we focus our attention on electron interference experiments using macroscopic and nanoscopic interferometers, which have been carried out since 1925. Particular attention is paid to what are referred to as the Young-type double-slit experiments that were performed in the early 2000s. We shall see that this designation, which refers to the famous experiment by Young in 1807, is in fact not accurate.

Chapter 4 describes a detailed analysis of a single-electron Young-type double-slit experiment. This experiment, based on low-energy He^{2+} + H_2 collisions, was theoretically described in 2004. During the collision, the He^{2+} ion targets captures both target electrons onto doubly excited states. After the collision, one electron is emitted from the projectile due to the Auger effect and scatters on both of the protons acting as the double slit. The ways to obtain a single-electron condition are discussed. The angular distributions of scattered electrons, as well as their energy profiles, are analyzed. A simple model, referred to as the Path-Interference model, based on the possible trajectories taken by the electron to reach the detector, is used to give a qualitative description of the angular distributions.

Due to the limitation of the previous model, which assumes that the electron is emitted at a given distance from the slits, a more refined analysis is made in Chap. 5 using the Final-State Interaction model. This model is based on a quantum description of the Auger effect. Using a Continuum Distorted Wave approximation, the energy profiles of the emitted electrons, as well as their angular distributions, are calculated. We shall see that, contrary to predictions, this model is unable to explain the interference pattern observed experimentally.

Finally, an attempt is made to describe the experimental interferences using a semi-classical approach. The orientation of the molecule, the time at which the electron is emitted, and the orientation of the electron velocity are randomly chosen. The Hamilton equations are solved numerically and electron trajectories are calculated. Then, at a fixed detection angle, the wave aspect of the electron is taken into account to calculate the phase shift induced by the delay in the trajectories, and the angular distribution of the emitted electrons is deduced. We shall see that, surprisingly, this model is promising, challenging the way we view the electron and the associated interference.

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Finally, my thanks to Helen McCombie, from Brest University, who proofread the book; Springer Verlag publishers who accepted this project; and Ms. Dhivya Geno, project manager from Manapakkam, India, who has shaped the book.

Contents

Chapter 1

Photon Interferences: History and Fundamental Aspects

1.1 The History of Light

1.1.1 Before Newton

1.1.1.1 Early Conceptions About Light

The conceptions of the ancient peoples about light and vision provoke a smile today, because they seem very naïve. However, one should not forget that scientific developments always stem from naïve ideas. On the one hand, the ancient peoples, by their inventiveness and imagination, laid down an essential basis for a better understanding of our world. On the other hand, strong personalities, such as Aristotle or Newton, as well as the power and influence of the Church, made questioning many of these bases difficult.

In all of the ancient civilizations, light was neither viewed as an object nor as a subject of study [1]. Light was, existed, appeared, but nothing was said about its origin or its nature [1]. Light was just one element among others, such as air, earth and fire, to name but a few. Light was necessary for life, and a stage in the Creation. Finally, light was often associated with darkness, the two existing, but separately, co-existing in order not to destroy each other.

In the ancient Greek civilization, two opposite concepts appeared. According to Democritus and Epicurus, simulacra (or ειδωλον in Greek), sort of material films composed of thin layers of atoms, streamed from the surface of objects and entered the eyes or mind, thereby causing vision and visualization [2]. The impact of these objects on our sense organs enabled us to perceive them. Plato, on the other hand, was convinced that a fire lived in the eye. This fire emanated from the eye (extramission theory), and mixed with daylight to form a transparent and homogeneous body that extended from the eye to the object [3]. With Aristotle, vision was only possible if the object acted on the eye through a material support between the eye and the object [4]. Euclid was the first to introduce mathematics to describe some of the effects of light. Observing the shadows projected by objects, he

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concluded that light propagated in straight lines, and was formed by individual rays. It was also Euclid who, after experimental observation, formulated the law of reflection.

1.1.1.2 The Arab Contribution

Optics made considerable progress from the ninth century on, essentially due to the contribution of Arab scientists, notably Al-Kindi, Ibn Sahl, and Ibn Al-Haytham, better known in the Western world as Alhazen [5]. Through experiment, they discovered some fundamental laws. They furthered Greek concepts, performed experiments on reflection and refraction, and worked on mirrors, especially those described by Archimedes. They established their own numerical tables in the case of refraction. Alhazen, known as the “Father of modern optics”, proved that light, consisting of individual rays, traveled in a straight line, with finite velocities depending on the nature of the object crossed by the light.

1.1.1.3 Light in the Western World: Beginnings of a Scientific Process

During the Middle Ages, optics studies were carried out in many countries throughout Europe, notably in England, Poland, Germany, and Italy. In England, the Arab works were translated and taught. Robert Grosseteste, Roger Bacon and John Peckham were the main actors in the discovery of optics as a science [6]. Direct, reflected and refracted rays were studied. Rainbows were analyzed [7], and the seven primary colors were introduced. The lens effect was discovered. The eye was studied as an optical object. Glasses were made for the old and the shortsighted.

In 1270, the Polish friar Witelo wrote one of the earliest treatises on optics, entitled *Perspectiva*. Using a goniometer derived from a similar instrument used by Alhazen, he focused on the refraction law from the observation of rainbows, and formulated his results as a table of values of the angles of incidence and refraction. He also described the production of artificial rainbows through refraction in crystals or in bottles filled with water.

Theodoric of Freiburg, from Germany, wrote a book on rainbows, entitled *De iride et radialibus impressionibus* [8]. He explained in detail the colors and the position of the primary and secondary rainbows, as well as the reason why the secondary rainbow displays the same colors in the reverse order and has a larger radius.

Many applications of optics were carried out in Italy. For example, at the end of the thirteenth century, Alessandro della Spina was making glasses [9]. Leon Battista Alberti wrote a treatise, *Della Pittura*, on linear perspective [10]. He used his knowledge of optics to determine perspective as an instrument of artistic and architectural representation.

However, despite the efforts of these specialists, the most phenomenal breakthrough occurred at the beginning of the sixteenth century, with the use of the telescope by Galileo. There are several contenders for the title of inventor of the telescope. It is generally considered that Hans Lippershey, from the Netherlands, came up with the earliest design. Galileo first observed the Moon [11], and then went on to discover four of Jupiter’s satellites. In 1676, the telescope allowed a Danish astronomer, Ole Rømer [12], to measure the speed of light for the very first time by studying one of Jupiter’s moons, Io, at different times of the year. The measurement was obtained with an error of only 30 %.

During the early seventeenth century, Johannes Kepler founded the basis of a new optical science. He defined the light ray, not to be confused with light itself. In his *Astronomiae Pars Optica* [13], he investigated the formation of pictures, explained vision by refraction within the eyes, and the depth of perception by the use of both eyes. He showed that the image of an object constituted the intersection point of light rays.

At the end of the seventeenth century, René Descartes discussed the nature of light [14] using a mechanical approach. For Descartes, space was filled with matter, and light was considered as nothing more than a certain movement or action. He also attempted to derive the reflection and refraction laws through a series of analogies to the behavior of balls on surfaces. Basing his argument on philosophical considerations, he maintained that light propagated instantaneously. He also added that vision was essentially a mechanical process, with rays of light mechanically stimulating the eyes, and then these stimulations passing mechanically to the interior of the brain. Using the laws of reflection and refraction, he confirmed by calculations that the angle subtended by the edge of the rainbow and the ray passing from the sun through the rainbow’s centre is 42° for the primary arc, and 52° for the secondary arc.

1.1.2 Newton and Huygens: Two Opposite Approaches

1.1.2.1 Grimaldi and Visualization of Undulations

A real revolution occurred with the discovery of the diffraction phenomenon by Francesco Maria Grimaldi in the middle of the seventeenth century [15]. Grimaldi let sunlight into a completely darkened room, through a very small slit. He inserted an opaque rod into the cone of light thus produced, and observed the shadow cast on a screen located behind the rod. He first noted that the size of the shadow was much greater than what rectilinear projection would have predicted. The shadow was bordered by alternatively bright and dark bands (fringes). This experiment contradicted the notion of an exclusively rectilinear passage of light, and created the possibility of a new mode of transmission. Diffraction constituted the first evidence of the fluid nature of light. However, Grimaldi did not discuss the notion of periodicity in the appearance of fringes.

1.1.2.2 Newton and the Corpuscular Vision of Light

In his works [16], Newton tried to describe the observable phenomena without regard to any hypothesis as to their cause. He demonstrated that, contrary to what was commonly accepted, colors were not produced by the material through which the light passed, but originated from the light itself. To do this, he carried out what he referred to as an *experimentum crucis* (crucial experiment), in which a beam of sunlight fell through a small hole onto a prism. The white light was decomposed into several colors. Separating out a blue ray, Newton demonstrated that when this ray was sent through a second prism it remained blue. However, when the entire spectrum of colors passed through the second prism, it was recomposed into white light on exiting the prism. He finally showed that the separation of light into its component colors was due to their degrees of refrangibility.

For Newton, light was composed of small massive particles, or corpuscles, whose size depended on their color. This vision was explicitly stated in one of his famous queries [17]:

> “Are not the rays of light very small bodies emitted from shining substances?”

This corpuscular theory was used to explain the reflection and refraction of light. Although reflection can be explained using corpuscles, refraction is more difficult to explain using this model because it leads to the conclusion that the velocity of light is greater in a material than in air.

Newton, on the subject of diffraction, was not opposed to the wave theory. To explain the diffraction phenomenon, he suggested that bodies acted on light at a distance to bend the rays. He attempted to link differences in refrangibility with differences in “flexibility” and the bending that may produce color fringes. He even suggested that vision might be the result of the propagation of waves in the optic nerves. In any case, wave behavior had nothing to do with the light itself, but with the medium.

1.1.2.3 Huygens and the Wave Vision

Christiaan Huygens published his works in 1690 [18]. He was not convinced by the corpuscular theory advanced by Newton. If light consisted of particles, two different light beams that cross should result in particles in all directions. But experiments proved the opposite. His wave concept was based on the experimental result by Rømer on the velocity of light. Since velocity was not infinite, light was propagated in a medium (ether). This ether consisted of uniformly elastic particles compressed very close together. Light was not an actual transference of matter but rather a “tendency to move”, a serial displacement similar to a collision proceeding through a row of balls. A colliding particle would transfer its tendency to move to all particles close to the first one. Huygens therefore concluded that new wavefronts originated around each particle touched by light and extended outward from the particle in the form of hemispheres. Single wavefronts originating at single points

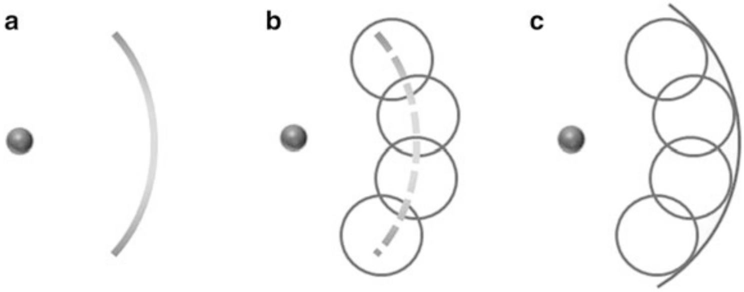

Fig. 1.1 A *spherical* wavefront produced by a light source (**a**), consisting of multiple secondary sources (**b**), and giving rise to a new wavefront (**c**)

were infinitely feeble, but where an infinite number of these fronts overlapped, there was light on the envelope encompassing all of the fronts of the individual particles (Fig. 1.1). This is "Huygens' principle".

Using this principle, Huygens was able to very easily explain reflection and refraction, as well as double refraction in Iceland spar. However, he was unable to explain colors or polarization.

1.1.3 Young: The Discovery and Formulation of Interferences

1.1.3.1 Beginnings of a Discovery

As mentioned above, Newton was not against an undulatory explanation of the effects of light, as the following example undoubtedly shows. The mixture of waves was reported for the first time from a strange observation [19]. In 1678, an employee of the East India Company, Francis Davenport, observed and reported very strange tidal patterns at a place called Batsha in the Gulf of Tonkin:

> [. . .] during the continuance at Batsha I have observed such an order of constancy in the course of the tides, that notwithstanding I must needs confess it different from all that ever I observed in any other Port.

In this place, there is only one tide per day, instead of two as commonly seen, with the highest tidal range coming at intervals of about 14 days, instead of the expected 15. Edmond Halley was the first to take up the matter, and said that "the effect of the moon upon the waters, in the production of the tides, [. . .] is the more wonderful and surprising, in that it seems different in all its circumstances from the general rules" [15]. He understood that the different effects of the tide were closely related to the Moon's position [15]. He proposed a simple formula, in which the cosine function was used to model the periodic nature of the tide.

In Book 3 of his *Principia*, Newton explained these anomalous tides [20]. *Principia* was published in 1687 and, alerted by Halley, his confident, Newton added a long paragraph providing an explanation. He suggested that the unusual ebb and flow at Batsha was the result of the combination of two separate tides flowing towards that port from different directions, one from the Indian Ocean to the South, the other from the South China Sea to the North. These tides would sometimes counteract each other, resulting in only one high and one low tide each day. Although he did not use the term *interference*, by implication Newton had hit upon the idea of wave interferences, a concept that would later play a decisive role for light and sound waves [21].

1.1.3.2 Young and the Concept of Interferences

The point we are going to develop here is one of the most important for understanding and correctly formulating analogies between photon and electron interferences. As mentioned in the introduction, many electron interference experiments are referred to as *Young-type double-slit experiments*, by analogy with the well-known experiment by Thomas Young in 1807. This analogy is erroneous, as shown a few years ago [22], and as we shall see later in more detail. It is also too restrictive, and emphasizes the ignorance of the amount of work performed by Young. Thus, it is of great importance to draw our attention to this decisive and fruitful period.

Before focusing on the nature and properties of light, Young studied medicine [23] and had “to deliver a lecture upon some subject connected with medical studies” [19]. He chose to focus on the human voice and sounds. He “collect[ed] all information relating to [the subject]” [24], and was so impressed with the resemblance between sounds and colors, that he “suspect[ed] an analogy between them”.

In 1801, Young invoked interference to explain the colors of thin plates. He clearly wrote [20]:

> But the general law [. . .] may be very easily deduced from the interference of two coincident undulations, which either cooperate, or destroy each other, in the same manner as two musical notes produce an alternate intension and remission, in the beating of an imperfect unison.

It is remarkable, in this proposition, that the condition of interferences is only that two waves have to overlap. It does not require that the components of the waves have a common source. We place particular emphasis on this point because, as we shall see later, the electron interference experiments we mentioned previously are based on this assertion by Young, rather than on Young’s 1807 experiment.

In 1804, Young carried out a preliminary experiment [25]. He made a hole in a window shutter, covered it with thick paper, and perforated it with a needle. Using a narrow slip of card, he observed the effects of a beam of sunlight on a wall. A pattern of fringes appeared, due to the combination of light waves passing on both sides of the card; more precisely, “Besides the fringes of colors on each side of the shadow, the shadow itself was divided by similar parallel fringes [. . .]” [21].

The famous double-slit experiment finally appeared in 1807, 6 years after Young’s first assertion. “The simplest case appears to be, when a beam of homogeneous light falls on a screen in which there are two very small holes or slits” [26]. Young recognized the importance of having a common source to observe the interference fringes. The phenomenon was, according to Young, exactly the same as that found when a wave of water reaches two stones. The double-slit arrangement was used to estimate the wavelength corresponding to different colors.

1.1.4 Michelson and Morley: A Genius and Decisive Experiment

For about 100 years, light was seen as a wave. The corpuscular theory disappeared. Gradually, the wave notion took on new dimensions, and theories were developed and finalized. At the end of the nineteenth century, James Clerk Maxwell introduced five equations to describe all electromagnetic waves, including light [27]. “The propagation of undulations consists of one of these forms of energy into the other,[1] alternatively, and at any instant the amount of energy in the whole medium is equally divided, so that half is energy of motion, and half is elastic resilience.” [28].

To summarize, Maxwell was convinced that a medium (ether) was necessary to transport electromagnetic waves. The question remained of the constitution of the ether. According to electromagnetic equations, the medium had to be fluid, much more rigid than steel, massless, without any viscosity, and completely transparent.

The solution to detect the presence of ether was provided by Albert Michelson and published in 1887 [28] with Edward Morley. Michelson built a very sensitive and complicated device, well-known today as the Michelson interferometer. This interferometer consisted of a light source (Fig. 1.2), delivering rays that were partly reflected and transmitted, and then returned by mirrors (1) and (2). The reflected rays were again combined and interfered. The resulting intensity was finally detected, and fringes expected to be observed.

If we suppose the ether to be at rest, the directions and distances traversed by the rays will be altered, depending on the direction of the Earth’s velocity in its orbit. Therefore, displacements of the fringes can be expected. Michelson’s theoretical estimation of the displacement was of the order of 0.4 fringe at maximum (dashed curve in Fig. 1.3), which is 20 times greater than that observed (full curve in Fig. 1.3).

Michelson concluded that if a relative motion between the Earth and the ether existed, it had to be small. Finally, since the concept of ether raised too many

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[1] Maxwell refers to the energy responsible for the motion, and the potential energy.

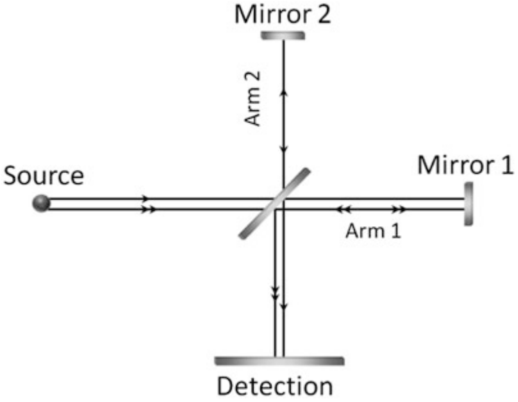

Fig. 1.2 Schematic view of the Michelson apparatus. The two rays on arms 1 and 2 originate from a unique source, and are combined and detected, after reflection on two mirrors

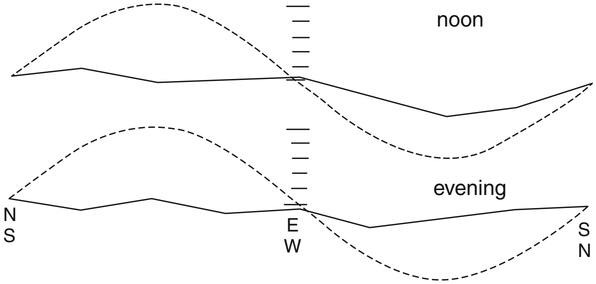

Fig. 1.3 Theoretical (*dashed curve*) and experimental (*full curve*) displacement of the fringes, for different positions of the interferometer relative to the direction of the Earth velocity, at noon (*top* of the figure) and in the evening (*bottom* of the figure)

problems, Einstein suggested that an electromagnetic wave did not need any medium to propagate, and that the speed of light was a constant, whatever the relative speed of the light source. In addition, the velocity of an object could reach the speed of light but not go beyond it.

Independently of these important conclusions, Michelson's interferometer is a reference apparatus for interferences, due to the high precision measurements. We shall see later its usefulness.

1.1.5 The Quanta Revolution and Corpuscular Vision

At the end of the nineteenth century, physics seemed to have clarified and solved all the problems.

> There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.

This statement, attributed to either Lord Kelvin or Michelson, well summarizes the frame of mind of the scientists of the time. However, at least one problem still remained, which would reopen the debate. Imagine a hollow metallic sphere, pierced with a small hole, and uniformly heated. The sphere exchanges its thermal energy with both the interior of the sphere, and the exterior, in the form of electromagnetic radiations. The average wavelength will vary depending on the values of the temperature inside. More precisely, the radiation color is not unique. The outgoing radiation is formed by a superposition of many radiations with different wavelengths, weighted by a probability associated with each wavelength. If we suppose that the energy can take any value, the calculation cannot reproduce the experiment. To avoid the divergence, Max Planck used a mathematical artifact [29]. He supposed that the energy could only take integer multiples of a certain minimum value ε_o, i.e., ε_o, $2\varepsilon_o$, $\ldots$, $n\varepsilon_o$. The agreement between theory and experiment can be found on condition that $\varepsilon_o = hc/\lambda$, where c is the light velocity, λ is the radiation wavelength, and $h = 6.62 \times 10^{-34}$ Js is a constant. Thus, radiation is no longer continuous, but discontinuous, or discrete. This discovery radically changed the old conception about physics. In fact, the small constant h highlighted another problem, and became the key to new physics.

The discovery of the photoelectric effect by Heinrich Hertz in 1887 [30] brought with it the first phenomenon of the action of light on matter that wave theory was unable to interpret. Suppose light with a wavelength λ illuminates a surface. If λ is less than a certain quantity λ_{min}, electrons will be removed from the surface. If λ is greater than λ_{min}, whatever the amount of light reaching the surface, no electron will be removed. In 1905, Einstein explained this result by introducing a corpuscular theory of light. He admitted that light was composed of small bullet-like particles, called quanta, whose energies were hc/λ. Note that this corpuscular theory was only partial, since the wavelength aspect remained.

Finally, one should keep in mind that, at the beginning of the twentieth century, the question of the nature of light remained unsolved.

1.1.6 Two Crucial Experiments

1.1.6.1 Light Interferences with an Attenuated Beam

The experiment by Geoffrey Ingram Taylor in 1909 marked a turning point in the concept of the electromagnetic wave. In this experiment, Taylor proved a prediction made by Joseph John Thomson two years earlier, a theory in which light energy was distributed unevenly over the wavefront [31].

> The theory considered in this paper – that the electric field is made up of a number of discrete units – is one which naturally suggests itself, if we use the conception of tubes of electric force for representing the state of the electric field. [32]

There were regions of maximum energy widely separated by large undisturbed areas, in contrast with the uniform wavefront of the usual electromagnetic theory. If Thomson's theory was correct, the intensity of light in a diffraction pattern would be modified when the source intensity was considerably reduced.

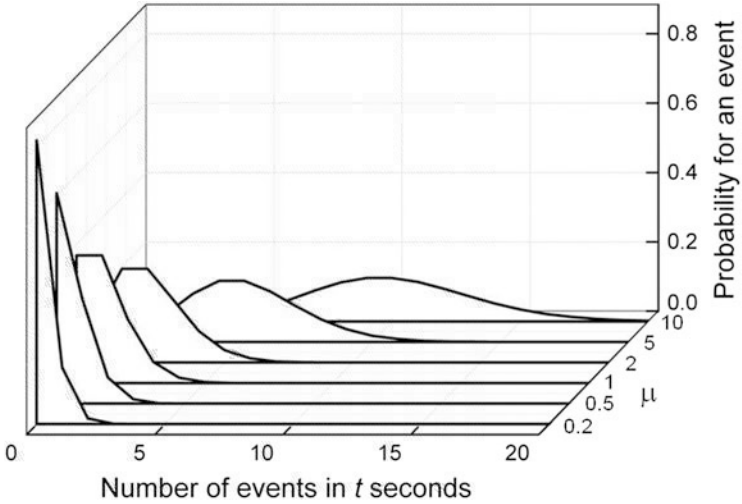

Fig. 1.4 Probability $p(k)$ as a function of k for five values of μ

Taylor used as a source a narrow slit placed in front of a gas flame [33]. Various screens were installed to reduce the intensity. The largest time of exposure was about 2,000 h, or 3 months. As observed by Taylor, "in no case, was there any diminution in the sharpness of the pattern".

1.1.6.2 Interferences with Single Photons

Taylor's experiment was considered for many years as a single photon experiment. Paul Dirac himself concluded from this experiment that *a photon can interfere with itself* [34]. In fact, as it was shown 80 years later, Taylor's experiment was not, strictly speaking, a single photon experiment. A light beam, attenuated or not, contains a number N of elementary particles per second. Suppose that there are on average μ events during a time t, the probability to detect k events in the same time is defined by the Poisson probability law:

$$p(k) = e^{-\mu} \frac{\mu^k}{k!} \tag{1.1}$$

The result for $p(k)$ is presented in Fig. 1.4 as a function of k, for five values of μ. If μ is much greater than one, the probability has the form of a Gaussian curve. If μ diminishes, the probability to obtain two or more than two events also decreases, but is never zero. In other words, Taylor's experiment only shows that, on average, one photon is detected. But the probability for the detection of two or more photons cannot be neglected.

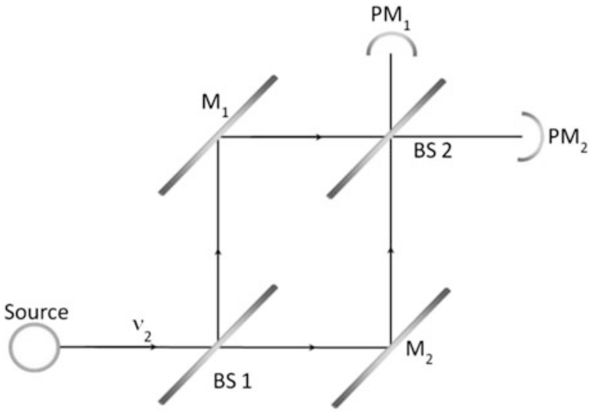

Fig. 1.5 Mach-Zender type interferometer. The light is split (BS1), reflected on Mirrors 1 and 2, and finally detected on PM1 and PM2

To show interferences with single photons, one must therefore be sure that only one photon at a time crosses the interferometer. The only solution consists of a randomly oriented photon source [35]. Photons are obtained by excitation with two lasers. After excitation, one atom of the crystal de-excites, emitting a group of two photons by radiative cascade. The first photon, with frequency ν_1, is used as a start for the detection of the second photon, of frequency ν_2, forming the one photon light pulse. Suppose now that two groups of photons are created at the same time. Because the emission is spontaneous, the photons are emitted in any direction, so that the detection of the second group is unlikely to occur.

The interference experiment was carried out in 1985 using a Mach-Zehnder interferometer. The light was first split (BS 1), then reflected on two mirrors (M_1 and M_2), and recombined using a second beam splitter. Finally, the resulting light was detected on two photomultipliers (PM_1 and PM_2), and the intensity recorded as a function of the path difference, controlled by the displacement of the mirrors (Fig. 1.5). The result is shown in Fig. 1.6, for four different times. The interference fringes are clearly visible, showing that one photon can really interfere with itself.

1.2 Characteristics of Interferences

1.2.1 Conditions for Interferences

To fix the problem, let us consider the case of two sources S_1 and S_2, delivering two electromagnetic waves, whose amplitude are, at a given point M on a screen:

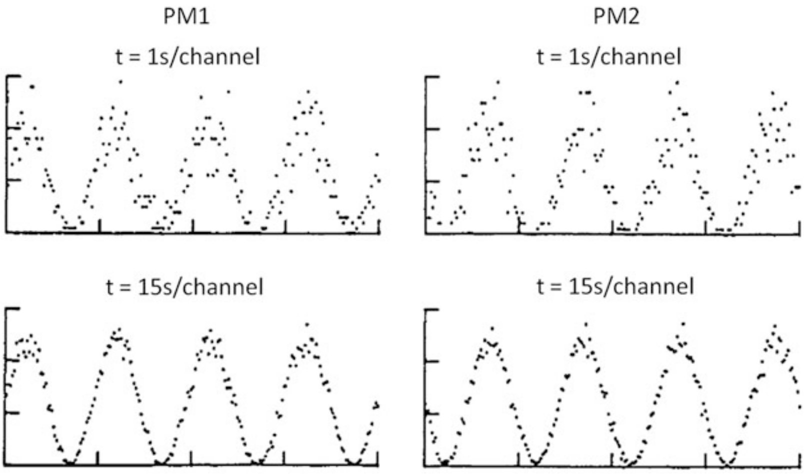

Fig. 1.6 Number of counts detected on PM1 (*left side*) and PM2 (*right side*), as a function of the path difference [36]

$$y_1(t) = a_1 \cos\left(\frac{2\pi c}{\lambda_1}\left(t - \frac{S_1M}{c}\right) + \varphi_1\right)$$
$$y_1(t) = a_2 \cos\left(\frac{2\pi c}{\lambda_2}\left(t - \frac{S_2M}{c}\right) + \varphi_2\right) \tag{1.2}$$

where λ_1 and λ_2 are the wavelengths, and φ_1 and φ_2 are phases. Let us suppose, to simplify matters, two independent sources of the same intensity, i.e., $a_1 = a_2 = a_o$. If these sources originate from the spontaneous emission of light, the phase difference $\Delta\varphi = \varphi_1 - \varphi_2$ will depend on time, since φ_1 and φ_2 also depend on time. The total intensity is given by:

$$I = I_1 + I_2 + \sqrt{I_1 I_2} \cos\left(\left(\frac{2\pi c}{\lambda_1} - \frac{2\pi c}{\lambda_2}\right)t + \frac{2\pi S_1M}{\lambda_1} - \frac{2\pi S_2M}{\lambda_2} + \Delta\varphi\right) \tag{1.3}$$

The total intensity I is averaged on time, giving rise to $I = 2\,I_o$, where I_o is the intensity of the primary source. No interference pattern is observed. To observe interference fringes, $\Delta\varphi$ has to be a constant over time. In this case, $\Delta\varphi$ does not play any role and, with the condition that the two wavelengths are both equal to the same value λ, the total intensity is:

$$I = 4I_o \cos^2\frac{\Delta\varphi}{2} \tag{1.4}$$

where $\Delta\varphi = 2\pi L/\lambda$ and $L = S_1M - S_2M$