United States Patent

[11] 3,577,159

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[54] **DIFFRACTION GRATING X-RAY SPECTROMETER WHEREIN AN ELECTRON BEAM IS SCANNED ACROSS A FIXED X-RAY EMITTING ELEMENT**
6 Claims, 9 Drawing Figs.

[52] **U.S. Cl.** **250/51.5,** 250/49.5
[51] **Int. Cl.** **G01n 23/22**
[50] **Field of Search** 250/51.5, 49.5; 356/79

[56] **References Cited**
UNITED STATES PATENTS

3,218,458	11/1965	Furnas	250/51.5
3,322,948	5/1967	Baak et al.	250/51.5
3,384,756	5/1968	Hasler et al.	250/51.5

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ABSTRACT: A diffraction grating spectrometer having an X-ray tube in a fixed position, the ray-source of which is rapidly moved back and forth on a definite curve. Diffracted beams from the grating surface are focused on a slit of a fixed electronic counter and the intensities of the spectral distribution are observed or measured by a suitable means. The positions of the ray-source and the counter are the reverse of those in the previously known spectrometers.

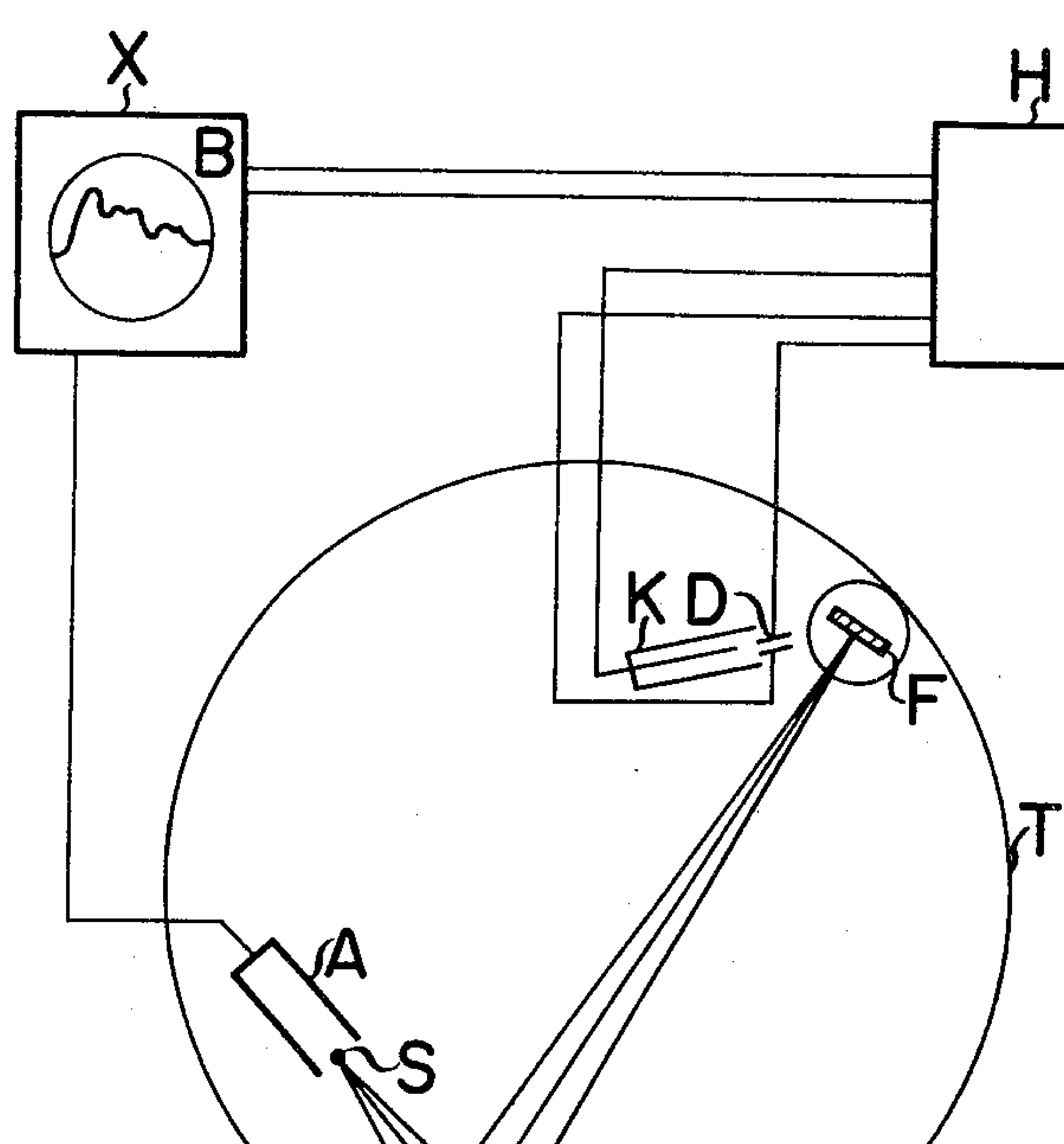


FIG. 1

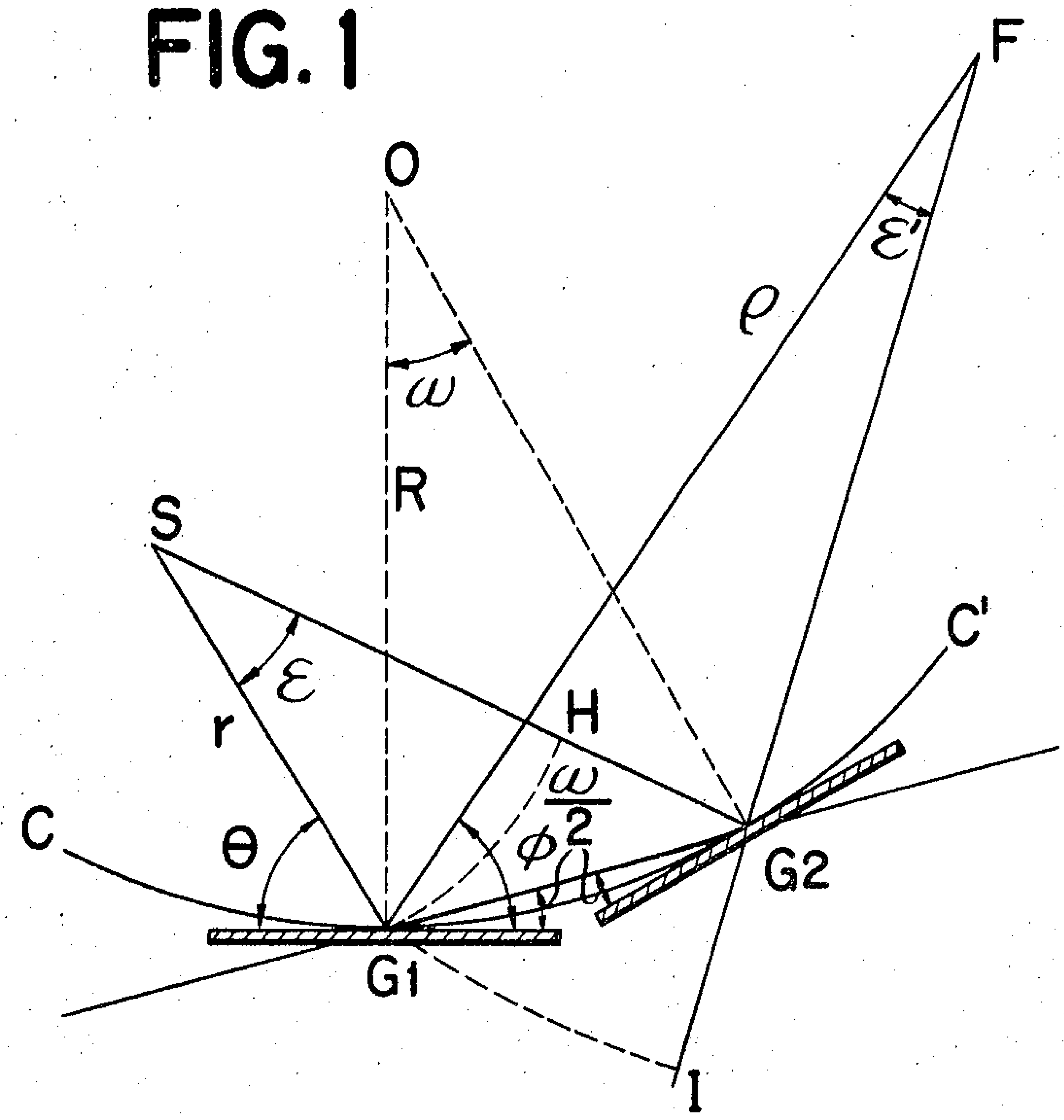
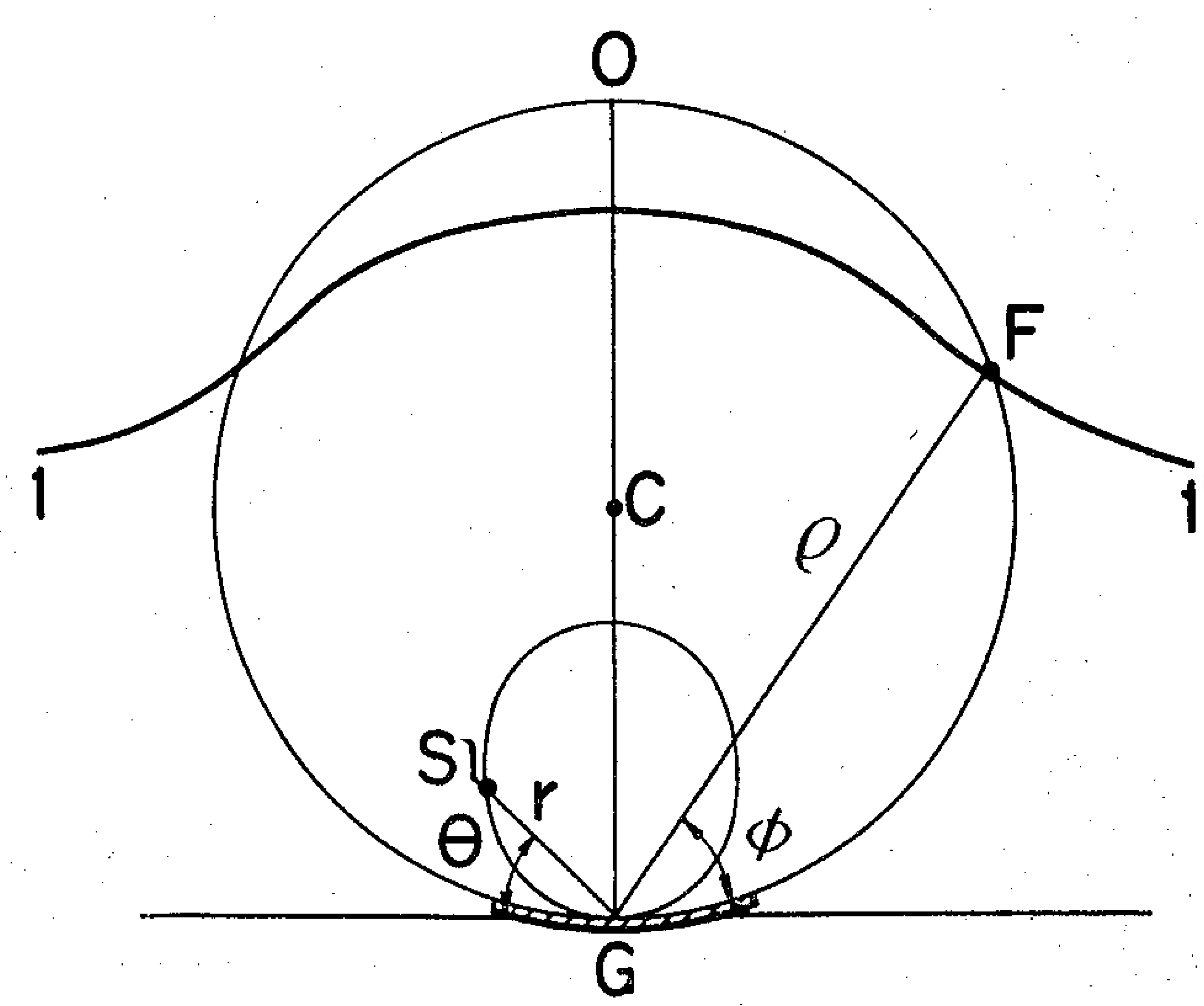


FIG. 2



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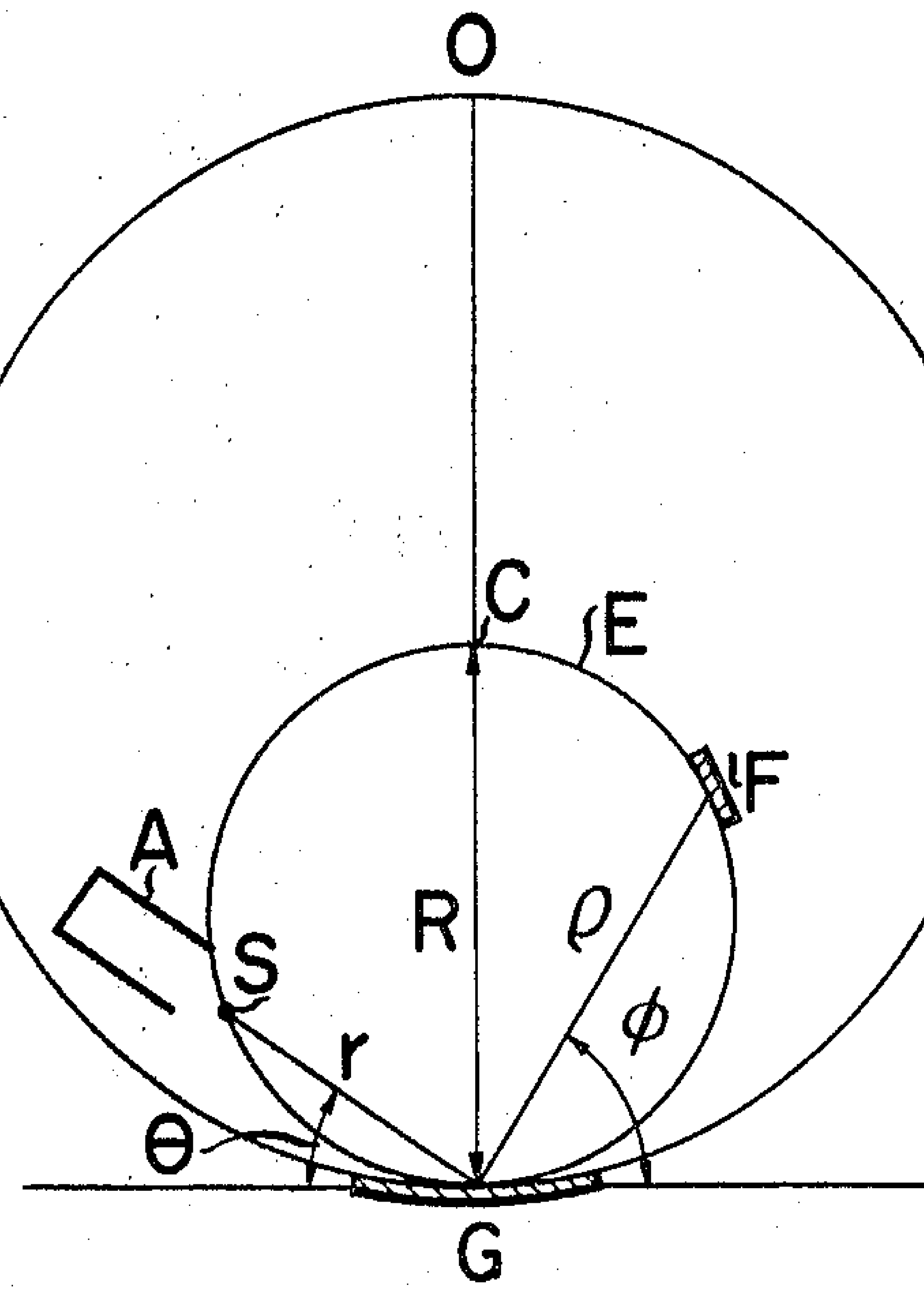


FIG. 3

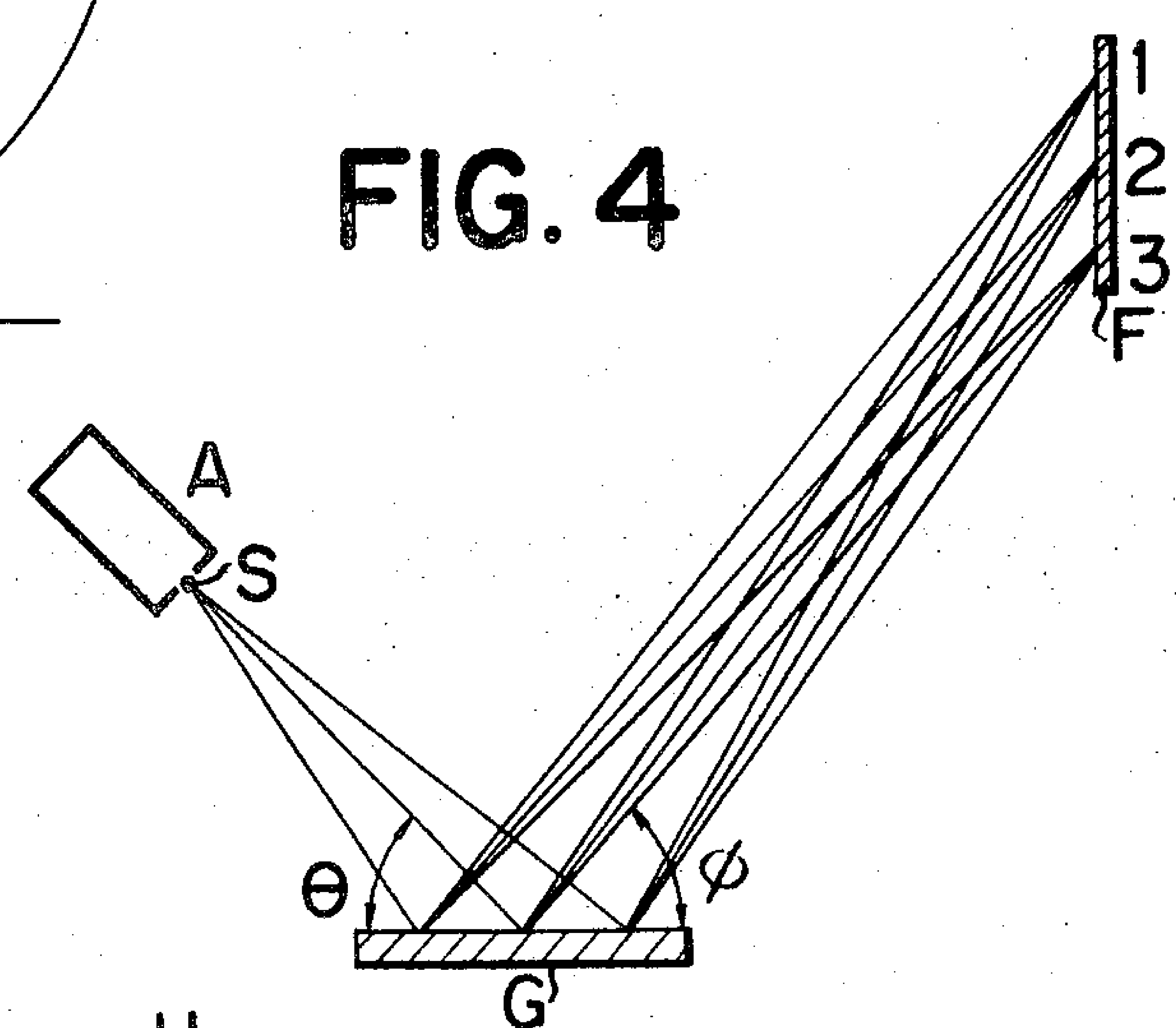
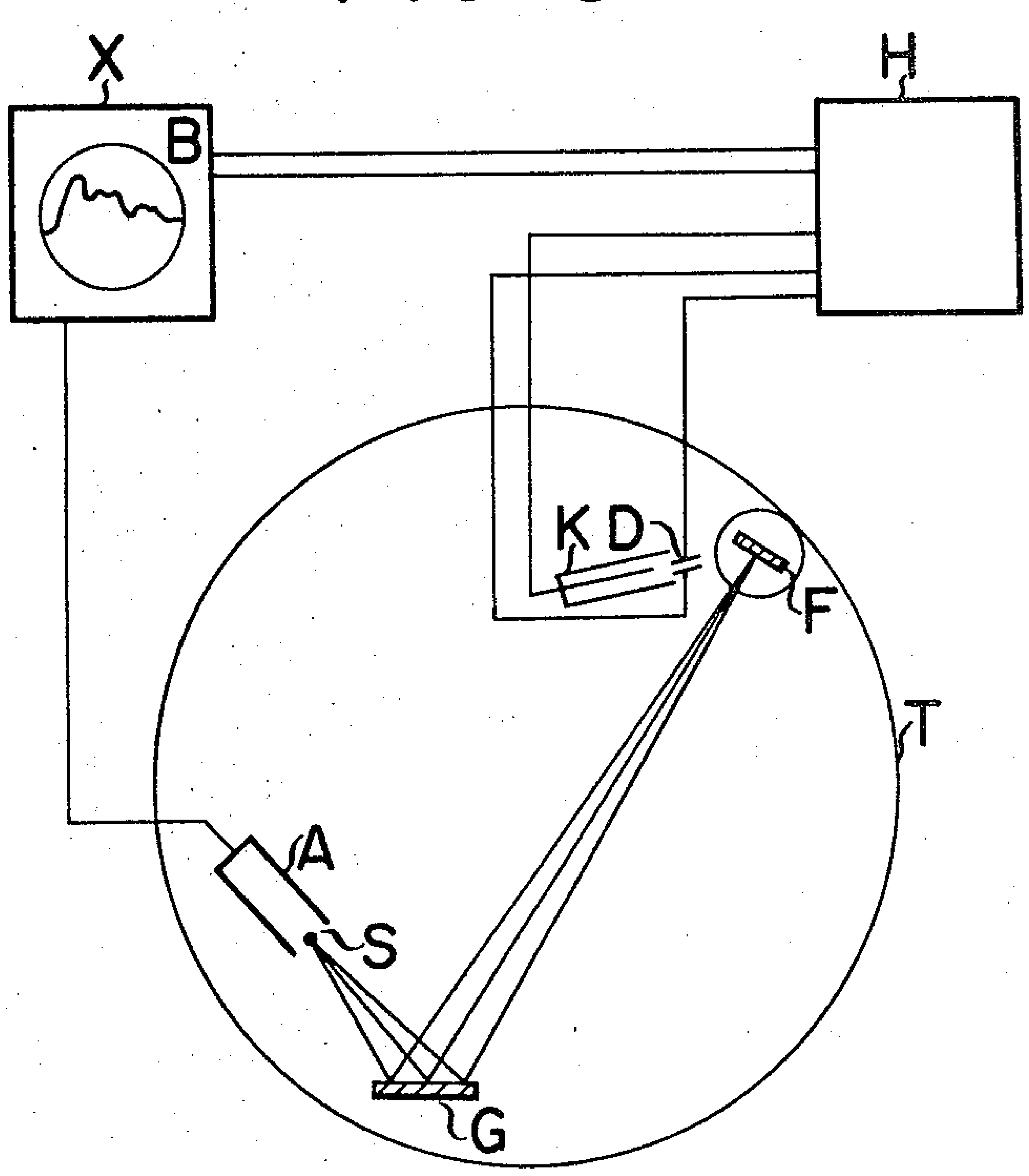


FIG. 4

FIG. 5



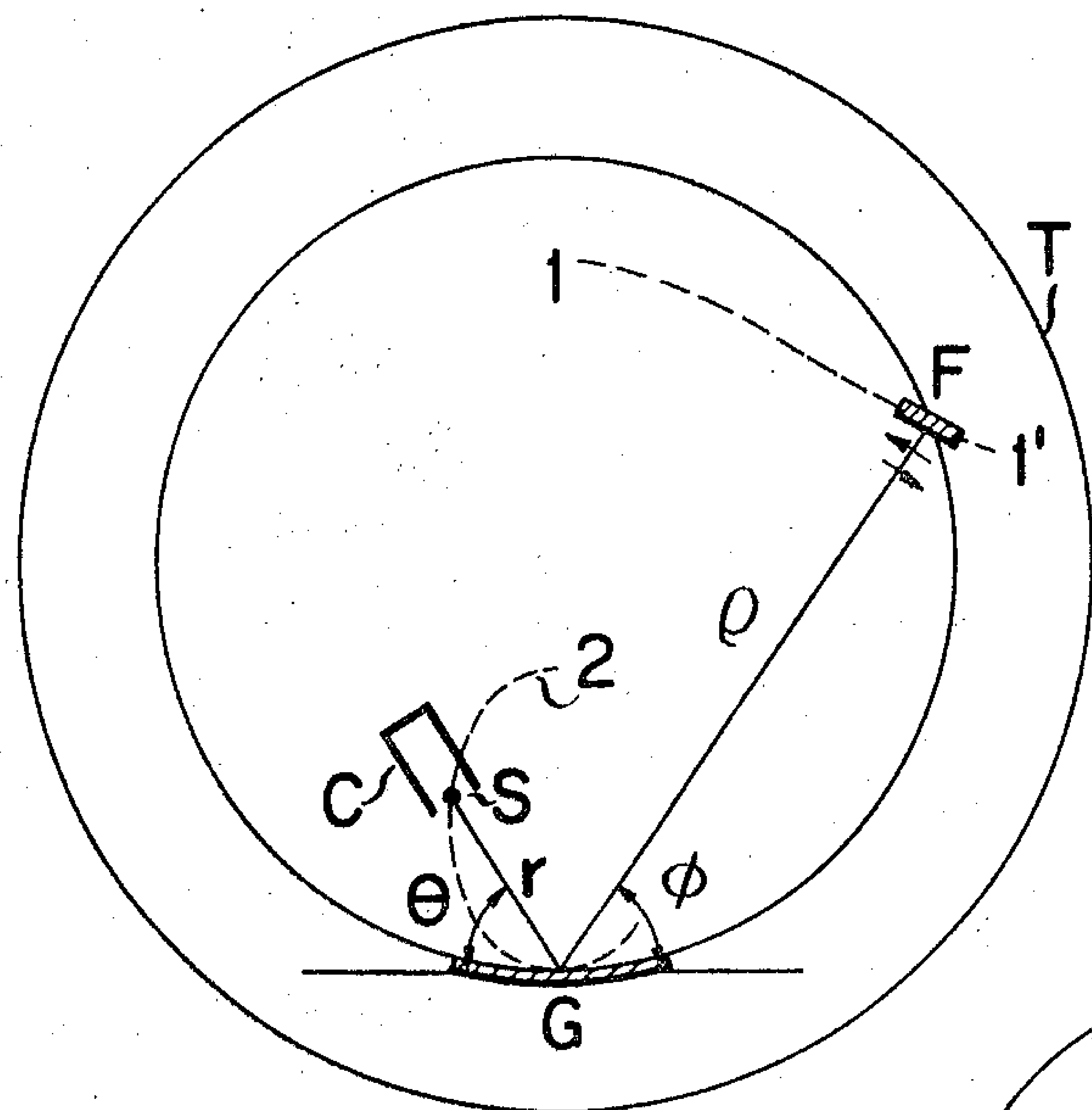


FIG. 6

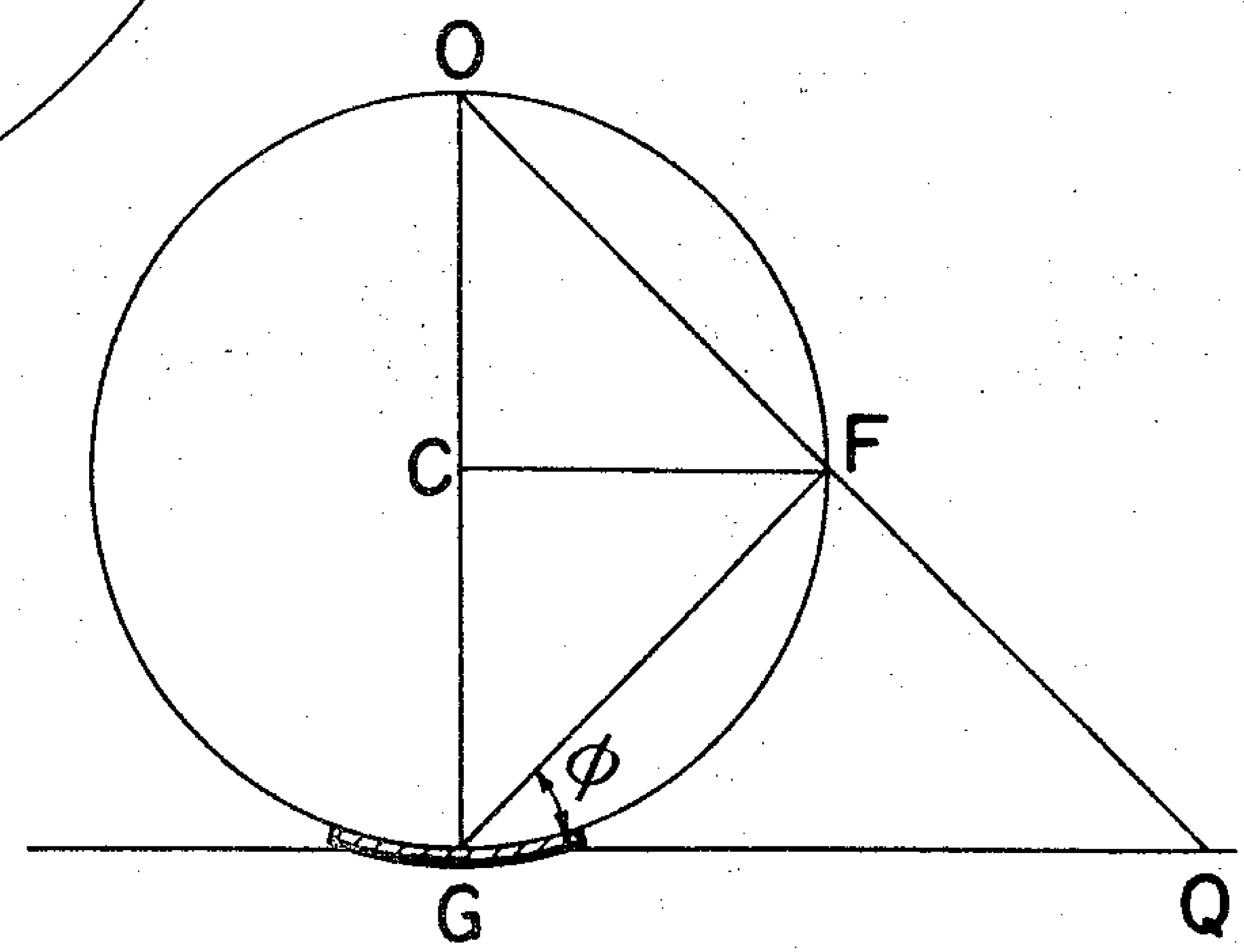


FIG. 7

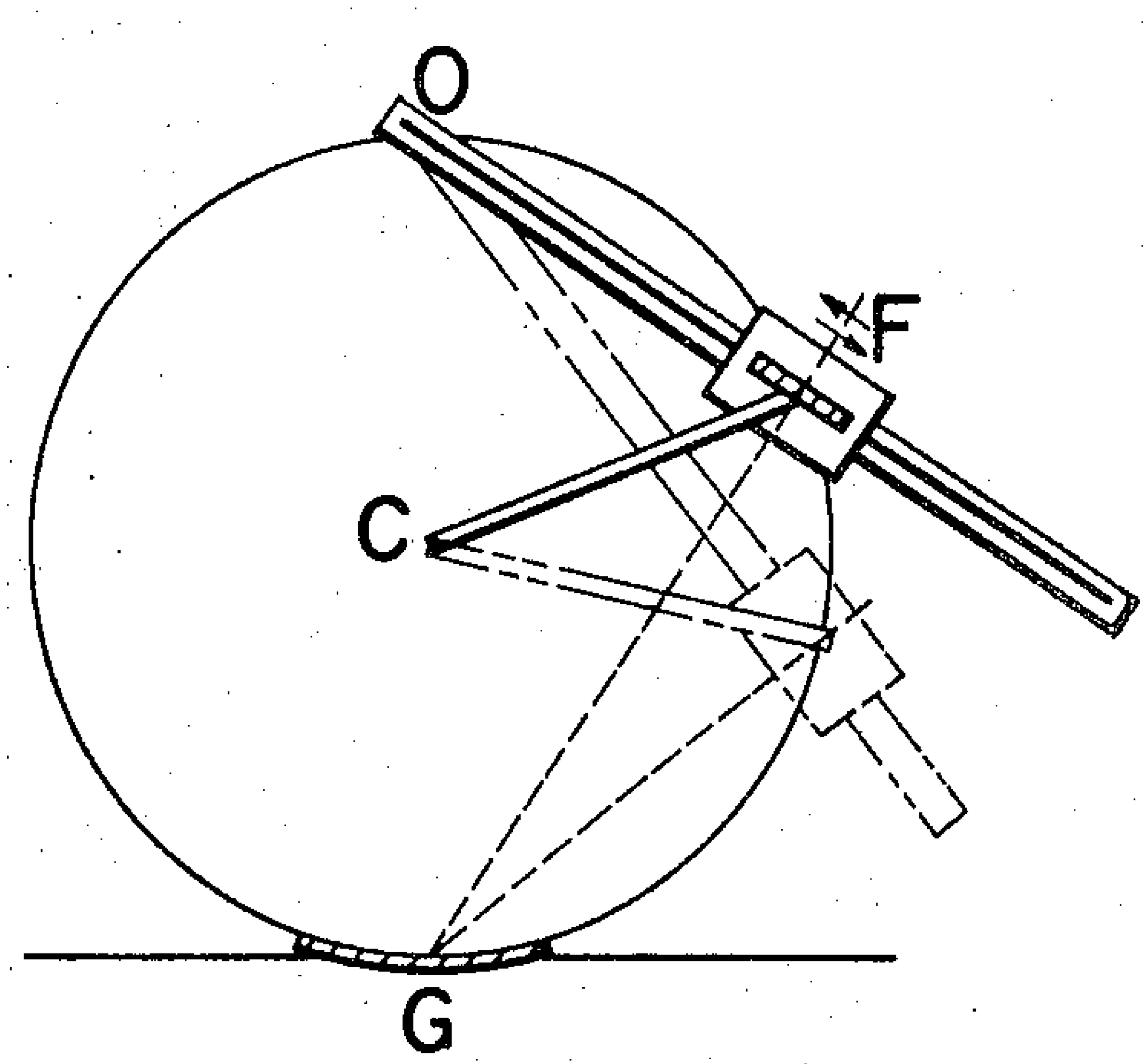
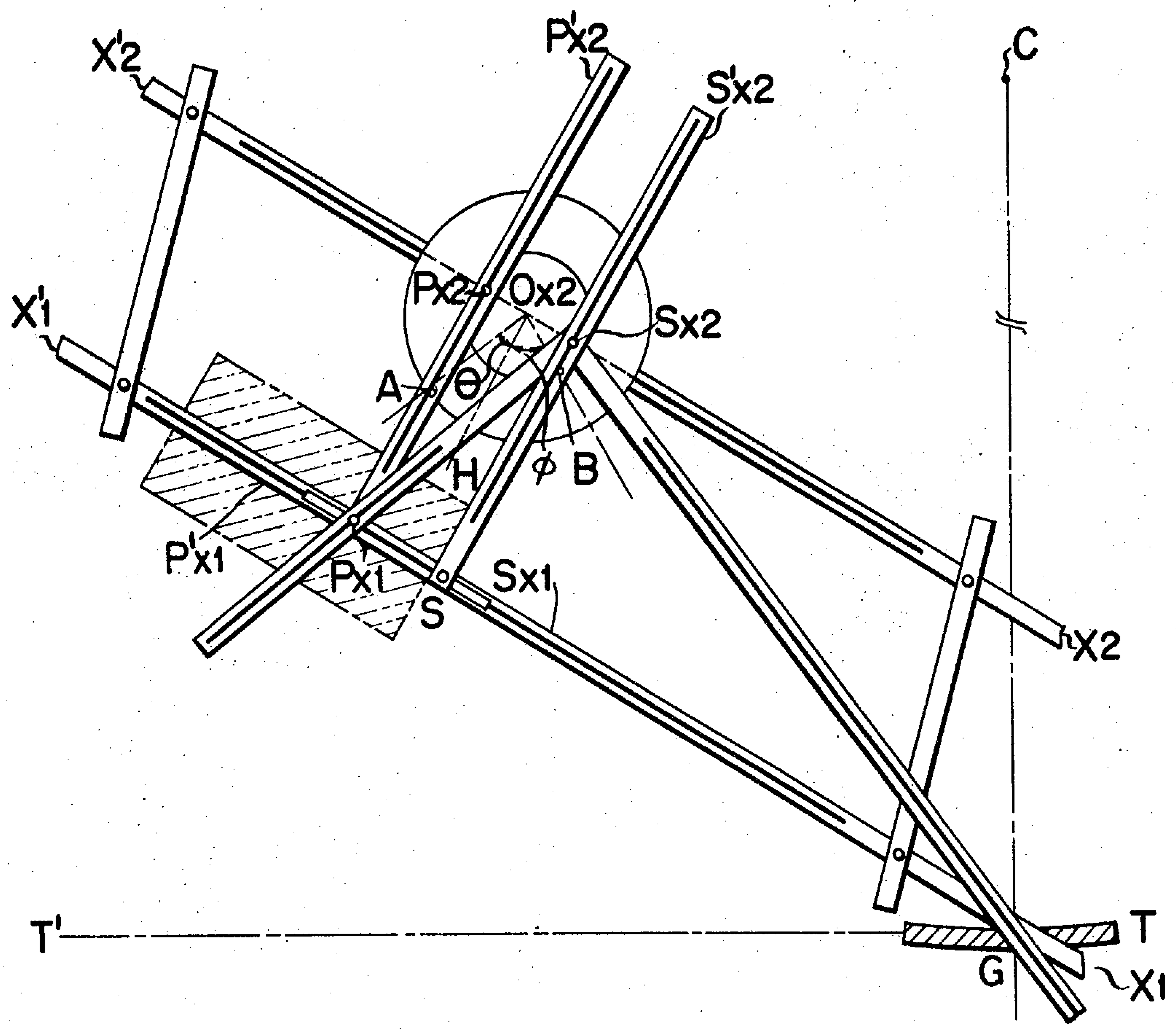


FIG. 8

FIG. 9



DIFFRACTION GRATING X-RAY SPECTROMETER WHEREIN AN ELECTRON BEAM IS SCANNED ACROSS A FIXED X-RAY EMITTING ELEMENT

BACKGROUND OF THE INVENTION

This invention relates to a grating spectrometer used for spectral distribution of any kind of rays such as α-rays, β-rays, γ-rays, X-rays, radio waves, light rays, sound waves etc.

The usual spectrometer having a plane or concave grating has been widely utilized for spectroanalysis or other purposes, and consists of a fixed radiation source and a photographic or movable counter. However, the construction and the operation of such spectrometer is complicated. The development of sensitive electronic counters with delicate and complex cooling systems makes movements of the undesirable.

It would be desirable to have a spectrometer with a simple electronic counter at a fixed position.

An object of the present invention is to provide a spectrometer which overcomes the above-mentioned troubles.

Another object of the present invention is to achieve accurate and rapid measurements of faint X-ray lines such as X-ray satellites.

SUMMARY OF THE INVENTION

In accordance with this invention a novel grating spectrometer has an electronic counter fixed in a predetermined position and an electronic ray-source on a fixed position. The correlating positions of the ray-source and the counter in the spectrometer of the present invention are the opposite of those in the grating spectroscopy. This is based on the principle of reversibility of optical paths.

The usage of the electronic scanning ray-source is one of the novel and important points of the present invention. The scanning of the X-ray source may be done by a specially designed microfocus X-ray tube that can scan the cathode-ray beams by electron beam deflectors as in the well known electron optics used in television and curve followers.

BRIEF EXPLANATION OF THE DRAWINGS

FIG. **1** is an illustrative diagram of the principles of known concave grating spectroscopy;

FIG. **2** is an illustrative diagram of loci of point wave sources and their images for concave grating spectroscopy according to the present invention;

FIG. **3** is an illustrative diagram of one embodiment of the present invention utilizing Rowland circle;

FIG. **4** is an illustrative diagram of another embodiment of the present invention using plane grating;

FIG. **5** is a schematic diagram of the plane grating spectrometer according to FIG. 4;

FIG. **6** is an illustrative diagram of another embodiment of the present invention using concave grating;

FIG. **7** is an illustrative diagram of the scanning direction of a wave source in the present invention;

FIG. **8** is a schematic diagram of the travelling mechanism of the X-ray tube of the novel spectrometer according to FIGS. **6** and **7**; and

FIG. **9** is a partial schematic diagram of a travelling mechanism of the counter correlated to that of FIG. **8**.

DETAILED DESCRIPTION

The relation between wave sources and their images will be mentioned briefly. The case of plane grating can be treated as a special case of concave grating, and so the concave grating will be treated first.

In FIG. **1**, there is shown a cross-sectional part of the spherical surface of a concave grating defined by a circular arc CC′. G_1 and G_2 are the traces of ruled grooves thereon, that is, elements of the grating. The divergent X-rays, hereafter the case of X-rays is adopted as one of general rays radiating from a point sources S (r, Θ), are assumed to be focused at a point F (ρ, Φ). Considering the path difference between the lines SG_1F and SG_2F, the following equation is well known,

$d(\cos\Theta-\cos\Phi)=n\lambda$ (1)

where d, λ, n, Θ and Φ are the grating constant, wavelength, its spectral order, angle of incidence and angle of reflection respectively.

The direction of the diffracted beam can be determined by Eq. (1), but yet there remains the problem of determining the magnitude of the vector of the diffracted beam. This is determined as follows. Two circles are described whose centers are at S and F with radii $SG_1=r$ and $FG_1=\rho$ and their intersection with SG_1 and FG_1 are designated H and I respectively. Let the central angle $\angle G_1OG_2$ be ω. This angle and an arc length $\overline{G_1G_2}$ are very small compared to $\Theta\Phi$, r and ρ. $\overline{G_1H}$ and $\overline{G_1I}$ are to be regarded as perpendiculars dropped to SG_2 and FG_2 respectively. We then have following relations in the triangles ΔG_1HG AND ΔG_1IG_2.

$$\overline{G_1H}=r\epsilon=d\cos\angle G_2G_1H=d\sin\left(\theta-\frac{\omega}{2}\right)\doteqdot d\sin\theta \quad (2)$$

Similarly,

$\overline{G_2I}=\epsilon'\approx\sin\Phi$ (3)

where ϵ and ϵ' are very small angles subtended by S and F on the circular arc G_1G_2.

Further we have,

$$d=R\omega=\frac{r\epsilon}{\sin\theta}=\frac{\rho\epsilon'}{\sin\phi} \quad (4)$$

where R is the radius of the spherical surface of the concave grating.

Next, in the triangles ΔSG_1G_2 and ΔFG_1G_2, equating the sum of the two inner angles to that of the external angle of the third one, we have respectively,

$d\Theta=\omega-\epsilon$ (5)

$d\Phi=\epsilon'-\omega$ (6)

where angles Θ and Φ are not independent of each other, but we have the following connection by differentiation of Eq. (1).

$\sin\Theta d\Theta-\sin\Phi d\Phi=0$ (7)

Substituting in the last formula the value of $d\Theta$ and $d\Phi$ of Eqs. (5) and (6), we have the grating formula

$$\left(\frac{\sin^2\theta}{r}-\frac{\sin\theta}{R}\right)+\left(\frac{\sin^2\phi}{\rho}-\frac{\sin\phi}{R}\right)=0 \quad (8)$$

When polychromatic and divergent X-rays emerge from a point S (r, Θ), the loci of their foci (ρ, Φ) of diffracted beams are determined by using a separation constant D that is a parameter, therefore we have

$$\frac{\sin^2\theta}{\rho}-\frac{\sin\phi}{R}=\frac{-1}{D} \quad (9)$$

and from Eqs. (8) and (9), we have for incident beams,

$$\frac{\sin^2\theta}{r}-\frac{\sin\theta}{R}=\frac{1}{D} \quad (10)$$

Now from Eqs. (9) and (10), we obtain

$$\rho=\frac{R\sin^2\phi}{\sin\phi-\frac{R}{D}} \quad (11)$$

and

$$r=\frac{R\sin^2\theta}{\sin\theta+\frac{R}{D}} \quad (12)$$

Eqs. (11) and (12) are mutually conjugate.

The ρ- and r-curves are called source and image curves, respectively, and vice versa. When one of them takes a negative value, it is the virtual image and is behind the grating at some distance on the same line. In such case, a divergent must be used.

When we choose the parameter D as $+\infty$, the above two equations reduce to a single circle

$r=R\sin\Theta$, $\rho=R\sin\Phi$,

both of them being the well-known Rowland circle as shown in FIG. 3. In this special case, the two curves (r, Θ) and (ρ, Φ) are self-conjugate.

Next in the two equations (9) and (10), let us choose any parameter D, and we can find their loci by a numerical calculation or a graphical method. When one curve becomes an oval (a closed curve), then its conjugate becomes an open V-, U-, W- or Ω-like curve having two asymptotes and two inflection points as shown in FIG. 2.

The shortest distance from the midpoint of the grating to a point of (ρ, Θ) curve, which is a very important item in the practical grating spectrometer, lies in the following direction,

$$\sin \phi = \frac{2R}{D}, \quad \text{where } D > 2R, \tag{13}$$

otherwise, Φ is imaginary, because $\sin \Phi > 1$.

And further we can see that it lies on a circumference of a circle whose center is at C, and having a radius of the grating R, as shown in FIG. 2,

$\rho = 2R \sin \Phi$ (14)

Secondly, we can find after some lengthy calculations, that the coordinates of their inflection points satisfy the following equation,

$3R \sin^2\Phi + 2D \sin \Phi - 6R = 0$ (15)

and the inflection points lie in the following direction,

$\sin \Phi = (-D + \sqrt{D^2 + 18R^2})/3R$ (16)

Moreover, the very special point which has a shortest distance and an inflection point can be obtained by equating $\sin \Phi$ of Eqs. (13) and (15), and the parameter D becomes

$D = \sqrt{6}R = 2.45R$ (17)

This special case is illustrated by a diagram shown in FIG. 2, and the circle of Eq. (14) is called the "Sawada circle" hereafter.

The design of a novel grating spectrometer in the present invention is based on the principle of reversibility of optical paths. Namely the positions of a wave source and its focus can be exchanged mutually. If a ray-source is located at a point F(ρ, Φ) in FIG. 1, the divergent rays from F diffract on the grating G_1G_2 to focus at a fixed point S(r, Θ), and Eqs. (11) and (12) come into existence exactly, where D is a parameter ($0 \leq D \leq \infty$).

Generally, the novel grating spectrometer in the present invention consists of an electronic scanning ray-source which is positioned at a point (ρ, Φ) and a fixed electronic counter which is fixed at a point (r, Θ). The relations which apply are given in the general formulas

$$\rho = \frac{R \sin^2 \phi}{\sin \phi - \frac{R}{D}}$$

and

$$r = \frac{R \sin^2 \theta}{\sin \theta + \frac{R}{D}}$$

where,

R : Radius of the concave grating.

ρ : Distance from the scanning ray-source to the midcenter of the grating.

Φ : Incident angle of divergent rays from the ray-source upon the grating.

r : Distance from the midcenter of the grating to the slit of counter.

Θ : Angle of diffracted rays from the grating to the slit of counter.

D : a parameter ($0 \leq D \leq \infty$).

These formulas are similar to Eqs. of (11) and (12).

There will now be described particularly three embodiments of spectrographic apparatus.

I. The case of utilizing Rowland mounting.

In this case, a small range of wavelengths can be treated. In FIG. 3, the X-ray point source F, having a few square microns in area, of white radiation lies on the Rowland circle E, and moves back and forth by a small amount (such as a few millimeters) on a fixed straight line which is a tangent to the Rowland circle E at F. Then all spectral images obtained by the diffraction on the grating G focus on the fixed slit S of the counter A, which lies also on the same Rowland circle E, that is $r = R \sin\Theta$ and $\rho = R \sin \Phi$ as mentioned before.

II. The case of plane grating.

In the case of a plane grating, letting $R = \infty$ in Eqs. of abovementioned general formulas, the following reduced equations are obtained.

$\rho = -D \sin^2\Phi$, and $r = D \sin^2\Theta$

When the parameter D is eliminated, we have

$$\rho = -\frac{R \sin^2 \phi}{r \sin^2 \theta}$$

The mutual curve becomes an oval of the same in size and shape but symmetrical with respect to the tangent which touches the midpoint of the grating. (Not shown in the FIGS.) This oval is flat on the top. Thus, the divergent slit must be used.

When we choose $\Phi = 60° A$, the tangent to an oval at this point (that is, the scanning direction) becomes normal to the surface of the grating G as shown in FIG. 4, and maximum dispersion just lies in the direction $\Phi = 54°12'$.

FIG. 5 is a schematic diagram of this plane grating spectrometer as a whole. Electron beams of an X-ray tube derived from a cathode filament K pass through a deflecting electrode D, and collide against the anticathode surface F to produce X-rays. The divergent X-rays are diffracted by the plane grating G to focus at the divergent slit S of a fixed electronic counter H. In the compartment A, there is a high voltage apparatus for generating the X-rays, and an electric source for the deflecting electrode etc. The counter A is connected to a multiple-channel-scaler X which provides, with a Brawn tube B, for direct observation of the spectral distribution. The scaler X is used not only for the direct observation, but for recording wavelengths and intensities of the spectrum and integrating the intensities thereof as a function of time.

T is a vacuum tank which contains cathode filament K, deflecting electrode D, anticathode F, grating G and counter A therein.

III. The case of Sawada mounting.

There is illustrated a Sawada mounting in FIG. 6, in which T is a vacuum tank with a radius of a little larger than that of the concave grating G. Within it, a circular track having the same radius as the concave grating G is provided. A track carrying an X-ray tube can be displaced along the circumference of the track, and can be set to the angular position Φ, according to the wavelength to be examined by Eq. (1), and also restricted by the angular position Θ of the prefixed counter C.

The electronic scanning direction of the point-focus-cathode-ray beam is determined as follows:

In FIG. 2, the curve 1–1′ is the loci of (ρ, Φ) curve determined by Eq. (11), but if the minimum distance from G is chosen, this point on the curve must satisfy Eq. (13). Then the curve 1–1′ should be rewritten as Eq. (14). The minimum points, as a function of Φ, namely as a function of wavelengths, lie on the circle with a radius R, that is, the Sawada circle.

Then the position (r, Θ) of the slit S of the fixed counter C is

$$r = \frac{R \sin^2 \theta}{\left(\sin \theta + \frac{1}{2} \sin \phi\right)} \tag{18}$$

from Eqs. (12) and (13). If a tangent FQ is drawn to the curve 1–1′ at F in FIG. 2 and as shown in FIG. 7, then its inclination is

$$\frac{dy}{dx} = -\cot \phi$$

and the inclination of the incident beam is $\tan \Phi$. Hence, evidently FG and FQ intersect at right angles to each other. It is very interesting that, on the Sawada circle, at any point F, the tangent thereat to the (ρ, Φ) curve passing through F is at a right angle to the radius vector $\overline{GF}$. Thus the direction of the scanning is always on the straight line that passes through the point O, diametrically opposite point G as shown in FIG. 7.

In the case of measuring of a very wide spectral region, the fixed positions of the counter are allowed to be as in the cases of embodiments I and II. In the case of embodiment III, however, the counter must be moved as well as the X-ray tube along the fixed beam (Θ = constant) when the measurement of extremely extended spectral regions is required. The X-ray tube must be moved from the fixed position to another, as shown in FIG. **8**, from the solid line to a dotted line successively. As the tube-holding beam OF turns, the X-ray tube slides on this beam, but its relative motion to the beam is only translational displacement without rotation of the X-ray tube. The period of a rotation of the X-ray tube about its own axis is just one-half of the period of the revolution of the X-ray tube around the center of the Sawada circle.

In synchronism, the counter can be moved along the fixed beam (Θ = constant) by the mechanism as shown in FIG. 9. In this FIG., a solid beam $X_1X'_1$ can rotate about the midpoint G of the grating, and the counter can slide freely along this beam. Another beam $X_2X'_2$ is set parallel to the arm $X_1X'_1$ and these two parallel beams are made to be separated from each other by the distance $\sqrt{R}\sin\Theta$. Two concentric circular discs with radii of unit length (Θ-disc) disc) and of one-half unit length (Φ-disc) disc) are made to slide freely along the beam $X_2X'_2$. The discs can be rotated independently, but they are always concentric. These two discs are provided for making the distance ($\sin\theta+½\sin\Phi$) between two vertical sides to $P'_{x2}P_{x1}$, $S_{x2}S$ and $P'_{x2}P_{x1}P'_{x1}$ of two L-shaped beams and $S'_{x2}SS_1$, and making these two L-shaped beams to slide on the arm $X_1X'_1$ according to the variation of the X-ray tube's position.

Namely, a pin A fixed to Θ-disc, whose distance from the axis of the Θ-disc is the unit length (for example, 1cm.), passes through the guiding beam $P_{x1}P_{x2}$. If we make an angle $\angle$HOA as Θ, the distance $P_{x2}0_{x2}$ becomes just equal to $\sin\Theta$. Similarly there is another pin B attached to the Φ-disc, and it can freely slide on the beam SS_{x2}. If we make an angle $\angle$HOB as Φ, the distance $\overline{O_{x2}S_{x2}}$ becomes equal to ½$\sin\Theta$. Therefore, $\overline{P_{x2}S_{x2}}$ is equal to ($\sin\Theta+½\sin\Phi$).

Next, the right angular apex SX_2 of another L-shaped beam $P_{x1}S_{x2}$ is caused to slide on the beam $X_2X'_2$, and simultaneously make two beams $S_{x2}G$ and $S_{x2}P_{x1}$ of the beam to pass through PX_1 and G respectively. In the right angular triangle ΔGSX_2PX_1, we have

$$\overline{P_{x1}S}\times\overline{SG}=\overline{SS_{x2}}^2 bxR\sin^2\Theta$$

If we put the slide of the counter at S, putting $\overline{SG}=r$, Eq. (18) is exactly satisfied.

The counter may be placed on the platform shown with SS_{x2} of the right angular beam $S_{x1}SSX'_{x2}$. Thus the X-ray tube and the counter can be moved synchronously, by mechanical or electrical coupling methods and there can be obtained the wide range of wavelengths as time resolved spectra successively and rapidly.

By using this spectrometer set at the spectral region of faint X-rays, it is possible to carry out the measurement in a few minutes and in a fixed position whereas the conventional photographic method requires several dozens or hundreds of hours for such measurement.

The mechanisms of Rowland mounting are simple, but the astigmatic aberrations are rather large. On the contrary, Sawada mounting provides better performance with regard to astigmatic aberrations.

The ray-source has been mainly concerned with X-rays, but it is also applicable to all ranges of electromagnetic and corpuscular radiations and sounds including liquid surface waves.

I claim:

1. A diffraction grating spectrometer comprising:

an X-ray tube including an X-ray emitting element mounted at a fixed position along a source focal curve represented by ρ=R $\sin^2\Phi(\sin\Phi/$ R/D),

a means for generating an electron beam, and means for scanning said electron beam across said x-ray emitting element;

a fixed grating mounted proximate to an image-focal curve represented by r=R $\sin^2\Theta/$ ($\sin\Theta$+R/D) for receiving X-rays from said source; and

an electronic counter having a slit on which the diffracted rays of different wavelengths, determined by the grating equation expressed by $n\lambda=d$ ($\cos\Theta-\cos\Phi$), are focused by said grating, said slit being mounted at fixed position on the image-focal curve, where:

λ = the middle wavelength to be examined;

n = the spectral order;

d = the grating constant;

R = the radius of the concave grating;

ρ = the distance from the X-ray source to the midpoint of the grating;

Φ = the angle of incidence;

r = the distance from the slit of counter to the midpoint of grating;

Θ = the fixed angle of diffraction; and

D = a parameter connecting a pair of the source- and image-curves.

2. A spectrometer according to claim **1** wherein said scanning means electronically scans said electron beam across said X-ray emitting element.

3. A diffraction grating spectrometer comprising:

an X-ray tube including an X-ray emitting element mounted at a fixed position along the source-focal circle represented by ρ=R $\sin\Phi$,

means for generating an electron beam, and means for scanning said electron beam across said X-ray emitting element, the scanning direction being tangential to said source-focal circle;

a fixed concave grating mounted proximate to the image-focal circle represented by r=R $\sin\Theta$ for receiving X-rays from said source; and

an electronic counter having a slit on which the diffracted beams of different wavelengths, determined by the grating equation expressed by $n\lambda=d(\cos\Theta-\cos\Phi)$, are focused by said grating, said slit being mounted at a fixed position on the image focal circle, where:

λ = the middle wavelength to be examined;

n = the spectral order;

d = the grating constant;

R = the radius of concave grating;

ρ = the distance from the X-ray source to the midpoint of the grating;

Φ = the angle of incidence;

r = the distance from the slit of the counter to the midpoint of the grating; and

Θ = the fixed angle of diffraction.

4. A spectrometer according to claim **3** wherein said scanning means electronically scans said electron beam across said X-ray emitting element.

5. A diffraction grating spectrometer comprising:

an X-ray tube including an X-ray emitting element mounted at a fixed position along the circle represented by ρ=2R $\sin\Phi$,

means for generating an electron beam, and means for scanning said electron beam across said X-ray emitting element;

a fixed concave grating mounted proximate to an image-focal circle represented by r=R$\sin^2$/ ($\sin\Theta$+½$B\sin\Phi$) for receiving X-rays from said; and

the scanning direction being perpendicular to a straight line between the midpoint of the grating surface and the center of said X-ray emitting element;

an electronic counter having a slit on which the diffracted beams of different wavelengths, determined by the grating equation expressed by $n\lambda=d(\cos\Theta-\cos\Phi)$, are focused by said grating, said slit being mounted at a fixed position on the image-focal curve; where:

λ = the middle wavelength to be examined;

n = the spectral order;

d = the grating constant;

R = the radius of the concave grating;

ρ = the distance from the X-ray source to the midpoint of the grating;

Φ = the angle of incidence;

r = the distance from the slit of the counter to the midpoint of the grating; and

Θ = the fixed angle of diffraction.

6. A spectrometer according to claim **5** wherein said scanning means electronically scans said electron beam across said X-ray emitting element.

UNITED STATES PATENT OFFICE

CERTIFICATE OF CORRECTION

Patent No. 3,577,159 Dated May 4, 1971

Inventor(s) Masao Sawada

It is certified that error appears in the above-identified patent and that said Letters Patent are hereby corrected as shown below:

On the cover sheet insert [32] Priority Aug. 29, 1967; Sept. 16, 1967 and Sept. 30, 1967 [33] Japan [31] 42/55437; 42/59551; and 42/63202 --.

Signed and sealed this 17th day of August 1971.

(SEAL)
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