# The 1973 AAPT Apparatus Competition

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Once again the American Association of Physics Teachers promoted an apparatus competition, the seventh such biennial competition. Because of budget problems the Council of AAPT had canceled the 1973 competition but reinstated the activity during its 1972 summer meeting. Due to the lateness of the reinstatement several wide-coverage announcements had been missed. However, both this Journal and *The Physics Teacher* carried announcements of the 1973 competition during the late summer of 1972. The response was indeed very gratifying since the total number of entries was slightly off the number of entries received during the past few competitions.

The AAPT Apparatus Committee is grateful to all who participated, for your interest in improving physics teaching, and for the support given the committee in this activity. A special thanks goes to many participants who gave unstintingly of their time in the demonstration of their apparatus during the convention. There were those both inside and outside the United States who came from distant points to be active participants. A sincere and warm Thank You to each of you.

Judges for the 1973 Competition were: Professor Walter Eppenstein, *Rensselaer Polytechnic Institute*; Professor John M. Goodman, *Claremont's Men's College*; and Professor Edward A. Piotrowski, *Roosevelt University*.

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# Optical Crystals

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*Optical crystals are one-, two-, and three-dimensional diffraction plates used to demonstrate Laue diffraction by using light rather than x rays or particles. The flexibility afforded by optical crystals makes them better suited for demonstration purposes than naturally occurring crystals. The sequence of optical crystals has been proven effective for demonstrating diffraction phenomena at the high school level and is applicable at all university levels in both classroom and laboratory situations. [The apparatus described in this article was first prize winner in the 1973 AAPT Apparatus Competition. This contribution was in the area of lecture demonstration—Editor]*

Optical crystals are diffraction plates that bridge the gap between double- or multiple-slit diffraction and diffraction by crystals. Optical crystals enable one to demonstrate how a diffraction pattern changes as a one-dimensional crystal is extended to a two-dimensional crystal and then further extended to a three-dimensional crystal. The sequence of optical crystals also illustrates the role of the form factor and structure factor in diffraction and, in turn, how the diffraction pattern is used to identify the structure of the crystal. The diffraction patterns can be projected on a screen by using a low-power laser beam or viewed by looking through the crystal directly at a point source. Optical crystals work well in an optical simulation of an electron microscope.

## I. RESURRECT VON LAUE FOR THE SAKE OF THE STUDENTS

The development of Bragg's law was indeed a stroke of genius. However, to visualize the various planes of reflection and their corresponding separations is not easy for a well-trained mind and is nearly an impossible feat for the inexperienced mind. To directly explain Bragg's law to beginning physics students is a waste of effort and time. Most treatments of basic physics recognize the importance of understanding diffraction, but fail to guide the student through a sequence of diffraction phenomena that clearly establishes why a crystal diffraction pattern takes on the form that it does and how the properties of the pattern indicate the structure of the crystal. In short, we have become so mired down in the convenience and routine use of Bragg's law that we have forgotten the relatively simple and logical step-by-step explanation of the phenomena afforded by Laue theory.

## II. SIMPLE LAUE APPROACH TO DIFFRACTION BY CRYSTALS

Consider a beam of radiation propagating along the $z$ axis and incident on a row of characters (one-dimensional lattice) lined up along the $x$ axis. The interference pattern produced on a distant screen which is parallel to the $xy$ plane consists of bright lines parallel to the $y$ axis. Actually these lines are hyperbolas that approach straight lines when they are near the $z$ axis. The mathematical treatment is similar to the derivation of double-slit interference, except that one should recognize that the pattern will extend in the positive and negative $y$ directions. In a similar manner, if the characters are lined up in the $z$ direction, the resulting interference pattern would be concentric bright rings about the intersection of the $z$ axis with the screen. The simple Laue explanation is completed by applying these two cases to a three-dimensional crystal.[1] Assembling these conditions in one's mind to comprehend the form of a diffraction pattern due to a three-dimensional crystal is difficult, particularly for the beginning students. However, optical crystals can be used to demonstrate these concepts and to piece these phenomena together in a logical sequence which eliminates the difficulties.

## III. GENERAL DESIGN AND USE OF OPTICAL CRYSTALS

Optical crystals are diffraction plates made by photographic reduction in a similar manner as some previously designed diffraction plates.[2,3] The primary differences between optical crystals and other diffraction plates are the particular elements (characters) used for the various arrays, the quality of the characters, and the particular arrays of these characters.

The sequence of optical crystals consists of seven 2-in.×2-in. slides, each containing four samples (optical crystals). A brief description of each crystal and its resulting diffraction pattern is given in Table I. Cover glasses are glued to the slides with epoxy to strengthen the slides and provide surfaces that can be cleaned without damaging the emulsion. The lattice spacings used vary between 0.01 mm and 1 mm, dependent upon the particular phenomena that the crystal is intended to demonstrate. The optical crystals can be studied directly in any of the following three ways: (1) Study them under a microscope; (2) project an image of them using a 2×2 slide projector; or (3) project them using either a measuring microscope or a microscope objective as a projector lens, and a laser beam as the light source.

The third method is particularly convenient since one can project an image of the sample on the screen, and then merely by removing the projector lens from the system the diffraction pattern is produced on the screen. This method illustrates the use of projector lenses in electron microscopes.

One can study the diffraction patterns in any one of three manners: (1) by placing an optical crystal in a laser beam the diffraction pattern can be studied on a screen; (2) by holding the crystal near one's eye and viewing a point source directly through a sample there will be a separate pattern for each of the wavelengths that are characteristic of the light source, illustrating that crystals can be used to measure the wavelength of the radiation; or (3) by using an optical simulation of an electron microscope.[4]

The first four slides are made up of dots that are designed to give an intense, general-form, factor-diffraction pattern. The intensity is so great that the diffraction pattern due to only a few dots is obvious.

### A. One-dimensional Crystals

Often, but incorrectly, a multiple slit diffraction plate is used to optically simulate a one-dimen-

TABLE I. Description of optical crystals.

| Sample | Composition | Diffraction Pattern |
|---|---|---|
| 1a | A random array of dots. | The sample demonstrates the amorphous form factor of the characters used in Samples 1a–4d. |
| 1b | A single row of dots making a one-dimensional crystal. | The sample produces a line diffraction pattern due to a one-dimensional lattice that can be aligned perpendicular or nearly perpendicular to the incident radiation. (See Fig. 2.) |
| 1c | A one-dimensional crystal having a smaller spacing than Sample 1b. | The sample produces a pattern similar to that of Sample 1b except that the lines are spaced farther apart showing the reciprocal relationship between the lattice spacing and the spacing of the diffraction pattern. |
| 1d | A one-dimensional crystal having a smaller spacing than Sample 1c. | See Sample 1c. |
| 2a | Two parallel rows of dots. | Each of the lines of the diffraction pattern produced by one row of dots is broken into a dashed line. The variation in intensity along each line is similar to that produced by a double slit. (See Fig. 3.) |
| 2b | Three parallel rows of dots. | Each of the lines of the diffraction pattern produced by one row of dots is broken into primary and secondary maxima resulting in an intensity variation along each line similar to that of a triple slit. |
| 2c | Four parallel rows of dots. | Each of the lines of the diffraction pattern due to one row of dots is altered in intensity so as to be similar to that of a quad slit. |
| 2d | Many parallel rows of dots (simple rectangular lattice). | The primary maxima produced by Samples 2a–2c reduce to bright spots and the secondary maxima vanish, leaving a spot pattern similar to the composition of the sample but rotated 90° due to the reciprocal relationship between the lattice and the diffraction pattern. (See Fig. 4.) |
| 3a | One row of dots. | See Sample 1b. |
| 3b | Two rows of dots at a 60° angle. | The diffraction pattern consists of two sets of lines with an angle of 60° between the sets. The pattern is brighter where the two sets of lines intersect. |
| 3c | Three rows of dots, each row making a 60° angle with the other rows. | The diffraction pattern consists of three sets of lines. Each set makes a 60° angle with the other two sets. The intensity is much brighter where the lines intersect. |
| 3d | More dots are added to Sample 3c to produce a full hexagonal array. | The diffraction pattern consists of bright spots (corresponding to the intersections of the lines of Sample 3c). The array of bright spots is similar to the array of dots in the sample except rotated 90°. |
| 4a | Two identical layers of dots randomly distributed in each layer. | Corresponding dots of the two layers can be aligned with the incident radiation. The resulting pattern consists of circular rings as predicted by Laue theory for two scattering centers aligned with the incident radiation. When the sample is rotated, the rings open up and approach straight lines similar to those produced by Samples 1b–1d. (See Fig. 5.) |
| 4b | A three-dimensional crystal consisting of two layers, each layer containing a hexagonal array of dots. | The spot pattern produced is quite similar to that produced by Sample 3d except that the interference due to the alignment of one dot from each layer with the incident beam removes some of the spots (see Sample 4a), thus limiting the spots to Laue zones. The pattern is typical of an electron diffraction pattern due to a thin monoclinic crystal. |

TABLE I—(*Continued*)

| Sample | Composition | Diffraction Pattern |
|---|---|---|
| 4c | A three-dimensional crystal consisting of two layers, each layer containing a rectangular array of dots. | The diffraction pattern is similar to that produced by electrons incident on a thin simple orthorhombic crystal. The rectangular array of diffraction spots due to one layer is restricted to Laue zones which are produced due to the near alignment of one dot from each layer with the incident radiation (see Sample 4a). As the sample is rotated, other sets of Laue zones move across the field of bright spots causing each spot to blink. (See Fig. 6.) |
| 4d | Similar to Sample 4c except different spacings. | See Sample 4c. |
| 5a | A random array of asterisks. | The diffraction pattern illustrates the form factor associated with an asterisk. |
| 5b | Similar to 5a except the asterisks are smaller. | The diffraction pattern is similar to that produced by 5a except that the diffraction pattern is larger, indicating the reciprocal relationship between the size of the symbol and the size of the diffraction pattern. |
| 5c | A random array of S's. | The diffraction pattern illustrates the form factor associated with an S. |
| 5d | Similar to 5c except the S's are smaller. | The diffraction pattern is similar to that produced by Sample 5c except that the pattern is larger. |
| 6a | A random array of A's. | The diffraction pattern is characteristic of an A (form factor). (See Fig. 7.) |
| 6b | One row of A's (one-dimensional crystal). | The resulting pattern combines the form factor and structure factor. A series of lines are produced characteristic of the periodicity of the crystal. (see Samples 1a–1d). These lines are only visible where there is brightness due to the form of the A (see Sample 6a and Fig. 8). |
| 6c | A two-dimensional rectangular crystal made up of A's. | The resulting pattern combines the structure factor illustrated by Sample 2d with the form factor illustrated by Sample 6a. |
| 6d | A two-dimensional hexagonal crystal of A's. | The resulting hexagon spot pattern as illustrated by Sample 6d is restricted by the diffraction patterns produced by Sample 6a. |
| 7a | A simple rectangular crystal of dots. | A diffraction pattern characteristic of a rectangular array is produced (see Sample 2d). The resolution is increased since many more dots are used. (See Fig. 9.) |
| 7b | Dots are added to the array of Sample 7a to produce a face-centered rectangular crystal. | The resulting pattern indicates Sample 7b does constitute a unique Bravais lattice. As is typical of x-ray diffraction by a face-centered crystal, the pattern is similar to that of a simple crystal except that some of the orders are missing. (See Figs. 9, 10.) |
| 7c | Dots are added to the array of Sample 7a to make a side-centered rectangular crystal. (See Fig. 13.) | The resulting pattern is similar to that of Sample 7a with no orders missing, indicating that this sample does not constitute unique Bravais lattice. It is a simple rectangular crystal. The intensity of the spots corresponding to every other row and column is greater. This variation in intensity is due to the form factor of the element which is arranged in a rectangular manner. (See Figs. 11, 12, 13.) |
| 7d | A random array of sets of three dots that constitute the element from which Sample 7c is made (see Fig. 13). | The resulting pattern should be compared to those produced by Samples 7a and 7c. This comparison clearly illustrates that the form factor of a set of the three dots as circled in Fig. 13 causes the variation of intensity of the spot pattern produced by Sample 7c. (See Figs. 12, 13.) |

sional crystal. When a multiple slit or diffraction grating is placed in a laser beam the resulting diffraction pattern is one row of spots (see Fig. 1), whereas Laue's theory predicts a set of lines. A one-dimensional optical crystal (one row of dots) does produce the predicted line pattern (see Fig. 2). When this row of dots is rotated so that it makes a small angle with the incident radiation, the lines of the diffraction pattern become curved lines.

A two-layer sample made by stacking emulsions is used to demonstrate the diffraction due to characters aligned parallel, or nearly parallel, to the incident beam. The sample can be tilted so that a character on one layer can be aligned with a character on the other layer. The intensity of the pattern is increased by using a random array of these pairs. This technique of increasing the intensity has been used in other works.[2,3] When the pairs are aligned with the incident beam, a ring diffraction pattern results as described by the simple Laue theory (see Fig. 5). As the sample is rotated these rings open and gradually approach straight lines. This type of sample is also convenient for demonstrating the interference of light from two coherent point sources.[5]

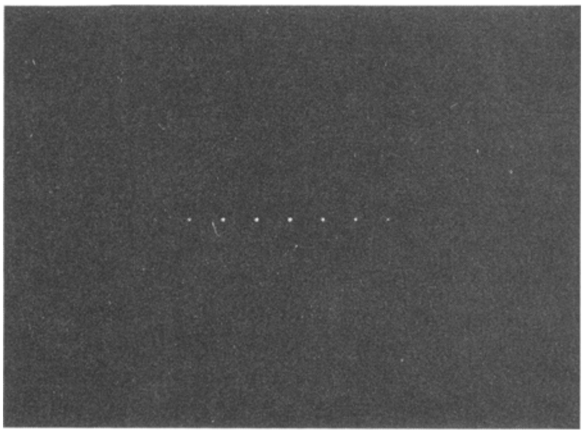

FIG. 1. The diffraction pattern is produced by a multiple slit. The spot pattern is not characteristic of a one-dimensional crystal as predicted by Laue theory. This and Figs. 2–12 are photographs of the diffraction pattern produced on a posterboard screen. A low power He-Ne laser was used as a light source.

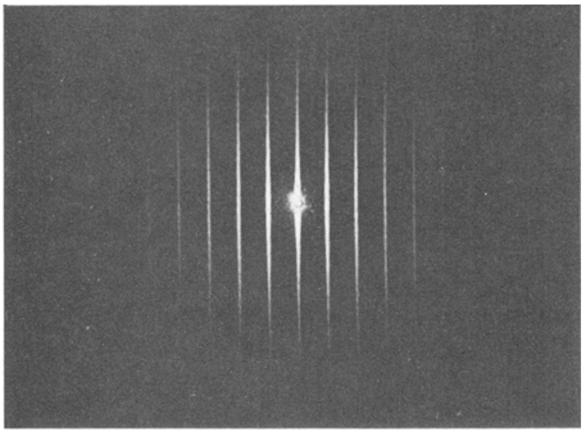

FIG. 2. The diffraction pattern is produced by a one-dimensional optical crystal aligned horizontally and perpendicular to the incident radiation. The line pattern is predicted by Laue theory. (See Sample 1b of Table I.)

### B. Two-Dimensional Crystals

In other works two-dimensional lattices have been made up of various characters.[2,3] These two-dimensional crystals are made of characters that either do not diffract much light or have unique shapes that diffract light in symmetrical patterns (form factors)[6] that partially obscure the structure factor pattern formed by the periodicity of the lattice.[7] The structure factor is the most im-

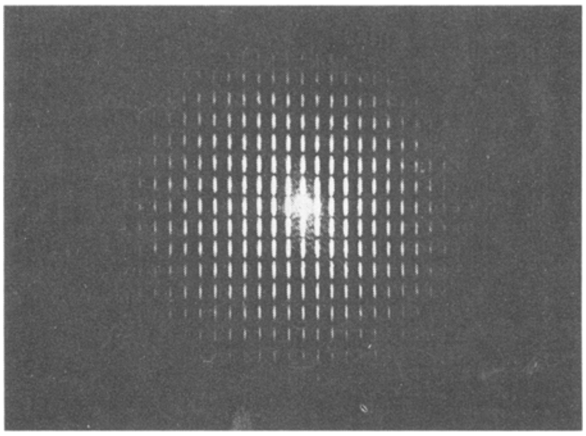

FIG. 3. The diffraction pattern is produced by two horizontal rows of dots. Note that the lines due to a one-dimensional lattice are broken into dashes due to the interference resulting from the existence of two rows. (See Sample 2a of Table I.)

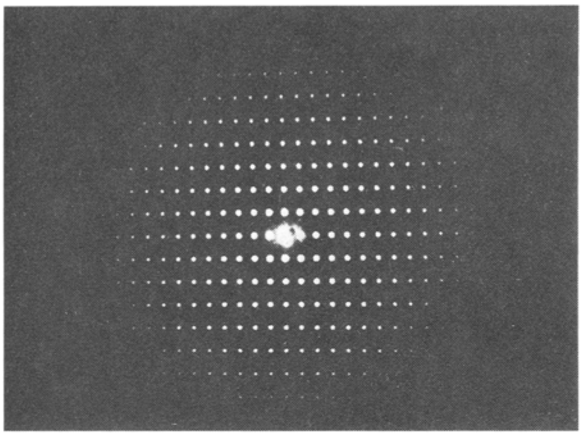

FIG. 4. The diffraction pattern due to many rows of dots shows that the dashes produced by two rows of dots are reduced to diffraction spots. (See Sample 2d of Table I.)

portant and elementary part of a crystal diffraction pattern, since it indicates the appropriate Bravais lattice of the crystal. The characters used in the first four slides of optical crystals are designed to produce a bright amorphous form factor pattern that does not detract from the structure factor part of the pattern, thus allowing the student to concentrate on the structure factor and how it relates to the arrangement of characters in the optical crystal. The two-dimensional lattices are built up by adding rows one by one and finally extending to full two-dimensional arrays (see Samples 2a-3d of Table I and Figs. 2 and 3).

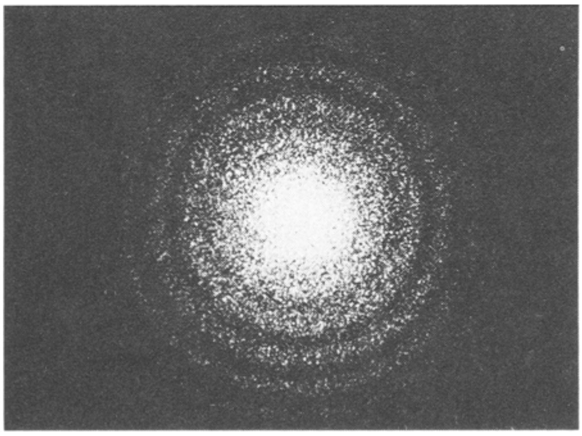

FIG. 5. The ring pattern is produced by pairs of dots aligned parallel to the incident radiation. This pattern is predicted by Laue theory for a one-dimensional crystal aligned parallel to the incident radiation. (See Sample 4a of Table I.)

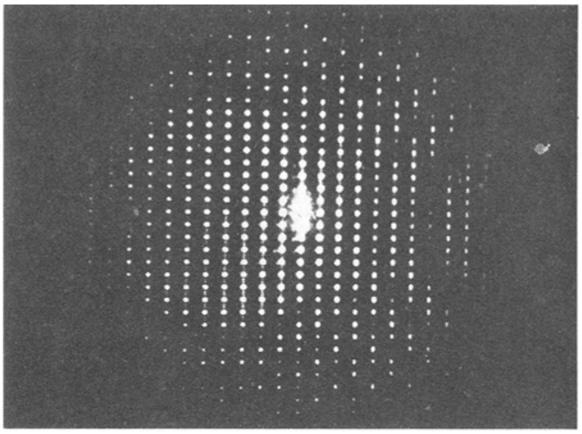

FIG. 6. The pattern is produced by a three-dimensional optical crystal. The spot pattern produced by a two-dimensional crystal is restricted to circular Laue zones. Two sets of Laue zones are shown. One set is centered about one inch from the left edge of the figure. The other set is centered about $\frac{5}{8}$ inch from the right edge of the figure. These circular zones are more obvious if one views the figure from an oblique angle. The Laue zones are more apparent when observing them directly because they move through the field of spots when the crystal is rotated. (See Sample 4c of Table I.)

### C. Three-dimensional Crystals

The three-dimensional optical crystals consist of two identical layers of periodic arrays of characters. The resulting diffraction patterns are similar to those produced by a two-dimensional crystal except that the interference due to characters nearly aligned with the incident radiation cancels

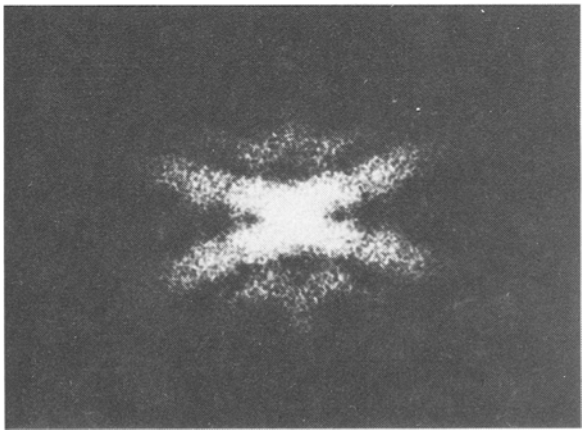

FIG. 7. The diffraction pattern is characteristic of an A and is described by the form factor of an A. (See Sample 6a of Table I.)

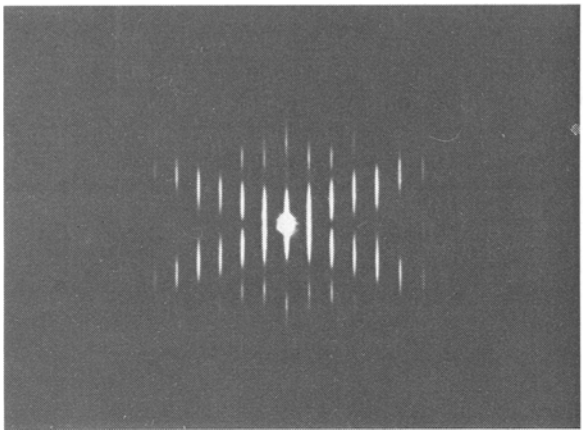

FIG. 8. The diffraction pattern is produced by a horizontal row of A's. The line pattern is characteristic of a one-dimensional crystal but the lines are restricted by the form factor of an A (see Fig. 7). (See Sample 6b of Table I.)

out some of the diffraction spots; thus, leaving circular zones of diffraction spots (see Samples 4b–4d and Fig. 6). These circular zones are known as Laue zones.[8] In electron diffraction of thin crystals the breadth of Laue zones is used to measure the thickness of crystals or to determine the number of molecular layers in the crystal.[9] As the number of layers increases, the breadth of the Laue zones decreases until the number of bright spots is reduced to those described by Bragg's law. When a three-dimensional crystal is rotated, numerous sets of Laue zones move across the field of diffraction spots due to alignment of a dot in one layer with various dots of the other layer, resulting in the blinking of each of the diffraction spots.

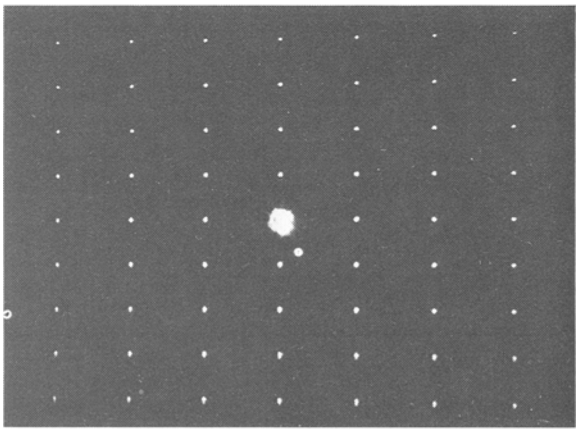

Fig. 9. The diffraction pattern is produced by a two-dimensional simple rectangular lattice. The small lattice spacings result in a large diffraction pattern of high resolution. (See Sample 7a of Table I.)

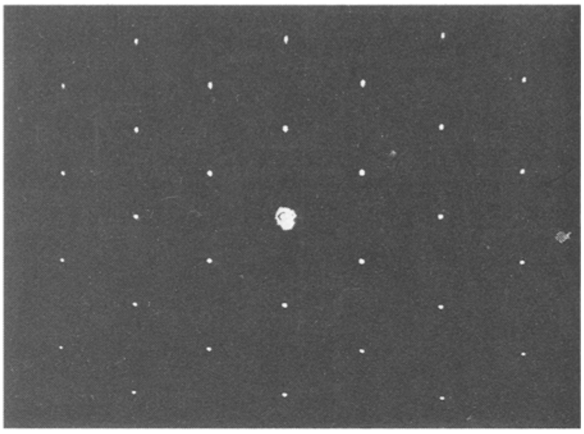

FIG. 10. The diffraction pattern is produced by a two-dimensional face-centered crystal having the same lattice constants as the optical crystal used in Fig. 9. The pattern is similar to that of Fig. 9 except that some of the spots are missing, indicating that the crystal is a unique Bravais lattice. (See Sample 7b of Table I.)

### D. Form Factor

The portion of a diffraction pattern described by the form factor is dependent on the shape of

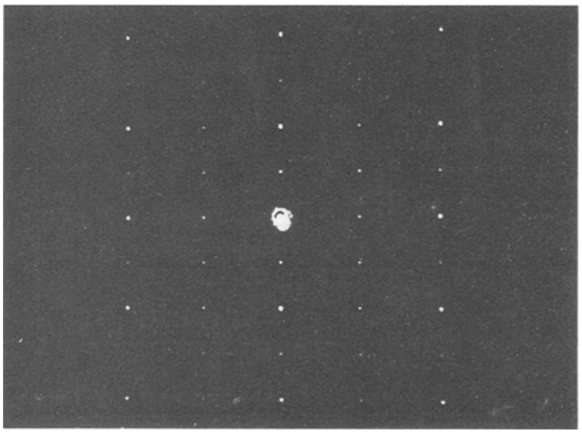

FIG. 11. The diffraction pattern is produced by a two-dimensional side-centered rectangular crystal (see Fig. 13) having the same lattice constants as the crystal used for Fig. 9. The resulting periodicity of the pattern indicates that the crystal is really a simple rectangular Bravais lattice corresponding to the ovals in Fig. 13. (See Sample 7c of Table I.)

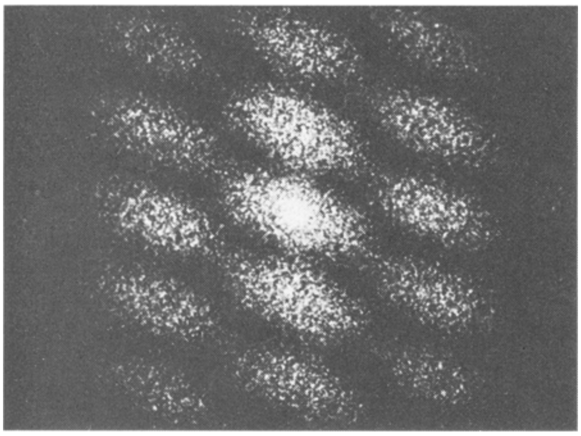

Fig. 12. The diffraction pattern is produced by an element made up of three dots as enclosed by an oval of Fig. 13; thus showing that the variation in intensity of the spots in Fig. 11 is due to the intracellular structure. (See Sample 7d of Table I.)

the characters.[6] The diffraction pattern due to particular characters can be intensified by using a random array of characters.[3] Samples 5a–6a are made up of random arrays of symbols. They are used to show form factor patterns and how the patterns depend on the size and shape of the characters.

### E. Combination of Form Factor and Structure Factor

The intensity of a total diffraction pattern is expressed as the product of the form factor and structure factor.[7] One- and two-dimensional crystals are made up of characters that have unique form factors. Having already seen both the form and structure diffraction patterns separately, one can readily see that the periodicity of the pattern identifies the Bravais lattice, and the variation in the intensity of the spot pattern is related to the form factor of the characters from which the crystal is made. (See Samples 6a–6d of Table I and Figs. 7 and 8.)

The last slide of optical crystals firmly establishes how a diffraction pattern is interpreted. This is accomplished by showing how:

(1) The diffraction pattern due to a face-centered rectangular two-dimensional crystal indicates that the crystal is a unique Bravais lattice. (See Figs. 9 and 10 and Sample 7b of Table I.)

(2) The periodicity of the diffraction pattern formed by a side-centered, rectangular, two-dimensional crystal indicates that the lattice does *not* constitute a unique Bravais lattice but is merely a simple rectangular crystal. (See Figs. 9, 11, and 13 and Sample 7c of Table I.)

(3) The variation in intensity of the spot diffraction pattern formed by a side-centered, two-dimensional, rectangular lattice is due to the form factor characteristic of an element made up of three dots (see Figs. 11, 12 and 13); thus, illustrating that the variation in intensity of the spot pattern yields information about the intracellular make up of the crystal.

## IV. CONCLUDING REMARKS

Optical crystals provide a meaningful sequence of demonstrations that illustrates crystal diffraction. The sequence includes diffraction by a one-dimensional crystal which is not attainable by x-ray diffraction, as well as two- and three-dimensional crystal diffraction. The sequence also clearly illustrates the distinction between form factors and structure factors which are used to describe x-ray diffraction patterns.

Optical crystals have a wide range of application. In addition to their obvious use in courses in solid state physics, crystallography, and optics, they have been found to be effective in qualitative presentations of Laue theory suitable for students of secondary school level or higher. The crystals

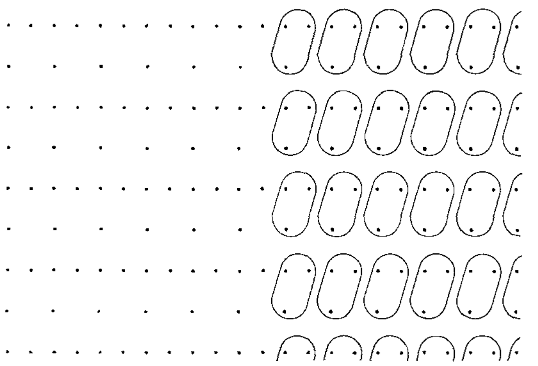

Fig. 13. The structure of a two-dimensional side-centered crystal is shown in the left half of the figure. This is really a two-dimensional simple rectangular Bravais lattice corresponding to the periodicity of the ovals. The set of three dots within an oval constitutes an element of the simple rectangular Bravais lattice.

are well suited for laboratory projects at all levels, with particular value in preparing students to use electron microscopes.

## ACKNOWLEDGMENTS

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[1] A more complete treatment is presented in C. F. Meyer, *The Diffraction of Light, X Rays and Material Particles* (J. W. Edwards, Ann Arbor, MI, 1949), 2nd ed., pp. 315–329.

[2] J. R. Meyer–Arendt, and J. K. Wood, Am. J. Phys. **29**, 341 (1961).

[3] R. B. Hoover, Am. J. Phys. **37**, 871 (1969).

[4] D. G. Ast, Am. J. Phys. **39**, 1164 (1971).

[5] B. Rossi, *Optics* (Addison–Wesley, Reading, MA, 1957), p. 115.

[6] E. Hect, Am. J. Phys. **40**, 571 (1972).

[7] A clear explanation of form factor vs. structure factor is given in R. W. Ditchburn, *Light* (Wiley, New York, 1963), 2nd ed., p. 203.

[8] P. B. Hirsch, *et al.*, *Electron Microscopy of Thin Crystals* (Butterworths, London, 1965), Chap. 5, pp. 112–116.

[9] See Ref. 8, Chap. 17, p. 421.