Interference with electrons - from thought to real experiments

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ABSTRACT

The two-slit interference experiment is usually adopted to discuss the superposition principle applied to radiation and to show the peculiar wave behaviour of material particles. Diffraction and interference of electrons have been demonstrated using, as interferometry devices, a hole, a slit, double hole, two-slits, an electrostatic biprism etc. A number of books, short movies and lectures on the web try to popularize the mysterious behaviour of electrons on the basis of Feynman thought experiment which consists of a Young two-hole interferometer equipped with a detector to reveal single electrons. A short review is reported regarding, i) the pioneering attempts carried out to demonstrate that interference patterns could be obtained with single electrons through an interferometer and, ii) recent experiments, which can be considered as the realization of the thought electron interference experiments adopted by Einstein-Bohr and subsequently by Feynman to discuss key features of quantum physics.

Keywords: interference of material particles, electron diffraction, build-up of electron interference patterns

1. INTRODUCTION

The double-slit interference experiment is usually adopted to discuss the superposition principle applied to radiation and to show the peculiar behaviour of material particles. This experiment was used by Einstein and Bohr to develop their considerations on the basic concepts of quantum physics. Following this debate, experiments were performed to demonstrate the interference of electron waves. Biberman et al., Faget and Fert, with their pioneering experiments, demonstrated clearly that the diffraction and interference patterns obtained with a large number of electrons or, alternatively, with single electrons passing through an interferometer were undistinguishable[1-3]. At that time, about fifty-sixty years ago, a detector able to reveal single electrons was not available so that only interference patterns, arising from the superposition of thousands of single electrons, were reported. Subsequently, Feynman made an extensive, conceptual

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use of the Young interferometer to compare, for example, the behaviour of water waves with that of electrons. Feynman described how an interference pattern from a double-hole set-up could be observed with a detector able to reveal single particles[4]. Soon after, the development of new recording devices demonstrated the possibility to observe diffraction from a hole and interference patterns from an electrostatic biprism as a cumulative spatial detection of single particles as a function of time[5-9]. This process is referred to as build-up. Today, a number of books, short movies and lectures on the web try to popularize the mysterious behaviour of electrons following the Feynman approach so that the general perception is that the dual slit experiment has already been carried out. However, only recently the true two-slit interference experiment with single electrons has been definitely performed[10-13]. The aim of the present article is to report a brief review of the historical background regarding the many efforts carried out up today to realize the two-slit "thought experiment" with single electrons.

2. DIFFRACTION AND INTERFERENCE EXPERIMENTS WITH SINGLE ELECTRONS

As it is well known Davisson and Germer and, independently, G.P. Thomson demonstrated the wave behaviour of electrons according to the de Broglie hypothesis of the existence of material waves. A few years later, in 1931, Max Knoll and Ernst Ruska realized the first electron microscope. Due to its versatility, this instrument has been widely used to carry out basic experiments concerning the Aharonov-Bohm effect[14] and holography with electrons [15-17].

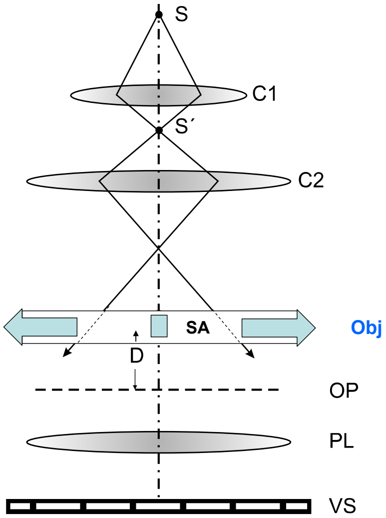

Figure1. Schematic drawing of a transmission electron microscope.

Figure 1, reports the basic scheme of a transmission electron microscope (TEM). Electrons emitted by the source S are controlled by the condenser lens system, formed by the magnetic lenses C1 and C2, to illuminate a sample SA under investigation. The objective lens Obj forms the first magnified image of the sample on the plane OP. A projector lens system conjugates the OP plane with the final viewing screen VS where an image is observed. This image can be recorded on a photographic plate or, using a CCD camera, transferred to a computer. Generally, interference experiments are realized by placing the interferometry devices, single slit, double slit, single crystal film, etc. at the sample level SA, Figure 1. As alternative device, an electrostatic biprism, which can be considered as the electron-optical analogous of the optical Fresnel biprism and whose working principle will be described in the following, is inserted below the Obj lens, at the selected area aperture plane.

In 1949, Biberman et al., performed a beautiful, little known, diffraction experiment using a transmission electron microscope and manganese oxide crystallites. The aim of their experiment was clearly pointed out by their own words: "Because experience shows the diffraction patterns to be independent of the electron flux intensity, courses in quantum physics invoke the thought experiment with successively diffracting electrons in order to conclude about the wave properties of an individual particle. Although this conclusion is hardly questionable at present, still, as far as the justification of quantum physics is concerned, diffraction experiments are important enough to warrant a real-life experiment on the diffraction of successively travelling electrons"[1]. Biberman et al. made a number of modifications to their TEM. They changed the electron optical conditions and, above the viewing screen VS, a Faraday cylinder was mounted to measure the intensity of the entire beam, Figure 1. Subsequently, the beam current was decreased in such a way that the beam was "... so weak that at any given time practically only one single electron passed through the apparatus which consequently was empty most of the time….the simultaneous passage through the apparatus of even two electrons would be a highly unlikely fluctuation."[1]. With these illuminating conditions a specimen, consisting of manganese oxide crystallites located on a collodium substrate, was used to obtain a diffraction pattern. As expected, the diffraction image recorded with a beam so weak was exactly the same as that obtained with beam intensities higher up to almost seven orders of magnitude.

Subsequently, in 1956, Moellenstedt and Duker invented an electrostatic biprism that is the electron optical analogous of the optical Fresnel version[18].

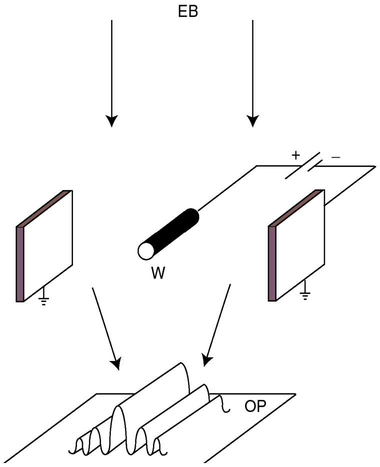

Figure 2. Working principle of the electrostatic biprism.

The electrostatic biprism consists of a thin conducting wire W placed between two metal plates connected to the ground, Figure 2. Let us consider that a parallel electron beam EB strikes on the biprism. When a positive potential is applied to W the electrons passing on its right hand side are deflected to left while electrons passing on the left side suffer a deflection to right. On the observation plane OP an interference pattern is formed. With increasing potential applied to the central wire W the number of fringes increases while their spacing decreases.

In France, Faget and Fert, using a transmission electron microscope, performed a number of experiments regarding Fresnel diffraction from a circular aperture, interference with a double-hole and an electrostatic biprism. These results were presented to de Broglie who replied with the following considerations: *"... it is of most interest to have obtained interference and diffraction patterns with electrons in analogy with light......it is even more interesting that the wave associated with electrons forms a coherent wave train......these results help the understanding of wave mechanics"*[2]*.'*

In 1961, Faget, repeated the same experiments using a very low intensity electron beam and pointed out the behaviour of an isolated corpuscle in vacuum.[3] The beam current of a TEM was strongly decreased and measurements were done with one electron at a time traveling through the microscope column. In particular it was demonstrated that interference fringes from a two-hole setup and from an electrostatic biprism became observable with the contribution of many individual electrons.

The experiments of Biberman et al. and Faget show clearly that, using a large number of electrons passing at the same time through a scattering device or, alternatively, using single electrons moving through the interferometer, the final diffraction and/or interference patterns take the same configurations. It is worthwhile emphasizing that in case of experiments carried out with electrons which travel individually through a crystal, an aperture, etc. the interference pattern can be observed only as a cumulative effect of a large number of charges which hit the detector.

In 1965, Feynman recalled attention to the peculiar behaviour of material particles by presenting an appealing version of the two-slit electron interference experiment. He warned the reader, "We should say right away that you should not try to set up this experiment. This experiment has never been done in just this way. The trouble is that the apparatus would have to be made on an impossibly small scale to show the effects we are interested in."[4].

Figure 3 shows a version of the Young interferometer adopted by Feynman to introduce the interference of electron waves. The interferometer consists of a source that fires electrons towards a thick metal plate with two holes 1 and 2. At a long distance with respect to the separation between the two holes, a back stop is placed with a movable detector which is connected to a loudspeaker. This arrangement was used to illustrate the probability distribution of single electrons in three cases: i) electrons go through hole 1 while hole 2 is blocked off; ii) electrons travel through hole 2 with hole 1 closed; iii) electrons move through both holes. According to Feynman these last case shows the wave behaviour of electrons. However, it must be underlined that this peculiar property of electrons is revealed also using the experimental conditions reported in scenarios i) and ii) mentioned above (for detailed comments see[19]). The interest of the Feynman experiment regards the possibility "to hear" the arrival of single electrons on the detector or, alternatively, to observe the hit of electrons on the detector as light flashes.

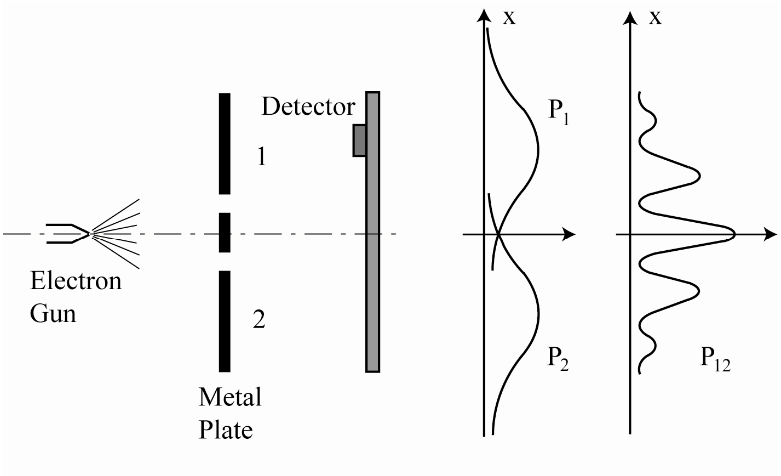

Figure 3. Schematic arrangement of the double-hole experiment to observe electron interference.

In 1969, Hermann et al., at Siemens, developed a new type of detector based on the use of a Secondary Emission Conductivity (SEC) tube connected to an image intensifier[5,6]. This new detector replaced the final viewing screen of a transmission electron microscope, Figure 1. For the first time, a detector to reveal single electrons as light flashes on a dark background was commercially available. Diffraction images from a small hole were recorded at various exposure times and at various final image current densities. With a small amount of electrons the diffraction pattern from the hole could not be distinguished whereas with a larger amount of electrons, obtained with increasing storage times, the image was gradually formed. According to Hermann et al., these results were the very first showing that "…the image is built up from the statistically distributed light flashes of individual electrons. A complete image is formed only when longer exposure times are used"[5,6].

In 1976 Joensson carried out the first electron interference experiment using single, double and multiple slit devices. It is worth mentioning that interference patterns were recorded on photographic plates with a large number of electrons so that the build-up of the fringes with single electrons was not reported[20].

The same type of detector developed by Hermann et al. was used by Merli, et al. in 1976 to show, for the first time, the build-up of interference fringes with an electrostatic biprism installed in a TEM[21]. This kind of experiment was repeated by Wohland in 1977 with a home-made channel plate image intensifier and subsequently by Hasselbach who developed a new miniature electron biprism interferometer[8,22]. A further experiment was carried out in 1989 by Tonomura et al. using a TEM equipped with a biprism and, in particular, a newly developed sensitive electron-counting system[9]. While Merli et al. recorded the interference patterns at varying electron beam densities, Hasselbach and Tonomura detected the arrival of electrons starting with an extremely low beam current. Images show that electrons were accumulated gradually over time to form interference fringes with increasing contrast.

In the lively debate between Merli et al. and Tonomura et al., about the priority regarding the realization of the first experiment showing the build-up of an electron interference pattern with a biprism[23,24], the experiment of Hasselbach[22] was not taken into consideration. Moreover, Tonomura emphasized the higher performance of his recording system and reliability of the results obtained, "The electrons arriving at the detector were detected with almost 100% efficiency. Counting losses and noise in conventional TV cameras mean that it is difficult to know if each flash of the screen really corresponds to an individual electron."[24].

Although the experiments carried out with a biprism regard the build-up of interference patterns, they cannot be considered as true two-slit interference experiments.

3. REALIZATION OF THE TWO-SLIT-THOUGHT EXPERIMENT

In 2009 a team in Bologna performed, for the first time, the true two-slit interference[10,13] considered by Feynman as a thought experiment. The slits were produced by milling a gold-carbon layer with a Focused Ion Beam technique[25] and inserted at the standard specimen level SA of a TEM, Figure 1. It must be underlined that, with respect to the experiments with an electrostatic biprism, the two-slit device has the following advantages: i) electrons travel through the slits in an electromagnetic field free region and, ii) the images are Fraunhofer patterns whose interpretation is much simpler than the images obtained with the electrostatic biprism.

In this experiment, the crucial role is played by the detector which must be able to record the hit of single electrons. The final viewing screen of a conventional TEM, Figure1, was replaced by a CMOS detector developed for experiments in future colliders[10]. Our detector consists of a matrix of 128x32 pixels-monolithic active pixel sensors equipped with a fast digital readout. Each square pixel (side-50μm) provides a hit/not-hit information tagged with a time stamp label. This device, that resulted very sensitive also to electrons, was connected to a fast recording system. With improved accuracy with respect to previous recording devices, it has been possible to reveal not only the impact points of single electrons on the detector, observed as light flashes, but also the build-up of high statistic single-electron interference patterns. For example, in a typical run 95.2% of the collected frames are empty, 0.1% have multiple hits and 4.7% one-hit events. Concerning the latter, by comparing the average time distance between the detected electrons (3.1ms) to the time of flight within the electron microscope (10ns), we see that an electron is completely read out before the next electron is emitted by the source. From the measurement of the time interval which separates two adjacent non-empty frames, the distribution of the arrival-time of electrons on the detector has been measured for the first time[12,13]. The final interference pattern is obtained from the superposition of a large number of recorded frames. With this procedure it is possible to observe, step by step, the build-up of an image by selecting the recorded non-empty frames. A careful analysis of the build-up of a double-slit pattern shows that interference maxima are clearly observable with the first 1000 electrons[13]. The new developed recording system has been used to select the electron optical parameters in which single electrons move through the electron microscope column. In this experimental condition, diffraction patterns from a couple of holes have been recorded to extend the discussion given by Feynman regarding the probability distribution of electrons in the Fresnel and Fraunhofer regimes[19].

In 2013, Bach et al. with their home made interferometer, performed a controlled double-slit experiment in which a movable mask, placed 240 μm away from the double-slit, was used to control the electron transit through the individual slits[26]. These authors considered their experiment as a full realization of the Feynman proposal. It has been reported either diffraction from a single slit or interference from a double-slit. The main obstacle to carry out every step of this experiment regards the control of electron transmission through one of the two slits while, at a same time, the other slit is closed. This problem is very difficult to overcome because the mask, used to cover one of the slits, should stop all the electrons impinging on that slit. The two-slit interference modulation should be washed out and one slit diffraction pattern should be displayed. The experimental results, however, report a two-slit modulation even when one of the slits is closed by the movable mask[26]. In spite of this limitation the experiment and the movies show clearly the build-up of typical wave-optical phenomena with electrons.

4. CONCLUDING REMARKS

In this brief review, the attention has been addressed mainly to diffraction and interference experiments with single electrons moving through vacuum. As reported, the first experiments with individual electrons moving through the interferometer were carried out by Biberman et al. and Fert et al. They demonstrated that diffraction or interference patterns took the same intensity distribution independently of the number of electrons moving through the interferometer. However, at that time, a detector to reveal the hits of single electrons was not available. A new kind of detector, developed by Herman et al., opened the way to the direct observation of the build-up of diffraction and interference patterns with single electrons.

It must be underlined that in the last 40 years experiments regarding electron interference, from single and double-hole devices, have been reported (see[27-29] and references therein). These experiments were realized mainly with electron microscopes equipped with commercially available sources. The cumulative effect of a large number of electrons was recorded with photographic plates or CCD cameras so that it was not possible to know if electrons travelled individually through the interferometer.

Our new detector, used to observe the build-up of two-slit interference fringes, has been employed to arrange the illuminating system of a TEM in order to have individual electrons traveling through the interferometer. With this modus operandi, diffraction and interference images with single electrons can be recorded on photographic plates or CCD cameras although the build-up of the patterns is not directly observed[19,30].

In conclusion, a short review of basic experiments realized to study interference patterns with electrons propagating through vacuum has been presented. By exploiting a new detector system together with the availability of a double slit device, the gedanken experiment adopted by Bohr and Einstein and subsequently used to discuss the peculiar behavior of material particles has been finally realized.

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