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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

A Photographic Investigation of Flame Movements in Gaseous Explosions. Part VII. The Phenomenon of Spin in Detonation

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II—A Photographic Investigation of Flame Movements in Gaseous Explosions

Part VII—The Phenomenon of Spin in Detonation

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[Plates 2–12]

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I—Introduction

In Part VI of this series,* the results of photographic investigations into the phenomenon of "spin" in gaseous detonations up to June 1931 were described, and it was stated that further experiments were in hand, particularly as regards

* 'Phil. Trans.,' A, Vol. 230, p. 363 (1932).

the effects of strong electric and magnetic fields upon the phenomenon, because it had already become evident "that the present theory of detonation in gaseous media needs revision."

Since that time we have been continuously investigating the matter, and have now reached a new view of it which will be set forth herein.

Before this can be done, however, it is necessary briefly to review the position three years ago when Part VI was published. It had been established, *inter alia*, (1) that while "spin" is usually, and perhaps invariably, associated with the initiation of detonation in gaseous media, in some cases, for example in hydrogen-oxygen media, it is transient only, while in others, such as carbonic oxide-oxygen media, it persists indefinitely; (2) that in certain mixtures, *e.g.*, in $CH_4 + O_2$ media, it may even be established during the "pre-detonation" stage of the explosion, and continue persistently throughout the detonation stage, with the concomitant abrupt development of a new "head" and new rotation frequency, *e.g.*, 110,000 instead of 68,000 per second in a tube of 1·3 cm internal diameter, at the instant when detonation is set up; and (3) that whenever in a $2CO + O_2$ medium a persistent "spin" with a single rotating "head" is established in a circular tube the velocity of such luminous "head" along its helical path is practically constant, the ratio of pitch/tube-diameter being very nearly 3·0, except in very narrow tubes when it was somewhat higher.

Moreover, considered as a whole, the results showed that "spin" cannot be due to any rotation of the gaseous medium itself but should be regarded as essentially a localized "head" of intensive combustion travelling spiral-wise, as a wave-front, through the otherwise stationary medium. Neither does there appear to be any primary dependence of "spin" upon such factors as the density or chemical composition of the medium, nor even upon the forward speed of flame-propagation in it, although there was some evidence of its occurring only within certain flame-speed limits, *e.g.*, between 1200 and 2500 metres per second.

There were two features associated with the phenomenon which, although invariably observed, were difficult to explain, namely (*a*) the strongly banded appearance in the resulting photographs of the flame after detonation had been set up, and (*b*) the fact that for a small fraction of a second after the initiation of detonation—which was always associated with an ignition-ahead in the compression wave immediately in advance of the actual flame-front—the actual forward flame-speed was always substantially higher than that finally established after the detonation had become normalized.*

It is to the further elucidation of such aspects of the phenomenon that our efforts have been chiefly directed during the past three years. They have been powerfully aided by the employment of a new revolving mirror type of high-speed photographic camera, specially designed for the purpose by one of us (R.P.F.), of a much greater

* Throughout the paper this term will be used to denote a detonation which has had a sufficient run for its forward flame-speed to have acquired its normal value, which in the moist $2CO + O_2$ medium mostly used in the experiments would be 1760 metres per second.

analysing power than was possible with a former revolving drum camera. In the latter a 9-inch duralumin drum, rotating at any desired constant speed up to 16,000 r.p.m., equivalent to a vertical film speed of up to 190 metres per second, had been employed; but the maximum analysing power of the new camera has been equivalent to that of a vertical film speed of 1000 metres per second. Moreover, notwithstanding this much greater analysing power, the definition of the resulting flame-photographs has been improved, so much so that they are capable of considerable enlargement. From such enlargements it has been possible to discern and measure with reasonable accuracy flame movements occurring in as short a time as one-millionth of a second.

Hitherto, "spinning" detonations have only been studied in tubes of circular section; but in the present experiments triangular, square, and oblong tubes have also been employed.

As will be shown presently, what is generally called the "detonation wave" in gaseous explosions is not—as formerly supposed—simply a homogeneous "shock wave" in which an abrupt change in pressure in the vicinity of the wave-front is maintained by the adiabatic combustion of the explosive medium through which it is propagated. It is now to be considered rather as a more or less stable association, or coalescence, of two separate and separable components, namely of an intensively radiating flame-front with an invisible "shock wave" immediately ahead of it.

According to the new view, detonation in an explosive gaseous medium is the propagation through it, as a wave, of a condition of intensive combustion, initiated and maintained in a "shock wave" by radiation from an associated flame-front; and "spin" ensues whenever the conditions are such that the radiation from an attenuated flame-front causes a localized intensive excitation of molecules in the "shock wave" just ahead of it. The resulting "head" of detonation, in which an intensive combustion is thus localized, then begins to rotate in the medium, eventually pursuing a spiral track along the tube quite close to its walls. There is, however, no rotation of the medium as a whole, but only of such a "head," or maybe "heads," of detonation.

If in such a "spinning" detonation influences are brought to bear such as would in any way destroy the spinning "head," not only does the "spin" itself cease, but separation of the flame-front from the associated "shock wave" also occurs, so that the flame-speed falls and detonation ceases. The phenomenon can be and is re-established, however, as soon as the distance between the detached, but still radiating, flame-front and its formerly associated "shock wave" from any cause becomes sufficiently reduced to enable the radiation to restore the former condition.

Such, in brief, is the new conception of detonation; the evidence supporting it, which is largely cumulative, will be described herein. This evidence has only become possible, however, through the extremely high analysing power of the new revolving-mirror high-speed camera employed, a detailed description of which will next be given.

II—The Fraser High-Speed Mirror Camera and General Experimental Procedure

The Camera

This camera, which was designed in 1931, employs a different principle from that embodied in the previously used revolving-drum cameras, in that the film is now

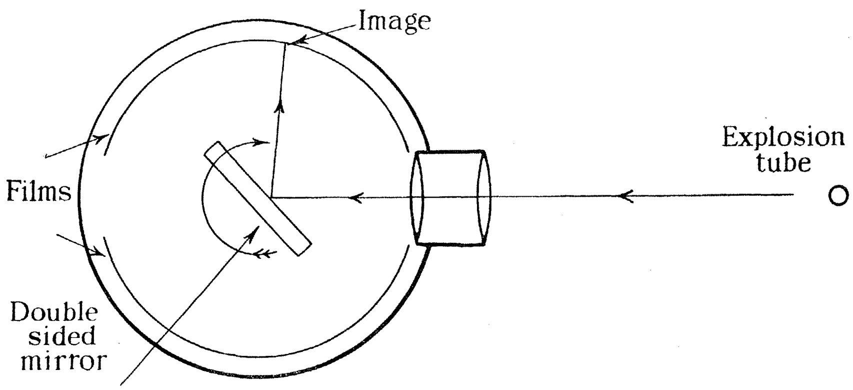

Fig. 1—Diagram of mirror camera

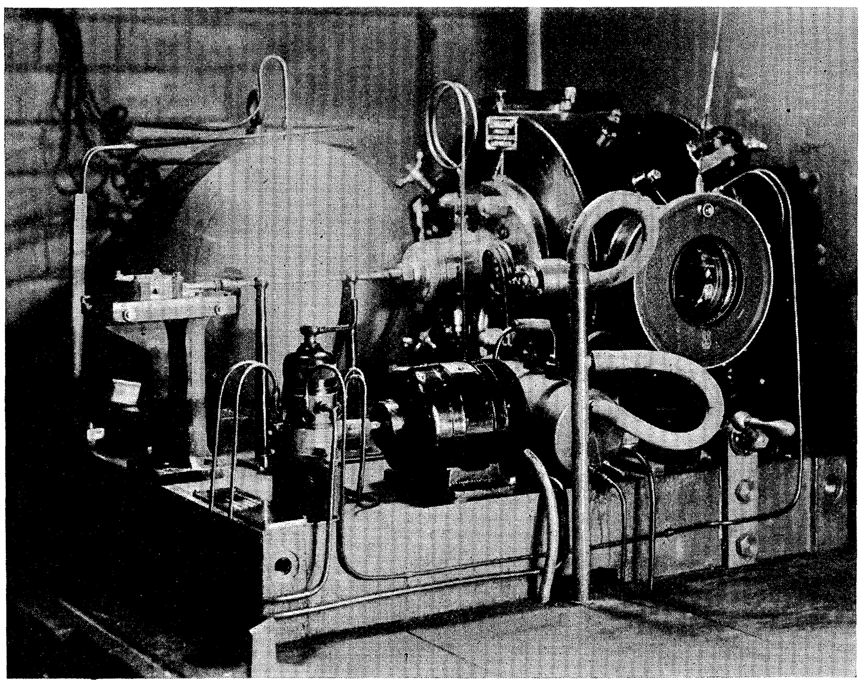

Fig. 2—Fraser high-speed mirror camera

held stationary and the image of the flame is rotated in a plane perpendicular to the axis of the explosion tube by means of a mirror, figs. 1 and 2. Two semicircles of film are suspended within a circular casing, upon the circumference of which is fixed a large aperture lens. A double-sided steel mirror is rotated at the centre

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of the circle formed by the films so as to throw the image from the lens upon them. This arrangement has the following characteristics: (1) the image of the flame in the horizontal tube is rotated at right angles to the direction of flame-travel; (2) each side of the mirror in turn rotates the image; (3) the image is rotated at twice the speed of the mirror. Thus, for example, rotation of the mirror at 30,000 r.p.m. is equivalent to 60,000 image rotations per minute, which, in this machine, is equal to 1000 metres of film covered by the image per second. To obtain such high speeds of rotation it is necessary to evacuate the camera casing to avoid all disturbance from air currents.

The camera casing is an Alpax casting designed to be sealed vacuum tight, carrying a large bearing-housing on one side and a removable cover on the other. Within the top and bottom of this casing two curved film carriers of flexible metal are suspended upon micrometer screws. Into these carriers the two films are slid through a sealable porthole at the back of the camera case. The curvature of the films can be altered by differentially adjusting the series of micrometer screws, so that accurate focussing can be obtained at all points along the films.

The double-sided steel mirror, 6 inches by 4 inches, is optically polished and integral with its shaft. It was made from a drop forging of stainless steel tempered to 80 tons tensile. It is radiused on each axis, and it is dynamically and statically balanced with extreme care. Its weight is $8\frac{1}{2}$ lb. The shaft is carried by three ball races, between two of which is arranged a high-speed centrifugal pump to prevent leakage of air into the vacuum casing.

The mirror shaft is driven by means of a small friction wheel in contact with a large steel wheel, with a spherical surface, connected to the axle of a 4 h.p. high-speed electric motor. This motor is fixed to a large turn-table so that the curved surface of the large spherical driving wheel has its centre upon that of the turn-table. The turn-table can be mechanically rotated in either direction at a constant and very slow speed by an auxiliary motor. By this means the gear ratio is altered progressively as the circle of contact on the spherical wheel becomes greater with the rotation of the turn-table. The high-speed motor is specially constructed to run at any constant speed up to 6000 r.p.m. and is controlled by an auxiliary dynamo whose voltage output is varied by altering a resistance in the shunt-field circuit.

The speed of the mirror is thus varied by the combined action of gear ratio between the spherical wheel and friction wheel and the shunt-field resistance of the dynamo, each of the speed controls being operated by a small pilot motor. Throughout the present investigation the speed of rotation of the mirror was measured by means of a "Hasler" speed-counter mounted in line with the mirror shaft. The possible error involved did not exceed 1 in 1000. The accuracy of the instrument itself was periodically checked by comparison with a tuning-fork.

The lens is a Dallmeyer "Pentac" 12-inch focus carried in a special focussing mount which can be sealed vacuum tight. This lens is anastigmatic, and its glasses are specially cemented to withstand the atmospheric pressure upon its face.

The Explosion Tube

This comprised two independent sections, shown in fig. 3, separated by a specially designed disc tap. The first section, X, which was used for the setting up of detonation in the explosive medium throughout all the experiments described herein—and to which another section, Y, specially adapted to the requirements of each individual experiment, was attached—consisted of a sparking plug, A, fitted to one end of a detonating box, B, the other end of which was joined with a 7-metre length of copper tubing, internal diameter 13 mm, terminated by a specially designed tap, D. This tap, shown in fig. 4, was composed of three metal discs through each of which a 13 mm hole was accurately bored. They were so arranged that merely by rotating the centre disc the first section could be shut off from the rest of the apparatus. Moreover, capillary holes were bored through the edge of each disc so as to allow

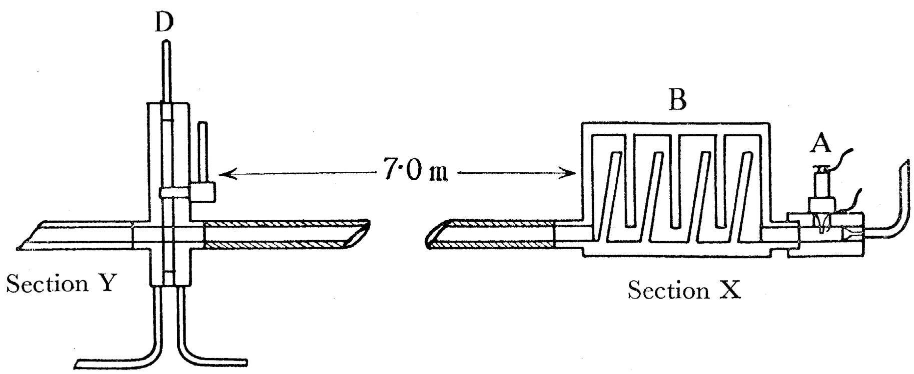

Fig. 3—Explosion tube

of the evacuation (and subsequent filling with the various experimental gaseous mixtures) of each of the two sections of the apparatus, as well as of the hole in the central disc.

Although the design of the second section, Y, of the apparatus was varied according to the requirements of each experiment, the portion of it along which the explosion flame was moving when actually photographed was always a horizontal glass (or glass-windowed) tube of suitable dimensions for the purpose involved. It should also be understood (i) that in the building up of any particular explosion tube special precautions were taken to ensure uniformity in the internal diameter throughout, and the end faces of all joints were accurately ground and butted together so as to be perfectly true, and (ii) while, during the evacuation and subsequent filling of the apparatus with the explosive medium, it was closed at each end, the stopper at the end furthest from the firing piece was removed immediately before the explosive medium was fired.

The Explosive Medium

Except when otherwise stated, a moist $2CO + O_2$ medium, saturated at 17 to 21° C, was employed throughout the investigation, because when exploded in the tubes used, it always developed a pronounced " spin " with only a single rotating " head," which made it eminently suitable for our purpose. It was always fired at room temperature, about 17 to 21° C, and atmospheric pressure. The carbonic oxide was prepared by the dropping of formic acid into pure strong sulphuric acid at 90° C, and was quite free from hydrogen. The nitrogen contents of the $2CO + O_2$ media were about 0·5%.

The Photographs

In examining the resulting photographs, it should be borne in mind that they represent what is equivalent to the vertically rotating image of a flame which was

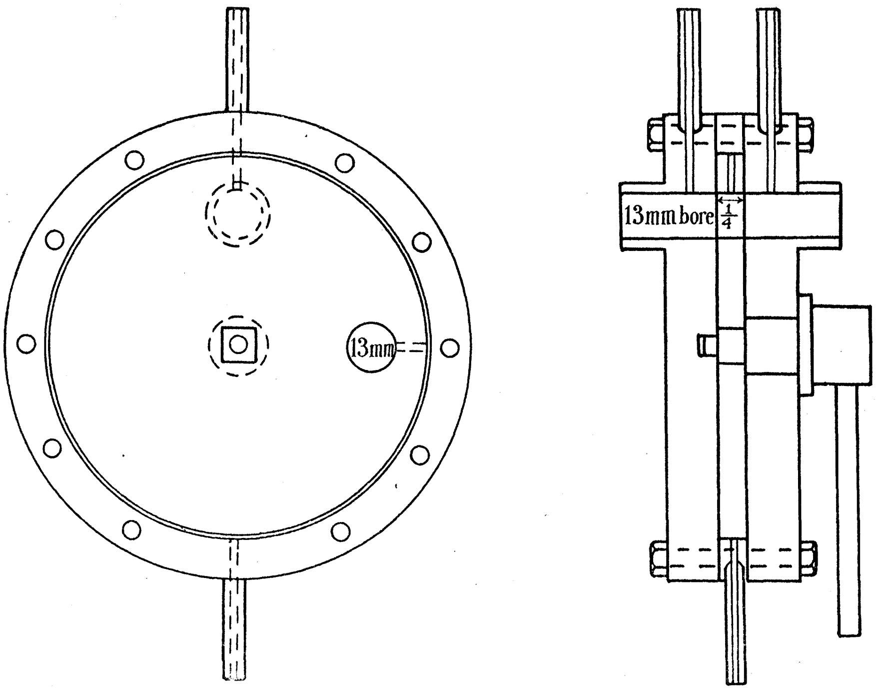

FIG. 4—Disc tap, D

actually moving horizontally along the explosion tube, and therefore that the graph traced by the flame in the photograph is compounded of the two velocities, the vertical and horizontal. Since the first named was always accurately known, the second could be calculated therefrom after the angle subtended by the graph with the vertical had been measured. Also, to ensure the utmost accuracy, the vertical speed of the flame-image was always so adjusted in the camera that the angle subtended by the resulting graph in the photograph with the vertical was approximately 45°. We estimate that the over-all inherent experimental error involved in the determination of the flame-velocity by the means adopted would not exceed 0·3%, even for the highest speeds measured during the investigation.

Time is represented by vertical height in the photographs, and a time-scale in millisecs is usually shown ; the length of the explosion tube photographed, usually about 1·5 metres, is represented by the width of the photograph.

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III.—New Photographic Evidence on the Initiation of Detonation and Development of "Spin" in a $2CO + O_2$ Medium

The advantage accruing from the much higher analysing power of the new as compared with the camera formerly used are well brought out by two photographs, figs. 5 and 7, Plates 2 and 3, illustrating the initiation of detonations, and the development of " spin " thereafter in a moist $2CO + O_2$ medium when fired in a tube of circular cross-section, with an internal diameter of 1·3 cm. These photographs will also serve admirably as an introduction to the new view of the phenomenon, which will be further developed and illustrated in the succeeding sections.

In Part V it was shown that " auto-ignition " ahead of the flame-front may occur during the pre-detonation stage of a gaseous explosion whenever the flame is travelling at a speed greater than that of any compression wave* through the medium ahead of it. Such " auto-ignitions " ahead of the flame are always conditioned by the close proximity of a flame-front to the compression wave which it is overtaking. Moreover, such compression waves are known to originate either in, or just behind, the flame-front of a burning medium whenever anything occurs suddenly to enhance its chemical activity. And although detonation need not result from the first of such " auto-ignitions," it is ultimately set up by some succeeding one of them.

Fig. 5, Plate 2, shows the initiation of detonation in a moist $2CO + O_2$ medium in a circular tube of 1·3 cm internal diameter. In this photograph, which is analysed in fig. 6, the flame is seen entering the picture at a speed of 1275 metres per second, and when a moment later it had reached a point just 6·37 cm behind a preceding compression wave an auto-ignition occurred in the latter. From this origin two new flame-fronts are seen to start ; both of them move forward, one at an initial speed of 2380 m/sec, but quickly rising to 3260 m/sec, and the other at an average speed of 350 m/sec. The last-named flame-front was shortly caught up by, and collided with, the original flame-front, the resulting collision giving rise to the " retonation wave " which travelled backwards through the still incandescent medium at a speed of 875 m/sec.

From the origin of the auto-ignition a wave was propagated forwards through the medium (as shown by the relatively dark line in the photograph) at a speed of 1320 m/sec. And yet a second wave was set up in the region, just ahead of the origin of the auto-ignition where the luminosity of the flame-front reached a maximum, and where its initial speed of 3260 m/sec. almost suddenly changed to 1980 m/sec. This point also marked the beginning of the " spin " in the detonation, the forward velocity of which was rapidly falling to its normal value of 1760 m/sec. This second wave, appearing as a bright line in the photograph, travelled forward behind the flame-front at an almost constant speed of 1320 m/sec.

* The terms " compression " or " shock " are sometimes used indiscriminately in describing such waves ; we prefer only to employ the latter in describing the intensive waves set up by " detonators " or when " detonation " is finally determined in a gaseous medium.

As in all other cases of such " spinning " detonations so far analysed by the higher resolving power of our camera, during a brief interval of time (about 1/100,000 sec) after the initiation of detonation the forward speed of the flame-front was always abnormally high, in this case 3260 m/sec, and the beginning of " spin " was not discernible until the flame-speed began to fall towards its final constant value, here 1760 m/sec. During the period of transition (about 1/4000 sec) between the initial abnormal and the final normal constant velocity, the flame-front progressed about 0·5 metres along the tube, and the pitch of the rotating " head "

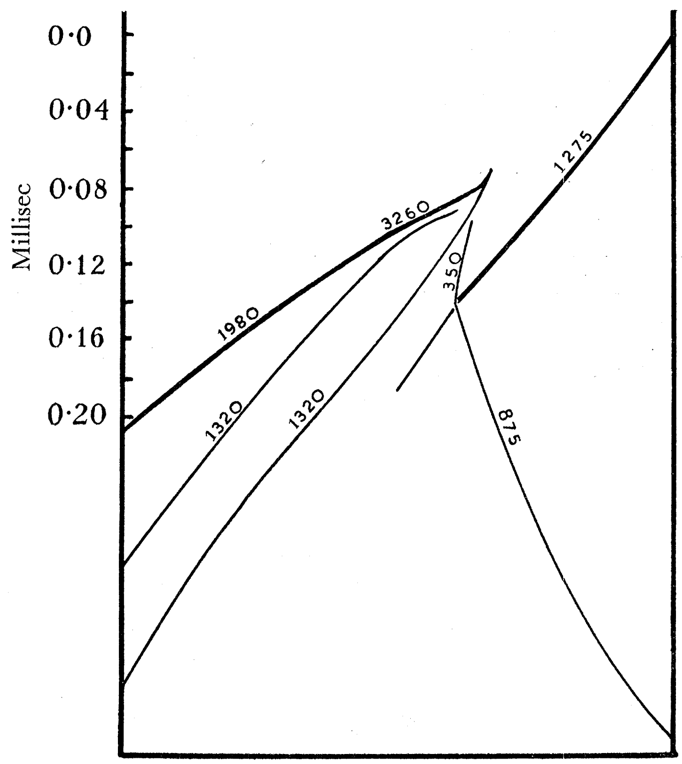

FIG. 6

of detonation increased until the circle of rotation corresponded with the internal diameter of the tube.

In the photograph, the detonation wave, in which "spin" is developing, passed out of the picture at a falling speed of 1980 m/sec, although eventually, as shown in the next paragraph, its forward speed would fall to the normal 1760 m/sec, and the " spin " would then attain its final constant frequency of 44,300 per second. The whole series of events shown therein occupied no more than 0·36 millisec, including 0·09 millisec for the pre-detonation stage, 0·03 millisec from the point of auto-ignition to that of the first sudden change in flame velocity from 3260 to 1980 m/sec, and 0·09 millisec from the last-named point to where the flame-front finally passed out of the picture.

This typical photograph, with its clearly shown wave system, will suffice to demonstrate the much greater complexity than was ever previously realized of the phenomena associated with the initiation of detonation in such a gaseous medium, and therefore the need of some revision of the hitherto accepted view of it.

Fig. 7, Plate 3, shows the "spinning" detonation in a moist $2CO + O_2$ medium in a tube 1·3 cm internal diameter. It shows the course of events during 0·11 millisec, while the normalized detonation ultimately set up after the event shown in fig. 5 traversed a distance of 25 cm. It discloses not only the sinuous track of the flame-front spinning with a frequency of 44,300 per sec, but also a hitherto unobserved feature, namely, that twice during each complete rotation of the "head" of detonation two distinct effects arise from a common origin in the flame-front. These appear in the photograph as a pair of divergent bright lines subtending an angle of 22° at such origin. One of these lines is due to luminous particles travelling forward in the rear of the wave-front with a velocity of 780 m/sec, the other being the luminous track of a compression wave travelling backwards through the incandescent medium with a resultant velocity of 320 m/sec.* Moreover, it is now seen for the first time that the horizontal banded appearance behind the wave-front, which hitherto has been described as the "tail" of the detonation, is merely a secondary effect produced by the criss-crossing of the two newly observed series of luminous lines referred to.

These new disclosures mean that twice during each complete rotation of the "head" of such a "spinning" detonation, there recurs abruptly either an ignition of a pocket of gas or a sudden increase in combustion intensity—for reasons given below, more probably the former—in or immediately behind the wave-front. Whichever it is, it constitutes a characteristic feature of the phenomenon.

Another point to be borne in mind is the extremely high temperature and radiating power of the "head" of detonation, as proved by the fact that on traversing a glass tube upon the inner wall of which a mirror of silver had previously been deposited, it cut a spiral track by volatilizing the deposited silver during its passage.

Theoretical—(A) The new explanation of detonation to which the cumulative evidence of our researches has led may now be amplified with the aid of fig. 8, which has been constructed from photograph, fig. 5. It represents diagrammatically the state of things at each of twelve successive instants, 1/100,000 second apart, in the explosion of a moist $2CO + O_2$ medium starting from a point in the pre-detonation stage 1/50,000 second before the auto-ignition occurs. The shaded areas in the diagram indicate flame, the relative luminosity of which is approximately shown by the density of the shading. The vertical lines indicate compression waves, and the curved lines flame-fronts. The numerals inserted are velocities in metres per second at the positions shown. At the outset, 1, the strongly radiating flame-front A is seen approaching a compression wave BB′ (composed of a condensation

* The lowness of this resultant velocity of 320 m/sec is due to the fact that the wave concerned is travelling through a medium which is moving as a whole in the opposite direction; the two component velocities being about 1100 and 780 m/sec.

B and a rarefaction B′ behind it. In 2, the flame-front is now closer up to BB′, and in 3, when it is only 6·4 cm from it, the radiation from A, on absorption by the compressed medium in B, both raises its temperature and strongly excites the

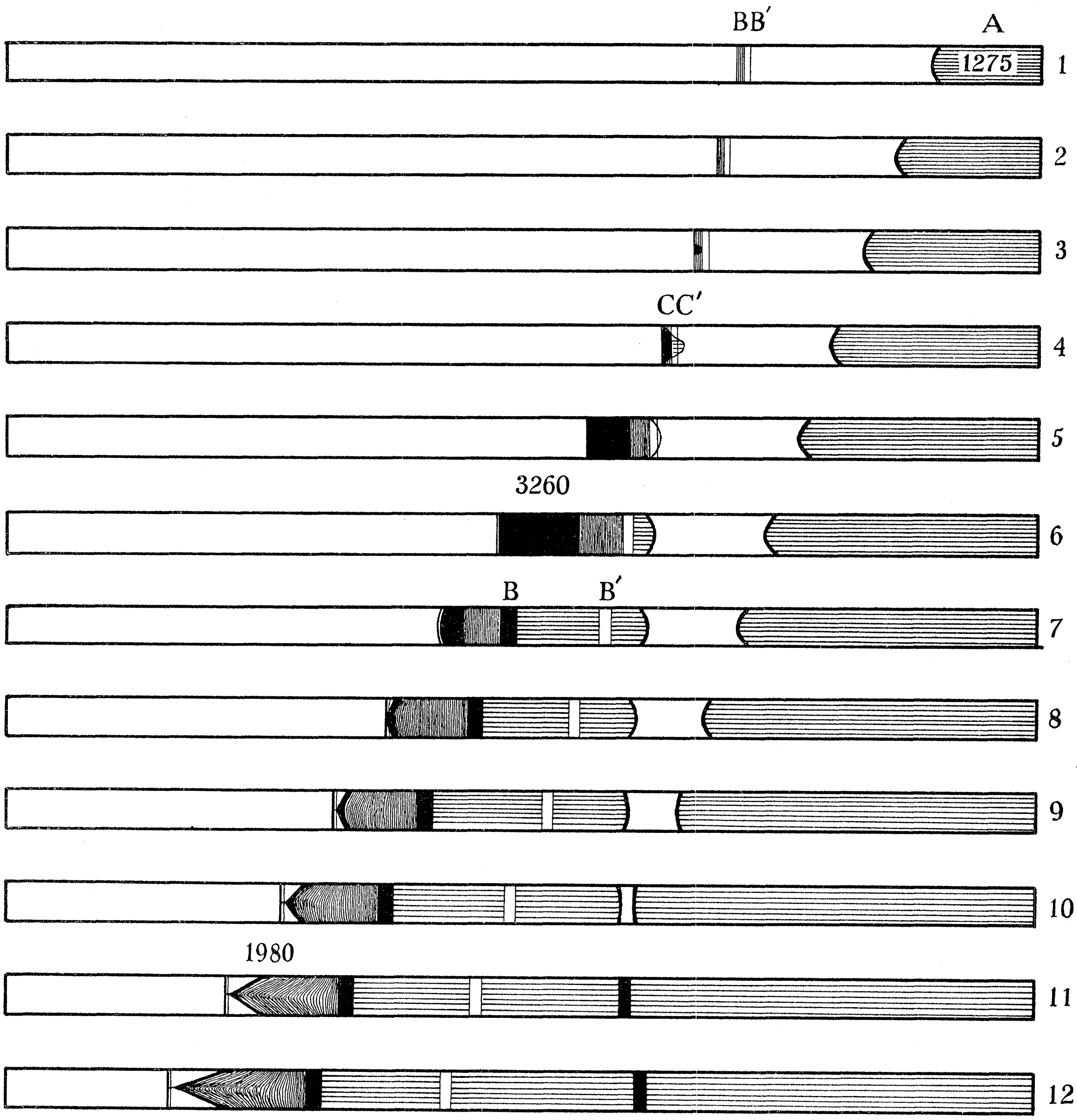

FIG. 8

molecules comprising it. Such excitation is, however, not uniform over the whole layer, but, being by symmetry greatest at or near its centre, causes a localized spot at which the auto-ignition ahead of the flame-front begins, and from which it rapidly spreads outwards throughout the whole of B. This starts two new flame-fronts CC′, 4; one of these, C, is identical with the forward-moving compression wave,

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whose velocity thus receives a strong impetus ; the other C′ also moves forward, but with a very small resultant velocity, there being, as we calculate, a general forward movement of the gaseous medium as a whole of about 600 m/sec.

In 6 the forward velocity of the new fastest moving flame-front, C, which in 5 was 2380 m/sec, attains its maximum of 3260 m/sec, the original flame-front A being still behind (though rapidly approaching) the auto-ignited and newly detonated region.

Whether or not a persistent "spin" develops in a detonation so initiated would seem to depend on the requisite degree of excitation of the combustible gas. In cases (such as when hydrogen is involved) where this is easily attained, the initial close association between the forward-moving compression wave and the burning medium in the detonation-front is so quickly and continuously maintained that the front does not become attenuated, and therefore no persistent spin can be developed. In other words, the detonation condition shown in 6 is continuously maintained, save only that the gap between it and the original flame-front soon disappears.

On the other hand, a persistent "spin" develops in detonations whenever the requisite degree of excitation of the molecules of the combustible gas, *e.g.*, carbonic oxide, is such as to render the association between the forward-moving compression wave and the burning medium in the detonation-front precarious, so that an attenuated (*e.g.*, cone-shaped) front develops.

In numbers 7 to 12 inclusive such an attenuated detonation-front—the "head" of detonation—is being developed, and "spin" is initiated because of the now uneven distribution of the radiation from it. With increasing attenuation the pitch of the "spin" becomes greater, until eventually the "head" of detonation moves along a spiral track close to the tube wall, with resulting normalization of the phenomenon so that the helical velocity of the head of detonation assumes a constant value, while the forward velocity of the attenuated front falls eventually to its final lower constant value.

At 10 the collision of the original flame-front A with the rear of the auto-ignited column produces the "retonation wave." During the interval 6 to 12 the component condensation and rarefaction layers B to B′ of the original compression wave BB′ separate, owing to the combustion having been initiated in the former only. Such separation produces the two wave-like effects which appear as bright or dark lines in fig. 5, Plate 2.

(B) In such cases of a "spinning" detonation, it follows geometrically that at each half-rotation of the "head" a pocket of unburnt gas will be enclosed on three sides by the flame, and thereby spontaneously ignited by its radiation. This would account for the two new effects shown in fig. 7 as arising from a common origin in the flame-front twice during each complete rotation thereof. Supporting evidence of the foregoing explanation has been derived from a series of shadow-photographs taken on a stationary film, by transmitted light, of the compression wave ahead of the approaching $2CO + O_2$ flame-front in the pre-detonation stages. Figs. 9, 10, and 11, Plate 2.

In fig. 9 the compression wave appears as a pair of dark and light narrow bands, corresponding with the condensation and rarefaction components, respectively, of the wave. Their combined thickness was 1·3 mm. The approaching flame-front, not shown in the photograph, is a metre behind the compression wave; the fine criss-cross lines immediately behind the wave are due to the strain set up by it in the glass walls of the explosion tube.

In fig. 10 the approaching flame-front is seen about 10 centimetres behind the compression wave, the width of which was increased to 2 millimetres; signs of impending disturbance are just discernible.

In another such shadow photograph, fig. 11, of a detonation wave, after it had been well established and normalized in a moist $2CO + O_2$ medium, there was evidence of considerable distortion in the wave-front; this aspect of the matter is being further investigated.

IV—Influence of Tube Diameter upon Flame-Speed and "Spin" in Moist $2CO + O_2$, etc., Detonations.

In Part VI it was shown that, in agreement with the previous observation of Campbell and Woodhead, the pitch p of the helical path pursued by the luminous "head" of a moist $2CO + O_2$ detonation along a tube of circular cross-section varies with its internal diameter d in such a way that the ratio p/d remains approximately 3·0, so long as d does not much exceed 2·5 cm beyond which two or more "heads" may be developed. It was, however, thought desirable to investigate the matter more closely, and especially down to the limiting diameter in narrow tubes where detonation in the medium is suppressed under the cooling influence of the walls.

Accordingly our apparatus was so arranged that a "spinning" detonation, already well established in its first section, was continued through a gradually tapered junction-piece into the second section of the apparatus where it was photographed, fig. 12. Although a moist $2CO + O_2$ medium, filling the whole apparatus from end to end, was mostly used, a few experiments with moist $3CO + O_2$ and $CO + N_2O$ media were included.

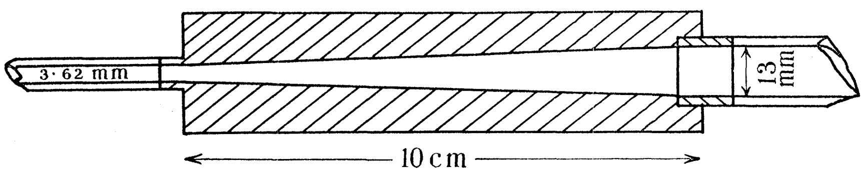


Fig. 12

The general results, Table I, showed for $2CO + O_2$ media, i to vi inclusive, a marked constancy of 3·0 for the p/d ratio, except with very narrow tubes, when it became sensibly higher, *e.g.*, 3·28 near the limiting diameter, about 3 mm, at which detonation is suppressed. The helical velocity of the "head" of detonation gradually increased from 2440 to 2620 m/sec. but the frequency of the spin rapidly fell from 148,000 to 23,000 per second as the internal diameter of the tube was increased from 3·62 to 25·4 mm. The forward general flame-speed, however, was not much affected.

Table I—Relation between Tube Diameter and Pitch of "Spin" etc., in Moist $2CO + O_2$ and other Similar Detonations

Gaseous medium	Exp. No.	Tube internal diameter d mm	Pitch of spin p mm	Ratio p/d	Frequency of spin f per sec	Flame-speed m/sec Forward	Helical
Moist $2CO + O_2$ Density ($H_2 = 1$) 14·7	i	3·62	11·9	3·28	148,000	1760	2440
	ii	4·15	13·4	3·23	132,000	1760	2460
	iii	12·8	38·4	3·00	44,800	1720	2490
	iv	13·0	39·5	3·04	44,300	1750	2515
	v	15·2	44·0	2·90	39,800	1750	2580
	vi	25·4	75·0	2·95	23,900	1795	2620
$3CO + O_2$ Density 14·5	vii	25·5	80·0	3·15	23,400	1870	2640
$CO + N_2O$ Density 18·0	viii	12·8	38·0	2·97	45,000	1715	2500

It is not to be concluded from the above results that the $p/d = 3·0$ ratio holds good for spinning detonations in *all* gaseous media; we have, for instance, observed ratios of about 4·0 for such a detonation propagated through a pure acetylene medium in tubes of 14·0 and 25·5 mm internal diameter, although for a detonation through a 90% C_2H_2/10% O_2 medium in a tube of 25·5 mm internal diameter the observed ratio was 3·2.

With the $3CO + O_2$ medium, vii, in a tube of 25·5 mm internal diameter, the pitch of the "spin" was definitely longer, with a somewhat lower frequency, than with the $2CO + O_2$ medium in a tube of practically the same diameter, *cf.* vi and vii. Although the helical velocity of the head of detonation was practically the same in both cases, the general forward flame-speed was definitely about 4% higher in the $3CO + O_2$ than in the $2CO + O_2$ medium, notwithstanding the somewhat lower density and much lower volumetric potential heat-content of the former. Campbell, Whitworth, and Woodhead have also observed with $CO - O_2$ media that the maximum rate of detonation occurs in those containing between 75 and 80% of carbonic oxide,* although their "peak" was not so pronounced as ours.*

It is also noteworthy how remarkably close are the corresponding data for the $2CO + O_2$ and $CO + N_2O$ media in tubes of like internal diameter, 12·8 cm, *cf.* iii and viii.

The following two photographs, figs. 13 and 14, Plate 4, obtained during this part of the investigation are of such outstanding interest as to warrant separate consideration.

* 'J. Chem. Soc.,' p. 59 (1933).

Fig. 13 is of two separate explosions (*a*) and (*b*) through a moist $2CO + O_2$ medium in a tube of 3·62 mm internal diameter, this being near the limiting diameter below which detonation would be altogether suppressed. The interesting fact is shown of the detonation being alternately damped down by the cooling action of the tube wall and afterwards re-initiated. This is, we think, due to the essentially dual character of the spinning detonation as an unstable and separable association of a "shock wave" and a flame-front. For with a sufficient cooling action of the tube walls, separation of the two is sooner or later effected with the result that the "shock wave" component goes on ahead of the retarded flame-front component. The velocity of the now invisible "shock wave," moving ahead, is, however, degraded faster than that of the following visible flame-front, so that eventually the two come together again and detonation is re-initiated. We have found that in such a tube of 3·6 mm diameter detonation can be so alternately damped down and re-initiated after short-time intervals indefinitely and with the greatest regularity.

In each of the two separate explosions (*a*) and (*b*), the forward flame-speed on entering the picture was 1225–30 m/sec; soon afterwards a detonation was initiated, as the result of an ignition ahead, the forward flame-speed suddenly increasing to 1840-60 m/sec, but very soon afterwards falling to the normal speed of 1760 m/sec. Owing to the cooling effect of the tube walls, however, this could not be maintained, the flame being quickly retarded to 1155–60 m/sec, while the associated "shock wave" went on ahead of it, so that detonation ceased. But after traversing another 80 cm the speed of the "shock wave" had been sufficiently degraded to allow of the flame-front catching it up again, with the result that detonation was re-initiated through a second ignition ahead, with an abnormal velocity of about 1810–50 m/sec, which soon fell again to the normal value of 1760 m/sec. During each detonation period the frequency of the "spin" was 148,000 and the helical velocity of the "head" 2440 m/sec. How very regular were the recurring phenomena under such conditions is shown by the data in Table II.

TABLE II

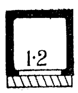
	Explosion	
	(*a*)	(*b*)
Flame-speed before first detonation	1225	1230 m/sec
Flame-speed at beginning and end of first detonation	1860–1760	1840–1760 m/sec
Average speed of "shock wave" between the two successive detonations	1160	1155 m/sec
Distance between the two detonations	0·8	0·75 m
Flame-speed at beginning and end of second detonation	1850–1760	1810–1760 m/sec

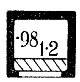
Fig. 14, Plate 4, is a photograph of two separate moist $2CO + O_2$ detonations in tubes of 4·15 and 12·8 mm internal diameter, respectively, Table I, ii and iii. In both cases a continuous "spin" was developed, and in all other respects the phenomenon was constant and regular throughout. It will be seen how much greater was the frequency of the spin in the narrower than in the wider of the two tubes, namely, 132,000 as against 44,800 per sec.

Taken together, figs. 13 and 14 show that the possibility of a continuous spinning detonation in a moist $2CO + O_2$ medium begins with a minimum (glass) tube diameter of somewhere between 3·62 and 4·15 mm, the former being probably somewhere near the limiting diameter below which detonation would be completely suppressed without prospect of re-initiation.

V—Influence of Tube Shape upon "Spin" and Flame-Speed in Moist $2CO + O_2$ Detonations

Hitherto, most if not all the published observations upon detonations in gaseous media have reference to their occurrence in glass or metal tubes of circular cross-section of various diameters; but so far little or nothing has been done with a view to ascertaining to what extent, if any, the phenomena concerned would be modified by varying the cross-sectional shape of the tubes employed. Moreover, no one has yet proved by actual experiment whether or not detonation is ever set up in gaseous media contained in other tubular vessels. Yet it seems doubtful whether at any rate the "spinning" variety would be observed in non-circular enclosures.

As it seemed desirable to investigate this aspect of the matter further, we had made for us a series of suitably dimensioned metal explosion tubes of triangular, square, and oblong cross-sections. Before connecting each one in succession, through suitable intermediate tubing of gradually changing cross-section, with the usual first section of our apparatus, a long oblong slit, 6 to 18 mm wide, was accurately cut out of one of its metal sides, and a long, thin glass window tightly fitted over the slit on either the inner or outer metal surface, *i.e.* (for a square tube) either 

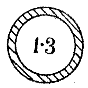
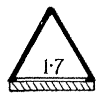
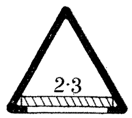
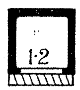
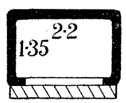
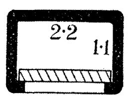
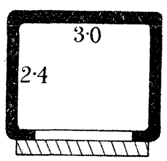
or 

so as to permit of the explosion flame being subsequently photographed. A moist $2CO + O_2$ medium was employed in all the experiments concerned, the detonation being normalized in it long before the flame entered the section of the apparatus where it was photographed.

To provide a basis for comparison, control experiments were first of all carried out in which the detonation was photographed while traversing (i) an explosive medium in an ordinary glass tube of circular cross-section and 1·3 cm internal diameter. Subsequently the experiments were repeated in such wise that the detonation was photographed while traversing the medium in one or other of the specially windowed metal tubes referred to. The cross-sections used in (ii) and (iii) were both equilateral triangles with sides 1·7 and 2·3 cm respectively. That used in (iv) was a square, of 1·2 cm side; while those used in (v), (vi), (vii), and (viii) were oblongs of varied dimensions and areas. Results of typical experiments are detailed in Table III, and may be summarized as follows.

(1) The spinning detonation, already well established at its normal forward-speed of 1760 m/sec. before entering the photographed section of the apparatus, was always propagated throughout it, mostly with but slight change in speed.

TABLE III—INFLUENCE OF TUBE SHAPE AND DIMENSIONS UPON "SPIN" IN MOIST $2CO + O_2$ DETONATIONS

Index No.	Explosion Tube Employed: Cross-section shape	Cross-section area a cm²	$\frac{\text{Surface}}{\text{Volume}}$ b	Periphery c cm	Circle of periphery c: Diameter d cm	Calculated pitch $p = 3d$ cm	Spinning detonation: Observed pitch p' cm	Forward flame-speed m/sec	Remarks
i		1·33	3·08	4·09	1·3	3·9	3·85	1760	
ii		1·25	4·08	5·1	1·625	4·875	5·08	1725	
iii		2·29	3·0	6·9	2·19	6·57	6·7–8·0	1625–1690	Circular, Triangular, and square sections, p' nearly $= p$. The head of detonation spins close to tube wall.
iv		1·44	3·33	4·8	1·525	4·58	4·10	1760	
v		1·175	3·71	4·36	1·39	4·17	4·20	1695	
vi		2·97	2·39	7·1	2·26	6·78	7·28	1780	
vii		2·42	2·72	6·6	2·1	6·15	3·75	1770	In oblong sections, the head spins along inscribed spiral track.
viii		7·2	1·5	10·8	3·44	10·32	3·23–4·5	1780–1820	

(2) In all tubes of triangular or square cross-section (ii to v inclusive) the " spin " continued to be well maintained, the " head " of detonation pursuing a spiral-like track close up to the walls of a pitch very nearly that which would have resulted in a tube of circular section with periphery equal to that of the triangle or square actually concerned, as shown by the approximate equality of the p and p' values in Table III. The " banded " appearance of the flame behind the wave-front in the photograph was also fairly well marked, though hardly so well as in control experiment (i) with the tube of circular section.

These results have confirmed the conclusion drawn from the experiments upon a moist $2CO + O_2$ detonation in a ribbed glass tube of circular cross-section and 1·3 cm diameter, as described in Part VI, pp. 381–2, namely, that the observed " spin " does not involve a rotation of the gaseous medium as a whole, but only of the " head " of detonation. For, were the former to occur, as some have supposed, it is unthinkable that the pitch of the " spin " in the triangular or square tubes now employed would have been that actually observed, *i.e.*, so nearly equal to what it would have been in a circular tube of like periphery. Hence this issue may now be regarded as finally settled.

(3) In the two oblong tubes, vi and vii, the spiralling " head " of detonation pursued a track approximating to that which it would have done in a circular tube of internal diameter equal to the shorter side of the oblong. In vii, however, it was somewhat confused, and there was no " banded " appearance of the flame behind the wave-front in the resulting photograph.

Figs. 15 to 18, Plates 4 and 5, inclusive, will suffice to illustrate this section of the investigation. Fig. 15 shows the detonation in the triangular tube (iii), fig. 16 that in the square tube (v), fig. 17 that in the oblong tube (vi), and fig. 18 that in the oblong tube (viii).

VI—The Suppression of a Spinning Detonation by Means of a Short Nitrogen-Gap

If the development of persistent " spin " in a gaseous detonation is primarily due to the instability of the association between the separable flame-front and shock wave involved as compared with that of a non-spinning detonation, it should be possible to suppress the phenomena in a $2CO + O_2$ medium by the interposition of a short gap of inert gas, such as nitrogen, between two columns of the medium in the first of which detonation has been set up. For the effect of such an inert gap should be to retard combustion in the flame-front and so reduce its velocity as to make it momentarily lag behind the associated " shock wave," thus causing a momentary separation of the two, and suspension of the condition upon which, according to our view, the spinning detonation depends. The " shock wave " would then go ahead of the retarded flame-front; but soon its energy, now unsustained by combustion, would be dissipated to such an extent that its velocity through the unburnt medium would become slower than that of the flame-front. Subsequently, therefore, the two should again become associated and the former "spinning" detonation be re-established. On putting the matter to an experimental test, this prediction was completely fulfilled.

Experiments with a 2CO + O_2 Detonation—The experimental arrangement and procedure were as follows. The two sections of the apparatus, fig. 19, p. 50, each comprising a sufficient length of tubing of 13 mm internal diameter, were separated by the disc tap as already described on p. 34. The tap being closed, each section of the apparatus was thoroughly evacuated and then simultaneously filled up to precisely the same pressures (atmospheric) with the same $2CO + O_2$ medium which had previously been dried for two days over phosphoric anhydride. Meanwhile, the $\frac{1}{4}$-in-long cavity in the disc tap had been evacuated, and afterwards filled up to precisely the same pressure with nitrogen. All being thus prepared, the disc tap was opened. The apparatus then contained two like columns of the explosive medium separated by a $\frac{1}{4}$-inch nitrogen-gap, all at precisely the same pressure. After a measured time-interval, which varied from 5 to 60 seconds in different experiments, the explosive medium in the first column was fired at the end farthest from the tap, and in due course the resulting detonation set up reached the N_2-gap, the effect of which upon the flame was studied by photographing its propagation through the explosive medium both before and after the gap.

The results of typical experiments, which are summarized in Table IV, showed (i) the establishment of a spinning detonation in the medium, with a forward flame-speed of 1780 to 1800 m/sec.* *before* the gap was reached ; (ii) the suppression of both "spin" and detonation by the N_2-gap, with consequent considerable reduction in flame-speed ; and (iii) the subsequent re-establishment after a varying short time-interval of both "spin" and detonation with the former flame-speed.

TABLE IV—EFFECTS OF N_2-GAP UPON A DRY $2CO + O_2$ DETONATION

Time interval between opening of tap and firing of medium	First detonation-speed ; before N_2-gap	Average flame-speed in next 10 cm after N_2-gap	Lowest flame-speed after N_2-gap	Time required for re-detonation after N_2-gap	Second detonation-speed ; after N_2-gap
secs	m/sec	m/sec	m/sec	millisec	m/sec
5	1800	890	715	1·4	1790
7·5	1780	1210	845	3·0	1780
10	1795	1600	860	1·6	1785
60	1790	1800	—	—	—

As might be expected, the observed effect of the N_2-gap upon the phenomenon varied with the time allowed for "diffusion" between the opening of this disc tap and the firing of the explosive medium, being largest where this was the shortest. But in all cases, except where it was purposely lengthened to 60 seconds so as to

* As will be shown later, the forward speed of detonation in a *dry* is always greater than in a *moist* $2CO + O_2$ medium.

allow of considerable diffusion of nitrogen into the explosive medium on either side of it, both " spin " and detonation were temporarily suppressed by the gap, though subsequently re-established.

Fig. 20, Plate 5, shows the effect of the N_2-gap after an interval of 7·5 seconds between opening the disc tap and firing the explosive medium. The flame entered the picture, with well-established " spin " and detonation, at a forward speed of 1780 m/sec. On passing the gap, which is indicated by a wide, black, vertical band in the photograph, detonation ceased instantly and " spin " very soon afterwards. Some 10 cm farther on, the flame-speed had fallen to 1210 m/sec, and eventually it reached a minimum of 845 m/sec, " spin " having completely disappeared. Finally, just after the flame left the picture, and 3 millisec after it had passed the N_2-gap, re-detonation occurred, the final flame-speed being 1780 m/sec or exactly the same as at first.

Comparative Experiments with Non-Spinning $2H_2 + O_2$ *Detonations*—For comparative purposes, several similar experiments were carried out with non-spinning $2H_2 + O_2$ detonations, allowing an interval of only 2 seconds, the shortest possible, between opening the disc tap and firing the medium. But neither with a $\frac{1}{4}$-inch nor yet with a 1-inch N_2-gap could any effect upon the speed and character of the detonation be detected in the resulting photographs. Nor was the result any different when the gap was filled with a mixture of $2H_2 + N_2$ of the same density as that of the electrolytic gas on either side of it. Such negative results accord with our view that the non-occurrence of persistent spin in a gaseous detonation, such as that of a $2H_2 + O_2$ medium, implies a much more stable association of the flame-front and " shock wave " than in detonations in which " spin " is developed.

VII—" Spin " and Flame-Speeds in the Detonation of P_2O_5-Dried $2CO + O_2$ Medium

In his Bakerian Lecture of 1893,* Dixon described experiments in which he had found that successive additions of moisture, up to about 5·6% *i.e.*, saturation at 35°, to a well-dried $2CO + O_2$ medium increased its rate of detonation as shown in Table V.

Table V

Condition of medium	Steam present %	Mean rate m/sec
Well dried	—	1264
Dried	—	1305
Saturated at 10°	1·2	1676
,, 20°	2·3	1703
,, 28°	3·7	1713
,, 35°	5·6	1738
,, 45°	9·5	1693
,, 55°	15·6	1666

* ' Phil. Trans.,' A, vol. 184, p. 97 (1893).

And from these results he concluded (p. 112) that "at the extreme temperatures of the explosion wave, as well as in ordinary combustion, carbonic oxide is oxidized by the steam and not directly by the oxygen."

It should be noted, however, that in the experiments referred to, DIXON measured the "rate of explosion" not by any photographic, but only by a chronographic method which recorded the average speed of the flame between two silver bridges about 100 m apart in a lead tube about 9 mm in diameter. He evidently thought a sufficiently long run of flame between the firing-point and the first bridge had been allowed to ensure the establishment of detonation before the explosion had reached the latter; yet although the distance so allowed (usually about 3 m) probably sufficed for most of the explosive media which he examined, it would now seem as though it had not sufficed for his $2CO + O_2$ media, whether dry or moist, but particularly the former.

Although DIXON's results and conclusions were accepted as correct for upwards of thirty years, recently evidence has been accumulated, and is now conclusive, not only that carbonic oxide is directly oxidized in flames, but also, as Dixon himself admitted, that pressure favours the direct as against the indirect oxidation. Since in detonation the combustion occurs in a flame-front which is also a region of high pressure, it might even be anticipated that the presence of moisture, so far from accelerating, would even impede the combustion in a $2CO + O_2$ detonation.

The first direct experimental contradiction of DIXON's results was in a paper by CAMPBELL, WHITWORTH, and WOODHEAD,* in which it was reported that, on comparing rates for $CaCl_2$-dried with those for moist mixtures of otherwise the same composition, no difference was obtained between the dry and the moist mixtures, although similar variations in moisture content are known to have a marked effect on the initial speed of inflammation. As this was a point of considerable importance that obviously called for re-investigation, we carried out the following new experiments, the results of which are, we think, quite decisive.

Experimental Procedure—Our procedure consisted essentially in (i) establishing in the first section of our apparatus, a normalized detonation in moist $2CO + O_2$, saturated at 17°, at a uniform speed of 1760 m/sec, and (ii) allowing it to be propagated through the disc tap into a P_2O_2-dried medium in the second section, where its "spin" and speed were photographically determined. A sketch of the apparatus is shown in fig. 19, where X = the first and Y = the second section of the explosion tube, separated by the disc tap D. The second section comprised two straight, horizontal glass tubes, each 1·5 m long and internal diameter 13 mm, connected, however, by an intermediate circular copper tube 3 m long and of the same internal diameter, the two glass pieces being arranged in parallel one over the other, so that in each experiment two successive photographs of the *dry* $2CO + O_2$ detonation could be obtained as the flame traversed the two glass tubes in opposite

* 'J. Chem. Soc.,' p. 59 (1933). These authors found a mean speed of 1752 m/sec for a moist $2CO + O_2$ medium, which accords well with our 1760 m/sec for it.

directions. For it was felt that agreement between the two flame velocities, deduced from the photographs, would leave no room for doubt about a stabilized detonation having been established in the P_2O_2-dried gaseous medium.

Before each experiment the whole of the inner surfaces of the second section, Y, of the apparatus and its connections had been thoroughly dried out by means of a current of P_2O_2-dried air, the operation being accelerated by the external application of heat, which kept the tubes at about 150° C. Each section, X and Y, of the apparatus, as well as the cavity of the disc tap D, were next thoroughly evacuated. Afterwards a moist $2CO + O_2$ mixture, saturated at 17° C, was admitted to the first section and the cavity of tap D, while at the same time a

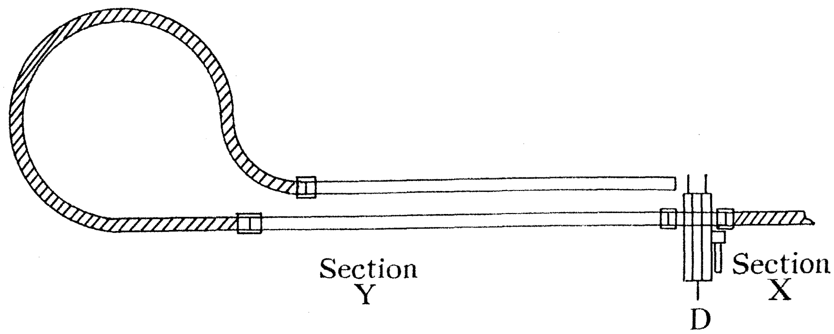


FIG. 19

P_2O_2-dried $2CO + O_2$ mixture was being filled into the second section Y, special care being taken at the end of the operations to ensure exact equalization of pressure (at atmospheric) throughout the apparatus. Finally, immediately after communication between X and Y had been made by opening tap D, and the end of section Y farthest from the firing-piece had been opened to the atmosphere, the moist $2CO + O_2$ medium in X was fired, so that its detonation, established in X, was communicated through tap D to the P_2O_2-dried $2CO + O_2$ medium in Y, where it was photographed.

Results (1)—In each and every one of five successive experiments, as the detonation passed from the *moist* into the *dry* medium its forward velocity was sensibly increased from 1760 m/sec to between 1790 and 1810, average 1802, m/sec, at which it was afterwards maintained, as the figures in Table VI show.

(2)—Besides these five experiments, at various times twenty-two other determinations were made of flame-speeds in normalized detonations in P_2O_2-dried $2CO + O_2$ media at atmospheric pressures. The values obtained ranged from 1790 up to as high as 1850, with a mean value of 1810 m/sec, the last-named average being 50 m/sec, or about 3% higher than the corresponding average rate of 1760 m/sec observed with moist $2CO + O_2$ media at the same temperature and pressure.

Fig. 21, Plate 6, resulted from an experiment in which the detonation was twice photographed during its passage through a P_2O_2-dried $2CO + O_2$ medium in the second section in the manner already described. There is a very marked

TABLE VI

	Expt		Flame-speeds during passage throughout the P_2O_2-dried $2CO + O_2$ media m/sec (1)	(2)
Flame-speed in	(i)		1805	1795
Moist	(ii)		1805	1800
$2CO + O_2$	(iii)		1810	1790
saturated at 17° C	(iv)		1790	1810
= 1760 m/sec	(v)		1810	1810
		Mean	1802	1803

" spin " in each of the two photographs, and both the forward velocity of the flame-front and the helical velocity of the " head " of detonation were slightly higher than the corresponding values observed with a moist $2CO + O_2$ medium in a tube of the same diameter under precisely the same conditions as the figures in Table VII show.

TABLE VII

Condition of $2CO + O_2$ media	Frequency of " spin " per sec	Pitch of " spin " cm	Flame-speed m/sec Forward	Helical
P_2O_2-dried	43,500	4·17	1800	2540
	44,000	4·10	1795	2565
Moist, saturated at 17° C	44,300	3·95	1750	2515

Another point that should be mentioned, probably connected with the somewhat faster forward speed of the flame, is that the " spin " in a *dry* has proved to be more stable than that in a *moist* $2CO + O_2$ detonation, as will be shown later in dealing with the influence of strong electric fields upon the phenomena.

Taken as a whole, this section of our work proves that, contrary to what has been thought hitherto, detonation in a moist $2CO + O_2$ can be quickened and rendered more stable by the total removal of moisture, a fact which constitutes another weighty addition to the rapidly growing body of experimental evidence that carbonic oxide is directly oxidized in flames, and that the presence of water vapour (or the like) is not essential to its combustion.

VIII—EFFECTS OF SUCCESSIVE ADDITIONS OF ELECTROLYTIC GAS UPON THE SPIN IN A MOIST $2CO + O_2$ DETONATION

If, as has been shown, in a moist $2CO + O_2$ detonation the flame can be quickened and the " spin " be rendered more stable by the mere removal of water-vapour from the system, it seemed likely that progressive additions of hydrogen, as electrolytic gas, should have similar effects, until finally a point should be reached when the association of the flame-front with the shock wave becomes so intimate that the instability causing "spin" disappears, so that the detonation becomes of the non-spinning $2H_2 + O_2$ type.

Accordingly, to test this, a series of experiments was carried out whereby, starting with a moist $2CO + O_2$ medium, the effects of successive additions of $2H_2 + O_2$, pure electrolytic gas, upon its detonation in a glass tube of 13 mm internal diameter were determined.

These results, which are given in Table VIII, showed that small additions of hydrogen, up to about 2·0%, had but little visible effect upon either the established "spin" or flame-speed in a $2CO + O_2$ detonation, although there was a tendency for both the frequency of the spin and the forward speed to increase. And, as will appear later, even quite small additions of hydrogen stabilize the "spin."

TABLE VIII—EFFECTS OF SUCCESSIVE ELECTROLYTIC GAS ADDITIONS UPON DETONATION IN A MOIST $2CO + O_2$ MEDIUM IN TUBE OF 13 MM INTERNAL DIAMETER

	Moist medium $2CO + O_2$ $+ x\,(2H_2 + O_2)$ x = approx.	% H_2	Frequency of established "spin" in detonation per sec	Observed average flame-speed in normalized detonation m/sec	Remarks
i	0	0	44,000	1760	In i to vii persistent "spin" always developed with tendency to multiplicity of heads of detonation with H_2 over 2%.
ii	$\frac{1}{640}$	0·1	44,000	1760	
iii	$\frac{1}{192}$	0·3	44,500	1760	
iv	$\frac{1}{64}$	1·0	46,000	1790	
v	$\frac{1}{32}$	2·0	46,500	1790	
vi	$\frac{1}{16}$	4·0	125,000	1795	
vii	$\frac{1}{8}$	8·0	170,000	1900	
viii	$\frac{1}{2}$	21·9	—	2123	In viii to xi no persistent "spin" was observed.
ix	1	32·0	—	2130	
x	2	43·9	—	2410	
xi	∞	66·6	—	2810	

Although a persistent "spin" was always observed when the H_2-content of the medium did not exceed 8%, it became progressively less distinct with successive H_2-additions, until it had completely disappeared. Also, it was noticeable that with more than 2% of hydrogen there was a tendency to multiply the number of "heads" of detonation, and, consequently, to make the "spin" more confused, and to increase its apparent frequency.

Again, although persistent "spin" was never observed with H_2-contents of 22% or more, a transient "spin," frequency about 44,000 per sec, could usually be detected just at the initiation of detonation.

Figs. 22, 23, and 24, Plates 6 and 7, show the effects upon its detonation of adding 3, 6, and 50% respectively of electrolytic gas to a $2CO + O_2$ medium. For particulars, *see* v, vi, and ix, Table VIII. The chief points to notice are (1) the evidence of a disturbed "spin" due to two heads of detonation in fig. 22, which shows two successive experiments, and (2) the complete suppression of persistent "spin" in fig. 24, although there was a transient "spin" just after the detonation had been set up. Fig. 23 shows an intermediate effect.

Effects of Small Additions of Iron Carbonyl or Calcium Chloride Dust upon a $2CO + O_2$ Detonation

At a subsequent stage of our investigation, the effects were studied of small additions of iron carbonyl, or fine calcium chloride dust, upon the normalized "spin" of a *dry* $2CO + O_2$ detonation with results such as are illustrated in fig. 25, Plate 7, $Fe(CO)_5$ and fig. 26, Plate 7, $CaCl_2$, respectively. Although in neither was there much, if any, alteration in the average forward flame-speed, in each there was a marked tendency for a "double spin" to be developed.

IX—The Influences of Magnetic and Electric Fields upon Detonation in a $2CO + O_2$ Medium

If the "head" of detonation is a localized region characterized by extreme intensity of combustion, presumably it should also be one in which considerable ionization occurs. For it has been known for more than a century that ordinary flames conduct electricity, which implies the occurrence of free ions and electrons in them. And the degree of such ionization must increase with the combustion intensity until the latter reaches its maximum in detonation.

Owing to the peculiar difficulties connected with the experimental investigation of the electrical properties of detonation flames, little has been done in regard to them. More than forty years ago, however, Turpin,* working in Dixon's laboratory at Owens College, Manchester, succeeded in showing that the electrical conductivity of the flame in the detonation of electrolytic gas far exceeds that of a steady H_2-flame and lasts for about a millisecond, or less ; and though the quantitative concordance of his experiments was perhaps not very great, there can be no doubt about their general validity.

In a discussion on Gaseous Combustion at the British Association Meeting at Sheffield in 1909,†, Sir J. J. Thomson said that as combustion is concerned not only with atoms and molecules but also with electrons, the latter might "precede the explosion wave and prepare the way for it by ionizing the gas," and therefore he suggested that, since their motions can be stopped by means of a transverse magnetic field, in which they curl up and are caused to revolve in small circles, "it would be of very great interest if Professor Dixon's experiments on the photography of the explosion wave could be repeated under such conditions as to determine whether the form of the wave could be modified by such a magnetic field."

* "Studies from the Physical and Chemical Laboratories of the Owens College," vol. I, pp. 283–95 (1893).

† 'Rep. Brit. Ass.,' Sheffield (1910), p. 510.

Accordingly, DIXON, in conjunction with CAMPBELL and SLADE, tried such experiments, the results of which were communicated to the Society in 1914.* Horizontally moving detonation flames in $2H_2 + O_2$, $2CO + O_2$, moist and dry, $C_2H_2 + 5O_2$, $C_2N_2 + O_2 + N_2$ and $CS_2 + 3O_2$ media respectively were photographed on a vertically moving film with a velocity of 40 m/sec, both before and after passing through 17 cm of a transverse magnetic field of approximately 10,000 gauss, but no visible influence of the field could be detected.

This negative result has sometimes been quoted against the supposition that free ions and electrons exist in such flames. But it can be shown that, even though they be regarded as moving forward at the high speed of the flame, a much stronger transverse magnetic field than 10,000 gauss would be required to change appreciably their movements in the wave-front. Moreover, the time during which the flame was traversing the field could not have exceeded 0·1 millisecs in any of the experiments referred to.

In 1924 MALINOWSKI† claimed to have arrested the explosion wave in a benzene-air mixture by passing it through a transverse electric field of no great intensity ; but although at the time he was unsuccessful with other explosive media, later on, in conjunction with LANROW,‡ he was able to report a slowing down, and occasional complete arrest, of the flame in similar experiments with methane, ethylene, and acetylene air media.

In 1931 LEWIS§ showed that on applying a longitudinal electric field to a stationary conical gas-flame maintained midway between the electrodes, the flame was invariably pulled towards the negative pole, indicating that the flame moves in the direction of the positive ion flow.

In 1931, also, we published‖ the results of two series of experiments upon the influence of strong electric fields upon flame propagation through intensively P_2O_2-dried $2CO + O_2$ media. In the first series, the flame entered and passed into a strong electric field from a " no-field " region, the polarity being reversed in successive experiments so that the flame entered the field across its positive or negative boundary alternately. The results showed that the conditions near the negative were much more, and near the positive pole rather less, favourable to combustion than in the " no field " region, showing that it was aided by concentration of positive, *e.g.*, $\overset{+}{CO}$ ions.

In the second series of experiments, the *dry* medium was ignited at a point mid-way between the two poles of a strong field, and the flame propagation was photographed and compared with that in a " fieldless " control-experiment with the same medium. The results proved conclusively not only how greatly the combustion was promoted by ionization of the medium, but also how much better it was maintained in the

* 'Proc. Roy. Soc.,' A, vol. 90, p. 506 (1919).
† 'J. Chem. Phys.,' vol. 21, p. 469 (1924).
‡ 'Z. Physik.,' vol. 59, p. 690 (1930).
§ 'J. Amer. Chem. Soc.,' vol. 54, p. 1304 (1931).
‖ 'Proc. Roy. Soc.,' A, vol 132, p. 1 (1931).

flame travelling towards the negative than towards the positive pole. Taken as a whole, and in conjunction with other available evidence, we regarded these experiments as strongly supporting the view that the combustion chiefly depends upon $\overset{+}{CO}$ ions.

If such a view is correct, there should be a concentration of $\overset{+}{CO}$ ions in the "spiralling" head of a $2CO + O_2$ detonation; and therefore it should be possible to disperse it and consequently to arrest the detonation by some proper application of sufficiently strong magnetic and/or electric fields. Accordingly, this was the problem we set out to solve in the following experiments.

1—Experiments with Magnetic Fields

Power Available—In order to ensure our obtaining the most powerful magnetic fields that could be made available in our circumstances, a special cable was laid from H.M. Office of Works Power Station in South Kensington direct to our laboratory, and arrangements made so that any time after the normal day main load on the station had ceased at 6 p.m., we could take off anything up to 1000 amps at 220 volts for short periods of about 5 seconds, which proved sufficient for our purpose. And with the object of exciting the strongest magnetic field by the electric power thus available, we consulted Dr. Cockcroft of the Cavendish Laboratory, Cambridge, and subsequently designed the following magnets on the lines laid down in his paper.*

Design of the Magnets—Two main points had to be borne in mind. The first was that the electrodynamic forces on the wire of the magnet coil may be very large—in exceptional cases far beyond the elastic limit of ordinary copper. The second was that the temperature of the coil should not rise during operation above the safe limit for the insulation used, and it was necessary first of all to determine the most efficient shape of coil in relation to the power available.

In order to cut down the space factor, square-section enamelled copper wire was used, and in the interests of efficiency the smallest possible internal radius for the coils was allowed.

The coils of our transverse and short longitudinal magnets, respectively, were designed for an estimated temperature rise of 30° per second, assuming a power dissipation at the rate of 110 kv amp. Later on, however, when a dissipation rate of 220 kv amp could be allowed, and the operating time cut down from 5 to 2 seconds, the design of our longer longitudinal magnet was based on a temperature rise of 50° C. per second. Details of the designs were as follows.

The short solenoid for axial field of 35,000 *gauss*, 500 *amp at* 220 *V*—The frame of this magnet, fig. 27, consisted of a $\frac{7}{8}$ in. diameter brass tube, 16 S.W.G., spun over bakelite cheeks 7 in. square and $\frac{1}{2}$ in. thick, the length between the cheeks being 8 cm. The wire used was No. 12 S.W.G. enamel with 0·002 in. enamel thickness,

* 'Phil. Trans.,' A, vol. 227, p. 317 (1928).

giving 0·113 in. square wire. There were 25 layers of 28 turns each, giving 700 turns in all. The solenoid was covered with a layer of mica, this being wrapped with six turns of spring steel and the whole tightly bound with six layers of steel wire. After the winding had been completed, the general structure was strengthened by a series of brass plates bolted on to its four sides.

Long solenoid for axial field of 22,000 *gauss*, 1000 *amp*, *at* 220 *V*—This solenoid was made on the same general lines as the first, but the length of tube between the cheeks was increased from 8 to 58 cm. There were six layers of 175 turns each, the

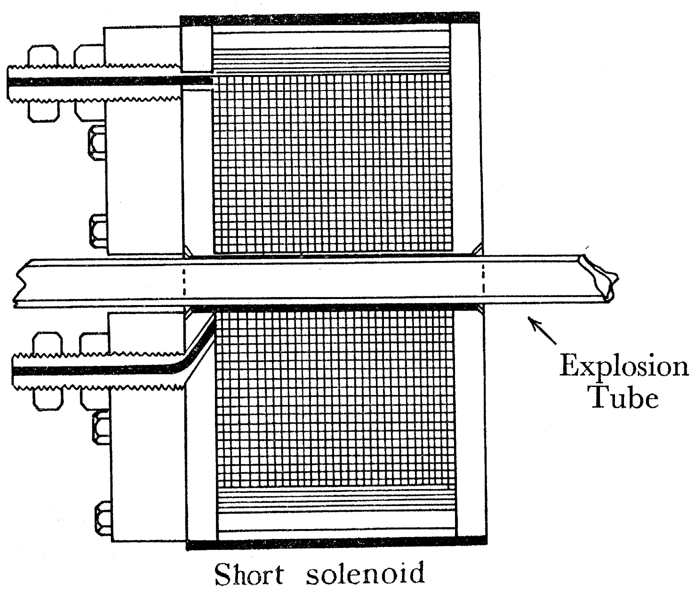


FIG. 27

wire used being No. 10 S.W.G. square section enamelled copper. This thicker wire was used in order that the power might be doubled.

Magnet producing transverse field of 35,000 *gauss*, 500 *amp*, *at* 220 *V*—In effect the transverse magnet, fig. 28, was made by building the short solenoid already described in two halves, separated by 19 mm, this being the space required for the insertion of the explosion tube. In view of the considerable magnetic attraction between the coils, they were held apart by a heavy steel yoke to which each was bolted.

Experiment with a Transverse Field

These experiments were essentially repetitions of those published in 1914 by DIXON and his collaborators, but with a much stronger field. The special section Y of our apparatus was so arranged that an already well-established "spinning" detonation in a moist $2CO + O_2$ medium was photographed while traversing a 10 cm length of the horizontal glass explosion tube, 13 mm internal diameter, to which the transverse magnetic field of 35,000 gauss, with a central core 2 cm in diameter, was applied.

Like those of Dixon, the results were all entirely negative, no visible effect of the field upon either the "spin" or the forward flame-speed of the detonation being detectable in the resulting photographs. Since, however, of the 0·057 millisec that the flame would be in the field it would be exposed to its strongest area for no longer than 0·005 millisec, our failure may be ascribed to its insufficiency, which is always the difficulty in such experiments with detonation flames.

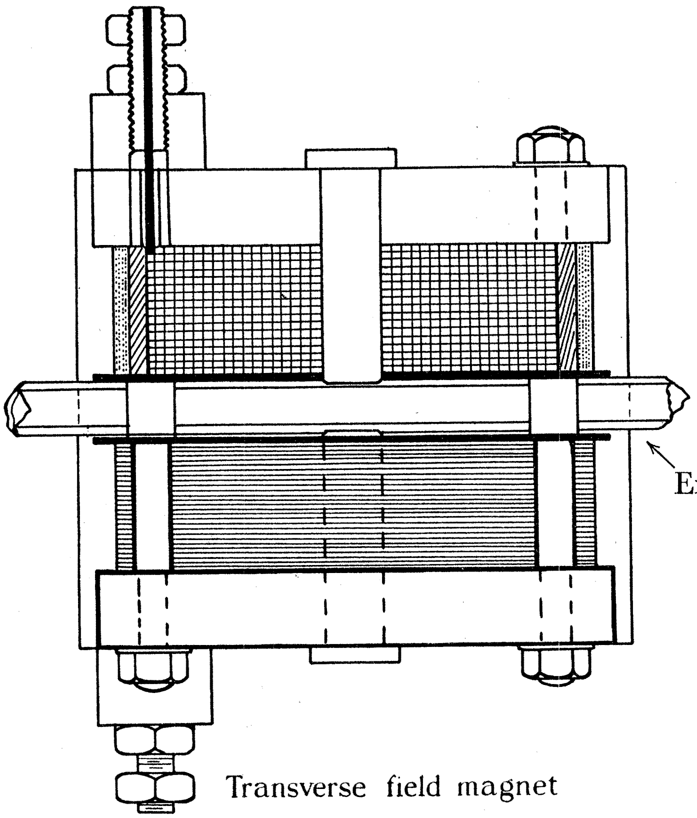


Fig. 28

Experiment with Axial Fields

We were, however, more successful in experiments with axial fields. The anticipation was that, whereas in a non-spinning detonation the motion of ions in the wave-front would be purely random, and therefore unaffected by any axial magnetic field, those of ions in a "spinning" "head" of detonation might in part be affected by its spiralling. If so, the field should have some effect upon them, for the ions could now have a resultant velocity component at right angles to the direction of the field. Consequently there should be a tendency for the ions to be driven towards either the wall or the axis of the tube, and this would cause a "drag" in the "head" of detonation; this anticipation was fulfilled.

First Series—In the first series of seven experiments, a well-established moist $2CO + O_2$ "spinning" detonation was photographed immediately *before* and *after*

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traversing the 8-cm long by 17-mm diameter field of 35,000 gauss set up by our shorter solenoid. The flame would be in the field for 0·045 millisec only. In each experiment its forward velocity was sensibly retarded by the field, the average fall in speed being from 1760 to 1720, *i.e.*, 40 m/sec, Table IX.

TABLE IX

Experiment	Flame-speed m/sec Entering	Flame-speed m/sec Leaving	Fall in field m/sec
(i)	1750	1735	15
(ii)	1760	1720	40
(iii)	1770	1720	50
(iv)	1760	1690	70
(v)	1760	1745	15
(vi)	1750	1710	40
(vii)	1765	1715	50
Mean	1760	1720	40

Second Series—In this second series of seven experiments, our longer solenoid, giving a field of 22,000 gauss, 58 cm long and 19 mm diameter, was used. The $2CO + O_2$ detonation flame would be in the field for 0·33 millisec, and again in each experiment its forward velocity was sensibly retarded by the field. The average fall in speed being now from 1760 to 1690, *i.e.*, 60 m/sec, Table X.

TABLE X

Experiment	Flame-speed m/sec Entering	Flame-speed m/sec Leaving	Fall in field m/sec
(i)	1755	1665	90
(ii)	1740	1640	100
(iii)	1750	1690	60
(iv)	1755	1680	75
(v)	1755	1720	35
(vi)	1755	1735	20
(vii)	1760	1710	50
Mean	1750	1690	60

Fig. 29, Plate 8, is a photograph obtained in the first experiment of the series, when the flame-speed was reduced from 1755 to 1665 m/sec after traversing the field. The flame is seen entering the picture at the former speed; an instant later it entered the magnetic field and disappeared from view into the solenoid. And on emerging therefrom its speed had been reduced by as much as 90 m/sec, as can be seen from the change from 38° to 36° in the inclination of its graph to the vertical, as indicated by the white lines.

Considering all the difficulties of such experiments, and especially the extremely short time that the flame was actually under the influence of the field, the quite definite retardation of the flame-speed observed in each of them, without exception, may be regarded as satisfactory proof of ionization in the "head" of detonation which, though not destroyed, was subjected to a "drag" in the field. It was evident, however, that to destroy the "head" would have required the longer application of much stronger fields than those at our disposal.

2—Experiments with Electric Fields

General Arrangements—For the following experiments the second section, Y, of our apparatus was so arranged that an electric field of any desired potential gradient from 500 to 10,000 volts per cm could be established between two electrodes situated

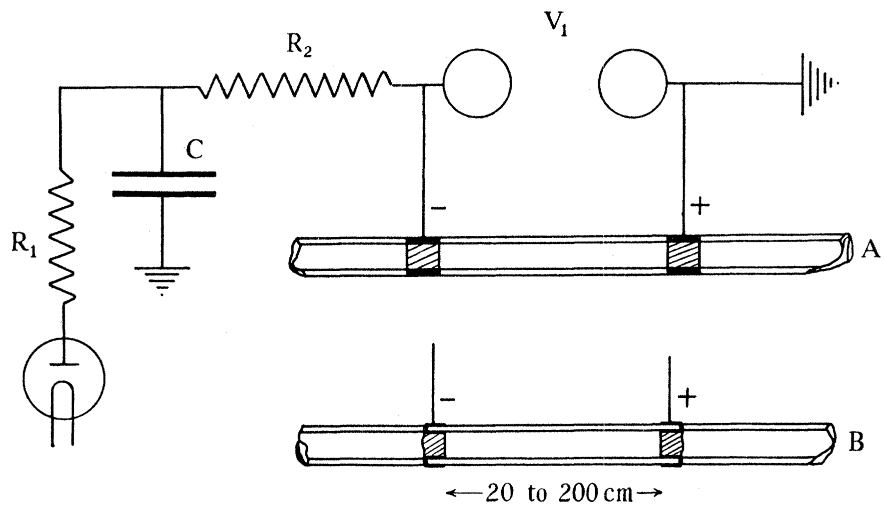


FIG. 30

from between 10 cm to 2 metres apart, according to the strength of field required. The electrodes consisted of either two silver mirrors, each 1 cm long, deposited on the inner and outer surface of the horizontal glass explosion tube, or two highly polished and accurately-ground steel cylinders inserted in series with the tube, internal diameter 13 mm, as shown diagrammatically in fig. 30. So accurately were the faces of all glass to glass and metal to metal junctions ground that a metre length of a composite tube, built up from five sections, could easily be stood up vertically on a surface plate without falling. In the actual experiment these junctions were bound round with a special tape so as to be quite vacuum tight; and many fieldless control tests proved that a "spinning" $2CO + O_2$ detonation flame could be passed through them without suffering the slightest detectable disturbance of either its "spin" or velocity, fig. 31, Plate 7, which is, perhaps, the severest test of their accuracy that could be applied. To safeguard against all possibility of error arising from any fault in the apparatus the precaution was always taken not only to begin and end each series of "field" experiments with such a control test, but also to alternate one between each successive "field" experiment throughout the series.

Apparatus—The general arrangement of the whole apparatus is also shown diagrammatically in fig. 30. A condenser, C, capacity about 0·007 μf, built so as to withstand a potential difference of well over 150,000 volts, was kept continuously charged through a kenotron diode to the required experimental potential by half-wave rectification of the output of a transformer, not shown, one end of the secondary of which was earthed. One plate of C was connected, through a high resistance R_2, about 1 megohm, to one of the field electrodes in the explosion tube, the other electrode of which was earthed. The resistance R_1, and also R_2, were included in the circuit with the object of damping out surges likely to arise in the event of the breakdown of the field. The potential in each experiment was measured by the sphere-gap voltmeter V_1. During an experiment all metal parts of the explosion tube and its connections, except the live electrode, were earthed.

Procedure—First of all, the explosion tube and its connections, including the disc tap separating sections X and Y, were thoroughly evacuated. Next the $2CO + O_2$ medium was admitted throughout up to the prevailing atmospheric pressure. Finally, when all was ready, the field was applied, and immediately afterwards the explosive medium was fired, with the camera duly in position to photograph the resulting detonation flame as it entered, passed through, and emerged from the electric field. It should also be stated that in the resulting photograph there was never any sign of a visible discharge during the passage of the flame between the electrodes.

Results. *First Series—Moist $2CO + O_2$ Detonation Flames Traversing Field in Positive to Negative Direction*

Altogether, thirty-seven successive experiments, alternated with a similar number of "no-field" controls, were made in which a well-established moist $2CO + O_2$ detonation flame traversed from positive to negative a field in which the potential gradient was set at some known point between 500 and 5750 volts per cm. Except, however, that a slight perceptible and momentary disturbance of the "spin," with slight increase in its pitch, could usually, though not always, be detected just before the flame reached the negative electrode, and that it was accompanied by a small increase, averaging 50 but never exceeding 100 m/sec, in the flame-speed, no large effects were ever observed.

Fig. 32, Plate 9, shows the results of (*a*) a "no-field" control experiment, and (*b*) an experiment with a potential gradient of 5250 to 5750 volts per cm between electrodes, the first two broad, black, vertical bands, 20 cm apart. In (*a*) the detonation flame is seen passing the electrodes quite undisturbed at an unaltered uniform speed of 1760 m/sec; while in (*b*) it is first seen traversing the field positive to negative with an enhanced velocity of 1790 which falls to 1730 and finally to

1700 m/sec after its emergence from the field. This is so typical of the other similar results obtained during this series of experiments that no further illustration of them is needed. There could be no doubt about the tendency to some acceleration of the flame during its passage through the field.

Second Series—Moist $2CO + O_2$ Detonation Flame Traversing Field in Negative to Positive Direction

Altogether forty-two successive experiments, alternated with the usual " no-field " controls, were made in which the moist $2CO + O_2$ detonation flame traversed from negative to positive a field in which the potential gradient was either 500–600, 2000, 3000–3500, or 5250–5750 volts per cm in each particular case. As will be seen from the summarized results in Table XI, both the probability and magnitude of the observed effect increased with the field intensity. There was always some disturbance of the " spin " as the flame crossed the negative boundary, but subsequent events varied, as stated below.

TABLE XI—EFFECTS ON $2CO + O_2$ DETONATION IN TRAVERSING NEGATIVE TO POSITIVE ELECTRIC FIELDS

Potential gradient	Distance apart of electrodes	Time for flame to traverse field	Total experiments	Minimum effect	Small effects	Medium effects	Maximum effect	Approximate percentage of (a) Min. Effects	Approximate percentage of (b) Max. Effects
Volts/cm	cm	millisec							
500–600	200	1·14	12	3	6	1	2	25	17
2,000	50	0·29	10	2	5	0	3	20	30
3,000–3,500	30	0·17	9	2	1	2	4	20	45
5,250–5,750	20	0·114	11	0	0	1	10	Nil	90
Totals	—	—	42	7	12	4	19	—	—

(*a*) *Minimum Effect*—In altogether 7 out of the 42 experiments nothing more was observable than a slight momentary disturbance of the " spin " just as the flame entered the field, such disturbance being unaccompanied by any measurable change in the forward flame-speed. The proportion of such cases, however, tended to diminish as the field intensity was raised, and disappeared altogether at its maximum strength.

(*b*) *Small Effects*—In 12 out of the 42 experiments, there was, in addition to a momentary disturbance of the " spin," a fall of between 50 and 100 m/sec in the flame-speed while traversing the field, normal conditions being speedily re-established on emergence therefrom. With one exception, all such results were confined to the two lower field intensities employed, at each of which they constituted half the total results obtained.

(*c*) *Medium Effects*—In 4 out of the 42 experiments, there was a decided disturbance of the " spin " accompanied by a fall of 150–350 m/sec in the flame-speed while traversing the field ; but recovery was always rapid on emergence therefrom.

(*d*) *Maximum Effect*—In the 19 remaining experiments, including all but one of the 11 in which the field potential exceeded 5000 volts per cm, very large effects were observed. For not only were both the " spin " and the detonation itself entirely suppressed as soon as the flame entered the field—the flame-speed falling from 1760 to about 900 m/sec in the field—but there was no recovery on emergence therefrom until upwards of 2 metres run after the flame had passed out of the region photographed. Figs. 33, 34, and 35, Plates 9 and 10, will suffice to illustrate the effects referred to.

Fig. 33 shows the one medium effect observed during the 11 experiments with the highest potential gradient. The flame is seen entering the picture with a velocity of 1760 m/sec and a well-developed " spin." Immediately after crossing the negative electrode, the spin was markedly upset, and the flame-speed fell to 1430 m/sec while passing through the fields. Immediately after emerging therefrom, however, re-detonation occurred, with restoration of its " spin," the flame finally leaving the picture with a velocity of 1745 m/sec.

Figs. 34 *and* 35 show the maximum effect observed in all but one of the 11 experiments with the highest field potential. In each case the flame entered the picture with a velocity of 1735 (or 1790) m/sec respectively and a well-marked normal " spin." As it nearly approached the negative electrode, both the pitch of the spin and its forward velocity momentarily increased. Immediately on passing the negative electrode, however, both " spin " and detonation were completely suppressed with rapid fall in the flame-speed until, on reaching the positive electrode, it had fallen to 1035 (or 982) m/sec ; subsequently, it continued to fall until, on leaving the region photographed in fig. 34, it was no more than about 850 m/sec.

Fig. 36, *Plate* 11—*Special Experiment*—Further to illustrate this part of the investigation, this very striking photograph, obtained during a specially designed experiment, is reproduced because it comprises all the features so far observed. A $2CO + O_2$ detonation is seen entering across a positive boundary into a positive to negative potential gradient of 2000 volts per cm, throughout which its speed was maintained at 1750 m/sec with a normal spin. On crossing the negative boundary it entered a second field with a negative to positive potential gradient of 5000 volts per cm, extending over 20 cm; immediately its "spin" was markedly upset, and the flame-speed fell to about 1500 m/sec. Finally, soon after passing the second positive boundary into a " no-field " region, re-detonation occurred with re-establishment of " spin," the flame-speed on leaving the region photographed being as high as 1850 m/sec.

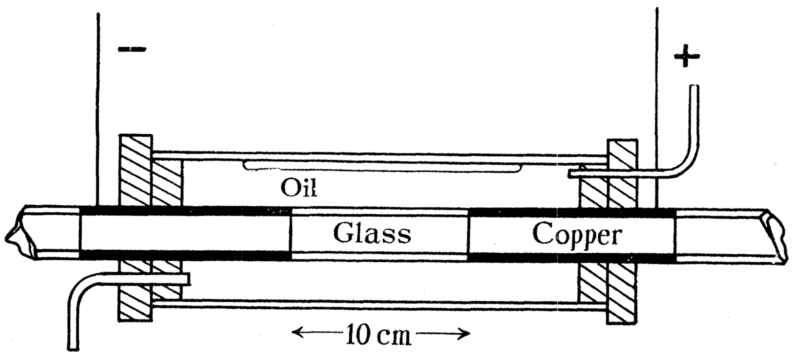
Third Series—Upon the Stabilization of " Spin " in a $2CO + O_2$ *Detonation Produced by either Drying the Medium or Adding Hydrogen Thereto*

Before concluding this part of our memoir, reference should be made to some remarkable effects upon the stability of the spin in a moist $2CO + O_2$ detonation produced either by drying the medium or by adding hydrogen to it.

(*a*) *Fig.* 37, *Plate* 12—*Enhanced Stability of* " *Spin* " *in a* P_2O*-dried* $2CO + O_2$ *Detonation*—In the course of our experiments, it has been found that the stability of the " spin " in a moist $2CO + O_2$ detonation may be so enhanced by drying the medium that a comparatively short P_2O_5-drying, 4 days, sufficed completely to counteract the damping influence of passing from negative to positive through a field of potential gradient of 10,000 volts per cm.

(i) We had previously found that the comparatively moderate degree of drying by some day's contact with calcium chloride had no great effect in stabilizing the " spin " of a $2CO + O_2$ detonation when traversing in a negative to positive direction a field of 5000 volts per cm potential gradient ; for in two out of these experiments results were much the same as with a moist medium, although in the third one only a small effect was obtained.

(ii) After the $2CO + O_2$ medium had been subjected to a four-days P_2O_5-drying, however, the application of a negative to positive potential gradient even as great as



Section Y

Fig. 38

10,000 volts per cm had no measurable effect upon either the " spin " or the flame-speed in any one of six experiments. The results of two successive experiments are shown in fig. 37. In each the flame appears to have been somewhat dimmed in passing through the electric field, but this is solely due to the fact that, in order to obtain so strong a field, the portion of the explosion tube between the electrodes had to be surrounded by an oil-bath, fig. 38, the liquid in which absorbed part of the radiation from the explosion flame. We think the stabilizing influence of the drying upon the " spin " and detonation thus revealed may be ascribed to the greatly enhanced radiation from the " dry " flame-front which was clearly evidenced by the greater density of the negative of the resulting photograph under our standard conditions of development.

(*b*) *Fig.* 39, *Plate* 12—*Enhancement of Stability of* "*Spin*" *in a moist* $2CO + O_2$ *Detonation by Small* H_2*-additions*—That the stability of the " spin " in a moist $2CO + O_2$ detonation can also be enhanced by small additions of hydrogen to the medium was proved in a series of fifteen experiments in which the flame was made to traverse in a negative to positive direction an electric field of 5000 volts per cm potential gradient. Addition of only 0·1% of hydrogen to the medium had hardly any stabilizing effects upon the " spin " ; but when 0·3% or more of hydrogen was present, such effect was always in evidence, and usually to the extent of completely counteracting what otherwise would have been the steady " damping " influence of the field.

Fig. 39 shows, by comparison with fig. 34, how much " spin " of a moist $2CO + O_2$ detonation was stabilized against the damping influence of a negative to positive field of 5250 volts per cm potential gradient by the addition of only 0·3% of hydrogen to the medium.

Fourth Series—Effects of Electric Fields upon a $CH_4 + O_2$ Spinning Detonation

Hitherto we have dealt with the case of a $2CO + O_2$ " spinning " detonation which is characterized by a comparatively low flame-speed of 1760 m/sec, and marked instability of the association between the highly radiating flame-front and the "shock wave" immediately ahead of it. It therefore seemed of importance to examine also the case of a $CH_4 + O_2$ explosion. The peculiar interest of this lies in the fact that, while a pronounced " spin " is developed even during the pre-detonation stage at flame-speeds exceeding 1200 m/sec with a frequency of about 68,000 per second in a tube of 13 mm internal diameter, on detonation the frequency is abruptly increased to about 110,000 per second with concurrent abrupt increase in the flame-speed to about 2600 m/sec. Also in such detonation a " double spin " (due to two spiralling " heads ") may also be developed.

According to our view of detonation, this would betoken a less attenuated flame-front and closer association between it and the "shock wave" than in a $2CO + O_2$ detonation. And this has been borne out by our observations upon the efforts of electric fields upon a $CH_4 + O_2$ detonation. For in eight different experiments in which it was caused to pass through a field of 3500 volts per cm—namely five in the negative to positive and three in the positive to negative direction—no measurable effect, other than a slight disturbance of the spin in approaching the negative electrode, was observed.

Fig. 40, Plate 12, shows a $CH_4 + O_2$ detonation entering the region photographed with a " spin " of 120,000 per second and flame-speed of 2600 m/sec, subsequently passing through 30 cm of a negative to positive field of potential gradient 3500 volts per cm without suffering any perceptible alteration in its " spin " or flame-speed.

Discussion

Reviewing the results of the electric field experiments as a whole, undoubtedly their outstanding feature was the proof afforded that while the flame of a *moist* $2CO + O_2$ detonation never suffered more than a slight momentary disturbance in traversing in a positive to negative direction a field of any potential gradient up to 5750 volts per cm—the highest employed—and that in such circumstances there was always a tendency to increase the forward flame-speed, it was always possible to effect a total suppression of both " spin " and detonation merely by reversing the polarity of the field traversed. Moreover, it seemed that whenever the flame crossed a negative boundary into a negative to positive field, its " spin " was abruptly upset, and that the probability of this being followed by its total suppression, and with it detonation also, so increased with the potential gradient that at about 5000 volts per cm it became practically a certainty.

Such a result is in general agreement with the view that the spiralling " head " of detonation is a localized intensive combustion due to a concentration of $\overset{+}{CO}$ ions and free electrons, the speed of combustion primarily depending on the former, and that the " detonation " is a comparatively unstable association of a radiating flame-front with a " shock wave " immediately ahead of it. For, if such were so, the effects of a strong electric field upon a flame traversing it in a positive to negative direction would be to drive electrons backward out of the " head " of detonation and to pull positive ions into it, with consequent stabilization of the " spin " and some increase in the forward flame-speed. On the other hand, in the reverse case, when the flame traverses an electric field in a negative to positive direction, not only would $\overset{+}{CO}$ ions be driven backwards out of the head of detonation but also electrons would be pulled forward into the region immediately ahead of the flame, until with a sufficient diminution of the concentration of positive ions and electrons in the " head," detonation would be suppressed, with consequent fall in flame-speed. In other words, while passage through an electric field in a positive to negative direction tends to stabilize both spin and detonation in a moist $2CO + O_2$ medium, a reversal of the direction of the field tends to suppress them. In the former condition, the stabilizing effect may be likened to that of either drying the medium or adding a small quantity of hydrogen to it—both of which quicken the combustion ; and in the latter case the suppressing effect may be compared with that of either a narrow tube or a N_2-gap in damping it down. And it would seem as though in a moist $2CO + O_2$ detonation the association of its two components is so near the border line of stability that it is liable to be much affected by comparatively small changes in either favourable or adverse conditions.

The great disparity between the effects upon a moist $2CO + O_2$ detonation observed on reversing the direction of an electric field through which it is passed may also, we think, be ascribed to the instability referred to. Because, whereas the least real dissociation of the two components of such detonation during its passage from negative to positive through a field of requisite intensity should, according to our view, suffice to destroy the conditions essential to detonation, with consequent considerable damping of the flame-speed, a reversal of the direction of the field, while exerting an equal but opposite effect upon the association of the two components, would only result in a comparatively small increase in the observed forward flame-speed. For on such reversal the unstable association of the two components of the detonation would merely be somewhat strengthened instead of being dissolved as in the former case. Indeed, so viewed, the seeming disparity is no more than might be expected in the circumstances.

Another point calling for comment is the undoubted uncertainty of the magnitude of the damping observed when a moist $2CO + O_2$ spiralling detonation was passed through a negative to positive field of given strength, except at the highest potential gradient employed. All that can be suggested at present is that, according to all the evidence in our possession, since the decisive part of the effect upon the "head" of detonation was always an abrupt and instantaneous happening just as the head crossed the negative boundary of the field, then if it happens to cross this boundary at some point which was already a point source of leakage the "head" would pass through the steep cathode fall of potential. The chances of this happening would increase with the field strength.

It has been fortunate for the elucidation of the phenomenon that the association of the two components of a moist $2CO + O_2$ detonation has proved so peculiarly unstable. Because its instability has enabled the dual character of a gaseous detonation to be experimentally demonstrated by means which otherwise could scarely have been successful; and although more remains to be done before the transition from an unstable spinning through a stabilized spinning to a non-spinning type of gaseous detonation can be fully explained, we regard our present investigation as affording substantial evidence of the dual character of all three types and therefore providing a new point of view from which future investigation may be directed.

In conclusion, we desire to acknowledge our indebtedness to the Royal Society for repeated grants from the Messel Fund towards the heavy expenses of the work; to Messrs. Nobels (I.C.I.), Ltd., for meeting the cost of making the high-speed mirror camera used and for annual supplementary grants; and to the Right Hon. VISCOUNT WAKEFIELD OF HYTHE for a donation which enabled one of us (W. H. W.) to continue his association with the work after the expiration of his Beit Fellowship in 1932.

X—SUMMARY

This paper embodies the principal results of the authors' further investigation of the phenomenon of "spin" in detonation since their previous paper in 1932. A description is given of the new Fraser high-speed mirror camera, which has enabled the accurate measurement of flame-speeds occurring in as short a time as one-millionth of a second, and some 29 typical photographs of detonation phenomena are reproduced in illustration of the principal new results obtained.

A new view of the detonation-wave in gaseous explosions is advanced. For it can no longer be regarded as simply a homogeneous "shock wave," in which an abrupt change in pressure in the vicinity of the wave-front is maintained by the adiabatic combustion of the explosive medium through which it is propagated; but it must now be viewed as a more or less stable association, or coalescence, of two separate and separable components, namely of an intensively radiating flame-front with an invisible shock wave immediately ahead of it; and whether persistent "spin" is developed or not depends upon the stability or otherwise of their association.

According to the new view, detonation in an explosive gaseous medium is the propagation through it, as a wave, of a condition of intensive combustion, initiated

and maintained in a shock wave by radiation from an associated flame-front ; and that " spin " ensues whenever the conditions are such that the radiation from an attenuated flame-front causes a localized intensive excitation of molecules in the "shock wave" just ahead of it. The resulting " head " of detonation, in which an intensive combustion is thus localized, then begins to rotate in the medium, eventually pursuing a spiral track along the tube quite close to its walls. There is, however, no rotation of the medium as a whole, but only of such a " head," or perhaps " heads," of detonation.

Moreover, if upon such a " spinning " detonation influences are brought to bear which will in any way destroy the spinning " head," not only does the " spin " itself cease, but separation of the flame-front from the associated " shock wave " also occurs so that the flame-speed falls and detonation ceases. The phenomenon can be and is re-established as soon as the distance between the detached, but still radiating, flame-front and its formerly associated " shock wave " becomes, from any cause, sufficiently reduced to enable the radiation to restore the former condition.

The experimental part of the work has been mainly concerned with detonations in a moist $2CO + O_2$ medium, which has proved to be specially adapted to the elucidation of the dual character of the phenomenon. And the chief features dealt with are (1) the influence of varying cylindrical tube-diameter upon flame-speed and frequency of spin, including the separation of the two components of the detonation near the limiting diameter below which it is altogether suppressed ; (2) the influence of tube shape, including tubes of triangular, square, and oblong cross-sections, upon the phenomenon, in which it is shown that in the two former types the head of detonation pursues a spiral track close up to the walls, of a pitch very nearly equal to that which would have occurred in a tube of circular section with periphery equal to that of the triangle or square, respectively ; (3) the suppression of a spinning detonation by means of a short nitrogen-gap ; (4) "spin" and flame-speeds in the detonation of a P_2O_5-dried $2CO + O_2$ medium, in which it is shown that the drying process both increases the flame-speed and stabilizes the spin ; (5) effects of small additions of hydrogen, iron carbonyl, etc., upon the "spin"; (6) the influences of magnetic and electrical fields upon the phenomenon.

In regard to the last named it is shown that the flame-speed of a moist $2CO + O_2$ detonation is sensibly reduced in passing through a powerful axial magnetic field, and that both " spin " and detonation can be entirely suppressed when the detonation traverses, in a negative to positive direction, a sufficiently strong electric field, the spin being abruptly upset just as it crosses the negative boundary of the field.

Description of Plates

Fig. 5—Initiation of detonation in a moist $2CO + O_2$ medium.

Fig. 7—Normalized spinning detonation in a moist $2CO + O_2$ medium.

Figs. 9, 10, 11—Shadow photographs of compression waves, etc.

Fig. 13—Intermittent detonation in a moist $2CO + O_2$ medium in narrow tube, internal diameter 3·6 mm.

FIG. 14—Comparison of spinning detonation in a moist $2CO + O_2$ medium in tubes (*a*) 4·5 and (*b*) 12·8 mm internal diameter, respectively.

FIGS. 15 to 18—Moist $2CO + O_2$ detonations in tubes of triangular, square, and oblong cross-section respectively.

FIG. 20—Effect of N_2-gap in damping an established $2CO + O_2$ detonation.

FIG. 21—Detonation in a P_2O_5-dried $2CO + O_2$ medium.

FIGS. 22, 23, 24—Effects of additions of electrolytic gas upon a moist $2CO + O_2$ detonation.

FIGS. 25, 26—Effects of additions of iron carbonyl and calcium chloride respectively on a $2CO + O_2$ detonation.

FIG. 29—Influence of axial magnetic field upon a moist $2CO + O_2$ detonation.

FIG. 31—$2CO + O_2$ detonation, control experiment.

FIG. 32—Influence of a positive to negative electric field upon a moist $2CO + O_2$ detonation.

FIGS. 33, 34, 35, 36—Influence of a negative to positive electric field upon a moist $2CO + O_2$ detonation.

FIG. 37—Stabilizing influence of a negative to positive electric field upon detonation in a P_2O_5-dried $2CO + O_2$ medium.

FIG. 39—Stabilizing influence of a small H_2-addition upon a moist $2CO + O_2$ detonation.

FIG. 40—Spinning detonation in a CH_4-$+ O_2$ medium passing through a negative to positive electric field.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

FIG. 5

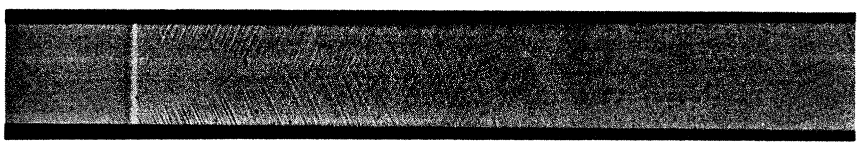


FIG. 9

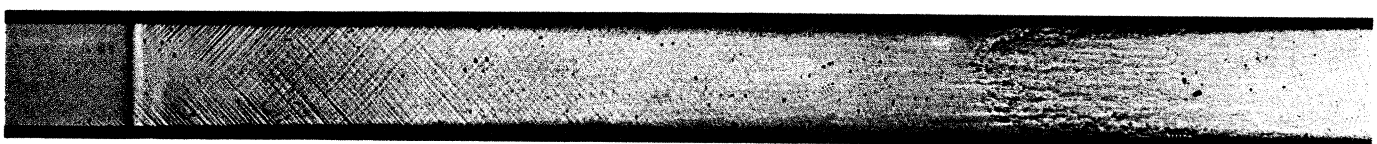


FIG. 10

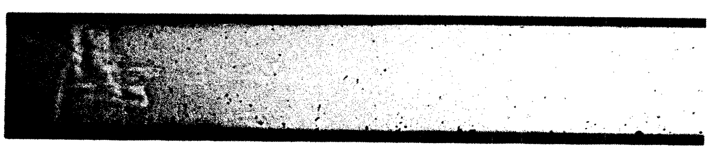


FIG. 11

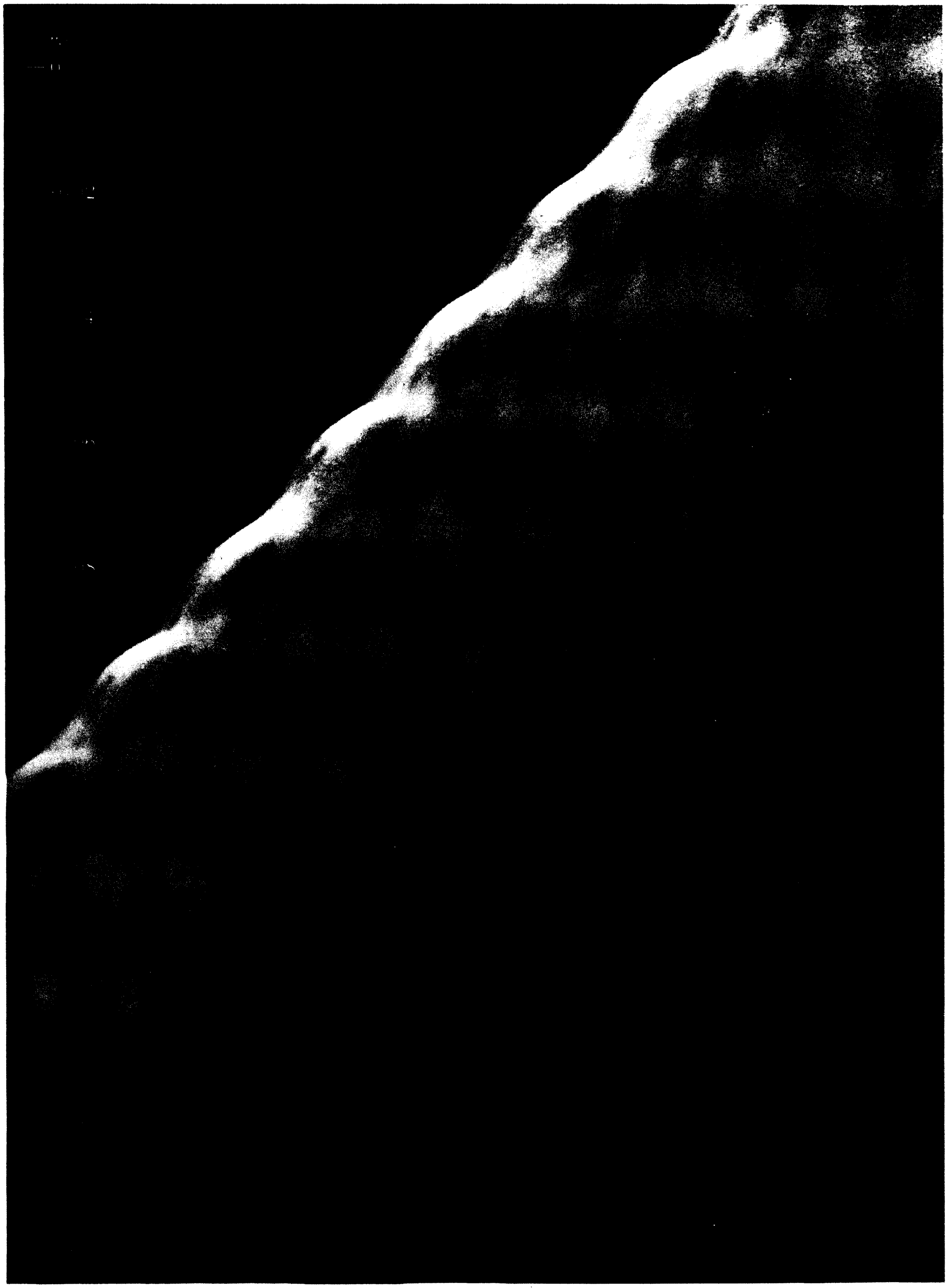
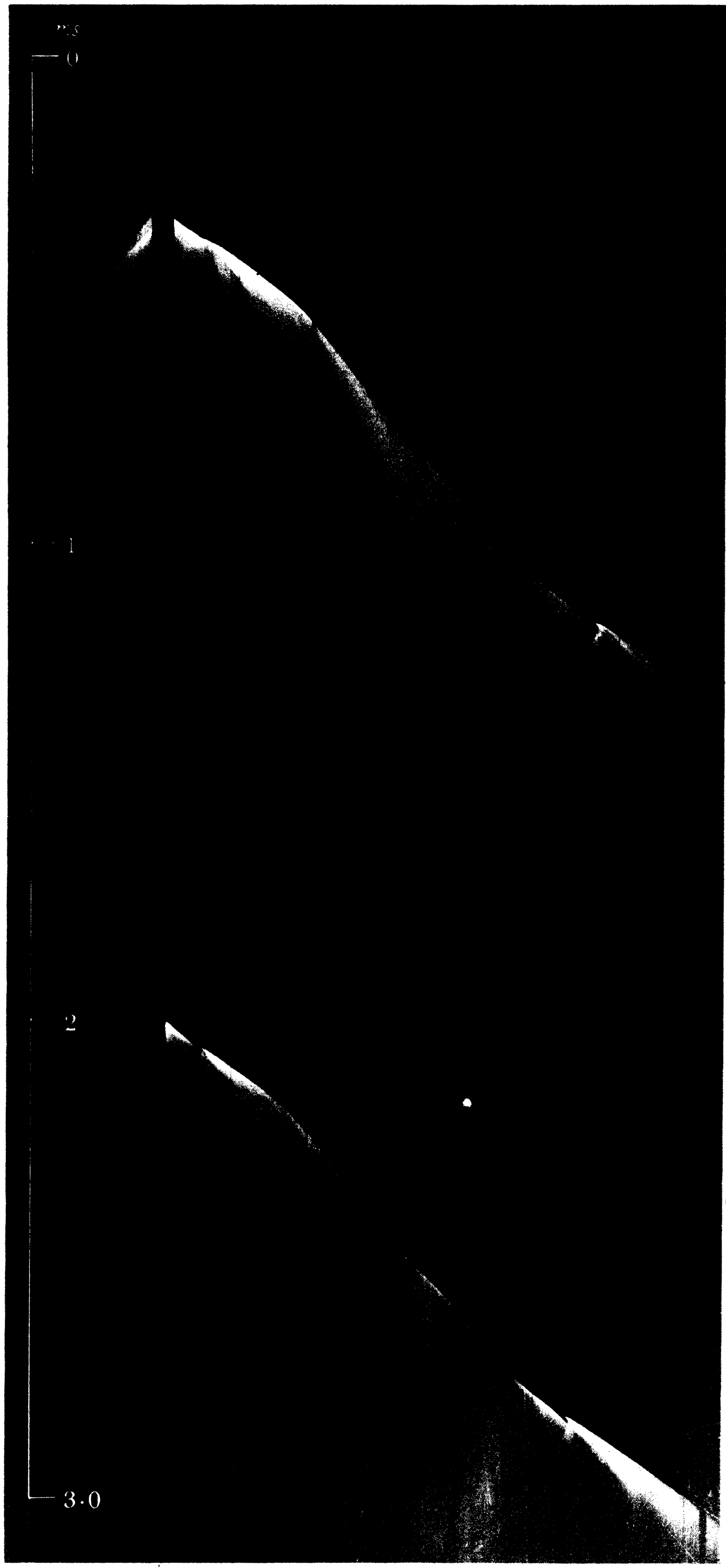


FIG. 7

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES



(*a*)

(*b*)

Fig. 13

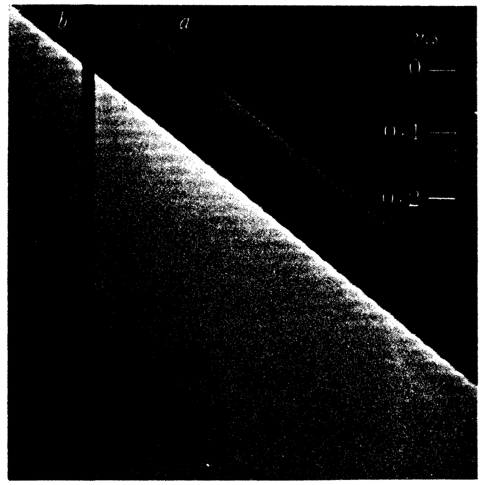


Fig. 14

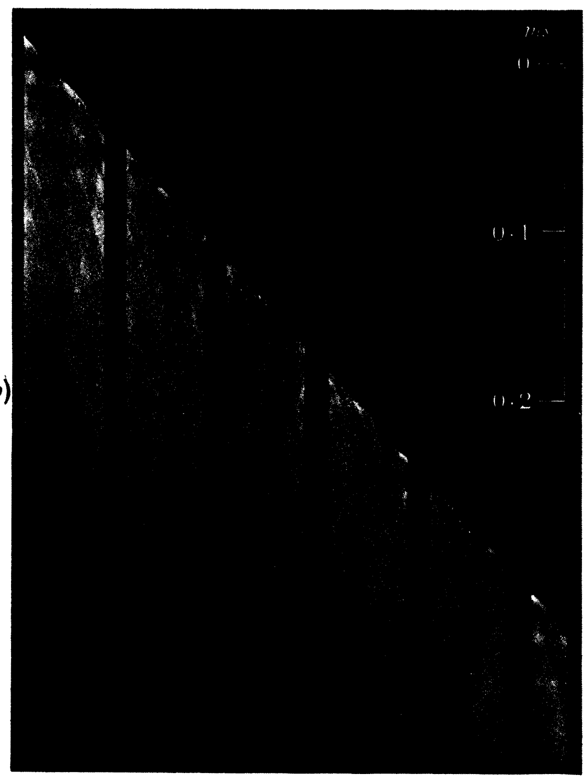


Fig. 15

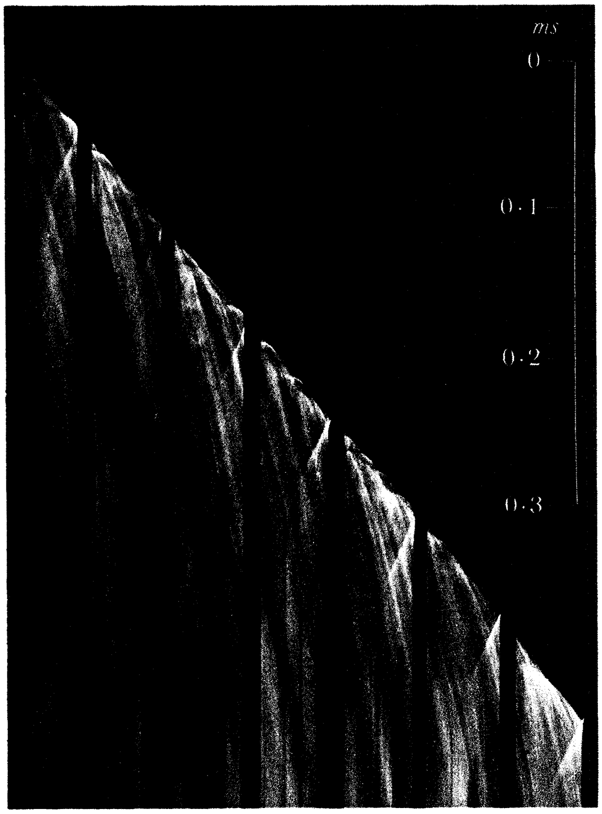


FIG. 16

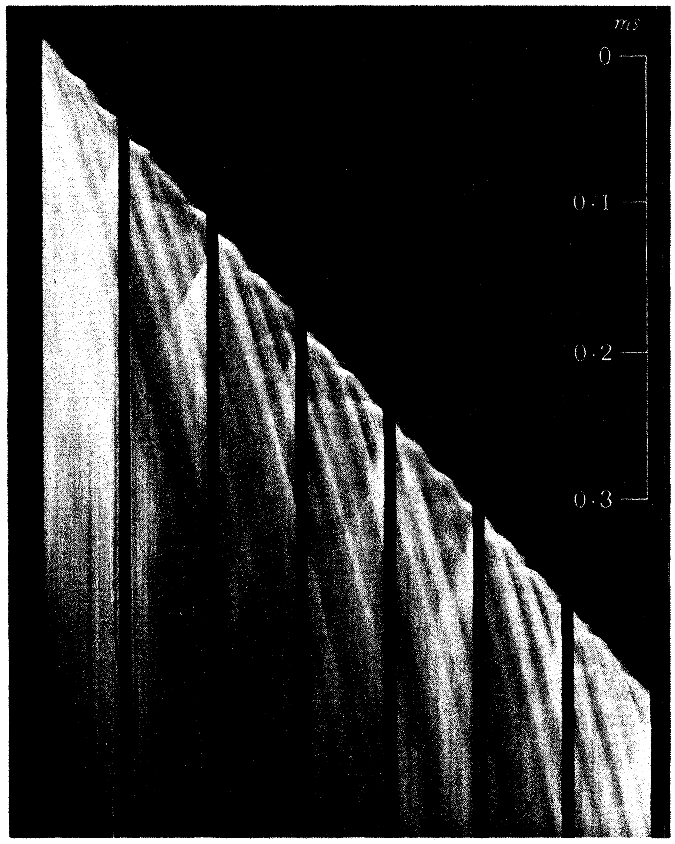


FIG. 17

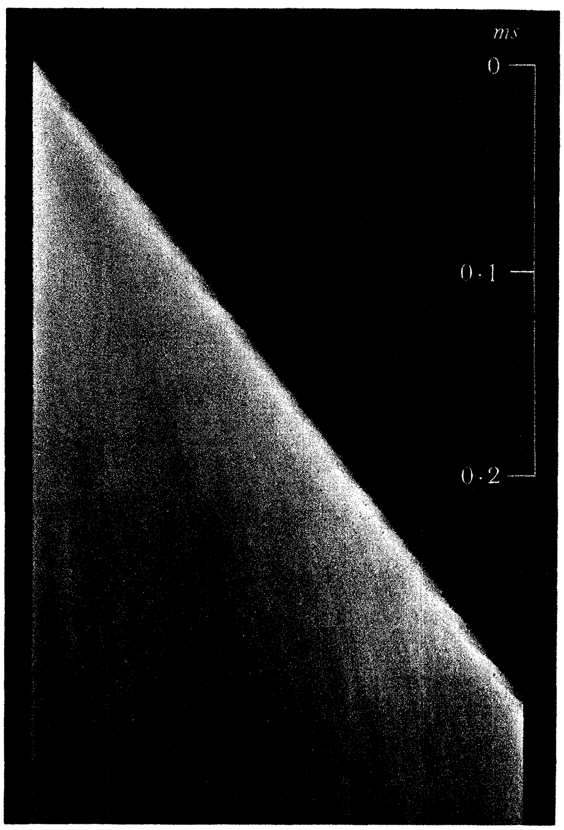


FIG. 18

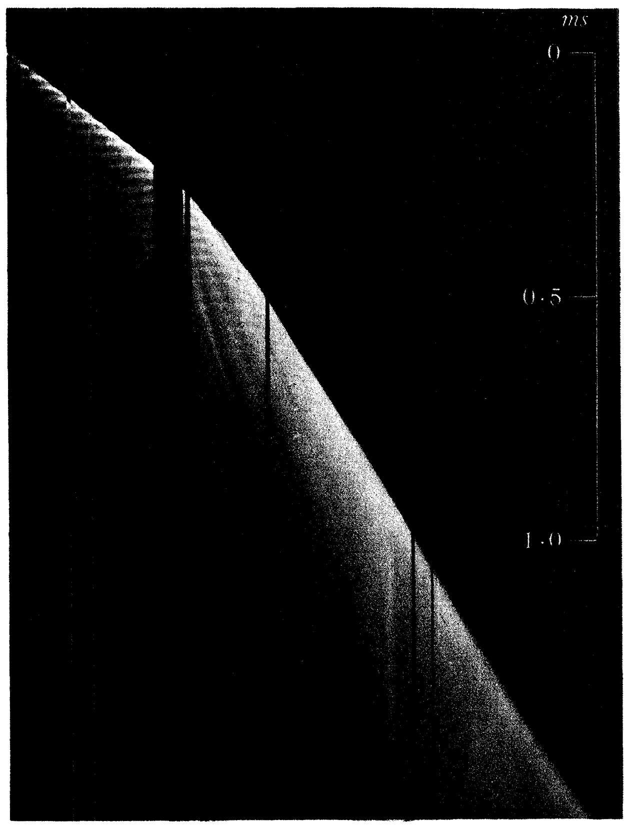


FIG. 20

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

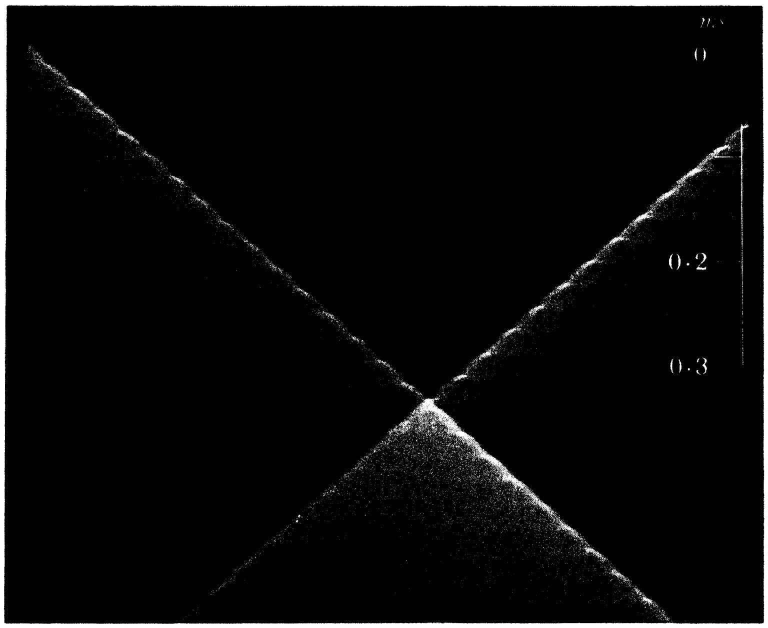


Fig. 21

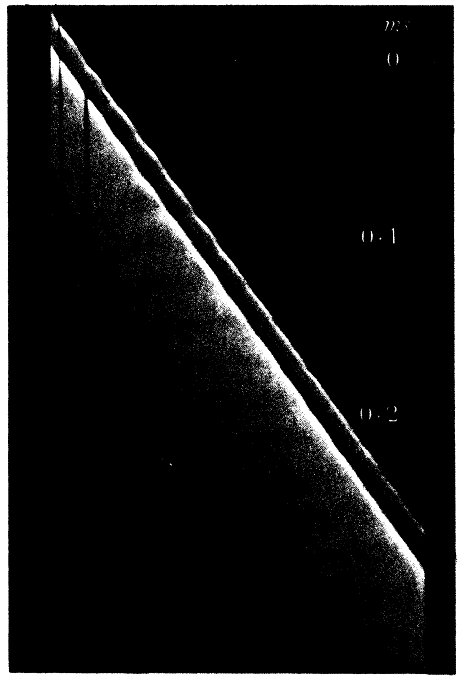


Fig. 22

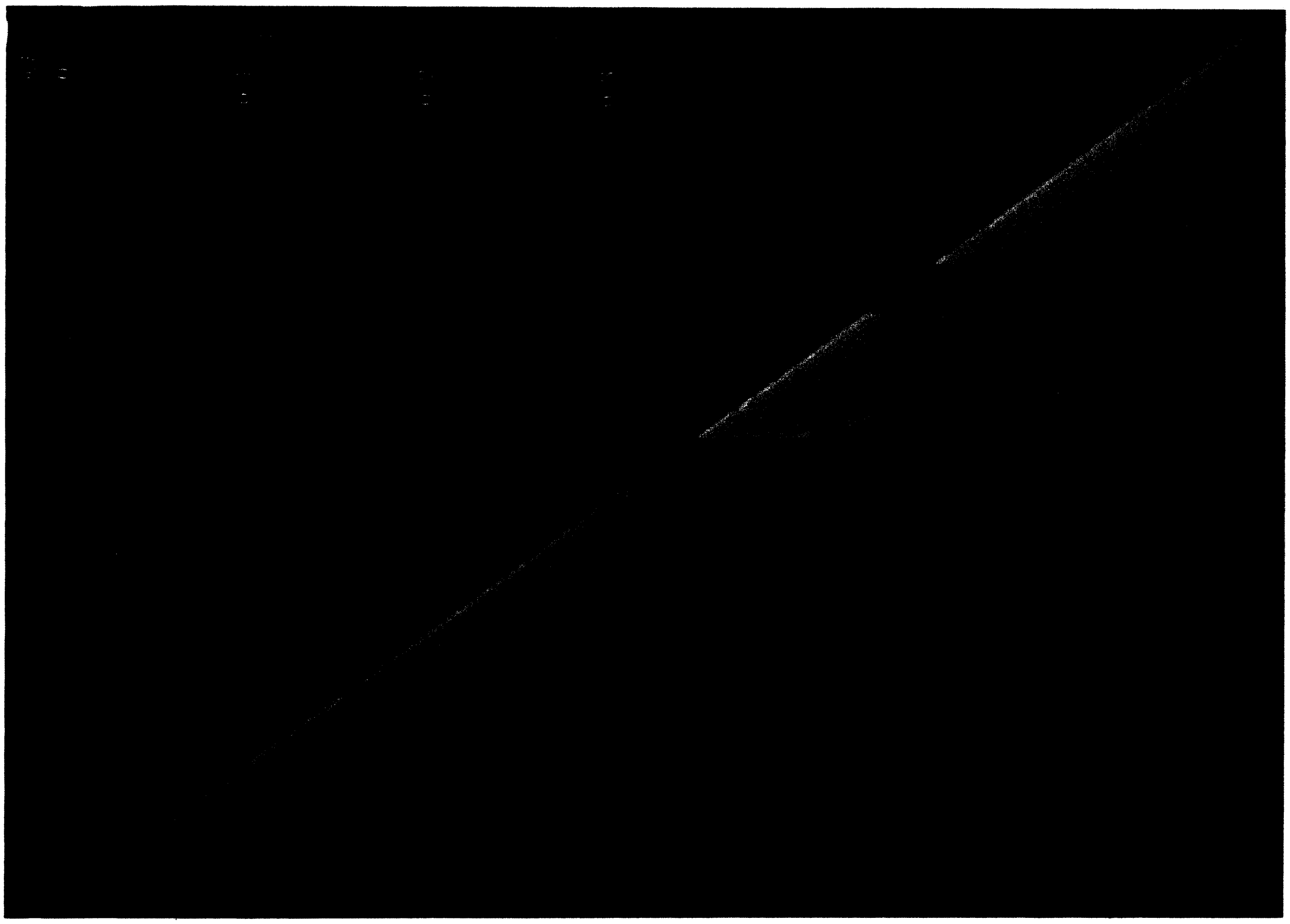


Fig. 23

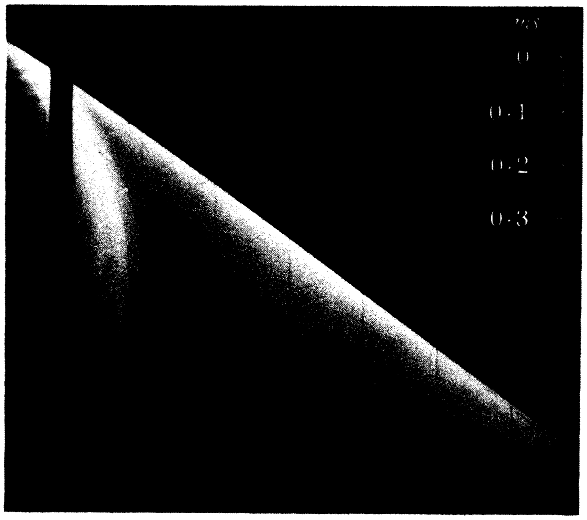


Fig. 24

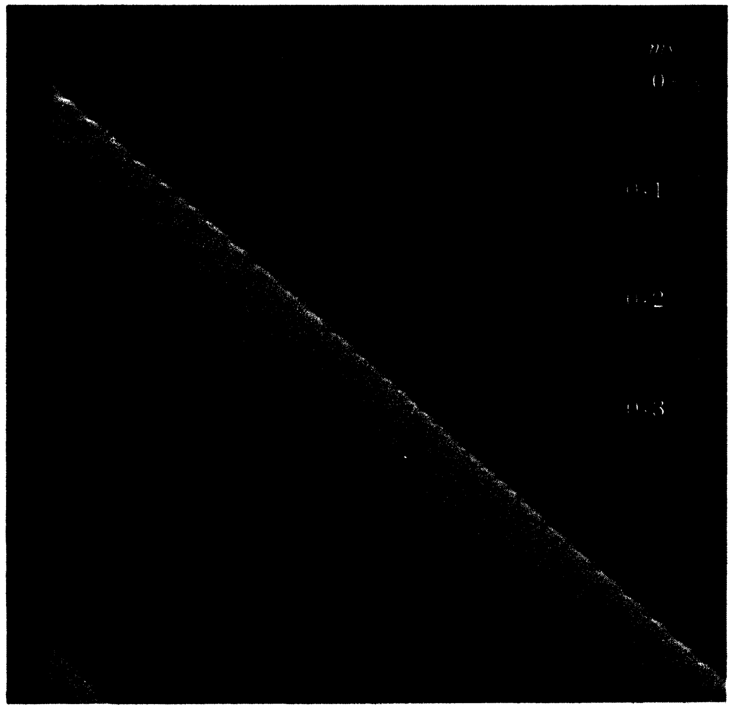


Fig. 25

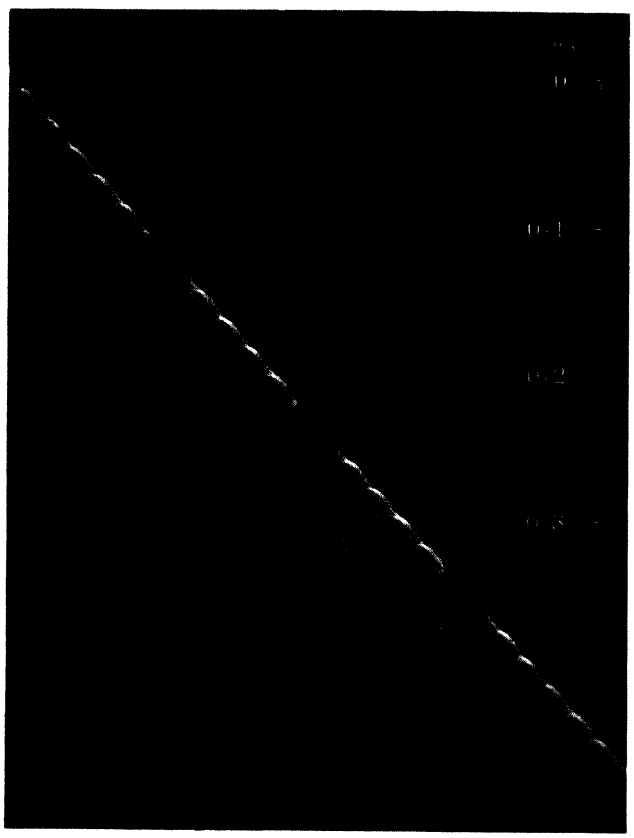


Fig. 31

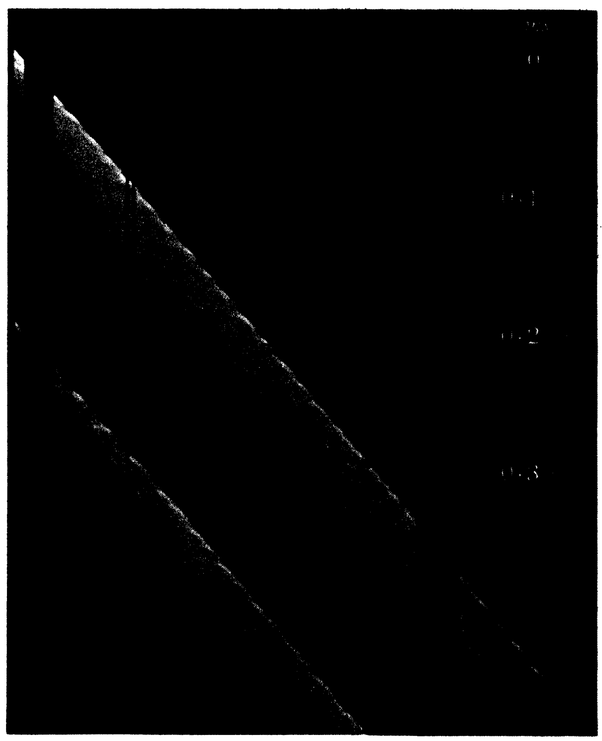


Fig. 26

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

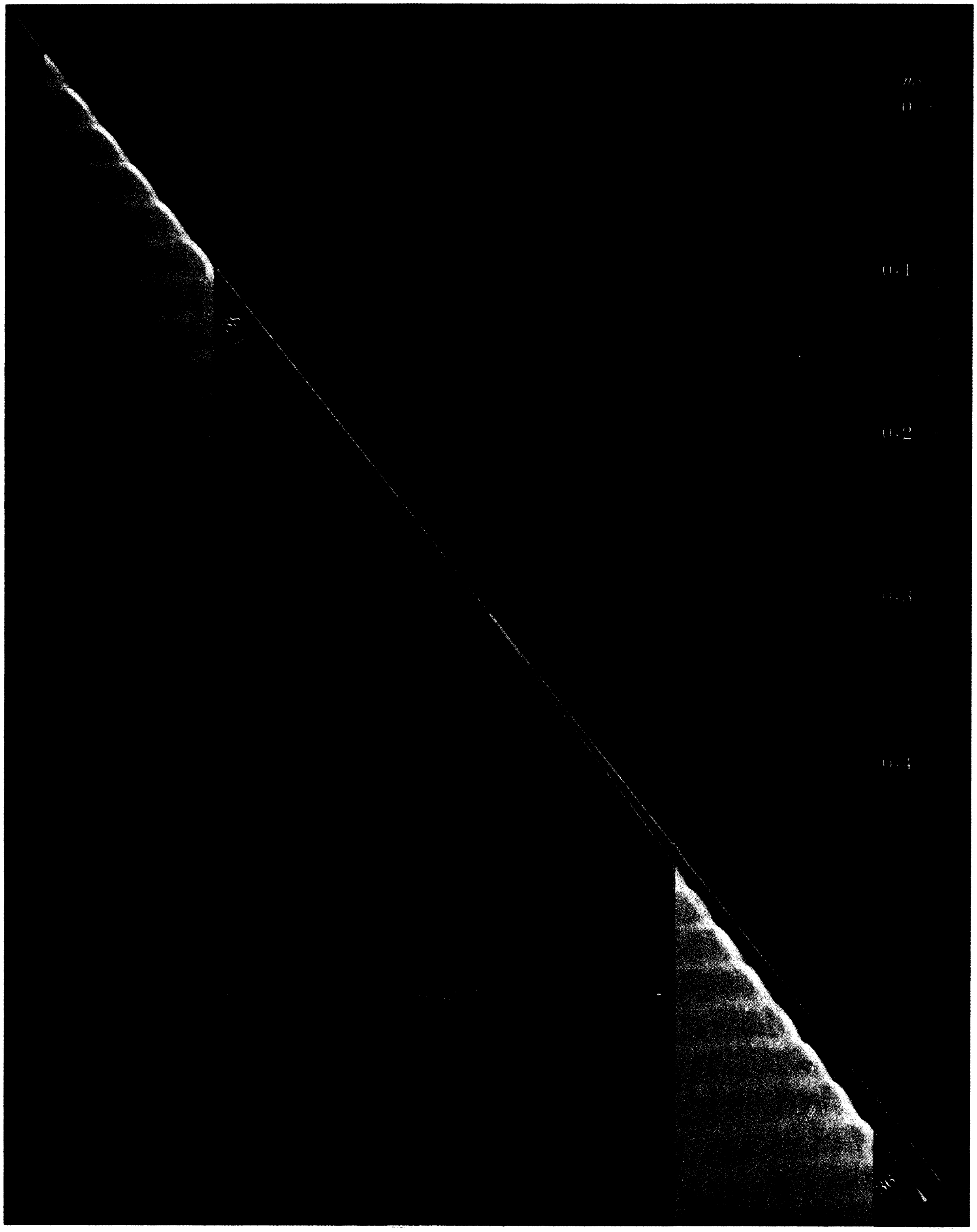


Fig. 29

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

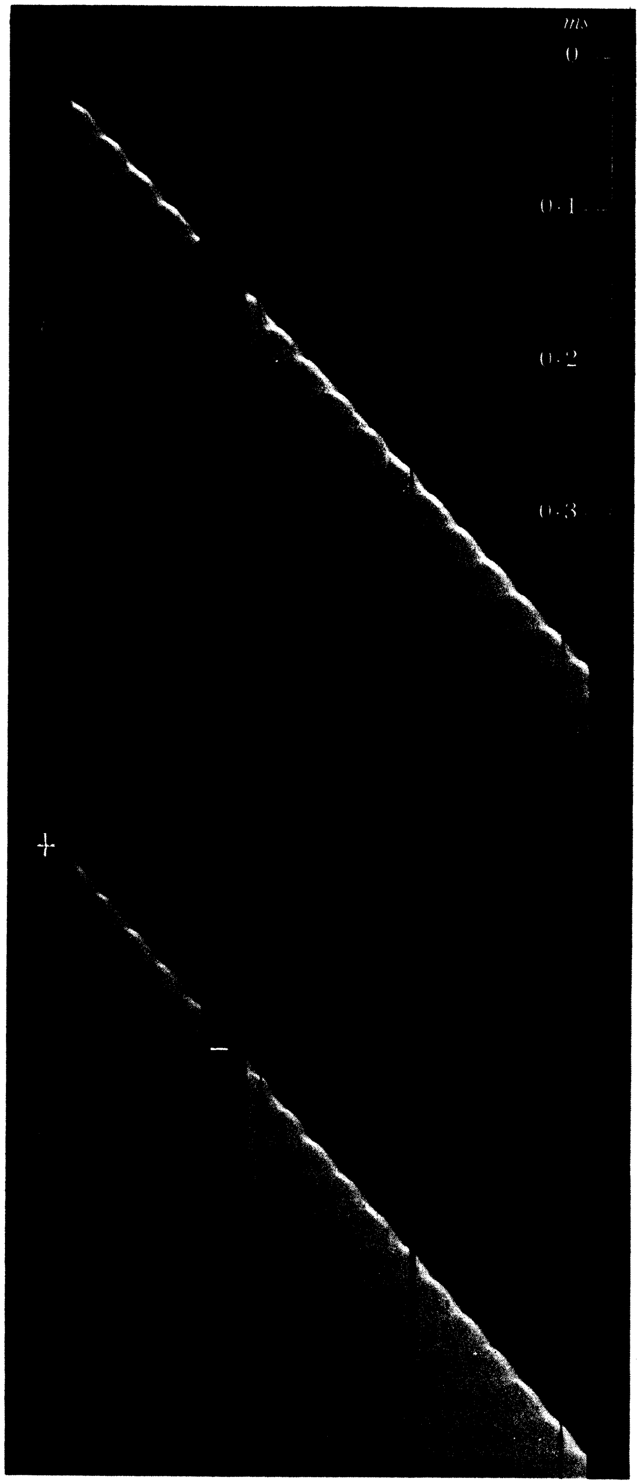


Fig. 32

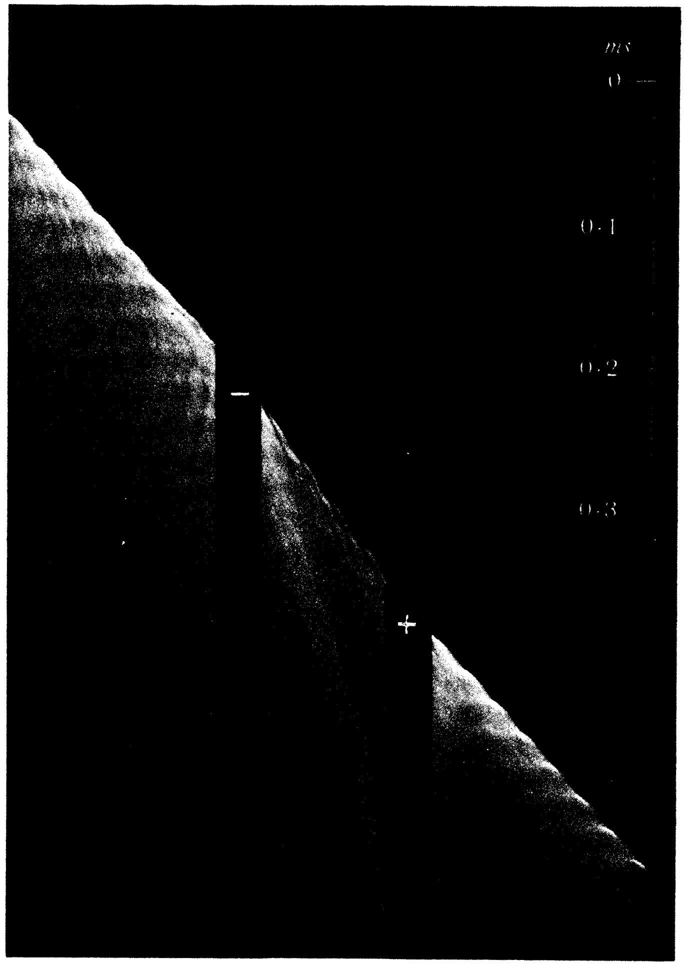


Fig. 33

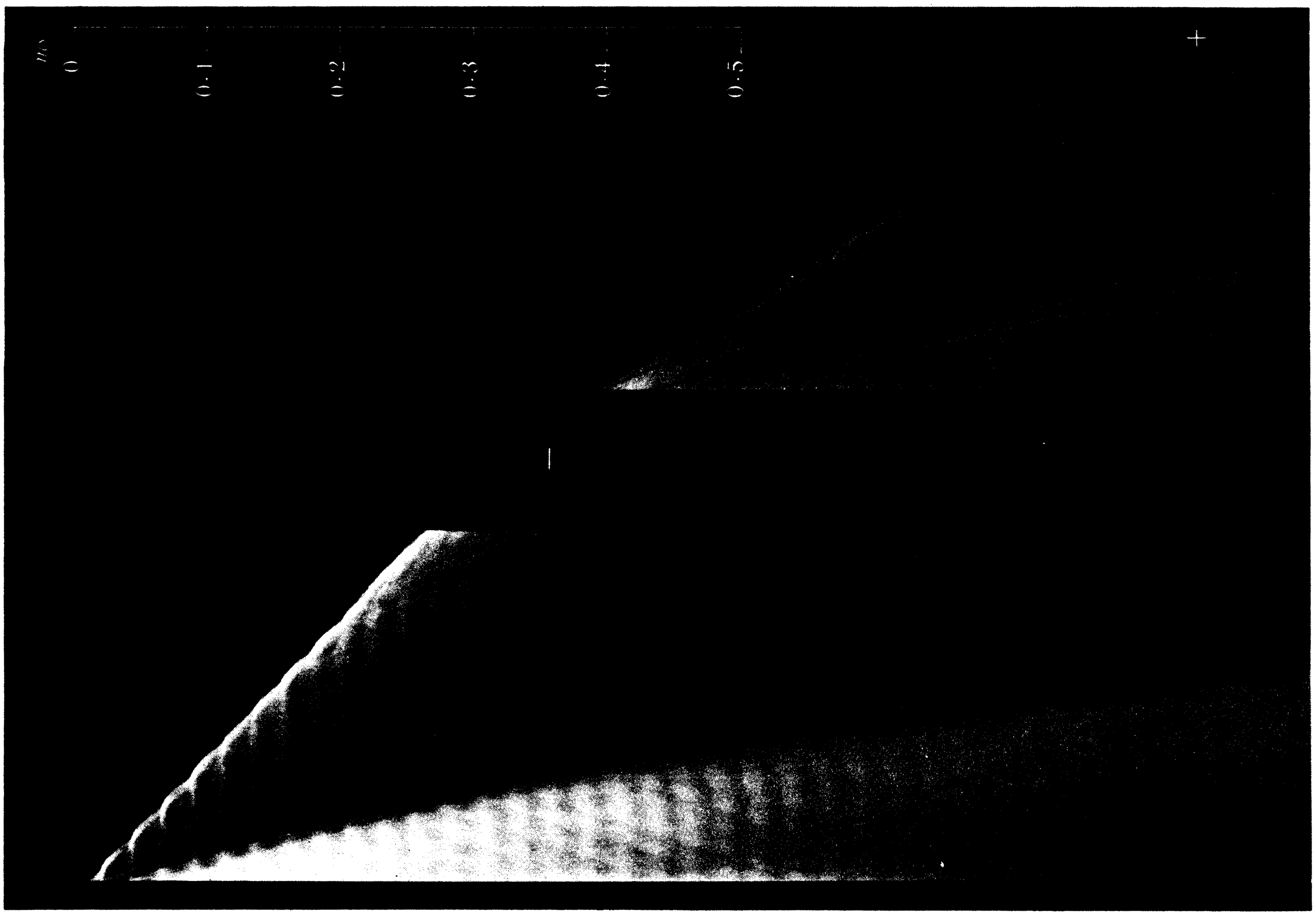


Fig. 35

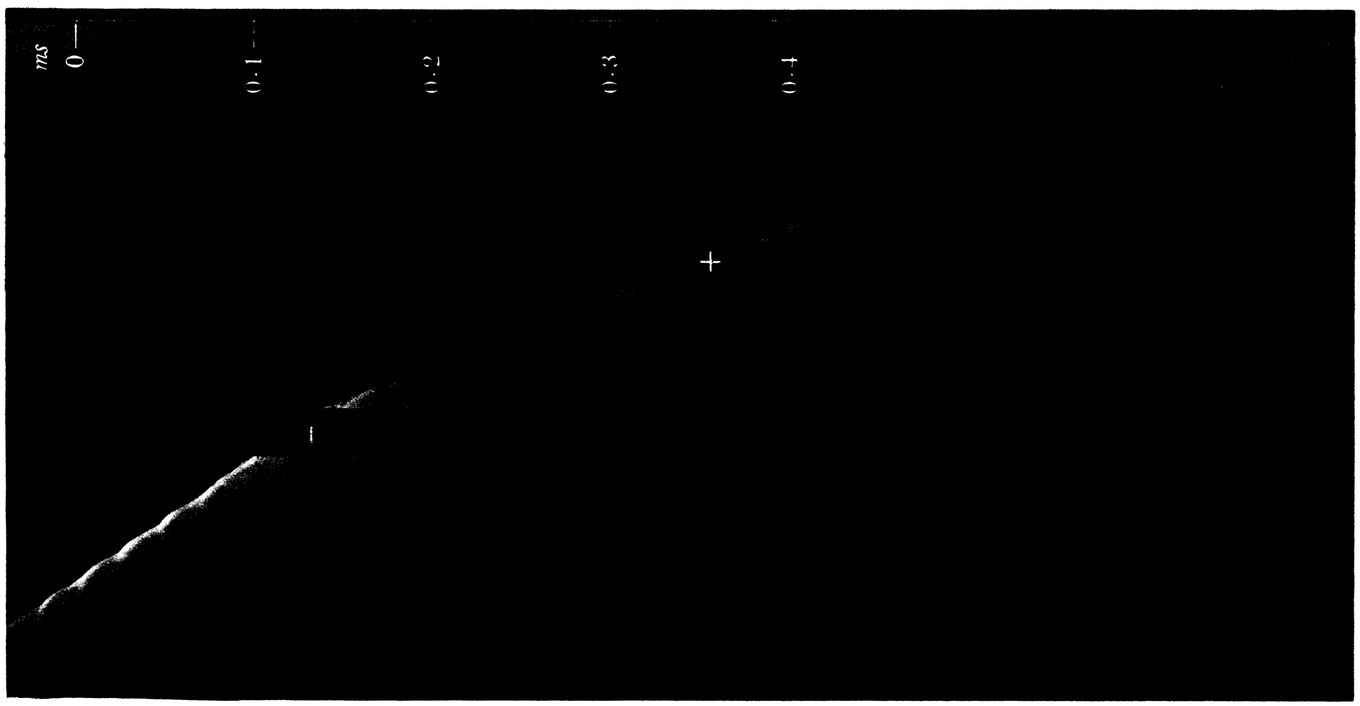


Fig. 34

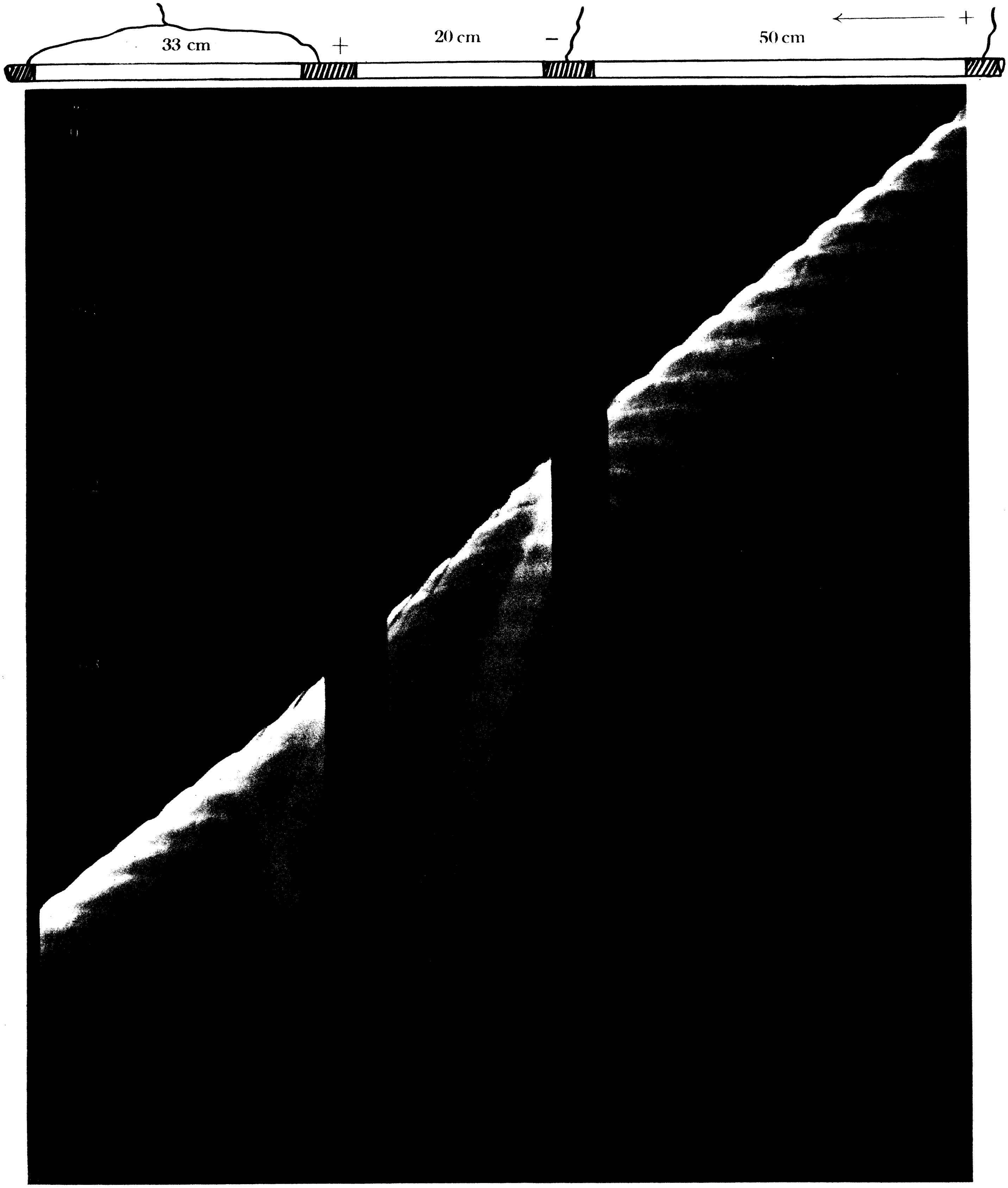


FIG. 36

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

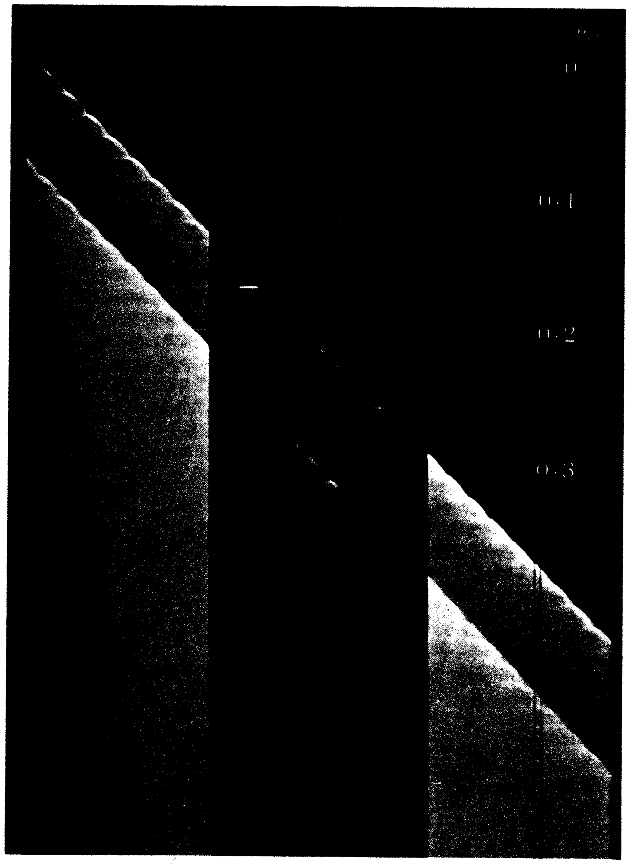


FIG. 37

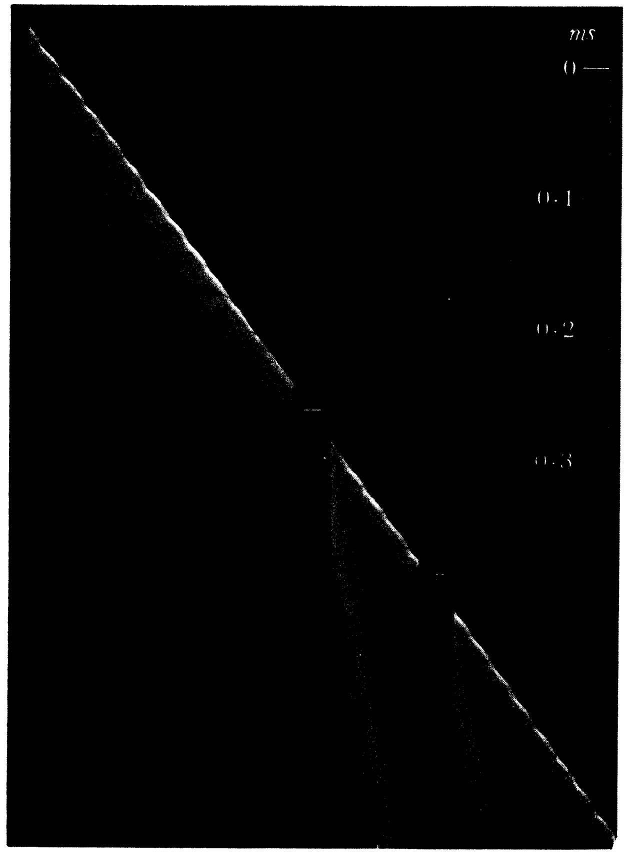


FIG. 39

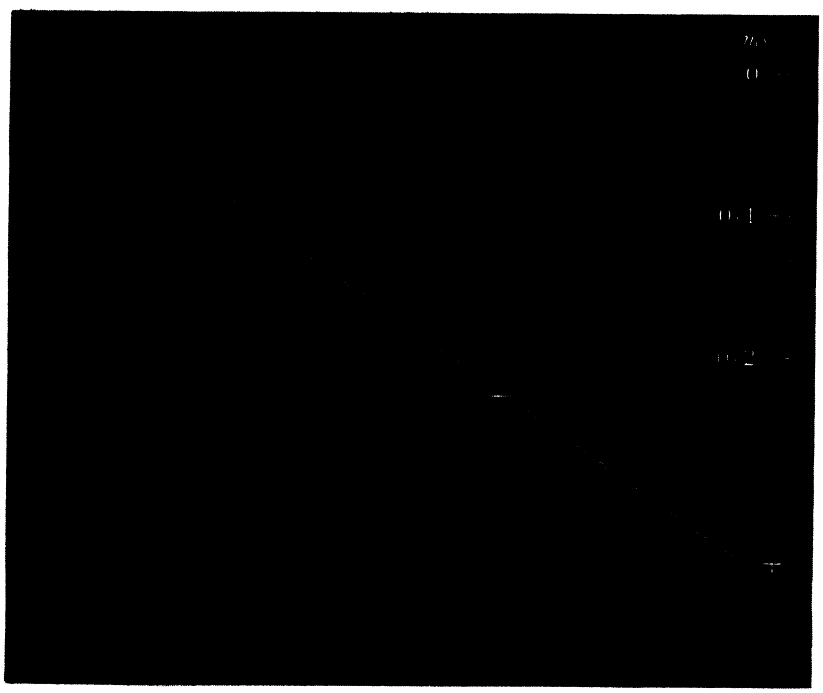


FIG. 40

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

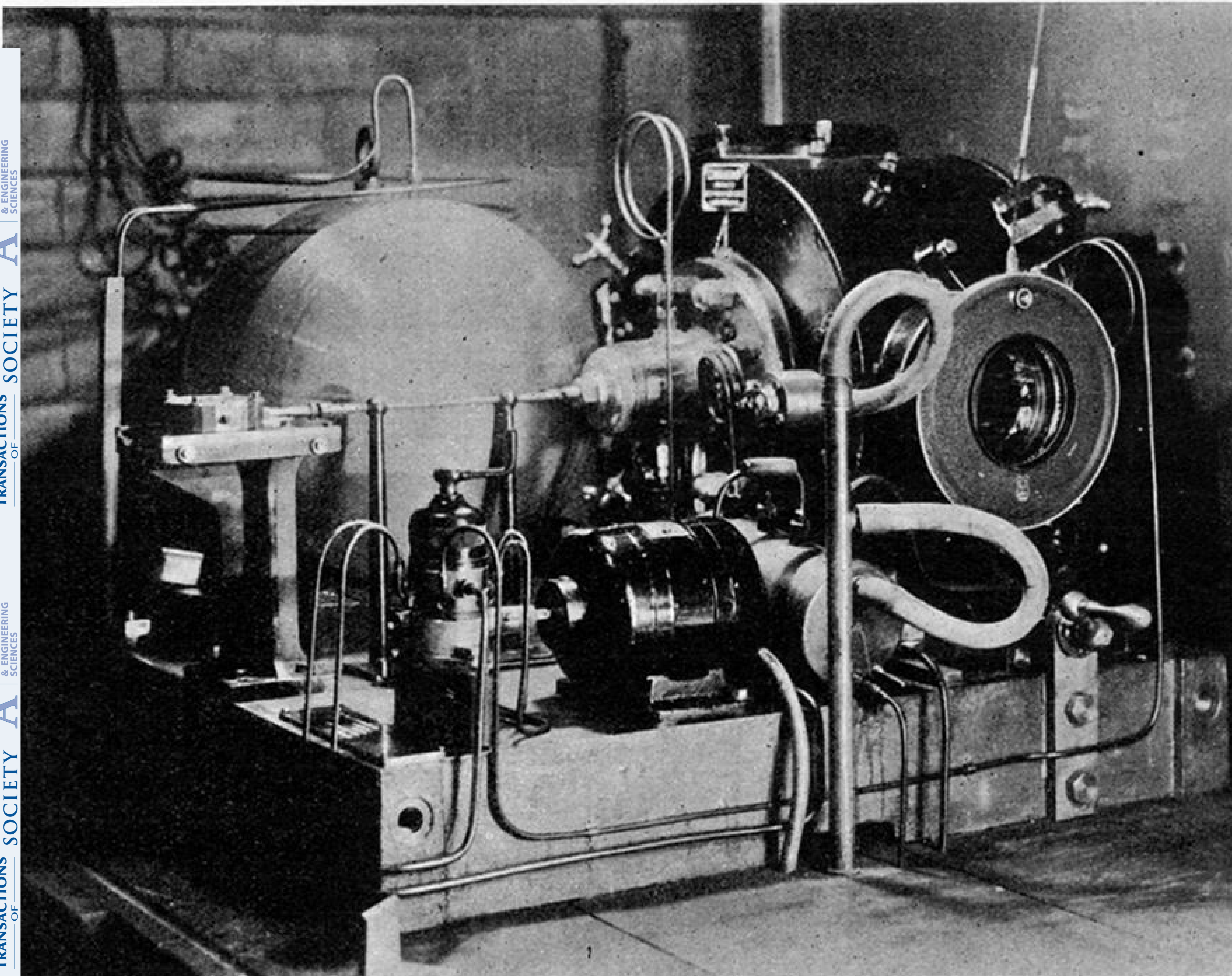


FIG. 2—Fraser high-speed mirror camera

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

FIG. 5

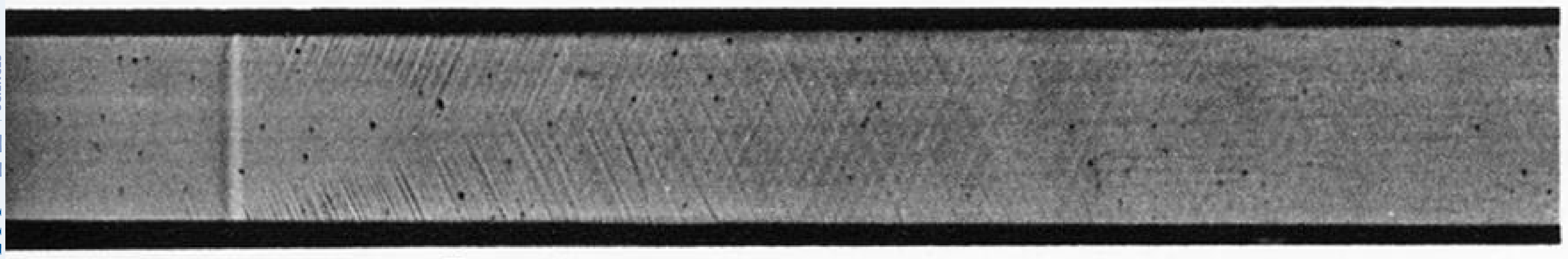


FIG. 9

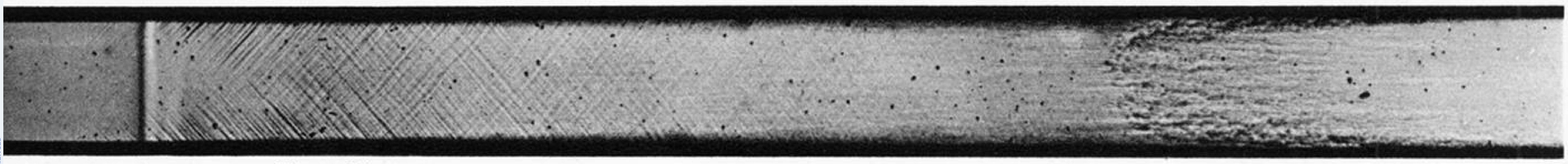


FIG. 10

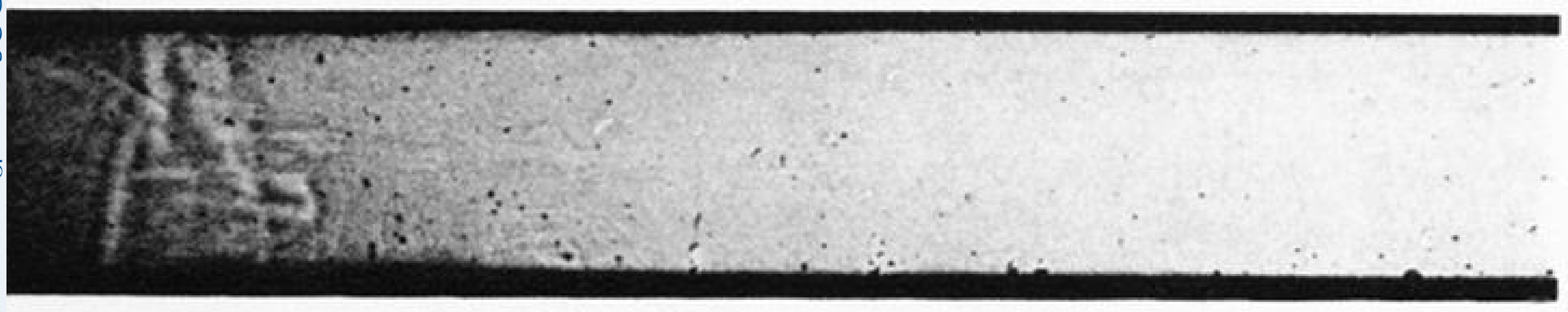


FIG. 11

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

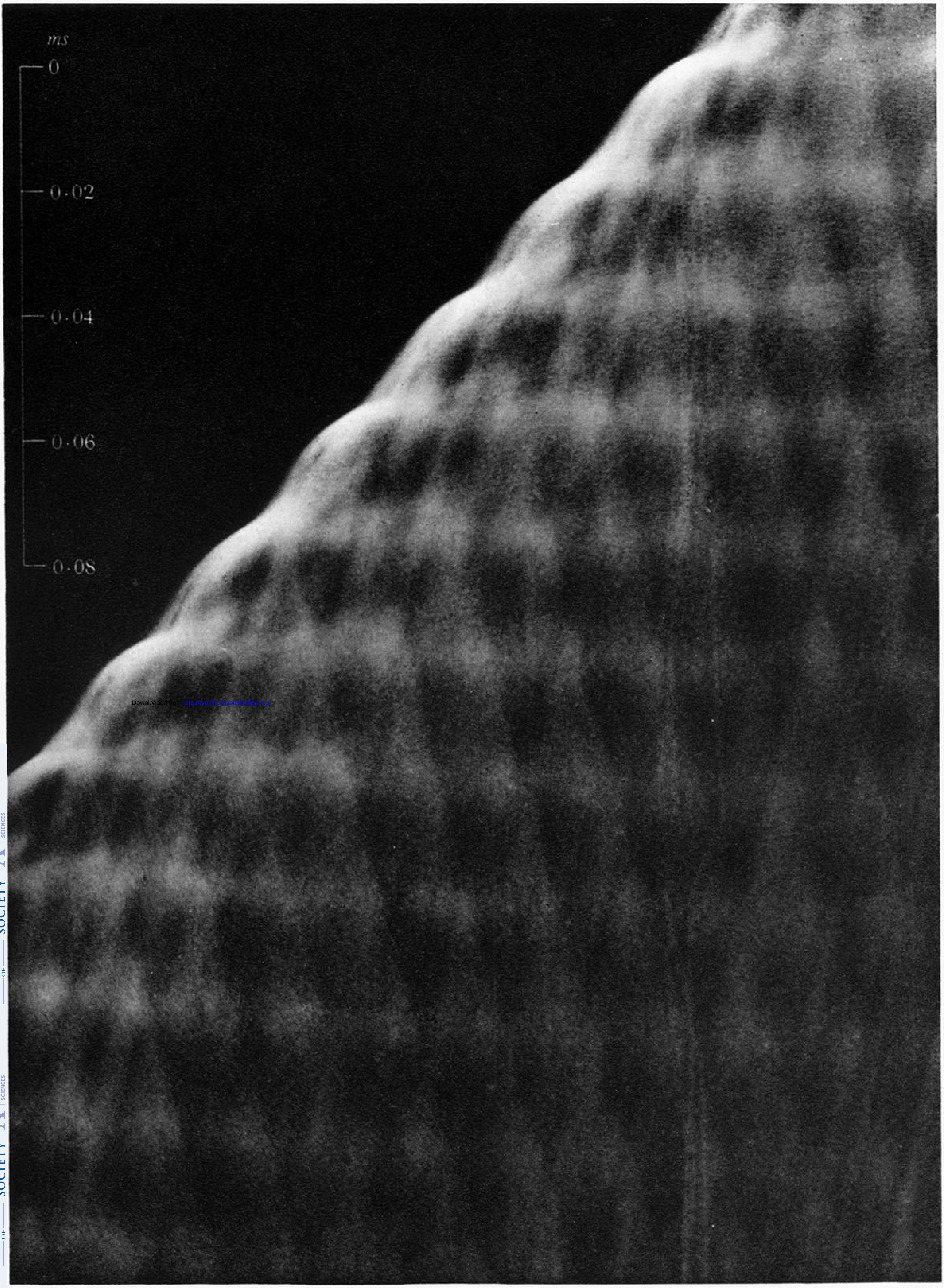


Fig. 7

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

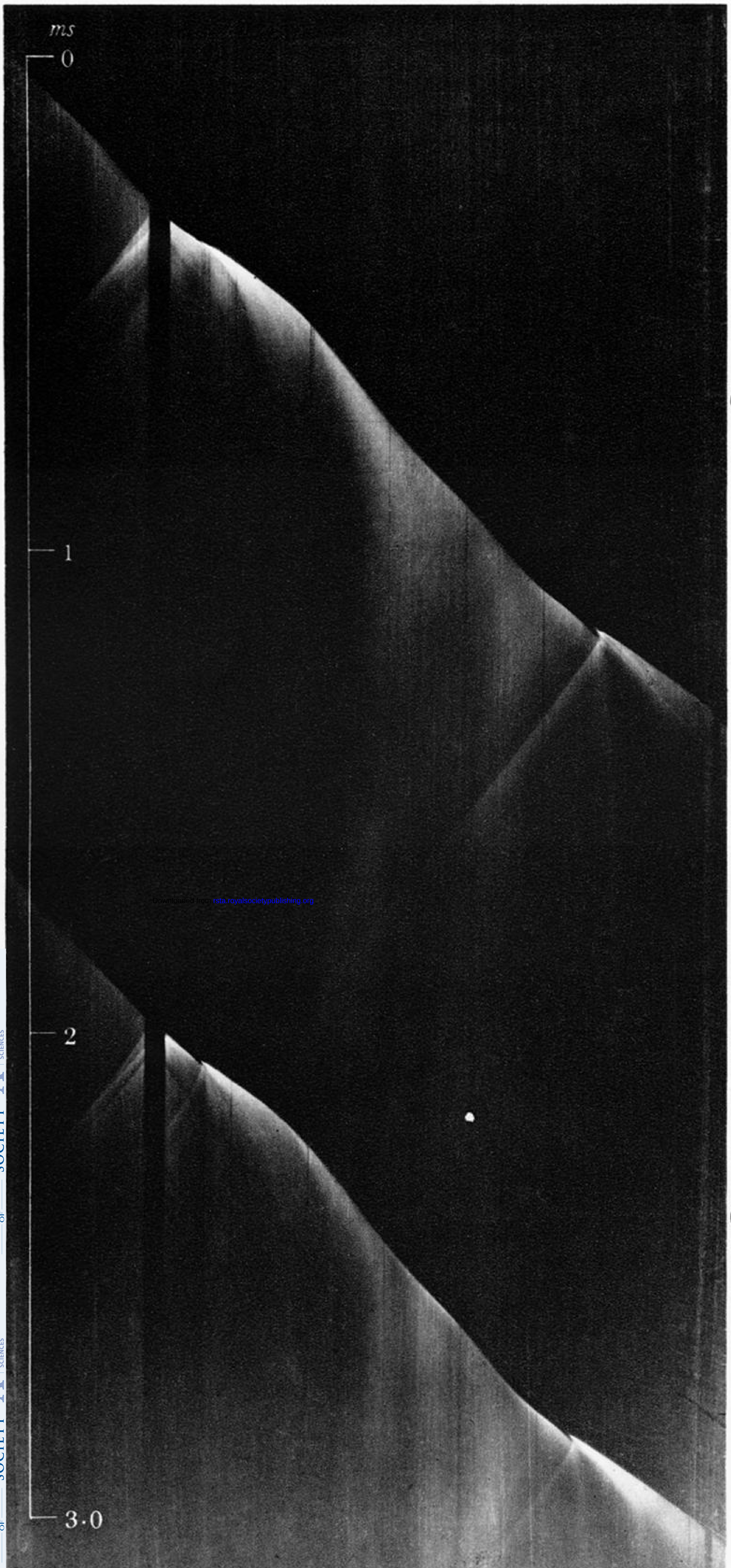


Fig. 13

(a)

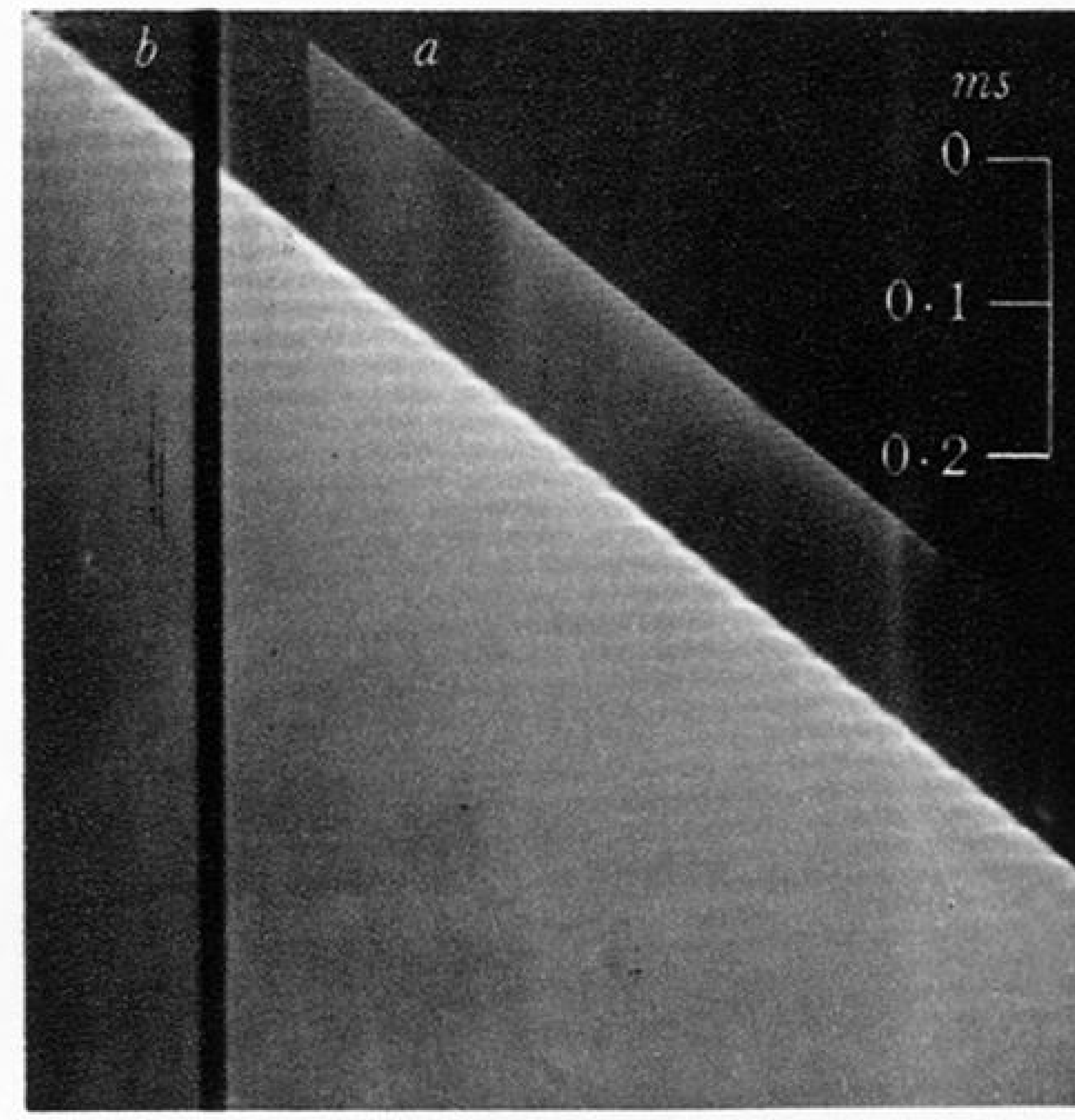


Fig. 14

(b)

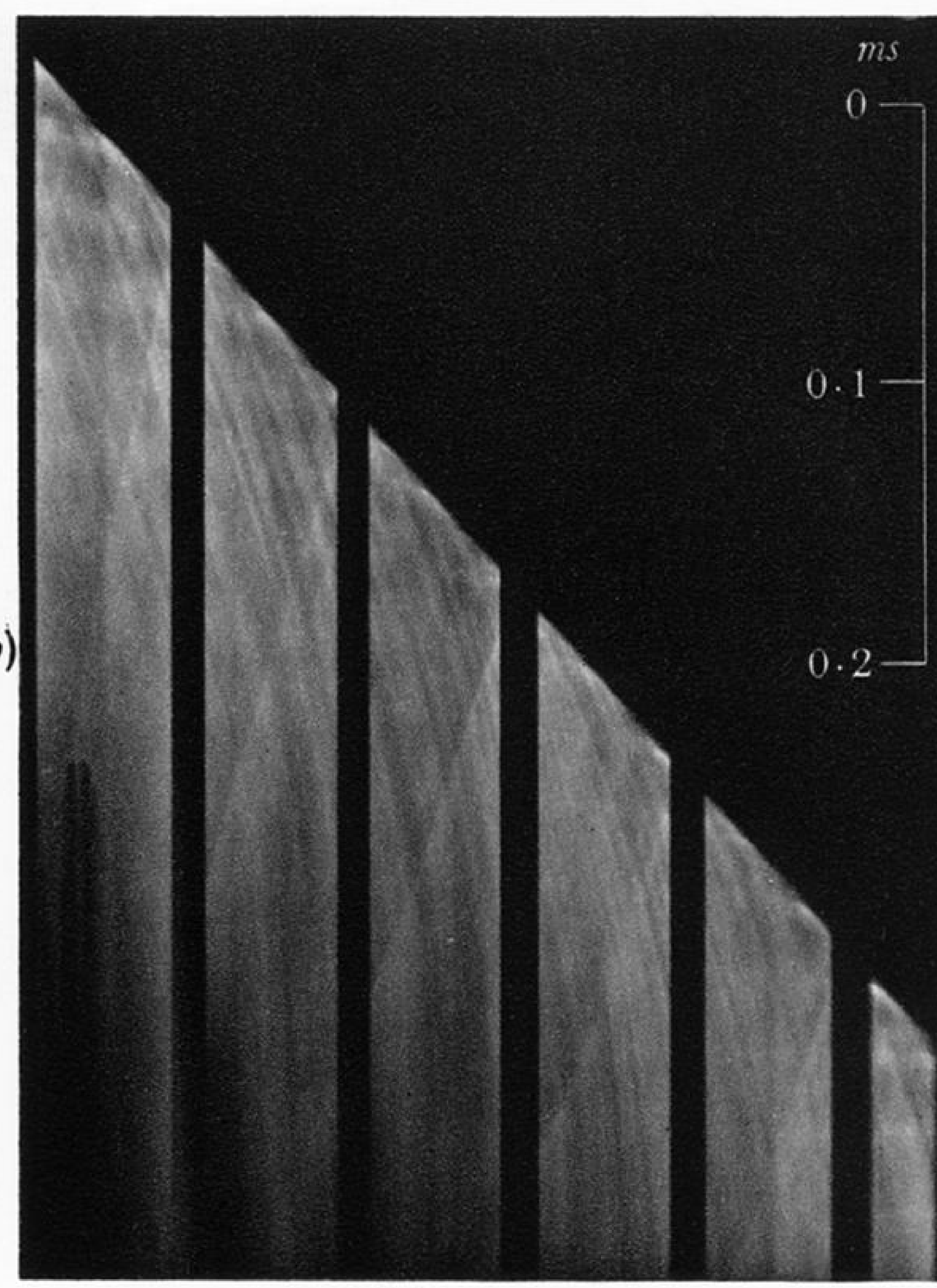


Fig. 15

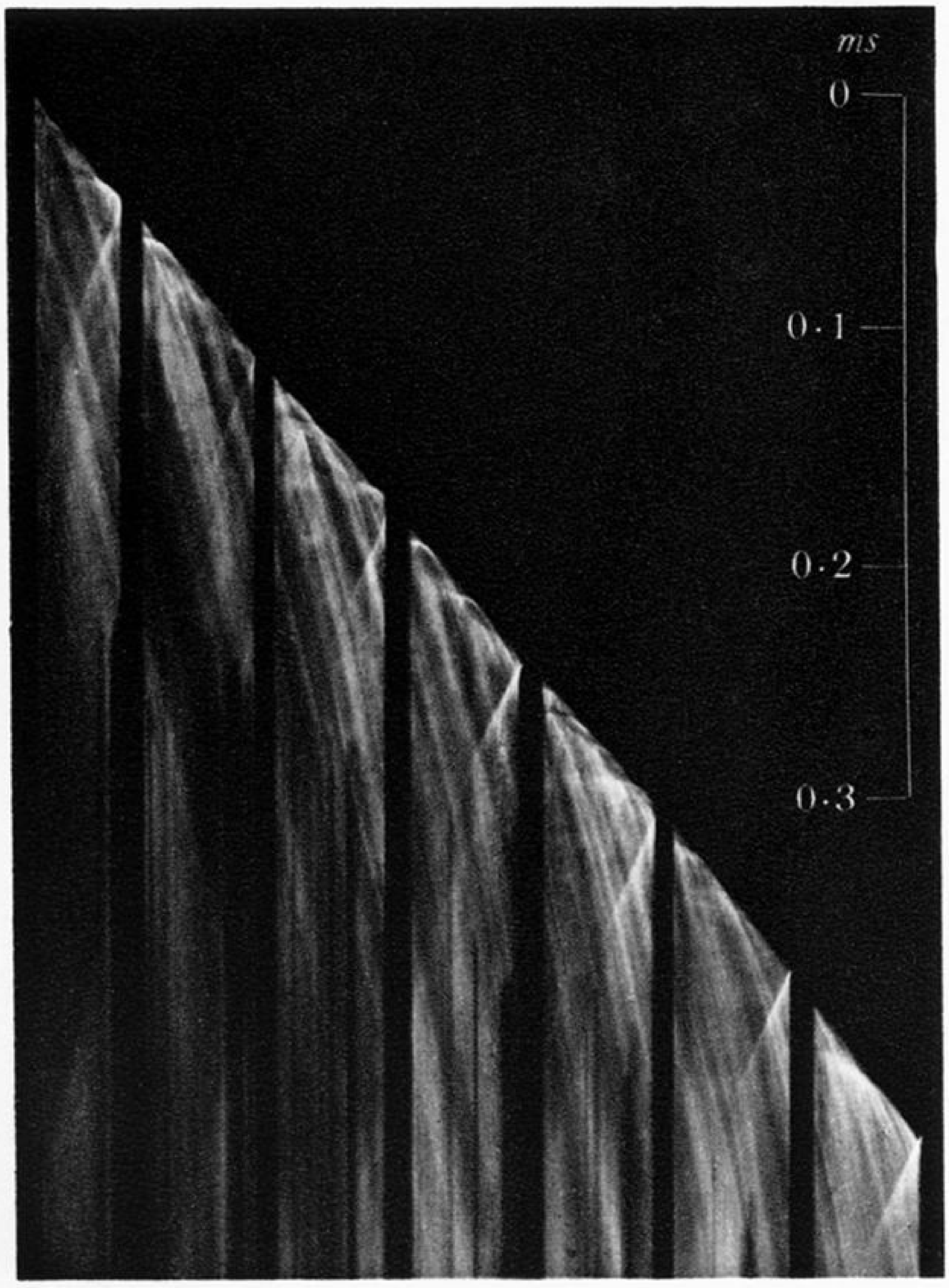


FIG. 16

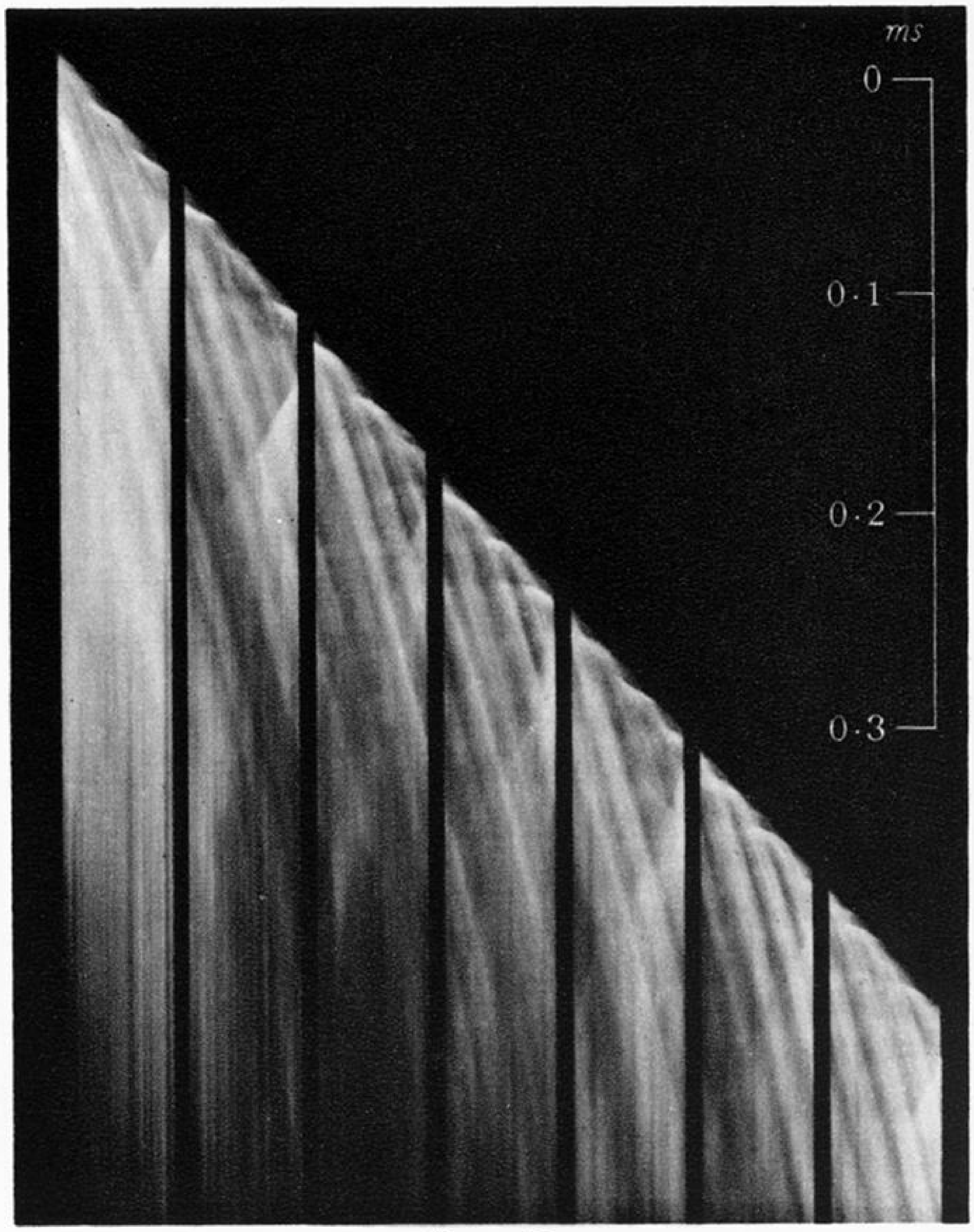


FIG. 17

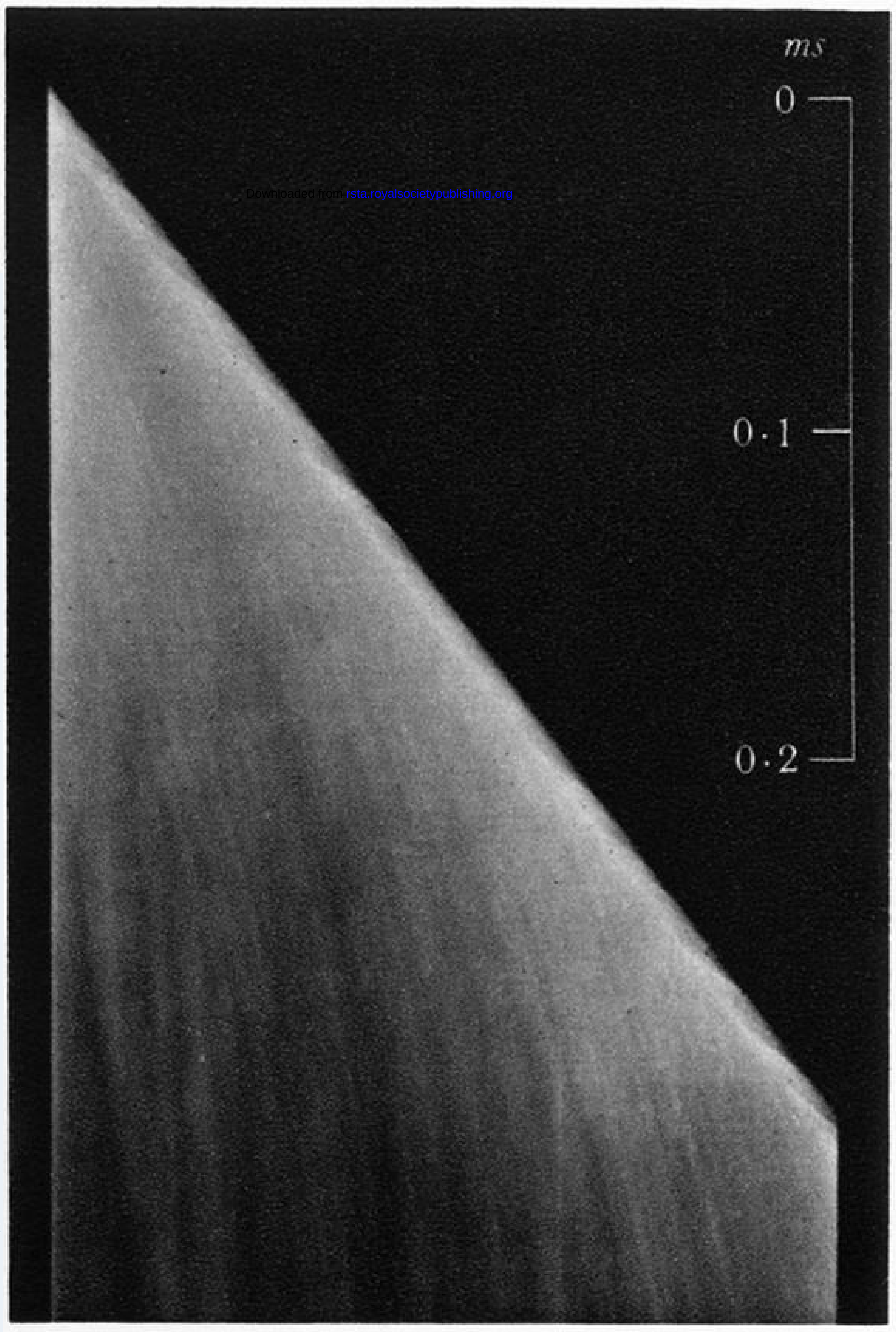


FIG. 18

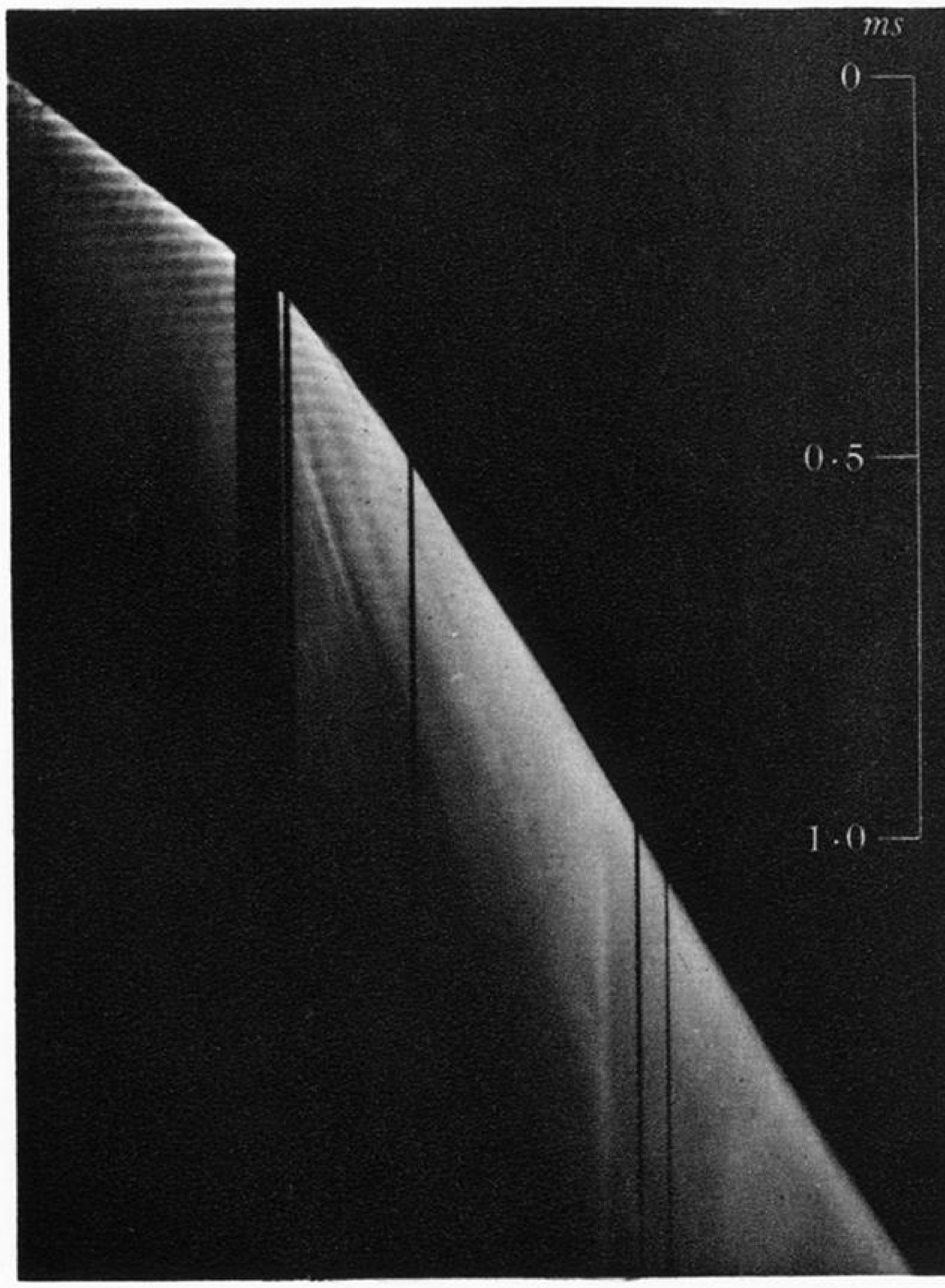


FIG. 20

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

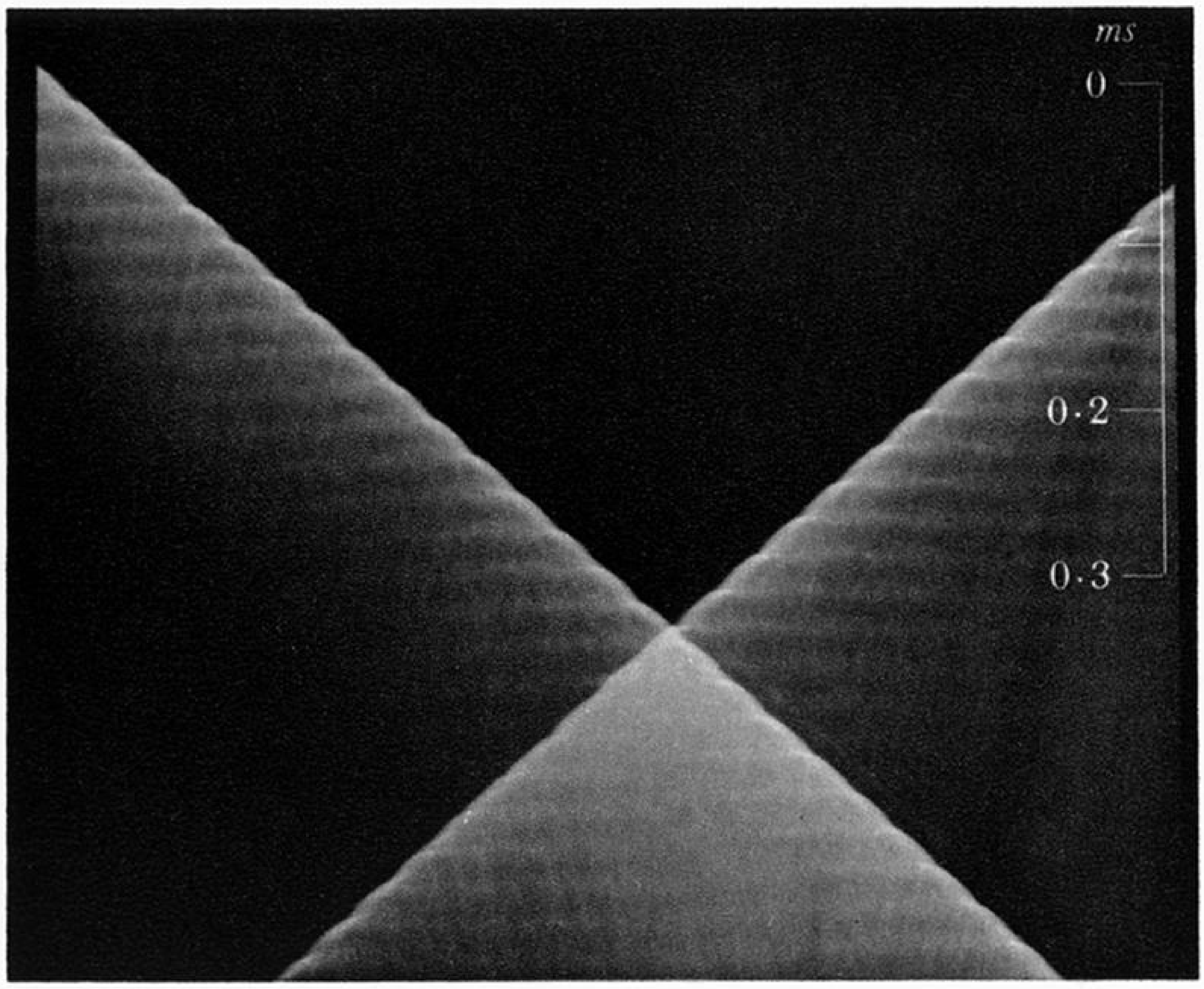


FIG. 21

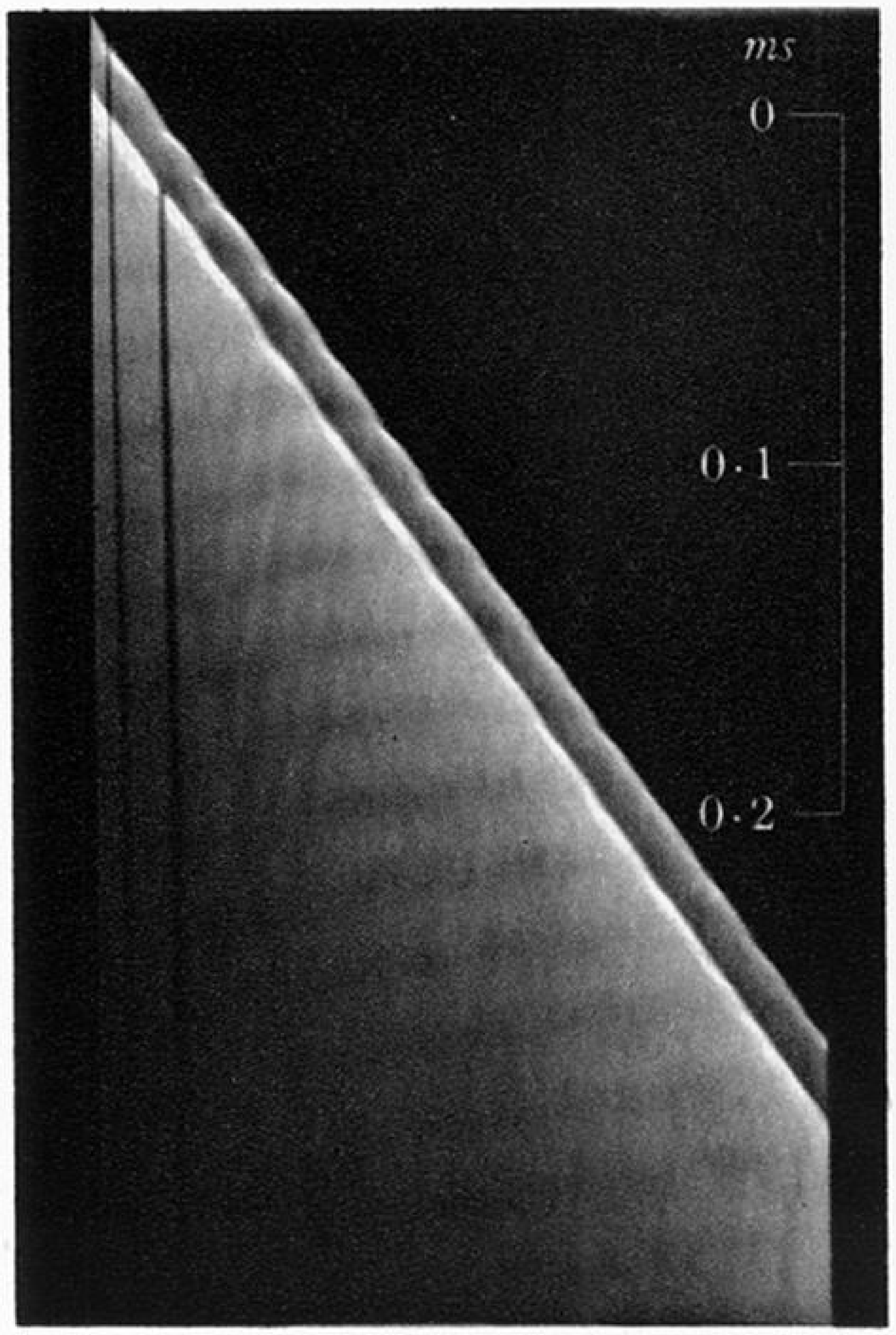


FIG. 22

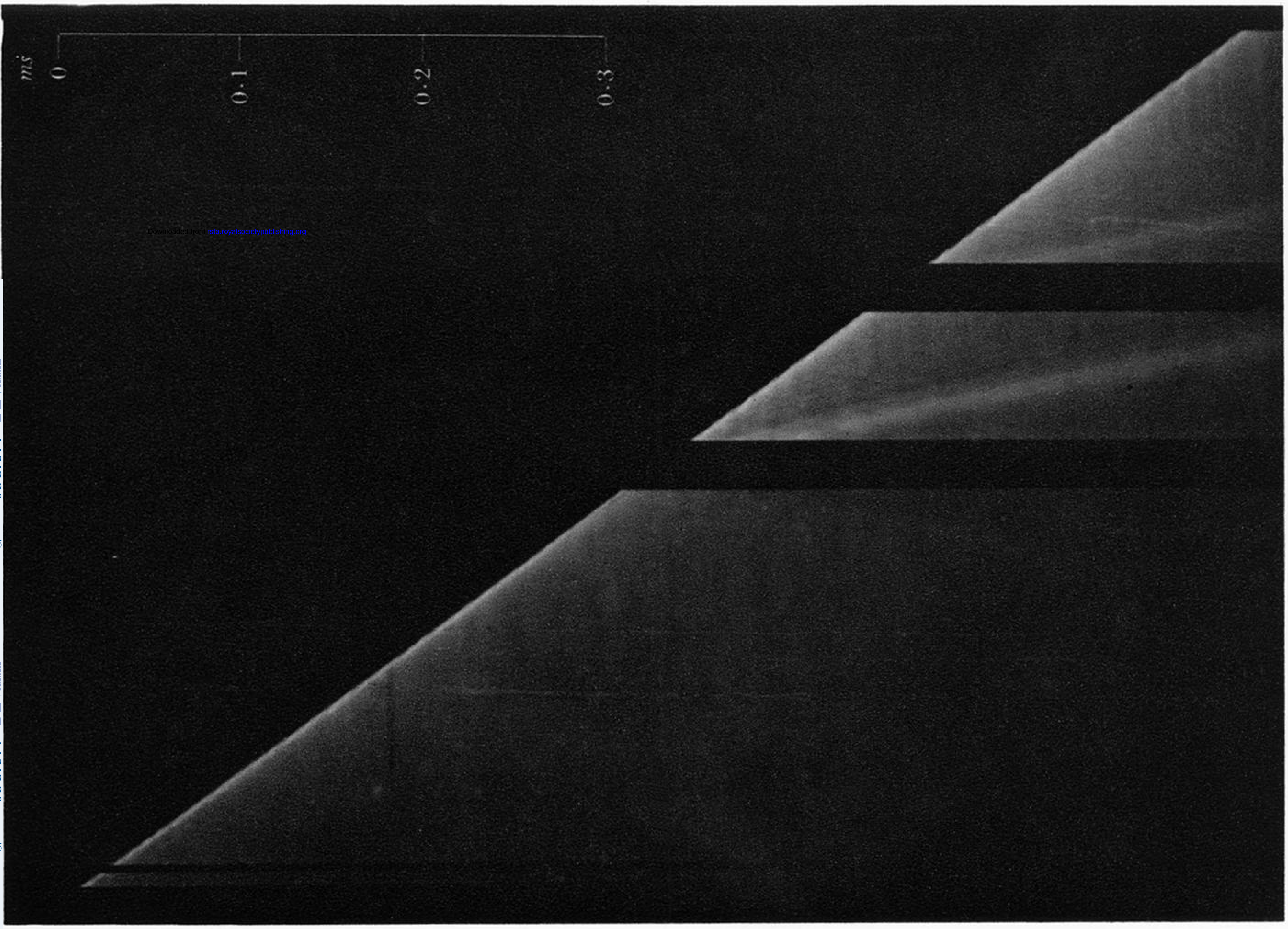


FIG. 23

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

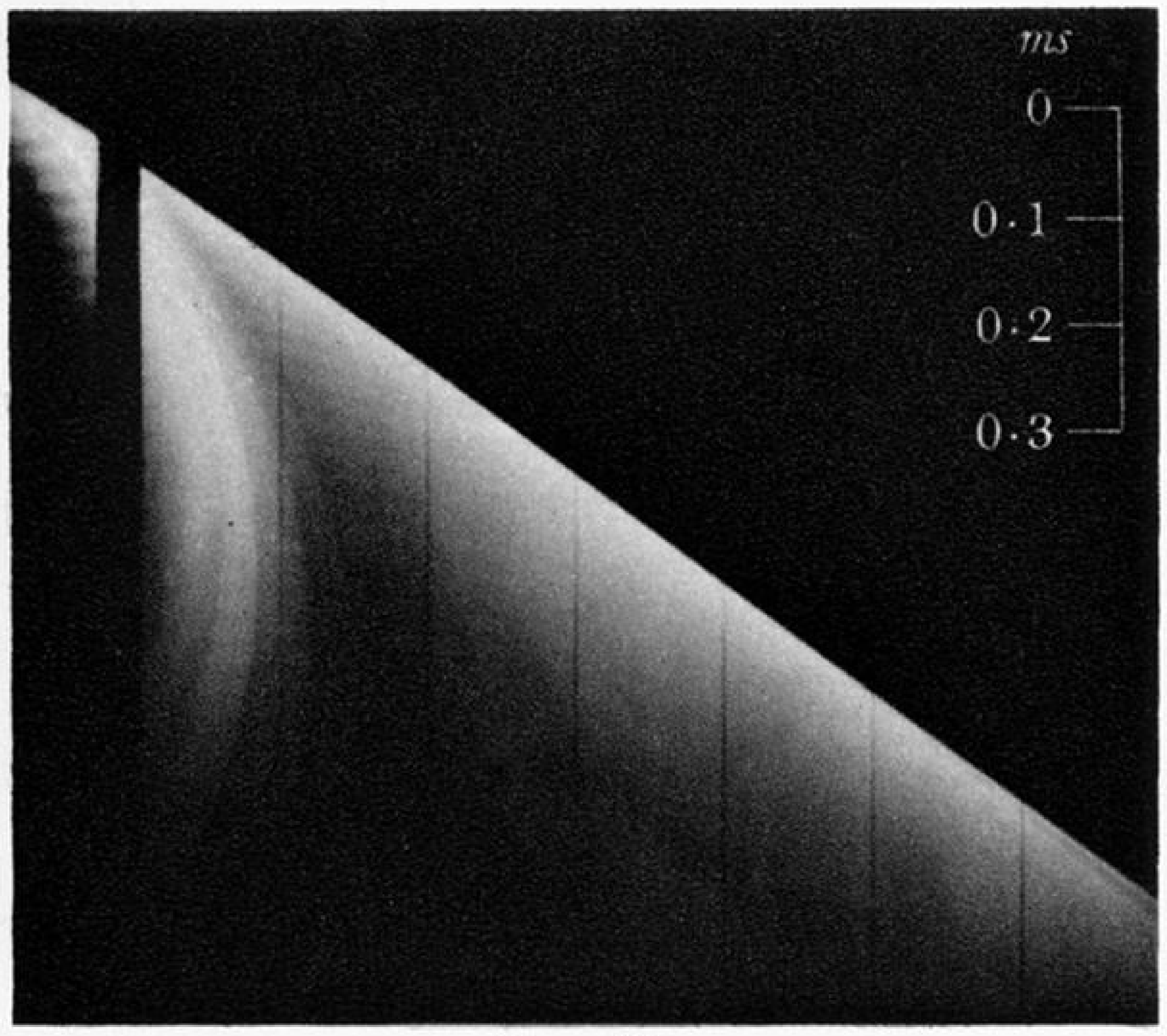


Fig. 24

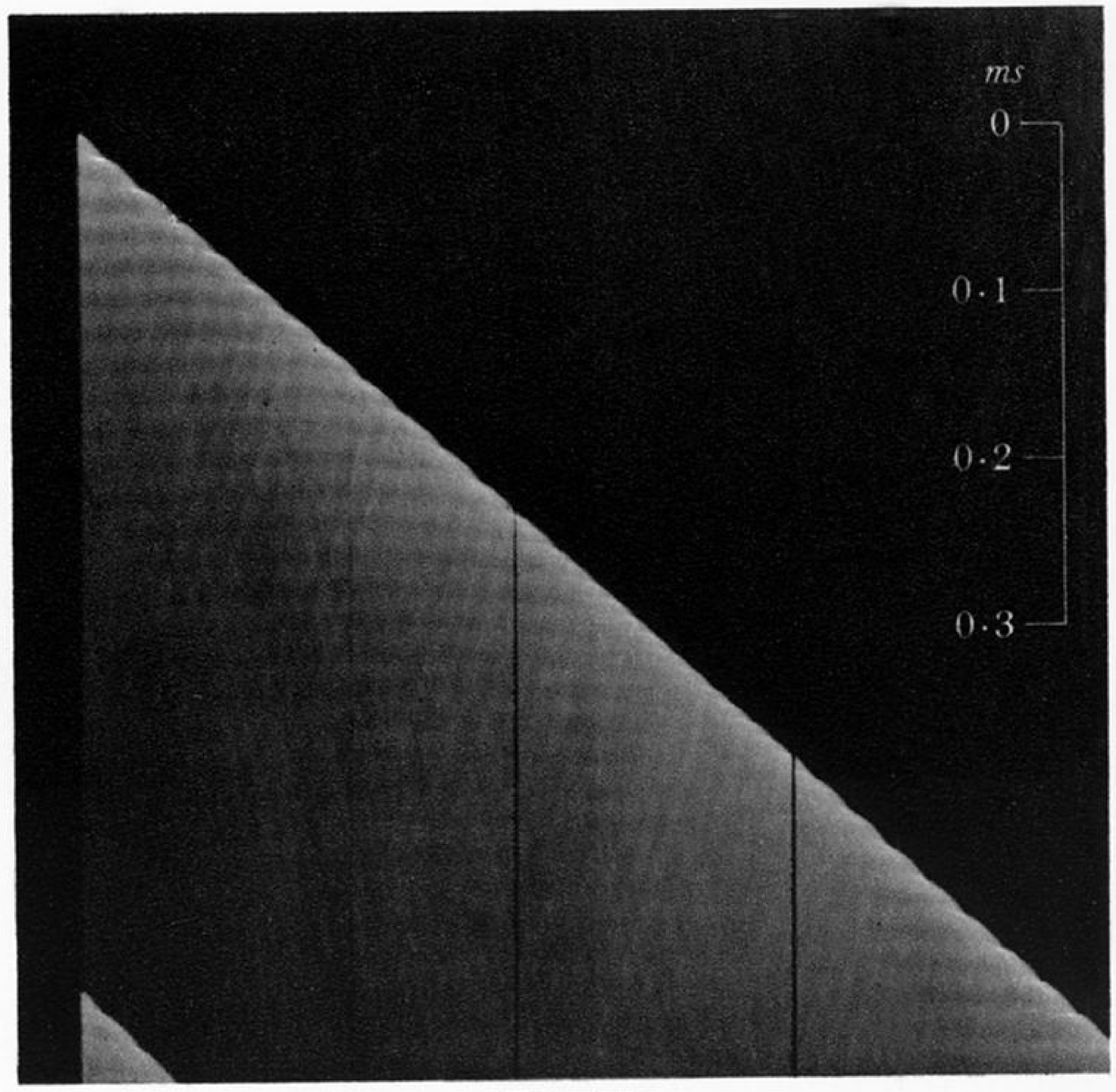


Fig. 25

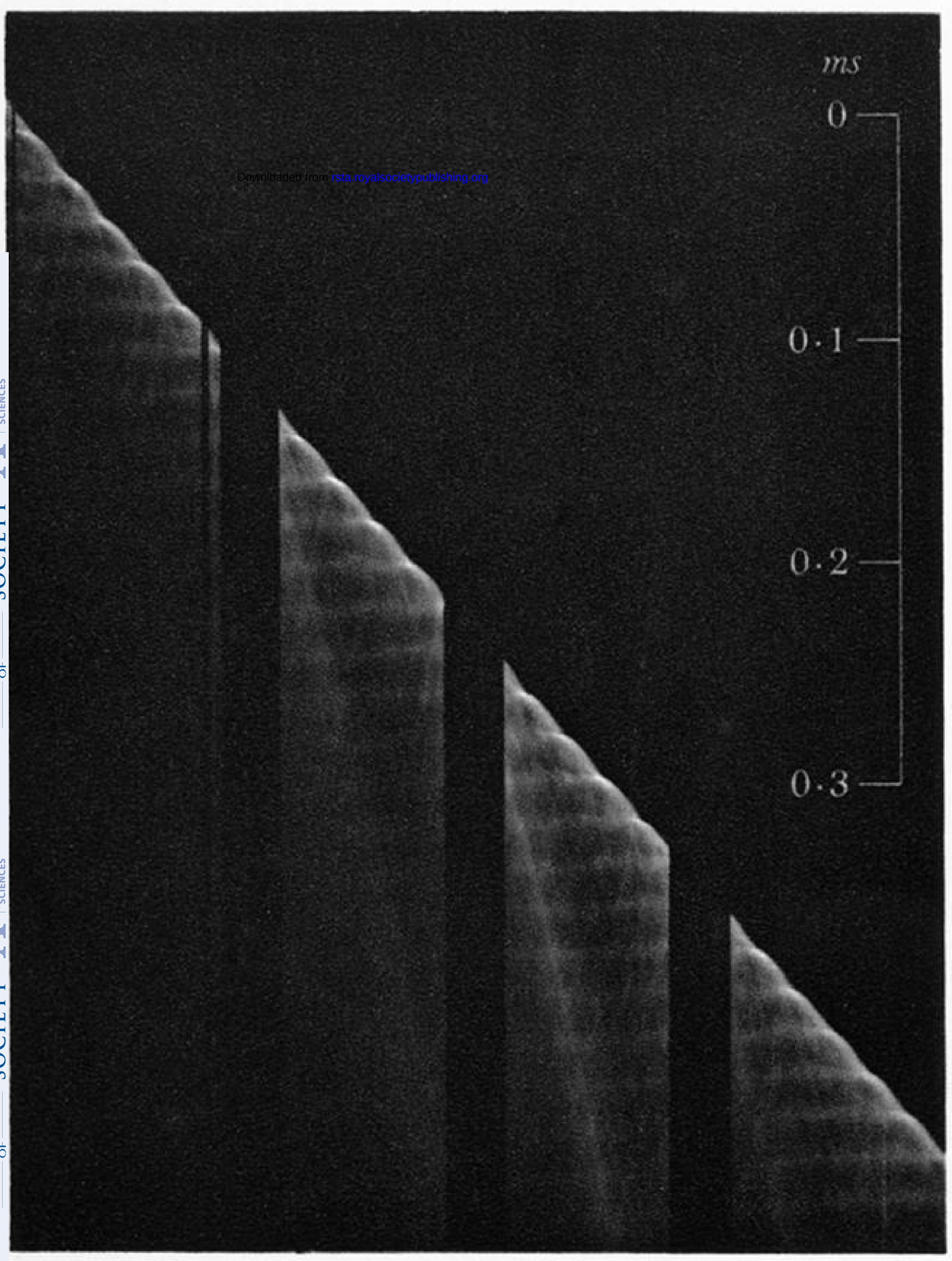


Fig. 31

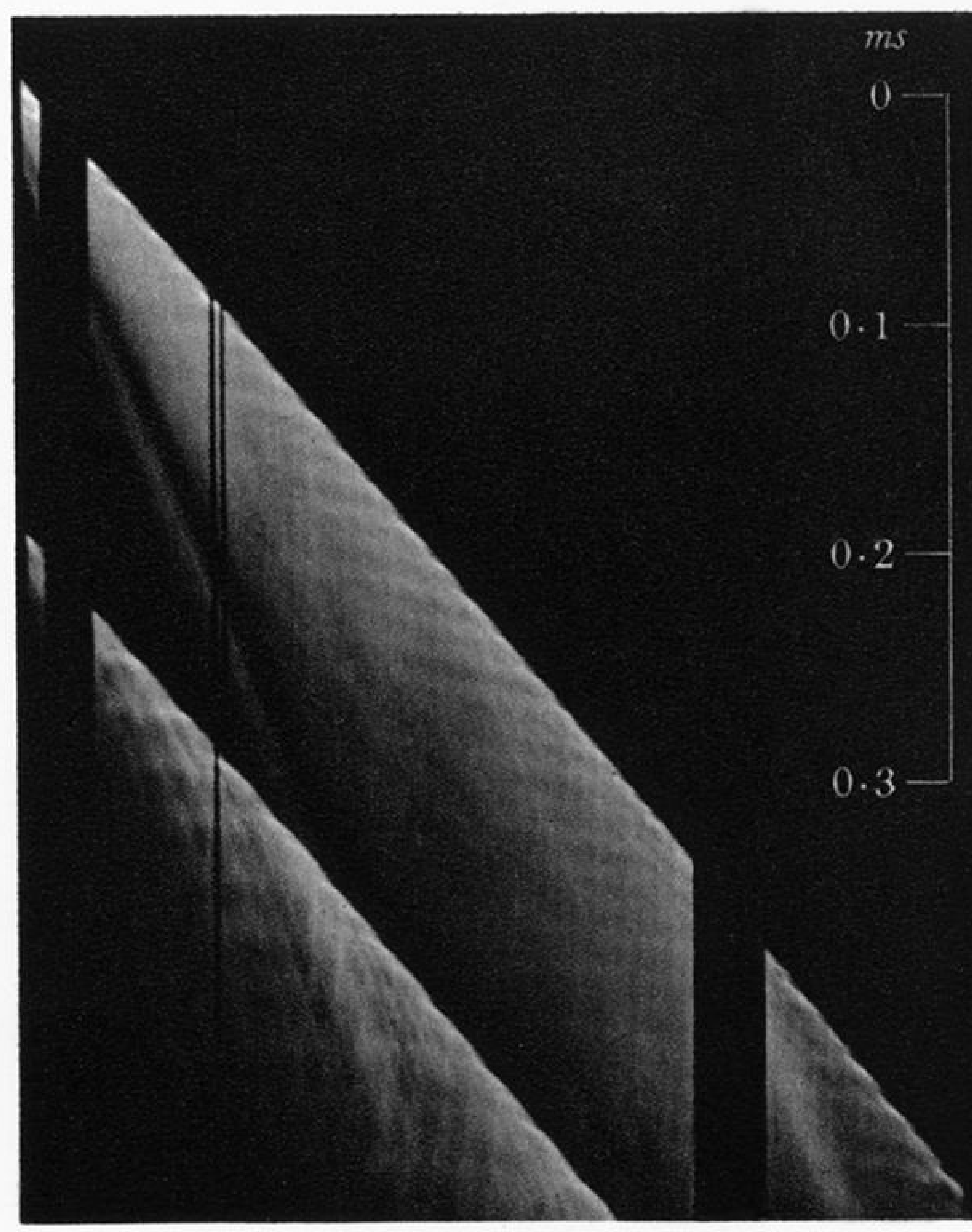


Fig. 26

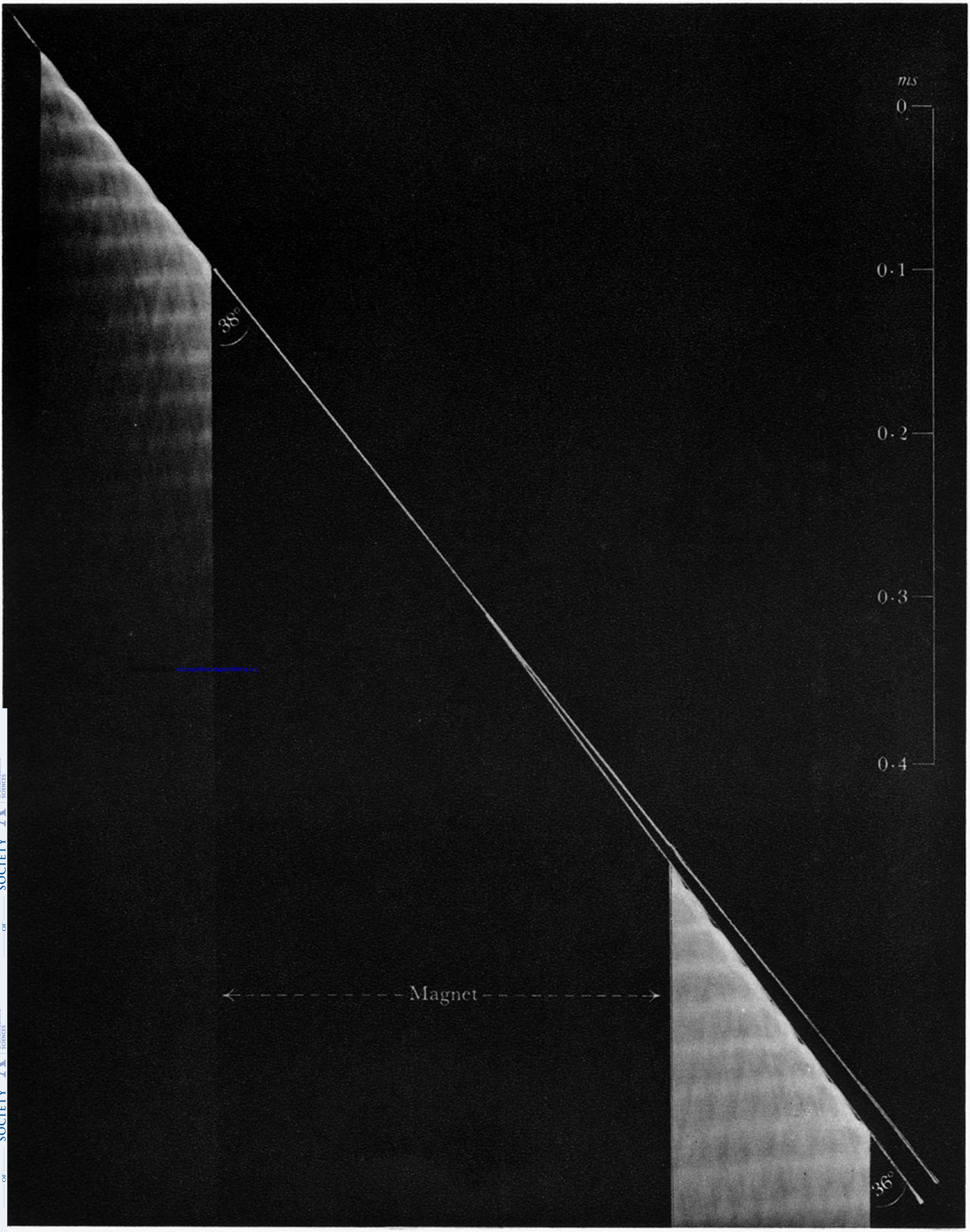


FIG. 29

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

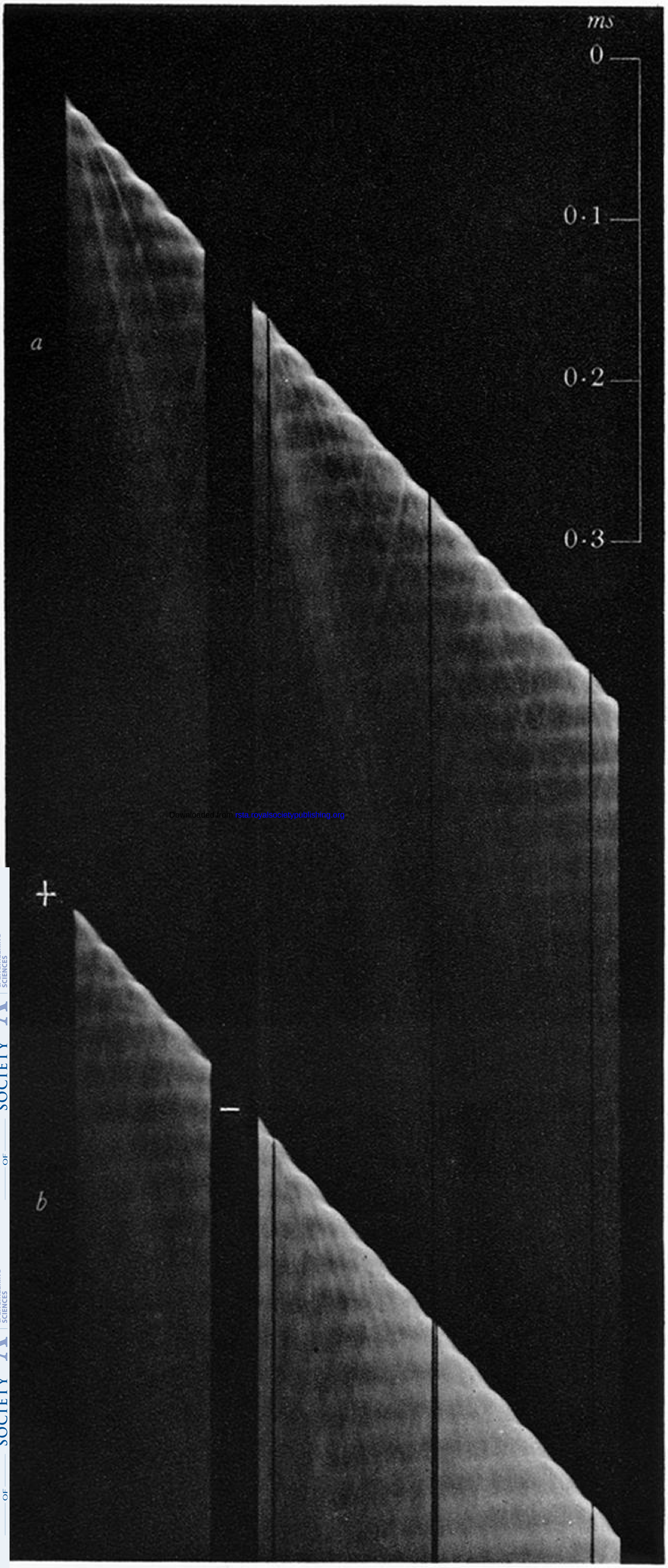


FIG. 32

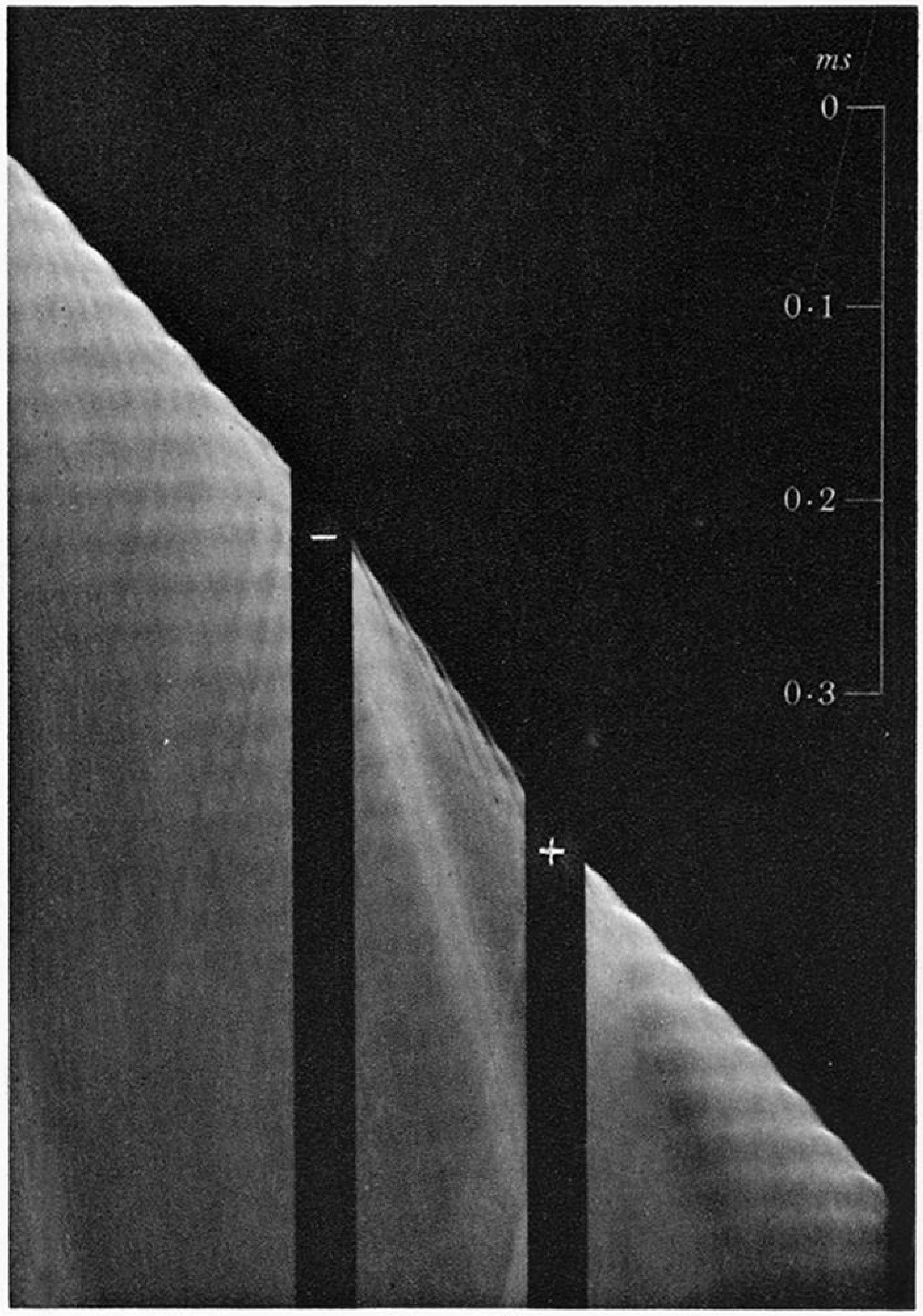


FIG. 33

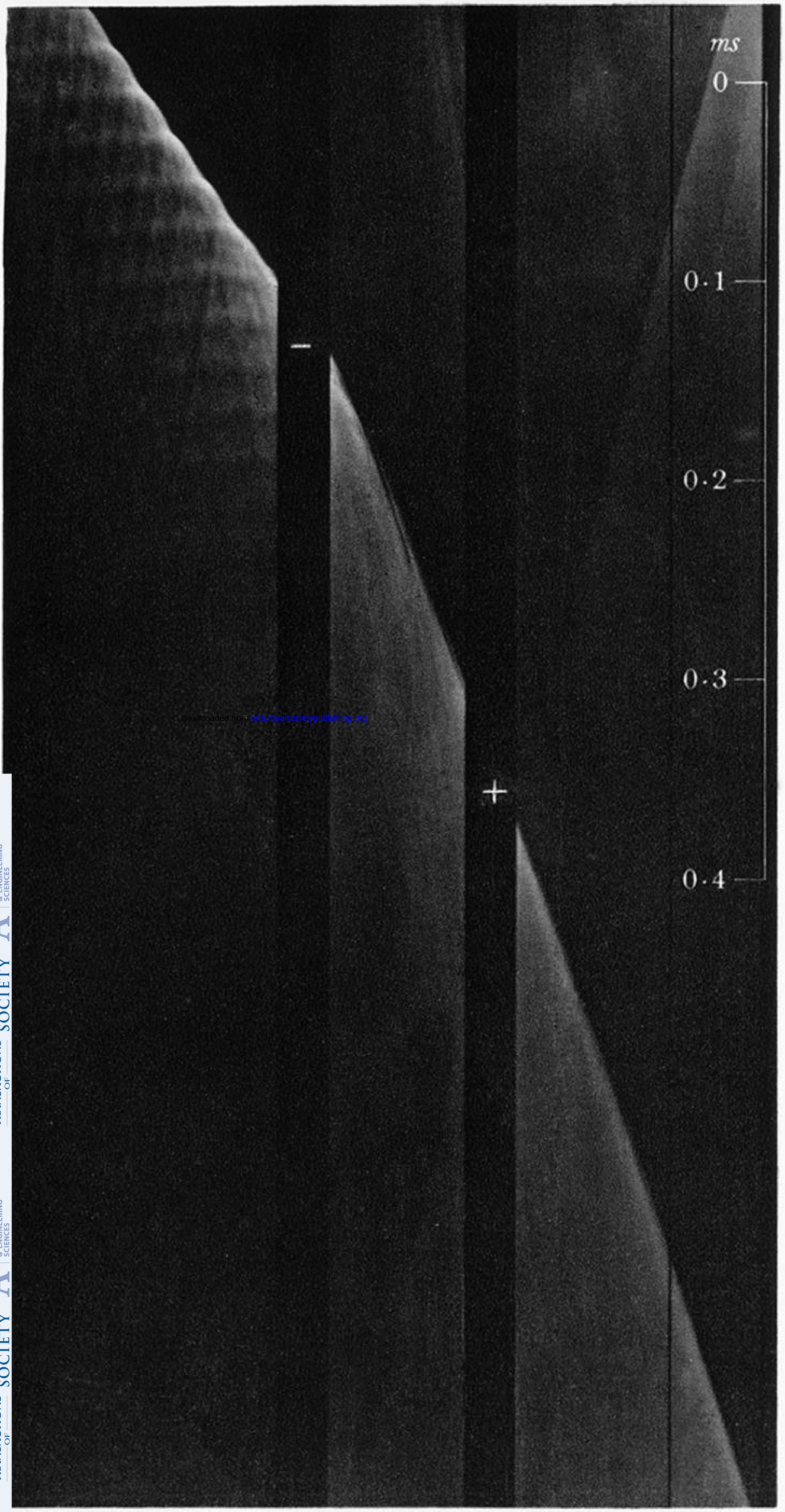


Fig. 34

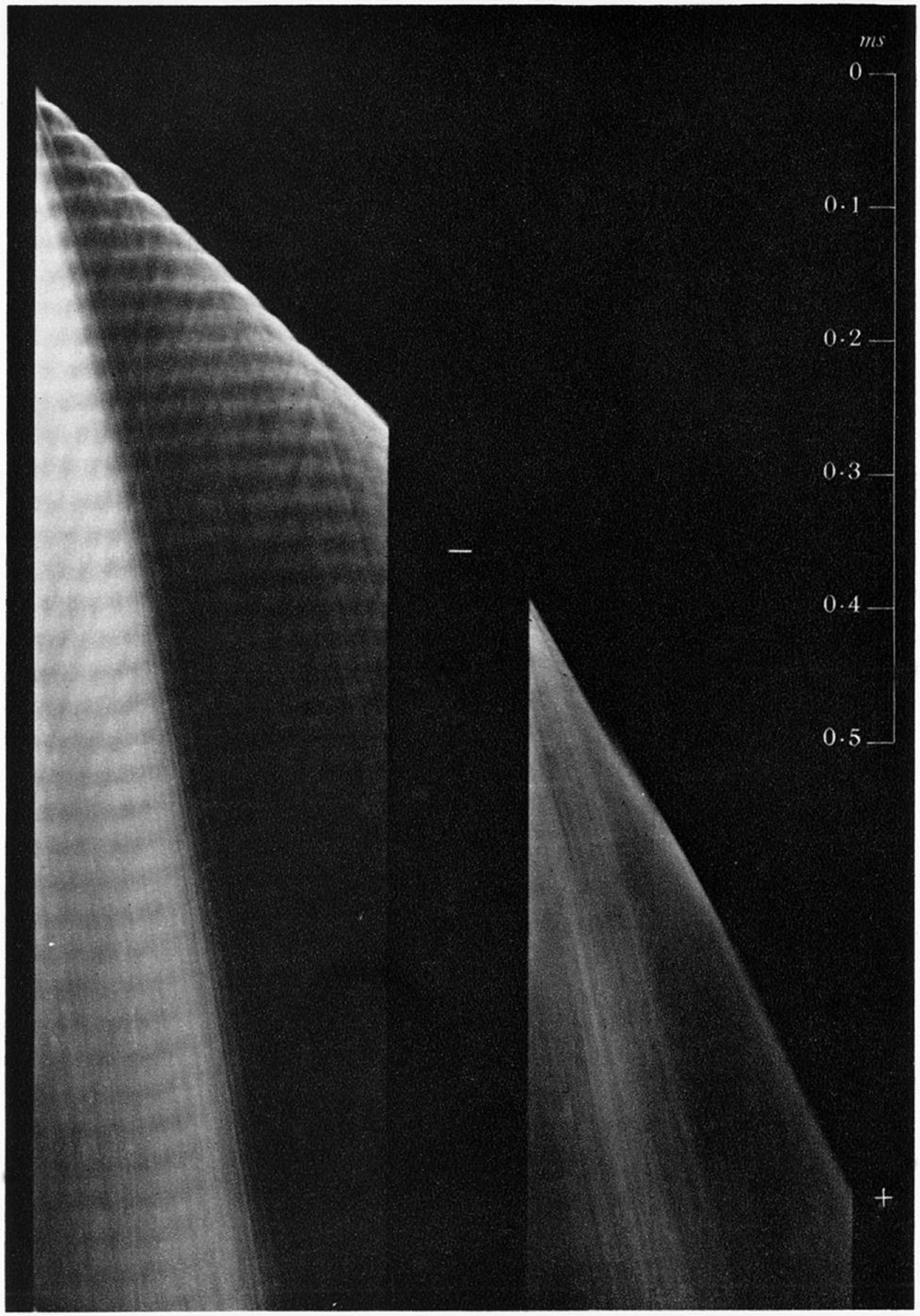


Fig. 35

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

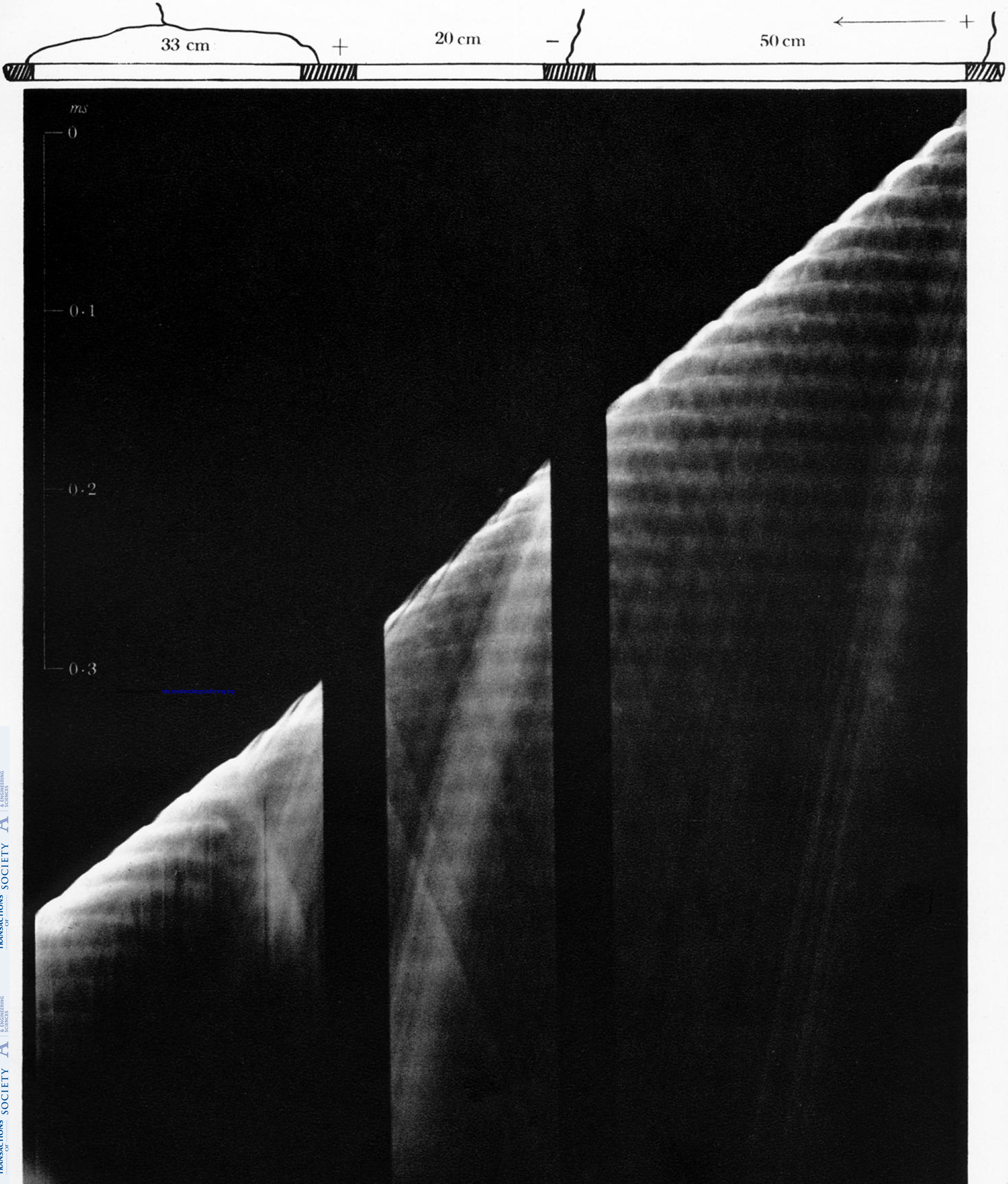


FIG. 36

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

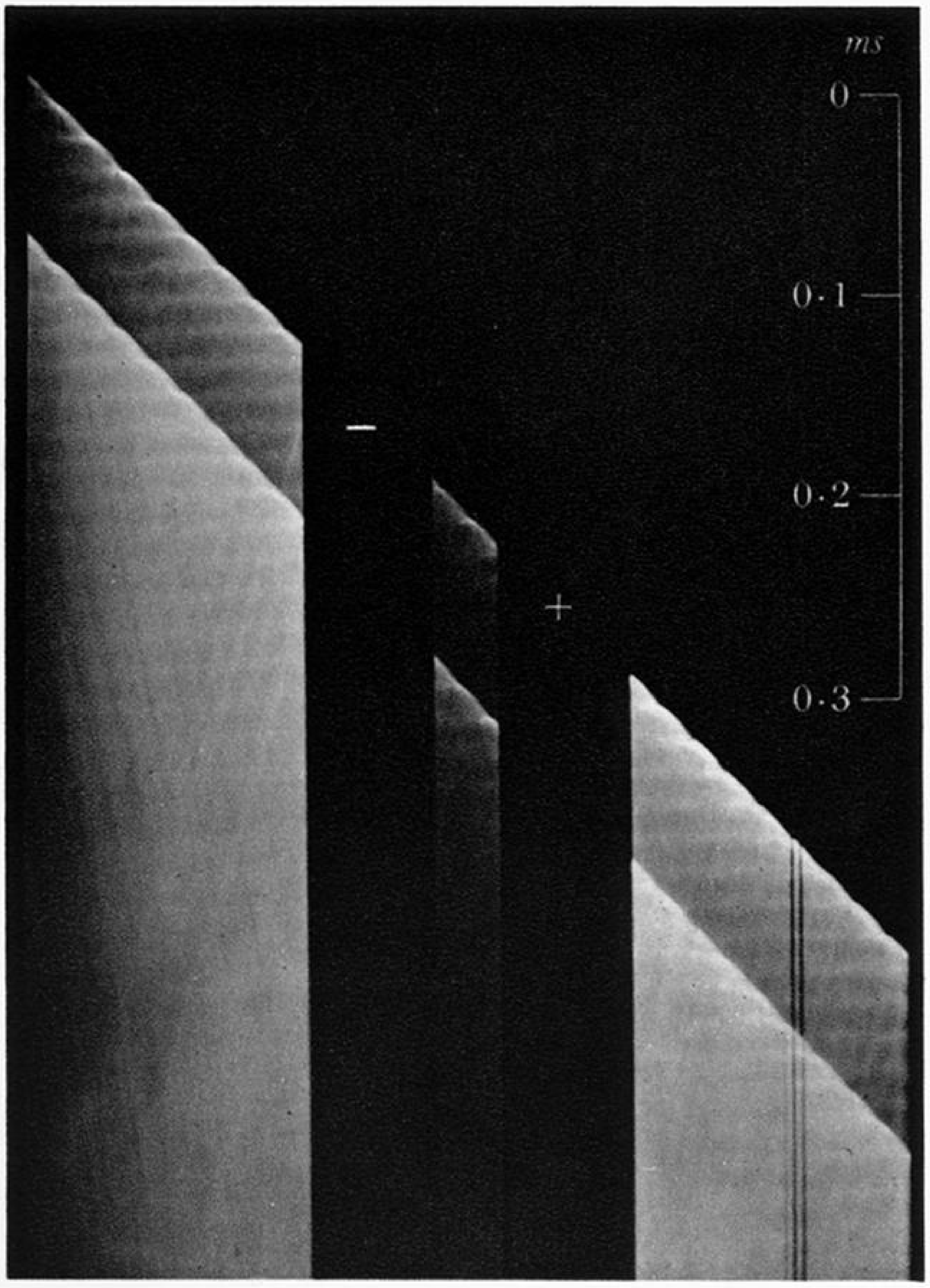


Fig. 37

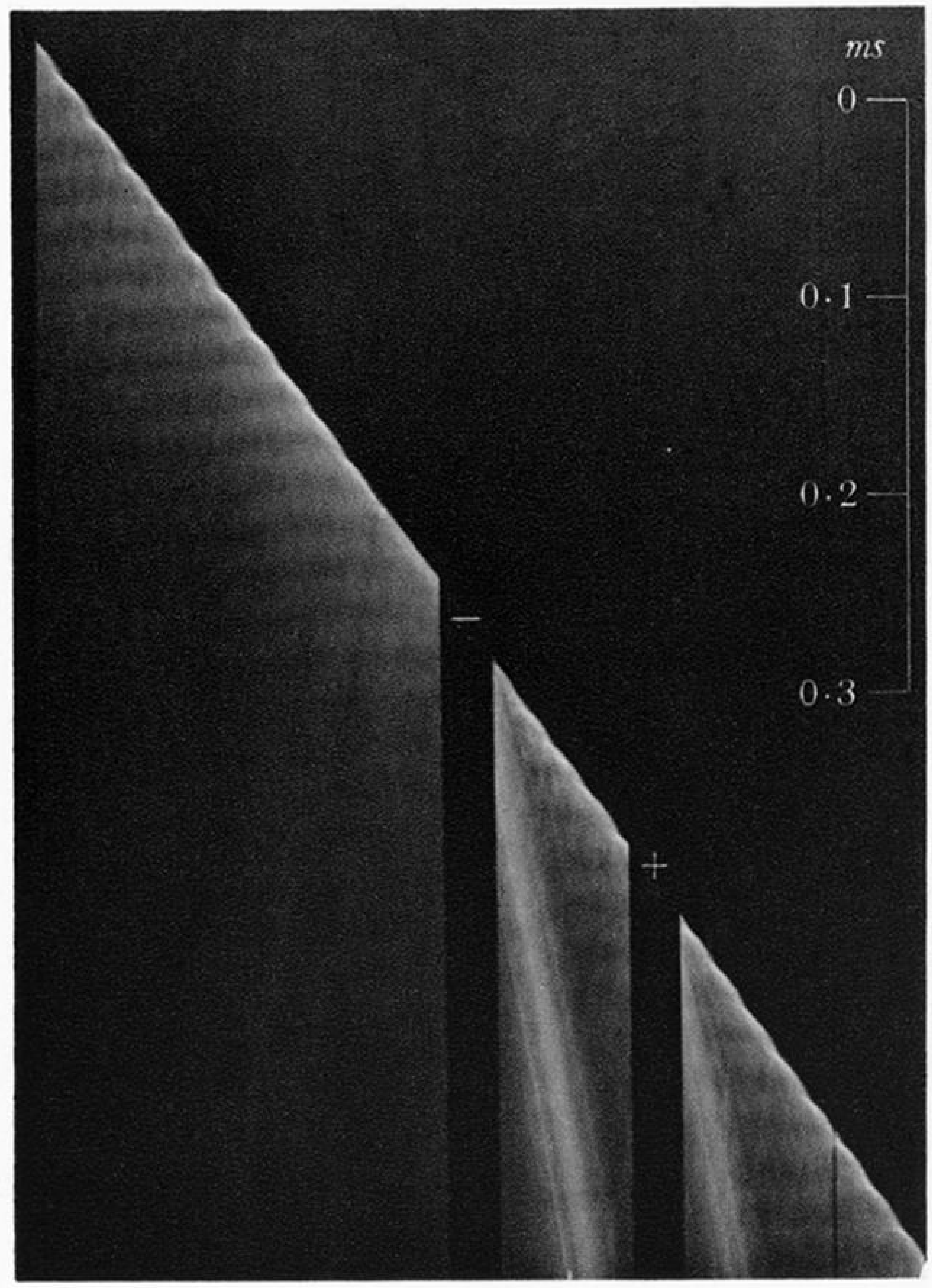


Fig. 39

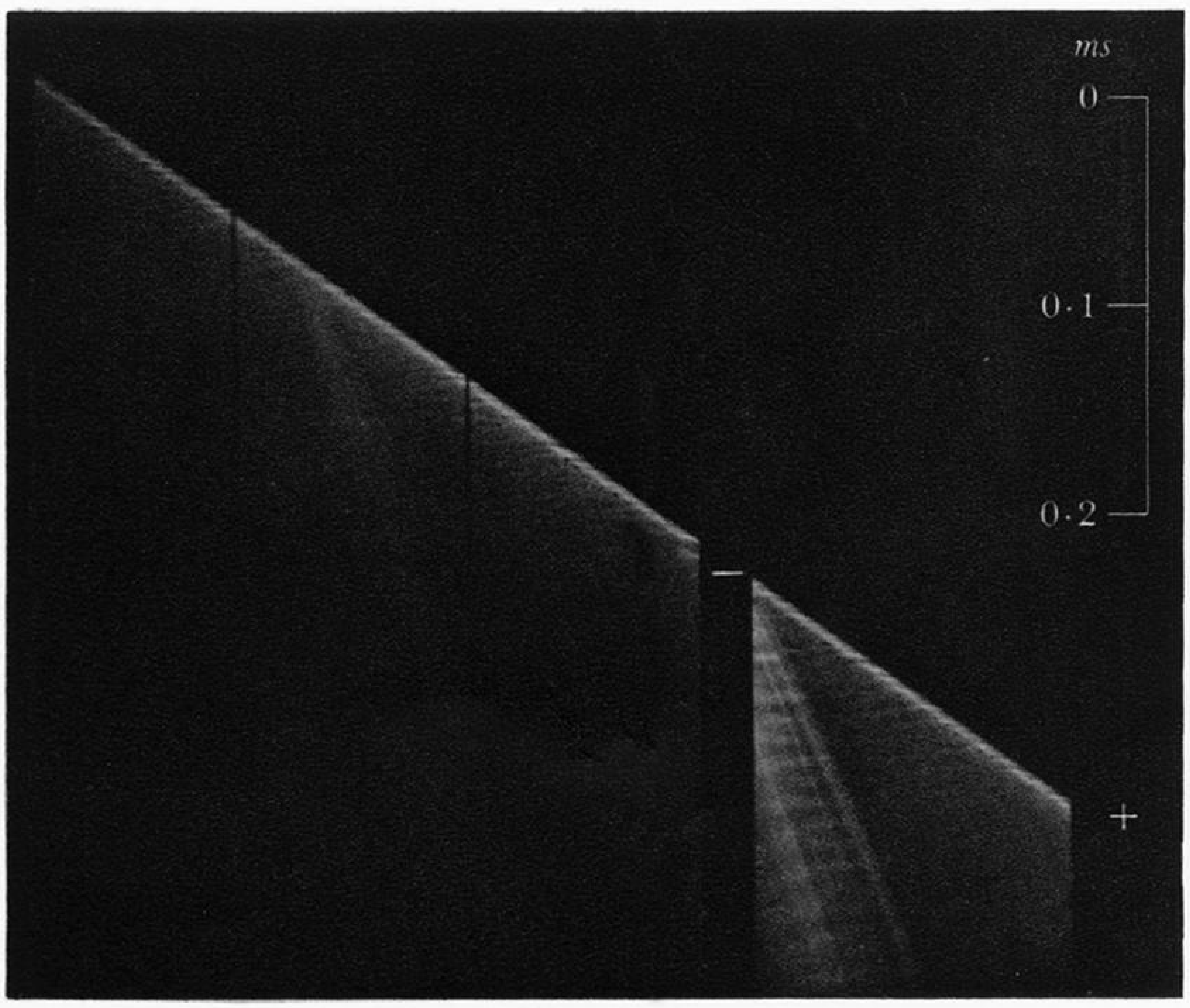


Fig. 40