A Recording Spectrograph for the Far Infra-Red

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This spectrograph records upon sheets of photographic paper 20×30 inches in size, spectra lying in the range between 18μ and 200μ. Of this range, 9μ may be spread over a single record, or as much as 100μ may be covered, depending upon the gratings and the adjustments used. The spectrograph is a vacuum instrument of high resolving power, being capable of separating sharp lines somewhat closer than 0.5 cm^{-1} apart. Detailed drawings of its construction together with several records are shown and described. The recorded galvanometer deflections are usually adjusted to lie between 100 and 300 mm.

IN 1932 there was described[1] an infra-red spectrograph of large aperture which, with suitable gratings, was to be also an instrument of large dispersion and high resolution. While usable in any portion of the spectrum its large aperture and large gratings made it particularly an instrument for the far infra-red. Subsequent work with this spectrograph[2] on rotational spectra in the far region demonstrated that it did indeed possess the desired qualities.

These first investigations also showed that if the instrument was to be used to investigate the spectra of other substances than water vapor it would be necessary to make it a vacuum spectrograph. This is because the rotational spectrum of water vapor is so intense in the far infra-red region. Drying agents do not remove the vapor sufficiently to prevent its complicated spectrum appearing, fairly strong, superimposed upon the spectrum of any other material under investigation. Moreover experience with a recording prism spectrograph,[3] also a vacuum instrument, had demonstrated the many advantages of automatic recording over personal observation. This large grating spectrograph was accordingly made over into a vacuum instrument, automatically recording. From the following description it will be evident that the optical system of the original spectrometer has been retained in all its essentials. To enclose so large an instrument in a chamber which can be evacuated presents many problems of design, particularly where all adjustments are to be made from the outside while the spectrograph is evacuated.

[1] H. M. Randall, R. S. I. **3**, 196 (1932).
[2] Wright and Randall, Phys. Rev. **44**, 139 (1933); Randall, Dennison, Ginsberg and Weber, Phys. Rev. **52**, 160 (1937).
[3] Randall and Strong, R. S. I. **2**, 585 (1931).

DESIGN OF OPTICAL SYSTEM

Referring to Fig. 1 we see that light diverging from the entrance slit 1 is formed into a parallel beam by the paraboloidal mirror 2 and directed against the grating 3. Returning from the grating, the light again strikes the mirror 2, and is then converged upon the exit slit 4 after reflection from a small plane mirror. An image of the exit slit reduced in linear dimension by about a factor of 3 is focused upon the thermopile 6 by the ellipsoidal mirror 5.

In designing such an optical system so as to produce maximum deflection of the galvanometer connected to the thermopile, it is necessary to give consideration to other factors than merely the amount of energy directed against the receiving surface of the thermopile; for it was shown[4] that the deflection produced by a D'Arsonval galvanometer, when connected to a thermopile of best design, is inversely proportional to the square root of the area of the receiver surface upon which the energy falls. Hence that optical system which converges the radiation upon the smallest thermopile will yield the greatest deflection for a given amount of energy. It is the purpose of the ellipsoidal mirror to form the smallest possible image of the exit slit upon the thermopile receiver by having the center of the exit slit and the center of the receiving area stand at the principal foci of the ellipsoid. Consequently aberrations are minimal and the image area is minimal. There is a limit, however, to the smallness of the image which can be produced, this limit being set by the condition that the included angle of the rays falling upon the thermopile cannot exceed about 100 degrees.

[4] F. A. Firestone, R. S. I. **1**, 630–649 (1931).

It follows that the greater the aperture of the beam passing through the exit slit, the smaller the factor by which the image can be reduced in size, and therefore the less sensitive the thermopile for a given amount of energy passing through the exit slit.

This dependence of the thermopile sensitivity upon the image area influences the design of the spectrograph as follows. Suppose we keep the length of the entrance slit constant, the size of the grating constant, and consider the effect of changing the focal length of the collimating mirror, 2. If we halve the focal length of the collimating mirror, we will get four times as much energy sent to the grating on account of the increased aperture; but this energy must be decreased by a factor of 2 due to halving the width of the entrance and exit slits in order to maintain the same spectral resolution. Maintaining the same diameter and short focal length of the ellipsoidal mirror, it is now necessary to move this mirror twice as close to the exit slit so that the linear reduction factor of the image is only half as great, and the area of the image is twice what it was before (remembering that the exit slit is now half as wide). The thermopile is therefore seven-tenths as sensitive as before, and receiving twice as much energy, consequently the deflection is 1.4 times as great as with the longer focal length collimating mirror. The deflection is proportional to the square root of the aperture of the instrument when that aperture is varied by varying the focal length of the collimating mirror. The deflection is therefore not very sensitive to changes of focal length, the advantage being in favor of the shorter focal length.

If we double the aperture of the instrument by doubling both linear dimensions of the grating, keeping the focal length of the collimating mirror and the width and breadth of the slits constant, the energy falling on the thermopile will be four times as great. However, the ellipsoidal mirror will have to be moved twice as close to the exit slit, so the image falling on the thermopile will be twice as long and twice as wide. The thermopile will therefore be one-half as sensitive, and the increased energy will be able to produce a deflection which is only twice as great as before. Thus the deflection is proportional to the linear dimension of the grating, assuming that the ratio of length to breadth of the grating is kept constant.

If we double the slit length, the thermopile will be seven-tenths as sensitive, but receiving twice as much energy so that the deflection will be increased by the factor 1.4. The deflection is therefore proportional to the square root of the slit length, again not very sensitive to this change of design.

In the above considerations we have neglected the influence of the aberrations of the paraboloidal and ellipsoidal mirrors. If the entrance slit were very short and placed on the axis of the paraboloid, the image of the spectral line produced after two reflections from the paraboloid and one from the grating would be free from aberration and very sharp. However, this image would fall upon the back side of the entrance slit and could not be conducted to a thermopile. It is therefore necessary to place the entrance slit at one side of the axis of the paraboloid and also to use a considerable slit length in order to increase the energy transmitted. Since the slits are somewhat off the axis, aberrations are introduced but these are much less serious than one might suppose, for the aberrations introduced by the first reflection from the paraboloid are partially corrected upon second reflection; they would be completely corrected if the returning beam struck the same portion of the paraboloid as the outgoing beam. These two points can be kept as close together as possible by keeping the grating as near to the collimating mirror as possible. From the standpoint of aberration, longer focal lengths of collimating mirrors are best; however, in the far infra-red where slits must be wide in order to get a sufficient amount of energy, the aberrations of the paraboloidal mirror have but little influence upon the resolution.

Although the center of the exit slit and the center of the thermopile lie at principal foci of the ellipsoid so that the central part of the image is free from aberration, the ends of the image lie off the axis and are broadened, due to aberration. The image of a narrow exit slit is of the form of an X, in which the acute angle of the X is completely filled with light. This may require some broadening of the ends of the thermopile receiver in order to catch all of the energy. Fortunately, this aberration is not great at the

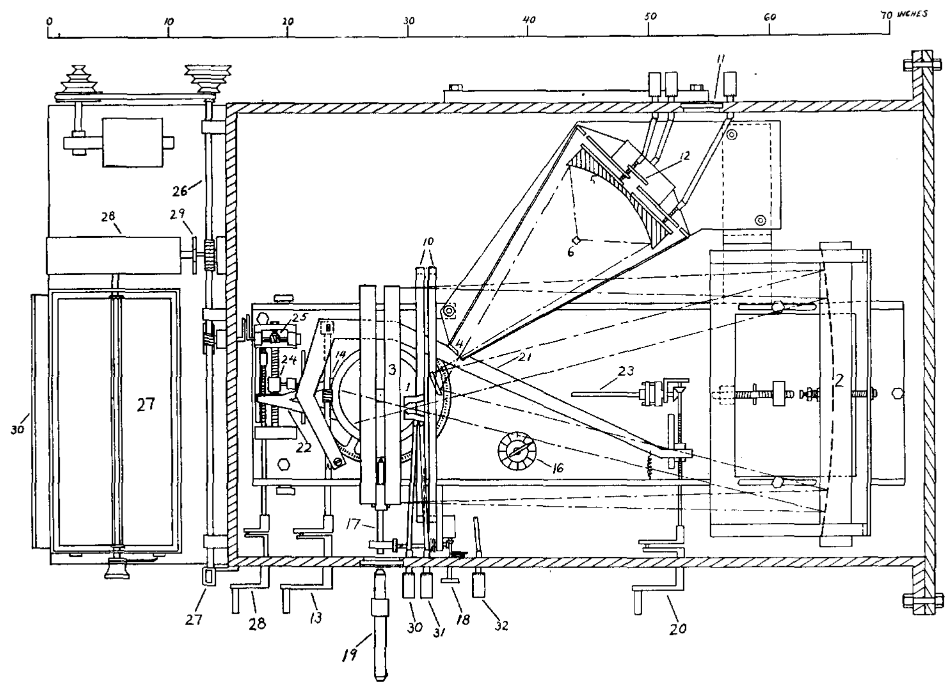

FIG. 1. Cutaway plan of spectrograph.

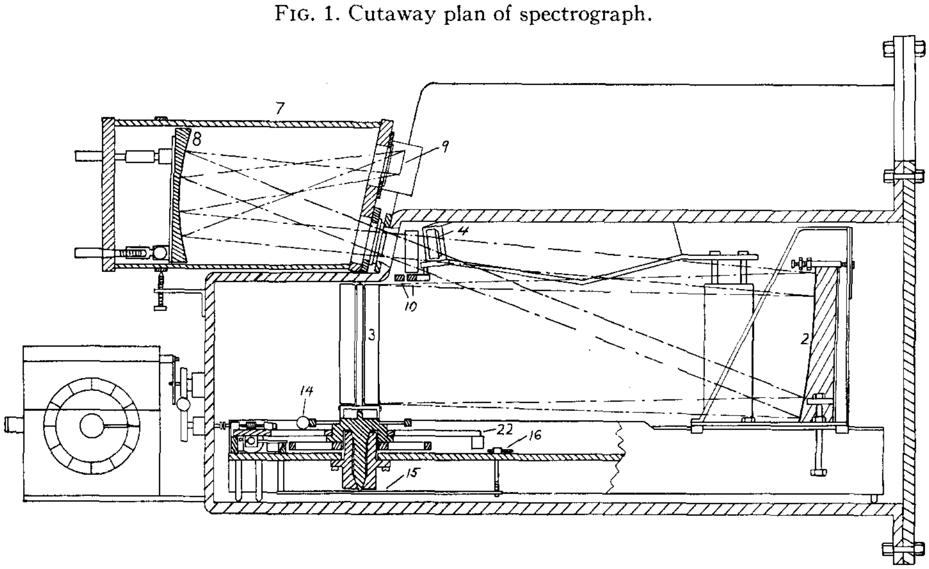

FIG. 2. Cutaway elevation of spectrograph, from operating side.

aperture in use, and it may be computed from the following formulas which we have derived, but whose proof will not be given here.

$$W=\frac{2sed^2}{f^2\{[4(1+e)^2-d^2/f^2][4(1+e)^2+e^2d^2/f^2]\}^{\frac{1}{2}}}\text{(exact)}$$

$$W=\frac{\text{sed}^2}{2(1+e)^2f^2}\quad\text{if}\quad\frac{d^2}{f^2}\ll 4(1+e)^2$$

$$W=(sd^2)/(8f^2),\ \text{within 10 percent if}\ e\leqq 0.5\ \text{and}\ d/f\leqq 2.$$

W is the width of the image formed by the ellipsoidal mirror at a distance s from the axis, assuming a narrow exit slit as object; d is the diameter of the mirror, f its shorter focal length, and e the eccentricity of the ellipsoid.

$e=(m-1)/(m+1)$ where $m=f'/f$, the ratio of the two focal lengths of the ellipsoid.

It will be noted from the final approximate formula above, that if we hold the diameter and the short focal length of the ellipsoidal mirror constant, as in the above deflection consideration, the broadening will be proportional to the length of the image on the thermopile, which length we saw was proportional to the aperture of the spectrograph. This is another point which somewhat favors the longer focal length of collimating mirrors. However, with the comparatively wide slits used in the far infra-red, the broadening of the image due to aberration of the ellipsoidal mirror is not important. We may therefore conclude that our designs considered above are not seriously modified by aberration.

Referring to Fig. 2 we see the absorption cell 7, which contains a spherical mirror 8 forming an image of the source 9 upon the entrance slit. The source and the slit lie in one line, the center of this line being the center of the sphere, part of whose surface is the surface of the spherical mirror. Since the sphere may be considered as a surface of revolution with this line as axis, and since any ray of light leaving an axis of revolution returns to the axis of revolution after reflection, there is no broadening of the image upon the entrance slit due to aberration. The lengthening of this image by aberration is overcome by making the source extra long.

Since the grating is the most expensive component in the spectrograph and we wish to utilize its entire surface with light from all parts of the slit, all mirrors should be large enough in diameter that they do not cut off a portion of the beam entering or leaving the grating. This requires that marginal rays be traced throughout the system, for it will be found, for instance, that there is a surprising divergence between the rays leaving the lower corners of the grating and passing through the upper end of the exit slit, and those rays which leave the upper corners of the grating and pass through the lower end of the exit slit. These considerations will require a much larger diameter of ellipsoidal mirror than would result from simple computations based merely upon the nominal aperture of the instrument.

The present instrument takes advantage of the above theories through the use of large gratings (10×20 inches), a collimating mirror of large aperture (diameter 2 feet, focal length 3 feet), and by the use of comparatively long slits (2 inches). This collimating mirror was originally intended for use in a telescope of new design having an exceptionally large aperture. When the hole was being drilled in the center, the mirror split into two pieces almost along a diameter. The larger piece is installed here, with the entrance slit lying almost on the axis of the paraboloid. The images are excellent in spite of the breakage.

When long slits are used, the spectral lines are quite appreciably curved due to the fact that the light coming through the ends of the entrance slit does not approach the grating horizontally but with a certain angle of dip or elevation. To these beams the grating space seems less than it does to the horizontal rays, so that the resulting spectral line image is curved and convex toward the central image. This curvature can be computed from the following formula:

$$y=(x^2/f)\tan i,$$

where y is the lateral displacement of that part of the spectral line which is a distance x above the center of the line, and i is the angle of incidence upon the grating (and assuming the angle of the diffracted beam equals i). The curvature depends only upon the angle of incidence upon the grating in the present type of instrument, and is independent of the grating constant. When the angle of incidence upon the grating is 45 degrees, and with the present slit length of two inches, the end of the image of a spectral line is displaced 0.71 mm relative to the center of the image. The central image is not curved. The curvature of the lines results in an error in the wave-length determinations unless a correction is made. In this instrument the spectral lines are made straight by using an entrance slit of adjustable curvature which is set according to the approximate angle at which the grating is being used; in measuring the central image this slit is straight.

Structural Design

Referring to Fig. 2 it can be seen that the entire optical path is evacuated. The source 9 is a heated platinum strip coated with thoria and enclosed in an evacuated and water-cooled box. This may be separated by a window from the absorption cell 7, in which the path length is approximately 33 inches. The absorption cell is entirely of glass, while the mirror supports and three spigots for adjusting the mirror are of Bakelite. The absorption cell and the spectrograph are provided with separate windows just in front of the entrance slit, these two windows merely abutting. By pulling the absorption cell back slightly, the space between these two windows becomes accessible for the introduction of absorption screens or a thin absorption cell, if desired.

The spectrograph proper is entirely enclosed within an evacuable box of welded one-inch steel plates whose general outline can be appreciated from the drawings. The entire optical system and mechanism is fastened to a single base, consisting of a piece of 15-inch *I*-beam, lying on its side and running the length of the instrument. This base is supported inside the box on three leveling screws only, so that the strains in the box due to evacuation cannot disturb the adjustment of the optical system. All controls and drives enter the box through lapped spigots and actuate the instrument through pairs of universal joints and end thrust sleeves, or through a lever with pin operating a lever with loose fitting slots. Thus the instrument is entirely free of any distortion which might accompany evacuation. The optical system is occasionally adjusted while sitting on ways outside the box, the instrument then being rolled into the case and evacuated. There has been no evidence that this adjustment has been disturbed by the evacuation.

Two crossbars 10 are separately supported from the base of the instrument, there being no metallic contact between them; one of these crossbars carries the entrance slit, while the other carries the small plane exit mirror and the front corner of the thermopile box which supports the exit slit. This construction prohibits the flow of heat from the entrance slit to the exit slit and thereby minimizes drifts which would otherwise occur because of the fact that an image of the edges of the jaws of the exit slit is formed upon the thermopile receiver surface. Drifts are further reduced by having the upper and lower halves of the thermopile in series opposition. Deflections are obtained by having a shutter in front of the entrance slit (not shown) which alternately and periodically covers the upper and lower halves of the entrance slit. This shutter is operated by a motor driven cam, the entire shutter mechanism being supported by a separate support from the base so that its operation can produce no mechanical displacement of the entrance slit position (shutter and driving mechanism not shown). The thermopile is connected through a shielded cable to a periodic radiometer amplifier similar to that described previously[5] which serves to remove completely all remaining drifts, so that automatic recording becomes possible. The thermopile has a window and its own evacuating system. A liquid-air trap containing charcoal, maintains a sufficient vacuum with only an occasional use of the pumps. A small unaluminized circle is left in the center of the thermopile mirror, thus enabling one to look directly through the small window 11 at the thermopile and to focus the image on the receiver surface with the aid of the three focusing and directing screws shown. One of these screws also carries a small metal flap 12 which serves as a shield in this sight path to avoid the entrance of disturbing radiation in the thermopile.

The grating table carries two full size gratings back to back, and these may be swung into position for use by means of the fast motion 13 which drives the worm 14. The grating table is carried on a cone having a double taper as shown, this construction combining a maximum length of spigot with a comparatively large angle of cone suitable for carrying a heavy load. The load is partially removed from the cone by a leaf spring 15, which pushes upward on the lower end of the cone and is adjustable by the knob 16, which is calibrated in pounds of weight of the gratings. The angular position of the grating is determined with a graduated circle which is read by the microscope 17, which is supported on the *I*-beam and has a filar micrometer operated through universal joints from the knob 18. The setting of the crosswires upon the image of one of the circle lines is accomplished by looking through the external microscope 19, which is supported on the case of the instrument. Readings of the filar micrometer are then made by looking through

[5] F. A. Firestone, R. S. I. 3, 163–188 (1932).

the window. This construction insures that the strains of evacuation will not change the circle reading.

In order to determine accurately wave-lengths from the automatically recorded deflections, it is necessary to provide an accurate mechanism for slowly turning the grating. By turning the crank 20, the fast motion worm can be simultaneously disengaged through the action of the arm 21, and the driving arm 22 clamped to the cone through the action of the shaft 23, which is provided with universal joints and end play. The driving arm 22 has a horizontal rod set into its edge, this rod being engaged by a vertical rod set into the base of the driving nut 24. Thus nut is accurately constrained from turning by means of a straight edge, and is carried on a lapped screw, which is rotated by a worm 25 connected through a spigot to the driving shaft 26. The driving screw is provided with a ball end thrust constraint, and the lost motion is minimized by means of a long spring (not shown) which pulls the driving arm toward this thrust bearing. Of course this drive is subject to tangent error, but since the record usually covers only about 5 degrees of motion of the grating, this error is very small if the drive is started near the center of its motion, as it should be. It is customary to read the circle a few times during each careful record, in order to check these driving errors. The gear ratios are so chosen that one revolution of the driving shaft 26 advances the grating by one second of arc; the Veeder revolution counter 27 therefore reads seconds of arc directly, except for the small tangent error. The crank 28 provides a manually operated slow motion by actuating a small screw and nut which pushes the same driving arm 22; however, the automatic recording has been so successful that the manually operated slow motion has never been used.

The driving shaft 26 also turns the photographic recording drum 27 through the worm gear box 28, and the change gears 29. By means of these change gears, one revolution of the recording drum can be set to record the spectrum corresponding to anywhere from seven minutes up to six degrees of rotation of the grating. Light from the recording galvanometer enters the opening 30 through a cylindrical lens along with light from a coordinate lamp flashed every 30 seconds of grating rotation. By holding a number of fingers in front of the cylindrical lens at the time when the coordinate lamp flashes, and simultaneously reading the grating circle, reference angles are established. The gear box end of the recording drum shaft is provided with a contactor which may be set to open a power relay and automatically shut off all drives, the source, and the recording amplifier upon completion of the record. Since a single record takes from one to eight hours, depending upon the gears used, this arrangement is advantageous, since it permits a record to be run while the investigator is absent.

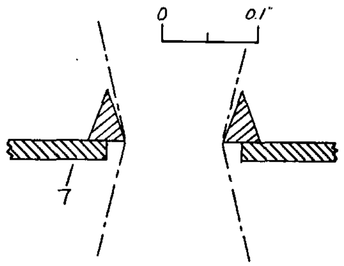

FIG. 3. Magnified cross section of curvable slit jaws and shield.

The periodic amplifier is similar to that previously described,[5] except that in order to diminish the zero unsteadiness due to Brownian motions, the period is 15 seconds. The primary galvanometer is a special Leeds and Northrup whose period was built up to this value largely by the addition of moment of inertia to the coil. The primary galvanometer is considerably less than critically damped so that the resonance of this galvanometer still furthur lengthens the time of response, with corresponding reduction in zero unsteadiness due to Brownian motion. The amplifier tube is a *UX* 222, and the entire amplifying system, exclusive of the primary galvanometer, is so designed as to give a maximum response to sinusoidal light variations having a period of 15 seconds, this being tested as explained in the original paper. The over-all sensitivity is such that a periodic voltage change of 10^{-8} volt in series with the thermopile produces a deflection whose double amplitude at the recording drum is 90 millimeters (the primary galvanometer resistance is 12.5 ohms and the thermopile resistance is 63 ohms). The zero unsteadiness is a double amplitude of about 11 millimeters.

Curvable Entrance Slit

As explained above, the curvature of the spectral lines is compensated by curving the entrance slit by an amount and direction which depend upon the angle of incidence on the grating. The edge of each of the jaws of this slit is formed by a blade whose magnified cross section is as shown in Fig. 3. Being of this shape, these blades bend more easily laterally than in any other direction. Fig. 4 shows the detail on the left jaw only, and shows that the center of the blade 1 is rigidly fixed, while the ends of the blade are connected through the thin strip 2 to the arms of the piece 3 which slides in the ways 4. The piece 3 is moved by the screw 5, which is turned through two sets of bevel gears from the shaft 6. Thus the slit jaws can be bent laterally by rotating the shaft 6, this being accomplished by turning the knob 30 of Fig. 1, which is graduated to read directly in angle of incidence on the grating. Cover plates 7, shown only in the lower view, are provided to keep light from passing around the outer side of the blades.

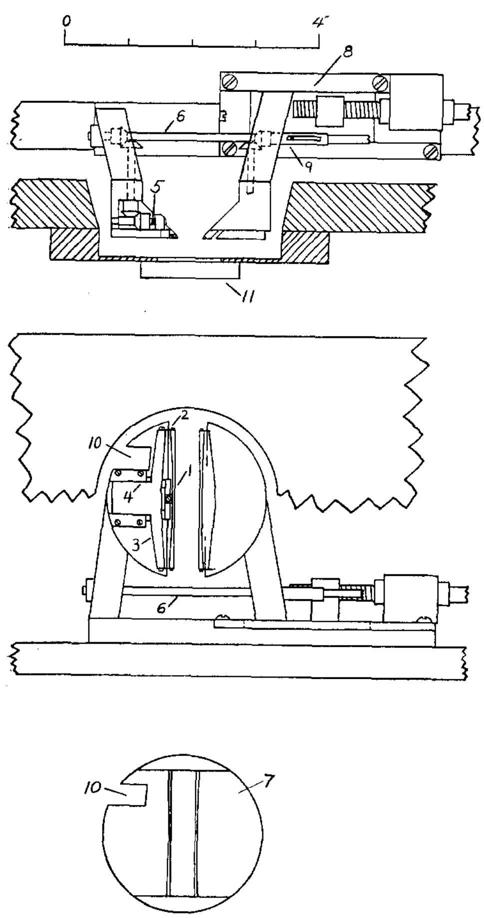

Fig. 4. Curvable slit, showing adjustments for slit curvature and slit width.

The left slit jaw is fixed and the slit width is adjusted by moving the right jaw, which is carried on the ways 8. This adjustment is accomplished by turning the knob 31 of Fig. 1, which is graduated in millimeters of slit opening. The exit slit has its left jaw adjustable by the knob 32, so that widening the slit does not change the calibration of the instrument. The motion for curving the right jaw of the entrance slit is transmitted from the shaft 6 through the sleeve 9, which can rotate the bevel gears while at the same time permitting motion of the right jaw for adjusting the slit width.

A wide slot 10 is provided through the left slit jaw; an arm reaches from the inside of the spectrograph through this slot and carries the periodically operated shutter (not shown) in the space between the slit and the entrance window 11 of the spectrograph. The supporting arm does not touch the slot 10 in passing through the left jaw, so the jaw is not deflected by frictional forces.

Operating Technique and Typical Records

This spectrograph, redesigned as just described, has been in operation for a year. A very general presentation of its essential features together with the first recordings and measurements was given at Indianapolis, December 28, 1937.[6] The set of records shown in Fig. 5 was, with the exception of *D*, obtained in the progress of a study of the rotational spectrum of heavy water and demonstrates the flexibility of this spectrograph somewhat more fully than did the first published records. For this work a plate of crystalline quartz 1.0 mm thick before the entrance slit seals the case of the spectrograph from the absorption cell. The source of radiation, a platinum strip covered with powdered gas mantle material, is enclosed in a vacuum-tight water-cooled chamber, sealed around the upper opening of the absorption chamber with a window of crystalline quartz 0.5 mm thick loosely mounted

[6] H. M. Randall, Rev. Mod. Phys. 10, 72 (1938).

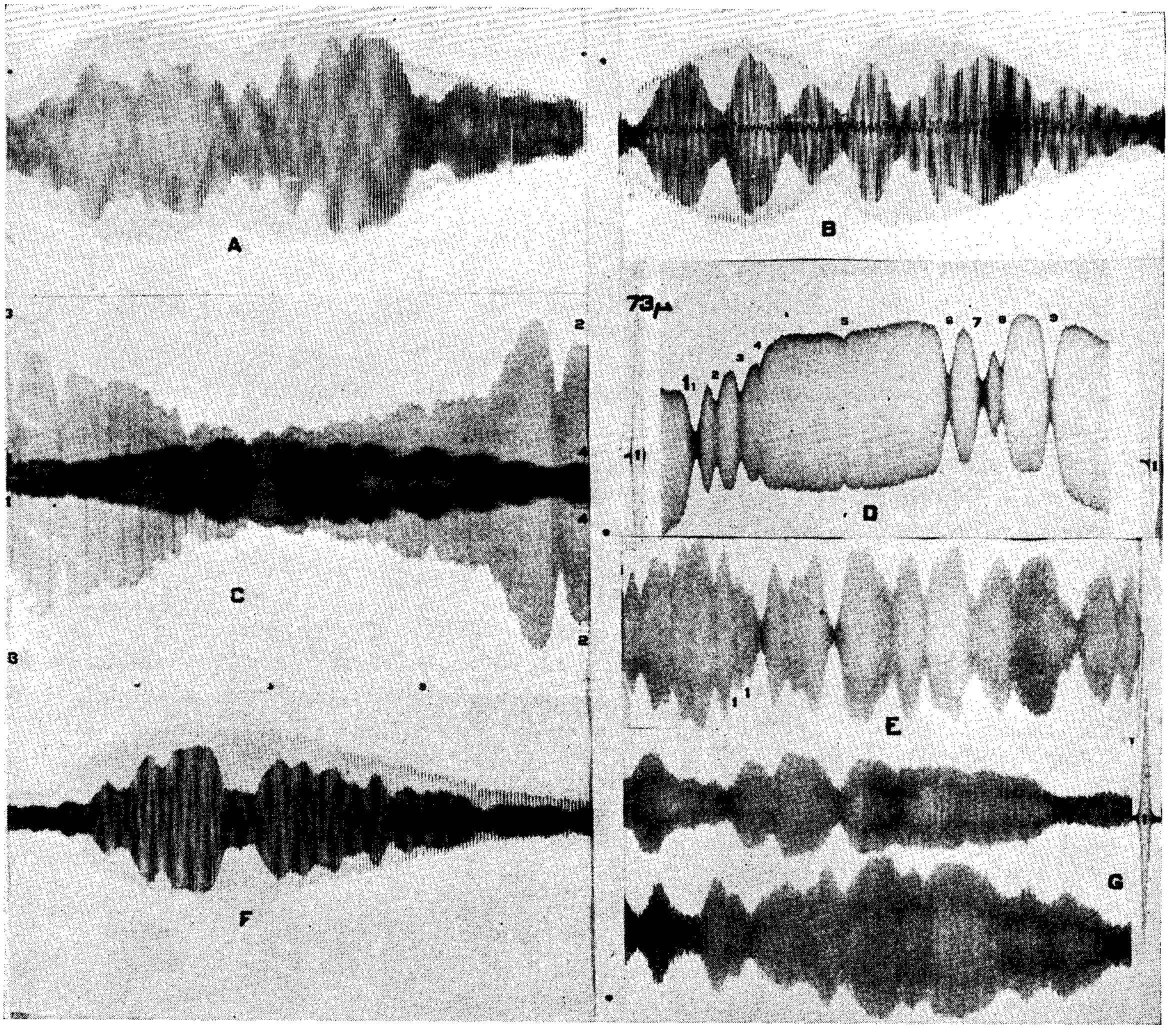

FIG. 5. Photographic reductions of typical records.

in between. This arrangement permits the separate evacuation of the spectrograph proper and the absorption chamber which now includes the source. The thermopile window was of paraffin 1.8 mm thick. A plate of paraffin 2.0 mm thick was placed immediately behind the emergent slit, making altogether an absorbing screen of paraffin of 3.8 mm thick. A single *reststrahlung* plate of KBr or KI together with a thin KI shutter was employed. With the exception of record *C*, where several second-order absorption lines appear near the 200μ limit, the purity of spectra obtained was excellent.

With both absorbing cell and spectrograph evacuated, the spectrum is that of the source as modified by the location of the blaze of the grating and by the absorptions and reflections which occur between the source and thermopile. The fainter records on *A*, *B* and *F* show such spectra. Since no fine structures are present, gears are chosen which speed up the rotation of the grating and the drum, so that the recording galvanometer makes a vibration about every 2 minutes of arc through which the grating has been turned. At this rate the time required to register this background spectrum extending over a spectral range of 35μ is about $\frac{3}{4}$ of an hour. In the cases of *A* and *B*, the range is from 63 to 98μ (153–100 cm^{-1}), the absorption of the 1.5 mm of quartz showing as a broad absorption line at

78μ immediately above the letters A and B. The *reststrahlung* plate for each is KBr which has its mid reflection at about 83μ. In F the *reststrahlung* plate was KI which moved the spectral region toward long wave-lengths or to between $75–110\mu$ ($133–90$ cm^{-1}). In the case of A and F, D_2O vapor was admitted into the absorbing cell, 12 mm pressure for A and 16 mm for F, the vacuum being maintained in the spectrometer case. The fine structure of the rotational spectrum of D_2O in these regions are recorded in the inner records. To obtain sharpness in the absorptions, the speed of turning the grating has been reduced with the result that the recording galvanometer traces out a complete vibration for each 30 seconds of arc through which the grating has turned. At this speed a record requires about 3 hours. The shadings in these records result from the lines of the two superposed records being periodically in and out of step.

When care is taken to maintain the radiation from the source constant over the entire time necessary to make these superposed records, it is possible to determine with considerable accuracy the percent of absorption of the vapor at the individual lines since the deflections are large. The maximum amplitude of the deflection of the recording galvanometer in A is 290 mm for the background spectrum, and in F it is 230 mm. The reference lines which are flashed on these records every 30 seconds of grating rotation are too fine and close together to show in any of these reproductions except possibly in D.

The record B covers the same spectral range as A but the spectrum is that of the H_2O vapor found in 16 cm of air admitted into the spectrometer case, the cell being now evacuated. The optical path is now about 500 cm instead of somewhat more than the 80 cm found in the cell. The third record which appears in B, is obtained by inserting in the path of the radiation a screen of KI so thin that it transmits the higher orders of the radiation of the region 63 to 98μ but is opaque to the radiation of the region itself. The small amplitude of this third record indicates that negligible amounts of higher order radiation are present.

The grating producing these spectra had a ruled surface of 10×20 inches and was ruled with 133 lines per inch. Its blaze or region of greatest concentration of energy is at 90μ. With slits set at 3 mm, the spectral region covered by the slits is from 0.6 to 1.0 cm^{-1} for records A and B and from 0.5 to .9 cm^{-1} for F. As many lines of water have to be measured whose frequency difference is less than 1 cm^{-1} the resolution of this grating is not sufficient and these three records are but preliminary ones, though single sharp lines can be accurately measured by means of them.

Records D, E and G are made with a grating of the same size but with a ruling of 360 lines per inch, the blaze being located at 77μ. These records cover spectral ranges of from 9 to 11μ each instead of the 35μ of the coarser grating. The resolution obtained is accordingly much better. Depending upon the spectral region covered, the frequency range of the slit widths used vary from 0.25 cm^{-1} for D where the slit width was 2 mm and the spectral range was from 64 to 73μ ($155–135$ cm^{-1}) to 0.4 cm^{-1} in E where the slits were 2.5 mm and the spectral range from $56–67\mu$ ($180–150$ cm^{-1}). This resolution has proven adequate as already demonstrated in the case of H_2O vapor. In fact, D is due to normal water vapor and is one of the records previously published. The two lines numbered 7 and 8 have a frequency separation of 0.75 cm^{-1}. In E the two lines marked 1, 1 differ in their frequency by 0.6 cm^{-1}. The maximum deflection in E is 250 mm. All the records showing the absorptions require about three hours to record, a galvanometer vibration occurring about every 30 seconds of rotation of the grating, except in the case of this record D. Here the time of recording was about 8 hours due to the fact that the grating was turned more slowly, galvanometer deflections being made about every 10 seconds of grating rotation. Records such as D and E permit measurements to be made within 0.05 cm^{-1} for sharp lines. Accuracy is increased by recording on each record the energy curve of the undeviated images. Such energy curves are shown at 1 at the ends of the records G and D.

Where the deflections are not too large, a double region may be covered by making two records, side by side upon a single sheet of photographic paper as in G where the total range of the two is from 70 to 90μ. Where a survey only is being made and the deflections are large, a longer spectral region may be covered by taking a continuous record with two complete revolutions of the drum. Thus in C the record starts at 100μ at 1,1 on the left and reaches 150μ at 2,2, starting the second rotation of the drum at 3,3 and attaining 200μ at 4,4. This record was made to locate the blaze of a grating having 87 lines per inch. The spectrum is not pure but satisfactorily locates the blaze at about 150μ.

These records have been chosen to show something of the flexibility of the instrument and the character and quality of its recordings. It has become customary to give the apparatus no attention after being started on a record; the experimenter return at the close of one records and starts another. The three records of B would require about 5 hours for the recordings alone. The time for changes in adjustments, the introduction of gases, etc., varies widely with circumstances. The 25 or more lines of the record E can be completely measured and computed in about $2\frac{1}{2}$ hours or during the time another similar record is being recorded.

The authors are indebted to Mr. H. M. Foley for running record D, which was included among the records recently published, and to Mr. Nelson Fuson for all of the others. They wish to express their appreciation also for the exceptional quality of the work done on this spectrograph by the staff of the instrument shop.

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A Tubular Vacuum-Type Centrifuge

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A method of spinning tubular rotors to high speeds in a vacuum is described. The rotors are spun by air-supported, air-driven turbines situated below the vacuum chamber. The maximum rotational speed attainable is set only by the bursting strength of the tubular rotor. The material to be centrifuged enters the spinning tube at the top at a continuous rate and is collected in light and heavy fractions at the bottom. The apparatus has been used for centrifuging materials in gaseous, vapor and liquid states.

THE vacuum-type air-driven ultracentrifuge[1, 2, 3, 4] has been found to be very efficient because of the absence of stirring or remixing of the materials during the centrifuging. Also the maximum centrifugal force attainable is set only by the bursting strength of the rotor. However, the quantity of material which can be centrifuged per unit of time is somewhat limited because of the size and shape of the rotors. This limitation results from two causes; first, for dynamical reasons the rotors are never made much longer than their diameters, or rather the moment of inertia about the axis of rotation is always greater than that about a perpendicular axis which limits the usable capacity of the centrifuge, and second, the material does not pass through the centrifuge continuously but the rotor must be stopped and removed from the vacuum chamber for emptying and refilling. In order to overcome these handicaps the vacuum-type tubular air-driven centrifuge[5] has been developed. In this apparatus the material to be centrifuged enters at the top and is collected in two fractions at the bottom of the spinning tube. Also improvements in the air cushion support make it possible to support very heavy rotors so that the length of the spinning tube and hence the rate of centrifuging may be made comparatively large. These tubular centrifuges have been run successfully with the air support and drive either above or below the spinning tube but in this paper details will be given only for the case where they are below.

[1] Beams and Pickels, R. S. I. **6**, 299 (1935).
[2] Bauer and Pickels, J. Exp. Med. **64**, 503 (1936); **65**, 565 (1937).
[3] Wyckoff and Lagsdin, R. S. I. **8**, 74 (1937).
[4] Beams, J. App. Phys. **8**, 795 (1937). Beams, Linke and Sommer, R. S. I. **9**, 248 (1938).
[5] Beams, Linke and Skarstrom, Science **86**, 293 (1937).