Electron interference experiment with optically zero propagation distance for V-shaped double slit

Ken Harada1,*, Tetsuya Akashi2, Yoshio Takahashi2, Tetsuji Kodama3, Keiko Shimada1, Yoshimasa A. Ono1, and Shigeo Mon2

1CEMS, RIKEN (Institute of Physical and Chemical Research), Hatoyama, Saitama 350-0395, Japan
2Research & Development Group, Hitachi Ltd., Hatoyama, Saitama 350-0395, Japan
3Graduate School of Science & Technology, Meijo University, Nagoya, Aichi 468-8502, Japan
4Department of Materials Science, Osaka Prefecture University, Sakai, Osaka 599-8531, Japan

*E-mail: kharada@riken.jp

Received December 14, 2020; revised December 26, 2020; accepted January 5, 2021; published online January 22, 2021

In an electron double-slit experiment, an optically zero propagation distance condition (infocus imaging condition), in which the double-slit position was imaged just on the detector plane (image plane), was realized in a 1.2 MV field-emission transmission electron microscope. Interference fringes composed of dot images were controlled by using two electron biprisms. Using a V-shaped double slit, we observed the interference features under the pre-interference condition, interference condition and post-interference condition of electron waves. We conclude that it is possible to observe the interference fringes only when the path information of the individual electrons is not available.

© 2021 The Author(s). Published on behalf of The Japan Society of Applied Physics by IOP Publishing Ltd

Double-slit experiments are known to have proved the wave nature of light, thus showing the essence of quantum physics of the particle/wave duality.1 In optics, using photons, the most advanced experiments have been performed such as confirmation of Bell’s inequality2–11 and “delayed choice” experiments with quantum erasers.5,23–26 In particle beam optics, electrons,9,18 atoms12 and molecules13 have been used to perform double-slit experiments. Among these, the most advanced is the electron beam technique using electron microscopy. The first double-slit experiment was reported by Jönsson in 196112,15 with a specially manufactured fine double slit. Further experiments using an electron biprism as a beam splitter were conducted by Merli et al. in 1976,24 Lichte in 198825 and Tonomura et al. in 1989.11 These experiments proved the particle/wave duality and were good demonstrations of the mystery of quantum physics.

In recent years, there have been numerous technology developments with regard to electron microscopes and their related technologies, such as high-brightness electron sources realizing coherent lengths of about 100 μm,16 highly sophisticated interferometers by using electron biprisms17–19 and a direct detection camera capable of recording single electrons at high speed.20 By using these technologies, several particle/wave duality experiments have been performed.7,21–27

In 2018, we conducted an interference experiment with an asymmetric double slit20 by controlling the width of each slit with a biprism using a 1.2 MV field-emission transmission electron microscope (FE-TEM).28 To find out which slit electrons passed through, we used the pre-Fraunhofer condition, which corresponds to a shorter propagation distance from the double slit to the image plane. However, it was not possible to distinguish which slit electrons passed through when interference fringes were formed. This is because if an electron behaves as a wave, the electron wave is diffracted out after passing through the slit and interference of two electron waves is generated,29–31 even if the propagation distance is short.

As indicated above, it is difficult to control the interference when the electron waves propagate naturally. To solve this problem, we devised an optical system that works under the infocus condition. This can be considered as a condition of an optically zero propagation distance from the double-slit position (the object plane) to the detector position (the image plane) because of the optical conjugate relation between the object and image planes. In the present study, this condition was optically realized and V-shaped double slits were adopted to observe interference features in one image under the pre-interference condition, interference condition and post-interference condition.

Figure 1 shows the conceptual optical setup of interference experiments under the condition of optically zero propagation distance equipped with two biprisms to control and superimpose the waves.17,18 The upper biprism is placed on the object plane where the double slit is placed for deflecting the propagation of the waves. The lower biprism is positioned between the objective lens and image plane for deflecting the two waves to overlap the slit images on the image plane. In Fig. 1(a), the deflection angle by the lower biprism is small so that the two waves after passing through the slit are not yet superimposed; thus, this is called the pre-interference condition. In Fig. 1(b), the deflection angle is increased so that the two slit images overlap on the image plane generating interference fringes; thus, this is called the interference condition. In Fig. 1(c), the deflection angle is further increased so that the two waves exchange places in the space above the image plane resulting in no overlap of the two slit images; thus, this is called the post-interference condition. When the objective lens and optical system have appropriately high spatial resolution for the double-slit imaging, for example, 1/10 times or less than the slit width, waves that passed through the left slit always converge and image at the right side on the image plane. It is possible to trace back from the place where the electron waves have reached on the image plane to which side of the slits they have passed through.
Figure 2 shows a schematic of the optical system constructed in the 1.2 MV FE-TEM. An acceleration voltage was set at 400 kV for flexible control of the electro-optical system. This lower acceleration voltage had the following additional advantages: reduction in number of inelastic electrons transmitted through the slit foils, increase in coherent lengths due to longer wavelengths and increase in interference-fringe spacings and fringe contrasts. The V-shaped double slit shown in the inset was set on the object plane between the objective lens (not shown in the figure) and first magnifying lens. The first image of the double slit was formed on the first image plane between the first and second magnifying lenses, where the upper biprism filament was placed. Then, the double slit and the upper biprism filament are in a conjugate relation. This filament electrode (1.6 μm in diameter) made of a quartz fiber with Pt-Pd coating, was positioned at the center of the double-slit opening image. The second image of the double slit was formed on the lower image plane. The lower biprism filament electrode (1.8 μm in diameter) was positioned on the second crossover plane under the second magnifying lens between the two crossover spots. The V-shaped double slit was made of copper foil 1.3 μm thick by using a focused ion beam instrument (NB-5000, Hitachi High-Tech Corp.) This double slit has two openings 0.18 μm wide, 0.93 μm long and with 1.1–1.9 μm spacing between the two openings. Images of the V-shaped double slit and interference fringes were observed and recorded by the direct detection camera system (not shown in the figure) (3711 × 3839 pixels, K2® Summit Camera, Gatan Co.).

Here, we discuss the detailed setup conditions of these double biprisms. As described above, the upper biprism filament electrode and V-shaped double slit have an optically equivalent relation, i.e. a conjugate relation. We set the upper electron biprism filament electrode to be in the shaded area between the slit-opening images so that the filament was not irradiated by the electron beams, resulting in the filament image being unobservable. When a voltage was applied to the upper biprism, the second crossover spot split into two,
between which the lower electron biprism filament electrode was placed so that it would not be irradiated by the electron beams. These two biprisms slightly deflected the electron waves by about $10^{-5}$–$10^{-6}$ rad. We note that this double-biprism optical system\cite{17,18} has the following advantage: the interference areas can be changed without varying the fringe spacings.

Figure 3 shows a series of interferograms of the V-shaped double slit by changing the voltage applied to the lower electron biprism, $V_{lf}$. In Fig. 3(a), two slit images before overlapping are observed under the pre-interference condition. With the increase in $V_{lf}$, both slit images move towards each other and overlap at the bottom of the slit images in Fig. 3(b). In this overlapped region, the interference fringes are generated in the vertical direction. With the further increase in $V_{lf}$, the interference regions move upwards. Figure 3(c) ($V_{lf} = 25.7 \text{ V}$) shows an X-shaped image with the diamond-shaped overlapped region having interference fringes. Finally, at $V_{lf} = 41.0 \text{ V}$ shown in Fig. 3(e), these two slit images change their sides under the post-interference condition.

Figure 4 shows intensity profiles of electron counts as a function of the pixel number in regions #1 to #5 in the inset image in Fig. 4(e). In Fig. 4(a) (region #1), the integrated electron count is about 80 at the top of the peak and about 5 or less at the bottom of the valley. The latter value is slightly larger than that of the background in region #5 of Fig. 4(e), which is probably due to the slight reduction of the coherence of electron waves used in the present experiment and to the slight instability of the system. The fringe contrast in region #1 is about 0.9, which is very high in electron microscope experiments. Region #2 [Fig. 4(b)] shows the edge of the interference-fringe region and the electron counts of the fringes decrease along the pixel number direction and finally becomes about 20, which is roughly equal to those of region #3 [Fig. 4(c)] in the pre-interference region and to those of region #4 [Fig. 4(d)] in the post-interference region. When profiles of regions #3 and #4 are studied in detail, electron counts at their peaks are about one quarter as large as those of region #1 and those at the bottom of the valley are larger than those of region #1. This is because the interference fringes are erased out so that the electron counts reduce to the same value as those of regions #3 and #4. These experimental results indicate that electron waves that passed through the V-shaped double slit had almost the same intensity and generated almost completely coherent two-wave interferences.

Figure 5 shows an enlarged interferogram of Fig. 3(c), where each electron was detected as a dot. The region surrounded by the red broken lines corresponds to images from the left slit and the region surrounded by the green broken lines corresponds to images from the right slit. These colors are associated with those in the optical systems shown in Fig. 1. The diamond-shaped region surrounded by pink broken lines corresponds to the interference region generated by superposition of the two electron waves that passed through both slits, where interference fringes are observed. The uniform intensity regions of the pre- and post-interference regions are also indicated, where the interference

---

**Fig. 3.** Series of interferograms of the V-shaped double slit with different applied voltage $V_{lf}$ to the lower electron biprism; (a) $V_{lf} = 10.0 \text{ V}$, (b) 20.0 V, (c) 25.7 V, (d) 31.0 V and (e) 41.0 V. Interference fringes appear only in the region where the two images are superimposed and uniform intensity distributions are observed at single slit regions. Averaged electron dose over the whole detector area was 0.015 electrons/pixel for 1 s exposure.
Fringes disappear and instead uniform electron count distributions appear. This disappearance and appearance of interference fringes is similar to that of the quantum erasing phenomena.\(^5\)–\(^8\)

First, we discuss the result from the electron optics point of view. We observed the V-shaped double slit under the infocus condition with a spatial resolution of about 1/100 of the size of the slit width. In the pre- and post-interference regions, we can determine within the resolution limit which slit opening electrons passed through after the electron arrived at the image plane and was detected as a dotted image. Since the electrons are deflected by the electron biprisms, we can also determine which side of the filament electrode of the biprisms electrons passed by. Therefore, it is possible to trace approximate trajectories of electrons from their passing through the slit opening to their arrival on the image plane. When we detect a single electron on the image plane, we can identify which side of the optical axis the electron has passed through. This indicates that the retroactive interpretation of electron trajectories, i.e. path information, can be obtained.

On the other hand, in the region where the two slit images overlapped, there are two possibilities in their path information: an electron passes through the left slit and follows a subsequent path to reach the image plane or an electron passes through the right slit and follows a subsequent path. In electron optics, the path information is not available even under a sufficiently high-resolution condition.

Next, we discuss the results from the quantum physics point of view. An electron wave is irradiated on the V-shaped double slit and passes through the slit openings, where the incident electron wave is divided into two partial waves localized at each slit position. However, we do not know which of the partial waves will be dominant when they reach the image plane. When an electron wave is detected in one of the slit images in the pre- and post-interference regions, the probability that the electron wave is detected in the other becomes zero. This means that the partial electron waves are collapsed into one dot in one or the other slit image. This experimental setup is similar to that of the de Broglie’s gedanken experiment.\(^3\)\(^\text{33}\)

In this experiment, two electron biprisms are arranged in the optical system so that they do not contact either electron wave directly. These two partial waves were superimposed using these biprisms and formed interference fringes in the overlapped region. A moving electron can be described in terms of a wave function and when it reaches the image plane it is detected as a dot. When large numbers of electron dot images are integrated, interference fringes appear. Therefore, the electrons as waves are considered to have passed through both slits.

Finally, putting these two ideas together, we find the following: in the pre- and post-interference regions, electrons arrive on the image plane with the image of the slit opening. When both slits are observed under the infocus condition, a dot image is formed on either of the slit images. In the interference region, after detecting the slit image, we cannot determine which slit the electron recorded as the dot image has passed through.

---

**Fig. 4.** (Color online) Intensity profiles of electron counts as a function of the pixel number in the rectangular regions in the inset interferogram in Fig. 4(e), which is the same figure as Fig. 3(c): (a) #1; interference region, (b) #2; boundary region between the interference region and pre-interference region, (c) #3; pre-interference region, (d) #4; post-interference region and (e) #5; background region. Electron counts of 80 in interference region #1 is four times as large as that of regions #3 and #4, indicating that electron waves are highly coherent and two waves with equal intensity generated interference fringes.
Fig. 5. (Color online) Enlarged interferogram of Fig. 3(c) with the assigned region names. Region surrounded by red broken lines corresponds to images from the left slit and the region surrounded by green broken lines corresponds to images from the right slit. Diamond-shaped region surrounded by pink broken lines corresponds to the interference region generated by superposing the two electron waves that passed through both slits. Pre-interference region and post-interference region are also indicated.

The above statement indicates that an interference fringe can be observed in the region where no path information is obtainable; in this region electron waves have passed through both slits and propagate through both paths. These findings confirm the early results by using a sophisticated electron interference system.

We conducted an electron interference experiment in an electron optical system of the 1.2 MV FE-TEM with operation acceleration voltage of 400 kV. The distance between the double slit and detector plane was set to optically zero propagation distance so that the V-shaped double slit can be observed on the image plane under the infocus condition, so that the slits were clearly observable and recorded as electron dots.

To identify which slit an electron has passed through and which side of the electron biprisms the electron has passed by, i.e. path information, we controlled the electron trajectory by using the biprisms and obtained X-shaped images of the V-shaped double slit on the image plane. These images are categorized by three regions: pre-interference region, interference region and post-interference region.

We have shown, by using a sophisticated electron interferometry setup, that interference occurs when the path information is not available, while no interference occurs when the path information is available.

Acknowledgments The authors would like to thank Prof. Hiroshi Ezawa of Gakushuin University and Prof. Yasunori Yamazaki of RIKEN for their valuable discussions. This work was supported by KAKENHI, Grant-in-Aid for Scientific Research [Grant No. (B) 18H03475].