Formation of the diffraction pattern in the transmision electron microscope

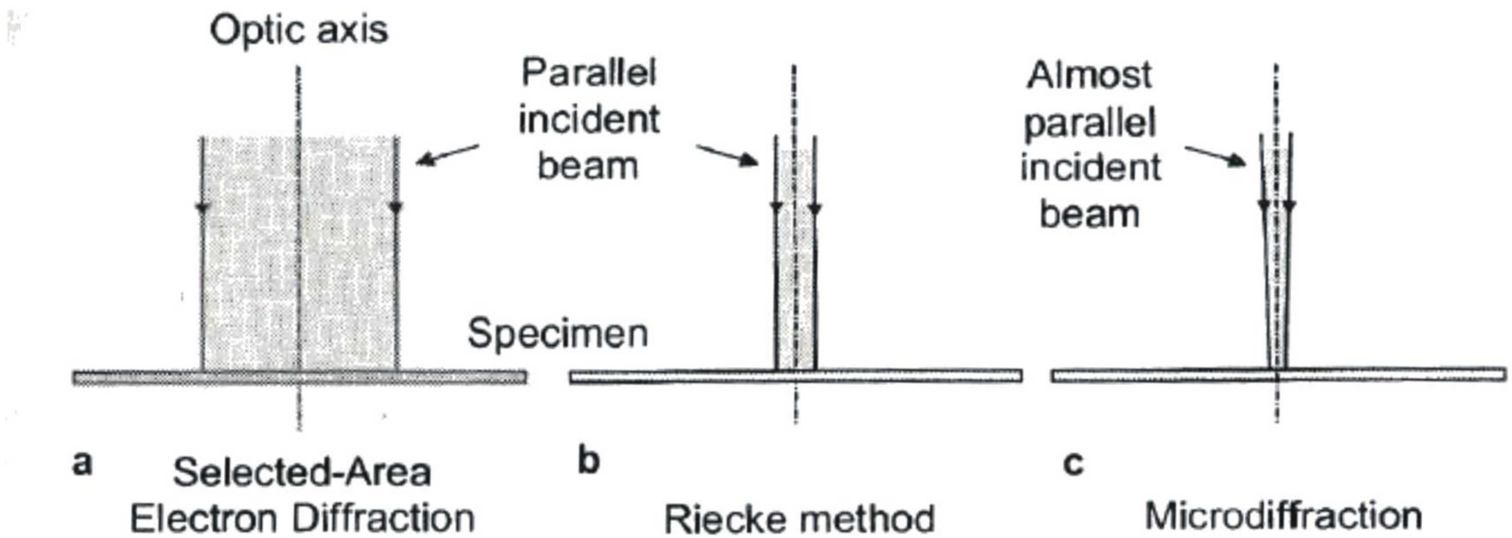
based on: J-P. Morniroli: *Large-angle convergent-beam diffraction (LACBED)*, 2002 Société Française des Microscopies, Paris.

Selected area (electron) diffraction

SAED pattern

J-P. Morniroli: *Large-angle convergent -beam diffraction (LACBED)*, 2002 Société Française des Microscopies, Paris.

Diffraction pattern produced by a parallel incident beam: e.g. SAED pattern



Electron diffraction with a parallel or almost parallel incident beam. Illumination conditions of the specimen.

a - Selected-Area Electron Diffraction (SAED). The incident electron beam is parallel and has a diameter of a few microns.

b - Riecke method. The incident beam is parallel and has a diameter of a few tens of nanometres.

c - Microdiffraction. The incident beam is almost parallel and has a diameter from a few nanometres to a few tens of nanometres.

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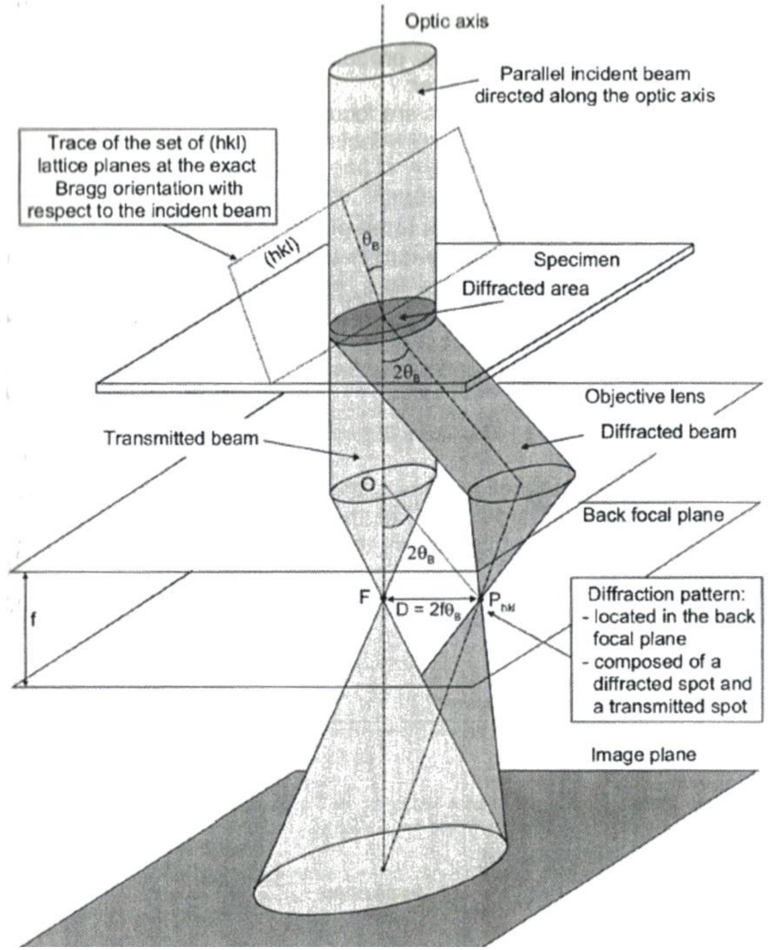
SAED pattern



Electron diffraction with a parallel incident beam (Selected-Area Electron Diffraction).

Electron ray-path at the level of the objective lens when a single set of (hkl) lattice planes is at the exact Bragg orientation with respect to the incident beam directed along the optic axis of the microscope. The diffraction pattern is composed of a transmitted spot and of a single diffracted spot. It is located in the back focal plane of the objective lens.

The diffracted area is selected with the selected-area aperture located in the image plane of the objective lens.

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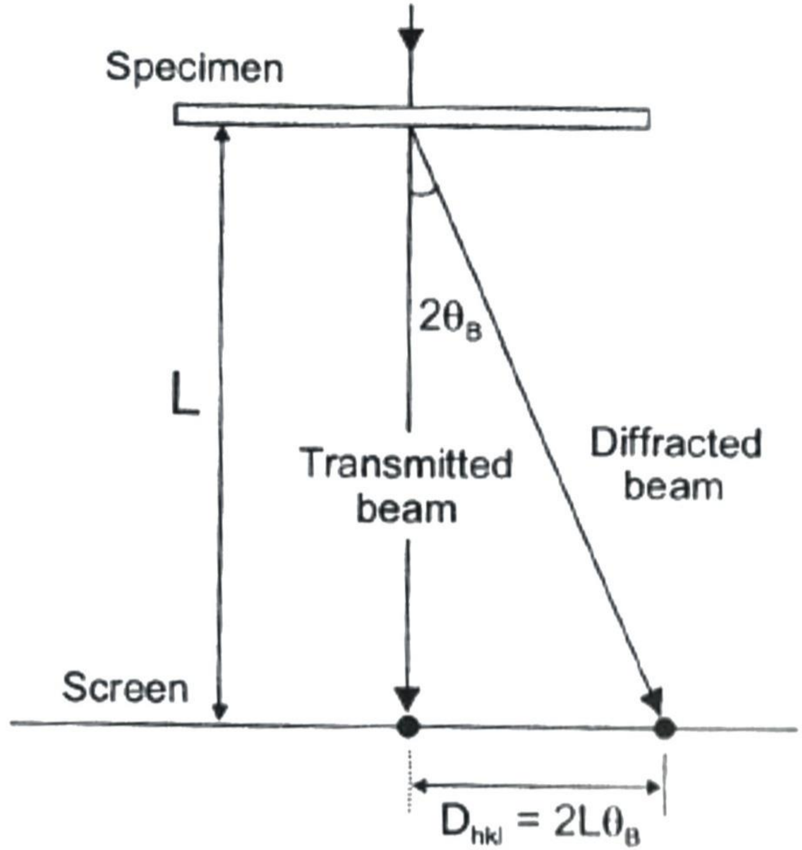
SAED pattern



Formation of the diffraction pattern on the screen of the microscope. The distance D_{hkl} between the transmitted beam and the diffracted beam is directly related to the Bragg angle θ_B and to the camera length L.

$\theta_B = \lambda / 2d_{hkl}$

$\rightarrow D_{hkl}\, d_{hkl} = L\, \lambda$

Camera constant $C = L\lambda$

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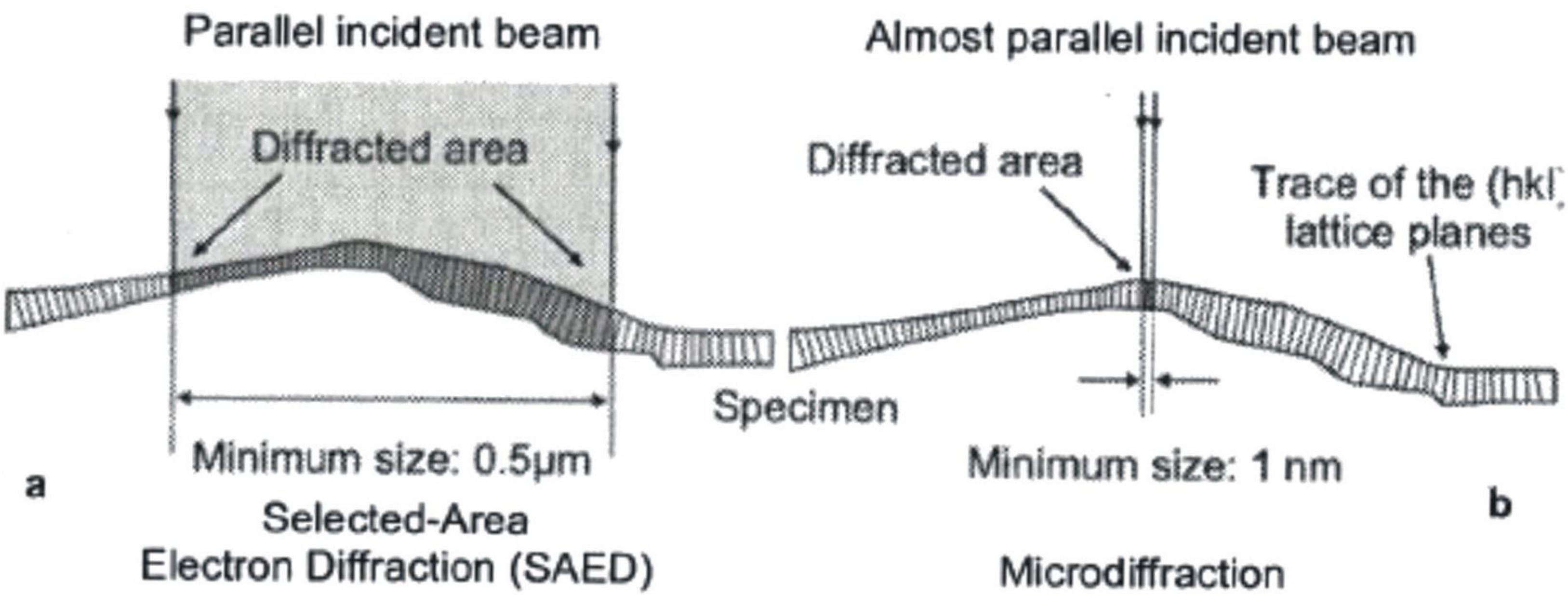
SAED pattern

SAED →the diffracted area of the specimen is selected with the selected-area aperture (located in the image plane of the objective lens).



Nature of the diffracted area.

a - Selected-area electron diffraction. The diffracted area is large and contains significant thickness changes and orientation variations of the (hkl) lattice planes. The resulting diffraction pattern is "averaged".

b - Microdiffraction. The diffracted area can be very small so that the thickness and the orientation of the lattice planes in the diffracted area can be regarded as constant. Thus, the diffraction pattern is typical of the crystal.

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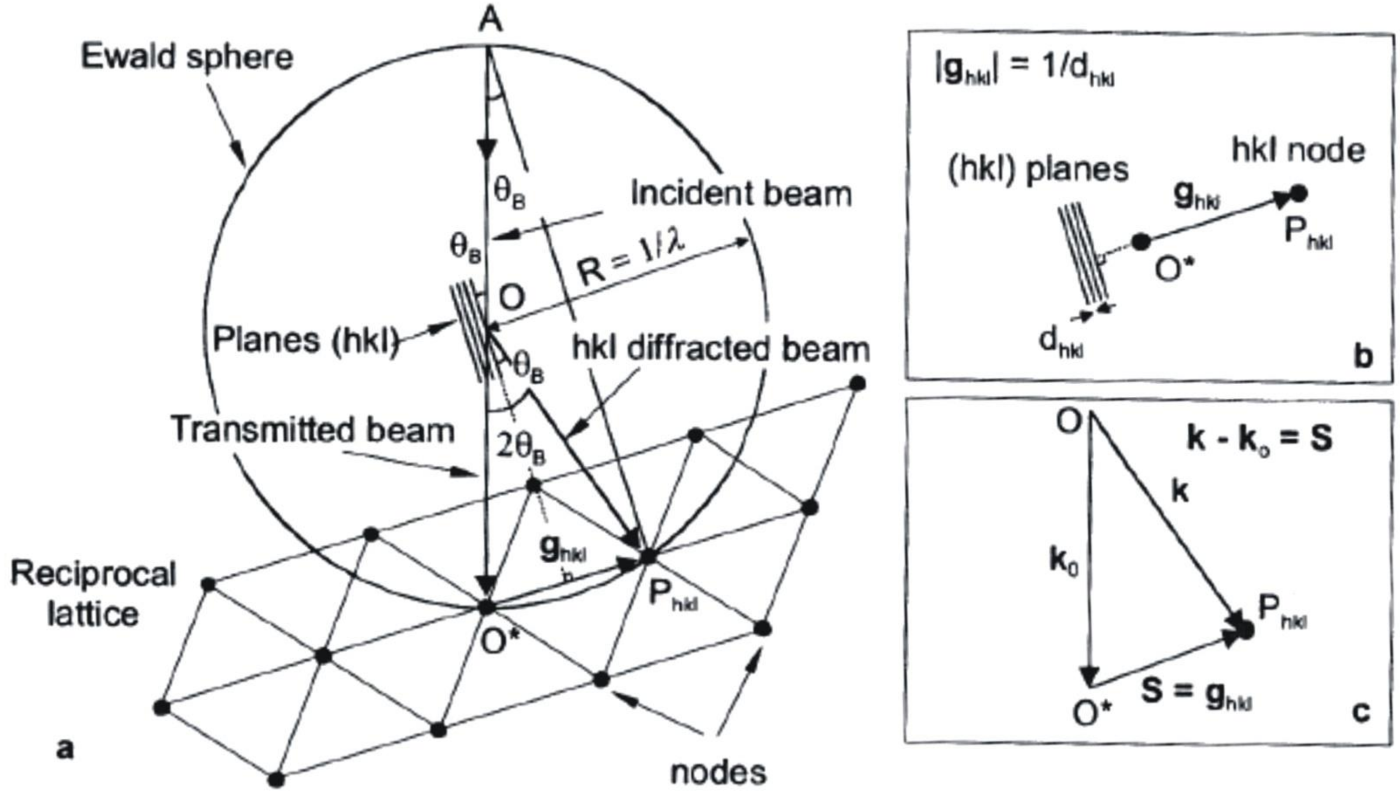
SAED pattern



Ewald sphere construction. General case.

a - A diffracted beam is produced if an hkl node of the reciprocal lattice is located exactly on the Ewald sphere. This situation occurs for the node P_{hkl}.

b - Relationship between a set of (hkl) lattice planes and its corresponding reciprocal lattice vector $\mathbf{g}_{hkl}$. This vector is perpendicular to the (hkl) lattice planes and its modulus g_{hkl} is equal to $1/d_{hkl}$.

c - Vector description of Bragg's law. Bragg's law is satisfied when the scattering vector **S** is equal to the reciprocal lattice vector $\mathbf{g}_{hkl}$.

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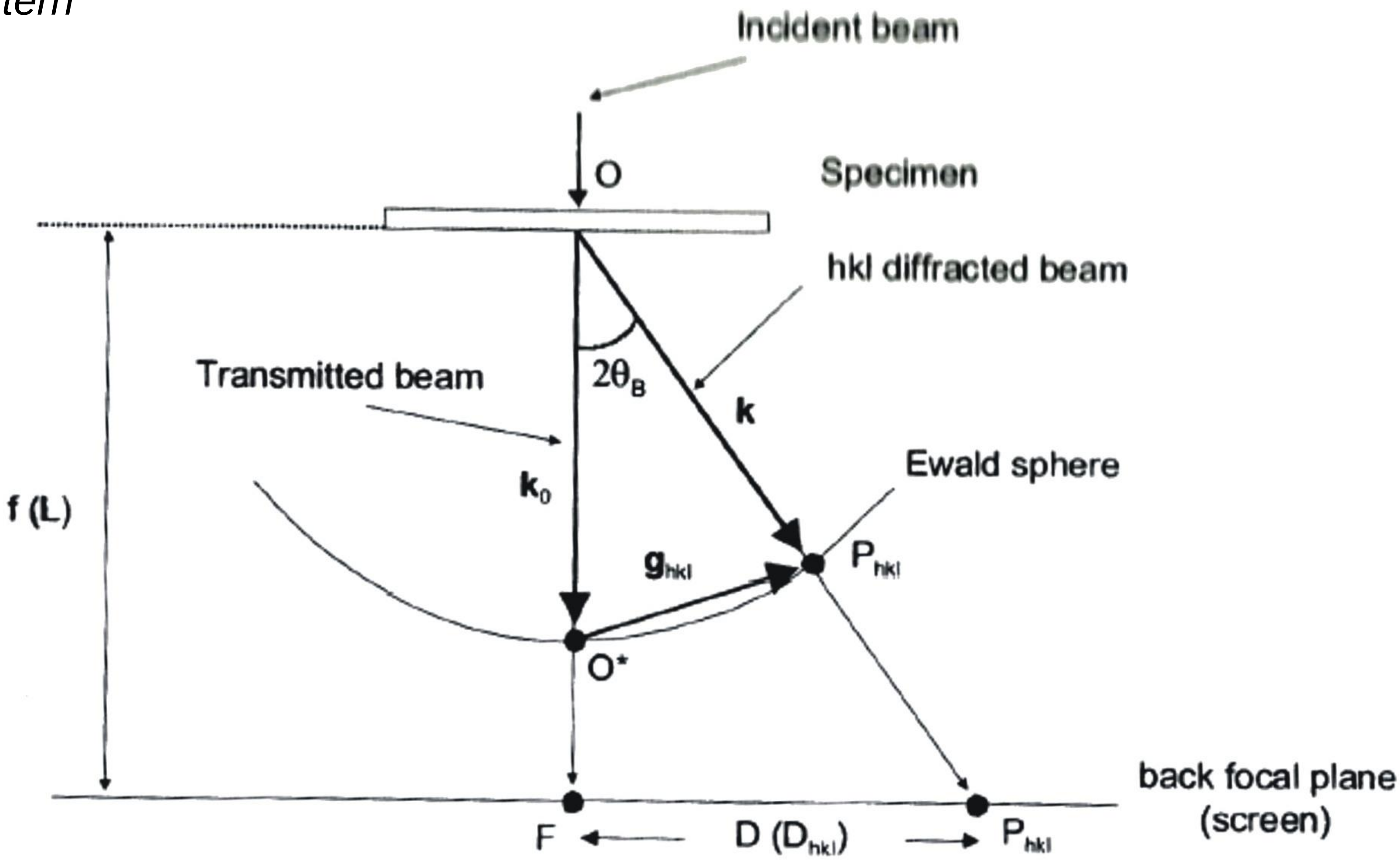
SAED pattern



Relationship between the Ewald sphere construction and the diffraction pattern located in the back focal plane (or on the microscope screen).

An hkl diffracted beam is produced when an hkl node of the reciprocal lattice is exactly located on the Ewald sphere.

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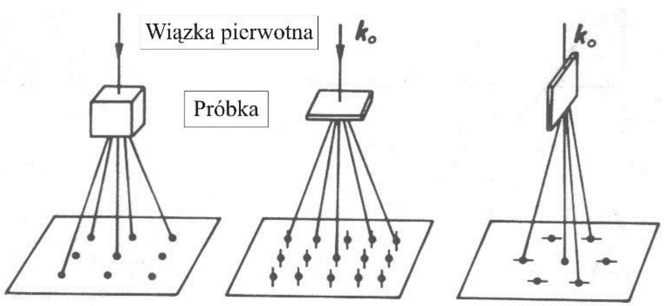
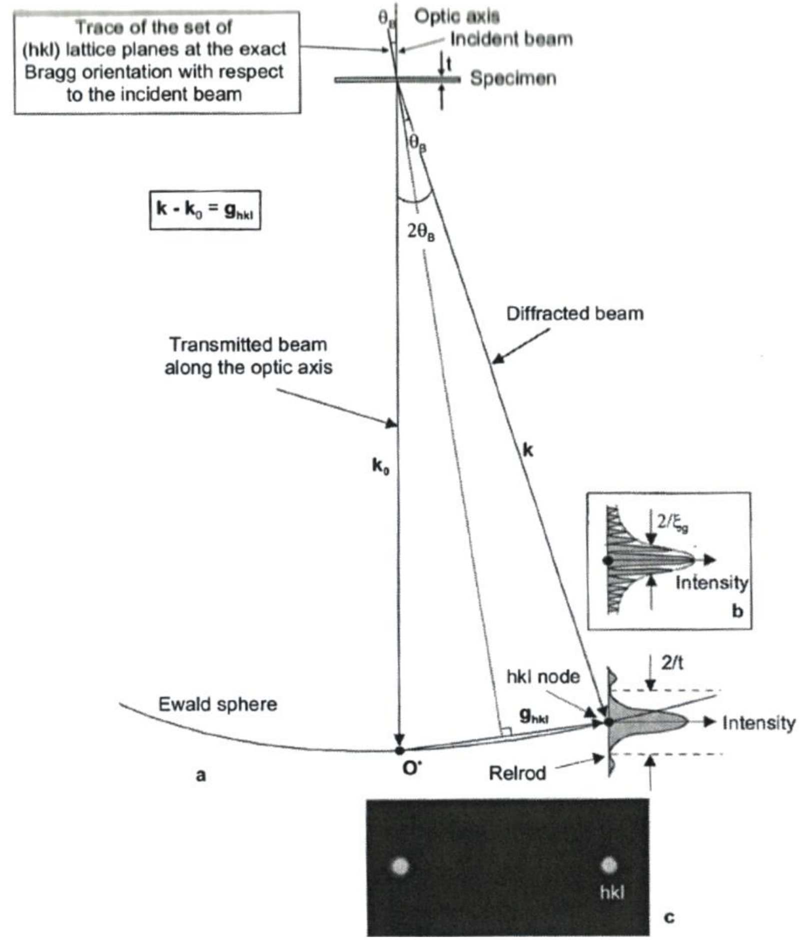
SAED pattern

Very small wavelenngth λ of the electron beam makes the radius R=1/ λ of the Ewald sphere very large (compared to the moduli g_{hkl} of the reciprocal lattice vector).

Specimens for electron microscopy are thin foils → the nodes of the reciprocal lattice are extended along the direction of least specimen thickness.





Ewald sphere construction for electron diffraction.

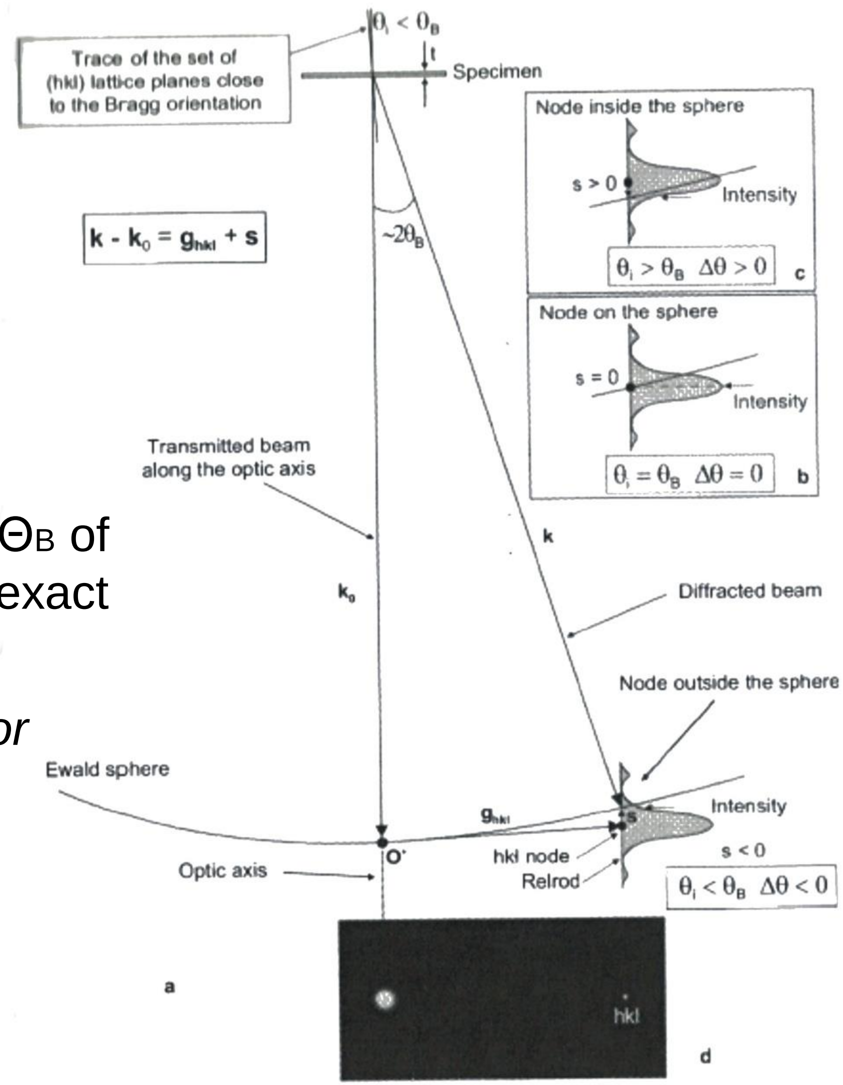
a - Ewald sphere construction for a set of (hkl) lattice planes at the exact Bragg orientation with respect to the incident beam directed along the optic axis. The radius of the Ewald sphere is much larger than the modulus of the g_{hkl} vector. The hkl node is located exactly on the Ewald sphere.

b - Complex aspect of the diffracted intensity along a relrod.

c - Example of an experimental pattern under exact two-beam conditions.

SAED pattern

A diffracted beam can be produced even if the set of (hkl) lattice planes is not at the exact Bragg orientation.



s – an expression of the misorientation $\Delta\Theta = \Theta_i - \Theta_B$ of the set of (hkl) lattice planes with respect to the exact Bragg orientation.

s – *excitation error*

Ewald sphere construction for electron diffraction.
a - Ewald sphere construction for a set of (hkl) lattice planes close to the Bragg orientation with respect to the incident beam directed along the optic axis. The hkl node of the reciprocal lattice is located outside the Ewald sphere (s < 0).
b, c - Examples of zero and positive deviation parameter s.
d - Experimental pattern near two-beam conditions. Compare the intensity of the hkl diffracted spot with the one displayed on figure III.7c.

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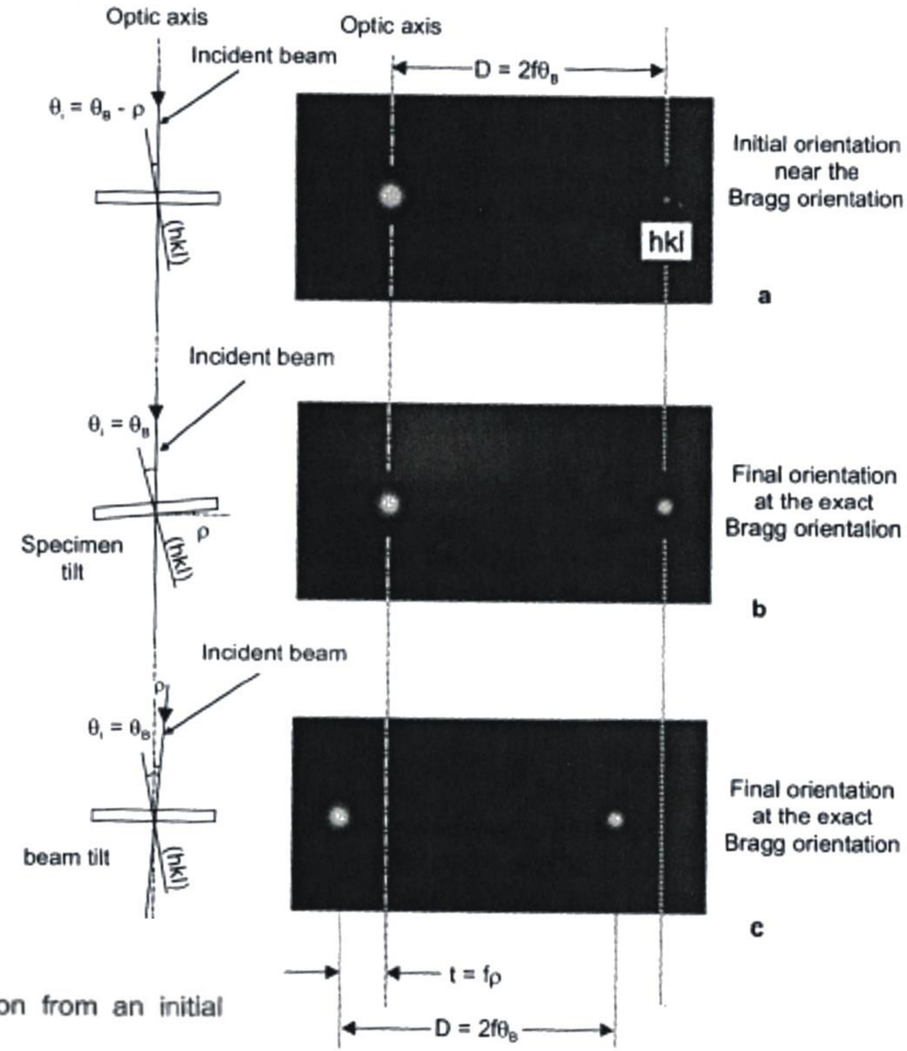
SAED pattern

A misorientation of the incident beam with respect to the optic axis leads to a shift of the „whole” diffraction pattern in the back focal plane of the objective lens.



Setting (hkl) lattice planes at the exact Bragg orientation from an initial orientation near the Bragg orientation.

a - Initial orientation. The lattice planes are close to the Bragg orientation.

b - The specimen is tilted by an angle ρ until the incidence angle θ_i is equal to the Bragg angle θ_B. During this operation, the intensity of the hkl reflection increases and reaches its maximum value.

c - The incident beam is tilted by an angle ρ until the incidence angle θ_i is equal to the Bragg angle θ_B. The corresponding pattern is identical with the previous one except that it is shifted by the distance $t = f\rho$ with respect to the optic axis.

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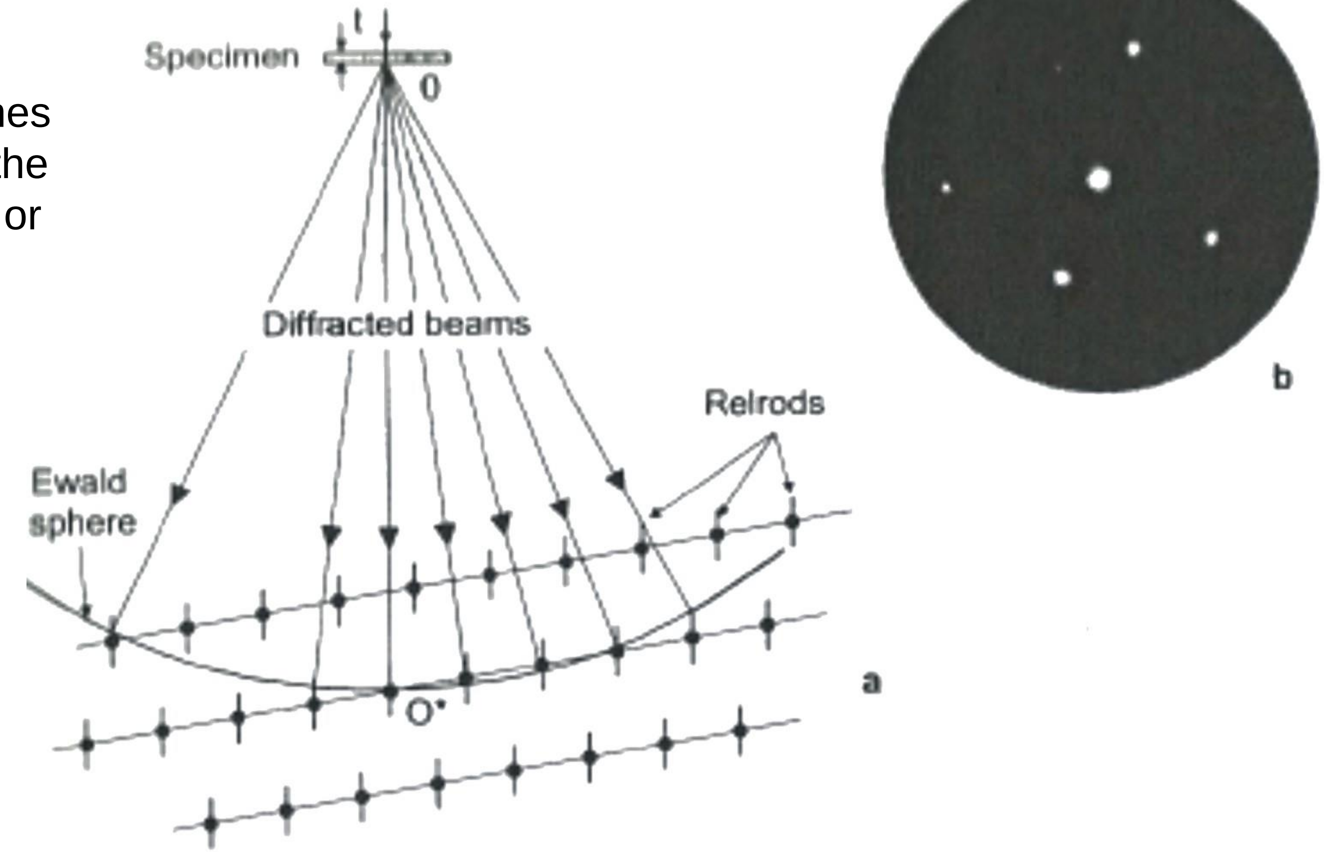
SAED pattern

General case:
Several sets of lattice planes can simultaneously be at the Bragg orientation (exactly or approximately).



"Multi-beam" conditions.

a - Ewald sphere construction. Several relrods simultaneously intersect the Ewald sphere and produce diffracted beams.

b - Example of an experimental diffraction pattern. It is composed of several spot reflections at the exact Bragg orientation or close to it.

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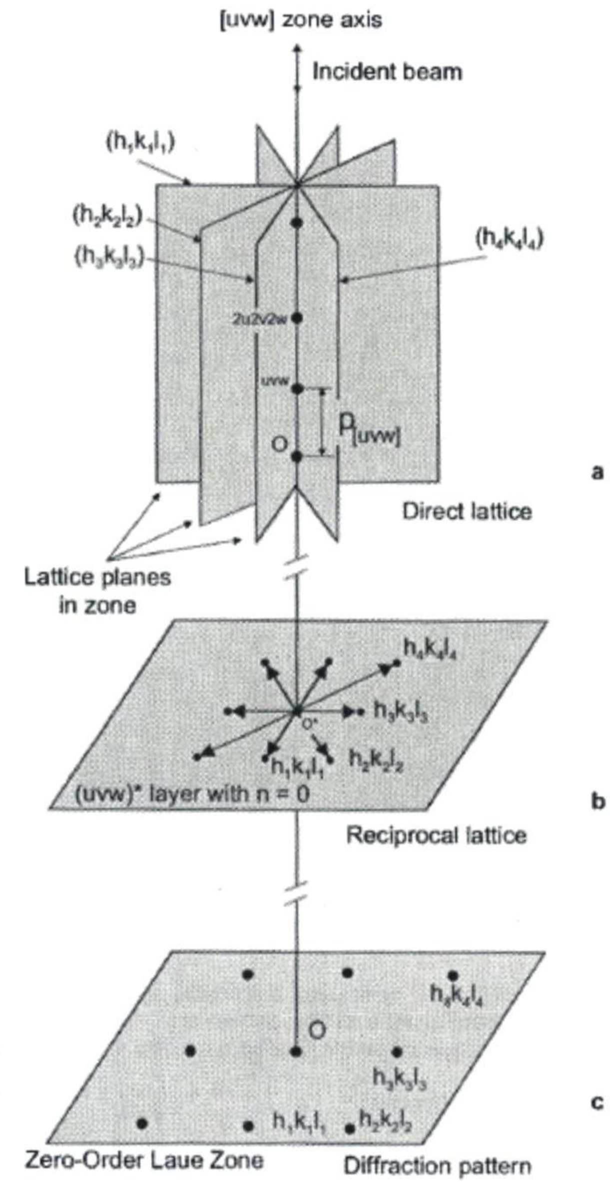
SAED pattern

Special case: [uvw] zone axis pattern (ZAP)

A very useful case occurs when a high symmetry [uvw] lattice of crystal is set paralel to the incydent electron beam.



[uvw] zone-axis diffraction pattern. The incident electron beam is parallel to the [uvw] zone axis. Relationship between the reflections located in the zero-order Laue zone and the (hkl) lattice planes containing the [uvw] zone.

a - Lattice planes containing the [uvw] zone axis (planes in the zone).

b - (uvw)* layer of the reciprocal lattice with zero order. This layer contains the origin O* of the reciprocal lattice and the hkl nodes that correspond to the planes in the zone.

c - Zero-order Laue zone of the diffraction pattern. It is a magnified image of the zero-order layer of the reciprocal lattice.

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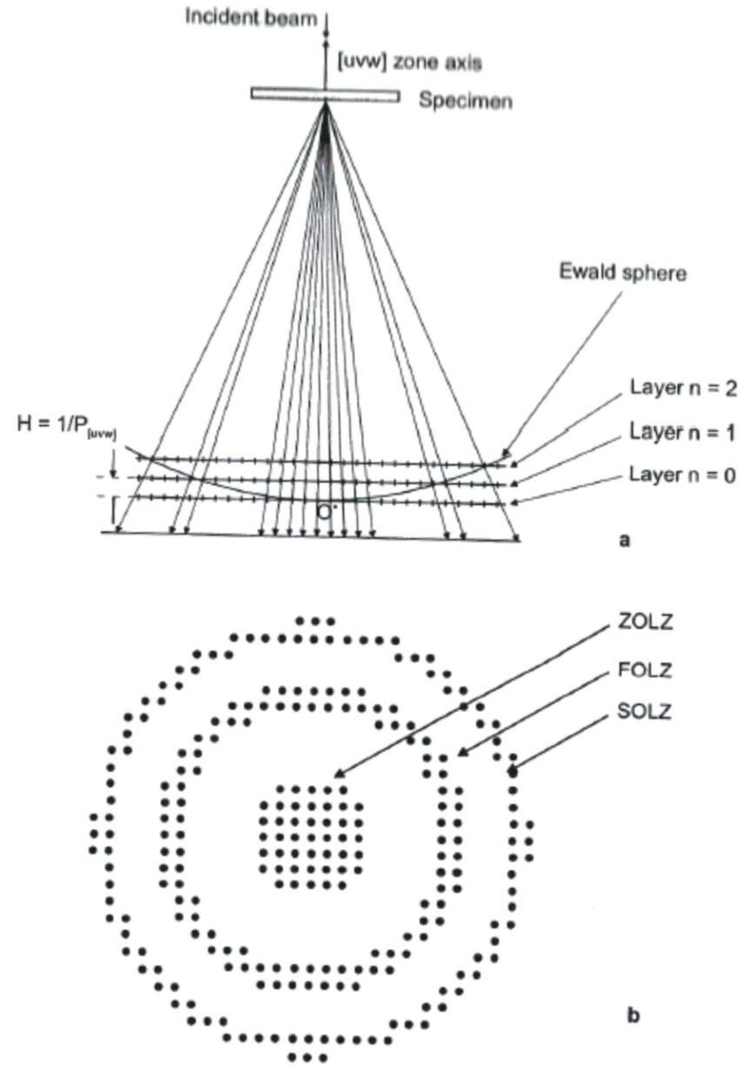
SAED pattern

The whole pattern composed of the Zero-Order Laue Zone (ZOLZ) and of all High-Order Laue Zones (HOLZs) gives <u>three-dimensional information about the reciprocal lattice</u> since is generated by several layers of the reciprocal lattice.



Electron diffraction pattern obtained when a [uvw] zone axis is parallel to the incident beam.
a - Ewald sphere construction. The reciprocal lattice nodes (or relrods) are located in parallel and equidistant layers. Some relrods located in the 0th, 1st, 2nd... layers intersect the Ewald sphere and give diffracted beams.
b - Corresponding diffraction pattern composed of Laue zones.

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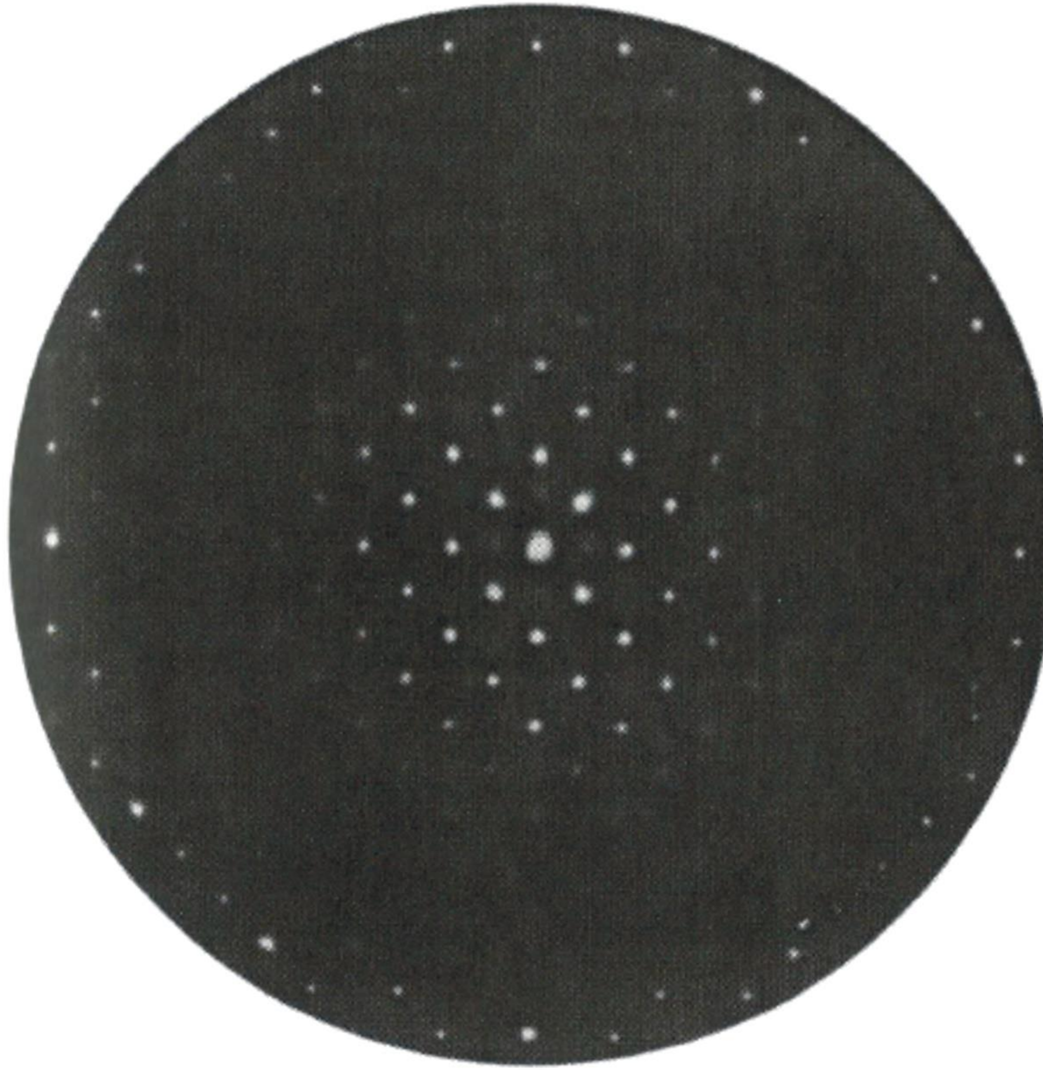
SAED pattern



Experimental [001] zone axis diffraction pattern from a thin gold foil. The reflections located in the central area of the pattern form the zero-order Laue zone. The reflections of the first-order Laue zone are located on a ring. Only the first-order Laue zone is visible on this pattern.
Gold specimen. Courtesy of J. Ayache.

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Convergent Beam Electron Diffraction

CBED pattern

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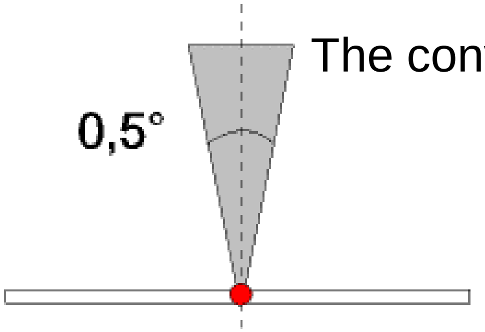
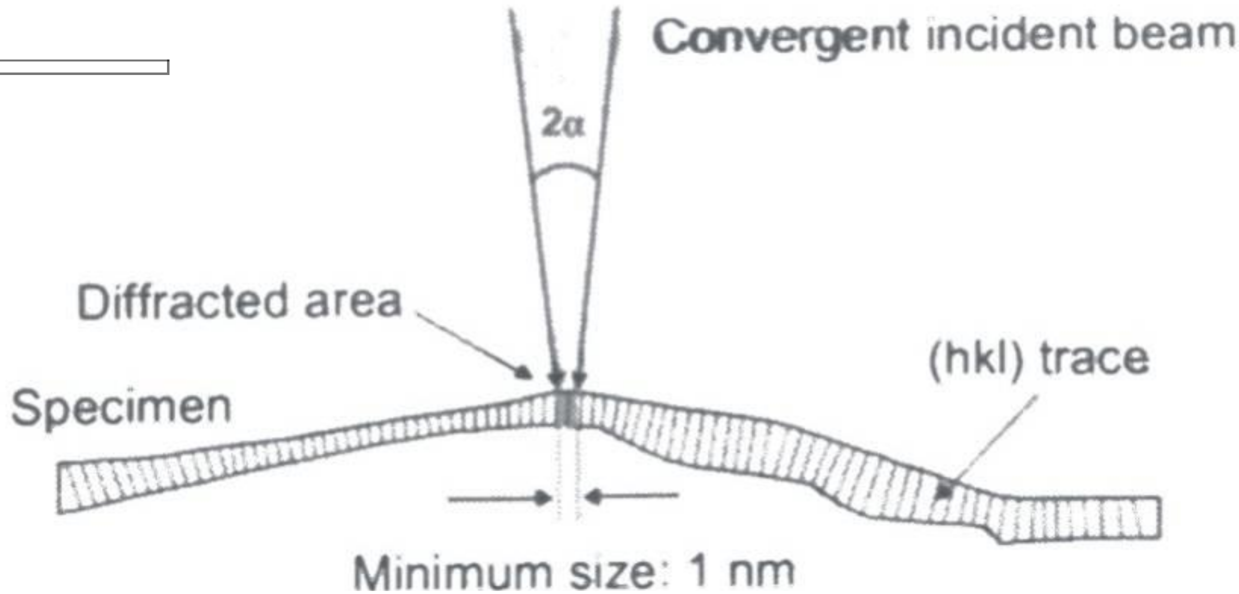
Diffraction pattern produced by a convergent incident beam: CBED pattern



The convergence angle α is of the same order as the Bragg angle θ_B.



Specimen illumination by a convergent incident beam. The diffracted area is defined directly by the size of the incident beam. The minimum size is about 1 nm with modern microscopes. The diffracted area does not include any thickness change and (hkl) lattice plane variation.

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CBED pattern

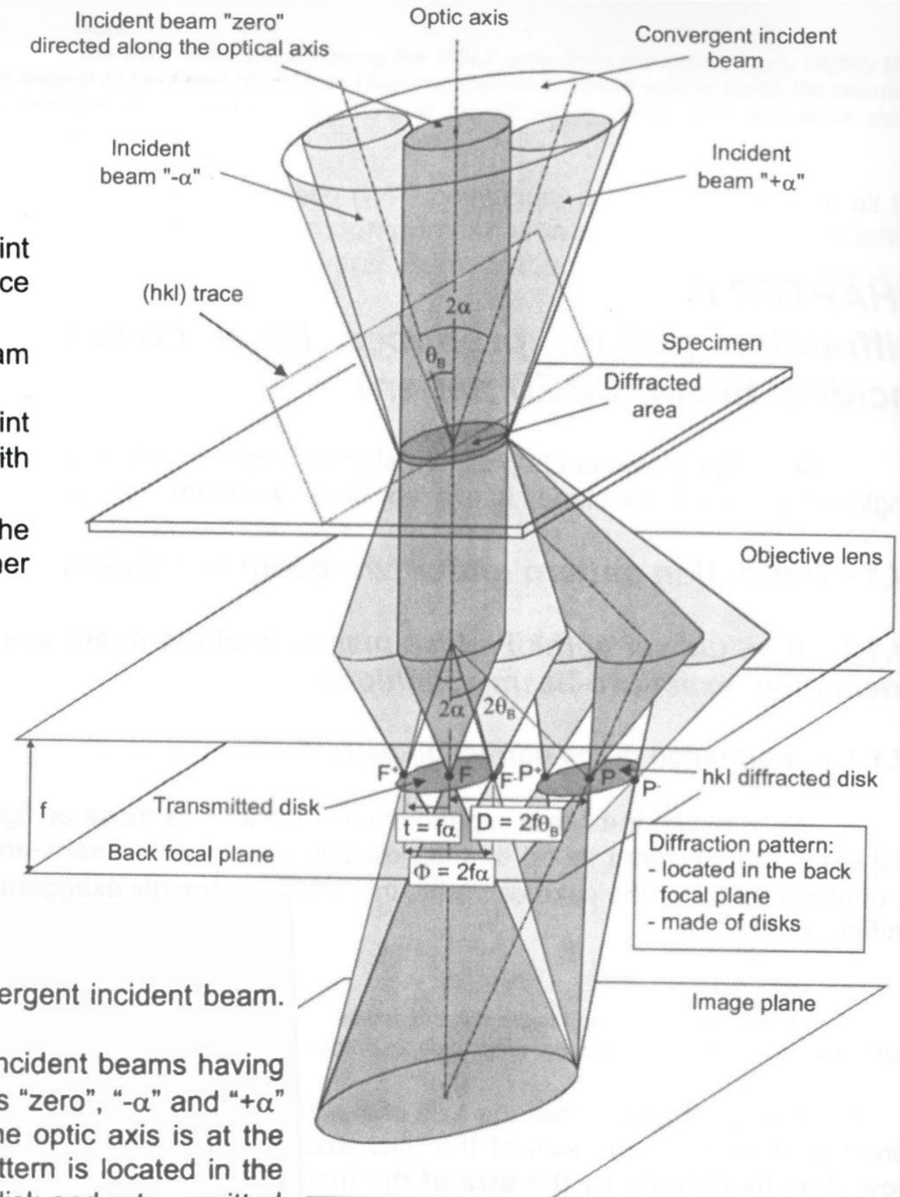
- the incident beam "zero" directed along the optic axis.

It produces a transmitted point located at the back focal point F, and a diffracted point P located in the back focal plane at the distance $D = 2f\theta_B$ from the focal point F.

- the incident beam with the extreme orientation "$+\alpha$ ". This beam behaves like the tilted incident beam

It produces a diffracted point P^+ and a transmitted point F^+. These two points are separated by $D = 2f\theta_B$ and are shifted, with respect to the two previous points F and P, by the distance $t = f\alpha$.

- the incident beam with opposite extreme orientation "$-\alpha$ ". In the same way, it produces a pair of points P^- and F^- shifted in the other direction by the distance -t.



Formation of the diffraction pattern produced by a convergent incident beam. Exact two-beam conditions.
The convergent incident beam is regarded as composed of a set of incident beams having all possible orientations within the incident cone. Three incident beams "zero", "$-\alpha$" and "$+\alpha$" are shown on this figure. The incident beam "zero" directed along the optic axis is at the exact Bragg orientation for the (hkl) lattice planes. The diffraction pattern is located in the back focal plane of the objective lens. It is made of an hkl diffracted disk and a transmitted disk.

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CBED pattern

If we take into account all the incident beams contained in the incident cone, **the pairs of transmitted and diffracted points form a transmitted and a diffracted disk.**

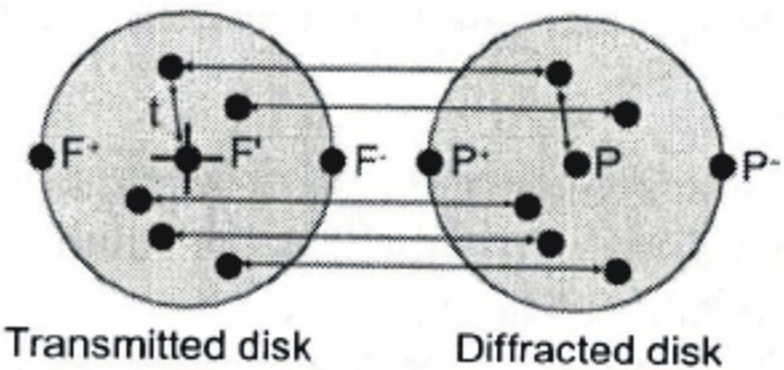
The diameter Φ these two disks is directly related to the convergence angle by the relationship:

$$\Phi = 2f \tan\alpha \approx 2f\alpha$$

Their centres are separated by the distance:

$$D = f \tan 2\theta_B \approx 2f\theta_B$$

This is the same as the distance separating the transmitted and diffracted spots in the case of a parallel incident beam



The convergent-beam diffraction pattern can be considered as made up of a collection of spot patterns.

The CBED pattern can be regarded as the collection of spot patterns that would result from parallel incident beams having all possible orientations within the convergent incident beam.

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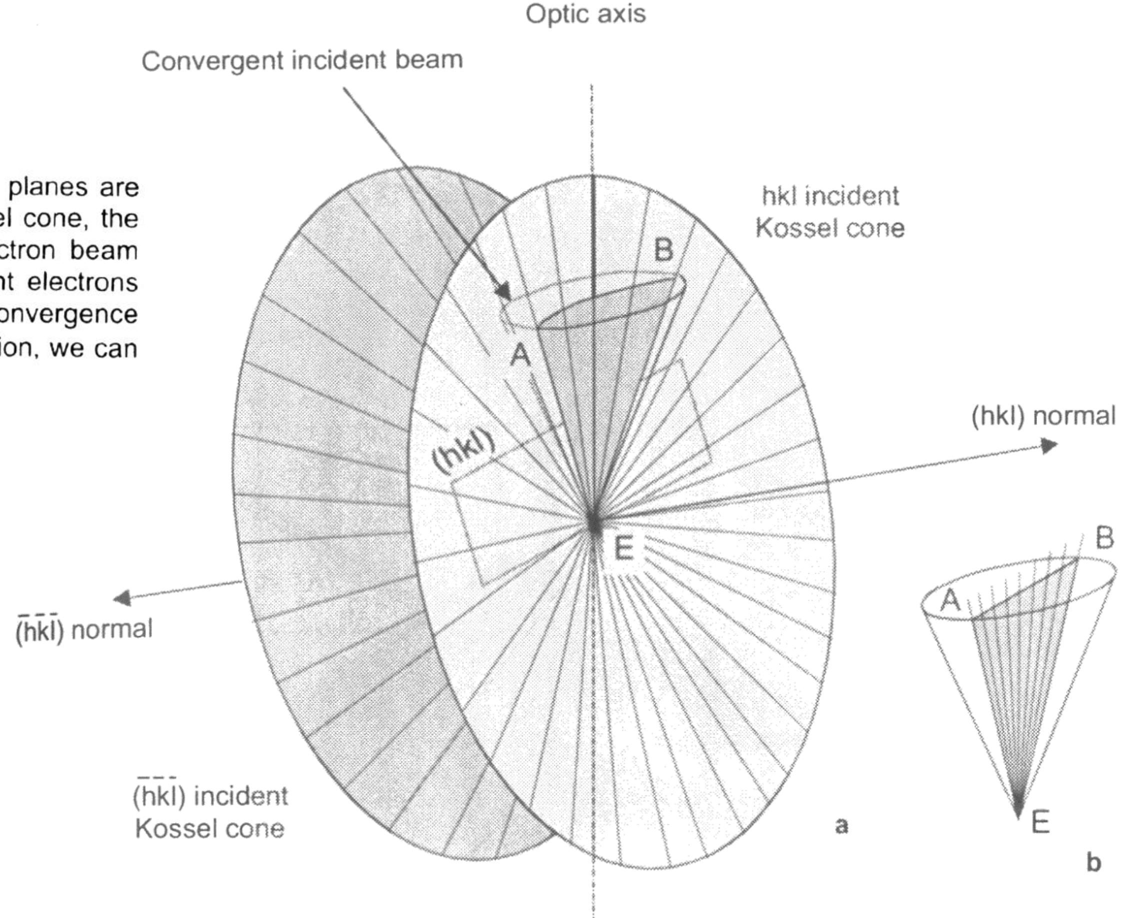
CBED pattern

According to the 3D description of Bragg's law the incident rays at the Bragg orientation for the (hkl) lattice planes are located on the hkl incident Kossel cone. A part of this Kossel cone, the ABE conical surface, is included inside the convergent electron beam Therefore, this surface contains all the incident electrons that are exactly at the Bragg orientation. Since both the convergence 2α and the Bragg angles θ_B are very small in electron diffraction, we can consider this conical surface as planar



Identification of the incident rays at the exact Bragg orientation.
a - Relative arrangement of the (hkl) incident Kossel cone and of the convergent incident beam. The conical surface ABE contains all the incident electrons at the exact Bragg orientation for the set of (hkl) lattice planes. The $\bar{h}\bar{k}\bar{l}$ incident Kossel cone is not involved.
b - The conical surface ABE can be assumed to be a plane taking into account the small value of the Bragg angles θ_B and of the convergent semi-angle α.

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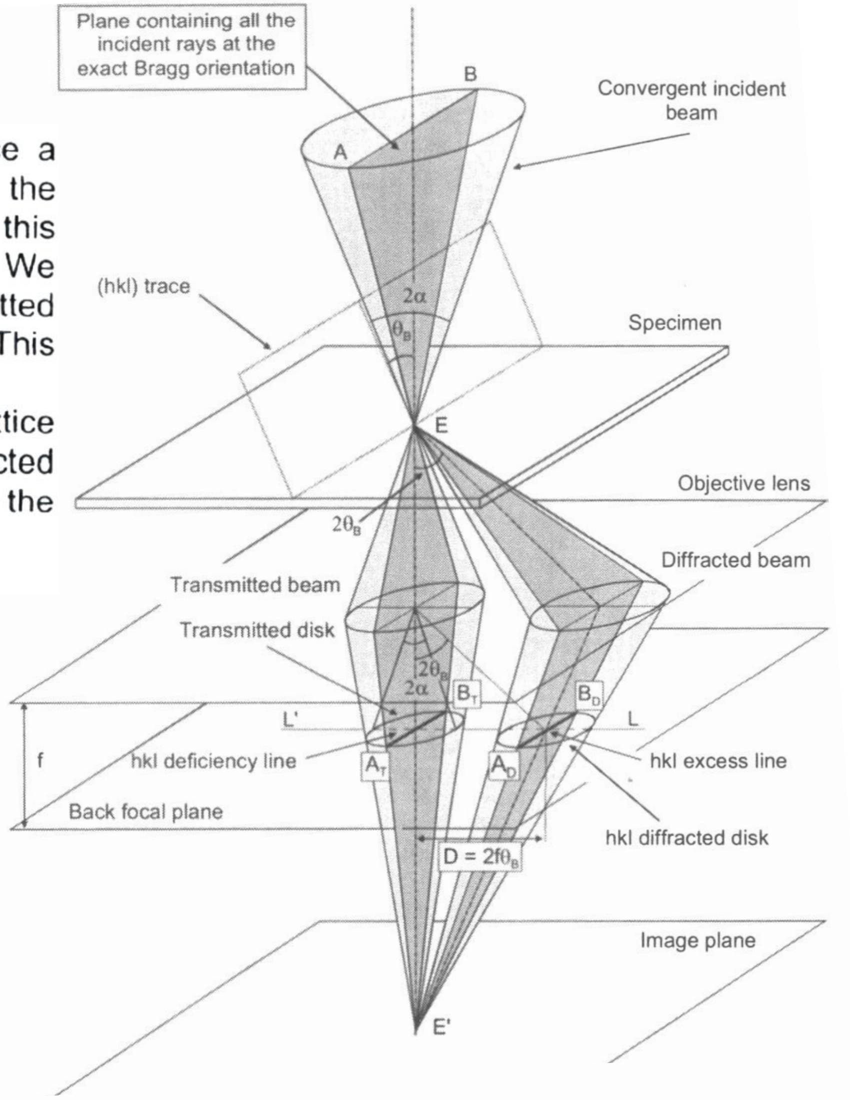
CBED pattern

The incident rays at the exact Bragg orientation produce a diffracted line A_DB_D in the back focal plane, which is brighter than the whole diffracted disk. It is called the **excess hkl line**. To produce this excess line, many electrons are removed from the ABE surface. We understand that a deficit of electrons is then produced in the transmitted disk along the line A_TB_T that appears darker than the rest of the disk. This dark line is called the **deficiency hkl line**.

These two lines are parallel to the trace of the set of (hkl) lattice planes. They run through the centre of the transmitted and diffracted disks, and display a separation, which is related to the Bragg angle by the relationship:

$D \approx 2f\theta_B$



Formation of the convergent beam diffraction pattern. Simplified diagram. The incident plane ABE contains all the incident rays at the exact Bragg orientation. These rays give an hkl excess line (A_DB_D line) located inside the diffracted disk and an hkl deficiency line (A_TB_T line) located inside the transmitted disk.

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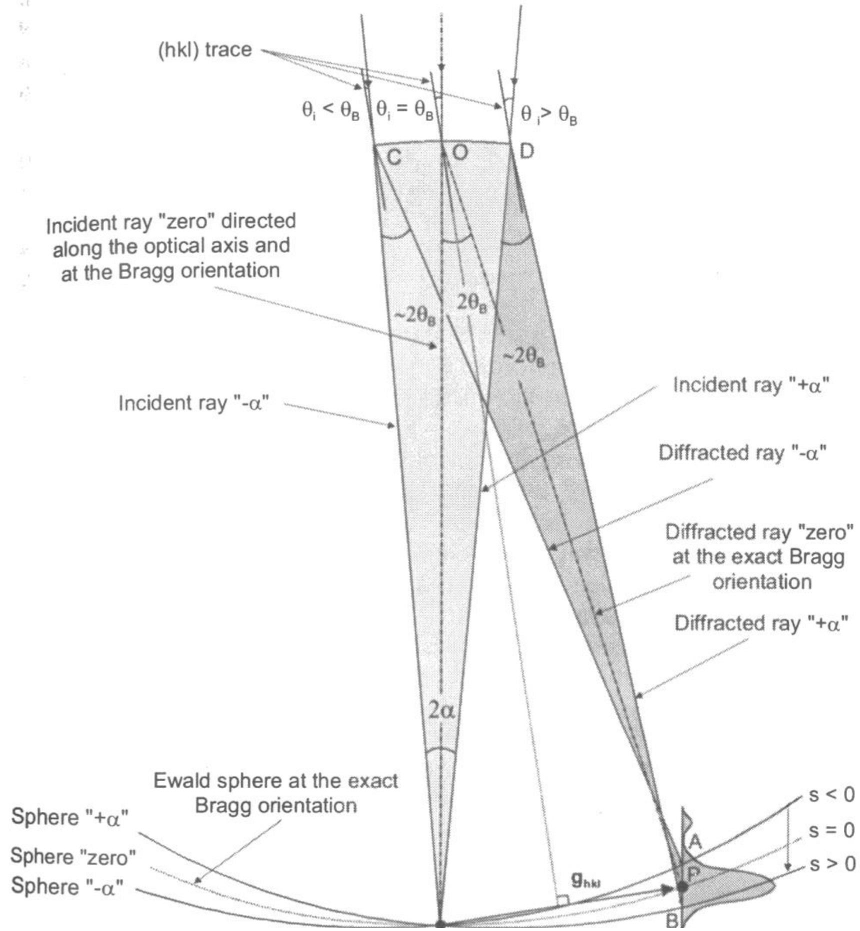
CBED pattern



Ewald sphere construction in convergent beam electron diffraction. Exact two-beam conditions.

An Ewald sphere is associated with each incident ray. Only three spheres corresponding to the incident rays “zero” directed along the optic axis, “-α” and “+α” directed along the two opposite extreme directions are drawn. These spheres produce the diffracted beams OP, CA and DB.

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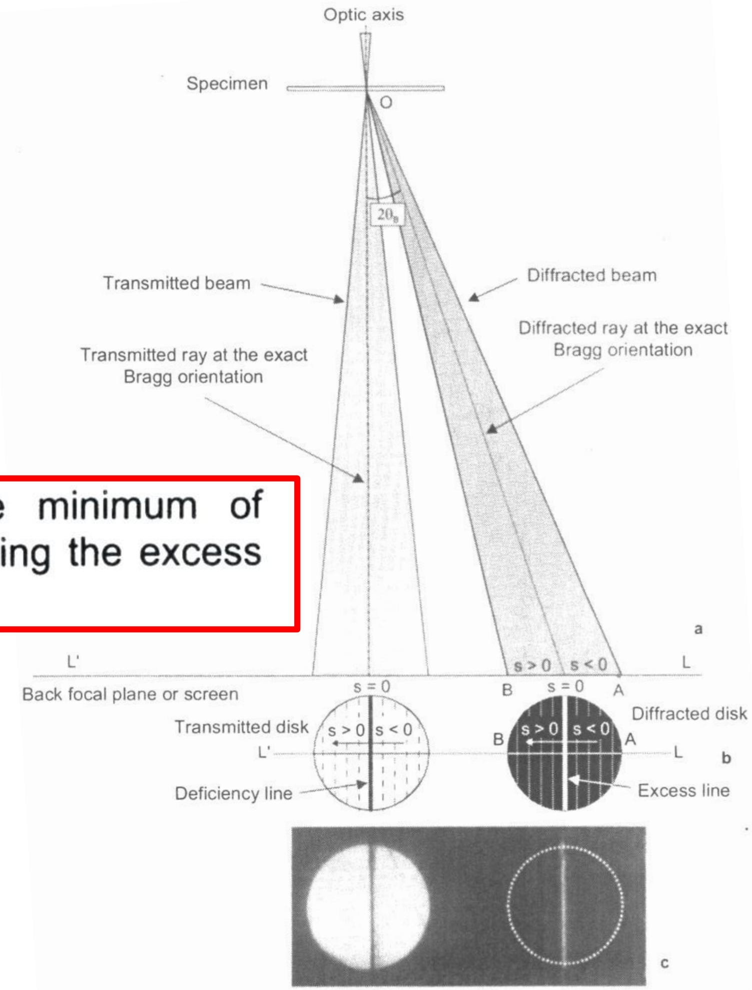
CBED pattern

s – excitation error

The maximum of diffracted intensity and the minimum of transmitted intensity are observed for the value s = 0 giving the excess and deficiency hkl lines r



Convergent-beam electron diffraction. Exact two-beam conditions.

a - Relationship between the Ewald sphere construction and the diffraction pattern. All the transmitted and diffracted beams are redrawn starting from a common origin O.

b - Variation of the deviation parameter s inside the diffracted disk. This variation occurs along lines parallel to the s = 0 line, which runs through the centre of the disk. The same variation occurs inside the transmitted disk.

c - Experimental diffraction pattern obtained under exact two-beam conditions. The hkl excess and deficiency lines run through the centre of the diffracted and transmitted disks.

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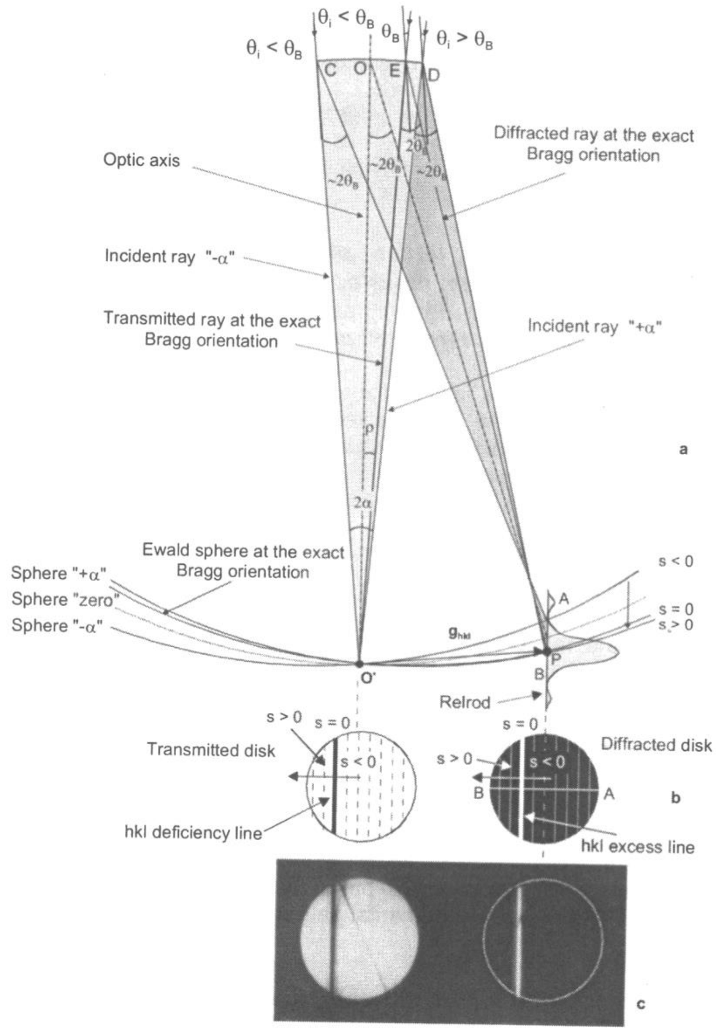
CBED pattern

The set of (hkl) lattice planes is not exactly at the Bragg orientation



Near two-beam conditions.
a - Ewald sphere construction.
b - Variation of the deviation parameter s inside the diffracted and transmitted disks.
c - Example of an experimental diffraction pattern obtained under the near two-beam conditions. The excess and deficiency lines do not run through the centre of the disks.

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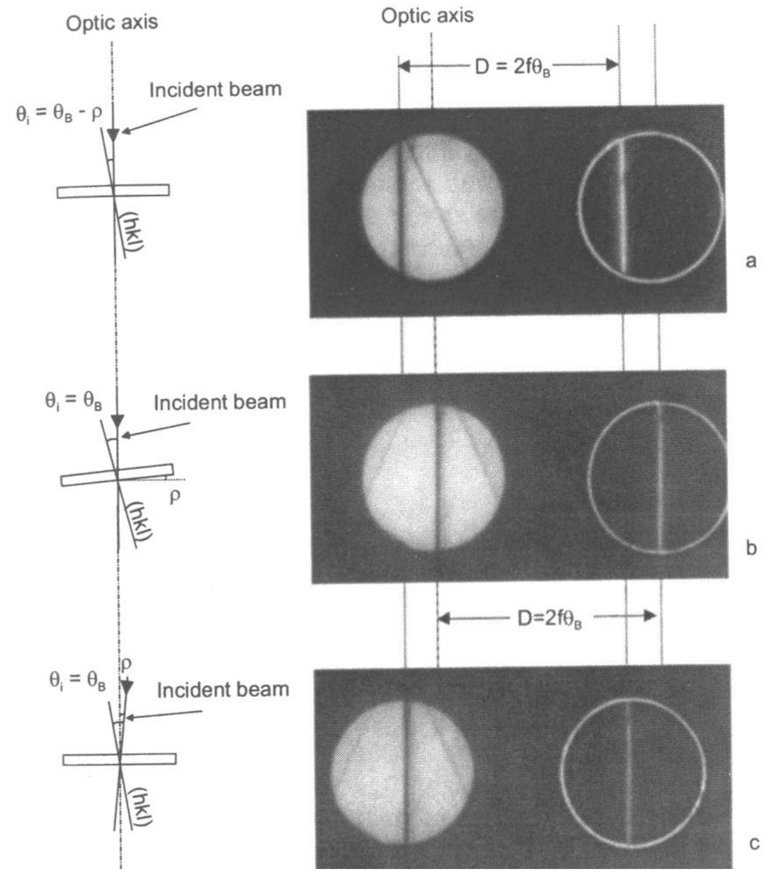
CBED pattern



Setting (hkl) lattice planes at the exact Bragg position starting from an initial approximate orientation.

a - Initial approximate orientation. The excess and deficiency lines do not run through the centre of the transmitted and diffracted disks.

b - The specimen is tilted by an angle ρ until the incidence angle θ_i equals the Bragg angle θ_B. The lines are shifted by a distance $t = f\rho$ and run through the centre of the disks. Note that the position of the disk remains unchanged.

c - The incident beam is tilted with respect to the optical axis by an angle ρ until the incidence angle θ_i equals the Bragg angle θ_B. The disks are shifted by the distance $t = f\rho$. The position of the lines remains unchanged, and they run through the centre of the disks.

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CBED pattern

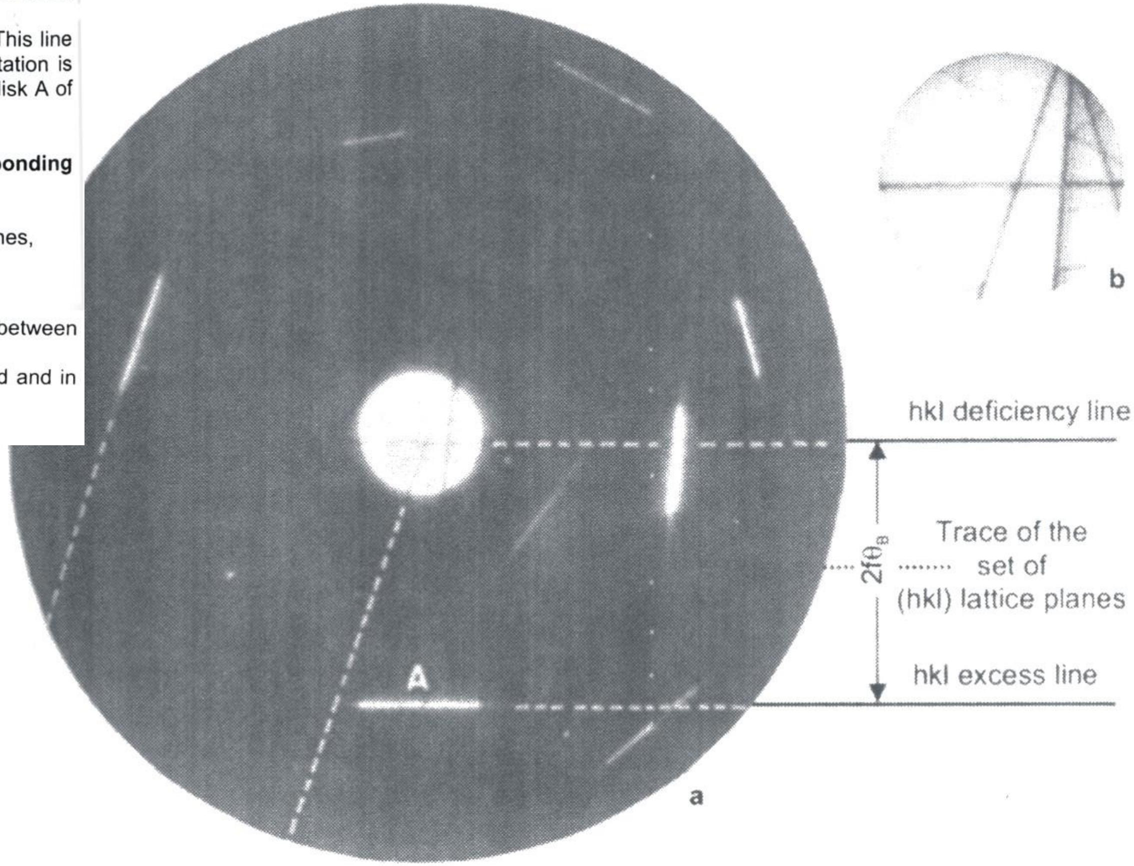
Usually, several sets of (hkl) lattice planes can simultaneously satisfy the Bragg orientation, exactly or approximately, and the diffraction pattern then displays simultaneously several diffracted disks

Each hkl diffracted disk contains its hkl excess line. This line runs through the centre of the diffracted disk if the Bragg orientation is exactly obtained. It is almost the case for the line located in the disk A of the experimental pattern

The transmitted disk contains all the corresponding deficiency lines.

We note that, for each pair of hkl excess and deficiency lines,

- the lines are parallel,
- they are separated by a distance $D = 2f\theta_B$,
- the trace of the (hkl) lattice planes is located halfway between the two lines
- they are located at equivalent positions in the diffracted and in the transmitted disk.



Diffraction pattern under many-beam conditions.

a - Whole pattern. Each set of (hkl) lattice planes produces an excess line situated inside its diffracted disk and a deficiency line located inside the transmitted disk. These two lines are separated by a distance $D = 2f\theta$ and the lattice plane trace is situated halfway between the transmitted and diffracted disks. The transmitted disk contains all the deficiency lines. The weak lines located outside the disks in the prolongation of the excess and deficiency lines are Kikuchi lines.

b - Enlargement of the transmitted disk.

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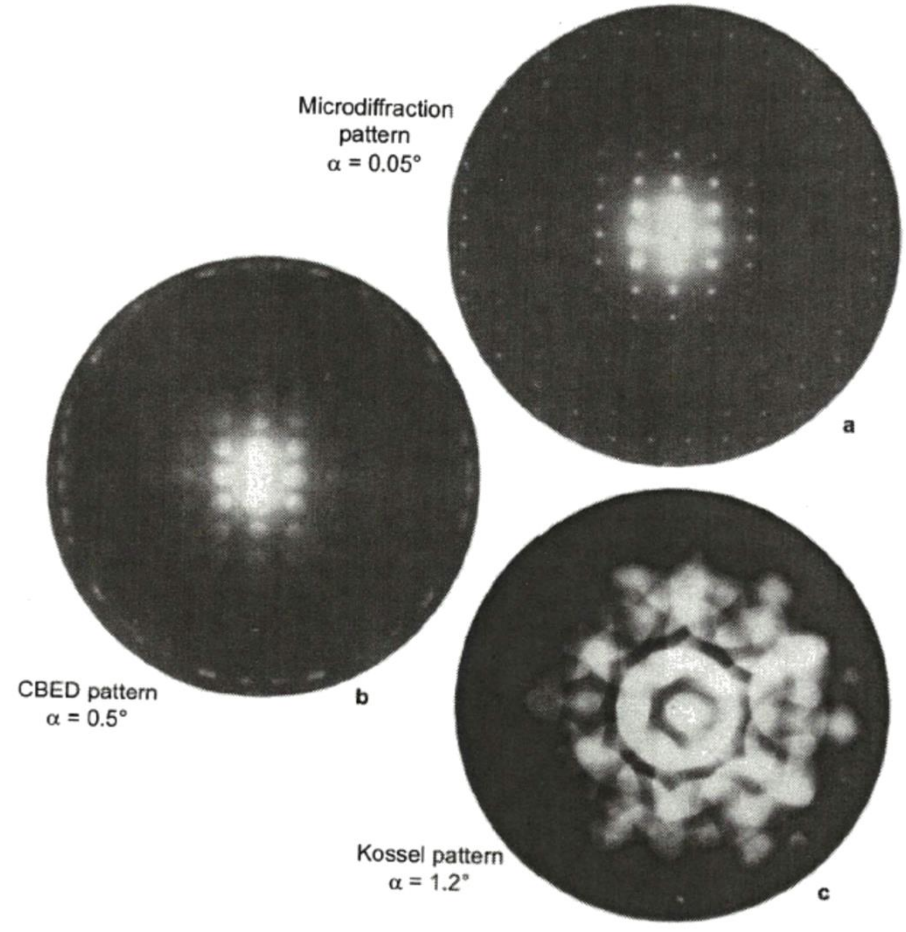
CBED pattern

The diameter of the transmitted and diffracted disks is related to the convergence angle α of the incident beam.



Influence of the convergence semi-angle α on the diffraction pattern. <310> zone-axis pattern from a ferrite specimen.

a - Microdiffraction pattern. The convergence semi-angle α is about 0.05°. The disks have a very small diameter.

b - CBED pattern. The convergence semi-angle α is about 0.5°. The disks do not overlap.

c - Kossel pattern. The convergence semi-angle α is about 1.2°. The disks overlap strongly.

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Large-angle convergent beam electron diffraction

LACBED pattern – Kossel patterns

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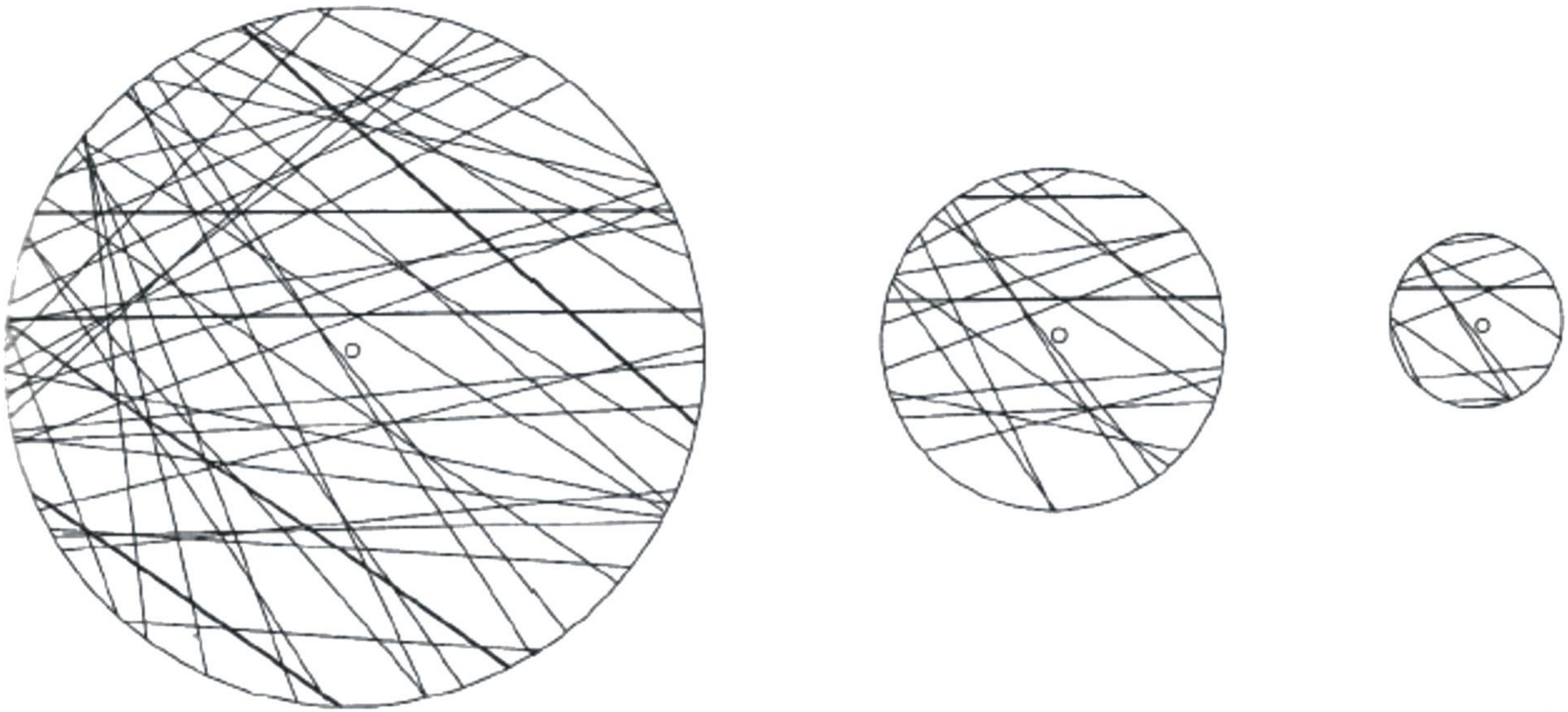
LACBED pattern – Kossel patterns

Advantage of a large convergence angle → the large transmitted disk



$\alpha = 1°$ $\alpha = 0.5°$ $\alpha = 0.25°$

Simulations of the transmitted disk of a convergent beam diffraction pattern for different values of the convergence semi-angle α. The larger the convergence angle, the larger the number of deficiency lines observed.

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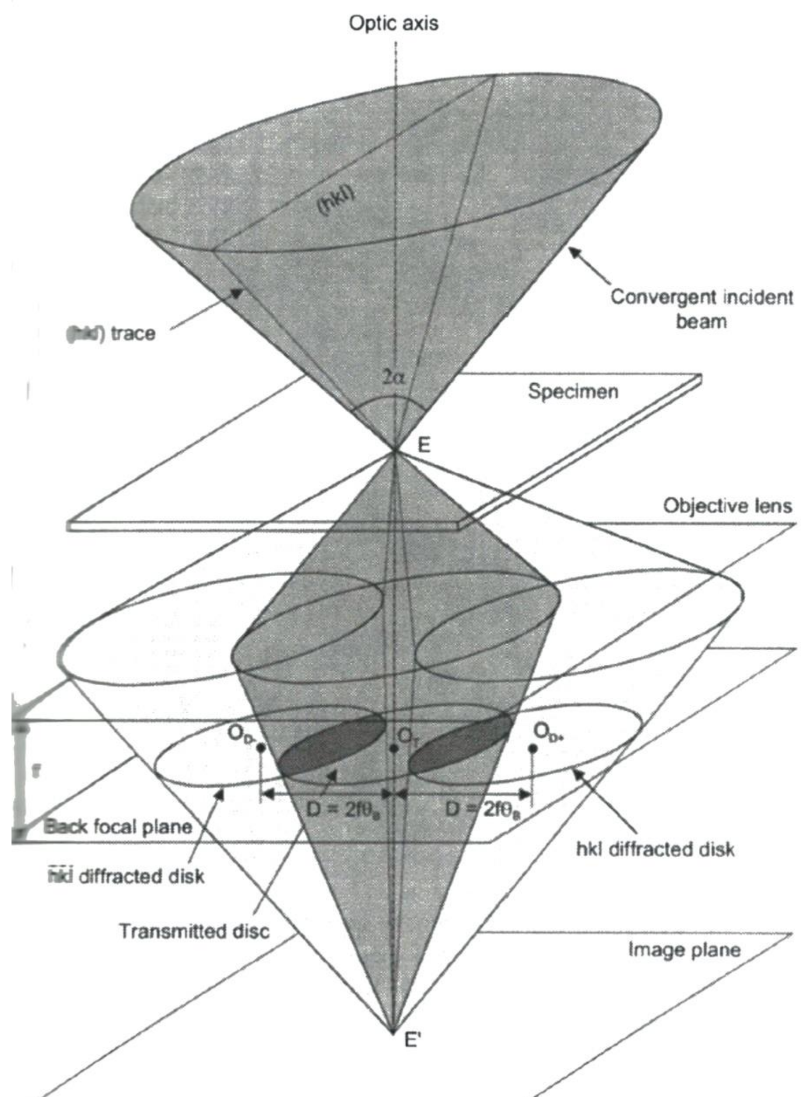
LACBED pattern – Kossel patterns

The disks overlap when the convergense angle α is larger than the Bragg angle θ_B (*since the distance between the centre of the two disks is $D=2f\theta_B$ and their diameter is $\Phi=2f\alpha$*).



Kossel pattern. Electron ray-paths of the diffracted and transmitted beams for a set of (hkl) lattice planes. Owing to the large convergence of the incident beam, the hkl and $\bar{h}\bar{k}\bar{l}$ diffracted disks are partially superimposed on the transmitted disk in the back focal plane of the objective lens.

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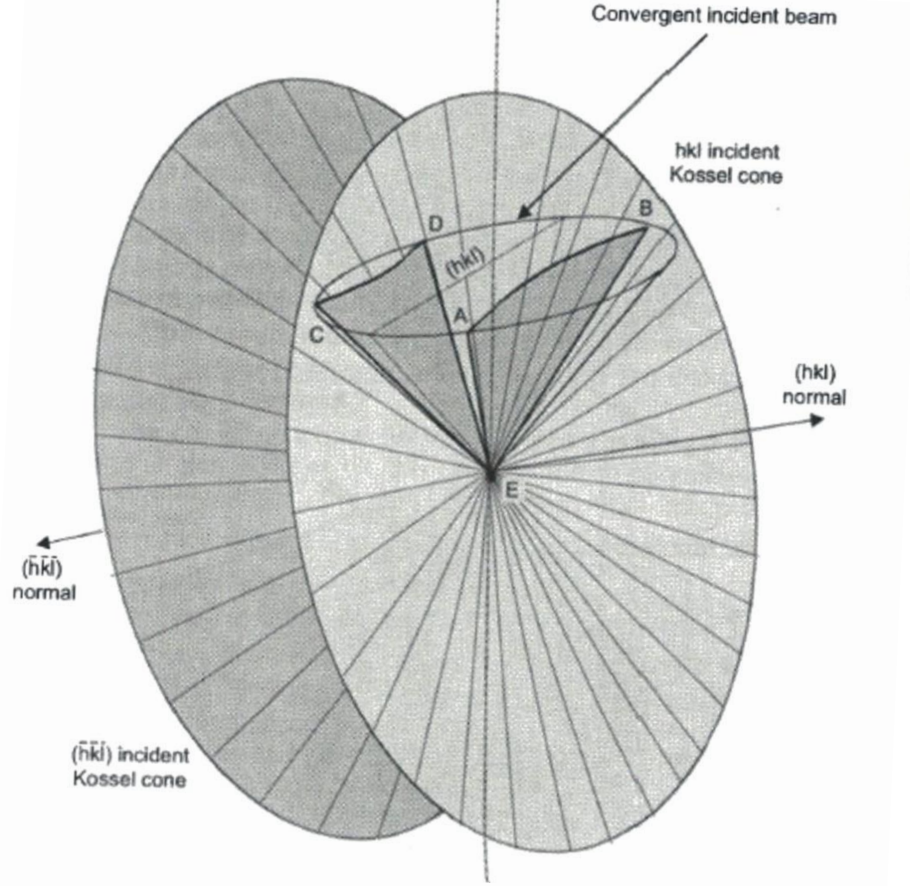
LACBED pattern – Kossel patterns

All the incident rays on the ABE surface give a bright hkl excess line located in the hkl diffracted disk, and a dark hkl deficiency line in the transmited disk. I the same way, the incident rays located in the CDE plane produce a –h-k-l deficiency line located in the transmitted disk.



Identification of the incident rays at the exact Bragg orientation.

a - Relative positions of the (hkl) and ($\bar{h}\bar{k}\bar{l}$) incident Kossel cones with respec[redacted] incident convergent electron beam. The conical surfaces ABE and CDE contain a [redacted] electrons that are at the exact Bragg orientation for the (hkl) and ($\bar{h}\bar{k}\bar{l}$) lattic[redacted] respectively. Taking into account the low values of the convergence and Bragg [redacted] and θ_B, the two conical surfaces ABE and CDE can be regarded as planes.

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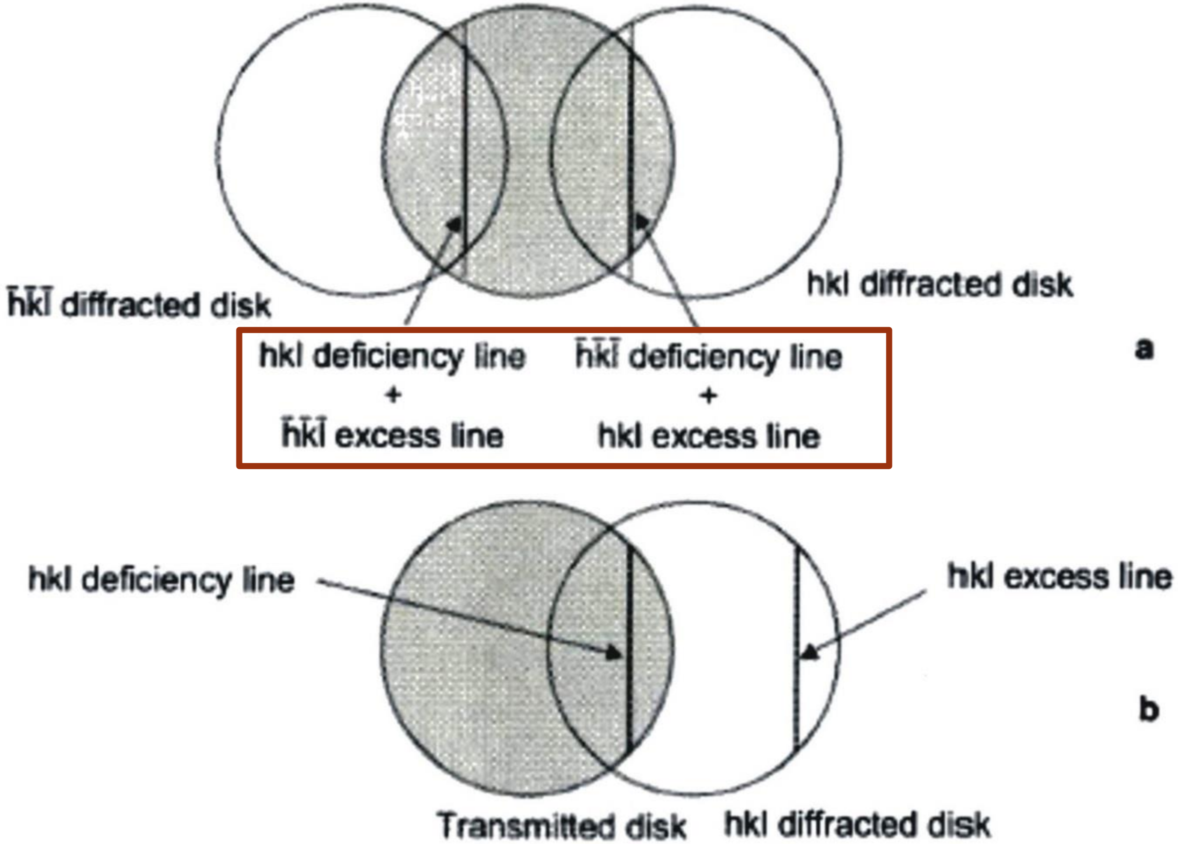
LACBED pattern – Kossel patterns



Schematic description of the two possible locations of a pair of lines on Kossel patterns.

a - The two lines of the pair are located inside the transmitted disk. They are superimposed and their contrast is poor.

b - One line of the pair (the hkl deficiency line) is located inside the transmitted disk and the other (the excess hkl line) is located inside the hkl diffracted disk. The two lines are not superimposed and their contrast is good.

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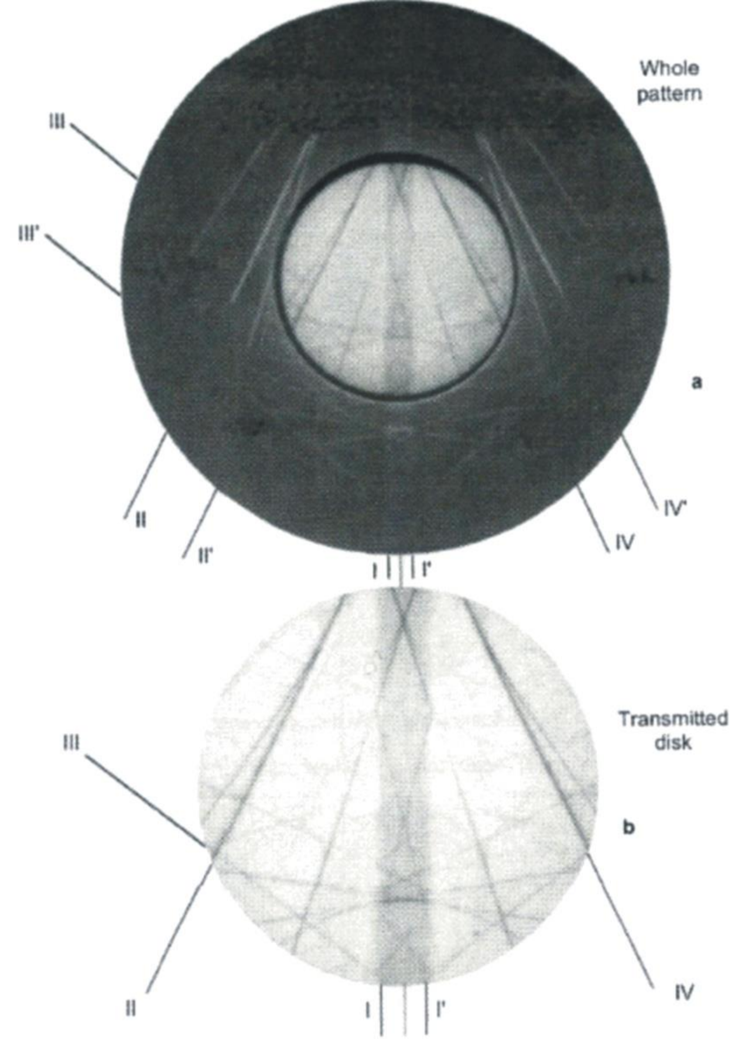
LACBED pattern – Kossel patterns



Kossel pattern from a silicon specimen close to the <001> zone axis.
a - Whole pattern. A montage was carried out in order to compensate for the strong brightness differences between the central and the peripheral areas of the pattern.
b - Enlargement of the transmitted disk.

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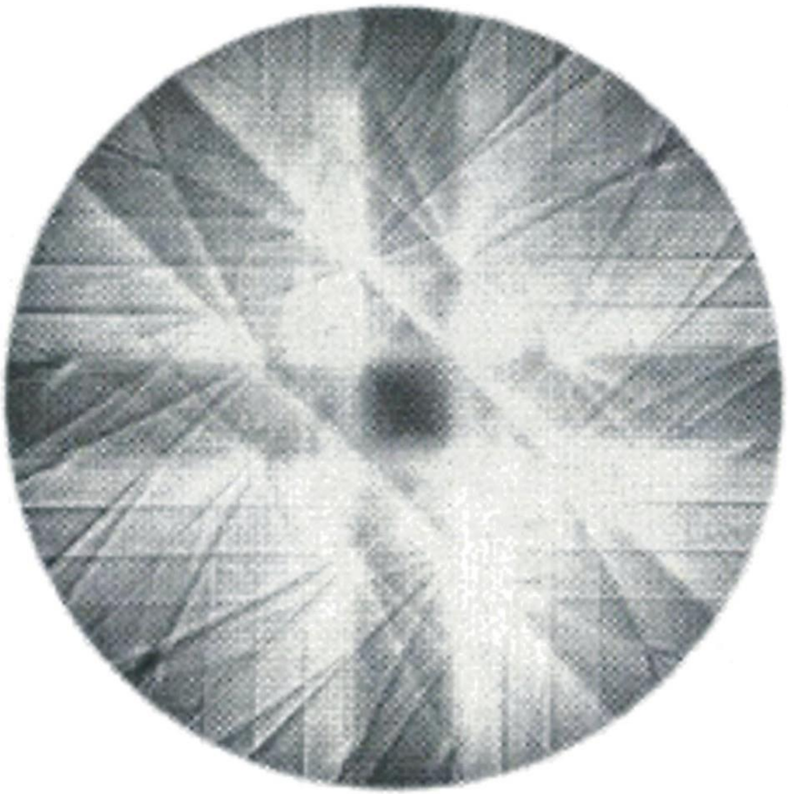
LACBED pattern – Kossel patterns



Transmitted disk of an experimental <001> zone-axis Kossel pattern from a silicon specimen. Owing to the strong spherical aberration of the magnetic lenses, the superimposition of the deficiency and excess lines is imperfect.

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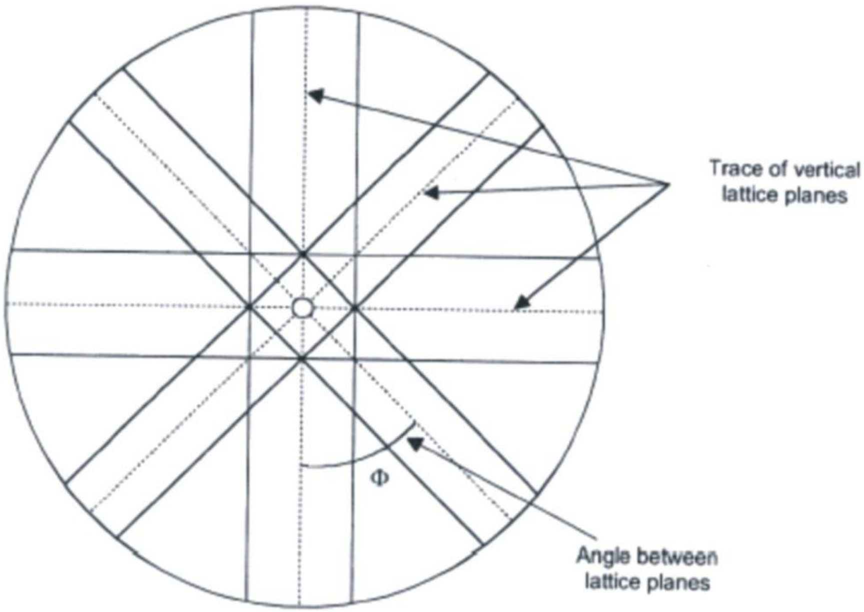
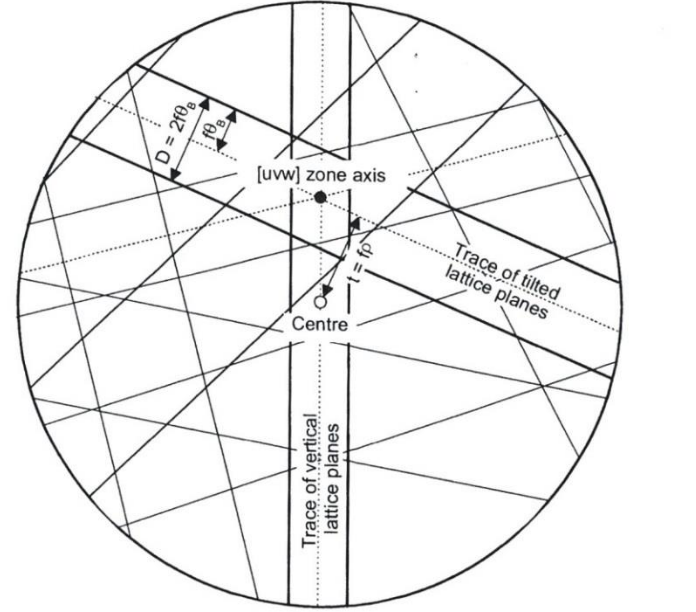
LACBED pattern – Kossel patterns





Main features of the transmitted disk of a Kossel pattern. The deficiency lines can be sorted into pairs of parallel lines. The traces of the sets of lattice planes are located halfway between each pair of lines. Two or several traces intersect along a [uvw] zone axis.

For each pair of lines

- the separation between the lines is directly related to the Bragg angle by the relationship:

$D = 2f\theta_B$

- the trace of the set of (hkl) lattice planes is located halfway between the two lines,
- the trace of a set of lattice planes running through the centre of the transmitted disk means that the planes are parallel to the incident beam axis. They are vertical in the microscope (if the incident beam axis is parallel to the optical axis).
- the trace of lattice planes located at a distance $t = f\rho$ from the centre of the transmitted disk corresponds to lattice planes tilted at an angle ρ with respect to the optic axis.
- two or several traces can intersect at a point, which corresponds to a [uvw] zone axis.

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LACBED patterns

The ilumunation conditions are the same as those used for the Kossel method, i.e. the incident beam has a large convergence and is focused on the object plane of the objective lens. The main difference concerns the specimen, which is now raised (or lovered) by a distance Δh from its normal position in the object plane (*M. Tanaka, R. Saito, K. Ueno and Y. Harada: Large angle CBED, Journal of Electron Microscopy, A31 (1980) 408*).

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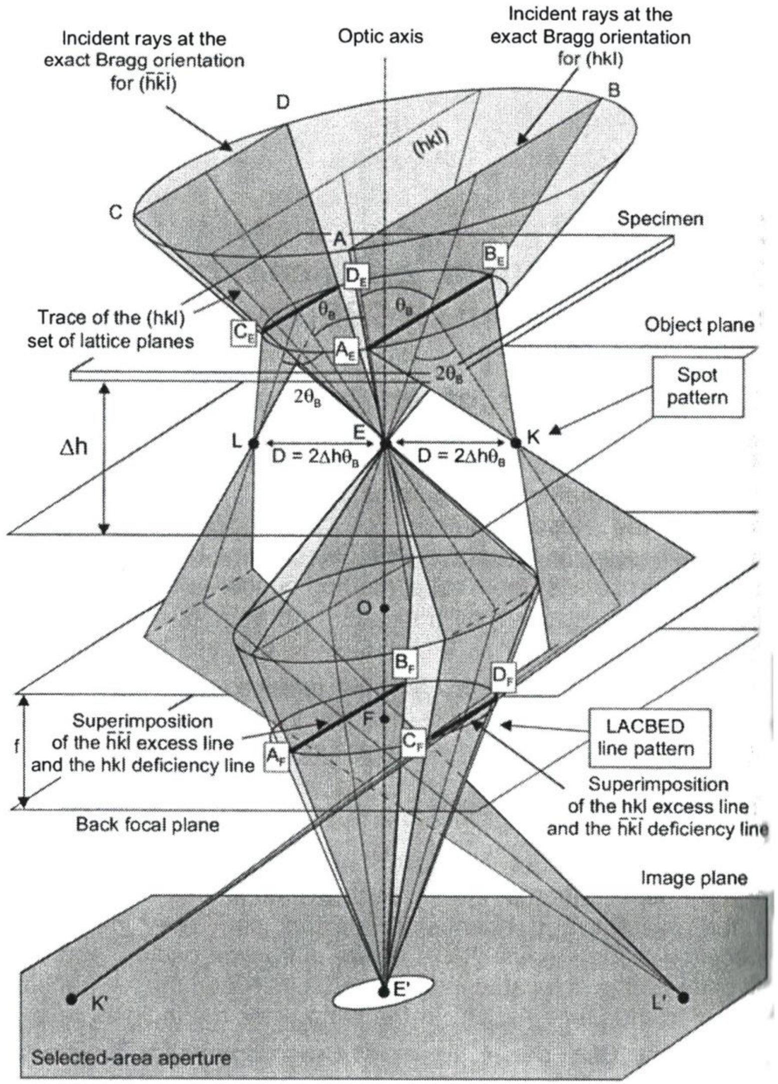
LACBED patterns



Formation of a LACBED pattern. Setting the specimen at the distance Δh from the object plane of the objective lens produces a spot pattern and a line pattern located in the object plane and in the back focal plane respectively. The transmitted beam is selected by means of the selected-area aperture.
For the sake of clarity, only the transmitted and the diffracted rays at the exact Bragg orientation are shown on this diagram.

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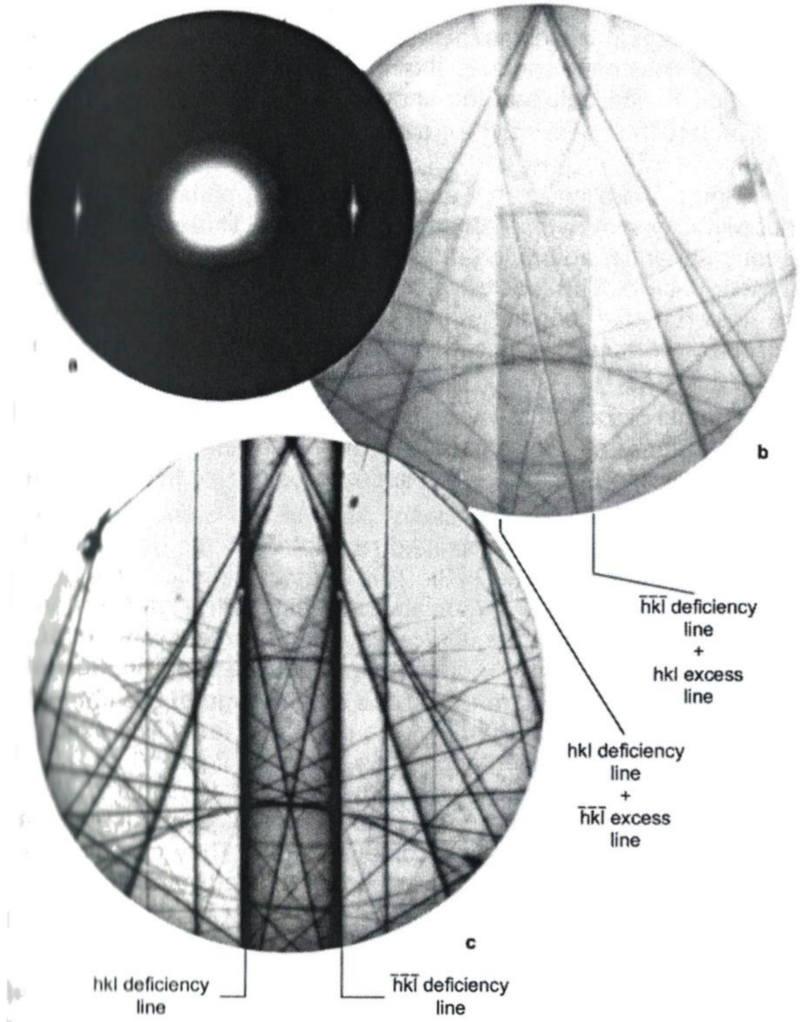
LACBED patterns



Formation of a LACBED pattern.

a Spot pattern located in the object and image planes of the objective lens.

b Line pattern located in the back focal plane of the objective lens. The hkl deficiency line and the hkl excess line are superimposed as are the $\bar{h}\bar{k}\bar{l}$ deficiency line and the hkl excess line. Their contrast is poor.

c Line pattern located in the back focal plane and observed with a selected-area aperture. Only the hkl and $\bar{h}\bar{k}\bar{l}$ deficiency lines are visible. Their contrast is excellent.

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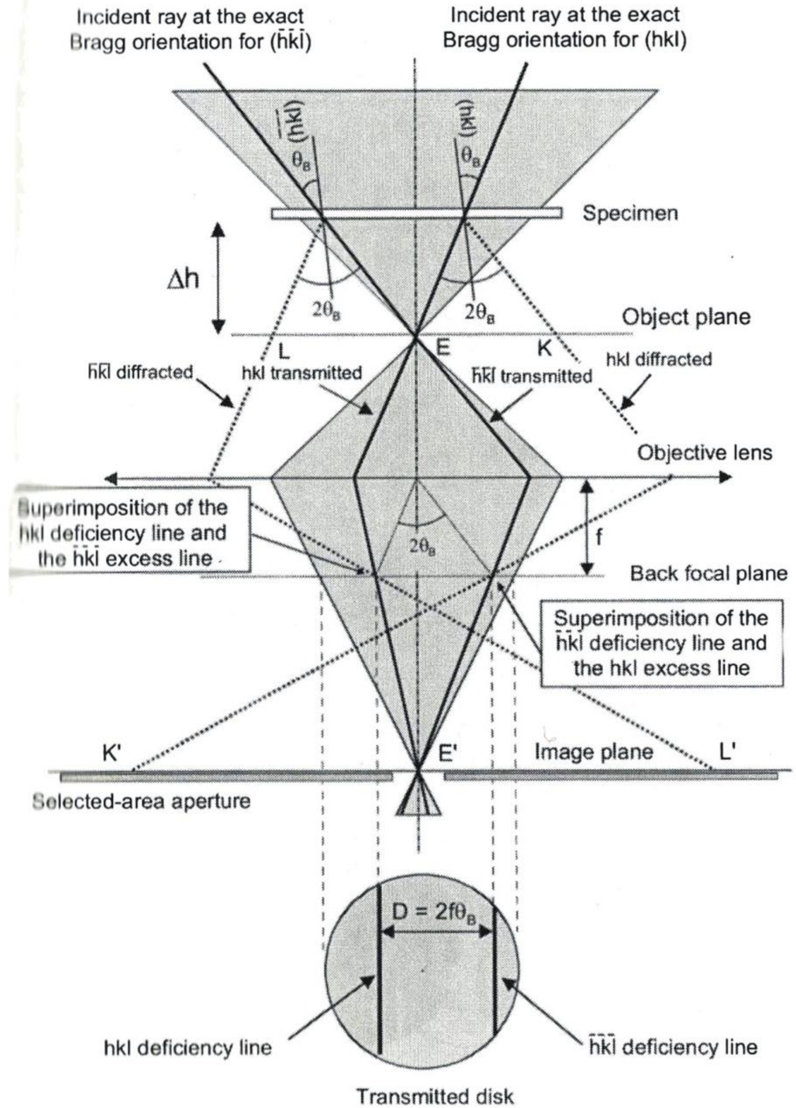
LACBED patterns



Formation of a bright-field LACBED pattern.

Only the hkl and $\bar{h}\bar{k}\bar{l}$ transmitted rays pass through the selected-area aperture and produce the hkl and $\bar{h}\bar{k}\bar{l}$ deficiency lines in the transmitted disk.

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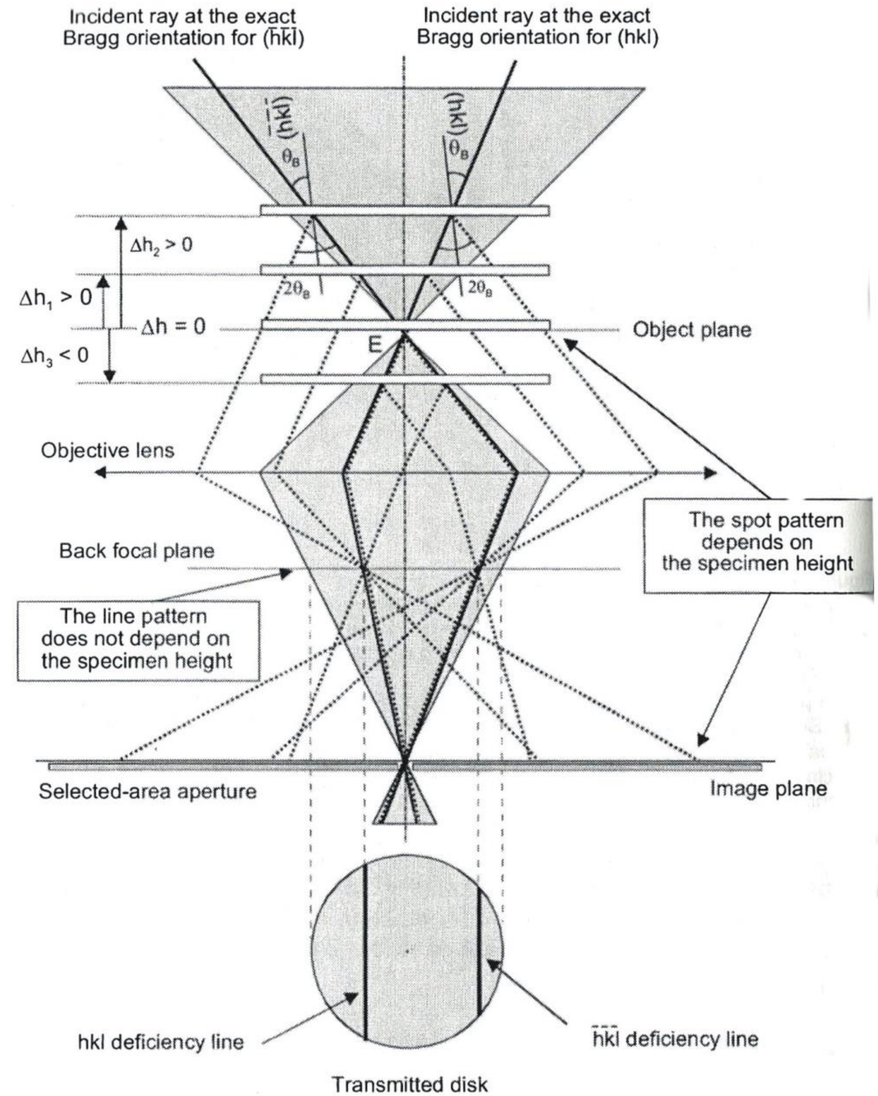
LACBED patterns



Effect of the specimen height Δh on LACBED patterns.
The spot pattern located in the conjugate object and image planes of the objective lens depends on the specimen height Δh. On the contrary, the line pattern located in the back focal plane of the objective lens does not depend on the specimen height.

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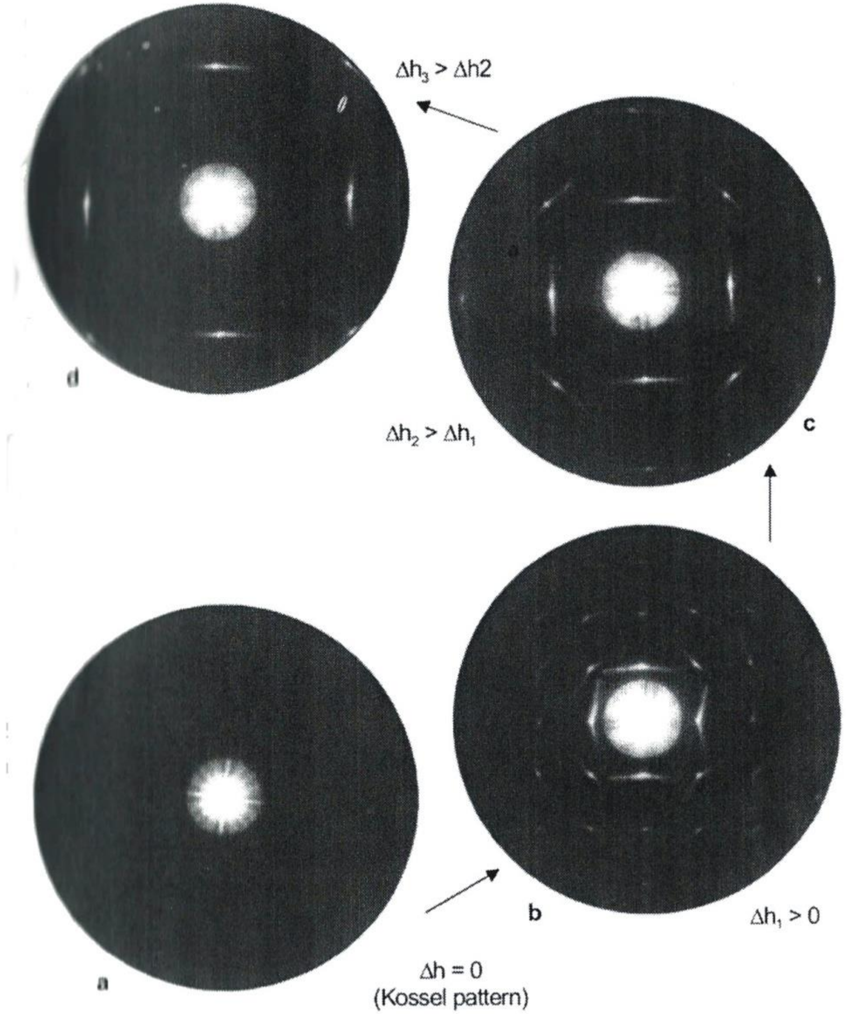
LACBED patterns



Effect of the specimen height Δh on the spot pattern located in the conjugate object and image planes of the objective lens. The specimen height modifies the magnification of the spot pattern.
a - The specimen is located in the object plane (Δh = 0). This location corresponds to the experimental conditions used to obtain Kossel patterns. A single spot is observed.
b, c, d - The specimen is located at various positive Δh values above the object plane of the objective lens. The magnification of the spot pattern increases.
The same effects are observed for negative Δh values (specimen located below the object plane).

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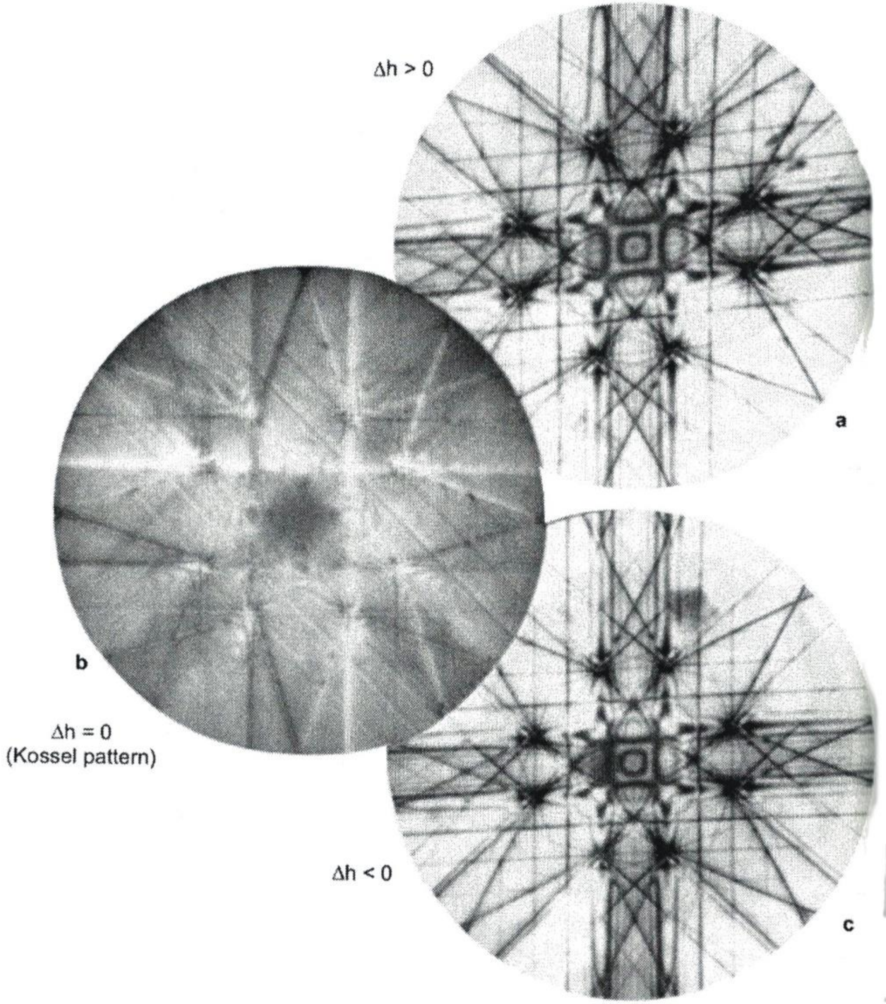
LACBED patterns



Effect of the specimen height on the line pattern located in the back focal plane of the objective lens. The line pattern does not depend on the specimen height.
a - The specimen is located above the object plane of the objective lens ($\Delta h > 0$).
b - The specimen is located in the object plane ($\Delta h = 0$) (Kossel pattern conditions). The excess and deficiency lines are superimposed.
c - The specimen is located below the object plane ($\Delta h < 0$).
The distortion of the LACBED patterns is due to a deformed specimen. Note that the Kossel pattern is not distorted.

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Kikuchi patterns

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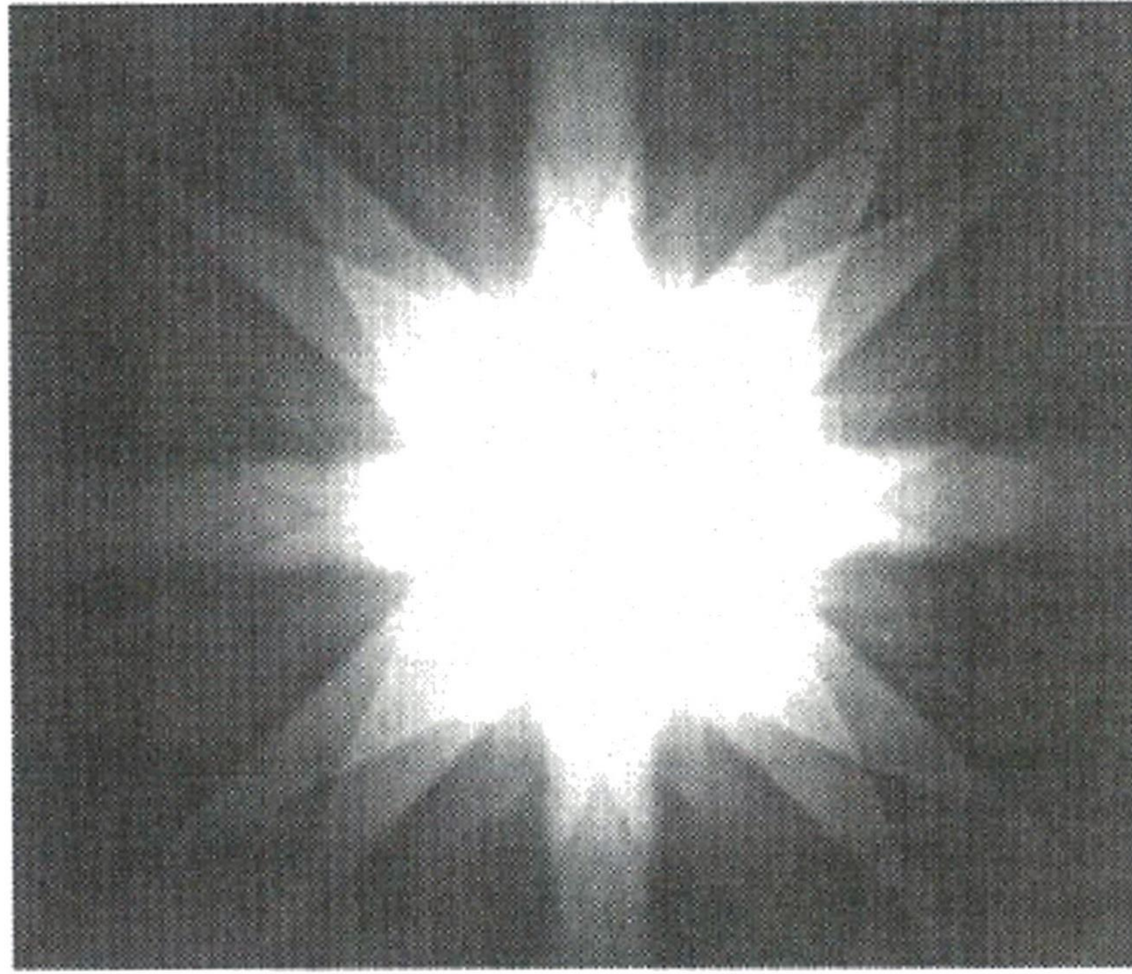
Kikuchi patterns



<001> Kikuchi pattern from a silicon specimen.

- For LACBED patterns, we indicated that the lines are produced by diffraction of the incident rays at the exact Bragg orientation. We recall that diffraction involves only elastic scattering.
- For Kikuchi patterns, two mechanisms are involved: a first inelastic scattering mechanism, followed by a second diffraction mechanism (elastic scattering).

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Kikuchi patterns

An estimation of the contribution of these inelastic phenomena to the intensity of the diffraction pattern at points C and D is obtained in the following manner. On figure the intensity I_2 is lower than I_1 since the scattering angle ρ_2 is larger than ρ_1 (the probability of inelastic scattering decreases with the scattering angle ρ).

We characterize the diffracted efficiency of the set of (hkl) lattice planes by a parameter p, which represents the ratio of the diffracted intensity to the incident intensity. At point A, the incident ray with intensity I_1 produces an hkl diffracted beam with intensity I_1p and a hkl transmitted ray with intensity $I_1(1 - p)$.

In the same way, at B, the diffracted ray has an intensity I_2p, and the transmitted ray, an intensity $I_2(1 - p)$.

In the back focal plane, the intensity at point C is:

$I_c = I_2p + I_1(1 - p) = I_1 + p(I_2 - I_1)$

Since $I_1 > I_2$:

$I_C = I_1 - p\Delta I$

with $\Delta I = I_1 - I_2$

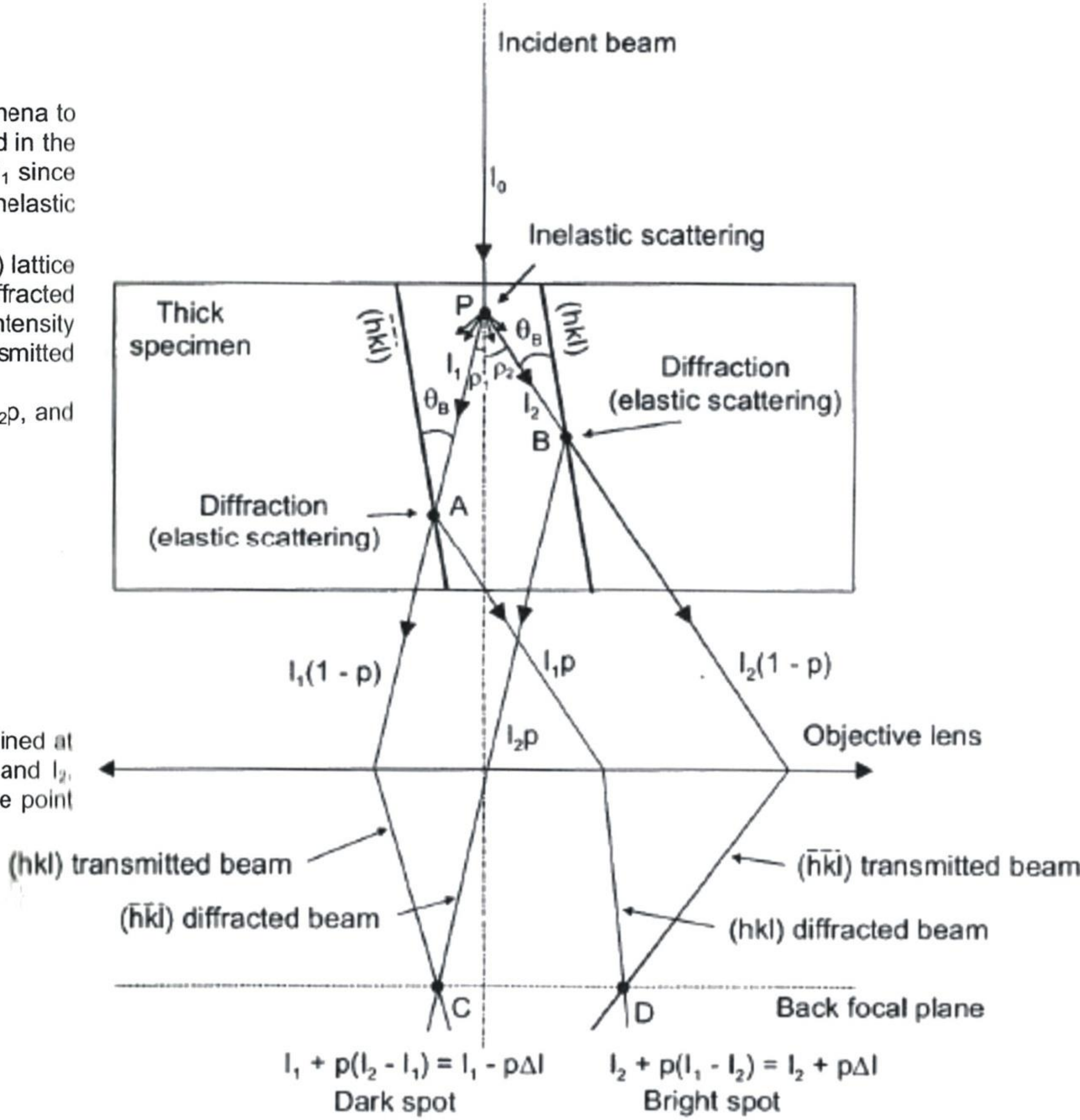
At point D:

$I_D = I_1p + I_2(1 - p) = I_2 + p(I_1 - I_2)$

This time:

$I_D = I_2 + p\Delta I$

In the absence of diffraction, the scattered intensities obtained at points C and D (background intensity) would be respectively I_1 and I_2. Consequently, the point C is darker than the background while the point D is brighter.



Formation of Kikuchi lines.

Incident electrons are scattered at P. Some of them are at the exact Bragg orientation for the (hkl) lattice planes and undergo diffraction at A and B. In the back focal plane of the objective lens, they produce a dark point C and a bright point D.

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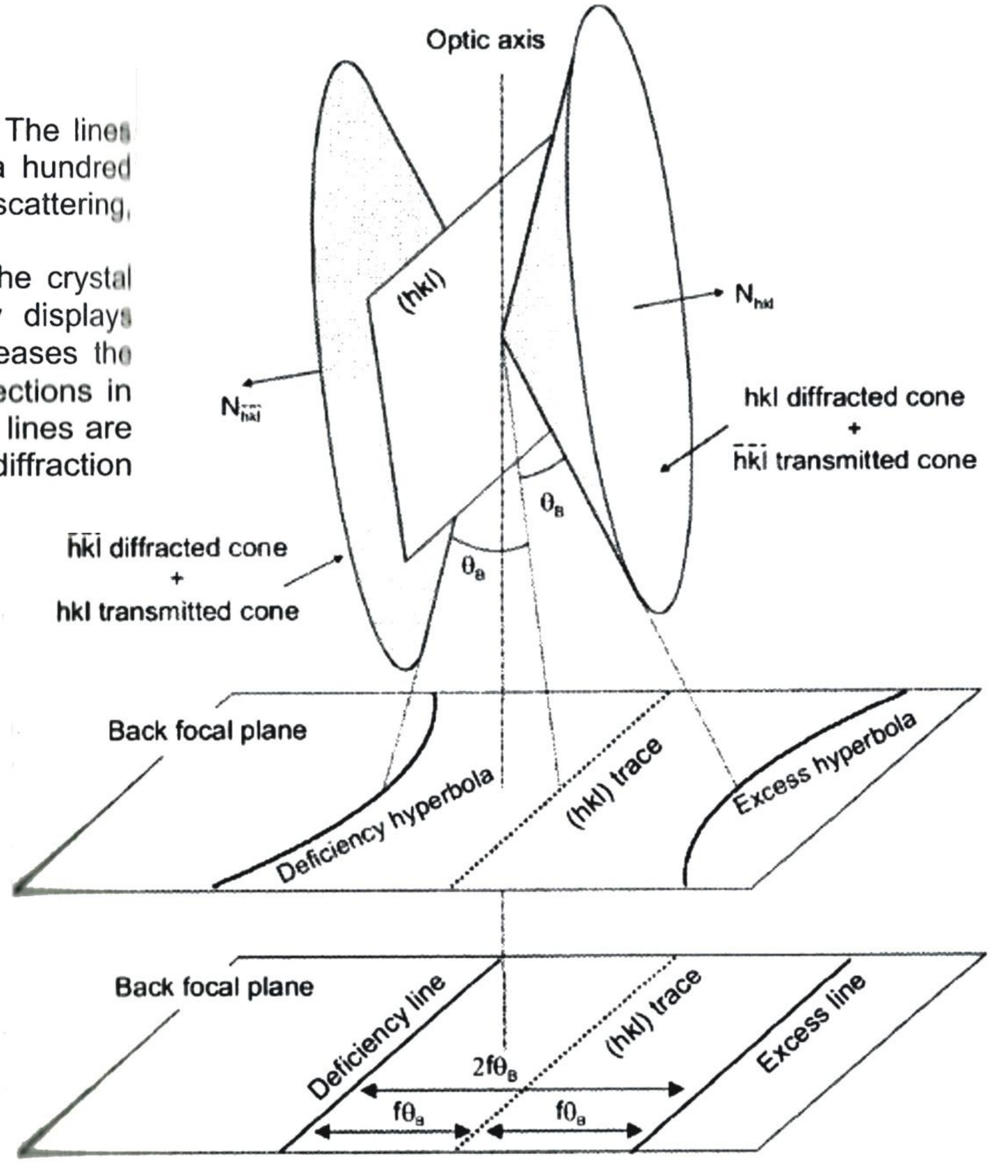
Kikuchi patterns

Kikuchi lines display some interesting features.

Their visibility increases with the specimen thickness. The lines become clearly visible as soon as the latter is larger than a hundred nanometres. This effect is related to the probability of inelastic scattering, which increases with the specimen thickness.

The quality of the Kikuchi lines greatly depends on the crystal perfection. A specimen containing crystal defects generally displays broad and fuzzy Kikuchi lines. A small probe size also increases the visibility of Kikuchi lines since the probability of finding imperfections in the diffracted area is strongly reduced. For this reason, Kikuchi lines are much more visible on CBED patterns than on selected-area diffraction patterns.



Formation of a Kikuchi pattern.

The intersection of the hkl and $\bar{h}\bar{k}\bar{l}$ transmitted and diffracted Kossel cones with the back focal plane (or the screen) produces two excess and deficiency Kikuchi hyperbolae. Taking into account the low value of the Bragg angles, these two hyperbolae can be regarded as straight parallel lines. The line near the optic axis is the dark deficiency Kikuchi line.

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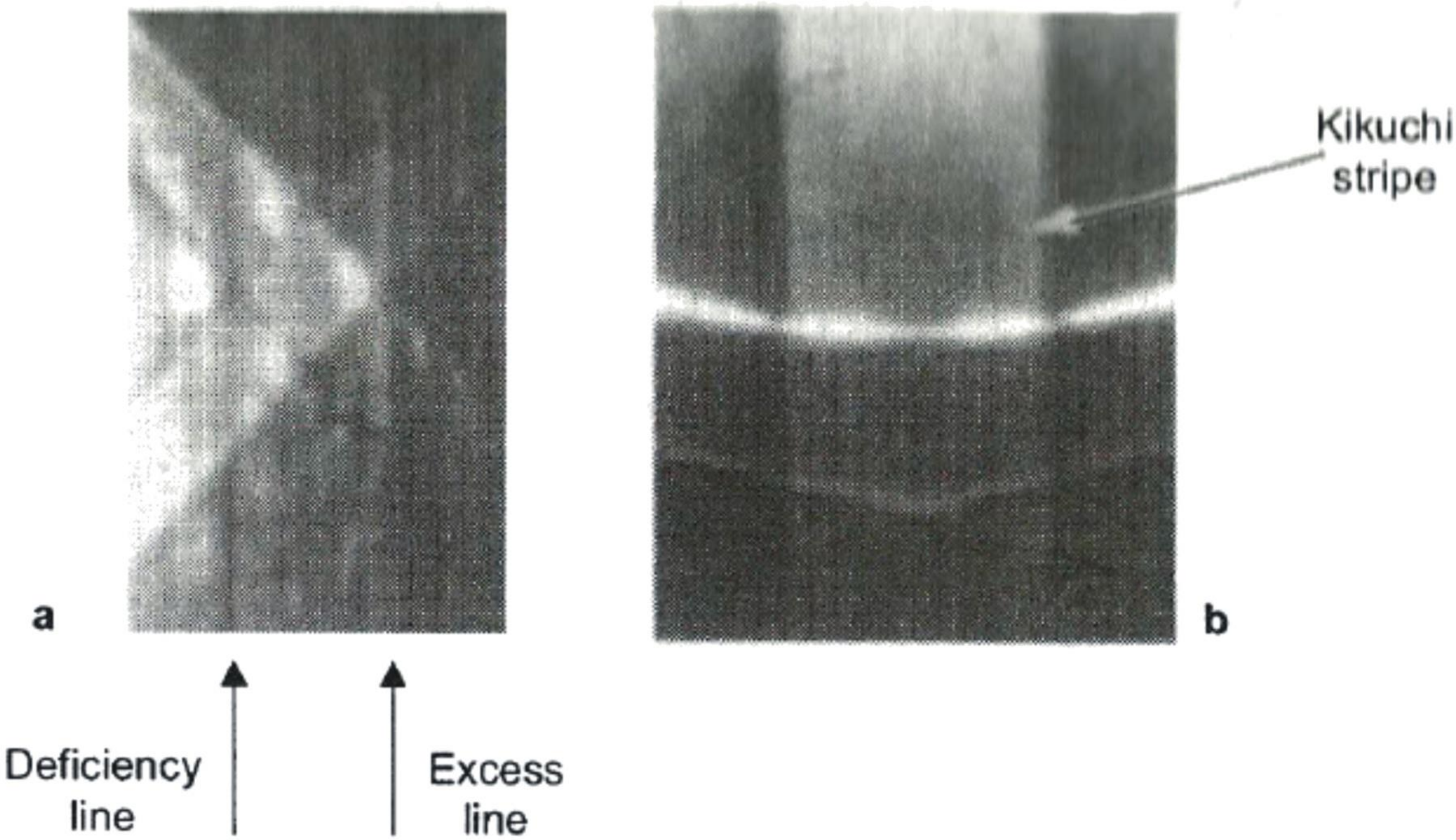
Kikuchi patterns



Kikuchi lines.

a - Pair of excess and deficiency Kikuchi lines.

b - Pair of Kikuchi lines corresponding to a set of vertical lattice planes. A Kikuchi stripe is observed.

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Kikuchi patterns

Inelastic interactions produce a divergence of the incident beam, the semi-angle α of which can reach several degrees
With 300 kV incident electrons, the beam divergence is of the order of ten degrees, which is a very large value compared to the Bragg angles. It is larger than those obtained with LACBED patterns. If physical phenomena are not taken into account, a divergent beam with semi-angle α resulting from interaction with the specimen has the same effect as a convergent incident beam α This feature explains the great similarity between Kikuchi, Kossel and LACBED patterns.

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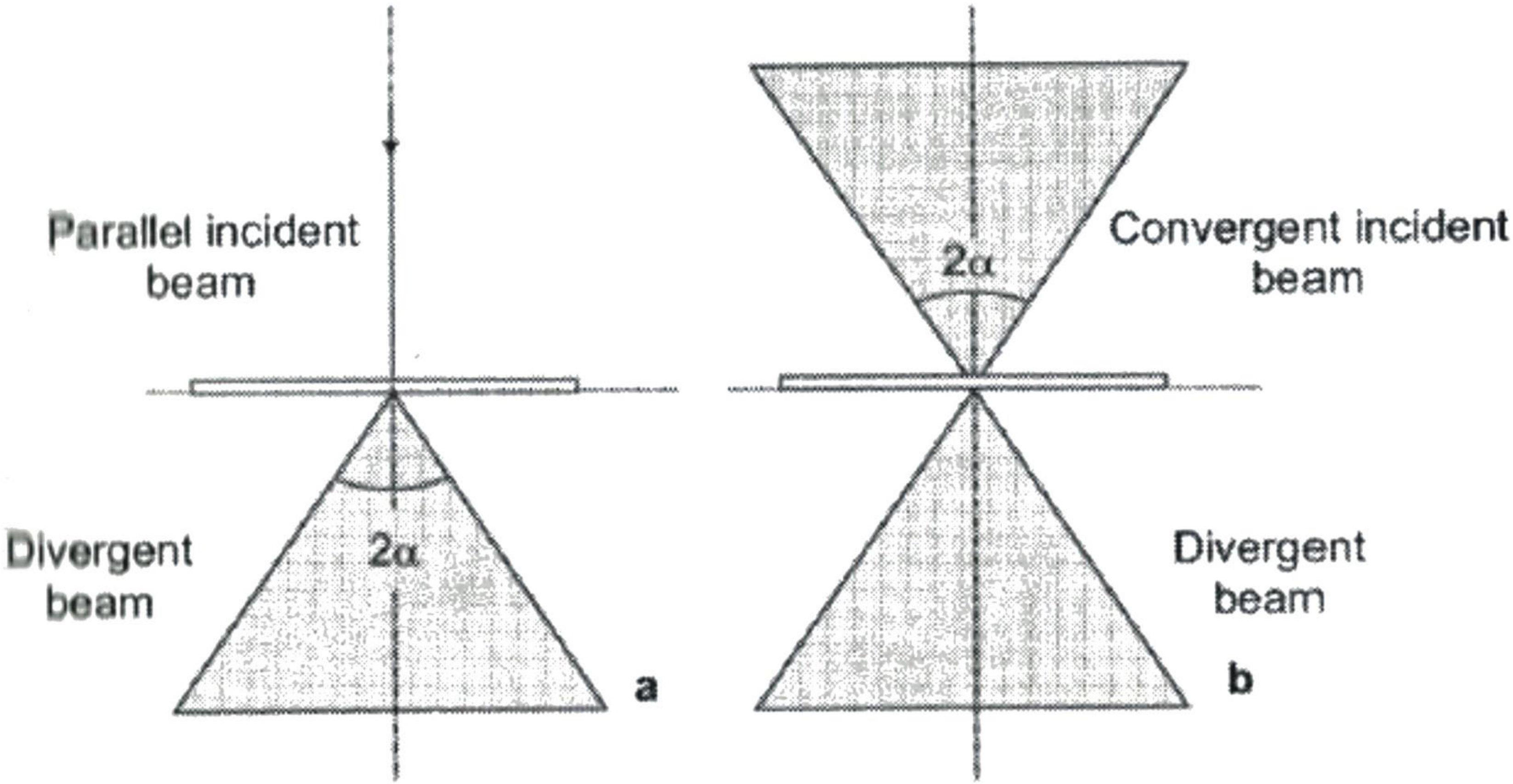
Kikuchi patterns



Analogy between Kikuchi and Kossel patterns.
a. Kikuchi pattern. Inelastic scattering produces a divergence α of the incident beam.
b. Kossel pattern. The incident beam has a convergence of semi-angle α.

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Kikuchi patterns

Like the excess and deficiency lines present on CBED and LACBED patterns, Kikuchi lines also arise from lattice planes. Consequently, they are "attached" to the specimen and undergo a shift when the specimen is tilted. On the other hand, they remain stationnary when the orientation of the incident beam is modified.

we indicated that diffraction produces the information inside the transmitted and diffracted disks of a CBED pattern. All the information outside the disks comes only from inelastic scattering phenomena. All the lines observed outside the disks are, thus, Kikuchi lines This does not necessarily mean that there are no Kikuchi lines inside the disks.

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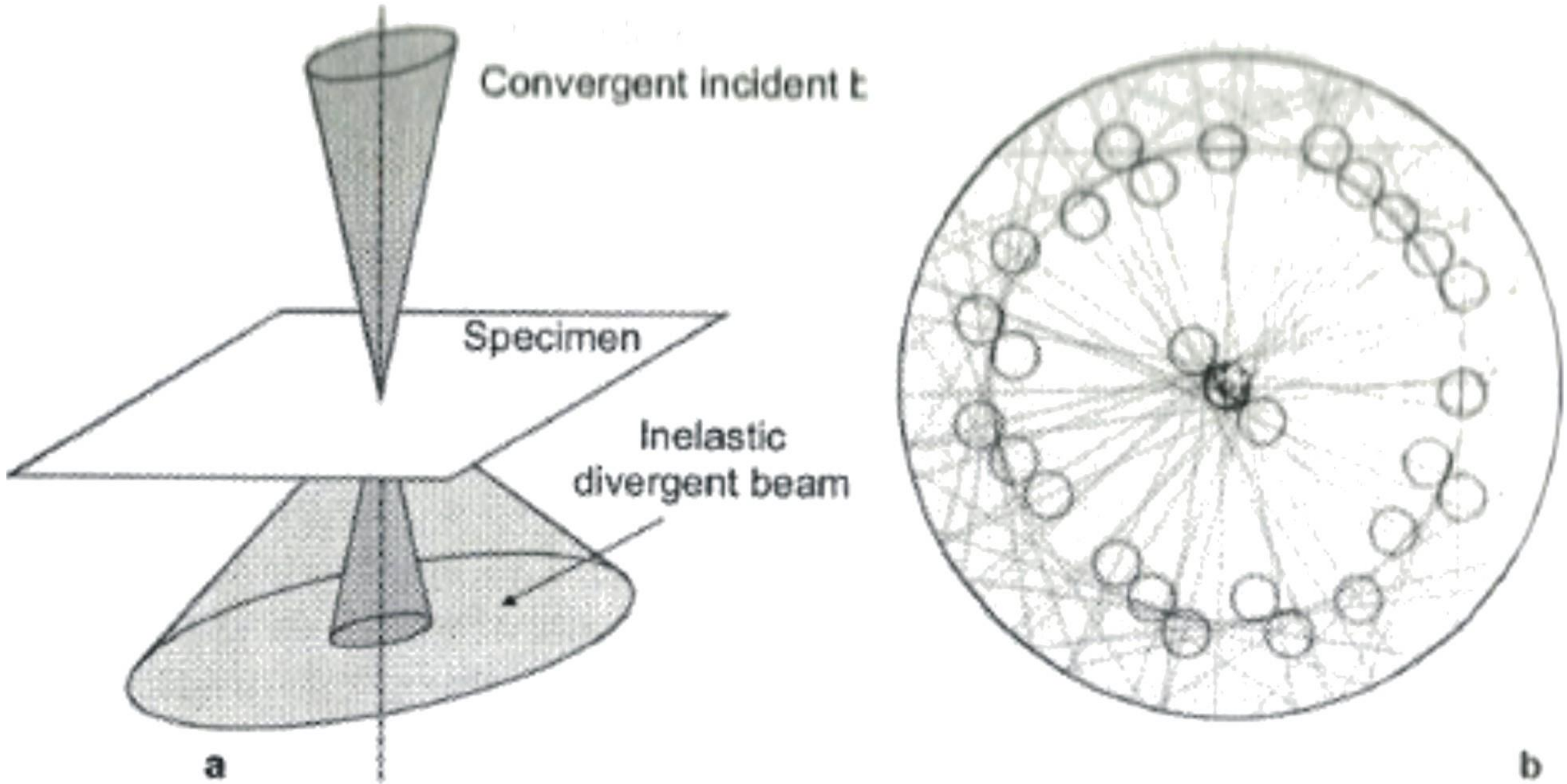
Kikuchi patterns



CBED and Kikuchi patterns.

a - The information inside the disks comes from the incident rays located in the convergent incident beam. The information present outside the disks (background and Kikuchi lines) comes from the inelastic divergent rays formed during the crossing of the specimen.

b - Simulation of the zero-order Laue zone of a CBED pattern and of its Kikuchi lines. The excess and deficiency lines (bold lines) are inside the transmitted and diffracted disks. Kikuchi lines (sharp lines) are outside the disks in the continuation of the excess and deficiency lines.

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