

Refraction of light at straight surfaces and investigation of ray paths in prisms and lenses

Objects of the experiment

- Validation of the Snell's law and determining the angle of total reflection.
- Determination of the critical angle of total reflection.
- Investigation of the ray path in lenses, trapezoidal plate and rectangular prism.

Principles

Optics has certainly changed the world in which we live: In medicine lasers are used as scalpels in operations. Optoelectronics has revolutionized data reading, data storage and data communication. All these applications need tiny optical elements like mirrors, lenses and prisms.

In this experiment the ray path of light in lenses, prismatic and circular bodies are studied using sectional models. The basic laws of refraction of light are verified. Additionally, the ray path in lenses and prisms is investigated.

The examination of the reflection of light bundles at mirrors is described in experiment P5.1.1.1.

Geometrical optics (ray optics) approximates light as light rays which propagate rectilinearly in vacuum and homogeneous media.

Experiment P5.1.1.1 demonstrates that a ray of light is reflected on a (polished) surface. However, the light passes also through the surface into the other medium. By passing from one (homogeneous) medium into another it changes its direction of propagation. This phenomenon is called refraction of light.

Only light rays which impinge at an oblique angle are refracted at the transition from one medium to another. Impinging ray, refracted ray and the normal of the surface between the different media lie in one plane.

According to W. Snell (1580 - 1626) this directional change of the light rays can be described by the following relation (Fig. 1):

$$\frac{\sin \alpha}{\sin \beta} = \frac{n_2}{n_1} \quad (I)$$

α : angle of incidence

β : angle of emergence (refraction)

n_1 : refractive index of medium 1 (here air)

n_2 : refractive index of medium 2 (here acrylic glass)

In the optically "denser" medium (inside the sectional models) the light ray is refracted towards the normal.

When light rays pass from the optically "denser" medium (greater refractive index) into the optically "lighter" medium (lesser refractive index) there is only refraction below a critical angle α_L . In the optically "lighter" medium (outside the sectional models) the light ray is refracted away from the normal.

According to equation (I) the critical angle α_L is called angle of total reflection and is determined by the ratio of the refractive indices n_1 and n_2 . For angles larger than the angle of total reflection the light cannot emerge into the optically "lighter" medium. Prism telescopes, fiber optics which are used for optical data communication and endoscopes for medical applications are based on this effect.

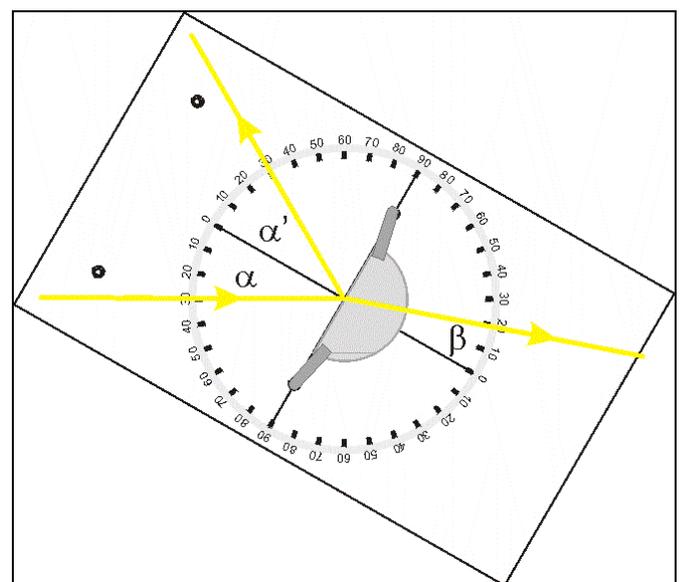


Fig. 1: Schematic representation of refraction and reflection of a light beam at a object with a plane surface (see equation (I)).

Apparatus

1 Optical disc with accessories	463 52
1 Lamp housing with cable	450 60
1 Incandescent lamp 6 V / 30 W	450 51
1 Transformer 6 V / 12 V	521 210
1 Small optical bench.....	460 43
1 Diaphragm with 5 slits.....	463 51
1 Lens in frame $f = +150$ mm	460 08
1 Stand base, V-shape, 28 cm.....	300 01
4 Leybold multiclamp	301 01
1 Stand rod, 25 cm	300 41

The application of equation (I) allows to investigate the ray path to sectional models of different shape:

The trapezoidal object represents an example of a plano-parallel plate in which double refraction occurs. The parallel displacement of the light beam is visualized. At both ends the plate is shaped to angles which can be used for deflection of light beams like in the prism. If these prism is arranged symmetrically and the angle of incidence is varied, a smallest angle of refraction (angle of minimum deviation) will be found. This position is used in the spectral analysis of light.

The ray path of light through different shaped lenses (concave and convex) is investigated. It is shown that convex lenses can be used for imaging objects. The spherical aberration can be visualized. Only rays near the optical axis intersect at the focal point of the spherical lens. Marginal rays intersect the optical axis between the lens and the focal point.

The cylinder shaped model is used for demonstrating the course of a light beams in thick lenses and spheres, for example, in raindrops, to explain the phenomenon of the rainbow.

Setup

The course of a light beam when passing from one medium into another (e.g. from air into glass or acrylic glass) can be made visible against the matt white background of the optical disk. The disk represents the plane of incidence, because the surfaces of separation of the media are normal to this plane. The angular graduation allows to measure the angle of incidence α , emergence β and reflection α' if the sectional objects are arranged appropriately.

Set up the lamp, the condenser lens $f = +150$ mm (without the diaphragm with 5 slits) and the optical disk on the small optical bench as shown in Fig. 2.

When illuminating the disk with the 6 V lamp adjust the lamp's insert that the lamp filament is aligned horizontally (for details see chapter 3 in instruction sheet 463 52). The optical disk might be readjusted in such a manner that the light beam glances the optical disk.

Set the distance between the lamp and the lens so that a parallel light beam can be observed on the optical disk.

It is helpful to chose the distance between the optical disk and the lens in such a manner that the disk can be rotated like shown in Fig. 4.

For an easy demonstration of different angles of incidence loose slightly the screw of the Leybold multiclamp holding the optical disk. Thus various angles of incidence can be demonstrated by just rotating the optical disk.

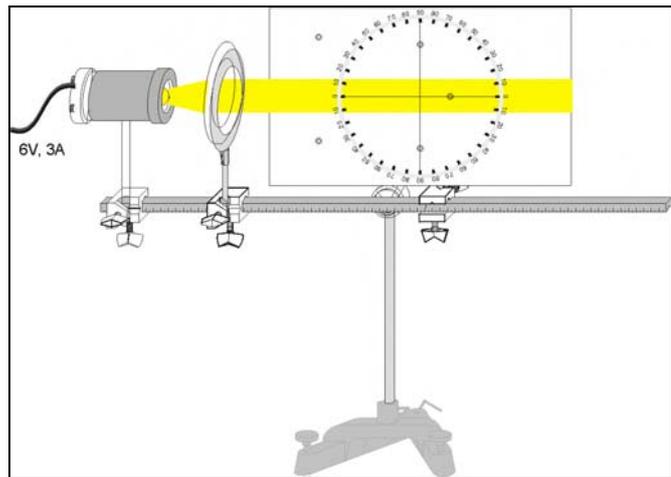


Fig. 2: Experimental setup to examine the refraction and reflection of light rays in various sectional objects with the optical disk.

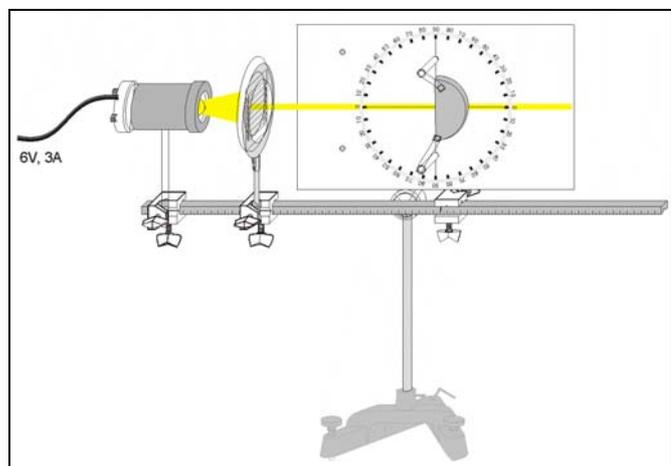


Fig. 3: Experimental setup to examine the refraction and reflection of light rays in a semicircular cylinder with the optical disk.

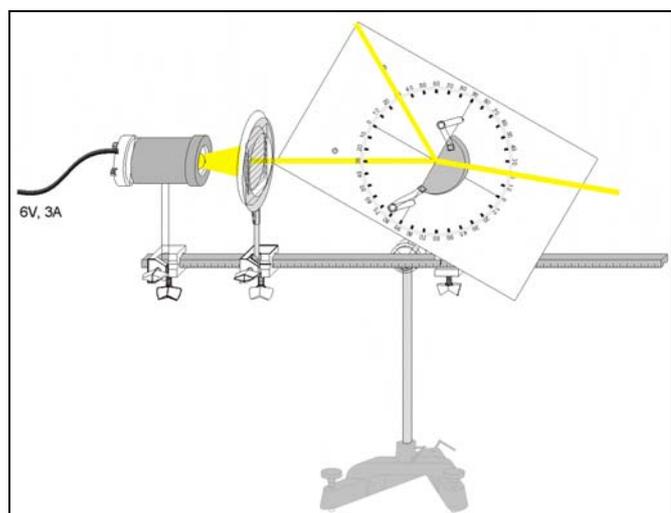


Fig. 4: Rotate the optical disk to determine the angle of incidence, emergence and reflection (see Fig. 1).

Carrying out the experiment

Hint: To optimize the brightening of the ray paths in the various setups (i.e. Fig 3. to Fig. 13) it might be necessary to rotate the lens $f = +150 \text{ mm}$ slightly around the axis of its stand rod.

a) Verification of Snell's law and determining the angle of total reflection

- Attach the holders with the planar semicircular cylinder towards the lamp on the optical disk as shown in Fig. 3.
- Attach the diaphragm with 5 slits on the condenser lens $f = +150 \text{ mm}$ and adjust the setup with using only one slit like depicted in Fig. 3.
- Measure the angle of emergence β for various angles of incidence α by turning the optical disk (Fig. 4).

Hint: By rotating the optical disk through 90° it can be observed that the angle of emergence will only change from 0° to an critical angle α_L . Larger angles of emergence cannot be produced.

- Observe for a specific angle of incidence, e.g. $\alpha = 10^\circ$ deg. Rotate the optical disk in such a manner that the angle of incidence is equal to $\alpha = -\alpha$ to demonstrate the reversibility of the optical path when a ray is reflected at a plane surface.
- Reverse the path of the light beam through the semicircular cylinder by arranging the semicircular cylinder like depicted in Fig. 5.

Hint: The advantage of the arrangement of the semicircular cylinder as shown in Fig. 3 is that the direction of the beam is changed by refraction only at the plane surface of the semicircular cylinder, but not at the cylindrical rear surface, because there all light rays passing through are the axis of the semicircular cylinder will have normal incidence.

When reversing the light path, i.e. when the light beam is made to enter through the cylindrical surface (where the incidence is normal for all angles) and emerges from the plane surface, reflection at this surface is very striking. This is in contrast to the previous experiment shown in Fig. 4 where only a weak reflection can be observed.

- Rotate the optical disk and observe that the light rays will not emerge from the semicircular cylinder into the air for an after an critical angle α_L . (This angle corresponds to the angle found in previous experiment (Fig. 4) when light will not enter the semicircular cylinder anymore.)
- Determine the critical angle of total reflection, i.e. the case when there is only reflection of light and no longer any refraction.

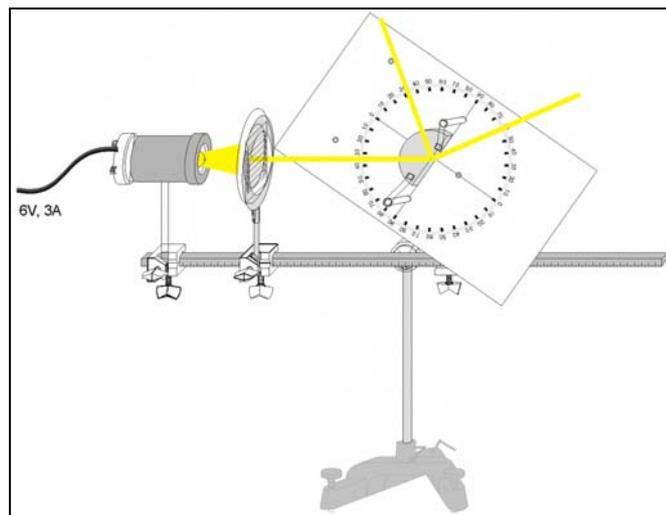


Fig. 5: Reversing the ray path to examine the refraction and reflection of light rays in semicircular cylinder (see Fig. 4).

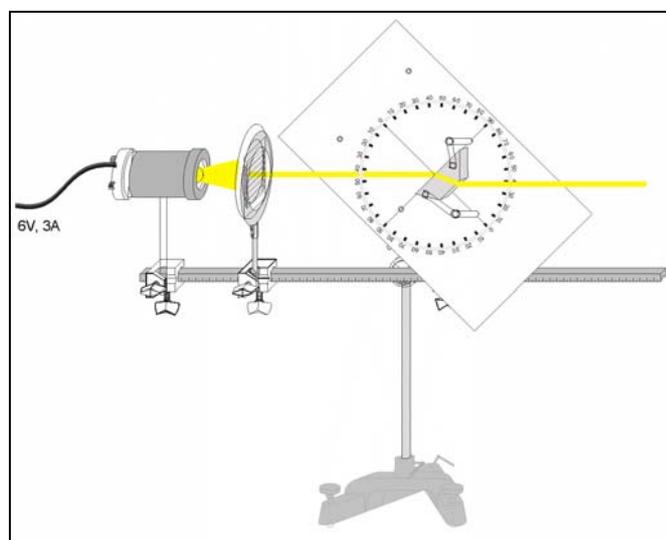


Fig. 6: Experimental setup (schematically) to examine the ray path through a parallel-sided plate (plano-parallel plate).

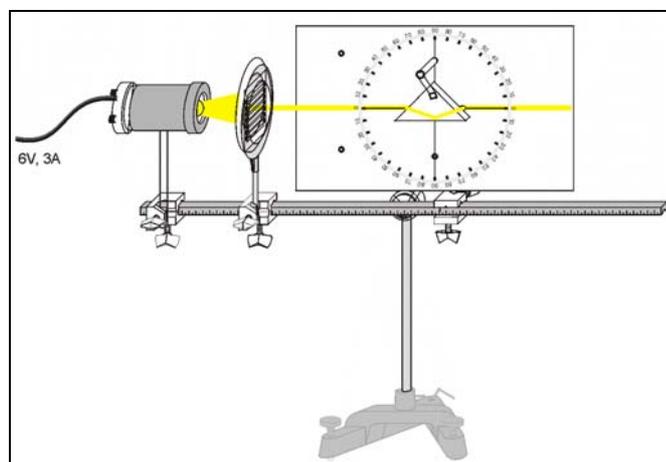


Fig. 7: Experimental setup (schematically) to examine the ray path through a prism (see also Fig. 8).

b) Ray path through the plano-parallel plate

- Attach the holders with the plano-parallel plate on the optical disk as shown in Fig. 6.
- Attach the diaphragm with 5 slits on the condenser lens $f = +150$ mm and adjust the setup with using only one slit like depicted in Fig. 6.
- Observe the light path through the plano-parallel plate for various angle of incidence. Make a note of your observation.

c) Ray paths through a prism

- Attach the holders with the right angled prism on the optical disk so that the base side (hypotenuse) is parallel to optical axis (Fig. 7).
- Attach the diaphragm with 5 slits on the condenser lens $f = +150$ mm and adjust the setup with using only one slit like depicted in Fig. 7.
- Observe the light path through the prism as shown in Fig. 7. Make a note of your observation for one and two light beams.
- Choose the orientations of the prism in respect to the incident light beam like shown in Fig. 8.
- Observe the light path through the prism as shown in Fig. 8. Rotate the optical disk. Make a note of your observation.
- Place the prism and the optical disk as depicted in Fig. 9 into the light beam.

d) Ray path through lenses**biconvex lens**

- Attach the holders with the biconvex lens on the optical disk like shown in Fig. 10.
- Attach the diaphragm with 5 slits on the condenser lens $f = +150$ mm and adjust the setup with using three slit like depicted in Fig. 10.
- Observe the light path through the biconvex lens (Fig. 10). Make a note of your observation.

biconcave lens

- Exchange the biconvex lens by the biconcave lens (Fig. 11). Make a note of your observation.

semicircular cylinder

- Exchange the biconcave lens by the semicircular cylinder (Fig. 12). Make a note of your observation for three slits open.

circular cylinder

The circular model can be used to demonstrate the course of rays in spheres, as for example, in a raindrops to explain the phenomenon of the rainbow (Fig. 13). The rainbow is formed by double refraction and one immediate reflection in the raindrop. The very much weaker secondary rainbow is formed by double reflection in the raindrop between these two refractions. These phenomena can be demonstrated with the acrylic glass model although the refractive index of the acrylic glass is greater than those of water ($n = 1.33$).

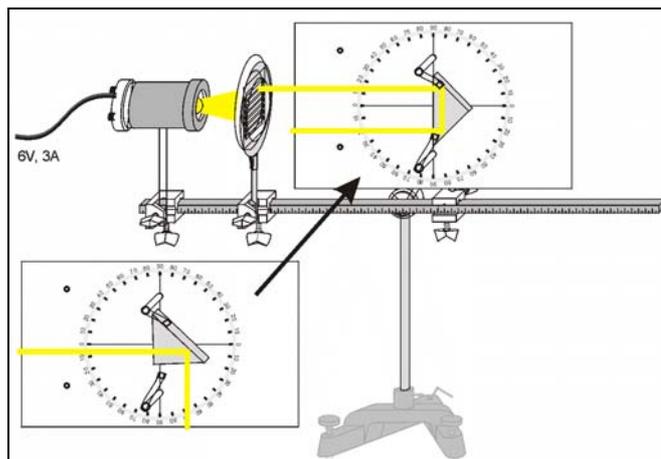


Fig. 8: Experimental setup (schematically) to examine the ray path through a prism (see also Fig. 7).

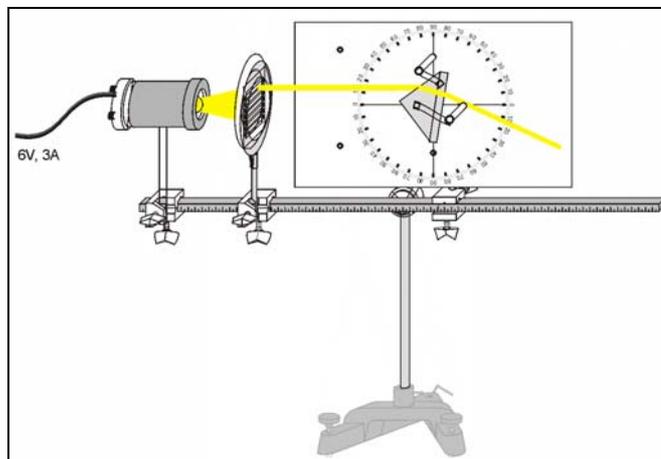


Fig. 9: Experimental setup (schematically) to examine the ray path through a prism (see also Fig. 7 and 8).

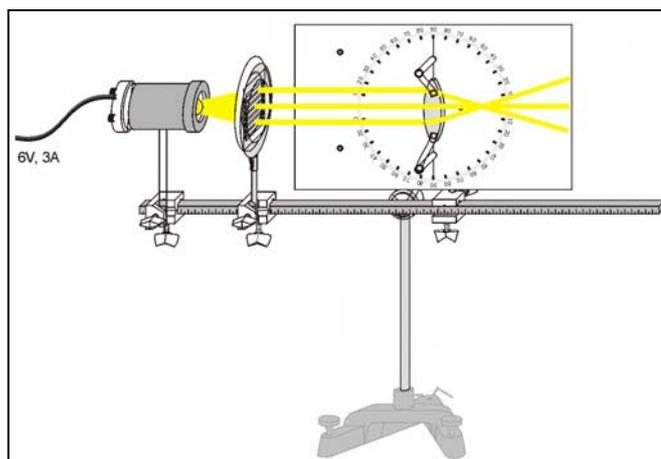


Fig. 10: Experimental setup (schematically) to examine the ray path through a biconvex lens (see also Fig. 11).

The direction of an incident light ray represents the direction in which the light comes from the sun (whose angle of evaluation must be small). The light which emerges after one reflection represents the direction and the weak light which emerges after two reflections represents the direction in which the eye sees the light (from the sun) through the sphere (rainbow).

Measuring example

a) Verification of Snell's law and determining the angle of total reflection

Table. 1: Measured angle of emerge β as function of the incidence angle α .

$\frac{\alpha}{\circ}$	10	20	30
$\frac{\beta}{\circ}$	6.7	13.2	19.8

The critical angle, i.e. the angle of total reflection, for the semicircular model is determined to

$$\alpha_L = 42.2^\circ$$

Evaluation and results

a) Verification of Snell's law and determining the angle of total reflection

Table. 2: Measured angle of emergence β as function of the incidence angle α for the experiment depicted in Fig. 4.

$\frac{\alpha}{\circ}$	10	20	30
$\frac{\beta}{\circ}$	6.7	13.2	19.8
$\sin \alpha$	0.17	0.34	0.50
$\sin \beta$	0.12	0.22	0.30
$\frac{\sin \alpha}{\sin \beta}$	1.5	1.5	1.5

For the experimental setup of Fig. 4 the light beam is directed into another direction at the transition from air into acrylic glass. The angle of incidence is greater than the angel of emergence (refraction). The light is refracted towards the normal. From last row of table 2 follows that the ratio of the sines of the angle of emergence and the angle of incidence is constant. According equation (I) the refractive index of the semicircular cylinder as the refractive index of the air can be approximated by $n_{air} \approx 1$:

$$\frac{\sin \alpha}{\sin \beta} = \frac{n_{acryl}}{n_{air}} \approx n_{air} = 1.5$$

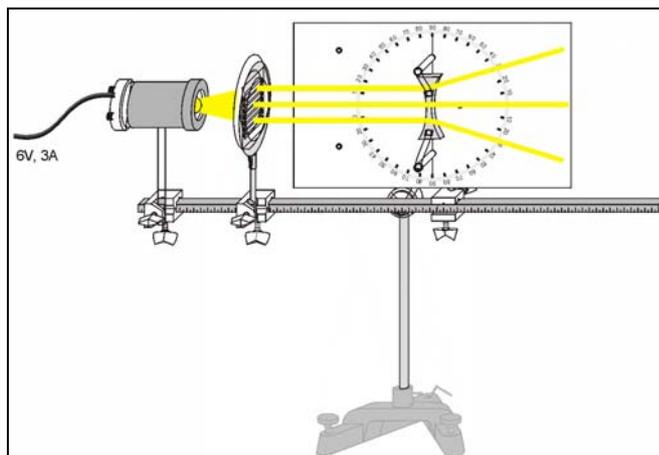


Fig. 11: Experimental setup (schematically) to examine the ray path through a biconcave lens (see also Fig. 10).

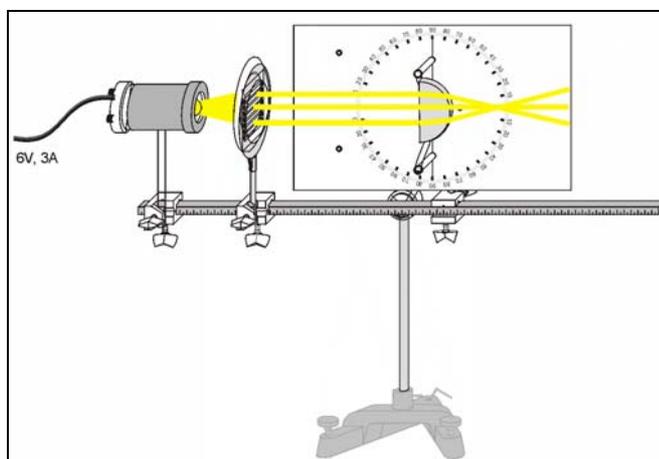


Fig. 12: Experimental setup (schematically) to examine the ray path through a semicircular cylinder (see also Fig. 11).

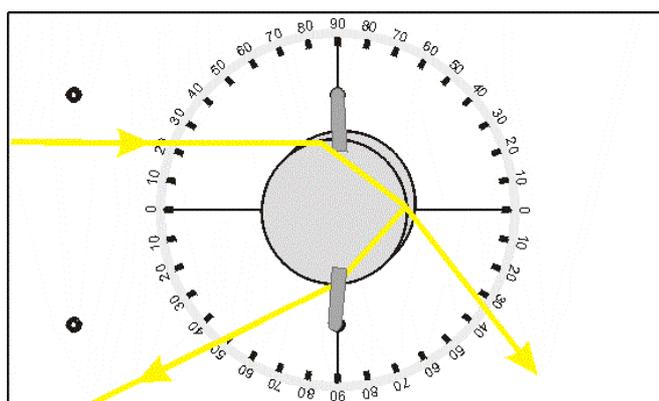


Fig. 13: Schematic representation of the rays through the spherical model.

Therefore, acrylic glass has a greater optical density.

For the experimental setup of Fig. 5 the angle of incidence is smaller than the angle of emergence (refraction). The light is refracted away from the normal. For angles of incidence which are larger than 42.5° all light is reflected at the transition from acrylic glass into air.

b) Ray path through the plano-parallel plate

The light beam which passes through a plano-parallel plate is refracted at both surfaces of the plate (Fig. 6). Due to symmetry reasons the direction of propagation is not changed, however, the incident beam and two-times refracted light beam are parallel and displaced. The displacement is proportional to the thickness of the plate, the refractive index of the material and the angle of incidence.

c) Ray paths through a prism

In the experimental setup of Fig. 7 the light beam is refracted, reflected at the base side (total reflection) and again refracted on leaving the prism. Due to symmetry reasons the light beam has not changed its direction of propagation.

When the prism is displaced the light beam leaving the prism is also displaced. When two light bundles enter the prism the light bundles are exchanged when leaving the prism.

Note: If an object is observed through a prism which base side is horizontal to the eye of the observer the image is upside down. These image reversion without change of direction is implemented by means of an Amici or Dove inverting prism, e.g. in telescopes.

In the experimental setup of Fig. 8 the light beam is entering a right angled prism perpendicularly through a small side. The light beam is reflected at the base side of the prism and leaves the prism deflected by an angle of 90° .

If the light bundle is entering the right angled prism at the base side the light beam is reflected at the small sides (total reflection) and leaves the prism parallel to the incident light bundle in the opposite direction.

Hint: Two combined deviating prisms are used, e.g. in binoculars (porro prism system). Thereby an upright image is observed and the overall length is reduced.

The same principle is used in reflectors (e.g. along road sides where triple mirrors are used) so that the light emitted by a car is exactly reflected in the direction of the car.

In the experimental setup of Fig. 9 the light bundle is deflected side-wards. The deflected light bundle has colored edges. The deflection angle depends on the position of the prism. There is a position at which the deflection is minimal dispersion takes place. The white light is dispersed into its color components, i.e., into a spectrum. The spectrum consists of the colors red, orange, yellow, green, blue, and violet.

As a consequence, white light can be produced via additive-colour mixture. This is made use of, e.g. in color monitors.

d) Ray path through lenses

biconvex lens

In the experimental setup of Fig. 10 the three light beams converge and intersect in a single point after leaving the lens. The distance between the lens and the focal point is called focal length.

Hint: Lenses which collect the light in a single point are called collecting lenses.

With a collector lens the sun light, for example can be collected in a single point on a sheet of paper until the paper burn.

The focal length of a biconvex lens (i.e. a collector lens having two convex surfaces) can be calculated from the curvature and the refractive index of the lens material.

biconcave lens

In the experimental setup of Fig. 11 the three light beams diverge after leaving the lens.

The focus of a diverging lens is located in front of the lens. It is the point from which the diverging light beams diverge.

semicircular cylinder

In the experimental setup of Fig. 12 the light beams converge and intersect in a single point after leaving the lens. The distance of the focus from the plane surface of the semicircular cylinder is different for marginal rays and central rays. This effect is called spherical aberration.

circular cylinder

The circular model allows to demonstrate the principle of the rainbow phenomenon (Fig. 13). The rainbow is formed by double refraction and one immediate reflection in the raindrop. The very much weaker secondary rainbow is formed by double reflection in the raindrop between these two refractions. The direction of an incident light ray represents the direction in which the light comes from the sun.

Supplementary information

The various principles studied in this experiment are used in optical devices, like microscopes, telescopes slide projection etc. For example the effect of total reflection allows to built "wires" for light which are nowadays used in many fiber optical applications.