I

Units and Constants

The choice of units suitable for the description of atomic and subatomic phenomena represents a delicate methodological problem.

It has become customary to measure the energies of particles in electron-volts (ev) and their momenta in ev/c (the momentum p in ev/c is numerically equal to the energy pc in ev). With these units, the energy of a particle with charge equal to the charge of the electron, that has been accelerated from rest through a potential difference V, is numerically equal to V. The momentum of this particle is related to the radius of curvature, R, of its trajectory in a magnetic field by the equation:

$$p \quad (\text{ev/c}) = 300\mathcal{B} \quad (\text{gauss}) \cdot R \quad (\text{cm}),$$

where $\mathcal{B}$ represents the component of the magnetic induction perpendicular to the trajectory.

Also, it is customary to measure velocities in terms of the velocity of light, c, and charges in terms of the electron charge, e. For example, one says that a particle has a velocity of 0.9 the velocity of light, rather than a velocity of $2.69798 \cdot 10^{10}$ cm sec^{-1}, and one will speak of a doubly charged nucleus rather than of a nucleus with a charge of $9.604 \cdot 10^{-10}$ e.s.u

The writer has pointed out (RB40.2) that the above units can be incorporated into a consistent system whose fundamental units are the centimeter, the velocity of light, the charge of the electron and the volt. This system, however, has a serious disadvantage in that it fails to bring out the dimensional homogeneity of physical equations. For example, it yields the following expression for the fundamental relation between total energy U, momentum p, and mass m of a particle [see Eq. (A.2.5)]:

$$U^2 = p^2 + m^2.$$

This feature, of course, is a direct consequence of the fact that, in the proposed system, two quantities with physical dimensions (the velocity of light and the charge of the electron) are taken as equal to one.

In this book we have chosen to sacrifice consistency for convenience. Thus we have used the C.G.S. system in most of our equations, while, when referring to numerical data, we have always given energies in terms of ev, momenta in terms of ev/c, charges in terms of e and velocities in terms of c.

The numerical values of the most important natural constants encountered in this book are listed in Table 1 [see refs. (DMJ48) and (DMJ49.2)].

Table A.1.1. Natural constants

Velocity of light:

$$c = 2.99776 \cdot 10^{10} \text{ cm sec}^{-1}.$$

Number of atoms per gram atom:

$$N = 6.024 \cdot 10^{23}.$$

Charge of the electron:

$$e = 4.802 \cdot 10^{-10} \text{ e.s.u.}$$

Mass of the electron:

$$m_e = 9.105 \cdot 10^{-23} \text{ g.}$$

Rest energy of the electron:

$$m_ec^2 = 5.1079 \cdot 10^5 \text{ ev.}$$

Classical radius of the electron:

$$r_e = e^2/m_ec^2 = 2.8176 \cdot 10^{-13} \text{ cm.}$$

Compton wavelength of the electron:

$$\lambda_e = h/m_ec = 2.4265 \cdot 10^{-10} \text{ cm.}$$

Fine structure constant:

$$\alpha = e^2/\hbar c = 1/137.027.$$

Mass of the proton:

$$M_p = 1836m_e.$$

Rest energy of the proton:

$$M_pc^2 = 938 \text{ Mev.}$$

Rest energy of the neutron:

$$M_nc^2 = 939 \text{ Mev.}$$

Mass of the $\pi^\pm$ meson:

$$m_\pi = 276m_e.$$

Rest energy of the $\pi^\pm$ meson:

$$m_\pi c^2 = 141 \text{ Mev.}$$

Mass of the neutral meson:

$$m_0 = 266m_e.$$

Rest energy of the neutral meson:

$$m_0c^2 = 136 \text{ Mev.}$$

Mass of the $\mu^\pm$ meson:

$$m_\mu = 209m_e.$$

Rest energy of the $\mu^\pm$ meson:

$$m_\mu c^2 = 107 \text{ Mev.}$$

Mean life of the $\pi^\pm$ meson:

$$\tau_\pi = 2.65 \cdot 10^{-8} \text{ sec.}$$

Mean life of the $\mu^\pm$ meson:

$$\tau_\mu = 2.10 \cdot 10^{-6} \text{ sec.}$$

APPENDIX

II

Review of Some Relativistic Equations

(a) ***Lorentz transformation.*** The equations

$$X' = \frac{X - \beta ct}{\sqrt{1-\beta^2}}, \qquad X = \frac{X' + \beta ct'}{\sqrt{1-\beta^2}},$$
$$Y' = Y,$$
$$Z' = Z, \tag{1}$$
$$ct' = \frac{ct - \beta X}{\sqrt{1-\beta^2}}, \qquad ct = \frac{ct' + \beta X'}{\sqrt{1-\beta^2}},$$

express the relations between the space and time coordinates X, Y, Z, t and X', Y', Z', t' of a point in two frames of reference that are moving with respect to each other. The same units of length are used in the two systems. The motion is a uniform translation along the coincident X-axes of the two frames of reference; c is the velocity of light, and β is the velocity of the second system with respect to the first divided by the velocity of light. As shown in the figure, the Y-axes of the two systems are parallel, and consequently the Z-axes also are parallel.

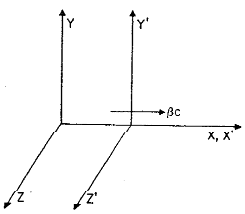

Fig. A.2.1. The Lorentz transformation.

From Eqs. (1) it follows that

$$X^2 + Y^2 + Z^2 - c^2t^2 = (X')^2 + (Y')^2 + (Z')^2 - c^2(t')^2 = \text{const.} \tag{2}$$

Any four quantities, whose values in two different frames of reference are related by the same equations (1) connecting X, Y, Z, ct with X', Y', Z', ct', are said to form a *four-vector.*

(b) ***Energy and momentum.*** The three Cartesian coordinates of the momentum of a particle, multiplied by c, cp_X, cp_Y, cp_Z, and the total energy of the particle, $U = E + mc^2$, form a four-vector. Thus the following transformation equations hold:

$$cp'_{X'} = \frac{cp_X - \beta U}{\sqrt{1-\beta^2}}, \qquad cp_X = \frac{cp'_{X'} + \beta U'}{\sqrt{1-\beta^2}},$$
$$cp'_{Y'} = cp_Y,$$
$$cp'_{Z'} = cp_Z, \tag{3}$$
$$U' = \frac{U - \beta cp_X}{\sqrt{1-\beta^2}}, \qquad U = \frac{U' + \beta cp'_{X'}}{\sqrt{1-\beta^2}}.$$

From these equations one sees as before that

$$c^2p_X^2 + c^2p_Y^2 + c^2p_Z^2 - U^2 = \text{const.} \tag{4}$$

Equation (4) indicates that the quantity $U^2 - p^2c^2$ is independent of the frame of reference. In the frame of reference in which the particle is at rest, $p = 0$ and $U = mc^2$; therefore in any frame of reference $U^2 - c^2p^2 = m^2c^4$ and thus

$$U^2 = c^2p^2 + m^2c^4. \tag{5}$$

One can obtain the expressions for the momentum and the energy as functions of the velocity by considering a particle at rest in the second frame of reference and computing its momentum and energy in the first frame of reference. If we put in Eqs. (3), $p' = 0$, and if we call U the total energy and p the momentum in the first frame of reference we obtain

$$p = \frac{m\beta c}{\sqrt{1-\beta^2}}; \qquad U = \frac{mc^2}{\sqrt{1-\beta^2}}; \tag{6}$$

where βc is the velocity of the particle in the first frame of reference.

(c) ***Velocity of the center of mass.*** Consider two particles with the same mass, m, one with momentum p, the other at rest. Let $c\beta_c$ be the velocity of the center of mass of the two particles. In the center-of-mass system, the total momentum of the two particles is zero, the total energy is $2mc^2/\sqrt{1-\beta_c^2}$. In the laboratory system, the momentum of the two particles is equal to the momentum, p, of the particle in motion and it is given by [see Eqs. (3)]:

$$p = \frac{\beta_c}{c}\frac{1}{\sqrt{1-\beta_c^2}}\, 2\frac{mc^2}{\sqrt{1-\beta_c^2}} = \frac{2mc\beta_c}{1-\beta_c^2}.$$

Thus β_c satisfies the equation:

$$\frac{\beta_c}{1-\beta_c^2} = \frac{p}{2mc} \tag{7}$$

One can obtain another expression for β_c as follows. Let U and U' be the total energies of *both particles* in the laboratory system and in the center-of-mass system respectively. These two quantities are related by the equation:

$$U = \frac{U'}{\sqrt{1-\beta_c^2}}.$$

On the other hand, p has the expression

$$p = \frac{\beta_c}{c}\frac{U'}{\sqrt{1-\beta_c^2}}.$$

One thus obtains:

$$\beta_c = \frac{cp}{U}. \tag{8}$$

Note that this equation has more general validity than Eq. (7). It gives the velocity of the center of mass of any number of particles, with arbitrary masses, for which the vector sum of momenta has the magnitude p and the sum of the total energies is U.

(d) ***Field of a charged particle in motion.*** One can best obtain the relations between the quantities describing the electromagnetic field, as viewed from two frames of reference in relative motion to one another, by considering the vector potential $\boldsymbol{A}$ and the scalar potential V. The three components of $\boldsymbol{A}$ and V form a four-vector. Thus:

$$\begin{aligned} A'_{X'} &= \frac{A_X - \beta V}{\sqrt{1-\beta^2}}, \qquad A_X = \frac{A'_{X'} + \beta V'}{\sqrt{1-\beta^2}}, \\ A'_{Y'} &= A_Y, \\ A'_{Z'} &= A_Z, \\ V' &= \frac{V - \beta A_X}{\sqrt{1-\beta^2}}, \qquad V = \frac{V' + \beta A'_{X'}}{\sqrt{1-\beta^2}}. \end{aligned} \tag{9}$$

From $\boldsymbol{A}$ and V, one obtains the electric and magnetic field intensities by means of the equations:

$$\begin{aligned} \boldsymbol{\mathcal{E}} &= -\text{grad}\, V - \frac{1}{c}\frac{\partial \boldsymbol{A}}{\partial t}; \\ \boldsymbol{\mathcal{B}} &= \text{curl}\, \boldsymbol{A}. \end{aligned} \tag{10}$$

In the particular case where the field in the second system is purely electrostatic, i.e., set up by charges at rest, one can put $\boldsymbol{A}' = 0$, and Eqs. (9) yield:

$$A_X = \frac{\beta V'}{\sqrt{1-\beta^2}} \qquad A_Y = A_Z = 0, \qquad V = \frac{V'}{\sqrt{1-\beta^2}}. \tag{11}$$

To derive the components of $\boldsymbol{\mathcal{E}}$ one uses Eqs. (10) and (11). For $\mathcal{E}_X$ one obtains:

$$\begin{aligned} \mathcal{E}_X &= -\frac{\partial V}{\partial X} - \frac{1}{c}\frac{\partial A_X}{\partial t} \\ &= -\frac{1}{\sqrt{1-\beta^2}}\frac{\partial V'}{\partial X} - \frac{1}{c}\frac{\beta}{\sqrt{1-\beta^2}}\frac{\partial V'}{\partial t}. \end{aligned}$$

V' is a function of X', Y', Z'; these quantities are the functions of X, Y, Z, t given in Eq. (1); thus:

$$\begin{aligned} \mathcal{E}_X &= -\frac{1}{\sqrt{1-\beta^2}}\frac{\partial V'}{\partial X'}\frac{\partial X'}{\partial X} - \frac{1}{c}\frac{\beta}{\sqrt{1-\beta^2}}\frac{\partial V'}{\partial X'}\frac{\partial X'}{\partial t} \\ &= \frac{1}{1-\beta^2}\mathcal{E}'_{X'} - \frac{\beta^2}{1-\beta^2}\mathcal{E}'_{X'}. \end{aligned}$$

Therefore:

$$\mathcal{E}_X(X,Y,Z,t) = \mathcal{E}'_{X'}(X',Y',Z',t'). \tag{12}$$

For $\mathcal{E}_Y$ one obtains:

$$\begin{aligned} \mathcal{E}_Y &= -\frac{\partial V}{\partial Y} - \frac{1}{c}\frac{\partial A_Y}{\partial t} \\ &= -\frac{1}{\sqrt{1-\beta^2}}\frac{\partial V'}{\partial Y} = -\frac{1}{\sqrt{1-\beta^2}}\frac{\partial V'}{\partial Y'}. \end{aligned}$$

Thus:

$$\mathcal{E}_Y = \frac{\mathcal{E}'_{Y'}}{\sqrt{1-\beta^2}}, \tag{13}$$

and, similarly:

$$\mathcal{E}_Z = \frac{\mathcal{E}'_{Z'}}{\sqrt{1-\beta^2}}. \tag{13a}$$

Equations (12) and (13) may be used to compute the electric field of a charged particle in motion. Suppose that this particle is at rest at the origin of the primed frame of reference, and therefore, moves with a velocity βc in the unprimed frame of reference. At a given point of the space, let us consider separately the components of $\boldsymbol{\mathcal{E}}$ in a direction parallel and perpendicular to the motion of the particle respectively. We may assume that the point under consideration is in the X, Y plane. In the primed frame of reference, the X- and Y-components of $\boldsymbol{\mathcal{E}}$ are given by

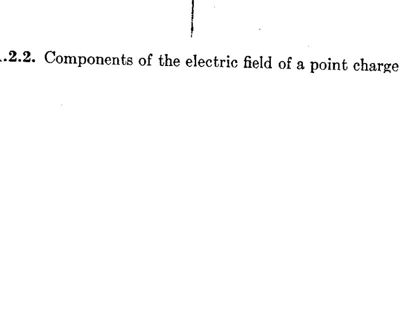

Fig. A.2.2. Components of the electric field of a point charge at rest.

$$\mathcal{E}'_{X'} = \frac{eX'}{(X'^2 + Y'^2)^{3/2}},$$

$$\mathcal{E}'_{Y'} = \frac{eY'}{(X'^2 + Y'^2)^{3/2}}.$$

These functions are represented, for a given value of Y, by the curves in Fig. 2.

In the unprimed frame of reference, the charged particle travels with the velocity βc. Consider the time $t = 0$, when the charged particle passes through the origin of the unprimed frame. At this time $X' = X/\sqrt{1 - \beta^2}$. This equation together with Eq. (12) shows that one obtains the curve representing $\mathcal{E}_X$ as a function of X from the curve

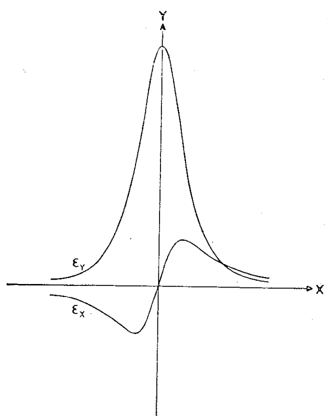

Fig. A.2.3. Components of the electric field of a point charge in motion.

representing $\mathcal{E}'_{X'}$ as a function of X' by contracting the scale of abscissae in the ratio of 1 to $\sqrt{1 - \beta^2}$ and leaving the ordinates unchanged. Similarly Eq. (13) shows that one obtains the curve representing $\mathcal{E}_Y$ as a function of X from the curve representing $\mathcal{E}'_Y$ as a function of X' by contracting the scale of abscissae in the ratio of 1 to $\sqrt{1 - \beta^2}$ and expanding the ordinate scale in the ratio of 1 to $1/\sqrt{1 - \beta^2}$ (see Fig. 3).

For the convenience of the reader we give in Fig. 4 the graphs of various functions of β that appear in the equations of this Appendix.

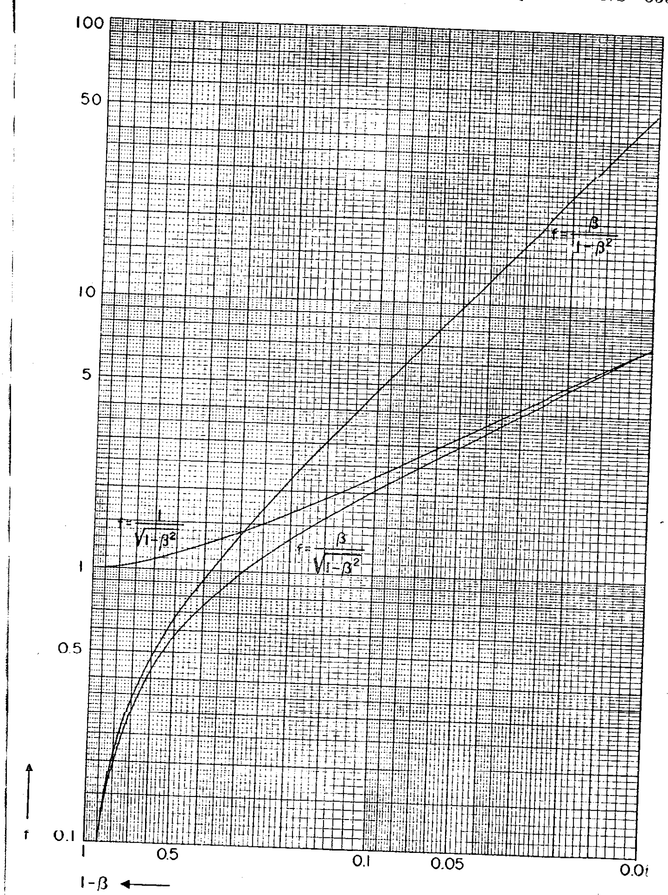

Fig. A.2.4. The quantities $\beta/(1 - \beta^2)$, $1/\sqrt{1 - \beta^2}$, and $\beta/\sqrt{1 - \beta^2}$ plotted as functions of $1 - \beta$.

APPENDIX III

The Poisson Formula; Statistical Errors

Consider an experiment where one counts events occurring at random in time. Select a time interval T, and assume that the *average* number of events occurring during an interval of this duration is n. We want to calculate the probability $p(m)$ that m events will occur in the selected interval.

First, assume the interval T to be subdivided into N equal intervals of duration T/N, such that the probability that an event will occur in any particular sub-interval is small. This probability is then n/N. Application of the multiplication theorem of probability theory gives a value of $(n/N)^m$ for the probability that one event will occur in each of any m predetermined sub-intervals. Similarly, the probability that *no* event occurs in a given sub-interval is $\left(1 - \frac{n}{N}\right)$, and the probability that no event occurs in any of $(N - m)$ predetermined sub-intervals is $\left(1 - \frac{n}{N}\right)^{N-m}$. The probability that events occur in m predetermined sub-intervals, but not in the remaining $(N - m)$, is the product of the two above probabilities and is:

$$\left(\frac{n}{N}\right)^m \left(1 - \frac{n}{N}\right)^{N-m}. \tag{1}$$

The number of ways in which one can select the first m intervals is:

$$\frac{N!}{m!(N-m)!}. \tag{2}$$

Using the addition theorem of the probability theory, one obtains the following expression for the probability that m events occur in the original interval, T:

$$\frac{N!}{m!(N-m)!}\left(\frac{n}{N}\right)^m \left(1 - \frac{n}{N}\right)^{N-m}. \tag{3}$$

The desired distribution function $p(m)$ is the limiting value of this expression as N tends to infinity; i.e.:

$$p(m) = \lim_{N\to\infty} \frac{N!}{m!(N-m)!}\left(\frac{n}{N}\right)^m \left(1 - \frac{n}{N}\right)^{N-m}. \tag{4}$$

Using Stirling's formula:

$$N! \to \sqrt{2\pi N}\left(\frac{N}{e}\right)^N,$$

one obtains from Eq. (4):

$$p(m) = \frac{e^{-n}}{m!} n^m. \tag{5}$$

Equation (5) is known as the *Poisson formula.* Several important properties of $p(m)$ may be derived from the identity:

$$e^n = \sum_{l=0}^{\infty} \frac{n^l}{l!}. \tag{6}$$

If one divides both sides of Eq. (6) by e^n, and substitutes m for l, one obtains

$$\sum_{m=0}^{\infty} \frac{e^{-n}}{m!} n^m = \sum_{m=0}^{\infty} p(m) = 1, \tag{7}$$

as must be true from the definition of $p(m)$.

If one multiplies both sides of Eq. (6) by ne^{-n}, one obtains:

$$n = \sum_{l+1=1}^{\infty} (l+1)\frac{n^{l+1}}{(l+1)!} e^{-n} = \sum_{m=0}^{\infty} m \frac{n^m}{m!} e^{-n} = \sum_{m=0}^{\infty} mp(m). \tag{8}$$

This expresses the obvious result that the average value of m is n.

If one multiplies both sides of Eq. (6) by n^2e^{-n} one obtains, considering Eq. (8):

$$\sum_{m=0}^{\infty} m^2 p(m) = n^2 + n. \tag{9}$$

As a measure for the statistical accuracy of a particular counting experiment one may take the mean square value of the deviations of m from n, i.e., the quantity:

$$\sum_{m=0}^{\infty} (m-n)^2 p(m) = \sum_{m=0}^{\infty} m^2 p(m) - 2n \sum_{m=0}^{\infty} mp(m) + n^2 \sum_{m=0}^{\infty} p(m). \tag{10}$$

On combining Eqs. (7), (8), (9), and (10), one obtains:

$$\sum_{m=0}^{\infty} (m-n)^2 p(m) = n. \tag{11}$$

Thus the root mean square statistical error (or "standard statistical deviation") of an experiment in which n counts should be recorded is $\sqrt{n}$. The *relative* value of this error is $\sqrt{n}/n = 1/\sqrt{n}$.

APPENDIX

IV

The Laplace and the Mellin Integrals

(a) ***The Laplace integral.*** Given a function, $f(x)$, of a real variable, x, the Laplace integral or Laplace transform of $f(x)$ is defined by the equation:

$$\mathfrak{L}_f(\lambda) = \int_0^\infty e^{-\lambda x} f(x)\, dx, \tag{1}$$

where λ is a complex parameter. We assume the integral to be convergent at the lower limit. If the integral converges at the upper limit for a certain value, λ_a, of λ, it also converges for all values of λ for which $R(\lambda) > R(\lambda_a)$, where R indicates the real part. On the other hand, if the integral diverges for a certain value, λ_b, of λ, it also diverges for all values of λ for which $R(\lambda) < R(\lambda_b)$. Hence, in general, the function $\mathfrak{L}_f(\lambda)$ is defined in the half-plane to the right of a straight line parallel to the imaginary axis.

The following formulae can easily be proved:

$$\mathfrak{L}_{f'}(\lambda) = \lambda \mathfrak{L}_f(\lambda) - f(0), \tag{2}$$

where $f' = df/dx$;

$$\mathfrak{L}_F(\lambda) = -\frac{1}{\lambda}[\mathfrak{L}_f(\lambda) - F(0)], \tag{3}$$

where $F(x) = \int_x^\infty f(x')\, dx'$;

$$\left[\frac{d^n}{d\lambda^n}\mathfrak{L}_f(\lambda)\right]_{\lambda=0} = (-1)^n \int_0^\infty x^n f(x)\, dx. \tag{4}$$

An important property of the Laplace transformation is that, under not very restrictive conditions, the correspondence between $f(x)$ and $\mathfrak{L}_f(\lambda)$ established by Eq. (1) is unique; i.e., there is only one function $f(x)$ that has $\mathfrak{L}_f(\lambda)$ as its Laplace integral. If $\mathfrak{L}_f(\lambda)$ is known, $f(x)$ can be determined by the following inversion formula:

$$f(x) = \frac{1}{2\pi i}\int_C e^{\lambda x}\mathfrak{L}_f(\lambda)\, d\lambda, \tag{5}$$

where the integration path, C, is a straight line running parallel to the imaginary axis, in the half-plane of convergence of $\mathfrak{L}_f(\lambda)$.

(b) ***The Mellin integral.*** Given a function, $f(y)$, of a real variable, y, the Mellin integral, or Mellin transform of $f(y)$, is defined by the equation:

$$\mathfrak{M}_f(s) = \int_0^\infty y^s f(y)\, dy, \tag{6}$$

where s is a complex parameter. If the integral diverges at the lower limit for a certain value, s_a, of s, it also diverges for all values of s for which $R(s) < R(s_a)$. If the integral diverges at the upper limit for a certain value s_b of s, it also diverges for all values of s for which $R(s) > R(s_b)$. Hence, if the Mellin integral converges anywhere, its field of convergence is a strip bounded by two straight lines parallel to the imaginary axis.

The following formulae can easily be proved:

$$\mathfrak{M}_{f'}(s) = -s\mathfrak{M}_f(s - 1), \tag{7}$$

where $f' = df/dy$;

$$\mathfrak{M}_F(s) = \frac{1}{s+1}\mathfrak{M}_F(s + 1), \tag{8}$$

where $F(y) = \int_y^\infty f(y')\, dy'$.

The Mellin transformation, like the Laplace transformation, is in general unique and can be inverted by the following formula:

$$f(y) = \frac{1}{2\pi i}\int_C y^{-(s+1)}\,\mathfrak{M}_f(s)\, ds, \tag{9}$$

where the integration path, C, runs parallel to the imaginary axis within the strip of convergence.

APPENDIX

V

The Gold Integral

The Gold integral is defined by the equation:

$$\mathcal{E}_n(x) = x^n \int_x^\infty \frac{e^{-s}}{s^{n+1}}\, ds, \tag{1}$$

or by the equivalent equation:

$$\mathcal{E}_n(x) = \int_1^\infty \frac{e^{-xs}}{s^{n+1}}\, ds. \tag{2}$$

Of particular interest in this volume are the Gold integrals corresponding to $n = 0$ and to $n = 1$, $\mathcal{E}_0(x)$ and $\mathcal{E}_1(x)$. The function $-\mathcal{E}_0(x)$ is also called the exponential integral, $Ei(-x)$:

$$-\mathcal{E}_0(x) = Ei(-x) = -\int_x^\infty \frac{e^{-s}}{s}\, ds = -\int_1^\infty \frac{e^{-xs}}{s}\, ds. \tag{3}$$

This function is extensively tabulated.* The function $\mathcal{E}_1(x)$ has the expression:

$$\mathcal{E}_1(x) = x \int_x^\infty \frac{e^{-s}}{s^2}\, ds, \tag{4}$$

or:

$$\mathcal{E}_1(x) = \int_1^\infty \frac{e^{-xs}}{s^2}\, ds. \tag{5}$$

Integration by parts of Eq. (2) yields a relation between $\mathcal{E}_n$ and $\mathcal{E}_{n-1}$; in particular:

$$\mathcal{E}_1(x) = e^{-x} - x\mathcal{E}_0(x), \tag{6}$$

or

$$\mathcal{E}_1(x) = e^{-x} + xEi(-x). \tag{6a}$$

Differentiation of (5) with respect to x yields:

* See, for example, Jahnke and Emde, Tables of Functions, Dover Publications, New York (1945).

$$\frac{d}{dx}\mathcal{E}_1(x) = -\mathcal{E}_0(x) = Ei(-x). \tag{7}$$

For $x = 0$ Eq. (5) gives

$$\mathcal{E}_1(0) = \int_1^\infty \frac{ds}{s^2} = 1. \tag{8}$$

To investigate the behavior of $Ei(-x)$ near $x = 0$, consider the identity:

$$-Ei(-x) = \int_x^{x_0} \frac{e^{-s}}{s}\, ds - Ei(-x_0).$$

For x and x_0 very small compared with 1, one can take $e^{-s} \approx 1$ and the above equation yields:

$$-Ei(-x) = \ln\left(\frac{x_0}{x}\right) - Ei(-x_0). \tag{9}$$

Equation (9) shows that $-Ei(-x)$ diverges logarithmically as x approaches zero. For $x \gg 1$, e^{-xs} decreases very rapidly with increasing s, so that the significant contributions to the integral in Eq. (5) come from values of the integrand in the neighborhood of $s = 1$. One thus obtains the following approximate expression for $\mathcal{E}_1(x)$:

for $x \gg 1$,

$$\mathcal{E}_1(x) \approx \int_1^\infty e^{-xs}\, ds = \frac{e^{-x}}{x}. \tag{10}$$

Figure 1 gives a graphical representation of the function $\mathcal{E}_1(x)$ for $0 < x < 14$. The approximate expression given by Eq. (10) is plotted for comparison.

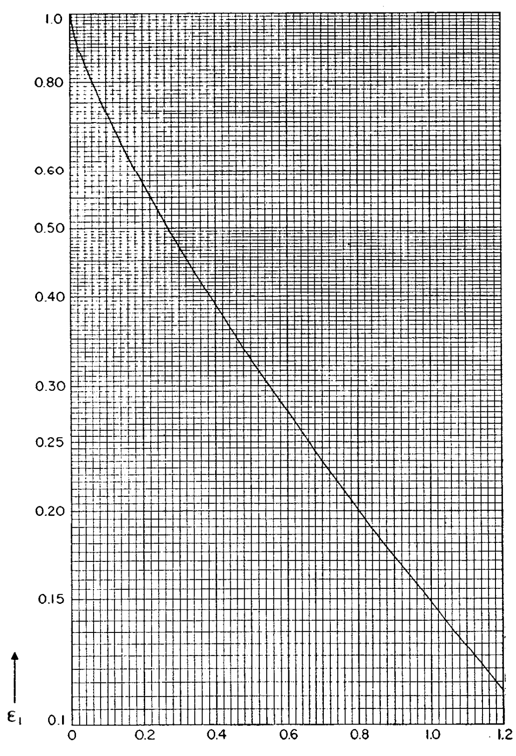

Fig. A.5.1. The solid lines represent the function $\mathcal{E}_1(x) = \int_1^{\infty} \frac{e^{-xs}}{s^2} ds$; the dashed line represents the function e^{-x}/x.

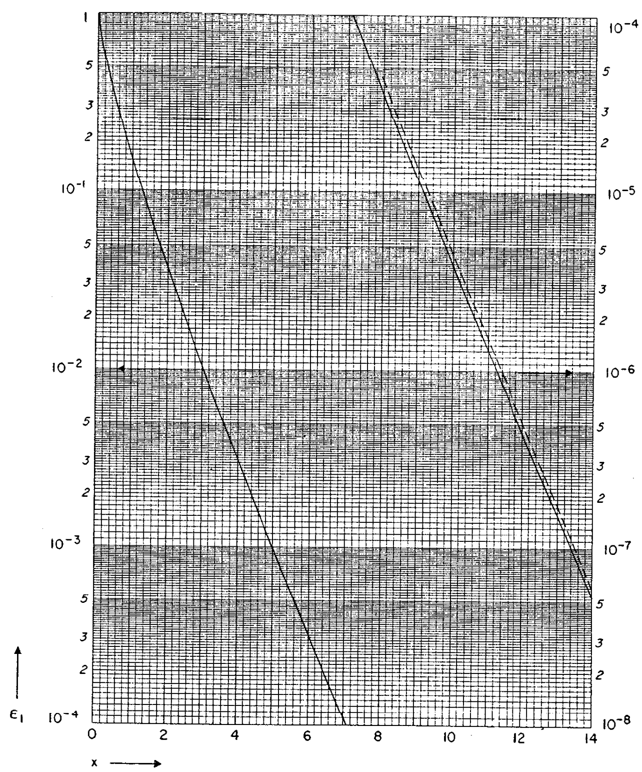

Fig. A.5.1. (Continued)

APPENDIX

VI

The Standard Atmosphere

In a static atmosphere, the pressure at any point measures the amount of material above this point, i.e., the "atmospheric depth," x. In a static and isothermal atmosphere, x is an exponential function of the altitude, z:

$$x = x_0 e^{-z/z_0}, \qquad (1)$$

where z is measured from the level where the pressure is x_0.

The average relation between x and z in the actual atmosphere at latitudes around 40° or 50° is shown in Fig. 1. This figure is constructed from the data given in the Report No. 538 of the National Advisory Committee for Aeronautics.

Figure 2 gives the relation between x and the quantity:

$$z_0 = -x \frac{dz}{dx}. \qquad (2)$$

This quantity also represents the ratio of x to the density of air, ρ:

$$z_0 = \frac{x}{\rho}. \qquad (3)$$

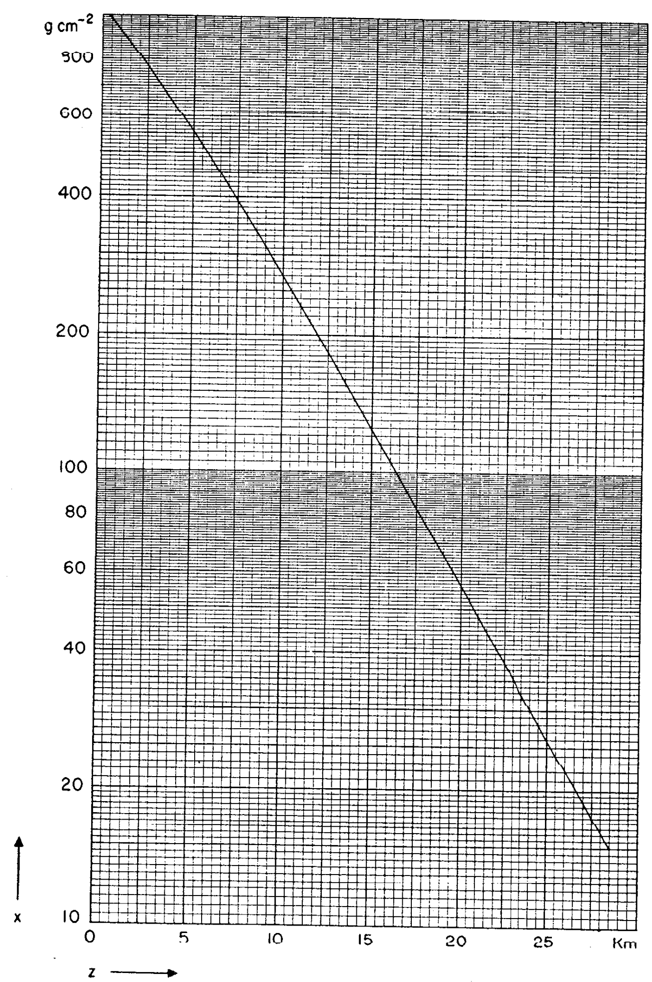

Fig. A.6.1. Atmospheric depth, x, as a function of altitude, z, from sea level in the standard atmosphere; z is measured in kilometers (10^5 cm).

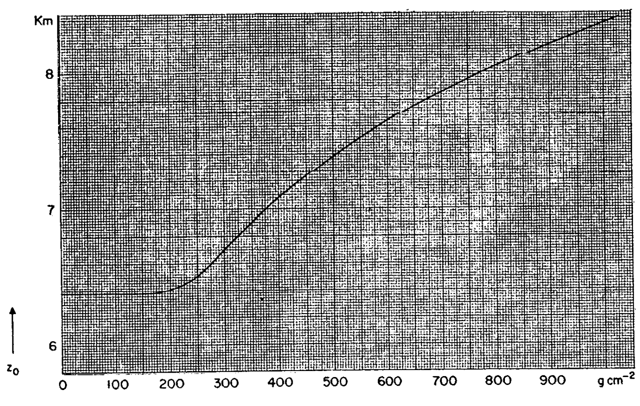

Fig. A.6.2. The quantity, $z_0 = x/\rho = -x(dz/dx)$ as a function of x in the standard atmosphere; z_0 is measured in kilometers.

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