Electron Interferometry

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THE UNWARY READER, seeing the combination of the words "interferometry" and "electron," may wonder about its significance. It is used here in the same way as in "electron optics" and its various branches such as electron microscopy. Thus electron interferometry means the use of electrons in place of light in interferometric systems.

For the past twenty-five years, many efforts have been made to build up a new discipline called electron optics, starting with the establishment of analogies between this and the geometrical optics of light. Many of the old and well-known effects have been catalogued and their places among the newer ones established. With the building up of this truly impressive edifice came increased insight into the operation of some older devices and at the same time the design of new and unexpected instruments.[1]

It is somewhat surprising that, although the geometrical analogue was emphasized, little effort was made to build up the physical optics of the electron. Some signs pointed in that direction. After all, even the resolving power of the electron microscope cannot be adequately explained without considerations of the wave nature of the electron. Also, the time came when it was necessary to work out the wave theory of aberrations in close analogy to light optics. However, the efforts were restricted to the wave-mechanical approach to geometrical optics and any efforts to build up the systematics of physical electron optics were still lacking.

I believe that the time has come when a systematic approach to physical electron optics is a necessity. Physical optics can be defined, in close analogy to light optics, as that branch of optics where the wave concept is essential and where the ray approximation becomes insufficient. In that sense physical electron optics encompasses phenomena of electron diffraction, electron interferences, electron scattering, and electron polarization. There may be other phenomena belonging in this category, but these four important subgroups constitute the bulk of what may properly be defined as physical electron optics. Electron optics as defined above is the physics of beams of free electrons; it is analogous to light optics, the physics of beams of photons.

The different branches of physical electron optics enumerated above have received varying degrees of attention in past years. The first to be known and studied was electron scattering, although at the beginning the study was entirely phenomenological. Since the advent of quantum mechanics, electron scattering has emerged from that primitive stage and today quite an amount of knowledge, both experimental and theoretical, has been accumulated on that subject.

Next was the discovery of electron diffraction, which for all practical purposes was contemporary with the advent of wave mechanics. This has since become a powerful tool for the exploration and determination of the structure of solids.

Electron polarization is rather little known. There have been definite attempts undertaken to observe polarized electron beams, but efforts have been rather fragmentary.

I have left the discussion of electron interferences to the last because their study is just beginning. This does not mean that electron interferences have not been observed in the past; ever since electron diffraction has been observed, we have seen electron interference phenomena. It may be said that we cannot have electron diffraction without electron interferences, but for all practical purposes we can have electron interferences without electron diffraction. The same is true for light, of course, where observation of diffraction is almost invariably accompanied by interference phenomena. Thus, electron interferences, while historically far from new, did not play a serious role in the physics of the free electron until quite recently.

A little over two years ago, Uyeda and collaborators (*1*) described a new type of effect which was observed in certain electron micrographs of graphite flakes. This consisted of equidistant dark bands running across the electron microscope image, which have been interpreted as interference fringes produced by the wedge-shaped flaking off of the lamellar crystals. In a recent paper, Rang (*2*) describes a different type of electron-interference phenomenon. It is seen when blisters produced in a thin layer of lead iodide are observed with an electron microscope. Because the front and back walls of the blister act as interferometer plates, interference fringes are observed across the image. To use a somewhat crude analogy, we may compare the observation of these two kinds of phenomenon to two distinct steps in the light-optical observation of interferences. The first observation of light interference phenomena was probably on oil slicks or other thin layers accidentally produced by nature. The next step was man-made surfaces put together to imitate some of these colorful phenomena, and thus were Newton's rings born. I should like to compare Uyeda's beautiful observation to the colored fringes found on oil slicks; and since Rang's experi-

[1] Good reading material on the subject of geometrical electron optics is contained in the books of W. Glaser, *Elektronenoptik*, Springer, Vienna, 1952; O. Klemperer, *Electron Optics,* Cambridge University Press, 1953; V. E. Cosslett, *Electron Optics*, Oxford Unviersity Press, 1950.

ment presents a more purposeful production of interferences, it may be compared to Newton's rings.

The decisive step in light optics was made by Young who finally established the wave theory of light, originally formulated by Huygens in 1678. Young created, about 1800, a system in which interferences can be produced at will and manipulated for measuring purposes, and from his experiments were derived all the modern light interferometers. The development of electron optics was not nearly as drawn-out as that of light optics. The conception of a workable electron interferometer (*3*) predates the publication of Uyeda's paper and the first definite results by means of such an instrument (*4*) were published almost simultaneously with Rang's paper.[2]

In the preceding considerations, I have freely used the analogy of light optics, not only because our concepts were based on such analogies, but also because their use conjures up images that make the understanding of the steps and of the phenomena much easier. This applies even more when we come to a discussion of the possibilities of electron interferometry and the means of realizing them. As in light optics, there exist essentially two distinct methods for the production of an interferometric measuring system. One is derived directly from Young's experiment. If a double slit is illuminated by coherent light issuing from a small source and if means for reuniting the two "rays," say in the shape of a lens, are provided, interference fringes can be observed in the image plane by such a lens. Many variants of this principle have been worked out and, in particular, the Rayleigh interference refractometer was derived from this principle. Its essential feature is that a spherical or cylindrical wave front, issuing from the point-like or line-shaped source, is split by means of a double slit into two separate narrow beams. The limitations of this kind of system are best indicated by the common name of the instrument, narrow-beam interferometer.

More commonly used are instruments known as wide-beam interferometers, the best known example of which is Michelson's interferometer. In this device an essentially parallel beam of light is split in two equal parts by means of a semitransparent mirror, and other mirrors (both semitransparent and fully reflecting) are used for bringing the two halves of the beam together again. The really distinctive feature of this kind of instrument is that the amplitude of the wave is split instead of the wave front. The advantages are well known. It is an instrument with a wide field of view and an enormously enhanced intensity, as compared with the narrow-beam instrument where many of the dimensions are very critical.

In attempting to build an electron interferometer, we first discarded any idea of using amplitude splitting—electron optics does not possess any true-reflecting and much less any semireflecting mirrors. In the absence of any such optical elements, our thinking gravitated toward an imitation of Young's experiment, or perhaps of Rayleigh's instrument. Unfortunately, conditions for such an experiment are extremely unfavorable.

Without saying at this point whether a scaling down of the light-optical consideration is justified, let us assume that we could calculate all the dimensions of such an experiment from a light optical model, substituting the short wavelength of the electron. The result of such calculation, or estimate of dimensions, is simply horrifying. For an electron wavelength of let us say 0.05 angstrom unit (which is a reasonable value for electron optical experiments) the slit dimensions would be somewhere between 10 and 100 angstrom units. The separation of the two slits would be about 10 times the slit width itself. To illuminate that double-slit system, we should need an electron source of about the same dimensions as the slit width. Under the assumed conditions, the experiment would yield fringes with a spacing of roughly 100 angstrom units.

Even assuming that we could create slits of this minute width and spacing, we still should not have solved the problem of the slit illumination. It has been demonstrated, however, by Gabor (*5*) that the reduced image of an electron source of reasonable physical dimensions could be used for illuminating such a system; and we may therefore assume that we could illuminate the slits by using an inverted electron microscope and operating our interferometer system by using a virtual instead of a real source. The next problem would be the viewing of fringes with 100-angstrom spacing. Obviously, we should have to use another electron microscope to make them visible. Therefore, an experiment such as this would consist of an instrument comprising two electron microscopes arranged head-on and a slit system between them that we do not yet know how to make. To my knowledge no one has yet had the courage to attempt this complicated instrumentation.

Having ascertained that the wave-front splitting system appeared to be impractical, we had to look for an amplitude-splitting system as the real solution. The mental block to the building of such a system is created by the high efficiency of the light-optical beam splitters. We had thought only of looking for something as efficient as a semisilvered mirror and neglected to look for less efficient systems. By abandoning the limitation of equal intensities of the two beams issuing from the beam splitter, we were able to look around for other beam splitters. The following description of a practical electron interferometer uses such a beam splitter; it is not very efficient in terms of a semitransparent mirror but is highly useful for electrons. I refer to the application of diffraction as a beam-splitting mechanism and its consistent use in an interferometrical system.

To describe an electron interferometer, let us look first at its light-optical counterpart. When a beam of light is sent through a transparent diffraction grating, part of the beam is transmitted and part of it is dif-

[2] Work on the electron interferometer at the National Bureau of Standards is part of a cooperative program of basic instrumentation research and development sponsored by the Office of Naval Research, the Air Research and Development Command, and the Atomic Energy Commission.

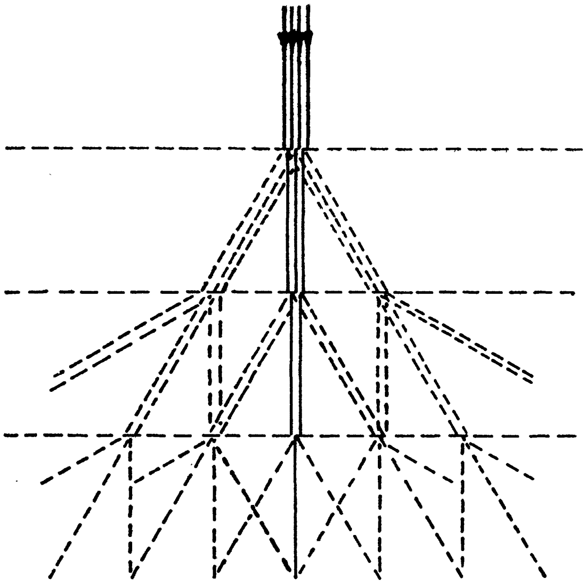

FIG. 1. Schematic representation of rays passing through three gratings (or crystals). Courtesy of *The Physical Review.*

fracted. Figure 1 shows only the first order diffraction and neglects any higher orders. By placing a second transparent diffraction grating at a certain distance parallel to the first one, it can be seen that the transmitted beam is again broken up into transmitted and diffracted components. The same applies to the beam diffracted by the first grating; this will be diffracted again on the second grating. At a distance from the second grating that is equal to the distance of the second from the first grating, a twice-diffracted beam meets up with a once-diffracted one. In placing at that point a third grating parallel to the first and second ones, and by placing convenient apertures, we can bring together, as shown in Fig. 2, two beams that have been diffracted twice.

Translating such a system into the language of electron optics is relatively simple, in principle. All we have to do is use electron beams instead of light beams and thin lamellar crystals instead of diffraction gratings.

The idea of using diffraction as a beam-splitting element is less revolutionary than it seems at first. When originally thinking of that system, I could not find anyone who knew of its light-optical counterpart. It is rather amusing, however, to report that this principle has been used more than 40 years ago in light optics by Carl Barus (*6*), who reported on it in several volumes published by the Carnegie Institution of Washington. For reasons that are not quite clear, none of the optical textbooks and treatises refer to the work of Barus, and I should like to use this opportunity to pay him belated homage.

In addition to the one described above, many other arrangements can be made to satisfy the conditions of interferometry. These include arrangements of crystals plus other electron optical elements or other electron optical elements alone. Some of these arrangements are more critical in that they require greater accuracy in the making or aligning of the optical element. It would take up too much space to discuss here the advantages and disadvantages of several interferometric combinations. The arrangement illustrated in Figs. 1 and 2 is the one proved most advantageous for the first experiment carried out at the National Bureau of Standards; a few more words about the details should be included here.[3]

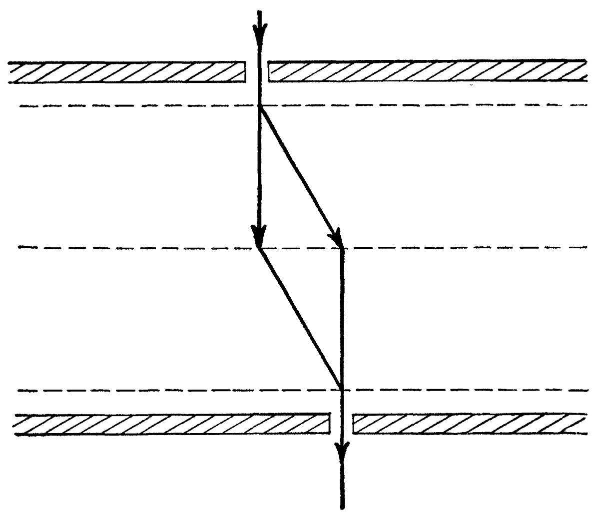

FIG. 2. Rays as limited by apertures. Courtesy of *The Physical Review.*

The thin crystals used for carrying out the experiment are metallic foils of about 100 angstrom units thickness, which have been grown on the cleavage face of a rock-salt crystal. If a thin layer of metal is deposited on such a rock-salt surface, which is heated to a selected temperature, complete alignment of the atoms within the metal layer, forming a single crystal, can be observed. For details of this process, known as epitaxy, reference is made to the literature (*7*). Good

[3] Let us investigate briefly the implications of this experiment from the point of view of the feasibility of an x-ray interferometer. It appears that such an instrument could be built, although the experiment may be a rather difficult one to carry out. Beam splitting, using diffraction or other optical phenomena, seems to be just as easy to achieve as for electrons. The difficulty will arise in aligning the optical elements and in observing the fringes. Present x-ray optics, using curved surfaces at grazing incidence (P. Kirkpatrick, *Nature,* **166**, 251 [1950]), can resolve distances of the order of 10^{-4} cm. A rather good alignment is needed to produce fringes of that spacing. This is where the greater resolving power of electron optics has proved of great value; we did not need the perfect alignment to observe fringes.

The various difficulties mentioned here should not discourage would-be investigators. There are at least two good reasons for undertaking this experiment. One is to check the absolute values of x-ray wavelengths. The other is to measure the length of the wavepacket for x-rays. On this last subject there exist some theoretical predictions which, to my knowledge, have never been submitted to experimental verification. (See, for instance, W. Kossel's paper in: C. Ramsauer, *Das freie Elektron in Physik und Technik,* p. 130, Berlin: Springer, 1940.) Such an experiment thus could contribute considerably to our knowledge of radiations.

single crystals of different metals, such as gold, silver, copper, nickel, and others, can be produced in this manner and are useful beam splitters for the electron interferometer.

For the practical achievement of the electron interferometry experiment, a modified electron microscope can be used. The electron microscope comprises optical elements that are needed for any successful interferometry work, that is, it has a beam-generating system, a beam-collimating system, and an electron optical system for the purpose of viewing the fringes. The experiment is thus carried out by replacing the object chamber of the conventional electron microscope with an interferometer chamber.

The first experiments, which confirmed the feasibility of the interferometer, had to be carried out entirely by means of photographic observation because the total available beam intensity was too low for visual alignment of the instrument by means of a fluorescent screen. This was, to put it mildly, tedious work; but, finally, proof is on hand that interference fringes that can be manipulated at will by changing the instrument parameters can be produced by means of electrons.

An interesting property of this interferometer is that it is achromatic. This means that its light-optical analogue produces fringes in white light and no monochromatic light source is required for its operation. This is because diffraction deflects the different wavelengths by different amounts and thus the instrument, so to say, has its own built-in monochromator. To be quite frank, this property was not recognized at the time the instrument was conceived. Later on, however, it proved quite advantageous during the experiments to find that the requirements on wavelength constancy (i.e., stability of the high-voltage power supply) were very much relaxed. This was one good reason for pushing the experiments with the three crystal arrangements (shown in Figs. 1 and 2) and putting in the background the search for other nonachromatic instruments.

The question invariably arises, what is this experiment good for?

There are a certain number of applications of the instrument in close analogy to the light interferometer. For instance, it could be used in extending the range of the light instrument in measuring shorter distances than were previously feasible. It should be well understood that this does not mean that it may supplant the light interferometer, for the upper limit of its operating range will be lower than that of its predecessor. It is a situation somewhat similar to that of the light microscope and the electron microscope. The two are complementary and not competitive. There exist other applications, such as the measurement of very weak field gradients, determination of Planck's constant, and interference spectroscopy, but the application that I want to discuss a little more in detail here is the improvement of our fundamental knowledge of the electron itself.

In all the description up to now I have avoided reference to the electron as a particle. Now, in order to state in what manner the interferometer can contribute to a better knowledge of the nature of the electron, I can no longer avoid referring to the old particle-wave concept. Let us start out by stating again that the building up of the electron interferometer was based entirely on a light-optical analogy. That means that all the design parameters were calculated by scaling down from a light-optical model by substituting the shorter wavelength of the electron for the light wavelength, the lattice constant of the crystals for the grating constant, and the electron diffraction angle for the light diffraction angle. The properties of the instrument including such features as the fringe spacing and the variation of that spacing with mechanical changes could then be calculated. The final observations showed surprisingly good agreement with this rather simple-minded model. In other words, not only does the electron behave like a wave, but in some respects this wave-like behavior exceeds our expectations.

To explain this last sentence I have to add that, although in principle the interference phenomena described here could be calculated on a straight quantum mechanical basis, to my knowledge no attempts have been made up to now in that direction. The difficulties of such a calculation are considerable, one of the complications being due to the dispersive nature of the medium in which the electrons propagate. Here again I need an added explanation: by dispersive it is meant that different wavelengths travel with different velocities. If we compare this behavior of electrons with that of light there is a marked difference. In the case of light, all wavelengths travel in vacuum with the same velocity. This is not true for material media, but gases, for instance, are so little dispersive that in calculating normal light optical instruments the contribution of air within the system can usually be neglected. No such simplification can be afforded for electron optical systems because even vacuum in absence of any fields is a dispersive medium for electrons. This means that the quantum mechanical calculation of intensity distribution in the interference pattern is complicated by the dispersive property of the medium of propagation, and this may be a partial explanation for the missing attempts in that direction. Several physicists, however, have made predictions on the outcome of the interferometer experiment based on "intuitive extrapolation." Although these predictions were rather unfavorable, the results of the experiments exceed these expectations in that the limit of experimental accuracy is much more favorable than was foreseen. Besides this disagreement with the extrapolation (which could be disregarded as based on insufficient experimental evidence), the interferometer experiment extended our knowledge of the electron in the following way: Within the limits of the present experiment, the exceedingly complex quantum mechanical calculations can be advantageously replaced by the much simpler scaled-down light-optical picture.

For those who are interested in specific details of interferometry: on one interferogram, 154 interference fringes were counted with an average spacing of 1650 angstrom units. The optical path difference, which was not measured directly but calculated from fringe spacing, was 276 angstrom units, or roughly corresponding to 5800 electron wavelengths.

The results of the experiment have shown that (*a*) a wave analogy can be successfully applied in describing the outcome of the experiment, and (*b*) the lower limit of the length of the "wavepacket" is at least 30 times greater than previous experimental evidence indicated. The length of the wavepacket denotes the length of that "coherent" wavetrain within the boundaries of which interference is possible (and thus by inference the phase relationship is not disturbed). The previous experimental evidence was based on observations of resolution in diffraction diagrams, which showed that the wavepacket had to be at least 200 wavelengths long to explain the observed data. Both the older estimates and our new results are considerably below the theoretically possible length of the wavepacket.

The numerical values for comparison can be presented in different ways. One rather striking representation consists of translating the length of the wavetrain into the time required for the "particle" to travel a distance equal to the path difference. According to the present measurement this time (the "coherence time" of the electron) is at least 2×10^{-16} sec,[4] whereas the older lower limit was 7×10^{-18} sec. The theoretical estimate involves a knowledge of the indeterminacy of energy of the electron; for electrons issuing from hot tungsten filaments it could be as high as 10^{-13} sec.

An experiment of this kind strengthens considerably the concept of the wave nature of the electron, and the question may arise whether any more strengthening of this concept is necessary. Another question can be asked: How does such an experiment affect our views of the "true" nature of the electron? Is the electron less of a particle than it used to be because of any such experiments? The answer to such questions may seem trivial, but several recent publications by outstanding theoretical physicists show that it is far from being trivial to the general scientific public (*8–10*). For this reason, I would like to add a brief summary of our present picture as it appears to an experimental physicist.

[4] This time is equal to the path difference of 276A (or 2.76×10^{-6} cm) divided by an electron velocity of about 1.4×10^{10} cm/sec.

There seems to be no reason for further discussion as to whether the electron is a particle or a wave, or as Eddington put it a "wavicle." The electron is none of them. With due apologies to the late Gertrude Stein, the electron is an electron. Old and conventional language cannot be used to describe the properties of something of which we had not the slightest inkling fifty years ago. If we say "particle," the word has certain connotations even in the most abstract mind. We conjure up the image of something solid like a ball or a bullet and try to adapt the properties of the so-called particle to the image in our minds. This kind of operation is feasible as long as there is a common understanding of how the image or model is to be used. For instance, if I call an object a stone by training or by habit or by both, I shall describe certain properties such as shape, color, mass, rigidity, and hardness. I will know that I have an object on hand which, if of proper size and structure, can be cut and used as a constructive element in building houses. The word electron has to convey to our senses a physical entity, which has charge and mass, can interact with fields of forces (both microscopic and macroscopic), can acquire and transfer momentum, and can show diffraction and interference phenomena. All such and other properties are contained in the word "electron." If I want to employ images or models, I can say that under specific conditions of the experiment we can describe the behavior of the electron as particle-like or wave-like, but let us remain conscious that when doing so we are trespassing the limitations of our language. It is about time to repeat and emphasize the warning quoted in Margenau's book: "Thou Shalt Not Make Unto Thee Any Graven Image."

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