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

Crystallographic Studies of Meteoric Iron

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Phil. Trans. R. Soc. Lond. A 1939 **238**, 393-421
doi: 10.1098/rsta.1939.0011

CRYSTALLOGRAPHIC STUDIES OF METEORIC IRON

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(*Communicated by S. W. J. Smith, F.R.S.—Received* 20 *March* 1939)

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Introduction

The first study of meteoric iron by X-ray methods was undertaken at the instigation of Professor S. W. J. Smith, F.R.S. some years ago. This research (Young 1926) resulted not only in the determination of the crystal structures of two of the main constituents, kamacite and taenite, but also in the important discovery of the nature of the mutual orientations of these constituents when the meteorite exhibits a Widmanstätten structure.

As is well known, the Widmanstätten figures in meteorites arise from the arrangement of kamacite lamellae on the planes of an octahedron, and for that reason a meteorite exhibiting these figures is generally referred to as an octahedrite. The kamacite lamellae, therefore, fix the $\{111\}$-planes of a hypothetical cubic lattice whose principal axes, XYZ, will be referred to as "the axes of the octahedrite".

The relationships found between the orientations of kamacite, taenite and the axes of the octahedrite may be briefly summarized as follows:

(1) A $\{111\}$-plane of the face-centred lattice of taenite is parallel to an octahedral plane of the Widmanstätten structure.

(2) A $\{110\}$-plane of the body-centred lattice of kamacite is parallel to an octahedral plane of the Widmanstätten structure, and, therefore, to a $\{111\}$-plane of taenite.

(3) The mutual orientations of kamacite and the octahedrite are such that a $[001]$-axis of the kamacite makes a small angle (not more than about 8°) with a $[1\bar{1}0]$-, $[\bar{1}01]$- or $[01\bar{1}]$-axis of the octahedrite—these axes being in the planes mentioned in (1) and (2).

When these conditions are considered, together with the lattice constants of kamacite and taenite, it is found that the network formed by joining lattice points in a $\{110\}$-plane of kamacite may be superimposed on the network belonging to a $\{111\}$-plane of taenite in such a way that the two networks fit approximately over a limited area. Figure 1 exhibits this relationship. The rhombus, $ABCD$, of angle 60° and side 2·53 A, represents a unit cell of the net on a {111}-plane of taenite, while the rhombus, $A'B'C'D'$, of angle 70° 32′ and side 2·48 A, is the corresponding unit on a {110}-plane of kamacite.

Such a fit of mutually parallel lattice planes can only occur if the principal axes of all taenite crystals are parallel to the axes of the octahedrite. That this is in fact the case is borne out by the well-known observation that taenite may often be traced from one octahedral plane of the Widmanstätten structure to another without encountering a grain boundary. The hypothetical cubic lattice mentioned above has, therefore, a real counterpart in the taenite lattice.

Let the planes $ABCD$ and $A'B'C'D'$ (figure 1) be exactly parallel and let μ be the angle between AC and $A'C'$. When $\mu = 0$ the fit is of a symmetrical nature, but in general $\mu \neq 0$ and the fit is asymmetric, the angle μ measuring the asymmetry of fit. If the orientations of the kamacite crystals are such that μ is constant but not zero, there will be twenty-four distinct orientations of kamacite—six on each Widmanstätten plane; but if $\mu = 0$, these will be reduced to twelve orientations—three on each Widmanstätten plane.

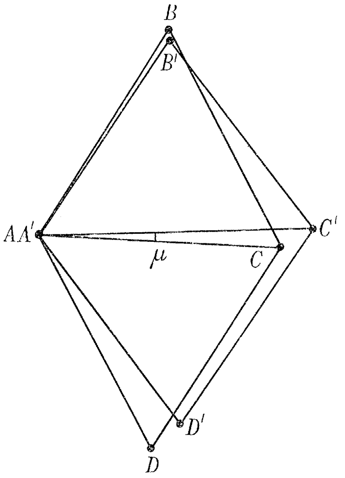

FIGURE 1

In the original investigation (Young 1926) four kamacite crystals of the Cañon Diablo meteorite were examined. The values of μ for these crystals, calculated from the data given in the paper, are 3°·6, 6°·9, 7°·5 and 3°·1. Thus it is evident that μ is neither zero nor constant. The symmetrical position appears to be avoided, but the number of crystals examined was too few to establish any preferred value or values of the angle of asymmetry.

An analysis (Young 1930) of some results obtained by Bøggild (1927) from observations of the orientations of kamacite crystals in the Toluca and Coopertown meteorites by means of the small rhabdite rods which they contained, showed that the number of preferred orientations was at least twelve. The scatter of the orientated positions, due to some extent at least to the inferior method of obtaining the orientations, was, however, too great to make a decision between twelve and twenty-four orientations possible.

In the original paper referred to above, it was pointed out that since segregation of the Widmanstätten type frequently occurs in artificial alloys, the results found for meteoric iron were important in indicating the type of orientation relationship which might be found in such manufactured alloys. A number of investigations have since been made on the orientations of crystals in some of the small-scale structures met with in artificial alloys, and in many cases orientations of the same kind as those found in meteoric iron have been proved to exist.

In particular, Kurdjumow and Sachs (1930) have examined, in a 1·4 % carbon steel, the orientations of both tetragonal and cubic martensite with respect to the single crystal of austenite from which they originated. The orientations found may be summarized as

$$\{011\}\alpha \text{ (martensite) } // \{111\}\gamma \text{ (austenite)},$$

$$[11\bar{1}]\alpha \quad ,, \quad // [\bar{1}01]\gamma \quad ,,$$

for both cubic and tetragonal forms. In the case of the cubic martensite, which has a lattice almost identical with that of kamacite in meteoric iron, the above relationships give $\mu = 5^\circ{\cdot}3$, and twenty-four orientations may occur in a single austenitic crystal.

Nishiyama (1934) has investigated the orientations of the α-crystals (body-centred) produced by cooling an alloy of nickel-iron containing 29·9 % of nickel (face-centred) in liquid air. He finds the relationships

$$\{011\}\alpha // \{111\}\gamma,$$

$$[100]\alpha // [01\bar{1}]\gamma.$$

Hence $\mu = 0$ and twelve orientations of the α-phase may be precipitated from each single crystal of the γ-phase.

Mehl and his co-workers have made extensive studies of the Widmanstätten structure in artificially produced alloys. In particular, the γ-α transformation in pure iron (Mehl and Smith 1934) and in the iron-carbon alloys (Mehl, Barrett and Smith 1933) has been examined. They find that in drastically quenched pure iron the Widmanstätten figures delineate the octahedral planes of γ-iron, and the orientations are similar to those found by Kurdjumow and Sachs for martensite. The pole-figure analysis, however, is not sufficiently good to fix the angle μ with a high degree of precision, and the relationships found must therefore be regarded as approximate only. For the slowly cooled hypo-euctoid iron-carbon alloys they obtained the orientations of the ferrite crystals using etch pits produced by copper ammonium chloride. A table of etch pit traces is given in which the observed and calculated values are compared. In spite of certain systematic residuals, they state that in their opinion the type of orientation proposed by Kurdjumow and Sachs is confirmed. An analysis of their residuals (r) by the method of least squares, using as the equation of condition

$$\mu = 5^\circ{\cdot}3 \mp r,$$

gives, however,

$$\mu = 3^\circ{\cdot}4 \pm 0^\circ{\cdot}4.$$

This value differs from $5^\circ{\cdot}3$ by more than four times the probable error, and therefore indicates a value of μ distinctly less than that proposed by Kurdjumow and Sachs.

So far as the artificial alloys are concerned it will be seen that, while all observers agree that the relationship $\{011\}\alpha // \{111\}\gamma$ occurs when a Widmanstätten structure is produced, there is some uncertainty about the exact value or values of μ. It was thought that a more exhaustive study of the crystals in meteoric iron might again have some bearing on the corresponding problems in the artificial alloys.

MATERIALS

For the first stage of this investigation the Cañon Diablo meteorite was again chosen. This meteorite is a coarse octahedrite containing about 7·3 % of nickel. It contains very little of the intimate mixture of kamacite and taenite commonly known as plessite, the taenite when present lying almost entirely in the grain boundaries of adjacent kamacite crystals. X-ray measurements of the lattice parameters of the two phases, kamacite and taenite, on such a common boundary were made and the following results obtained:

Kamacite	2864·4 X.U.
Taenite	3582·9 X.U.

DETERMINATION OF THE AXES OF THE OCTAHEDRITE FROM MEASUREMENTS OF WIDMANSTÄTTEN FIGURES

The specimen of the Cañon Diablo meteorite consisted of a flat slab of approximately 150 cm.^{2} area and 7 mm. thickness, one face of which had been polished and etched so as to reveal the familiar Widmanstätten figures. In order to determine the approximate directions of the axes of the octahedrite two other faces were cut perpendicular to the face of the slab and to one another.

Measurements of the directions of the Widmanstätten figures on all three faces of the specimen were then made and it was possible by tracing the figures over the edges of adjacent faces to assign to each trace a number by means of which the Widmanstätten plane from which the trace originated could be identified. These directions are shown in figure 2.

For purposes of reference, rectangular specimen axes, PQR, were chosen, the axes P and Q lying in the prepared face of the slab and R perpendicular to it (see figure 2). The direction cosines of the Widmanstätten planes 1, 2, 3 and 4, with respect to PQR were then calculated and the angles, ω_{12}, etc., between the Widmanstätten planes obtained as follows:

$$\omega_{12} = 105^\circ{\cdot}6,\quad \omega_{13} = 110^\circ{\cdot}9,\quad \omega_{14} = 110^\circ{\cdot}6,\quad \omega_{23} = 109^\circ{\cdot}9,\quad \omega_{24} = 113^\circ{\cdot}2,\quad \omega_{34} = 107^\circ{\cdot}3.$$

Some of these angles differ considerably from the tetrahedral angle of 109°·5, and thus it is only in an approximate sense that the four Widmanstätten planes may be regarded as lying along the {111}-planes of a cubic crystal. A similar phenomenon was noted in the Sacramento meteorite by S. W. J. Smith (1908). It has been found to some extent in all the octahedrites examined in this laboratory and appears to be particularly marked in the coarse octahedrites.

The direction cosines of the four Widmanstätten planes were used to compute the directions of the axes of the octahedrite, i.e. the principal axes of a cubic crystal whose {111}-planes approximate most closely to the observed Widmanstätten planes. The directions of these axes, XYZ, with respect to the specimen axes, PQR, are given below in the form of a cosine matrix (*a*):

$$\begin{array}{cccc} & P & Q & R \\ X & +0{\cdot}699 & +0{\cdot}530 & +0{\cdot}480 \\ Y & +0{\cdot}023 & -0{\cdot}688 & +0{\cdot}726 \\ Z & +0{\cdot}715 & -0{\cdot}497 & -0{\cdot}493 \end{array} \tag{a}$$

No great accuracy is claimed for this orientation, nor is it indeed possible from the nature of the data to obtain it. The orientation is required, first, for comparison with that obtained later by means of X-rays; secondly, because it enables the crystals of kamacite to be sorted out into families according to the Widmanstätten planes to which they belong; and thirdly, in order to eliminate from the discussion crystals of kamacite which do not belong to the Widmanstätten structure.

According to the orientation (*a*), the Widmanstätten planes 1, 2, 3 and 4 are associated respectively with the planes $(1\bar{1}\bar{1})$, (111), $(\bar{1}1\bar{1})$, and $(\bar{1}\bar{1}1)$ of the octahedrite.

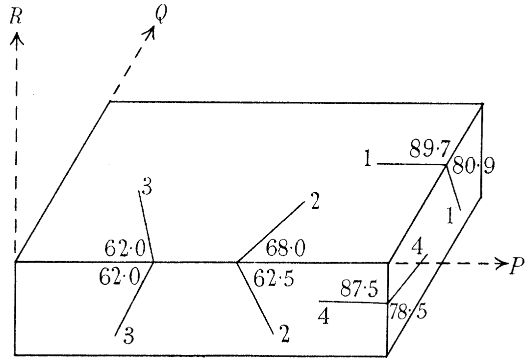

Figure 2

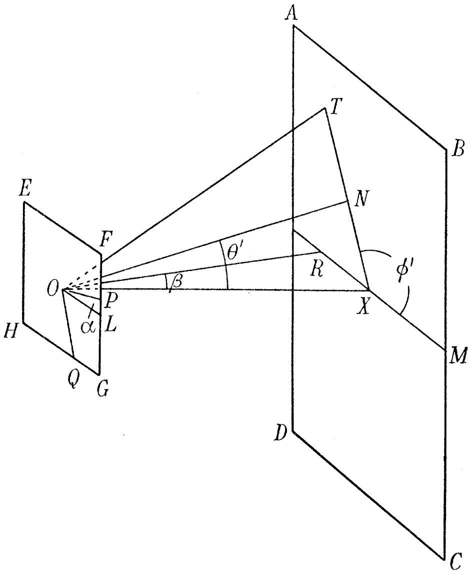

Figure 3

X-ray determination of the orientations of the kamacite crystals

The "back-reflexion" method was used to determine the orientations of the kamacite crystals. In this method the horizontal X-ray beam, XO (figure 3), limited by passing through a cylindrical tube of small bore impinges on the vertical prepared face, $EFGH$, of the specimen and irradiates a small region surrounding the point O. A crystal plane in this region whose normal, ON, makes an angle, θ', with OX will produce a Laue spot at T on the flat film, $ABCD$, where $TOX = 2\theta'$. If the direction XT on the film makes and angle ϕ' with the horizontal reference line, XM (in practice parallel to the shadow of the edge of the film-holder), the co-ordinates, θ' and ϕ', serve to specify the direction of ON with respect to the X-ray camera. In order further to define the direction of ON with respect to the specimen axes, PQR, the angle of setting, α, which OP makes with the horizontal line OL on the surface of the specimen, and the angle, β, which the normal OR, to the face, $EFGH$, makes with the X-ray beam, OX, must be obtained.

In the experiments described in this part of the investigation the specimen face was normal to the X-ray beam and thus $\beta = 0$. Hence, if the spherical co-ordinates of ON with respect to OR as pole and OP as initial line are θ, ϕ, then $\phi = \alpha - \phi'$ and $\theta = \theta'$.

In general, three Laue spots are required to compute the orientation of a single crystal. In practice, more than three were generally present, and in such cases the calculation was carried out from those which gave mutual angles of inclination most nearly agreeing with the theoretical values. The orientations so obtained rarely gave residuals of more than 0°·5 when applied to reflexions which had not been used in the calculations, and solutions by the method of least squares were therefore deemed unnecessary.

A simple transformation of co-ordinates, using the matrix, (*a*), enabled the orientation of a kamacite crystal with respect to the axes of the octahedrite to be obtained. For example, in the case of crystal *A*, the cube axes, xyz, of the kamacite are related to the axes, XYZ, of the octahedrite by means of the matrix, (*b*), given below:

$$\begin{array}{cccc} & X & Y & Z \\ x & +0{\cdot}076 & +0{\cdot}758 & -0{\cdot}648 \\ y & +0{\cdot}148 & +0{\cdot}634 & +0{\cdot}759 \\ z & +0{\cdot}986 & -0{\cdot}154 & -0{\cdot}064 \end{array} \qquad (b)$$

It is then found that the $(0\bar{1}1)$-plane of crystal *A* is inclined at an angle of 1°·5 to the $(1\bar{1}\bar{1})$-plane of the octahedrite. Thus crystal *A* belongs to the family of kamacite crystals which have formed on Widmanstätten plane 1, a fact which agreed with visual observation of the crystal on the plane of section, *PQ*.

Some 21 kamacite crystals were examined in this manner. Of these 15 were found to satisfy the test that a $\{110\}$-plane of the kamacite was nearly parallel to a $\{111\}$-plane of the octahedrite. In all these cases the crystals lay along the well-defined directions of the Widmanstätten figures. In the remaining six cases no $\{110\}$-plane of the kamacite came within 9° of a $\{111\}$-plane of the octahedrite and the crystals were either of irregular outline, or contained schreibersite inclusions (swathing kamacite). These crystals do not belong to the Widmanstätten structure. It should be remarked, however, that these six non-Widmanstätten crystals were picked out for special study, and do not therefore represent a random sample of the kamacite crystals. By far the greater proportion of kamacite crystals are of the Widmanstätten type.

Analysis of the X-ray data

The directions of the {110}-planes of the kamacite crystals which were nearly parallel to the {111}-planes of the octahedrite were used to find four mean directions corresponding to the four Widmanstätten planes. These mean directions with respect to the axes of the octahedrite, XYZ, (a), are as follows:

Plane 1:	+0·602	−0·577	−0·573
Plane 2:	+0·557	+0·566	+0·608
Plane 3:	−0·564	+0·577	−0·591
Plane 4:	−0·581	−0·611	+0·538

The angles between these planes were found to be

$$\omega_{12} = 109^\circ{\cdot}2,\quad \omega_{13} = 108^\circ{\cdot}8,\quad \omega_{14} = 108^\circ{\cdot}5,\quad \omega_{23} = 110^\circ{\cdot}3,$$
$$\omega_{24} = 110^\circ{\cdot}0 \quad\text{and}\quad \omega_{34} = 110^\circ{\cdot}0.$$

None of these angles differs from the tetrahedral angle by more than 1°·0 and it is therefore considered that these directions give a better approximation to the [111]-axes of the octahedrite than the corresponding directions derived from visual observations of the Widmanstätten figures. Using these directions, a new solution of the octahedrite axes, XYZ, with respect to the specimen axes, PQR, was computed. This is given by the matrix, (c), below, and by its means the orientations of the fifteen kamacite crystals with respect to the octahedrite were obtained.

$$\begin{array}{cccc} & P & Q & R \\ X & +0{\cdot}723 & +0{\cdot}503 & +0{\cdot}474 \\ Y & +0{\cdot}030 & -0{\cdot}708 & +0{\cdot}706 \\ Z & +0{\cdot}691 & -0{\cdot}496 & -0{\cdot}526 \end{array} \qquad (c)$$

For each crystal the angle, λ, which the {110}-plane associated with the Widmanstätten plane made with the corresponding {111}-plane of the octahedrite, as given by (c), was computed. The angle of asymmetry, μ, is only given by the angle which the [001]-axis of the kamacite makes with the corresponding [1$\bar{1}$0]-axis of the octahedrite when $\lambda = 0$. However, since λ is small, μ may be determined with sufficient accuracy by taking the complement of the angle which the [1$\bar{1}$0]-axis of the kamacite makes with the [1$\bar{1}$0]-axis of the octahedrite to which it is perpendicular when both λ and μ are zero. (All the axes mentioned in this paragraph lie, of course, nearly in a Widmanstätten plane.)

Table 1 gives for each kamacite crystal the direction cosines with respect to XYZ of the {110}-planes associated with the Widmanstätten planes and the angles λ and μ as explained above. The mean values of λ and μ are 1°·1 and 3°·8 respectively. Only for one crystal, H, does λ exceed 2°·0 and this crystal gives also an abnormally high value of μ. In all other cases μ lies between 2°·2 and 4°·7.

Figure 4 shows diagrammatically the distribution of the angles of asymmetry. It is evident that a strong concentration occurs at about 4°·1. These results therefore indicate that the symmetric position of Nishiyama and the asymmetric position of Kurdjumow and Sachs are both definitely avoided by the kamacite crystals of this meteorite. The value of μ, however, only differs by 1°·2 from that obtained by Kurdjumow and Sachs.

Table 1

Crystal	X	Y	Z	λ	μ
A	+0·565	−0·581	−0·586	0°·9	4°·7
B	+0·583	−0·580	−0·566	0°·6	4°·1
D	+0·599	+0·565	+0·567	1°·5	3°·9
E	+0·574	+0·572	+0·586	0°·6	2°·6
F	+0·567	+0·576	+0·589	0°·9	3°·2
G	+0·598	+0·582	+0·551	1°·9	2°·2
N	+0·586	+0·572	+0·575	0°·6	4°·0
O	+0·585	+0·566	+0·581	0°·8	4°·2
H	−0·551	+0·576	−0·603	2°·1	6°·1
I	−0·568	+0·570	−0·594	1°·1	4°·2
J	−0·578	+0·574	−0·580	0°·2	3°·0
M	−0·599	+0·562	−0·571	1°·6	2°·3
K	−0·566	−0·578	+0·588	0°·9	4°·1
U	−0·575	−0·596	+0·560	1°·4	4°·5
V	−0·576	−0·589	+0·568	0°·9	3°·9

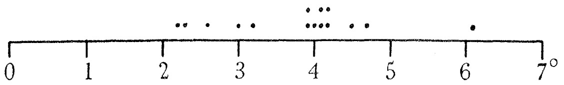

Figure 4. Distribution of angles of asymmetry.

The difference between the mean angle of asymmetry, 3°·8, and the most frequent angle of asymmetry, 4°·1, points to a slightly asymmetric distribution of the crystals round the most frequent position. The number of crystals examined is, however, insufficient to decide the reality of this effect.

The distortion of the Widmanstätten structure

A curious feature of the distribution of the {110}-kamacite planes listed in table 1 became apparent when these were plotted on a stereographic projection. Instead of showing small random deviations from the [111]-axes of the octahedrite, the poles of these {110}-planes were found to be arranged in a roughly linear manner on small portions of great circles passing through the [111]-axes. This effect is fairly well marked in the cases of crystals associated with planes 2 and 3.

In Mehl's investigation (Mehl and Derge 1937) of the Cañon Diablo meteorite this phenomenon is probably confused by the rotation of all the crystal poles into the same quadrant. No mention of such an effect is made by him.

In order to exhibit any relationship between the aforementioned great circles, the poles of the {110}-kamacite planes were plotted on gnomonic projection (in which great circles are straight lines). This is shown in figure 5.

The direction cosines of the Widmanstätten planes referred to the same system of reference are:

Plane 1:	+0·575	−0·587	−0·569
Plane 2:	+0·640	+0·570	+0·516
Plane 3:	−0·590	+0·577	−0·565
Plane 4:	−0·596	−0·551	+0·585

These planes are also shown in figure 5. It will be seen that their poles lie approximately on the same great circles as the poles of the {110}-planes. The great circles may be drawn to pass through a single point, *A*, whose direction cosines are −0·62, −0·15, +0·77.

The origin of such a phenomenon is very difficult to trace. Small deviations of crystals from their theoretical orientations are extremely common in crystal growths and are not yet fully understood. It is possible, however, to eliminate explanations involving purely crystallographic forces originating in the immediate neighbourhood of a crystal.

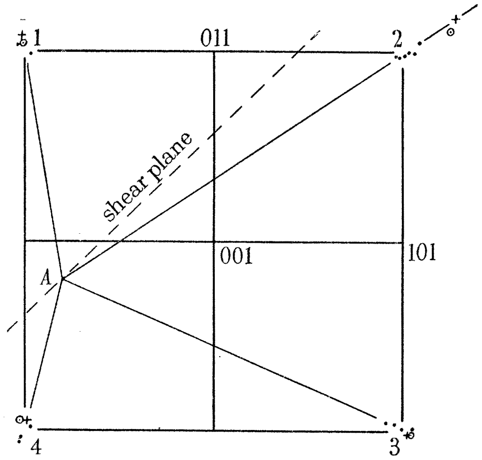

FIGURE 5. · poles of {110}-kamacite planes; ⊙ poles of Widmanstätten planes; + calculated poles of Widmanstätten planes.

On any Widmanstätten plane there are six possible orientations of the kamacite crystals arranged in trigonal symmetry about the related [111]-axis of the octahedrite. If, therefore, a kamacite crystal is subjected to forces at the time of its growth which would produce a rotation about some particular axis associated with an axis of the γ-lattice, the deviations should show trigonal symmetry about the [111]-axis of the octahedrite. Thus star effects and not linear effects should be produced in the diagram.

Among other explanations the effect of shearing of the whole mass of the meteorite is worthy of consideration.

The effect of shearing forces on a crystal aggregate is twofold: (1) to produce gliding in the crystals; (2) to produce rotations of the crystals. From this point of view the mean directions of the {110}-kamacite planes associated with the Widmanstätten planes serve as approximate reference axes of the undistorted meteorite, while the Widmanstätten planes themselves serve as indicators from which the amount of bulk distortion which has taken place can be determined.

Various attempts were made to account for the observed distortion in a quantitative manner by calculating the effect of shearing about a single axis. It was found that shear involving double slip was inconsistent with the large rotation of plane 2 (5°·1), and that only by assuming slip to have been confined mainly to a single set of parallel planes could the observed results be explained. It is easy to see that shearing of this nature would produce displacements of the poles of the Widmanstätten planes along great circles passing through the pole of the slip plane, while individual crystals would be rotated by varying amounts. This is approximately the effect which is brought out by the diagram.

Taking a shear of 5°·2 and shear plane $-0{\cdot}64$, $+0{\cdot}67$, $-0{\cdot}38$, the Widmanstätten planes would be displaced to the points shown by crosses in figure 5. These agree within the limits of observational error with the actual Widmanstätten planes.

The above results may be taken as suggesting that the meteorite was, at some period of its history, subjected to very large shearing forces, probably while still hot but after or during the period of the γ-α transformation.

Distortions of the Widmanstätten structure in meteorites have previously been noted by many observers. Among the suggestions made as to their probable origin the effect of impact with the earth has been put forward. The occurrence of Neumann bands in the kamacite is generally regarded as a result of such impact, but the fact that Neumann bands are extremely well developed in Cañon Diablo while slip planes are almost, if not entirely, absent seems to prove that plastic deformation did not then occur.

There are fairly strong grounds for believing that meteorites have originated inside some heavenly body of planetary dimensions and distortion may have taken place through the action of internal forces. The slip planes produced might then have healed by prolonged annealing before the body became disrupted into meteorites. The shearing effects discussed in this section give some support to this view.

Conclusions

The most important result of this investigation of the orientations of crystals in the Cañon Diablo meteorite is the definite confirmation that every kamacite crystal belonging to the Widmanstätten structure is related crystallographically to one and only one set of rectangular axes *XYZ*, corresponding roughly with the axes of the octahedrite as determined by visual observations.

The mode of orientation of each crystal is such that (110)-kamacite is parallel to (111)-octahedrite, and [001] kamacite is inclined at about 4° to $[1\bar{1}0]$ octahedrite, these axes lying in the planes mentioned. Small deviations from parallelism of the mutually related planes and small variations of the angle of asymmetry occur.

The structure of the meteorite thus involves twenty-four distinct orientations of the kamacite crystals.

These relations are the most convincing proof that the body-centred, α-crystals of kamacite are the result of a precipitation from a single face-centred γ-lattice of uniform orientation whose axes are those of the octahedrite.

PART II. THE MICROSCOPIC WIDMANSTÄTTEN STRUCTURE

Introduction

As is well known, the morphological characteristics of kamacite in a meteoric iron exhibiting Widmanstätten figures vary with the percentage of nickel. In octahedrites of low nickel content (7–8 %), the kamacite lamellae are relatively thick and the directions of the Widmanstätten figures not very well defined. This is shown well in the low power photograph of the Cañon Diablo reproduced in figure 10 (plate 18). As the percentage of nickel increases the kamacite lamellae decrease in thickness and the general directions of the Widmanstätten figures become more definite (see figures 11 and 12, plate 18). Thus in octahedrites containing from 10 to 14 % of nickel, the kamacite crystals are, on account of their small thickness, not so suitable for individual examination by X-ray methods as those in meteorites containing less nickel, but more accurate measurements of the directions of the Widmanstätten figures may be obtained. Such meteorites contain in addition to the macroscopic crystals of kamacite and taenite, a relatively fine-grained structure known as "plessite", in which small scale Widmanstätten figures of kamacite and taenite can be observed, even with a low power, in a still finer ground mass of the same constituents. The scale of this plessitic structure is comparable with those of similar structures found in artificial alloys, and consequently, an investigation into the directional relationships of the constituents is very desirable apart from its importance from the point of view of the origin and history of meteoric iron itself.

In this paper the structure of plessite in the Butler and Carlton meteorites is examined, and for comparison the orientations occurring in an artificial nickel-iron are also investigated.

Butler meteorite

General

The Butler meteorite is a fine octahedrite containing about 10·0 % of nickel. The large scale kamacite lamellae, bounded by taenite, run in very definite directions throughout a ground mass of coarse plessite in which the Widmanstätten structure is repeated on a much smaller scale. A low-power photograph of the actual specimen which was used is reproduced in figure 11 (plate 18).

The mean lattice parameters of the two main constituents of both the macroscopic and microscopic structures were determined and are as follows:

Macroscopic structure:

Kamacite, 2862·4 X.U.; Taenite, 3579·1 X.U.

Microscopic structure:

Kamacite, 2861·6 X.U.; Taenite, 3573·9 X.U.

Widmanstätten figures

The specimen consisted of a flat slab of material about 25 cm.^{2} in area and 0·6 cm. in thickness. Rectangular reference axes, PQR, were chosen such that P and Q lay in, and R at right angles to, one face of the slab. Measurements of the traces of the Widmanstätten planes, 1, 2, 3 and 4, were made on three mutually perpendicular planes, PQ, PR and QR, and are respectively as follows:

Plane PQ. Angles with P-axis, (P to Q+ve);

179°·5, 17°·0, 72°·0, 104°·5.

Plane PR. Angles with P-axis, (P to R+ve);

—, 9°·5, 135°·0, 66°·5.

Plane QR. Angles with Q-axis, (Q to R+ve);

78°·5, 149°·0, 19°·5, 36°·0.

The direction cosines of the four Widmanstätten planes with respect to the axes, PQR, calculated from the above data are as follows:

Plane 1:	+0·009	+0·980	−0·199
Plane 2:	+0·150	−0·493	−0·857
Plane 3:	+0·703	−0·230	+0·673
Plane 4:	−0·904	−0·234	+0·357

Hence, using the same notation as in Part I, the angles between the planes are:

$$\omega_{12} = 108^\circ{\cdot}2,\quad \omega_{13} = 110^\circ{\cdot}6,\quad \omega_{14} = 107^\circ{\cdot}9,\quad \omega_{23} = 111^\circ{\cdot}1,\quad \omega_{24} = 109^\circ{\cdot}0,\quad \omega_{34} = 110^\circ{\cdot}7.$$

None of these angles differs from 109°·5 by more than 1°·6. When they are compared with the corresponding angles in the Cañon Diablo meteorite (greatest deviation, 3°·9), the greater perfection of the Widmanstätten figures of the Butler meteorite is at once evident. The orientation of the axes, XYZ, of the octahedrite determined from the above data is, therefore, much more likely to be reliable than the corresponding orientation determination for the Cañon Diablo.

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This orientation is given by the matrix (*d*) below:

$$\begin{array}{cccc} & P & Q & R \\ X & +0{\cdot}755 & -0{\cdot}637 & -0{\cdot}157 \\ Y & +0{\cdot}635 & +0{\cdot}648 & +0{\cdot}422 \\ Z & -0{\cdot}167 & -0{\cdot}418 & +0{\cdot}893 \end{array} \qquad (d)$$

The orientations of the taenite crystals

A series of back-reflexion photographs of a plessitic area on the plane of section *PQ* were taken at intervals of 2° in the angle β (see Part I), using unfiltered iron and chromium K-radiations. Two of these are reproduced in figures 14 and 15 (plate 19). In addition to characteristic reflexions from the orientated kamacite crystals, the photographs show faint circles from randomly orientated taenite crystals on which are single spots originating from a strongly preferred orientation of a considerable portion of the taenite. For example, D125, taken with iron radiation, shows a strong spot on the $\{113\}$-α-circle but none on the $\{222\}$-α-circle, while D133 taken with chromium radiation shows a strong spot on the $\{022\}$-α-circle and a weak one on the $\{113\}$-β-circle.

Equal exposures and developments were given to all photographs. The values of β and ϕ' at which the reflexions reached maximum intensity were determined, the value of β being estimated to about 0°·5.

The following results were obtained:

$$(022)\text{-Cr:}\quad \theta' = 25^\circ{\cdot}5, \quad \phi' = 27^\circ{\cdot}8, \quad \beta = -3^\circ{\cdot}3, \quad \alpha = 62^\circ{\cdot}5,$$

$$(113)\text{-Fe:}\quad \theta' = 26^\circ{\cdot}5, \quad \phi' = 156^\circ{\cdot}8, \quad \beta = +0^\circ{\cdot}5, \quad \alpha = 103^\circ{\cdot}4.$$

The direction cosines of these axes of taenite with respect to *PQR* are respectively:

$$+0{\cdot}330 \quad +0{\cdot}198 \quad +0{\cdot}923,$$

and

$$+0{\cdot}264 \quad -0{\cdot}351 \quad +0{\cdot}899.$$

The angle between these directions is 32°·1 as compared with the theoretical angle of 31°·5 between the [011]- and [113]-axes of a cubic crystal. It is evident, therefore, that a possible explanation of these spots is a single, strongly preferred orientation of the taenite crystals.

The directions quoted lead to two solutions for such an orientation. The $(\bar{1}13)$-β spot obtained with chromium radiation was found to be in almost exact agreement with one of these solutions, the observed and calculated values of ϕ' being 255°·5 and 255°·6, respectively. This solution is given by matrix (*e*) below:

$$\begin{array}{cccc} & P & Q & R \\ X & +0{\cdot}753 & -0{\cdot}644 & -0{\cdot}134 \\ Y & +0{\cdot}636 & +0{\cdot}660 & +0{\cdot}401 \\ Z & -0{\cdot}170 & -0{\cdot}387 & +0{\cdot}906 \end{array} \qquad (e)$$

When orientations (*d*) and (*e*) are compared they are found to be practically identical, the angles between the corresponding X, Y and Z axes being 1°·4, 1°·4, and 1°·9, respectively.

X-ray photographs of different plessitic regions of the plane PQ always gave the same general pattern, although slight variations became evident when measurements of the films were made. Here we have a direct proof that in the plessite of meteoric iron a considerable portion of the taenite is so orientated that the mean directions of its principal axes differ little from the axes of the octahedrite.

The values of ϕ obtained from five back-reflexion photographs of different plessitic regions with chromium radiation and $\beta = 0$ were 27°·0, 30°·3, 28°·8, 27°·8 and 29°·2, while with iron radiation the corresponding values were 308°·3, 307°·7, 308°·0, 305°·7 and 307°·4. These values give for the probable variation in the direction of a single axis of a taenite crystal ±0°·32 (in one degree of freedom only). By comparing the directions of the Widmanstätten planes and the [111]-axes of the system XYZ (*d*), the probable error of a single axis of orientation (*d*) was found to be ±0°·55 (in two degrees of freedom). The probable deviation of corresponding axes of (*d*) and (*e*) from one another, if statistically identical, is therefore ±0°·7. Although the actual deviations are all greater than this value, they are not substantially so, and the differences cannot, therefore, be regarded as significant from the point of view of the theory of errors. These residuals, therefore, cannot with certainty be ascribed to physical effects such as, for example, shearing.

More reliable evidence that this meteorite has been subject to shear is of course available from the measures of the angles between the Widmanstätten planes themselves, but such shear, if it exists, is evidently small compared with that found in the Cañon Diablo meteorite. This is not surprising in view of the considerable differences in the macroscopic structures of the two meteorites: in Cañon Diablo the large kamacite crystals would present little resistance to gliding, while in Butler the fine-grained ground mass of plessite would offer a greater resistance.

The orientations of the kamacite crystals

The series of back-reflexion photographs referred to in the previous section also served to determine the orientations of the kamacite crystals. From these orientations the pole figure shown in figure 6 was constructed. A stereographic projection was used, the scale being indicated by the small circle 30° from the R-axis. No attempt has been made to show details of the figure by graded shading, but the loci of maximum intensity are indicated by dotted lines.

Assuming an angle of asymmetry of 4°·0, the positions of all poles of {110}-planes of the twenty-four kamacite crystals falling within the region of the diagram were computed, orientation (*e*), determined by X-rays, being used. These poles are shown by round dots on the figure.

Each pole is marked with a capital letter indicating the Widmanstätten plane to which the kamacite crystal belongs, A, B, C and D representing (111), $(1\bar{1}\bar{1})$, $(\bar{1}1\bar{1})$ and $(\bar{1}\bar{1}1)$ planes respectively. When the Widmanstätten type of orientation occurs, the kamacite crystals may be divided into three groups of roughly similar orientation (cf. Bøggild 1927). The crystals of these groups have been lettered X, Y and Z, depending on whether a kamacite cube axis makes an angle of about 10° with the X, Y or Z axis. The crystals have also been designated a or b in order to distinguish between the two crystals belonging to the same Widmanstätten plane and of the same approximate orientation but having equal and opposite values of μ. Thus the pole ZCa is due to a kamacite crystal belonging to the $(\bar{1}1\bar{1})$ Widmanstätten plane (plane 1 of this meteorite), one cube axis of which makes an angle of about 10° with the Z-axis of the octahedrite; ZCb fulfils the same conditions but the angle of asymmetry is opposite to that of ZCa.

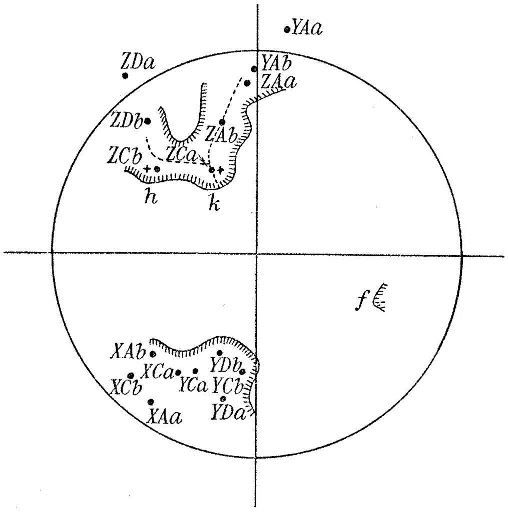

FIGURE 6. [110]-pole diagram for Butler meteorite.

It will be seen that except for the faint figure marked f there is general agreement between the predicted positions of the [011]-axes and the distribution of the observed diffraction effects. This must be regarded as proof that twenty-four orientations of kamacite of the type found in Cañon Diablo occur also in the plessite of the Butler meteorite and that the angle of asymmetry μ cannot differ greatly from 4°. The way in which the bulges h and k fit round the poles ZCb and ZCa is very striking. A value of μ as great as 5°·3, corresponding to the Kurdjumow-Sachs type of orientation, is definitely too large to fit the figure well. This is at once evident from the positions of the small crosses which represent the theoretical positions of ZCa and ZCb for $\mu = 5^\circ{\cdot}3$.

In order to determine μ more accurately an attempt was made to locate the position of maximum intensity of ZCa. This spot is both strong and well isolated and therefore its position is not likely to be affected much by overlapping.

The position of maximum was found to be given by the quantities

$$\theta' = 17^\circ{\cdot}4, \quad \phi' = 348^\circ{\cdot}5, \quad \beta = -2^\circ{\cdot}5, \quad \alpha = 103^\circ{\cdot}4,$$

from which the direction cosines with respect to XYZ are $-0{\cdot}366$, $+0{\cdot}466$, $+0{\cdot}806$.

When $\mu = 4°{\cdot}0$, the theoretical direction of ZCa with respect to XYZ is given by $-0{\cdot}358$, $+0{\cdot}457$, $+0{\cdot}815$, which makes an angle of $0°{\cdot}8$ with the observed direction. The observed direction of the axis ZCa also makes an angle of $0°{\cdot}8$ with the plane $(\bar{1}1\bar{1})$ of the taenite as determined by X-rays and an angle of $1°{\cdot}8$ with the Widmanstätten plane 1 as determined from measurements of the macroscopic Widmanstätten figures. The spot ZCa corresponds, therefore, to that {110}-plane of kamacite which is perpendicular to the Widmanstätten plane. It is interesting to note that the mean orientation of the aggregate of kamacite crystals giving rise to the spot ZCa agrees more closely with that to be expected from the taenite lattice in their neighbourhood than with that given by the Widmanstätten figures.

The angle of asymmetry can be obtained from the direction corresponding to the spot ZCa by taking the complement of the angle which this direction makes with the [110]-axis of the taenite. This gives

$$\mu = 4°{\cdot}1 \pm 0°{\cdot}3.$$

This value is identical with that already found for the Cañon Diablo meteorite.

The faint diffraction spot f, which is not accounted for by the predicted orientations of the kamacite, was found to be absent from photographs of different regions of the section PQ. The spot doubtless arises from an isolated kamacite crystal not orientated according to the usual rule.

Of frequent occurrence in the plessite of the Butler meteorite are small specks of a material known as schreibersite (nickel-iron phosphide). This material is found more plentifully, however, in other meteorites and is always surrounded by kamacite, known technically as "swathing kamacite". Researches made in this laboratory have shown that swathing kamacite is not orientated according to the rules found for the kamacite of the Widmanstätten structure. It is not surprising, therefore, that crystals of kamacite have been found in both the Cañon Diablo and Butler meteorites, which do not conform to the laws found to apply in a Widmanstätten structure.

Carlton meteorite

General

The Carlton meteorite, like the Butler, is a fine octahedrite. It contains about 12·8 % of nickel, but the plessitic fields are not so extensive as, and of a much finer texture than, those of the Butler. A low-power photograph of the actual specimen is reproduced in figure 12 (plate 18).

The mean lattice constants of the main constituents are as follows:

Macroscopic structure:

Kamacite, 2863·8 X.U.; Taenite, 3578·1 X.U.

Microscopic structure:

Kamacite, 2862·4 X.U.; Taenite, 3570·8 X.U.

Results of the investigation

As the method of investigation was similar to that adopted in the case of the Butler meteorite, the details of the observations will be omitted and the results given in a condensed form.

The angles between the Widmanstätten planes were 107°·5, 108°·5, 107°·3, 110°·0, 110°·5, and 112°·8.

The largest residual from 109°·5 is 3°·3 as compared with 1°·6 in the Butler and 3°·9 in the Cañon Diablo, while the corresponding root mean square residuals are ±1°·9, ±1°·3 and ±2°·5, respectively. These figures clearly indicate that the magnitude of the distortion occurring in the Carlton meteorite lies between those of the Cañon Diablo and Butler. This is the nature of the result which would be expected if the resistance to distortion arises mainly in the fine-grained plessitic fields, of which the largest occurs in the Butler and the smallest (practically none) in the Cañon Diablo.

The orientation of the octahedrite determined from the Widmanstätten figures agreed very closely with the mean orientation of the taenite in the plessitic fields, the deviations in the axes, XYZ, being 0°·6, 0°·8 and 0°·9, respectively. As already shown for the Butler meteorite these are all within the accidental errors of a determination of orientation using Widmanstätten figures.

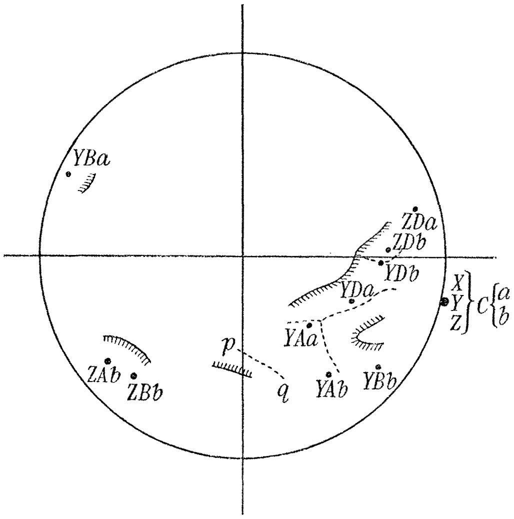

FIGURE 7. [110]-pole diagram for Carlton meteorite.

The pole figure for the Carlton meteorite (figure 7) was constructed in a similar manner to that of the Butler meteorite, the angle of asymmetry being again taken as 4°·0. There can be little doubt that here also there are twenty-four preferred orientations of the kamacite crystals, but the maxima are not sufficiently marked to exclude definitely the Kurdjumow-Sachs type of orientation.

The figure also shows a strong maximum pq, not belonging to the Widmanstätten type of orientation, thus confirming a phenomenon already met with in the other meteorites which have been studied. As the Carlton is very rich in schreibersite, there is little difficulty in ascribing this sporadic maximum to swathing kamacite.

NICKEL-IRON ALLOY

Widmanstätten figures

It is well known that imperfect Widmanstätten structures can be produced on a small scale in the grains of some artificial alloys of nickel and iron, and it is interesting, therefore, to compare the orientation relationships existing in such structures with those found in the natural nickel-iron alloys of meteorites.

An alloy containing nearly the same percentage of nickel as that found in the Butler meteorite had been prepared for Professor Smith by Mr G. O. Harrison. Analysis had given Ni, 10·5 %; Fe, 89·5 %; Mn, trace. The alloy had cooled from the molten state in the furnace and a portion of it was placed at my disposal.

Two grains were picked out which showed remarkably good Widmanstätten figures and which were of sufficient area to be investigated by X-ray methods. A micrograph, of the better of these (grain 2), is shown in figure 13 (plate 18). The usual reference axes, *PQR*, were chosen and the angles which the Widmanstätten figures on the plane of section, *PQ*, made with the *P*-axis were measured and are as follows:

Grain 1	40°·4,	71°·4,	134°·7,	148°·1.
Grain 2	29°·2,	99°·0,	151°·7,	156°·2.

A set of such measurements on one section of a single grain cannot give a unique solution for the orientation of the γ-lattice from which the crystals in that grain are presumed to have been precipitated, but two solutions which are mirror images of one another in the plane of section can be obtained. One of these only is correct.

The solutions found for grains 1 and 2 are given by (*f*) and (*g*) respectively.

$$\begin{array}{cccc} & P & Q & R \\ X & +0{\cdot}979 & +0{\cdot}125 & \pm 0{\cdot}162 \\ Y & -0{\cdot}104 & -0{\cdot}380 & \pm 0{\cdot}919 \\ Z & -0{\cdot}177 & +0{\cdot}917 & \pm 0{\cdot}358 \end{array} \qquad (f)$$

$$\begin{array}{cccc} & P & Q & R \\ X & -0{\cdot}709 & +0{\cdot}214 & \pm 0{\cdot}672 \\ Y & +0{\cdot}557 & -0{\cdot}413 & \pm 0{\cdot}720 \\ Z & +0{\cdot}432 & +0{\cdot}885 & \pm 0{\cdot}174 \end{array} \qquad (g)$$

The directions of the traces of {111}-planes of the γ-lattices of grains 1 and 2 on *PQ* were calculated from (*f*) and (*g*) and are as follows:

Grain 1	41°·9,	71°·9,	133°·5,	147°·5.
Grain 2	28°·9,	98°·6,	151°·7,	157°·8.

These values agree sufficiently well with the observations to prove that the figures observed are indeed traces of {111}-planes of lattices whose orientations are given by (*f*) and (*g*) above, and that these orientations must be correct to within a few degrees.

Orientations of the α-crystals

Back-reflexion photographs of grains 1 and 2 were taken with chromium radiation and with $\beta = 0^\circ$. These are reproduced in figures 16 and 17 (plate 19).

The photographs show two sets of diffraction spots due to {211}-planes of the α-crystals. These spots lie on circles at $\theta' = 12^\circ{\cdot}3$ and $\theta' = 27^\circ{\cdot}2$. No spots or other diffraction effects due to the presence of γ-crystals are observable on the photographs and other photographs taken at different angles of the plane of section with the X-ray beam failed to exhibit such effects. This is in agreement with the work of others on the iron-nickel system but it does not preclude the possibility of a very small amount of the γ-phase being present.

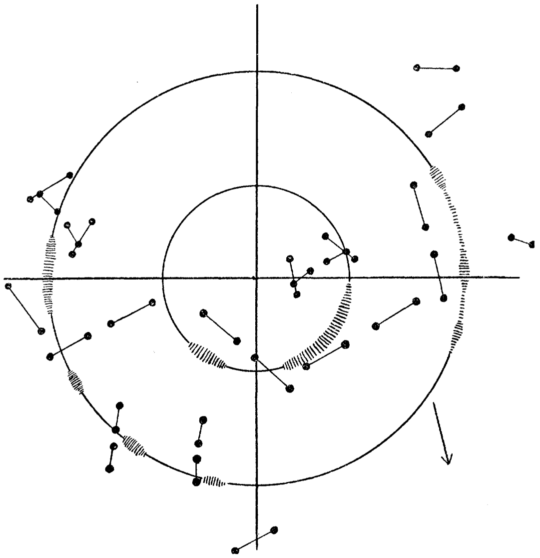

FIGURE 8. [211]-pole diagram for grain 1.

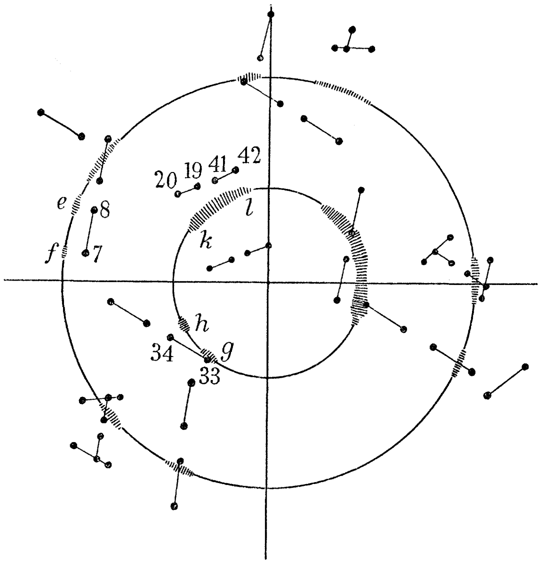

FIGURE 9. [211]-pole diagram for grain 2.

Adopting the usual condition of parallelism of a {110}-plane of the α-lattice with a {111}-plane of the γ-lattice and a value of $3^\circ{\cdot}0$ for the angle of asymmetry, the orientations (*f*) and (*g*) were used to predict the directions of all [112]-axes of α-crystals for which $\theta' < 35^\circ$. It was found that one of the two solutions for each grain gave approximate agreement between the observed positions of the diffraction spots and the predicted directions of the [112]-axes.

Figures 8 and 9 were obtained by plotting θ' and ϕ' as polar co-ordinates, θ' being taken as radius vector. The intensity maxima on the diffraction circles at $12^\circ{\cdot}3$ and $27^\circ{\cdot}2$ have been indicated on the diagrams. Poles joined by straight lines belong to crystals of nearly the same orientation but having equal and opposite values of μ.

For grain 1 (figure 8) there is only an approximate agreement of the positions of diffraction maxima with the ϕ'-angles of nearby [211]-poles. There can be little doubt, however, that this is largely due to a small error in orientation (f), for by displacing the poles in the direction of the small arrow a much better fit is obtained.

For grain 2 (figure 9) there is much better agreement between observation and theory. In particular a zero value of μ is definitely excluded. Although no exact value of μ can be obtained from the figure, a value of slightly over 3° does not appear unlikely. This is borne out, for example, by the identification of spots e and f with poles 8 and 7, g and h with 33 and 34, and the almost continuous arc kl with the almost equally spaced poles 20, 19, 41 and 42.

Whatever the exact value of μ may be there can be little doubt that in this alloy of nickel and iron the α-crystals are orientated according to the general rules found to apply in meteoric iron.

Examination of alloy after heat treatment

The specimen was heated in a vacuum furnace to a temperature of 400° C at which it was maintained for two hours and then allowed to cool. X-ray examination showed no change in the nature of the diffraction effects. Similar treatments up to 501° C and 557° C gave similar results. When, however, the specimen was heated to 582° C for three hours and allowed to cool, a small amount of γ-phase could be detected.*

Photograph AX39R, figure 18 (plate 19), was obtained after heating to 602° C for three hours. This is a back-reflexion photograph of grain 2 taken with iron radiation and settings $\alpha = 0$ and $\beta = 0$. Table 2 gives the θ' and ϕ' co-ordinates of the diffraction maxima due to the γ-phase, and the crystal planes from which these maxima originate.

TABLE 2

Spot	Int.	Plane	θ'	ϕ'
1	*s*	131	26°·5	+ 0°·9
2	*w*	311	26°·5	−131°·4
3	*m*	400	11°·8	+122°·3
4	*w*	400	11°·8	+ 5°
5	*w*	400	11°·8	− 16°

Spots 2, 4 and 5 are not visible in the reproduction but are quite definite in the original negative.

The spots 1 and 2 were found to be due to the (131)- and (311)-planes of lattice (g) with the positive signs in R, and therefore serve to eliminate one of the two alternative lattice orientations deduced from the measurements of the Widmanstätten figures. On this view these two spots come from γ-crystals which are due to α-crystals having retransformed in such a way as to reproduce the original γ-orientation.

The orientation of these γ-crystals is not quite identical with that adopted in the

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* It is of interest to note that Dr D. E. Adams, working under the direction of Professor Smith upon the thermo-magnetic properties of this alloy, had come to exactly the same conclusion.

discussion of the orientations of the α-crystals in the preceding section. The angles, ϕ', computed for the (131)- and (311)-planes of orientation (*g*) gave residuals of $-4^\circ{\cdot}8$ and $+4^\circ{\cdot}2$ when compared with the observed values. A new solution (*h*) of the orientation of the γ-lattice was therefore made and gave residuals of $-0^\circ{\cdot}2$ and $0^\circ{\cdot}0$ in ϕ'.

$$\begin{array}{cccc} & P & Q & R \\ X & -0{\cdot}697 & +0{\cdot}243 & +0{\cdot}675 \\ Y & +0{\cdot}568 & -0{\cdot}386 & +0{\cdot}726 \\ Z & +0{\cdot}437 & +0{\cdot}890 & +0{\cdot}131 \end{array} \qquad (h)$$

The calculated directions of the traces of the {111}-planes of (*h*) on the plane of section *PQ* are $28^\circ{\cdot}6$, $98^\circ{\cdot}7$, $151^\circ{\cdot}3$ and $157^\circ{\cdot}6$ and are still in very good agreement with the observed directions of the Widmanstätten figures. It is probable, therefore, that (*h*) gives the orientation of the original γ-lattice with considerable accuracy.

Spots 3, 4 and 5 which are due to reflexions from {400}-planes of γ-crystals do not originate from such crystals having the original orientation (*h*) of the γ-lattice. In order to account for these spots it must be realized that if the orientation relationships which have been shown to occur in a γ-α transformation also hold for an α-γ transformation any α-crystal has a choice of twenty-four ways of retransforming to γ. There are thus 24×24 ways in which a γ-crystal can be formed from the original γ-solid solution by the double transformation γ-α-γ. Not all of those 24×24 orientations are, however, distinct: the original orientation occurs twenty-four times; four others each occur six times; sixteen occur thrice; and 480 occur once, giving altogether 501 distinct orientations. It seemed plausible that spots 3, 4 and 5 might arise from γ-crystals orientated in some of the 500 distinct ways which differ from the original orientation.

As the three spots in question all arise from cube planes, it is very easy to test this theory of their origin. The direction cosines, $X_c Y_c Z_c$, of cube planes of all the 501 orientations were calculated, assuming $\mu = 3^\circ{\cdot}0$ (as these belong to twenty-four general types it is only necessary to compute twenty-four orientations, the others being obtained cyclically). It was then found that three of these cube planes had nearly the same direction cosines as those, *XYZ*, corresponding to the spots on the photograph. Table 3 gives the observed and calculated direction cosines with respect to the *XYZ* system, orientation (*h*) being used. The calculated co-ordinates θ_c and ϕ'_c and the residuals $\phi' - \phi'_c$ are also given.

TABLE 3

Spot	X	Y	Z	X_c	Y_c	Z_c	θ_c	ϕ'_c	$\phi' - \phi'_c$
3	$+0{\cdot}694$	$+0{\cdot}716$	$-0{\cdot}073$	$+0{\cdot}689$	$+0{\cdot}712$	$-0{\cdot}131$	$15^\circ{\cdot}1$	$120^\circ{\cdot}7$	$1^\circ{\cdot}6$
4	$+0{\cdot}513$	$+0{\cdot}834$	$+0{\cdot}202$	$+0{\cdot}513$	$+0{\cdot}828$	$+0{\cdot}201$	$10^\circ{\cdot}7$	$3^\circ{\cdot}3$	$1^\circ{\cdot}7$
5	$+0{\cdot}537$	$+0{\cdot}801$	$+0{\cdot}265$	$+0{\cdot}419$	$+0{\cdot}823$	$+0{\cdot}285$	$14^\circ{\cdot}8$	$12^\circ{\cdot}4$	$3^\circ{\cdot}6$

In view of the uncertainty in μ the agreement between the observed and calculated values may be regarded as satisfactory. Thus there is no difficulty in accounting for the observed spots by means of the double transformation γ-α-γ, the orientation relationships obtaining in the α-γ transformation being the same as those found for the γ-α transformation.

Determination of the mean angle of asymmetry

The photograph AX39R shows, in addition to the five reflexions from γ-phase crystals, several from α-phase crystals. Three of these latter reflexions are very strong, the {220}-planes concerned lying practically at the correct glancing angle, and are sufficiently well defined to make a more precise determination of the angle of asymmetry possible. Table 4 gives the observed values of θ' and ϕ' for these spots (which originate from crystals belonging to the same Widmanstätten plane), and the corresponding values of θ_3, ϕ'_3 and θ_4, ϕ'_4 calculated for angles of asymmetry of 3°·0 and 4°·0, respectively.

Table 4

Spot	θ'	ϕ'	θ_3	ϕ'_3	θ_4	ϕ'_4
6	17°·4	−76°·5	17°·6	−76°·8	17°·5	−73°·9
7	17°·4	−64°·5	17°·2	−63°·7	17°·2	−66°·7
8	17°·4	−43°·2	17°·6	−46°·3	17°·8	−43°·5

As the calculated values of ϕ' depend on the orientation (h) which may be in error by anything up to 1°, the differences in ϕ' for different spots are more significant than the absolute values. For spots 6 and 7 the data give a value of μ of 3°·19, and for 7 and 8 a value of 3°·67. These give a mean value of 3°·4. A probable error of ±0°·5 in the measurement of ϕ' gives a probable error of ±0°·1 in the resulting value of μ. It would therefore appear that a slight discrepancy exists in the values of μ determined from different pairs of spots, but it must be realized that the calculations are based on the assumption that a {110}-plane of an α-crystal is exactly parallel to a {111}-plane of the original γ-lattice and this is probably not strictly true.

It is important to recognize that any one of the aforementioned spots arises from numerous small crystals having approximately the same orientation. Measurements of the positions of such spots yield, therefore, a statistical mean value of the angle of asymmetry and not isolated values for particular crystals.

The sizes of the spots 6, 7 and 8 indicate a range in the angle of asymmetry of about ±1°·5. These spots, however, all lie on a fairly continuous diffraction arc, showing that in addition to the group of crystals orientated fairly closely to $\mu = 3°·4$, there is a residue in which the orientation approximates only to the Widmanstätten type. These latter crystals may deviate from the Widmanstätten orientation by angles up to 7 or 8 degrees.

PART III. THE MECHANISM OF THE γ-α TRANSFORMATION

Theory of the mechanism

The mechanism of the γ-α transformation has been discussed by Nishiyama (1934), Kurdjumow and Sachs (1930), Mehl and Derge (1937) and others. These discussions, however, are mainly concerned with attempts to account for the exact orientation of the α-lattice with respect to the γ-lattice from which it originated and do not add very much to what was originally proposed by Professor S. W. J. Smith and myself concerning the origin of the Widmanstätten structure. In particular, they cannot explain the occurrence of taenite in meteorites.

As is well known, a body-centred (α) cubic lattice can be obtained by contracting a face-centred (γ) cubic lattice in a [001]-direction and expanding it uniformly in a plane at right angles to that direction, by definite amounts. If a_γ and a_α are the lattice parameters and b_γ and b_α the identity periods along the [110]- and [111]-axes of the γ and α lattices respectively, the following relations hold:

$$a_\alpha = \frac{\sqrt{2}}{\sqrt{3}}\, a_\gamma \left(\frac{b_\alpha}{b_\gamma}\right), \quad \text{and} \quad a_\alpha = \frac{2}{\sqrt{3}}\, b_\gamma \left(\frac{b_\alpha}{b_\gamma}\right).$$

For kamacite and taenite, $\dfrac{b_\alpha}{b_\gamma} = 0{\cdot}980$. Hence the kamacite lattice may be derived by a contraction of about 20·0 % in the [001]-axis and an expansion of about 13·1 % in the [110]- and [$1\bar{1}0$]-axes of the taenite, these axes becoming the three cube axes of the kamacite.

The result of this mechanism would be to orientate a kamacite crystal with respect to the γ-matrix of taenite according to relations of the type I, given below.

Type I [001]-kamacite // [001]-taenite,
[010]-kamacite // [$\bar{1}10$]-taenite,
[100]-kamacite // [110]-taenite.

Relationships of this type would give rise to three possible orientations of the kamacite crystals corresponding to the three ways in which a taenite cube axis can become a kamacite cube axis. Such orientations of the crystals of meteoric iron were described by Bøggild (1927), but it was pointed out (Young 1930) that his results were more accurately represented by relations of the type II, given below.

Type II (101)-kamacite // (111)-taenite,
[010]-kamacite // [$\bar{1}10$]-taenite.

Relationships of this second type would give rise to twelve distinct orientations of the kamacite crystals, but these differ in orientation by some 10° only from related members of type I. Hence it is merely in a very rough sense that the crystals of meteoric iron so far discussed can be said to obey relationships of type I, and they do not even obey exactly relationships of type II which requires $\mu = 0$.

Orientations of type II were found by Nishiyama (1934) in an artificial nickel-iron in which γ-α transformation had taken place at a low temperature and a very simple mechanism was suggested by him to account for the observed results.

This mechanism consists of a shearing of (111)-planes over one another in a $[11\bar{2}]$-direction followed by an expansion of the whole lattice in a $[1\bar{1}0]$-direction in such a way that the $[10\bar{1}]$- and $[01\bar{1}]$-axes remain practically unaltered in length. The amount of the shear is such that the atoms *B* and *D* (figure 19) in the planes immediately above and below the (111)-plane containing the atoms *C* move by $\frac{1}{6}$ of the distance between atoms along a $[11\bar{2}]$-axis, the atoms *A* and *E* (not shown in the figure) two planes above and below *C* by $\frac{2}{6}$, etc. The expansion in the $[1\bar{1}0]$-direction is of course perpendicular to the direction of shearing and is of such a value that the resulting crystal is body-centred cubic. In figure 19 the initial positions of the atoms are shown by black dots; the intermediate positions after shearing by circles; and the final positions by crosses.

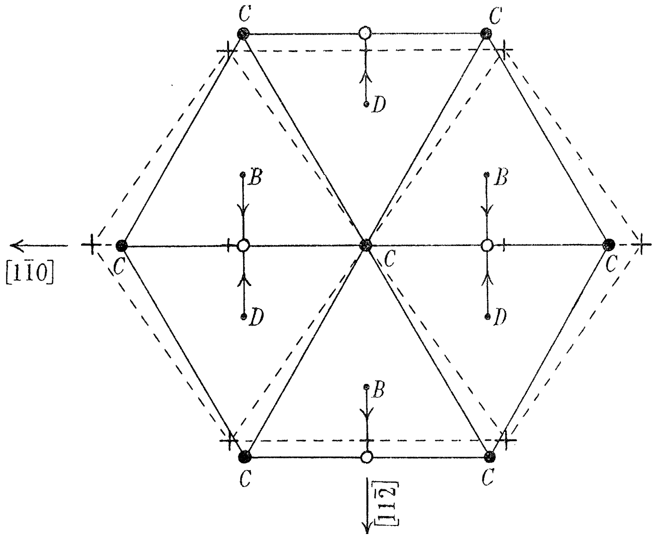

FIGURE 19. The Nishiyama mechanism.

It is not suggested that the shearing and expansion movements actually take place consecutively—the mechanism is to be regarded merely as a convenient way of describing the resultant displacements of the atoms.

The Nishiyama mechanism has the advantage of involving simple symmetrical movements of the atoms. Thus in the shearing movement the atoms *B* and *D* move symmetrically with respect to the atoms *C*. In the mechanism proposed by Kurdjumow and Sachs (1930), however, an asymmetric shearing movement is required parallel to a $[10\bar{1}]$- or $[01\bar{1}]$-axis and it consequently involves closer approaches of atoms than those required in the Nishiyama mechanism. A further shearing of atoms in a (111)-plane has then to take place before the body-centred crystal is formed. On these grounds the Kurdjumow-Sachs mechanism appears unnecessarily complicated and somewhat unsound theoretically. It should be pointed out, in this connexion, that although the movements parallel to a $[10\bar{1}]$-axis are in the direction in which a face-centred cubic crystal usually glides, that the displacements required are of quite a different magnitude from those required in simple gliding in which an atom *B* has to travel to one of the adjacent positions *B*. There is no reason even to assume that in gliding the movement of an individual atom is along the straight line *BB* and not, as is more probable, along some curved path between adjacent lattice points.

The Kurdjumow-Sachs mechanism would give rise to orientations of the type III, given below.

Type III (101)-kamacite // (111)-taenite,

$[1\bar{1}\bar{1}]$-kamacite // $[10\bar{1}]$-taenite.

$\mu = 5^\circ\, 16'$.

Mehl and Derge (1937) have recently obtained results from a study of the Cañon Diablo meteorite which favour orientations of this type. Their method of analysis, however, is not such as would determine the mean value of μ with any precision.

In Part I of the present investigation it is clearly shown that the value of μ (4°·1) in the Cañon Diablo meteorite is definitely less than the value (5°·3) required by the Kurdjumow-Sachs mechanism.

Further, in Part II it is shown that μ is 4°·1 in the Butler meteorite and 3°·4 in an artificial alloy containing the same percentage of nickel. In the Carlton meteorite μ has not been determined so accurately, but while the Kurdjumow-Sachs value is not definitely excluded, there is no doubt that it is greater than zero. Where the value has been determined with some precision, however, it is always definitely less than 5°·3.

Mehl has suggested that orientations of type III occur at high temperatures and those of type II at low temperatures. It is of some interest to examine this suggestion in the light of the results obtained in the present investigation.

An α-crystal may be considered as growing from a small nuclear crystal of the same material. It is the orientation of this nuclear crystal which determines the orientation of the complete crystal and it is therefore important to consider how the nuclear crystal is formed. The simplest way in which this formation can take place, fulfilling the condition that (101)-α is parallel to (111)-γ, is by means of the Nishiyama mechanism. At the boundary of the crystal there is probably a region of transition through several atomic layers from the α-lattice to the γ-lattice. In order to simplify the problem, however, it is useful to consider the case of sudden transition at the common boundary of the two lattices. As the crystals of kamacite grow in the form of plates, the conditions obtaining at the surfaces of the plates are more significant than those at the edges. Consequently only the former need be considered.

Now the identity period along the [010]-α axis is 2864 X.U., while that along the parallel $[\bar{1}10]$-γ axis in the adjacent layer of the γ-matrix is 2531 X.U. It is evident that, at a place some five identity periods along the [010]-α axis from a place where the two lattices fit approximately, there will be a close approach of atoms in the adjacent crystals. The effect of a gradual transition from one lattice to the other will produce a similar result except that the number of identity periods involved will be larger.

Now an α-crystal produced by the Nishiyama mechanism is, because of the symmetrical nature of the resulting orientation, in equilibrium with its surroundings. The effect of the close approaches along its [010]-axis may, however, produce an instability, particularly if thermal agitation is considerable. The crystal would then be rotated slightly about its [101]-axis into some position of more stable equilibrium. A similar but smaller effect would arise from the interaction of the [$\bar{1}$01]-α and [$\bar{1}\bar{1}$2]-γ axes.

Next consider a nuclear crystal orientated according to the relations of type III in which, for example, the [$\bar{1}$11]-α axis is parallel to the [$\bar{1}$01]-γ axis. The identity periods along the two axes are 2480 X.U. and 2531 X.U. respectively, and a close approach of atoms will take place at a distance of some twenty-five identity periods from the nucleus of crystallization. This orientation, therefore, should also be avoided at high temperatures. Thus the close-packed [$\bar{1}$01]-γ axis may be regarded as a potential barrier preventing further rotation of the α-crystal. A similar but less effective barrier is provided by the action of the [$\bar{2}$11]-γ axis on the [$\bar{1}$31]-α axis corresponding to a value of μ of 4° 44′. Other related axes are probably insufficiently close-packed to be of much importance in controlling the orientation.

It is apparent, therefore, that if the transformation takes place according to the Nishiyama mechanism the nuclear crystal will be forced, except possibly at low temperatures, to take up some position in which μ lies between 0° and 5°·3. Alternatively, if the Kurdjumow-Sachs mechanism were operative, the values of μ would probably be slightly greater and slightly less than 5°·3. The fact that only one crystal was observed in Cañon Diablo for which this value was exceeded is difficult to explain on the Kurdjumow-Sachs theory; while the fact that orientations of type II have actually been observed in artificial alloys transformed at low temperatures is strong evidence in favour of the Nishiyama theory.

Kamacite orientations in the tesseral octahedrites

Of considerable interest in connexion with orientations of type I are the tesseral octahedrites found in the Bethany (Gibeon) iron and described by Rinne (1910).

In these meteorites there exist, in addition to the usual octahedral lamellae, lamellae parallel to the planes of the cube. There can be little doubt that these cubic lamellae were formed before the octahedral lamellae, for they cut across the whole structure of the latter in a very striking manner. The occurrence of such cubic lamellae strongly suggests orientations of type I for the kamacite crystals of which they are primarily composed.

Examination of Rinne's photographs indicates, however, that the directions of the Neumann bands are inconsistent with such an hypothesis. The way in which the octahedral lamellae appear in places as outgrowths from, and having the same orientation as, the cubic lamellae suggests strongly that the kamacite crystals of these latter lamellae are also orientated according to the laws which have been found to hold in the octahedrites. It is most desirable that direct X-ray evidence on this point should be obtained.

THE FORMATION OF THE WIDMANSTÄTTEN STRUCTURE

It is outside the scope of the present paper to discuss in detail the formation of the Widmanstätten structure of meteorites. It is relevant, however, to consider how far the lattice mechanism derived from the observed orientation relationships serves to explain the Widmanstätten structure.

The fact that Widmanstätten figures can be observed at all arises from the growth of kamacite in the form of plates which in meteorites are surrounded by taenite. In the report of the original investigation it was remarked that the plate-like nature of kamacite probably owed its origin to the fact that a $\{110\}$-plane of this crystal was "ready-made" as a $\{111\}$-plane of the γ-lattice and the shearing movements involved in the γ-α transformation were indicated. Such shearing movements of the (111)-planes over one another in a $[11\bar{2}]$-direction and their expansion in a $[1\bar{1}0]$-direction, in accordance with the Nishiyama mechanism, will produce a condition of disturbance at the edges of the incipient crystal conducive to rapid growth outwards in the (111)-plane. Plate-like crystals will therefore be produced.

Such a theory can explain in some considerable degree the imperfect Widmanstätten structures of artificial nickel-irons, but it is doubtful if it can wholly account for the extraordinarily good Widmanstätten figures in many meteorites, and it certainly does not explain the occurrence of taenite or the plessitic fields.

There can be little doubt that the precipitation of kamacite from the γ-lattice occurs as a result of a gradual fall in temperature of the meteorite. Such precipitation must be accompanied by a transference of atoms across the taenite-kamacite interface in such a way that the kamacite becomes poorer, and the taenite richer, in nickel than the original γ-solid solution. This continues until a state of equilibrium is set up. It is well known that such equilibrium is very difficult to attain in nickel-irons. It is probable, however, that meteorites have cooled so slowly that perfect or almost perfect equilibrium has obtained during the γ-α transformation. Such a state of affairs would produce on the taenite side of the γ-α interface a very much higher concentration of nickel than would occur in alloys prepared in the laboratory. The effect of this would be to slow down the growth of kamacite in a direction perpendicular to the lamellae. It is suggested that the long and perfect lamellae of kamacite in meteorites owe their origin, in part at least, to the operation of this effect.

Researches carried out under the direction of Professor S. W. J. Smith, which will be submitted for publication shortly, tend to confirm this theory.

In conclusion, it should be remarked that the theory that kamacite arises from a lattice mechanism which orientates the crystals does not necessarily mean that lamellar growths on $\{111\}$-planes of the γ-lattice must take place. The occurrence of cubic lamellae of kamacite in the tesseral octahedrites is sufficient proof of this contention.

Other evidence, in ordinary octahedrites, has recently been obtained by Professor Smith.

The orientations of the crystals in such cubic lamellae are, nevertheless, consistent with a lattice mechanism of the type found in other meteorites. It is possible that growth may have followed some abnormality (e.g. a slip plane) of the γ-lattice. The outgrowths from the cubic lamellae prove, however, that the natural direction of growth is along octahedral planes.

The orientations of the α-lattice found in artificial nickel-irons should be regarded as showing that the γ-α transformation is primarily of a lattice-mechanical nature. The occurrence of the same orientations in the kamacite of meteorites proves that the Widmanstätten structure arises as a result of the same γ-α transformation, but the operation of additional physical factors is probably necessary if the structure is to be produced with any degree of perfection.

It is a great pleasure to me to express my thanks to Professor S. W. J. Smith, F.R.S., who first aroused my interest in this subject and who generously provided facilities for its study. Many of the ideas put forward in this paper have been the result of informal discussions with him.

I also wish to thank Dr D. W. Davison who took the series of X-ray photographs of the Cañon Diablo meteorite, and Dr D. E. Adams who carried out the heat treatments of the nickel-iron alloy.

SUMMARY

A detailed investigation of the mutual orientations of the chief constituents, kamacite and taenite, of the octahedral meteoric irons and their relationship to the Widmanstätten structure has been made.

In Cañon Diablo (Part I), fifteen crystals belonging to the macroscopic Widmanstätten structure were separately examined. These showed small deviations from the twenty-four orientations of the type:

(110)-kamacite parallel to (111)-octahedrite,

[001]-kamacite inclined at 4°·1, (μ), to [$\bar{1}$10]-octahedrite.

In Butler and Carlton (Part II), the microscopic Widmanstätten structure was examined. The taenite crystals showed a very strongly preferred single orientation identical with that of the octahedrite, while the kamacite crystals were orientated in the same way as those in Cañon Diablo.

In a heat-treated artificial nickel-iron (Part II), containing 10 % of nickel, the orientations of the γ-phase and α-phase constituents were found to be similar to those of the taenite and kamacite, respectively, in the meteoric irons. The value of μ (3°·4), however, was somewhat lower.

In all cases in which μ could be determined with some precision the orientation of an α-phase crystal lay between that found by Nishiyama and that proposed by Kurdjumow and Sachs.

An attempt is made (Part III) to account for the orientations found by supposing that the γ-α transformation proceeds according to a lattice mechanism of the Nishiyama-type modified by the effect of temperature agitation. Reasons are given for supposing that the orientations for which $\mu = 0°$ and $\mu = 5° 16'$ involve high potential energies at the kamacite-taenite interface and the consequent avoidance of such orientations of the kamacite crystals.

These orientation studies give the most convincing proof that the body-centred α-crystals of kamacite are the result of a precipitation from a single face-centred γ-lattice of uniform orientation whose axes are those of the octahedrite.

The distortion of the Widmanstätten structure was also examined (Part I). It is shown that the bulk distortion of the Widmanstätten structure and the rotations of individual crystals are consistent with the effects of plastic shearing of the whole portion of meteorite examined.

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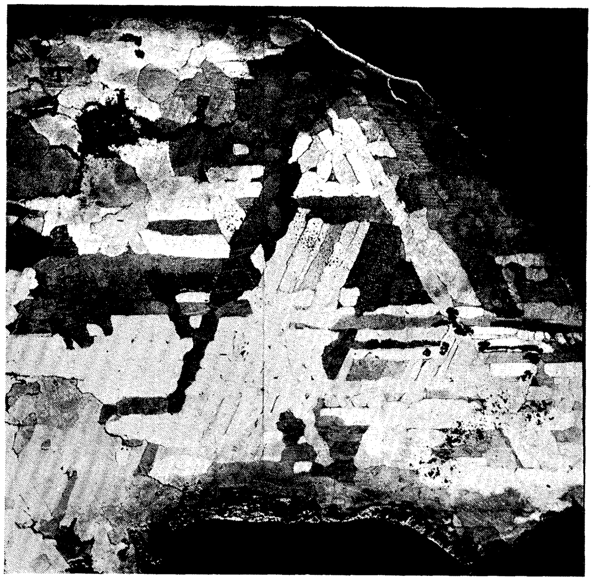

Figure 10. Cañon Diablo (× 1).

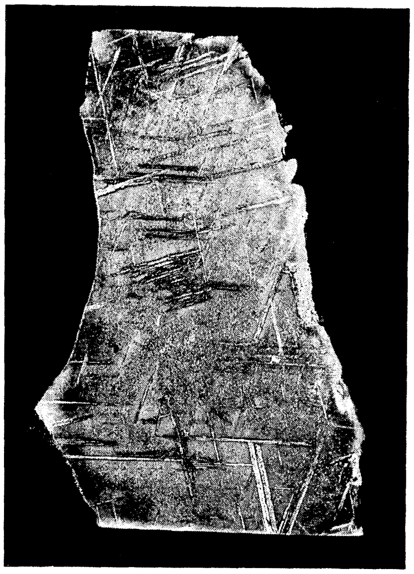

Figure 11. Butler (× 1).

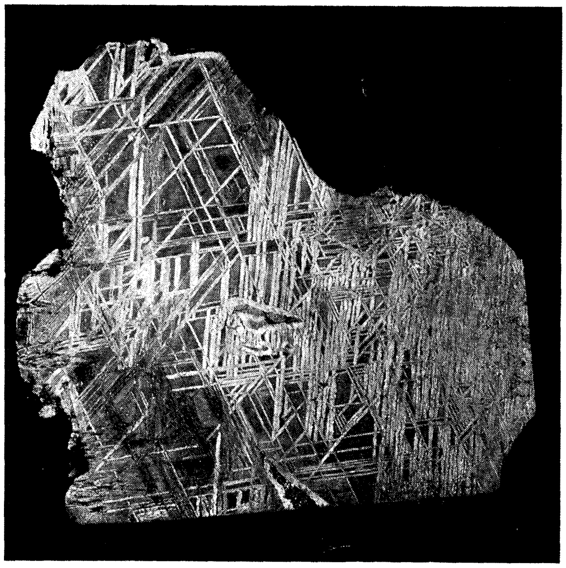

Figure 12. Carlton (× 1).

Figure 13. 10 % Nickel-iron (× 380).

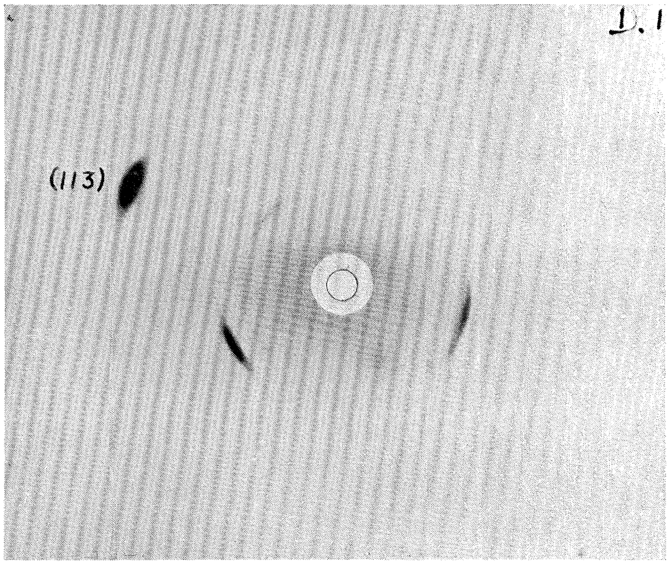

FIGURE 14. D 125 (Fe-K-radiation).

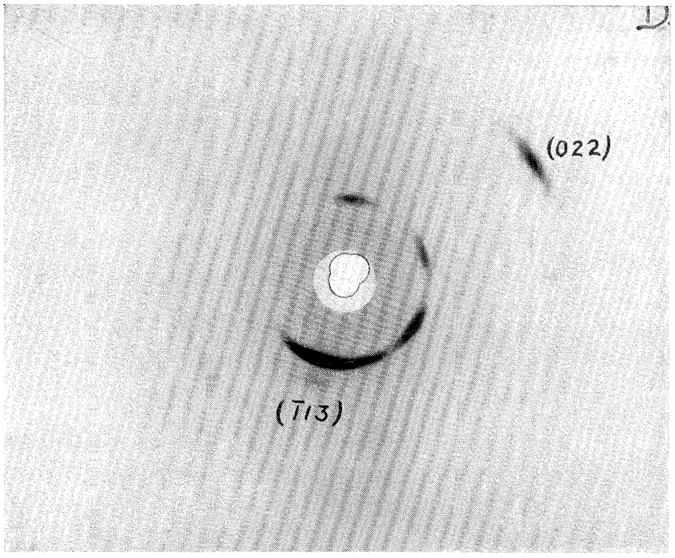

FIGURE 15. D 133 (Cr-K-radiation).

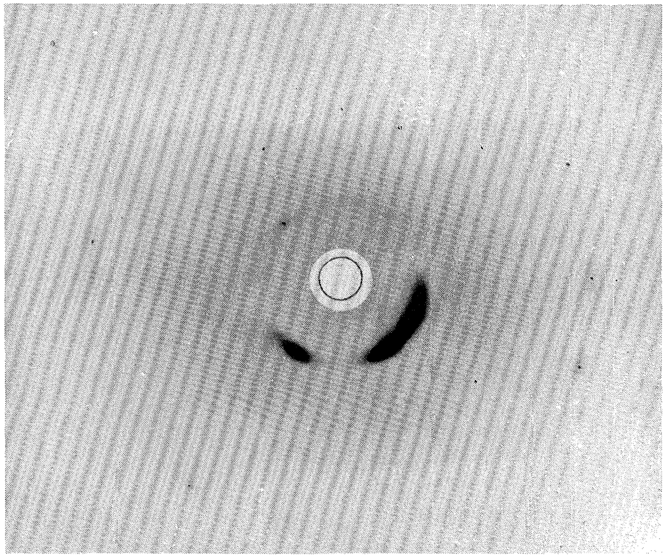

FIGURE 16. Grain 1 (Cr-K-radiation).

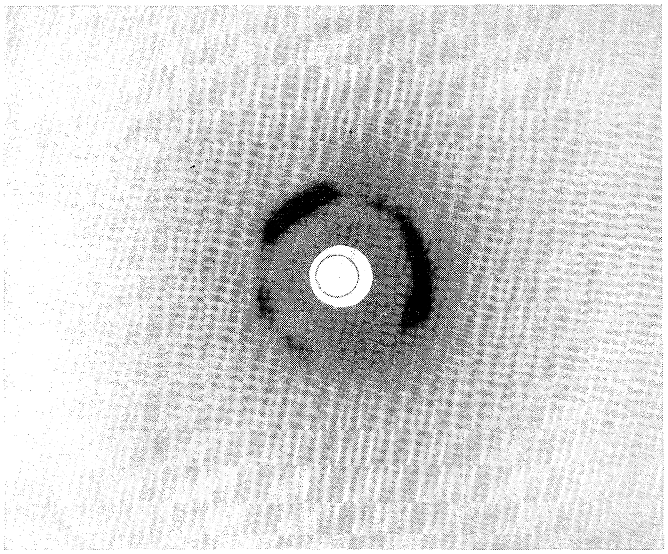

FIGURE 17. Grain 2 (Cr-K-radiation).

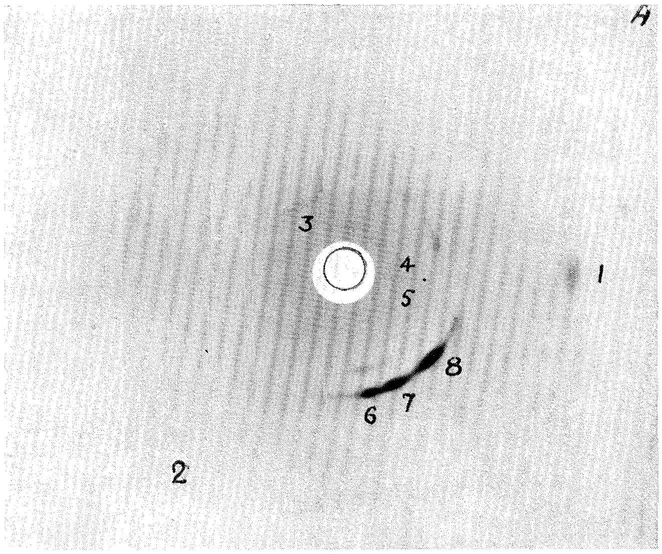

FIGURE 18. AX 39 R (Fe-K-radiation).

FIGURE 10. Cañon Diablo (×1).

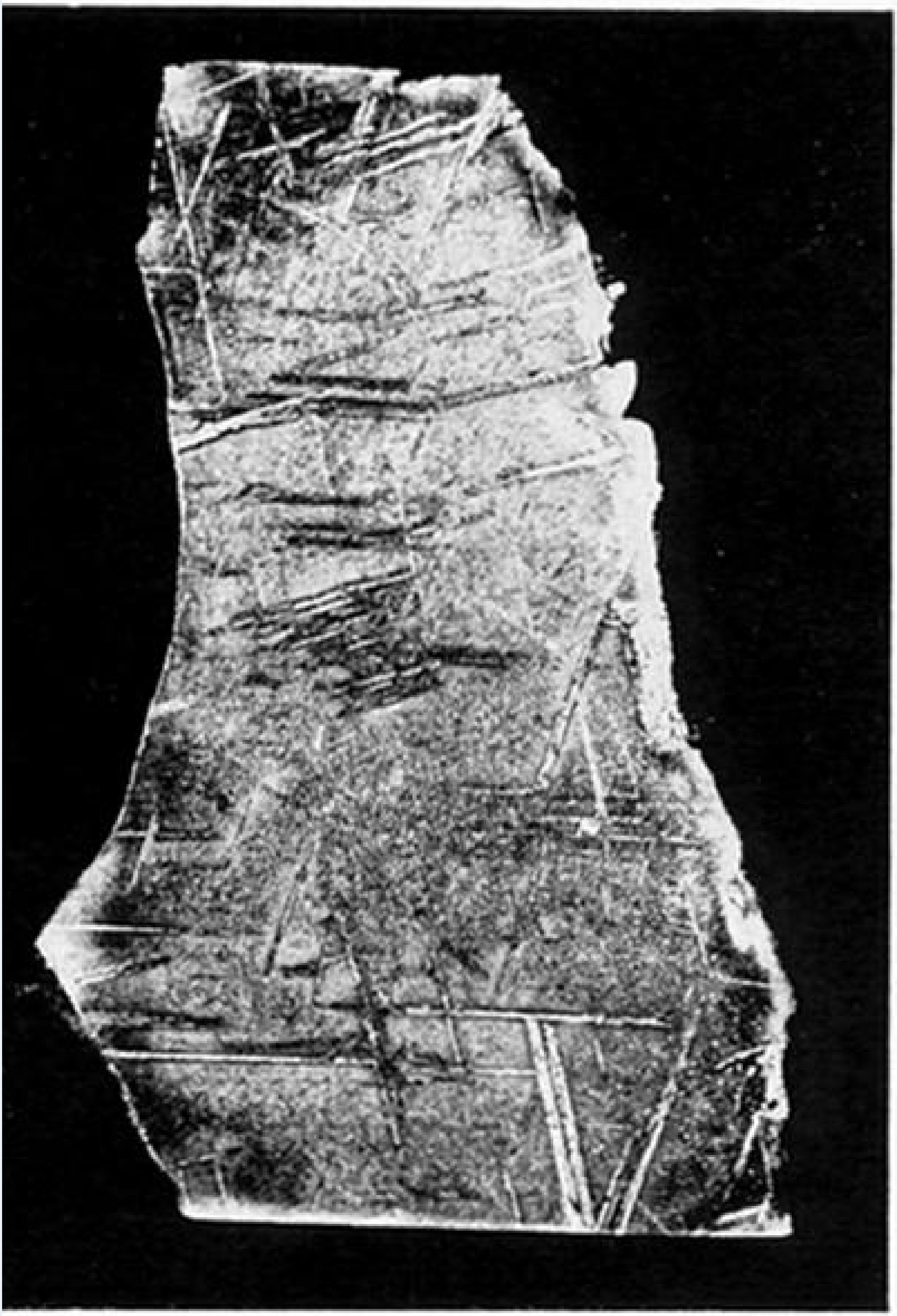

FIGURE 11. Butler (×1).

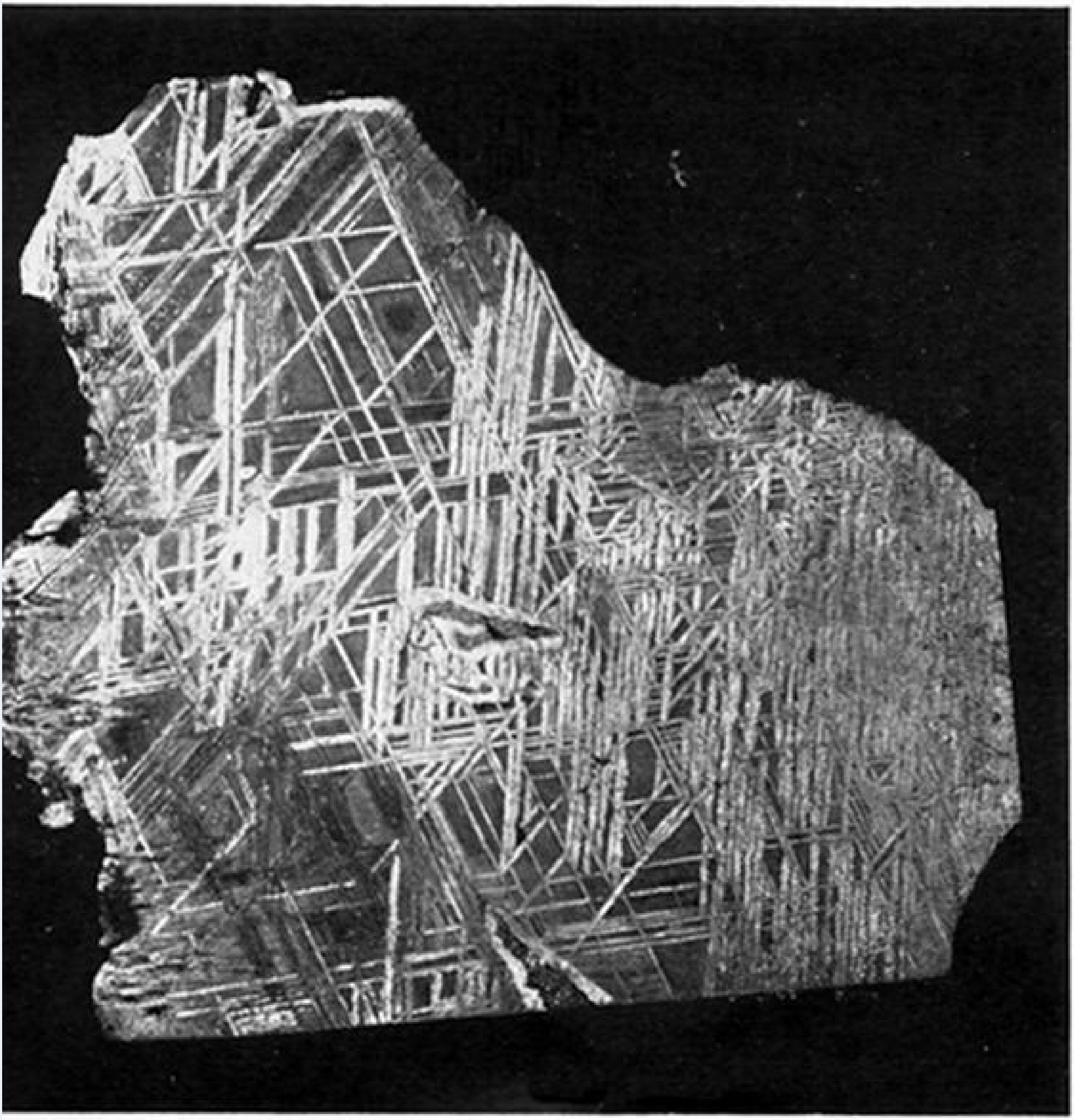

FIGURE 12. Carlton (×1).

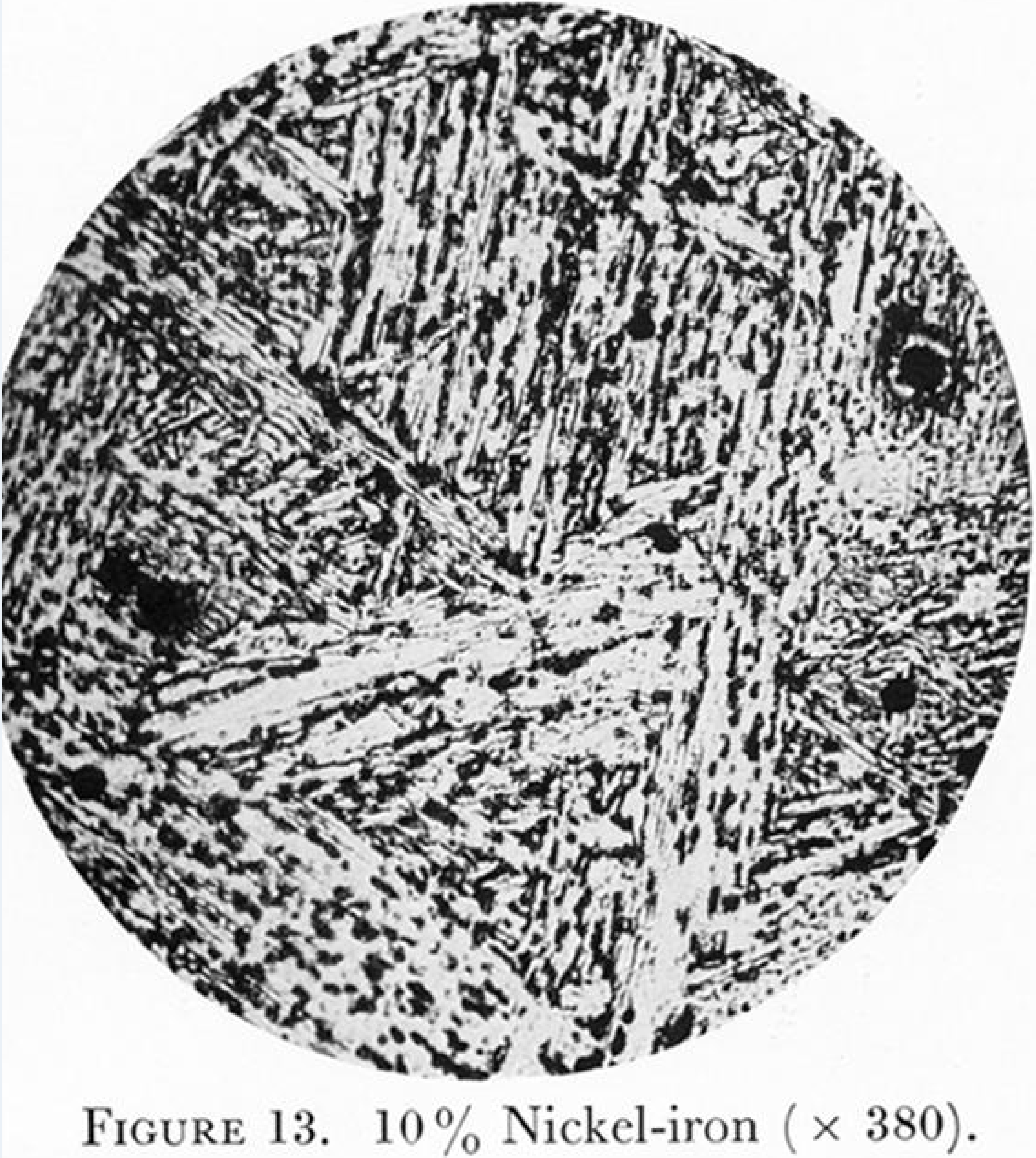

FIGURE 13. 10% Nickel-iron (× 380).

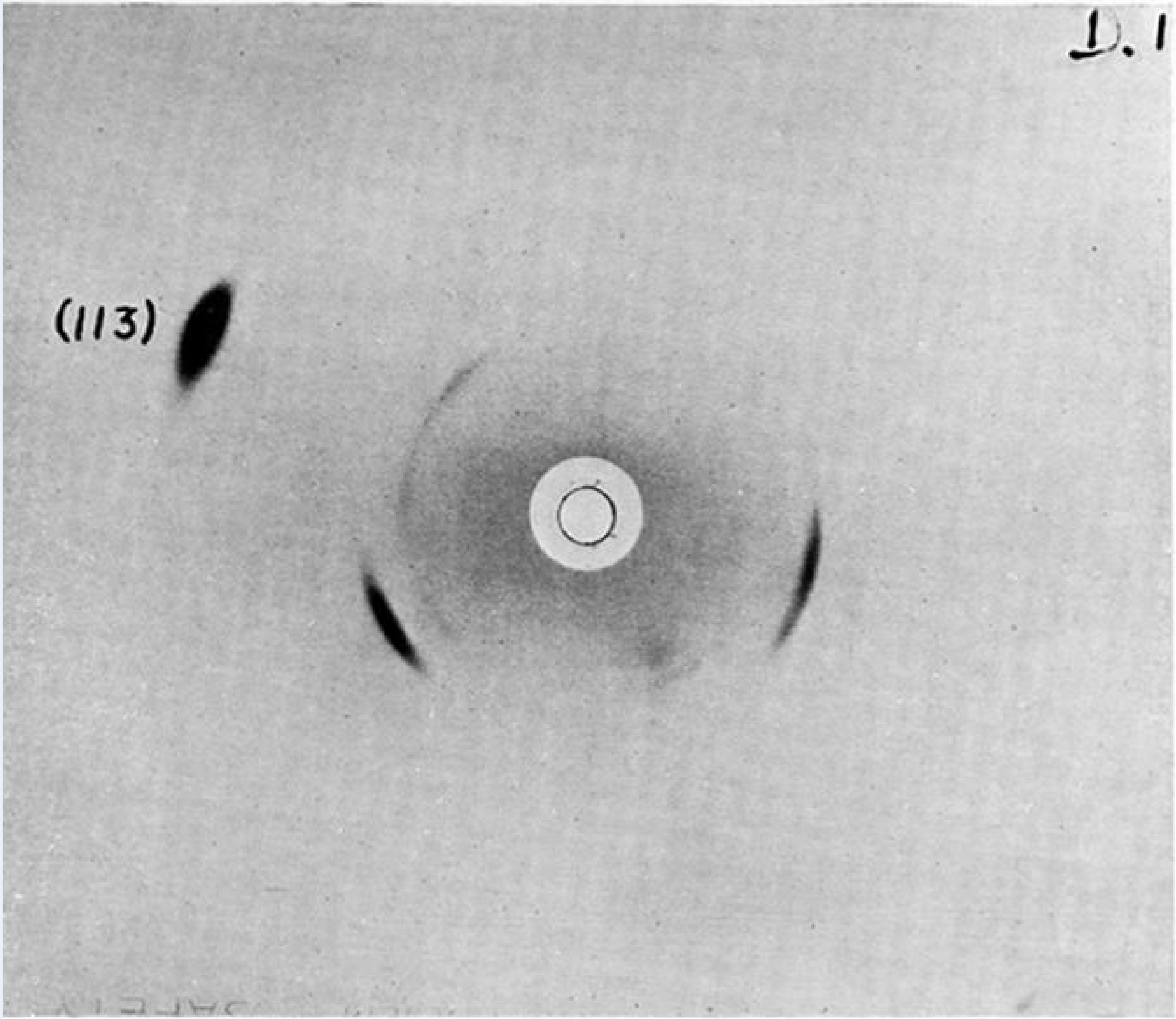

FIGURE 14. D 125 (Fe-K-radiation).

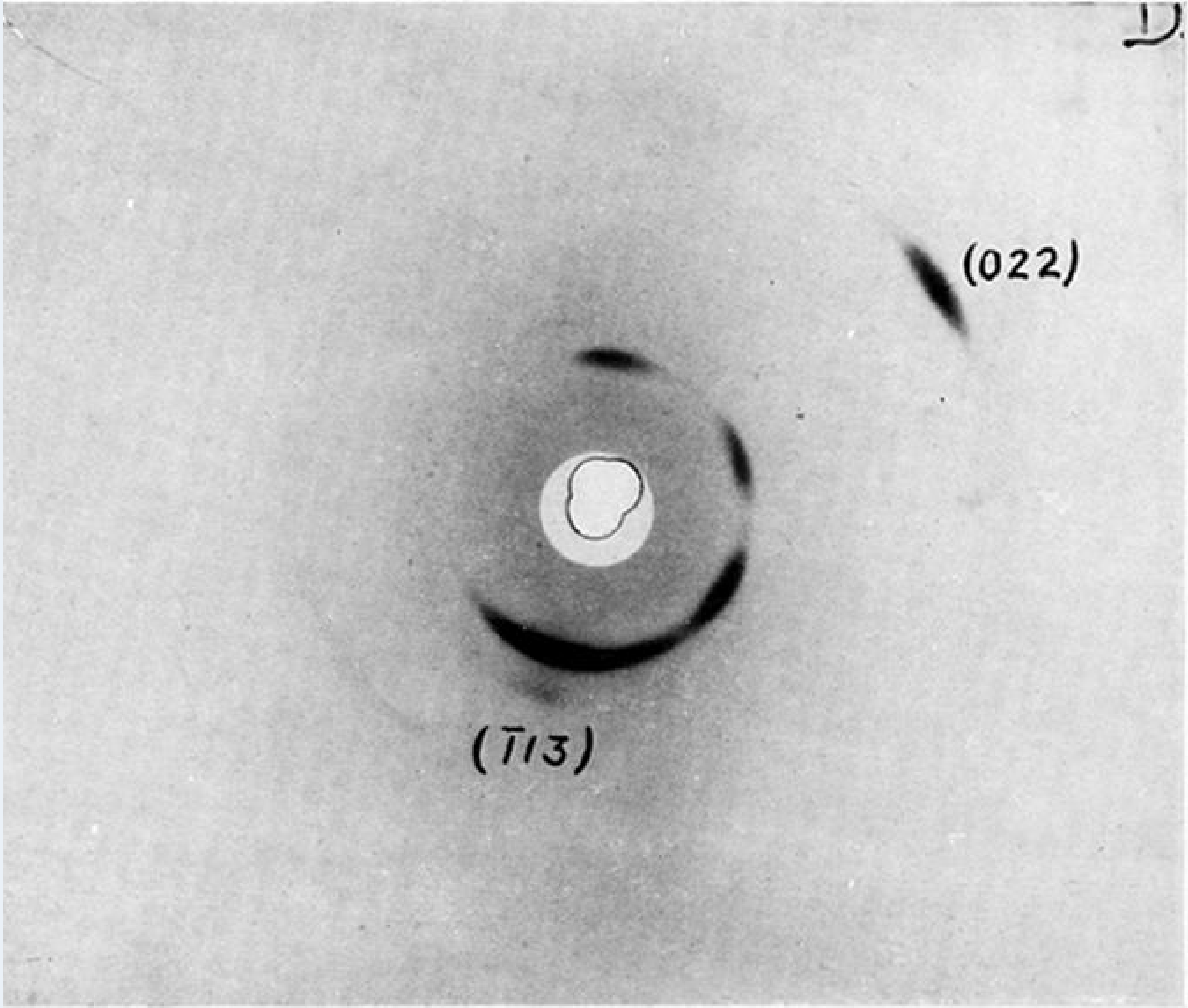

FIGURE 15. D 133 (Cr-K-radiation).

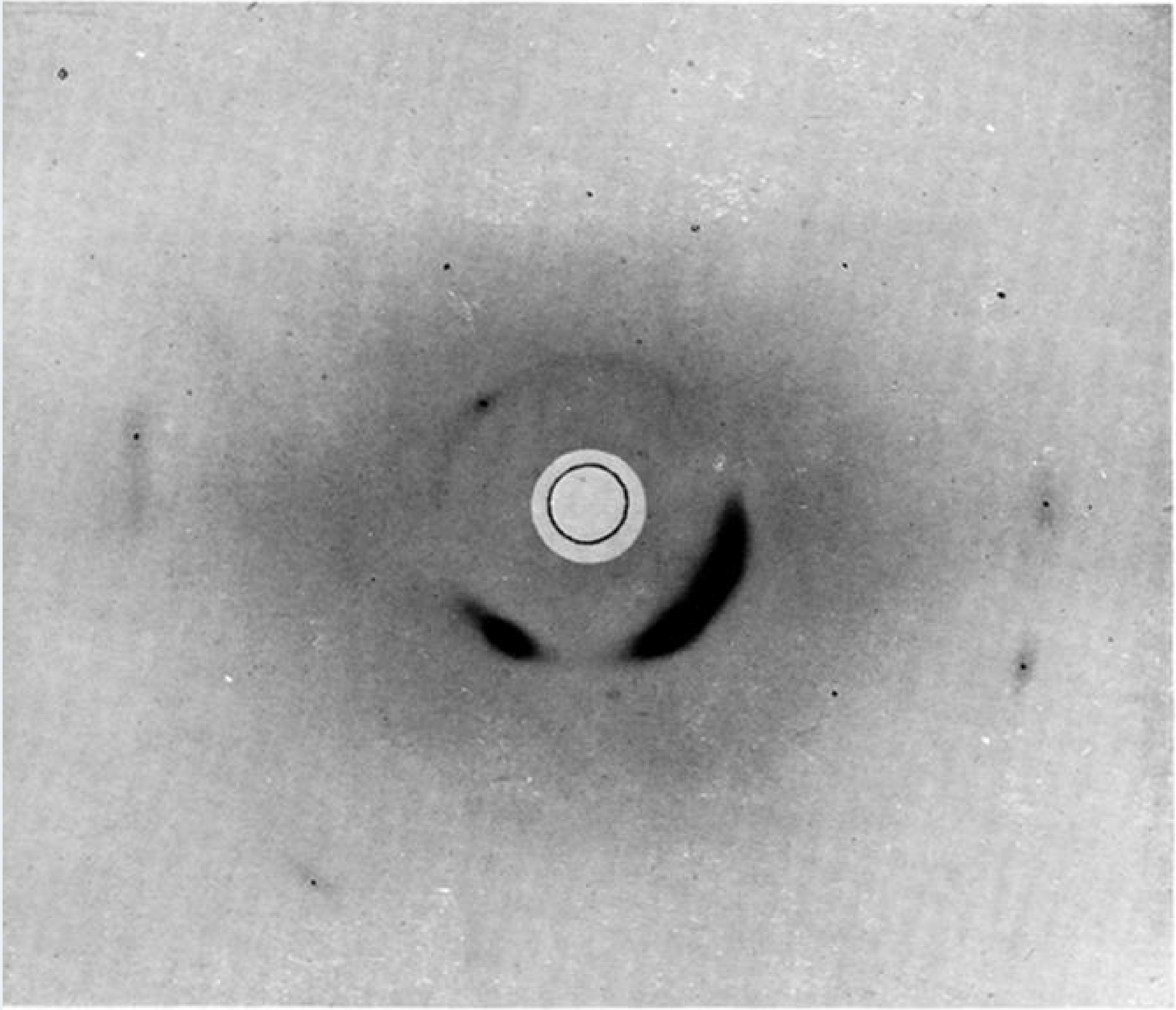

FIGURE 16. Grain 1 (Cr-K-radiation).

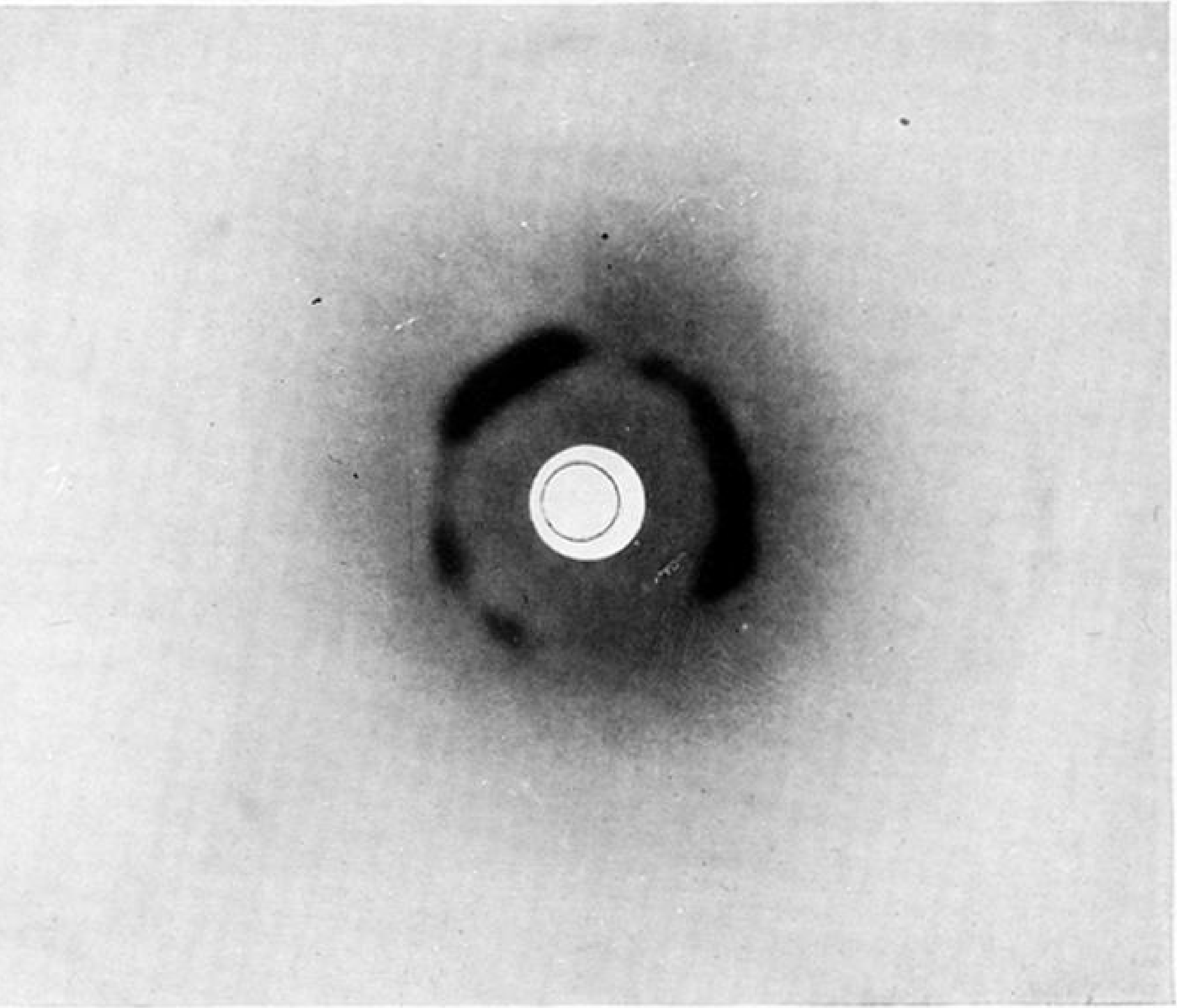

Figure 17. Grain 2 (Cr-K-radiation).

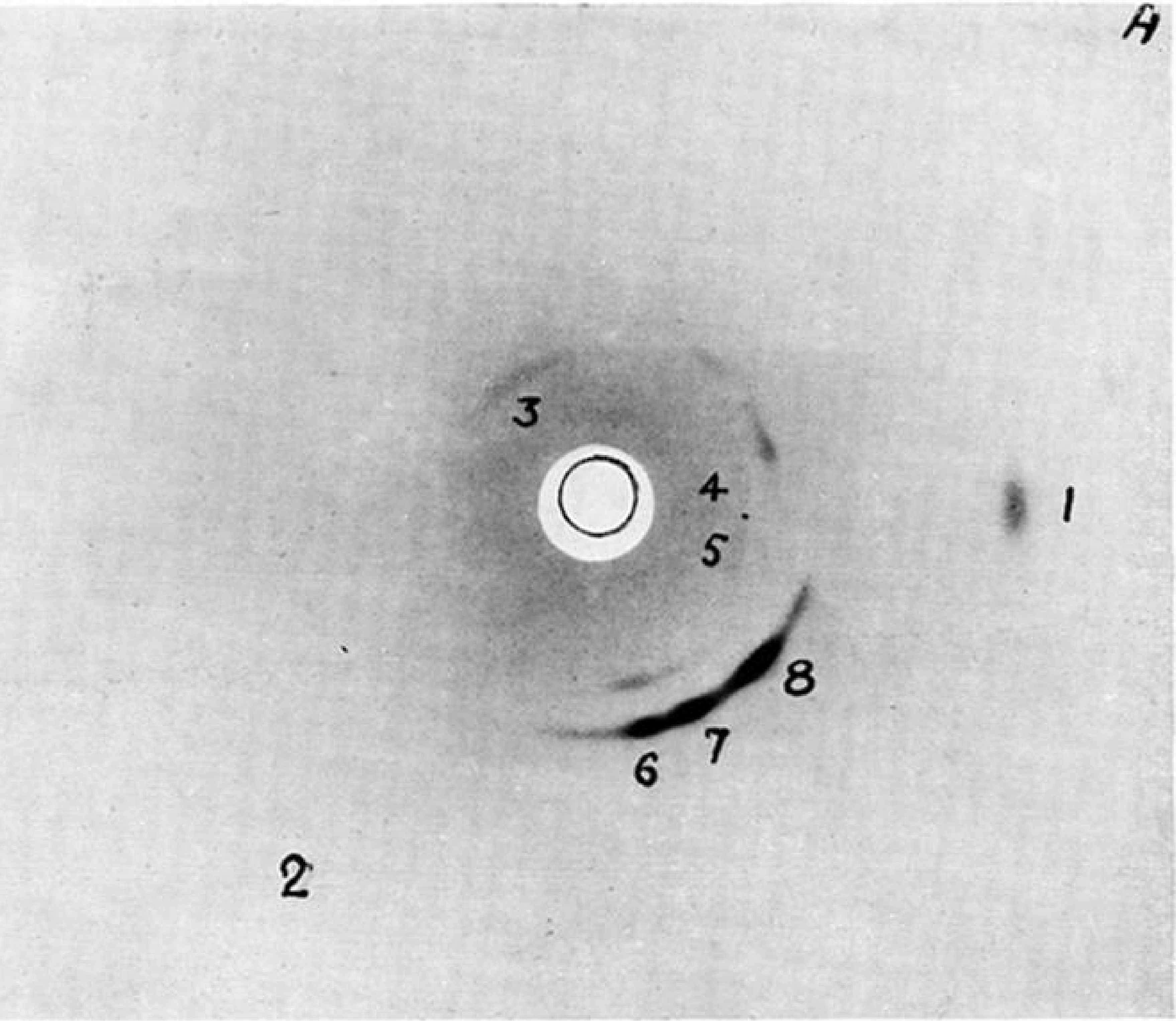

FIGURE 18. AX 39 R (Fe-K-radiation).