

# Table of Physical Constants

Some important physical constants	(CODATA values from Dec. 2014)	
Avogadro constant	$N_A$ ,	$= 6.022140857 \cdot 10^{23} \text{ mol}^{-1}$
Gravitational constant	$G$	$= 6.6674 \cdot 10^{-11} \text{ N m}^2/\text{kg}^2$
Electric field constant	$\varepsilon_0$	$= 8.854188 \cdot 10^{-12} \text{ A s/V m}$
Magnetic field constant	$\mu_0$	$= 12.566370 \cdot 10^{-7} \text{ V s/A m}$
Velocity of light in vacuum	$c$	$= (\varepsilon_0 \mu_0)^{-1/2} = 2.997925 \cdot 10^8 \text{ m/s}$
Wave resistance of vacuum	$Z_{\text{el}}$	$= (\mu_0 / \varepsilon_0)^{1/2} = 376.73 \text{ Ohm}$
Relative atomic mass of the proton	$(A)_p$	$= 1.007277 u^*$
Relative atomic mass of the neutron	$(A)_n$	$= 1.008665 u^*$
Rest mass of the proton	$m_p$	$= 1.672621 \cdot 10^{-27} \text{ kg}$
Rest energy of the proton	$(W_p)_0$	$= 9.382720 \cdot 10^8 \text{ eV}$
Rest mass of the electron	$m_0$	$= 9.101383 \cdot 10^{-31} \text{ kg}$
Rest energy of the electron	$(W_e)_0$	$= 5.10999 \cdot 10^5 \text{ eV}$
Ratio of proton mass/electron mass	$m_p/m_0$	$= 1836.152$
Elementary electric charge	$e$	$= 1.602177 \cdot 10^{-19} \text{ A s}$
Specific charge of the electron	$e/m_0$	$= 1.760366 \cdot 10^{11} \text{ A s/kg}$
Faraday constant	$F$	$= 96485.3329 \text{ A s/mol}$
Boltzmann's constant	$k$	$= 1.380648 \cdot 10^{-23} \text{ W s/K}$ $= 8.617325 \cdot 10^{-5} \text{ eV/K}$
Stefan-Boltzmann constant	$\sigma$	$= 5.670367 \cdot 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$
Planck's constant	$h$	$= 6.626070 \cdot 10^{-34} \text{ W s}^2$ $= 4.135667 \cdot 10^{-15} \text{ eV s}$
Bohr magneton	$\mu_B$	$= he/4\pi m_0$ $= 9.274010 \cdot 10^{-24} \text{ A m}^2 (= \text{J/T})$
Classical electron radius	$r_{\text{el}}$	$= \mu_0 e^2 / 4\pi m_0 = 2.820419 \cdot 10^{-15} \text{ m}$
Rydberg frequency	$R_y$	$= e^4 m_0 / 8\varepsilon_0^2 h^3 = 3.289842 \cdot 10^{15} \text{ s}^{-1}$
Rydberg constant	$R_y^*$	$= e^4 m_0 / 8\varepsilon_0^2 h^3 c = 10973731.6 \text{ m}^{-1}$
Compton wavelength	$\lambda_C$	$= h/m_0 c = 2.426310 \cdot 10^{-12} \text{ m}$
Sommerfeld's fine structure constant	$\alpha$	$= e^2 / 2\varepsilon_0 h c = 1/137.036$
	$\alpha$	$= \frac{\text{Electron's velocity } v_0 \text{ in the smallest H orbit}}{\text{Velocity of light } c}$

\*  $u$  is the atomic mass unit,  $u = 1.660539 \cdot 10^{-27} \text{ kg}$ .

See <http://physics.nist.gov/cuu/Constants/index.html>.

# Solutions to the Exercises

## I. Electromagnetism

1.1.  $I = 4.98 \text{ A}$

1.2. 745 hours

1.3. The voltmeter is connected in series with a resistance of  $99 \Omega$ .

1.4.  $R_{\text{shunt}} = 5.025 \text{ m}\Omega$

1.5.  $R = U/(I - U/R_V)$  (If OHM's law does not hold for the conductor, then  $R$  depends on  $I$ .)

1.6. Two values of  $R_2$  fulfill this condition:  $R_2 = 1 \Omega$  and  $4 \Omega$ !

1.7. The battery has an internal resistance  $R_i$  of  $1 \Omega$ ,  $U_i = 1.25 \text{ V}$

1.8.  $N = 147$

1.9.  $I = 0.167 \text{ A}$

1.10.  $U = 6.8 \text{ kV}$

1.11. a)  $I = 1.25 \text{ A}$ , b)  $\dot{Q}_2/\dot{Q}_1 = 3$

2.1. a)  $\varrho = -\sigma/h$ ; b)  $E = -(1/\epsilon_0)\varrho(h-x)$ , up to the height  $h$ ,  $E$  is negative, and for  $x \geq h$ ,  $E = 0$ ; c)  $U_x = -(1/\epsilon_0)\varrho(x^2/2 - hx)$ ; d)  $U = (1/\epsilon_0)\varrho h^2/2$

2.2.  $C = 356 \mu\text{F}$

2.3.  $C = 0.9995 \text{ nF}$

2.4.  $C_V = 0.9 \text{ nF}$

2.5.  $N_e = 5.54 \cdot 10^{10} \text{ cm}^{-2}$

2.6.  $C/l = 93 \text{ pF/m}$

**2.7.** a) 1.37 m from  $Q_1$ , on the side away from  $Q_2$ ; b) 25 cm away from  $Q_1$ , between the two charges

**2.8.**  $\int U dt = 10^{-5} \text{ V s}$

**2.9.** a)  $t_{1/2} = RC \ln 2$ ; b)  $C = 44.8 \text{ pF}$

**2.10.** With  $I = dQ/dt$  and  $U = -Q/C$ , we find  $dQ/dt = -Q/RC + U_g/R$ , ( $U_g = 157 \text{ V}$ ), with the solution  $Q = Ae^{-t/RC} + U_g C$ , ( $A = U_{\max} - U_g$ ,  $U_{\max} = 220 \text{ V}$ ). It then follows that  $\tau = 1.16 \text{ s}$ .

**2.11.**  $W_{\text{Batt}} = U_0 \int I dt = U_0 Q = U_0^2 C$ ,  $W_C = (1/2)U_0^2 C$  (Eq. (3.19)). Half of the energy supplied by the battery is therefore converted to heat in the resistor, independently of its resistance! This result however does not hold for  $R = 0$ , since then the condenser would be charged within an infinitely short time without allowing any energy to be converted to heat. See Chap. 10, “Electrical Oscillations”.

**2.12.** 17 plates

**2.13.**  $\varepsilon = 2.8$

**2.14.** 6.5 % of the volume between the plates is filled with metal. This reduces the spacing of the plates effectively by 6.5 %, i.e. the capacitance is increased by about 7 %. This leads to  $\varepsilon = 1.07$ .

**2.15.** Corresponding to Eqns. (2.11) and (2.25), the capacitance of the completely filled condenser would be  $C = \varepsilon \varepsilon_0 (a b/l)$ , and thus the energy stored in it would be  $W_e = (1/2) \varepsilon \varepsilon_0 (U/l)^2 a b l$ . In the present experiment, the energy thus increases when  $h$  increases, by an amount  $\Delta W_e = (1/2)(\varepsilon - 1) \varepsilon_0 (U/l)^2 h b l = F h$ . The liquid is thus pulled up into the condenser with a constant force  $F$ .  $h$  is then found by setting  $F$  equal to the opposite force of the weight of the liquid which has been pulled up:  $h = (1/2)(\varepsilon - 1) \varepsilon_0 (U/l)^2 / (\rho g)$ .

**2.16.** The electrical energy is  $W_e = (1/2) \varepsilon \varepsilon_0 (U/l)^2 A l$ . This leads (compare Eqns. (3.17) and (3.11) in Sect. 3.7) to the force  $F = (1/2) \varepsilon \varepsilon_0 (U/l)^2 A$ .

**3.1.** The weight of the brass plate is  $F = 1.6 \text{ N}$ . Using Eq. (3.12), this leads to  $l = 50 \mu\text{m}$  (this corresponds roughly to the thickness of a human hair; see Vol. 1, Sect. 1.2). The roughness of the polished stone causes an average spacing which is however certainly much smaller, so that a considerable fraction of the potential drop must occur within the stone!

**3.2.**  $R = 80 \text{ nm}$

**3.3.** The capacitance  $C$  and thus also the energy  $W_e$  vary by a factor  $n$ . If  $n < 1$ , then energy will be pumped back into the current source.

**5.1.**  $\int U dt = 3.2 \cdot 10^{-4} \text{ V s}$ , in good agreement with the observed 10 scale divisions

**5.2.** a)  $u = 2.04 \text{ m/s}$ ; b)  $\int U dt = 3.9 \cdot 10^{-5} \text{ V s}$ , in good agreement with the observed 1.2 scale divisions ( $3.8 \cdot 10^{-5} \text{ V s}$ )

**5.3.** a)  $B_h = 2.5 \cdot 10^{-5} \text{ V s/m}^2$ ; b)  $\varphi = 66^\circ$  (In Göttingen, the horizontal component of the earth's magnetic field points to the north and its vertical component points downwards).

**5.4.**  $\nu = 1.06 \text{ Hz}$

**5.5.** The voltmeter indicates zero! (See also the first paragraph in small print in Sect. 5.5). The pilot could indeed detect an electric field, e.g. by carrying out the experiment of W. WIEN described at the end of Sect. 7.3, but he cannot detect the voltage of  $U = 0.8 \text{ V}$  between the wing tips as given by Eq. (5.9), since it will be compensated by the charges which collect on the wing tips. (The “insulated wire” corresponds to the conductor CA in Fig. 7.2).

**5.6.** The angle between the field vector  $\mathbf{B}$  and the surface vector  $\mathbf{A}$  is  $\alpha = 2\pi\nu t$ . From this, it follows from Eq. (5.10) that  $U = -d/dt(BAN \cos(2\pi\nu t)) = 2\pi\nu BAN \sin(2\pi\nu t)$ , i.e. an AC voltage, as described in Chap. 8 (Fig. 9.3). Note that this result does not depend on the frame of reference.

**6.1.** a)  $I = 93 \text{ A}$  ( $\int H ds = 1.85$  scale divisions); b) measured:  $H = 1360 \text{ A/m}$ , calculated with Eq. (4.1):  $H = 1610 \text{ A/m}$ ; c)  $\int H ds = 500 \text{ A}$

**6.2.** a) Since the magnetic potentiometer measured outside all the remaining coils along a closed path (Fig. 6.7), we find  $U_{\text{mag}} = 0$ ; b) From a), it follows that  $U_{\text{mag,i}} = -U_{\text{mag,a}}$ .

**6.3.** If we combine the two methods of measuring the magnetic potentials  $U_{\text{mag,a}}$  and  $U_{\text{mag,i}}$ , a closed path results. Around this path, the magnetic potential is always equal to zero unless the path encloses a current. This is the case here, since, as mentioned in Sect. 6.3, each tunnel bored through the material does not pass through individual molecules but rather between them; i. e. no molecular currents can be included. We thus have  $U_{\text{mag,i}} = -U_{\text{mag,a}}$ . The same result follows also from the MAXWELL equation (14.12). (See also Exercise 6.2.)

**8.1.**  $B = 3.37 \cdot 10^{-4} \text{ T}$

**8.2.**  $M_{\text{mech}} = 0.1 \text{ N m}$

**8.3.** From the area which is marked with dashed lines, we obtain the flux  $\Phi \approx 1.5 \cdot 10^{-6} \text{ V s}$ . The magnetic flux measured in Video 5.1 is  $8 \cdot 10^{-6} \text{ V s}$ .

**8.4.**  $W_{\text{magn}} = (1/2)\mu_0(N^2/l)I^2\pi r^2$ .  $W_{\text{magn}}$  increases when  $l$  becomes smaller. In order to prevent this, we require a force of  $F = 10^{-2} \text{ N}$ .

**10.1.**  $L = 0.55 \text{ H}$

**10.2.**  $L_N = N^2 L_1$

**10.3.**  $R = 3.466 \Omega$

**10.4.**  $I_{\text{eff}} = 0.796 \text{ A}$

**10.5.**  $\nu = 50 \text{ Hz}$

**10.6.**  $L = 123 \text{ mH}$

**10.7.**  $\nu = 97.5 \text{ Hz}$

**10.8.**  $L = 158 \text{ mH}$

**10.9.**  $LC = 2.53 \cdot 10^{-8} \text{ s}^2$

**10.10.** a)  $Z_{RL} = 849 \Omega$ ,  $\varphi_1 = 87.4^\circ$  (the current in the  $RL$  branch “lags behind” the applied voltage); b)  $I_{RL,0} = 86 \text{ mA}$ ,  $I_{C,0} = 84.85 \text{ mA}$ ,  $I_0 = 86 \text{ mA} \cdot \sin 2.6^\circ = 3.9 \text{ mA}$ ,  $\varphi_2 = 15.2^\circ$ ; c) It follows from these values that  $Z = 73 \text{ V}/3.9 \text{ mA} = 1872 \Omega$ , and from Eq. (10.33), we find  $Z = 1840 \Omega$ , in agreement with the value found in b) (compare this value also with the one that can be read off at the maximum of the curve in Fig. 10.20).

**10.11.**  $\Lambda = 0.139$ , in agreement with the value in Fig. 10.20.

**10.12.** a) The active current is  $3.77 \text{ mA}$  and the reactive current is  $1.0 \text{ mA}$ ; b)  $\dot{W} = (1/2) U_0 I_0 \cos 15^\circ = 0.138 \text{ W}$ ,  $\dot{W}_{RLC} = (1/2)(I_{RL,0})^2 R = 0.141 \text{ W}$ , and thus within the error limits, the values are the same.

**10.13.** The current in the primary coil is  $I_p = I_{p,0} \sin \omega t$ , with  $I_{p,0} = U_{p,0} I_p / (\mu_0 \omega N_p^2 A_p)$  (Eq. (10.4)). From this we find, with Eqns. (4.1) and (5.4), the flux density  $B$  of the magnetic field from the primary coil, and with it, applying the law of induction (Sect. 5.6), the voltage across the secondary coil,  $U_s = N_s (-dB/dt) A_p$ . This leads finally to Eq. (10.39).

**10.14.** a) Owing to the phase difference of  $90^\circ$  between the current and the voltage, in the primary circuit we expect  $\vec{W} = 0$ . b) With a finite value of  $R$ , a current will flow in the secondary circuit. The thermal energy from JOULE heating in the secondary circuit then must come from the primary circuit. The mechanism for this is that the current in the secondary circuit induces an additional current in the primary circuit, so that the phase difference there is no longer  $90^\circ$ , and a finite active current results.

**11.1.** The voltage across the condenser is  $U_C = Q/C$ . The voltage across the coil is  $U_L = L dI/dt = L d^2 Q/dt^2$ . These voltages are equal and opposite at all times:  $Q_C/C + L d^2 Q/dt^2 = 0$ . This differential equation can be solved by the trial function  $Q_C = Q_{C,0} \cos \omega t$ . This then yields  $\omega = \sqrt{1/LC}$ . Thus, we find that  $U_C = (Q_0/C) \cos \omega t$  and  $I = dQ/dt = -U_{C,0} \omega C \sin \omega t$ .

**11.2.**  $U_L = L dI/dt$  (Eq. (10.16)). Therefore,  $U_{L,1} = L_1 dI/dt$  and  $U_L = (U_{L,1} + U_{L,2}) = (L_1 + L_2) dI/dt$ . From this, it follows that  $|U_{L,1}/U_L| = L_1/(L_1 + L_2)$ . The coils thus act as a voltage divider. An application is shown by the experiment described in Fig. 11.7. With the correct choice of the inductance of the wire loop relative to the overall inductance of the oscillator circuit, a voltage will be induced which causes the lamp to light up without burning out.

**11.3.** With the values of the capacitance  $C = 3.2 \text{ nF}$  and the inductance  $L = 0.048 \text{ mH}$ , we find the frequency to be  $\nu_0 = 400 \text{ kHz}$ .

**12.1.** The rectifier allows only half of the sinusoidal current to pass. The throttle coils in Fig. 12.21 pass only the low-frequency FOURIER components of this current (for FOURIER analysis, see Vol. 1, Sect. 11.3). These components include a direct-current contribution which is proportional to the amplitude  $I_0$ , and it will be indicated by the galvanometer.

**12.2.** a) Using the trial function  $E_x = E_{x,0} \sin \omega(-t + z/c)$ , superposition with the incident wave gives  $E_{\text{tot}} = 2E_{x,0} \sin \omega(z/c) \cos \omega t$ , that is a standing wave with a node at  $z = 0$ , as seen in Fig. 12.28. b) The magnetic component of the incident wave is described by the term  $B_y = -B_{y,0} \sin \omega(t + z/c)$ , and thus its amplitude points in the negative  $y$  direction (right-handed coordinate system, wave propagation in the negative  $z$  direction). The reflected magnetic component is given by  $B_y = B_{y,0} \sin \omega(-t + z/c)$  (in phase with the electrical component; the sign follows again from the right-handed coordinate system). Superposition of the two magnetic components gives  $B_{\text{tot}} = 2B_{y,0} \cos \omega(z/c) \sin \omega t$ , i.e. again a standing wave, but now it has a maximum (wave crest) at the reflecting surface ( $z = 0$ ), with the amplitude  $2B_{y,0}$ .

**12.3.** a)  $E = 220 \text{ V/m}$ ,  $B = 1.8 \cdot 10^{-4} \text{ V s/m}^2$ ,  $S = 31.5 \text{ kW/m}^2$ ; the POYNTING vector points towards the interior of the spiral, as if the thermal power were deposited in the spiral from outside. b)  $b = 1.35 \text{ kW/m}^2$ ,  $E = 713 \text{ V/m}$ ,  $B = 2.38 \cdot 10^{-6} \text{ V s/m}^2$  (also effective values).

**12.4.** The electromagnetic wave which is radiated from the outside and is used to excite the small dipoles of the water molecules (Fig. 12.6) has a wavelength of  $\lambda = 3 \text{ m}$ . With its velocity of propagation,  $c = 3 \cdot 10^8 \text{ m/s}$ , we find its frequency to be  $\nu = 10^8 \text{ Hz}$ . The dielectric constant of water at this frequency is  $\varepsilon = 81$  (Table 13.2 and Fig. 13.11); thus its index of refraction is  $n = 9.0$ . It follows from this that  $R = 0.64$  (at normal incidence). 36 % of the incident radiation thus penetrates into the water; this is sufficient to excite the small dipoles.

**13.1.** The energy changes from  $(1/2)QU_0$  to  $(1/2)QU_m$ , where  $U_m = U_0/\varepsilon$ . The excess energy is taken up by the person who places the plate into the condenser.

**13.2.** The voltage is  $U' = E(l - d) + (E/\varepsilon)d$  with the electric field  $E = U/l$ . Solving for  $\varepsilon$ , we find  $\varepsilon = d/(d + l(U'/U - 1))$ . In this example, the result is  $\varepsilon = 5$ .

**13.3.** The voltage between the points 1 and 2 is zero when the voltage drop over the capacitance  $C_1$  is equal to that over the resistance  $R_1$ . Since the charges  $Q$  on the two condensers are then equal, we have  $Q/C_1 = I/R_1$  and  $Q/C_x = I/R_2$ . From this, it follows that  $C_x = C_1 R_1/R_2$ .

**13.4.** The electric field  $E$  experiences no depolarization (Eq. (13.11)). It follows that  $D = \varepsilon D_0$ . The displacement density in the rod is thus larger than in the space outside it. The concept of “depolarization” refers to the field  $E$  (see also “demagnetization”, Sect. 14.6)

**13.5.**  $P = 3((\varepsilon - 1)/(\varepsilon + 2))\varepsilon_0 E_0$  (compare this result with the magnetization of a sphere, Eq. (14.18))

**13.6.**  $p_p = 3.04 \cdot 10^{-30} \text{ A s m}$ , and thus only half a large as measured in the gas phase. The reason for this discrepancy is that in deriving the CLAUSIUS-MOSSOTTI equation within the “cavity”, the interactions between neighboring molecules were not taken into account; that is, for water, the hydrogen bonds between the water molecules (see H. Fröhlich, “Theory of dielectrics”, Oxford University Press (1949), p. 137).

**13.7.** In paraelectric materials,  $\varepsilon$  depends on the temperature, both due to the equation of state of ideal gases and to the LANGEVIN-DEBYE theory. For the electric susceptibility, one finds  $\chi_e = \varepsilon - 1 = (1/3\varepsilon_0)p_p^2/(kT)^2 \cdot p$  (to distinguish it from the pressure  $p$ , the dipole moment is denoted here by  $p_p$ ). This explains the difference between the two values of  $\chi_e$  to better than 1 %.

**13.8.** a) From Fig. 13.11, we read off the dielectric constant at this frequency, thus obtaining the index of refraction  $n = 9.0$ . It then follows that  $\lambda_w = 1.36 \text{ cm}$ . b)  $\bar{W} = 697 \text{ W}$ . c)  $S = 11.6 \text{ kW/m}^2 = 8.6 E_e$  (this is about the same as the value of the solar constant on the planet Mercury!) (For reflection losses, see Exercise 12.4).

**14.1.**  $\chi_m = -1.42 \cdot 10^{-5}$ . The permeability  $\mu$  is thus only slightly greater than 1.0, so that the demagnetization effect can be neglected.

**14.2.** a) Analogously to Eq. (13.15), we have here  $H = H_0 + H_m$ . Comparing with Eq. (14.18), we then find  $H_m = -M/3 = -((\mu - 1)/(\mu + 2))H_0$ . b) From Eq. (14.7), it follows that  $B_m = (2/3)\mu_0 M$ .

**14.3.**  $H_i = 3\mu_a H_a / (\mu_i + 2\mu_a)$ ; from this, we find  $\mu_i = 1$  and  $H_a = H_0 / \mu_a$ :  $H_i = 3H_0 / (1 + 2\mu_a)$ , and for  $\mu_a \gg 1$ :  $H_i \approx (1.5/\mu_a)H_0$ .

**14.4.**  $F_0 = 600 \text{ N}$ ,  $F_d = 17.6 \text{ N}$ . Due to the hysteresis of the iron (Fig. 14.7), we must consider these values to be only rough estimates.

**14.5.** a) and b): Following the rapid change of the current during the first second, both measurements show an exponential variation with a relaxation time of  $\tau_r = 10 \text{ s}$ . c) Here, also, following an initial rapid change, an exponential variation begins, but with a relaxation time of 110 s. Only near the saturation value does the rate of change become more rapid and again approaches a relaxation time of 10 s. For a qualitative explanation: During the initial rapid variation, of which we can see an inkling even in experiment c), the magnetic domains cannot follow. The coil thus has a small inductance during this variation. Thereafter, the reversals of the domains delay the rate of change of the current in the coil in the same manner as the changes of the current in the coil delay its rate of change due to induction. The coil now has a larger inductance because of the iron core. From experiments a) and b), we obtain  $L = \tau_r R = 1300 \text{ H}$ . In experiment c), the delay of the current changes in the coil is even greater, since in the first 60 seconds, the magnetic domains (remanent magnetization) rotate through  $180^\circ$ , causing the induced voltage which delays the current change to be increased. This results in a still larger inductance:  $L = 14000 \text{ H}$ . Only near the end of the increase in the current, after the remanent magnetization has been completely overcome, does the rate of change again correspond to the same time constant as in experiments a) and b);  $L$  is thus again smaller.

**14.6.** In Exercise 14.2, it was shown for a magnetized ball that the field  $H_m$  in its interior is given by  $H_m = -NM$  ( $N$  is the demagnetization factor). Starting from Eq. (14.14), it can be shown that the same result holds for every ellipsoid of rotation which is magnetized parallel to its axis of rotational symmetry. For the disk with  $l/d = 0.1$ , we find  $N = 0.863$  (Table 13.4). For a long rod ( $l/d = \infty$ ),  $N = 0$ , and the field  $H_m$  is thus zero. From this, with Eq. (14.7) we find for the field  $B_m$  in the disk the value  $B_m = \mu_0(M - 0.863M) = 0.137\mu_0 M$ , and for the rod,  $B_m = \mu_0 M$ . These flux densities continue into the space outside the material, since  $\text{div } B = 0$  (MAXWELL's equation (14.13)).

## II. Optics

**16.1.** From the expressions for the law of refraction on both sides of the prism,  $\sin \alpha_1 = n \cdot \sin \beta_1$  and  $\sin \alpha_2 = n \cdot \sin \beta_2$ , we obtain from the sum and the difference:  $\sin \alpha_1 \pm \sin \alpha_2 = n \cdot (\sin \beta_1 \pm \sin \beta_2)$ . Rearranging, this gives  $\sin((\alpha_1 + \alpha_2)/2) \cdot \cos((\alpha_1 - \alpha_2)/2) = n \cdot \sin((\beta_1 +$

$\beta_2)/2) \cdot \cos((\beta_1 - \beta_2)/2)$  and  $\cos((\alpha_1 + \alpha_2)/2) \cdot \sin((\alpha_1 - \alpha_2)/2) = n \cdot \cos((\beta_1 + \beta_2)/2) \cdot \sin((\beta_1 - \beta_2)/2)$ ; dividing these two equations yields:  $\tan((\alpha_1 + \alpha_2)/2)/\tan((\alpha_1 - \alpha_2)/2) = n \cdot \tan((\beta_1 + \beta_2)/2)/\tan((\beta_1 - \beta_2)/2)$ . With  $\beta_1 + \beta_2 = \gamma$  and  $\alpha_1 + \alpha_2 = \delta + \gamma$ , Eq. (16.8) follows. b) Inserting the values of  $\beta_1 = 19.47^\circ$  and  $\gamma/2 = 30^\circ$  into Eq. (16.8), we obtain a quadratic equation for  $\tan(\delta/2)$ , and thus initially two solutions for  $\delta$ . To find the correct solution, we consider a sketch corresponding to Fig. 16.13. The result is finally  $\delta = 47^\circ$ .

**16.2.** The point at which the incident beam in Fig. 16.24 is reflected by the mirror is called A, and the angle of reflection is  $\alpha$ . Then we have  $AF = FZ = R/(2 \cos \alpha)$ . For rays near the axis of the mirror (paraxial rays),  $\alpha$  is small and so  $\cos \alpha \approx 1$ . It follows that  $f = R - FZ = R/2$ .

**16.3.** A scale drawing corresponding to Fig. 18.1 for a concave mirror with an object  $y$  at a distance  $a$  and the associated image  $y'$  at a distance  $b$  allows us to compare similar triangles and obtain  $y/y' = f/(b - f) = a/b$ , from which it follows that  $1/f = 1/a + 1/b$ .

**16.4.** A parallel shift of light beams, even when they have differing wavelengths, leaves the image in the focal plane of the eye unchanged (see e. g. Fig. 18.24, with parallel light beams between the lens and the eye).

**17.1.** a)  $d \approx 100$  m; b)  $B \approx 11$  cm

**17.2.**  $2\varphi_{\min} = 1.04 \cdot 10^{-7}$ ,  $\alpha = 2.28 \cdot 10^{-7}$

**18.1.** Considering two pairs of similar triangles in Fig. 18.1, we find  $y/y' = a/b = f'/(b - f')$ . From this, it follows that  $1/a + 1/b = 1/f'$ .

**20.1.** a)  $m_{\max} = 133$ ,  $x = 21$  cm, b)  $x_{10} = 1.19$  m

**20.2.** The observation is carried out at an angle of inclination  $\beta_m$ , which can be treated as constant for small changes in the order number. Then from Eq. (20.4), we find  $d = (1/3)\lambda/2 = 0.1 \mu\text{m}$ .

**21.1.** a) No change, since over the whole slit, the same path differences are found; b) likewise no change, since the path difference due to the glass,  $\Delta = d(n - 1)$ , is an integral multiple of the wavelength ( $\Delta = 145.8 \lambda$ , thus nearly the “order-one position”); c)  $\alpha = 8.2^\circ$ . since in general the quantities  $d$ ,  $n$  and  $\lambda$  are not known with sufficient accuracy, this calculation shows how one can obtain the two positions in practice.

**21.2.** Due to the phase difference of  $\lambda/2$  between the two halves of the slit, in making the construction, we must rotate the arrows 7 to 12 by  $180^\circ$ ; we then obtain the diffraction pattern of the order-two position, that is with extrema at  $\sin \alpha = N\lambda/B$ , where  $N = 1, 3, \dots$  for the maxima and  $N = 0, 2, 4, \dots$  for the minima. (A more precise calculation shows that the maxima at  $N = 1$  (Fig. 21.12) are slightly shifted.)

**21.3.** The angular range of the principal maximum determined by the width  $B$  of the slit ranges over  $\sin \alpha = \pm \lambda/B$ . The maxima which occur through interference with immediately neighboring slits are found at  $\sin \alpha_m = \pm m\lambda/D$  ( $m = 0, 1, 2, \dots$ ). Then for a), we observe only three maxima, but for b) there are 39 maxima.

**21.4.** a) In this case, the whole surface of the grating radiates with the same phase; diffraction occurs only at its edges. b) The diffracted waves which emerge from two neighboring pairs of beams and slits produce a diffraction pattern as shown in Fig. 21.12, lower left. The superposition



of the waves emerging from all the beams and slits leads to a sharpening of the maxima (Fig. 22.6), but leaves their positions and relative heights unchanged.

**21.5.** Since in the order-two position ( $\beta$ ), the radiant power is zero for the non-deflected beam ( $\alpha = 0$ ), the power of the light which passes through the gaps and the “grating beams” must be the same. Thus, if we can neglect absorption in the grating beams, they must have the same width, i.e.  $L/D = 1/2$ .

**21.6.**  $c = m\lambda v / (m \sin \alpha) = 875 \text{ m/s}$

**22.1.** a)  $\lambda = 600 \text{ nm}$ , b)  $n = 1.33$

**26.1.** a) The equation of motion for free damped oscillations is given by  $F_R + F_D = m d^2 l / dt^2$ , with  $F_R = -\alpha dl/dt$  (frictional force) and  $F_D = -Dl$  (elastic force). That the expression  $l = l_0 e^{-\delta t}$ , with  $\delta = (1/2)(\alpha/m)$ , is a solution of this equation of motion can be demonstrated by substituting it into that equation. For the relation between  $\alpha$  and  $\Lambda$ , we obtain with this solution  $\alpha = 2\delta m = 2\lambda v_0 m$ . b) The equation of motion is now given by  $F_p + F_R + F_D = m d^2 l / dt^2$ , or, after inserting the forces and dividing by  $m$ :  $d^2 l / dt^2 + 2\Lambda v_0 dl/dt + 4\pi^2 v_0^2 l = (F_0/m) \cos(2\pi v t)$ . We now insert the complex trial solution  $l = l_0 e^{i(2\pi v t)}$  together with its first and second time derivatives into the equation of motion, obtaining  $4\pi^2[(v_0^2 - v^2) + i(\Lambda/\pi)v_0 v] = (F_0/l_0 m)e^{i\varphi}$ . From this, applying the mathematical relations  $a + ib = r(\cos \varphi + i \sin \varphi) = r e^{i\varphi}$  (Eq. (25.27)) and  $\sin^2 \varphi + \cos^2 \varphi = 1$ , we obtain equations (26.1) and (26.3). (For literature on “forced oscillations”, see e.g. The Feynman Lectures, Vol. 1, Chap. 21-5 (<http://www.feynmanlectures.caltech.edu/>), or <http://hyperphysics.phy-astr.gsu.edu/hbase/oscdr.html>).

**27.1.**  $(1/2)l_{0,\max}^2/l_{0,\max}^2 = (\Lambda/\pi)^2 v_0^4 / [(2v_0)^2(v_0 - v)^2 + (\Lambda/\pi)^2 v_0^4]$ ,  
 $(1/2)(2v_0)^2(v_0 - v)^2 = (1/2)(\Lambda/\pi)^2 v_0^4$ ,  $2(v_0 - v) = H = (\Lambda/\pi)v_0$ . This result holds for every harmonic oscillator, in particular for an electrical resonator.

**27.2.** Let the deflection be  $x = l_0 \sin \omega t$ ; taking the time derivative gives:  $\dot{x} = \omega l_0 \cos \omega t$ . The kinetic energy is thus  $W_{\text{kin}} = (1/2)m\dot{x}^2 = (1/2)m(\omega l_0 \cos \omega t)^2$ . With the average value of  $\cos^2 \omega t = 1/2$  over a whole oscillation, it follows that  $\overline{W}_{\text{kin}} = (1/4)m(\omega l_0)^2$ .

# Index

## A

Abbe, Ernst  
  imaging and diffraction, 340, 434  
Aberration  
  astronomical, 460  
  spherical, 344  
Absorbance, 579  
Absorption, 492  
  and electrical conductivity, 565  
  and forced oscillations, 557  
  by atomic and colloiddally dissolved metals, 570  
  by free electrons in metals, 565  
  interpretation of, 556  
  weak and strong, 496, 497  
Absorption band, 559  
Absorption coefficient, 258, 494  
Absorption constant, 492, 559  
  definition, 492  
  in the X-ray region, 538  
  Table, 493  
Absorption spectra  
  analysis, 560  
AC (alternating current)  
  generator, 195  
  resistance, 183  
  synchronous motor, 166  
Achromatization, 351  
Active current, 190  
Activity, optical, 486  
Acuity  
  visual (sharpness of vision), 363  
Aepinus, F. U. T., 36  
Air  
  in a magnetic field, 266  
  molecular picture, 34  
Air gap of an electromagnet core, 272  
Alkali halides  
  absorption of light, 537  
  reflectivity, 543  
Alternating current, 161  
  production, 195  
  production, high-frequency, 198  
Alternating current = AC, 180

Alternating-current generator, 161, 164  
Ammeter or ampere-meter, 11  
Ampere second, 21, 47  
Ampere, unit of current, 12  
Ampere's law, 119, 122  
Ampere-turns, 96  
Amplitude, 181, 182, 208  
Amplitude of a light wave, 318  
Amplitude of alternating current, 181  
Amplitude structure, 422, 436  
Analyzer, 479, 481  
Angle of inclination  
  of principal rays, 363  
Angle of vision, 333  
  definition, 353  
  increase (magnification), 356  
  increasing, 354  
Angled mirror, 324  
Angles  
  units, 314, 333  
Angular momentum, 97, 277  
Angular velocity or circular frequency, 181  
Antenna, 31, 234  
Anti-reflection coatings, 502  
Aperture, 310  
Aperture diaphragm, 299  
Aperture stop, 342  
Aperture, numerical (*NA*), 358  
Area turns, 107  
Astigmatism, 311, 345  
Atmospheric ray refraction, 555  
Atomic model, Bohr's, 277  
Attraction  
  electric, 72  
  electric, of current-carrying conductors, 7  
  magnetic, 156, 273  
Attractive force  
  magnetic, of current-carrying conductors, 139  
Auer mantle, 585  
Autocontrol (feedback)  
  with diodes, 204

Avogadro constant, 274  
Axis, optical, 471

## B

Babinet's theorem, 416, 436  
Ballistic deflection or impulse deflection, 21, 52  
Ballistic galvanometer, 145  
Barkhausen effect, 285  
Barlow's wheel, 109  
Beam boundary, 299  
Beam splitter, 384  
Beer's formula, 509, 542  
  Drude's approximation, 566  
Beer's law, 494  
Belt generator, 44  
Birefringence, 478, 574  
  due to flow, 574  
Birefringence or double refraction, 468, 472  
  of calcite, 473, 474  
  of mica, 475, 478  
  of quartz, 473, 488  
Black body, 372, 379, 580, 594  
Black-body radiation, 580  
Black-body temperature, 587  
Blazed grating, 453  
Bohr magneton, 277  
Bohr's atomic model, 277  
Boltzmann's constant, 256, 275  
Bose, G. M., 75  
Bound charges, 63, 245  
Boundaries of light beams  
  and perspective, 367  
Boyle, Robert, 33  
Bragg spectrograph, 455  
Braun's tube, 22, 77  
Brewster's angle, 498  
Brewster's law, 498  
Bridge circuit, 244  
Bright-field illumination, 358, 433  
Brightness, 600  
Brilliance, 611  
Brownian molecular motion, 19  
Buildup of a conduction current, 177

**C**

- Calibration factor
  - of instruments, 108
  - of measurement instruments, 13
- Candela (cd), unit of the luminous intensity, 593
- Capacitance, 56
  - of a parallel-plate condenser, 56
  - of a sphere, 57
  - with a dielectric, 62, 243
- Capacitive reactance, 185
- Capacitive resistance, 185
- Carrier of electricity, 31
- Cathode-ray tube, 22, 77
- Cat's eye, 325
- Cauchy's formulas, 513
- Central projection, 366
- Characteristic (*I-V*) curves, 204
- Charge carrier, 42, 81
- Charge, electric, 34, 37
  - bound, 245
  - definition, 48
  - influence, 41, 52
  - measurement, 46
  - moving; production of magnetic fields, 94
  - separation, 52, 159
  - surface density of, 51
- Charging a condenser, 59
- Choke coil, 225
- Christiansen filter, 514
- Chroma, 605
- Chromatic aberration, 350
- Chromatic colors, 604
- Circular vibrations, 170
- Clausius-Mossotti equation, 254, 549
- Closure bar
  - for magnetic circuit, 147
- Coaxial cable, 237
- Coercive field, 268, 288
- Coherence condition, 385, 390, 407
- Coherence, partial, 408
- Collimated beams, 300, 381, 491
  - of light, 301
- Collimator, 444
- Color centers, 559, 570, 571
- Color filters for pure hues, 606
- Color hue, 588, 605
- Color temperature, 588
- Colors
  - achromatic, 603
  - chromatic, 604
  - of the spectral regions, 322
  - tints and shades, 605
- Coma, 348
- Compass needle, 4, 88, 92, 96, 155
- Complementary colors, 607
- Complex index of refraction, 508, 509
- Complex numbers, 507
- Compound lenses, 335
- Concave gratings, 453
- Concave lenses, 315
- Concave mirrors, 315
- Concentration, definition, 494
- Condenser, 30, 72
  - charging and discharging, 59
  - electrolytic, 61
  - in an AC circuit, 184
  - technical, 61
- Condenser = capacitor, 28
- Condenser lens, 342, 343, 358, 363
- Condenser plates, attraction of, 72
- Condensers
  - examples, 31, 56
  - parallel circuit, 56
  - series circuit, 56
- Conductance
  - specific, 16
- Conductivity, 16
  - electrical, 36, 565
  - specific, 232
- Conductor, 36
- Continuous spectrum, 320
- Control grid, 203
- Control of voice currents, 165
- Converging lenses, 315
- Convex lenses, 315
- Corner mirror, 325
- Corona ring, 53, 73
- Coulomb = 1 ampere second, 48
- Coulomb, Charles A., 52
- Coulomb's law, 52, 72
- Creeping galvanometer, 145
- Critical angle for total reflection, 306
- Crystal
  - principal plane, 472
- Crystalline axes in mica, 475
- Curie constant, 264
- Curie temperature, 248, 264
- Curie's law, 264
- Current
  - as a moving charge, 96
  - during electric-field decay, 46
  - during magnetic-field decay, 179
  - effective value, 181
  - electrolytic effect of, 9
  - examples, 17
  - time integral, 20
- Current impulse, 20, 46
  - measurement of, 145
- Current meter = ammeter, 11
- Current resonance, 189
- Current sources, 159

- inductive, 160

- Current transformer, 190

- Curved light rays, 553

- Cyclotron frequency, 237

- Cylindrical lenses, 310

- Cylindrical rotor, 162

**D**

- Damping, 496, 557

- Damping constant, 207

- Damping, aperiodic limit, 145

- Dark-field illumination, 358, 433, 436

- Dazzling, 602

- DC motor, 167

- Debye, cgs unit for molecular electric dipole moments, 246

- Debye-Scherrer method, 440

- Debye-Sears experiment, 426

- Decrement, logarithmic, 207

- Deflection of a current-carrying conductor in a magnetic field, 7, 138

- Delimiting of light beams, 343

- Demagnetization, 271

- Demagnetizing factor, 251, 271

- Depolarization, 250

- Depolarizing factor, 251

- Depth of field or depth of focus, 365

- Depth of focus, 365

- Diamagnetic materials, 263, 264, 279

- Dichroism, 471, 573

- artificial, 573

- Dielectric, 62, 243

- Dielectric constant, 62, 217

- complex, 566

- definition, 243

- frequency dependence, 257, 549

- measurement, 243

- of dielectric materials, Table, 246

- Table, 244, 246

- Dielectric materials, 246, 252

- Dielectric polarization, 245

- Dielectric susceptibility, 245

- Diffraction, 317, 318, 328, 413

- by a step, 422

- model experiments, 318

- of X-rays, 438

- Diffraction pattern

- from a semi-plane, 416

- from a slit, 319, 407

- from a step, 422

- from a wire, 417

- from circular disks and

- openings, 414

- in model experiments, 318, 423

- Diffuse reflection, 306, 517, 532

- Diodes, 204
- Diopster = unit of lens power, 314
- Dipole
  - electric, 81, 213, 215
  - electric field of, 223
  - in water, 217
  - magnetic, 153
  - radiation field of, 228
- Dipole field, 225
- Dipole moment, 82, 245
  - electric, 520
  - electric, of polar molecules, 521, 564
  - molecular, 246, 257
- Dipole radiation, 518, 521
- Direct-current dynamo, 163
- Direct-current generator, 162
- Direction of the electric current, 93
- Direction of the magnetic field, 93
- Dispersion, 322, 443, 539
  - anomalous, 538, 540
  - by free electrons, 566
  - curves, 538, 539, 541, 547
  - demonstration experiment, 539
  - interpretation, 546
  - normal, 444, 538
  - of a prism, 445
  - of NaCl, 550
  - quantitative treatment, 548
- Dispersion formula, 550
  - for gases and vapors, 550
- Displacement current, 123, 184
- Displacement current density, 124
- Displacement density, 52, 123
- Displacement law of W. Wien, 583
- Distinct vision
  - distance of, 353
- Diverging lenses, 315
- Doppler effect, 463, 520
- Double refraction
  - due to inner strains, 489
  - of an optically-active material, 487
- Double-fiber voltmeter, 14
- Drag of light, 552
- Dressing of glass surfaces, 502
- Drift velocity, 141
- Du Fay, C. F., 34
  
- E**
- Earth
  - electric field, 53, 54
  - magnetic field, 94, 108
- Earth inductor, 109
- Echelette grating, 453
- Eddy currents, 142
- Eddy-current damping, 145
- Effective values, 181
- Einstein
  - theory of relativity, 103, 133
- Electret, 85, 132, 248, 251
- Electric charges
  - bound, 63
  - free, 63
- Electric current, 4, 10
- Electric dipole, 81, 213, 215
  - in an inhomogeneous electric field, 83
- Electric dipole moment, 82, 520
  - from influence, 84
  - of polar molecules, 564
  - permanent, 85
- Electric field, 27, 30, 114
  - decay of, 36, 211
  - direction of, 49
  - energy of, 78
  - force on a charge, 68
  - general definition of, 70
  - gradient of, 54
  - measurement of, 49
  - of a dipole, 225, 228
  - path integral of, 50
  - shielding of, 42
  - within matter, 249
- Electric field constant, 52
- Electric field lines, 30, 71, 75
- Electric field strength, 49
- Electric fields
  - dependence on the frame of reference, 129
  - in vacuum, 33
- Electric flux, 55
- Electric flux density, 52
- Electric motor, 166
- Electric polarization, 249
- Electric potential, 80
- Electric voltage, 13
- Electric waves, see Waves, electromagnetic, 211
- Electric wind, 58
- Electrical conductivity, 565
- Electrical oscillations, see Oscillations, electrical, 196
- Electrification, 84
- Electrodeless ring current, 202
- Electrolytic condenser, 61
- Electromagnet, 143, 156, 272
- Electromagnetic fields, 135
- Electromagnetic waves, see Waves, electromagnetic, 211, 230
- Electron, 77
  - mass of, 527
- Electron beam, made visible, 137
- Electron volt (eV), energy unit, 538
- Electronic spin, 278
- Electrons, 276
  - free, 565
  - number density, 527
  - quasi-elastically bound, 560, 562
- Elementary electric charge, 77
- Elliptically-polarized light, 476, 479
- Emissivity
  - of the sun, 376
- Emitter area, projected, 373
- Enamel or varnish paint, 610
- Energy
  - electrical, measurement of, 23
  - of the electric field, 78
  - of the magnetic field, 156, 179
  - resonance curve, 209
- Energy current, 401
- Entrance pupil, 340, 343
- Equipotential surface, 79
- Equivalence principle
  - Faraday, 141
  - Faraday's equivalence principle, 12
- Exit pupil, 340, 343
- Exit window, 363
- Extinction
  - by large metal colloids, 572
  - by scattering, 492, 523
  - by scattering of X-rays, 526
  - by small, strongly-absorbing particles, 569
  - by very fine colloidal metal particles, 572
- Extinction constant, 492, 523
  - molar, 494
  - of a metal, 541
  - of NaCl, 538
  - specific, 494
- Eye
  - acuity (sharpness of vision), 365
  - adaptation, 598
  - as a radiation detector, 293
  - fixing, 362, 599
  - fovea centralis, 363
  - nodal points of, 338
  - range of accommodation, 353
  - resolvable angle of vision, 333
  - retina, 332, 599
  - rise and accumulation times, 600
  - sensitivity, 599
  - spectral sensitivity distribution, 597
- Eyeball
  - turning while observing, 363
- Eyes
  - of insects, 555
  
- F**
- Farad, unit of capacitance, 56
- Faraday cage, 42
- Faraday constant
  - equivalence principle, 12, 141

- Faraday effect, 486
- Faraday, M., 101
- Feddersen spark, 198
- Feedback
  - in a klystron, 235
  - with triodes, 202
- Feedback = autocontrol, 203
- Fermat's principle, 304
- Ferrites, 287
- Ferroelectric materials, 247
- Ferromagnetic materials, 264, 266, 280
- Field gradient, 55
- Field lens, 363
- Field lines
  - electric, 30, 71, 75
  - electric, closed loops, 113, 201, 228
  - magnetic, 4, 87
    - around and in a conducting wire, 200
- Field of view, 362
- Field of view aperture, 363
- Field strength, 92
  - electric, 31, 49
  - magnetic
    - at the center of a cylindrical coil, 120
- Field, electric; see Electric field, 27, 30, 114
- Field, magnetic; see Magnetic field, 87
- Filter, 323
  - for infrared, 323
  - for pure hues, 606
  - for ultraviolet, 323
- Fixed stars, 333, 408
  - aberration, 460
  - color temperature, 589
  - parallax, 601
- Fixing with the eye, 362, 599
- Flame, light absorption, 578
- Flickering, limiting frequency, 596
- Flow birefringence, 574
- Fluctuations, 410
- Fluorescence, 380
- Fluorescent tube, 586
- Flux
  - electric, 55
  - magnetic, 106, 261
- Flux density
  - magnetic, 107, 261
- Focal length, 312, 336
- Focal plane, 313
- Focal point, 313
  - virtual, 315
- Focal ratio, 366
- Force
  - in an electric field, 68
  - in an inhomogeneous electric field, 83
  - in an inhomogeneous magnetic field, 151
- Forced oscillations, 205, 517, 520, 548
  - quantitative treatment, 207
- Forced oscillations = forced vibrations, 566
- Forces
  - between two parallel currents, 139
  - in electric fields, 70
  - in magnetic fields, 137
  - inhomogeneous, 263, 265
  - on moving charges, 137
- Forward scattering, 530, 534
- Fovea centralis, 363
- Frames of reference, 103
- Franklin, Benjamin, 42
- Fraunhofer's observation mode, 406, 416
- Free charges, 63
- Fresnel zone plate, 428
- Fresnel's formulas, 501
- Fresnel's observation mode, 416
- Fresnel's zone construction, 413
- Frictional electricity, 45
- Frictional electrification machine, 22
- f-stop
  - camera lens, 366
- Fundamental oscillation, 217
- G**
- Galilean telescope, 360
  - or terrestrial telescope, 361
- Galvanometer, 7, 11, 19, 102, 145
- Gas molecules
  - average spacing, 33
  - mean free path, 34
- Gauss (unit) =  $10^{-4}$  T, 107
- Generator, 159
- Geometric distortion, 349
- Gilbert, W., 84
- Gold-leaf electrometer, 14
- Gold-leaf voltmeter, 14
- Gradient
  - in the refractive index, 553, 555
- Granulation, 419
- Grating constant
  - optical, 446
- Grating spectrometer, 446
- Grating, optical, 423, 451
  - resolving power, 447
  - sine-wave, 424
  - sinusoidal modulation by, 424
- Gray, S., 36
- Grazing angle, 439, 455
- Green flash, 555
- Grey filter, 543
- Grey scale, 603
- Ground, 31
- Grounding, 80
- Group velocity, 238, 459
- Guericke, Otto von, 45, 76
- Guericke's levitation experiment, 76
- Gyromagnetic ratio, 277
  - of an electron, 278
- H**
- Half-maximum width, 208
- Halfwidth, 448
  - of diffraction patterns, 444
  - of spectral lines, 559
  - of the energy-resonance curve, 558
- Halo phenomena, atmospheric, 305
- Hammer interrupter, 192
- Harmonic oscillator, 517
- Harmonic oscillator circuit, electrical, 212
- Harmonics, 218
- Hauksbee, F., 586
- Headlight, 378
- Heating by electric current = Joule heating, 8
- Heaviside layer, 568
- Hefner candle, 594
- Helmholtz coils, 120, 137
- Henry, J., 173
- Henry, unit of inductance, 175
- Hering's triangle, 606
- Hertz, H., 227
- Heusler alloys, 268
- Hilsch, R., 204
- Holography, 431
- Hysteresis loop, 247, 267
- I**
- Illuminance, 594, 600
- Illuminances
  - definition of two equal, 595
- Illumination intensity, 594, 600
- Image definition
  - aberrations, 349
- Image distance, 335
- Image formation, 327
  - by a pinhole camera, 427
  - by a steel sphere, 427
  - by circular rings, 427
  - by concave mirrors, 327
  - by lenses, 327
  - using water waves, 328
- Image point, 310
  - as a diffraction pattern, 328
  - from a lens, 328

- real, 311
- virtual, 315
- Image scale, 314
- Image-plane arching, 345
- Imaging
  - and irradiance, 376
  - by a pinhole camera, 365
  - by a ring grating, 428
  - by lenses, 311, 331
  - by zone plates, 429
  - of invisible objects, 432
  - of non-emitting objects, 435
  - of three-dimensional objects, 365
- Imaging aberrations, 344
  - astigmatism, 345
  - chromatic, 350
  - distortion, 349
- Imaging errors
  - coma, 348
  - spherical aberration, 344
- Immersion fluid, 357
- Impedance, 183
  - or AC resistance, 183
- Impulse, 107, 145
- Impulse deflection, 21
  - mechanical, 146
- Incandescent gaslight, 584
- Incandescent light, 397, 481, 482, 580
- Inclination angle, 314
- Increase
  - of the angle of vision, 356
- Index of refraction, 233, 302
  - Table, 303, 322
- Inductance, 175
- Induction, 101, 142, 265
  - in conductors at rest, 104
  - in moving conductors, 108, 131
- Induction coil, 101, 116, 191
- Induction damping, 145
- Induction furnace, 191
- Induction phenomena, relativity, 103
- Inductive reactance, 180, 183
- Inductive resistance, 180, 183
- Inertia
  - mechanical, 176
  - of a magnetic field, 176
- Influence, 38, 71
- Influence machine, 19, 29
  - Holtz, 19
  - Wimshurst, 19
- Infrared, 323
- Initial curve = new curve, 267
- Insulator, 36
- Intensity, 373
  - of scattered radiation, 519
- Interaction cross-section, 495, 522
- Interference, 238
  - A. Fresnel's biprism experiment, 389
  - curves of constant inclination, 396
  - due to particles which redirect the light, 404
  - experiment of T. Young, 388, 406
  - H. Lloyd's experiment, 389
  - microscopy, 398
  - model experiments, 387, 389
  - of polarized light, 481, 483
  - redirection of radiant power by, 401
  - sharpening the fringes, 397
  - spectrometer, 454
    - of FABRY and PÉROT, 454
  - with a continuous spectrum, 399
  - with planar, parallel plates, 390
- Interference filter, 402, 579
- Interferometer
  - after A.A. Michelson, 409
  - optical, 408
- Interrupter, electrolytic
  - Wehnelt, 192, 204
- Ionization chamber, 298, 529
- Iron core, 146
- Irradiance, 296, 318, 319, 374, 376, 592
  - of the solar image, 379
- Irradiation intensity, 374, 592
- J**
- Joule heating, 8, 23, 177
- K**
- Kenelly-Heaviside layer, 568
- Kepler's telescope or astronomical telescope, 356, 360
- Kerr effect, 575
- Kirchhoff's law, 578
- Klystron, 234
- L**
- Lambert's cosine law, 372, 379, 533
- Lambert's law of absorption, 492
- Landé g-factor, 278
- Langevin-Debye formula, 257
- Larmor precession, 279
- Laser, 301, 399, 430
- Lattice constant
  - crystallographic, 455
- Laue diagram, 439
- Law of induction, 105, 106, 109, 174
  - most general form, 110
- Law of reflection, 302
- Law of refraction, 302
- Lead tree, 9
- Lecher line, 220
- Lecher system, 220
- Lens
  - focal ratio  $N_f$ , 366
- Lens formulas, 312
- Lenses
  - for electromagnetic waves, 236
  - image points from, 328
  - model experiment, 546
  - resolving power, 331
  - thick, 336
  - with gradients in the refractive index, 555
- Lenses, "rubber", 352
- Lenz's law, 142, 145, 177
- Levitation experiment, 75
- Leyden jar, 61
- Lichtenberg, G. C., 34, 38
- Lichtenberg's figures, 38
- Light
  - absorption of, 538, 541
  - as a transverse wave, 468
  - drag, 552
  - in a moving reference frame, 460
  - in gravitational fields, 556
  - monochromatic, 383
- Light beam, 299, 300
  - boundaries of, 343
  - principal ray, 310
- Light density or radiance, 197
- Light rays, 300
  - curved, 553
- Light source, 598
  - in the moving frame of reference, 461
  - linear, 342
  - measuring the diameter of, 407
  - pointlike, 383
  - thermal, 584
- Light sources, 301
- Light vector, 471
- Light waves
  - amplitude of, 318
- Light waves as electromagnetic waves, 233
- Light waves, standing, 403
- Light-beam boundaries, 334, 340
  - and energy transport, 371
  - and perspective, 368
- Line grating, 423, 452
  - for X-rays, 453
- sinusoidal modulation by, 424
- Line spectrum, 448
  - in the X-ray region, 456
- Line structure, 454

- Logarithmic decrement, 187, 189, 207  
 Lorentz contraction, 130, 133, 139  
 Lorentz force, 132, 137, 144, 160  
 Loss factor, 190, 207  
 Loupe, 354  
 Low-voltage transformer, 191  
 Lumen (lm), unit of luminous flux, 594  
 Luminance, 594, 602  
   Table, 602  
 Luminosity function, 598  
 Luminous efficiency, 598  
 Luminous energy, 594  
 Luminous flux, 594  
 Luminous fountain, 307  
 Luminous intensity, 593  
 Lummer-Gehrcke plate, 454  
 Lux (lx), unit of illuminance, 594
- M**
- Mach's stripes, 294  
 Madelung, E., 563  
 Magnetic charge, 153  
 Magnetic constant, 106  
 Magnetic dipole, 153  
 Magnetic field, 87, 113, 153  
   direction of, 89, 93  
   gradient, 151, 263  
   homogeneous, 89, 91  
   inertia of, 176  
   of a current-carrying wire, 5, 118, 120  
   of a long coil, 89, 93, 120  
   of a permanent magnet, 90, 270  
   of a ring coil, 91  
   of an oscillating dipole, 229  
   of the earth, 108  
   production of, 94  
   switching on and off, 177  
   unit of, 93  
 Magnetic field constant or induction constant, 106  
 Magnetic field lines, 4, 87, 200  
   of the earth's field, 94  
 Magnetic field of the earth, 94  
 Magnetic field strength, 92  
   at the center of a cylindrical coil, 120  
 Magnetic field, rotating, 170, 184  
 Magnetic fields  
   dependence on the frame of reference, 129  
 Magnetic flux, 106, 146, 152, 154, 261  
 Magnetic flux density, 107, 261  
 Magnetic moment, 148, 262, 275  
   of a molecule, 275  
   of an electron, 278  
 Magnetic polarization, 262  
 Magnetic poles, 88, 152  
 Magnetic potential difference, 115  
 Magnetic potentiometer, 116, 117  
 Magnetic shielding, 272  
 Magnetic susceptibility, 262  
 Magnetizability  
   molecular, 273  
 Magnetization, 262, 270  
   remanent, 147, 268  
 Magnetometer, 93  
 Magneton, Bohr, 277  
 Magnetron, 236  
 Magnification, 354  
 Magnification or power  
   of a microscope, 356  
   of a telescope, 355, 361  
 Magnifying glass, 354  
 Magnitudes  
   of stars, 601  
 Malus, E. L., 498  
 Mass  
   of the electron, 527  
 Maxwell equations, 124, 125  
   in matter, 270  
   in vacuum, 55, 89, 114, 124, 125  
 Maxwell, J. C., 140  
 Maxwell's relation, 233, 549  
 Mean free path of molecules, 34  
 Meissner-Ochsenfeld effect, 265  
 Meniscus lens, 339, 347  
 Mercury vapor, optical detection, 562  
 Michelson interferometer, 409  
 Microphone, 165, 248  
 Microscope, 356  
   free object distance, 359  
   immersion fluid, 357  
   magnification, 356  
   making phase structures visible, 437  
   numerical aperture, 358  
   oblique illumination, 437  
   resolving power, 357  
   telecentric optical path, 367  
   with dark-field illumination, 358  
 Microwaves, 237, 258  
 Millikan, R. A., 77  
 Mirror charge, 71  
 Mirror galvanometer, 11, 19  
 Mirror image, 302  
 Mirror prisms, 324  
 Mirror surface grating, 453  
 Mirror, concave, 328  
 Modulation length, 239  
 Molecular currents, 97, 147  
 Molecules  
   and dispersion, 548  
   electric polarizability, 523, 552  
   non-polar, 246  
   number density  
     optical determination, 559  
   polar, 246, 521, 564  
 Monochromatic (single-frequency)  
   sound waves, 444  
 Monochromatic light, 309, 322, 344, 351, 396, 397, 419, 421, 422, 424, 425, 430–432, 443, 449  
   hologram, 431, 432  
   laser, 399, 410, 430  
   single-frequency, 443  
 Monochromatic wave group, 449  
 Monochromatic wave train, 383, 429–431  
 Monochromator, 449  
 Motion pictures, image changing  
   without flickering, 596  
 Muller's stripes, 399
- N**
- Nanometer (nm) =  $10^{-9}$  m, 322  
 Natural light, 301, 320, 449  
   spectrum, 320  
 Néel temperature, 286  
 New curve, 267  
 Newton's rings, 396  
 Nicol prism, 471  
 Night glass, 362  
 Nodal points, 338  
 Non-reflective coating, 401  
 Normal element, 15  
 Number density, 254, 274  
   of electrons, 527  
   of molecules, 495, 567  
 Numerical aperture NA, 358
- O**
- Object distance, 335  
 Objective, 335, 358  
 Objective lens, 355  
 Ocular, 351, 355, 363  
 Oersted, H. C., 87  
 Ohm, unit of resistance, 16  
 Ohmic resistance, 16, 182  
 Ohmic voltage, 182  
 Ohm's law, 16, 17  
 Opaque or topcoat paints, 610  
 Opening angle, 299, 314  
   and radiant flux (power), 375  
 Opening-angle ratio = focal ratio, 352  
 Optical activity, 486, 487  
 Optical axis, 471, 472  
 Optical constants  
   Beer's formula, 509  
   measurement of, 500, 513



of Na and K, 572  
 Optical path, 304, 397, 444  
 Optical temperature measurements, 586  
 Order  
   of interference fringes, 384  
   of interference maxima, 389, 395  
   of interference rings, 392  
 Order-one and order-two positions of a step grating, 422  
 Oscillations  
   autocontrol, 204  
   damped, 196  
   electrical, 196  
   energy resonance curve, 209  
   forced, 205, 207, 520, 548, 566  
   resonance frequency, 196  
   undamped, 202  
 Oscillator circuit, electrical, 196, 214  
 Oscillator strength, 561  
 Oscillator, electrical, 206  
 Oscilloscope, 77  
 Overcorrection, spherical, 345  
 Overtones, 218  
 Oxygen, liquid, in a magnetic field, 266

## P

Paper condenser, 61  
 Paraelectric materials, 246, 252  
 Parallax, 601  
 Parallel circuit, 188, 189, 195, 209  
   of condensers, 56  
   of resistor, coil, and condenser, 188  
   of resistors, 17  
 Parallel light beams, 381  
   separation by image formation, 316  
 Parallel-bounded beams, 491  
   of light, 300  
 Parallel-plate condenser, 28, 35, 56, 77, 243  
   attraction of the plates, 72  
 Paramagnetic materials, 264, 265, 274, 280  
 Parsec =  $3.08 \cdot 10^{16}$  m, 601  
 Path difference, 383, 478  
 Path integral of the electric field, 50, 115  
 Path, optical, 304, 397, 444  
 Penetration depth  
   mean, of light, 493, 538, 541  
   of X-rays, 544  
 Permanent magnets, 97, 121, 149  
 Permeability, 261  
 Permeability constant, 106

Permittivity of vacuum = electric field constant, 52  
 Perspective, 343, 366  
 Phase grating, 425  
 Phase jump on reflection, 392, 502, 510  
 Phase shift, 183, 184  
 Phase structure, 425, 437  
 Phase velocity, 237, 457  
   in metals, 542  
 Phase-contrast method, 437  
 Phasor diagram, 183  
 Photocell, 297  
 Photodiode, 297  
 Photometry, 293, 593, 599  
 Photomultiplier, 298  
 Piezoelectric crystals, 86  
 Pinhole camera, 331, 338, 365, 427  
 Planck's constant, 277, 582  
 Planck's radiation formula, 582  
 Plane of incidence, 302  
 Plasma oscillations, 566  
 Poisson's spot, 414  
 Polar molecules, 246, 256, 521, 564  
 Polarizability, 255  
   electric, 523, 552  
   molecular, 253  
 Polarization, 467, 470  
   by birefringence, 469  
   by reflection, 498  
   by scattering, 528  
   electric, of a dielectric material, 63, 84, 245, 249  
   magnetic, 262  
   of electromagnetic waves, 231, 233  
 Polarization angle, 498  
 Polarization foils, 471, 483  
 Polarized light, 467  
   elliptic, 476, 479  
   interference, 481, 483  
 Polarized light (partially polarized), 502  
 Polarizers, 468–470  
   for ultraviolet, 474  
   for X-rays, 529  
 Polarizing  
   in the infrared, 498  
 Pole regions  
   forces between, 152  
 Poles of magnet coils, 90  
 Poles of magnets, 154  
 Polychromatic light, 351  
 Potential, 80  
 Potential difference, 81  
   magnetic, 115  
 Potentiometer, 18  
 Potentiometer circuit, 18

Potentiometer, magnetic, 116, 117  
 Pot-type magnet, 157  
 Power of a lens, 314  
 Power, electric, 25  
   of alternating current, 189  
 Poynting vector, 231  
 Precession, 280  
 Primary light source, 358, 602  
 Principal angle of incidence, 498  
 Principal orientation, 155  
 Principal plane, 335  
   of a crystal, 472  
   of a prism, 309  
 Principal points, 338  
 Principal ray, 310, 314, 336, 343  
   angle of inclination, 314, 336, 340, 343  
 Principle of relativity, 132  
 Prism, 309, 451, 472  
   direct-vision, 540  
   made of ZnO, 539  
   principal plane, 309  
   Wollaston, 474  
 Prism spectrometer, 443  
 Probe coil, 107  
 Prometheus, 585  
 Propeller, electric, 58  
 Pupils, 340  
 Purcell's experiment, 520  
 Purple, 607  
 Pyroelectric crystals, 85  
 Pyrometer, 587

## Q

Q-factor, 207, 559  
 Quality factor or Q-factor, 207  
 Quarter-wave plate, 480  
 Quartz, birefringence, 472, 473, 487  
 Quetelet's rings, 404

## R

Radiance, 373, 579  
   of an emitter, 376  
   spectral, of a black body, 581  
 Radiant energy, 594  
 Radiant exitance, 375  
 Radiant flux, 371  
 Radiant intensity, 373, 448  
   direction-independent, 381  
   of X-rays, 381  
 Radiant intensity (or Intensity), 591  
 Radiant power, 296, 297, 401, 578, 591  
 Radiation detectors, 296  
 Radiation field of a dipole, 228  
 Radiation formula of M. Planck, 582  
 Radiometer, 296, 491  
 Rainbow, 419



- Ram, hydraulic, 176
- Raster grating, 425
- Rate of change
  - of a magnetic field, 106, 113
  - of an electric field, 123
- Rayleigh scattering, 520, 522
  - and compressibility, 525
  - dependence on the wavelength, 522
  - extinction constant, 523
- Reactance
  - capacitive, 185
  - inductive, 180, 183
- Receiver, 371, 519
- Redshift, 465
- Reflection, 302
  - avoiding, 502
  - elimination of, 401
  - from a weakly-absorbing material, 501
  - of linearly-polarized light, 499
  - with strong absorption, 509
- Reflection coefficient, 232, 603
- Reflection filters, 401
- Reflection grating, 450
- Reflection source, 598, 602
- Reflectivity, 232, 497, 501, 509, 542
  - metallic, 509, 542
- Refraction, 302, 550, 552
  - by a plane-parallel glass block, 320
  - reduction to scattering, 545
  - Table, 552
- Refractive index, 537
  - and gas density, 552
  - complex, 508, 509
  - for X-rays, 551
  - imaginary, 568
  - of mica, 475
- Refractometer, 307
- Reis P., 165
- Rejection circuit, 189
- Relative aperture  $N_f$ 
  - of a lens, 366
- Relativity principle, 103, 132
- Relativity, theory of, 103, 133
- Relaxation of a conduction current, 179
- Relaxation time, 60, 178, 208
- Remanence, 268
- Residual rays, 543
- Resistance, 16, 23
  - capacitive, 185
  - electrical, 177
  - inductive, 180, 183
  - measurement by field decay, 60
  - negative differential, 204
  - Ohmic, 16, 182
  - specific, 16
- Resistivity, 16
- Resistors
  - in parallel, 17
  - in series, 17
- Resolvable angular spacing, 332
- Resolving power, 331
  - of a grating, 447
  - of a lens, 333
  - of a microscope, 357
  - of a prism, 445
  - of spectrometers, 448
- Resonance, 186, 188, 207
- Resonance curve, 209
  - for the energy, 560
- Resonance frequency, 186, 196
- Resonant transformer, 199
- Resonators
  - properties of optical, 562
- Retina, 332, 599
- Reversing prism, 324
- Rheostat, 18
- Ring coil, 91, 262
- Ring current, electrodeless, 202
- Ring current, molecular, 276
- Ring grating, 428
  - with only one focal length, 430
- Rochon prism, 474
- Rotary condenser, 60
- Rotating field, 143
- Rotating field, magnetic, 143, 170, 184
- Rotating-coil ammeter, 7, 11, 145
- Rotating-coil instrument, 8
- Rotating-field motor, 171
- Rotational frequency of electric motors, 167, 171
- Rotor, 168
  - in motors, 166
- Rowland's experiment, 94, 129
- Rubber lenses, 352
- Ruby glass, extinction spectrum, 570
- S**
- Saccharimeter (sugar content), 307, 487
- Saturation magnetization, 266
- Savart's plate, 485
- Scattered light, 306
- Scattered radiation, 519
- Scattering, 300, 492
  - angular dependence, 519
  - by weakly-absorbing particles, 530
  - from matte surfaces, 532
  - of X-rays, 526
  - Rayleigh, 520, 522
  - significance of, 517
  - transition to diffraction, 532
- Scherrer, P., 456
- Schlieren method, 432
- Schmidt mirror, 352
- Secondary light source, 358, 375
- Secondary radiation, 522, 533
- Sector wheel
  - with radial sectors, 596
- Sector wheel or chopper, 592
- Seignette salt crystals, 247
- Self-inductance, 173, 199
- Series circuit, 187, 195, 209
  - of a resistor and a coil, 178, 182
  - of condensers, 56
  - of resistor, coil and condenser, 186, 207
  - of resistors, 15
- Shadow, 413
- Shallow-water lens, 328, 555
- Shimmering colors, 611
- Shine, 611
- Short-circuit current, 168
- Shorted rotor, 143
- SI = Systeme International d'Unités, 12
- Sine condition, 348, 357, 377
- Sine-wave grating, 424, 429
- Skin effect, 199
- Sky blue, 523
  - color temperature, 589
- Slide projector, 364
- Slip, 143
- Soft-iron ammeter, model, 8
- Solar constant, 376
- Solar image, diameter of, 315
- Solar surface
  - radiation, 376
  - temperature, 583
- Solid angle, 373
- Space charge, 54
- Spark, 37
- Spark gap, 197
- Sparking, 197
- Specific resistance, 16
- Spectral apparatus
  - after Fabry and Pérot, 398
- Spectral lines, 443, 446
  - X-ray, 456
- Spectrometer
  - after Lummer and Gehrcke, 454
  - and incandescent light, 449
  - for X-rays, 455
- Spectrum
  - produced by a plane-parallel block, 320
  - produced by a plane-parallel glass plate, 443
  - produced by a prism, 321, 448

- Spherical aberration, 344  
 Spin, 278  
 Spinning top, 98  
 Split-pole motor, 184  
 Standard light source, 593  
 Standing light waves, 403  
 Standing waves, 220, 229  
 Stark effect, 132  
 Stars  
     deflection of rays, 556  
 Starter, 168  
 Stefan-Boltzmann law, 582  
 Strain birefringence, 489  
 Streak focal line, 381  
 Superconductivity, 177, 265, 272  
 Superparamagnetism, 282  
 Surface, 514  
 Surface tension, reduction by an  
     electric field, 74  
 Susceptibility  
     dielectric, 245  
     magnetic, 262
- T**
- Tangent condition, 350  
 Tank circuit, 206  
 Telecentric optical path, 341, 458  
     image side, 341  
     object side, 367  
 Telegraph equations, 223  
 Telegraph of Gauss and Weber, 145  
 Telegraphy, wireless, 197  
 Telephone as an alternating-current  
     generator, 164  
 Telephoto objective lens, 337  
 Telescope, 407  
     Galilean or Huygens, 360  
     Kepler's or astronomical, 333,  
         356  
     magnification, 355, 361  
     perspective, 370  
     single-lens, 355  
 Telescopic optical path, 360  
 Temperature measurements  
     optical, 586  
 Temperature radiation, 577  
 Temperature, true and black-body,  
     587  
 Terrestrial telescope, 360  
 Tesla coil, 198  
 Tesla, unit of the magnetic flux  
     density, 107  
 Test charge, 68  
 Theory of relativity  
     special, 130  
 Thermal radiation, 577  
     selective, 583  
 Thermocouple, 297  
 Thermoelement, 586
- Thick lenses, 336  
 Thomson, J. J., 528  
 Three-dimensional viewing of  
     two-dimensional images, 370  
 Three-phase current, 171  
 Tinting and shading triangle, 606  
 Tints and shades  
     of chromatic colors, 605  
 Toepler's schlieren method, 433  
 Toggle action, 192  
 Toggle oscillations, 205  
 Tolansky, S., 399  
 Top, spinning, 278  
 Toriodal coil, 262  
 Torque, 81, 82, 147, 166  
 Torsional waves, 496  
 Total reflection, 306, 470, 504  
     by electrons, 568  
     critical angle, 306  
 Tourmaline crystal, 86  
 Transformer, 190  
 Transmission coefficient, 609  
 Transmitter, 165, 224  
 Transverse waves, 467, 478  
 Triode, 203  
 Tungsten lamps, 585  
 Tunnel effect, 504  
 Two-phase AC motor, 171  
 Tyndall effect, 470
- U**
- Ultramicroscope, 569  
 Ultraviolet, 323  
 Undercorrection, spherical, 344  
 Unipolar induction, 110  
 Unit  
     of electric current, 12  
 Unit system, 12  
 Usable wavelength range, 447, 451
- V**
- Vacuum tube  
     with three electrodes (triode),  
         203  
 Van de Graaff generator, 44  
 van de Graaff, R. J., 45  
 Variable resistor, 18  
 Vector diagram, 183  
 Velocity  
     critical (electromagnetism), 140  
     of electromagnetic waves, 223  
     of electrons in metals, 141  
 Velocity of light, 140, 231, 457  
     in vacuum, 130, 223  
     measurement by Foucault, 458  
     measurement by interference  
         experiments, 462  
     measurement by Römer, 457  
     measurement using the  
         astronomical aberration,  
         461  
 Versorium, 84  
 Vibrations  
     circular, 170  
     forced, 517, 520, 566  
 Visual sharpness (acuity), 595  
 Volt balance, 13  
 Volt, unit of potential difference, 24,  
     70  
 Voltage  
     effective value, 181  
     examples, 17  
     induced, 106, 113  
     Ohmic, 182  
     time integral of, 102  
     unit of, 70  
 Voltage divider, 18  
 Voltage impulse, 102, 116, 174  
     measurement of, 145  
 Voltage or potential difference, 13  
 Voltage resonance, 187  
 Voltmeter, 14  
     current-carrying or dynamic, 16  
     galvanic, 16  
     static, 14
- W**
- Waitz, J. S., 42  
 Walkiers de St. Amand, 45  
 Watt second = 1 newton meter, 24  
 Watt, unit of power, 25  
 Wave center  
     extended, 385  
     pointlike, 383, 385  
 Wave groups, 237, 383, 449  
     length of, 399  
 Wave resistance, 231  
 Waveguide, 237  
 Wavelength, 322, 537  
     measurement of, 229  
 Waves  
     mathematical representation,  
         506  
 Waves, electromagnetic, 211, 230  
     energy transport by, 231  
     polarization of, 231, 233  
     reflection of, 228  
     refraction of, 233  
     standing, 220  
     velocity of, 223, 231  
 Waves, electromagnetic, travelling  
     detection of, 229  
 Wehnelt interrupter, 192, 204  
 White light = natural light, 301  
 Wien's displacement law, 583  
 Wilcke, J. C., 30, 32, 38  
 Wimshurst machine, 19

Wind, electric, 58  
Wire wave, electromagnetic, 222  
Wollaston prism, 474  
Wood, R.W., 540

**X**

Xerography, 38  
X-ray spectrometer, 455  
X-rays, 381, 453, 455  
  absorption of, 537, 541  
  diffraction of, 438

line spectrum, 456  
penetration depth, 544  
polarized, 529  
refractive index, 537, 551  
scattering of, 526

**Y**

Young, Thomas, 384, 387, 405, 409,  
  450, 502, 520  
Young's interference experiment,  
  388, 406

**Z**

Zernike, F., 437  
Zinc oxide  
  dispersion of, 539  
  selective radiation, 584  
Zone construction, Fresnel, 413  
Zone plate, 428  
Zoom lenses, 352