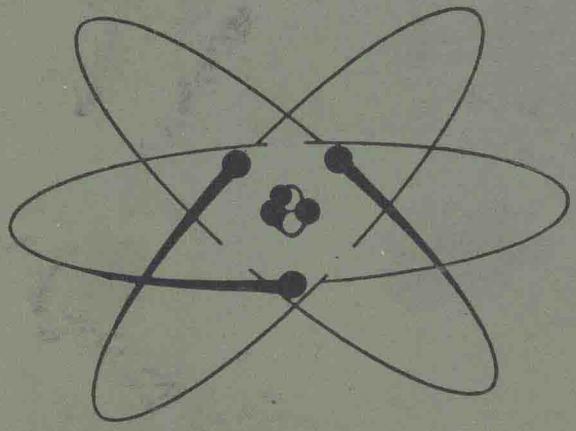
RADIOLOGICAL HEALTH

HANDBOOK

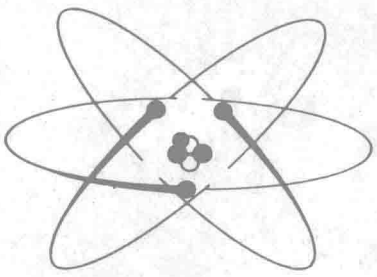


REVISED EDITION
JANUARY 1970

U.S. DEPARTMENT OF
HEALTH, EDUCATION, AND WELFARE
Public Health Service

RADIOLOGICAL HEALTH HANDBOOK

Compiled and edited
by the
Bureau of Radiological Health
and the
Training Institute
Environmental Control Administration



Revised Edition
January 1970

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service
Consumer Protection and Environmental Health Service
Rockville, Maryland 20852

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price $4.00

FOREWORD

Twenty years ago the Public Health Service developed the first Radiological Health Handbook as a training aid, and it has since become a basic reference and a major resource for professional personnel and students in the field of radiological health. Credit for the development of the Handbook goes to members of the radiological health training staff, who through the years compiled and revised the information and data included in the book.

New knowledge, new technological advancements, and the enactment of Public Law 90-602, "Radiation Control for Health and Safety Act of 1968," made the last edition outdated and inadequate. In 1968, Mr. James G. Terrill, Jr., then Director, National Center for Radiological Health, initiated revision of the Handbook. Suggestions for additions, corrections, and deletions were obtained from Handbook users across the United States and in a number of foreign countries. An advisory committee, representative of major programs in the Bureau of Radiological Health, helped select the content for the revised edition, and a number of the Bureau's technical programs provided new data which are reflected in some of the charts and tables. Mr. John E. Munzer and Mr. Ralph E. Bunge of the training staff assumed major responsibility for work on the revision. The present text includes information unavailable ten years ago: a new chart of the nuclides, a universal decay table in place of individual isotope listings, microwave and laser glossaries, film-speed charts, depth-dose tables, and a "rules of thumb" section.

Although contributions from individuals and organizations are too numerous to list in detail, appreciation is expressed to all who made suggestions, provided material, and permitted the reprinting of data as acknowledged in the Handbook.

Mr. John C. Villforth, Director
Bureau of Radiological Health

Mr. George R. Shultz, Director
Training Institute

TABLE OF CONTENTS

SECTION I
PHYSICAL, CHEMICAL, AND MATHEMATICAL DATA

SIGNS AND SYMBOLS

Mathematics

+	plus, addition, positive
-	minus, subtraction, negative
±	plus or minus, positive or negative
∓	minus or plus, negative or positive
÷, /, ___	division
×, ·, ()	multiplication
(), []	collection
=	equal to
≠	not equal to
≡	identical to
≅	equals approximately, congruent
>	greater than
≯	not greater than
≥, ≧	greater than or equal to
<	less than
≮	not less than
≤, ≦	less than or equal to
::	proportional to
:	ratio
~	similar to
∝	varies as, proportional to
→	approaches
∞	infinity
∴	therefore

√	square root
$\sqrt[n]{}$	nth root
a^n	nth power of a
a^{-n}	reciprocal of nth power of a, $= 1/a^n$
log, $\log_{10}$	common logarithm
ln, $\log_e$	natural logarithm
e, ε	base of natural logs, 2.71828183 . . .
π	pi, 3.14159265 . . .
∠	angle
⊥	perpendicular to
||	parallel to
n	any number
|n|	absolute value of n
$\bar{n}$	average value of n
n°	n degrees
n'	n minutes, n feet
n''	n seconds, n inches
f(x)	function of x
Δx	increment of x
dx	differential of x
Σ	summation of
sin	sine
cos	cosine
tan	tangent

GREEK ALPHABET

A α Alpha	I ι Iota	P ρ Rho
B β Beta	K κ Kappa	Σ σ Sigma
Γ γ Gamma	Λ λ Lambda	T τ Tau
Δ δ Delta	M μ Mu	Υ υ Upsilon
E ε Epsilon	N ν Nu	Φ φ Phi
Z ζ Zeta	Ξ ξ Xi	X χ Chi
H η Eta	O ο Omicron	Ψ ψ Psi
Θ θ Theta	Π π Pi	Ω ω Omega

SIGNS AND SYMBOLS
ALPHABETICALLY BY NAME

about ---------- ca
absolute ---------- abs
absolute temperature (Kelvin) -- K
absorption coefficient, energy, for air = $\tau + \kappa + \sigma_a$ μ_a
absorption coefficient, linear, effective or apparent -------- μ
absorption cross section in barns ---------- σ_a
acceleration, linear ---------- a
activation cross section in barns ---------- σ_{ac}
activity, original ---------- A_o
alkali ---------- alk
alpha ---------- α
alpha particle ---------- α
alternating current ---------- a.c.
ampere ---------- A, amp.
angle between incident and scattered radiation ------ θ
angstrom ---------- Å
anno (year) ---------- a
aqua ---------- aq.
aqueous ---------- aq.
approximately ---------- ca
area ---------- A, σ
asymmetrical ---------- asym.
atmosphere (atmospheric) ------- atm, atmos.
atomic mass number ---------- A
atomic mass unit--^{12}C ---------- u
atomic mass unit--^{16}O (old) ---- amu
atomic number ---------- Z, at.no.
atomic weight ---------- at.wt.
atto (prefix) ---------- a
average ---------- av, avg.
Avogadro constant ---------- N_A
barn ---------- b
barn (cross section) ---------- σ
base of natural logarithm ------ e
barometer ---------- bar.
beta ---------- $\beta, \beta^-, {}_{-1}^{0}\beta$
beta particle ---------- ${}_{1}^{0}e, \beta, \beta^-, {}_{-1}^{0}\beta$
billion electron volt ---------- BeV, GeV
biological decay constant ------ λ_b
biot ---------- Bi
boiling point ---------- b.p.
British thermal unit ---------- Btu
buildup factor ---------- b
calorie ---------- cal
candela ---------- cd
capacitance ---------- C
Celsius ---------- C
centi (prefix) ---------- c
centigrade ---------- C
centimeter ---------- cm
centimeter-gram-second unit system ---------- CGS
chemical ---------- chem.
chemistry ---------- chem.
circa ---------- ca
circular ---------- cir.
circular mill ---------- c.m.
coefficient ---------- coef.
cologarithm ---------- colog
Compton absorption coefficient ---------- σ_a
Compton collision coefficient -- σ

Compton scatter coefficient	σ_s
concentrated	conc
concentration	C
concentration, air	χ
cosine	cos
constant	const.
coulomb	C
count rate	R
counts per minute	cpm
cubic	cu.
cubic centimeter	cc, c.cm., cu.cm., cm^3
cubic foot	cu.ft.
cubic foot per minute	cfm
cubic inch	cu.in.
cubic meter	cu.m., m^3
cubic millimeter	mm^3
cubic yard	cu.yd., yd^3
curie	Ci
curie (old)	c
cylinder	cyl.
day	d
decay constant	λ
deci (prefix)	d
decibel	dB
decontamination factor	DF
deka (prefix)	da
density, general	d
density, general or vapor	ρ
deuterium	D
deuteron	d
dielectric constant	ϵ
dilute	dil
disintegrations per minute	dpm
distribution factor	DF
dose	D
dose, absorbed	D
dose equivalent	DE
dyne	dyn
effective cross section in barns	σ_{eff}
electric charge	Q
electric field intensity	$\vec{\mathcal{E}}$
electron	e, e^-, $_{-1}^{0}e$
electron capture	ϵ
electron volt	eV
energy	E,Q
exposure	X
Fahrenheit	F
farad	F
femto (prefix)	f
film density	D
finite increment	Δ
force	F
franklin	Fr
frequency	f
frequency (wave motion quantum theory)	ν
gamma	γ
gamma ray	γ
gastrointestinal	G.I.
gauss	G
giga (prefix)	G
gram	g
gram-molecule weight	mole
gravitational constant	G
half-life, biological	T_b
half-life, effective	T_{eff}
half-life, physical	$T_{\frac{1}{2}}$
half-value layer	HVL

hecto (prefix)	h
height	h
henry	H
hertz	Hz
hour	h
hundredweight	cwt
initial intensity	I_o
insoluble	insol.
intensity of radiation	I
joule	J
kayser	K
Kelvin	K
kilo (prefix)	k
kilogram	kg
kilovolt constant potential	kVcp
kilovolt peak	kVp
kilowatt	kW
kilowatt-hour	kWh
kinetic energy	K.E.
length	l
limit	lim
linear	lin
linear acceleration	a
linear distance	d,s
linear energy transfer	LET
liquid	liq
liter	l
logarithm	log
logarithm, common	$\log_{10}$
logarithm, natural (hyperbolic or Napierian logarithm)	ln,$\log_e$
logarithm to the base e	$\log_e$
logarithm to the base 10	$\log_{10}$
mass	m
mass of the hydrogen atom	m_H
mass of the neutron	m_n
mass of the proton	m_p
mass unit	mu
maximum	max
maxwell	Mx
maximum permissible concentration	MPC
maximum permissible dose	MPD
maximum permissible radionuclide body burden	q
mean free path	$\bar{l},\bar{\lambda}$
median lethal dose	LD_{50}
medium	med.
mega (prefix)	M
megaelectron volts	MeV
melting point	m.p.
meter	m
meter-kilograms-second-ampere system	MKSA
micro (prefix)	μ
microbar	μbar
microcurie	μCi
micromicro	p
micromicro (use p)	μμ
micromicron (use p)	μμ
micron (old)	μ
microseconds	μs
milli (prefix)	m
millibarns	mb
milligram	mg
milliliter	ml
millimeter	mm
millimicro	n
millimicron	mμ
minute	m,min
mole	mol
molecular weight	mol.wt.

molecule ---------- mol.

momentum ---------- p

nano (prefix) ---------- n

negatron ---------- $e, e^-, {}^{0}_{-1}e$

neutrino ---------- $\tilde{\nu}$

neutron ---------- ${}^{1}_{0}n$, N

neutron number ---------- N

newton ---------- N

number ---------- N, N_A, no.

number of radioactive atoms at zero time ---------- N_o

number, original ---------- N_o

numeric ---------- N

observed standard deviation ---- S

oersted ---------- Oe

ohm ---------- Ω

original activity ---------- A_o

ounce ---------- oz

pair production coefficient ---- κ

pico (prefix) ---------- p

pint ---------- pt.

photoelectric coefficient ------ τ

photon energy ---------- $h\nu$

Plank constant ---------- h

poise ---------- P

positron ---------- $e^+, {}^{0}_{+1}e, \beta^+, {}^{0}_{+1}\beta$

potential ---------- V

potential drop ---------- V

potential energy ---------- P.E.

pound ---------- lb.

power factor ---------- p.f.

precipitated ---------- precip., pptd

pressure ---------- p

Protective Action Guide -------- PAG

proton ---------- p

quality factor ---------- QF

quantity ---------- Q

quantum ---------- $h\nu$

radian, measure of angle; radioactivity ---------- A

Radiation Protection Guide ----- RPG

Radioactivity Concentration Guide ---------- RCG

radio frequency ---------- rf

radius ---------- r

radius, nuclear ---------- R

range (radiation) ---------- R

reaction energy in MeV --------- Q

relative biological effectiveness ---------- RBE

resistance ---------- R

resolving time ---------- τ

rest mass of electron ---------- m_e

revolutions per minute --------- rpm

roentgen ---------- R

roentgen (old) ---------- r

rutherford (obsolete)---------- Rd

scattering cross section in barns ---------- σ_s

second ---------- s

soluble ---------- s,sol.

source to film distance -------- SFD

source to skin distance -------- SSD

square centimeter ---------- cm^2

square meter ---------- m^2

square millimeter ---------- mm^2

standard temperature and pressure ---------- s.t.p.

Stefan-Boltzman constant ------- k

temperature, absolute ---------- T

temperature, general ---------- t

tera (prefix) ---------- T

tesla ---------- T

theoretical standard deviation ---------- σ

time ---------- t

time increment ---------- ϕ

total cross section in barns --- σ_t

universal gas constant ---------- R

velocity of light in vacuum ---- c

velocity, linear or particle --- v

watt ---------- W

wavelength ---------- λ

weber ---------- Wb

weight ---------- wt.

work ---------- W

work function ---------- ϕ

year (anno, annum) ---------- a,yr

Prefixes

deci	$(= 10^{-1})$	d	deka	(= 10)	da
centi	$(= 10^{-2})$	c	hecto	$(= 10^{2})$	h
milli	$(= 10^{-3})$	m	kilo	$(= 10^{3})$	k
micro	$(= 10^{-6})$	μ	mega	$(= 10^{6})$	M
nano	$(= 10^{-9})$	n	giga	$(= 10^{9})$	G
pico	$(= 10^{-12})$	p	tera	$(= 10^{12})$	T
femto	$(= 10^{-15})$	f			
atto	$(= 10^{-18})$	a			

SIGNS AND SYMBOLS
ALPHABETICALLY BY SYMBOL

a _____ acceleration, linear; anno (year); atto (prefix)

A _____ ampere; area; atomic mass number; radioactivity

Å _____ angstrom

abs _____ absolute

a.c. _____ alternating current

alk _____ alkali

amp. _____ ampere (use A)

amu _____ atomic mass unit--^{16}O (old) [use u]

A_o _____ activity, original

aq. _____ aqua; aqueous, water

asym. _____ asymmetrical

at.no. _____ atomic number

at.wt. _____ atomic weight

at, atmos _____ atmosphere (atmospheric)

av, avg. _____ average

b _____ barn; buildup factor

bar. _____ barometer

BeV _____ billion electron volt

Bi _____ biot

b.p. _____ boiling point

Btu _____ British thermal unit

c _____ velocity of light in vacuum; centi (prefix); curie (old) [use Ci)

C _____ capacitance; Celsius; centigrade; concentration; coulomb

ca _____ about; approximately; circa

cal _____ calorie

cc _____ cubic centimeter

cd _____ candela

cfm _____ cubic foot per minute

CGS _____ centimeter-gram-second system

chem. _____ chemical; chemistry

cir. _____ circular

c.m. _____ circular mill

cm _____ centimeter

cm^2 _____ square centimeter

cm^3 _____ cubic centimeter

coef. _____ coefficient

colog _____ cologarithm

conc _____ concentrated

const. _____ constant

cos _____ cosine

cpm _____ counts per minute

cu. _____ cubic

cu.cm. _____ cubic centimeter

cu.ft. _____ cubic foot

cu.in. _____ cubic inch

cu.m. _____ cubic meter

cu.yd. _____ cubic yard

cwt _____ hundredweight

cyl. _____ cylinder

d _____ day; deci (prefix); density, general; deuteron; distance, linear

D _____ density, film; deuterium; dose; absorbed dose

da _____ deka (prefix)

dB _____ decibel

DE _____ dose equivalent

DF _____ decontamination factor; distribution factor

dil _____ dilute

dpm _____ disintegration per minute

dyn _____ dyne

e _____ base of natural logarithm

E---------- energy

$\mathcal{E}$---------- electric field intensity

e, e^--------- electron; negatron

$^{0}_{-1}e$--------- electron; beta particle;

$e^+, ^{0}_{+1}e$------ positron

f---------- femto (prefix); frequency

F---------- farad; fahrenheit; force

Fr---------- franklin

G---------- gravitational constant; gauss; giga (prefix)

GeV--------- giga electron volts

G.I.-------- gastrointestinal

h---------- Plank constant; hecto (prefix).; height; hour

H---------- henry

$h\nu$---------- photon energy; quantum

HVL--------- half value layer

Hz---------- hertz

I---------- intensity of radiation

I_o---------- initial intensity

insol.------ insoluble

J---------- joule

k---------- Stefan-Boltzman constant; kilo (prefix)

K---------- kayser; Kelvin; absolute temperature

K.E.-------- kinetic energy

kg---------- kilogram

kVp--------- kilovolt peak

kVcp-------- kilovolt constant potential

kW---------- kilowatt

kWh--------- kilowatt-hour

l---------- length; liter

$\bar{l}$---------- mean free path

lb.--------- pound

LD_{50}-------- median lethal dose

LET--------- linear energy transfer

lim--------- limit

lin--------- linear

liq--------- liquid

ln---------- natural logarithm

log--------- logarithm

$\log_e$-------- logarithm to the base e; natural, hyperbolic or Napierian logarithm

$\log_{10}$------- common logarithm; logarithm to the base 10

m---------- mass; meter; milli (prefix); minute

m_e---------- rest mass of electron

m_H---------- mass of the hydrogen atom

m_n---------- mass of the neutron

m_p---------- mass of the proton

m^2---------- square meter

m^3---------- cubic meter

M---------- mega (prefix)

max--------- maximum

mb---------- millibarns

med.-------- medium

MeV--------- megaelectron volts

mg---------- milligram

min--------- minute

MKSA-------- meter-kilogram-second-ampere system

ml---------- milliliter

mm---------- millimeter

mm^2--------- square millimeter

mm^3--------- cubic millimeter

mol--------- mole; molecule

mol.wt.----- molecular weight

mole-------- gram-molecule weight

m.p.-------- melting point

MPC--------- maximum permissible concentration

MPD--------- maximum permissible dose

mu---------- mass unit

Mx---------- maxwell

mμ---------- millimicron (use nano)

n---------- nano (prefix)

$^{0}_{1}n$---------- neutron

N---------- neutron; neutron number; newton; number; numeric

N_A ---------- Avogadro constant; number

no.---------- number

N_O---------- number of radioactive atoms at zero time; number, original

Oe---------- oersted

oz---------- ounce

p---------- momentum; pico (prefix); pressure

P---------- poise

PAG---------- Protective Action Guide

P.E.-------- potential energy

p.f.-------- power factor

precip., pptd-------- precipitated

pt.--------- point; pint

q---------- maximum permissible radionuclide body burden μCi

Q---------- electric charge; energy; quantity; reaction energy in MeV

QF---------- quality factor

r---------- radius; radial distance; roentgen (old)

R---------- range (radiation); rate, count; resistance; roentgen; universal gas constant; radius, nuclear

rad--------- radian, measure of angle

RBE--------- relative biological effectiveness

RCG--------- Radioactivity Concentration Guide

Rd---------- rutherford (obsolete)

rf---------- radio frequency

RPG--------- Radiation Protection Guide

rpm--------- revolutions per minute

s---------- distance, linear; second; soluble

S---------- observed standard deviation

SFD--------- source-to-film distance

sol.-------- soluble

SSD--------- source-to-skin distance

s.t.p.------ standard temperature and pressure

t---------- temperature, general; time; ton

T---------- temperature, absolute; tera (prefix); tesla

T_b---------- half-life, biological

T_{eff}--------- half-life, effective

$T_{\frac{1}{2}}$---------- half-life, physical

u---------- atomic mass unit--^{12}C

V---------- potential; potential drop; volt; volume

v---------- velocity, linear or particle

W---------- watt; work

Wb---------- weber

wt.--------- weight

x---------- absorber thickness

Z---------- atomic number

α---------- alpha; alpha particle

$\beta, \beta^{-}, {}^{0}_{-1}\beta$---- beta; beta particle

$\beta^{+}, {}^{0}_{+1}\beta$------ positron

γ---------- gamma; gamma ray

Δ---------- finite increment

ϵ---------- electron capture; dielectric constant

θ---------- angle between incident and scattered radiation

κ---------- pair production coefficient

λ---------- decay constant; wave length

$\bar{\lambda}$---------- mean free path

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λ_b ---------- biological decay constant

μ ---------- absorption coefficient, effective or apparent, linear; micro; micron (prefix)

μ_a ---------- $\tau + \kappa + \sigma_a$ = energy absorption coefficient for air

μbar ---------- microbar

μCi ---------- microcurie

$\mu\mu$ ---------- micromicro; micromicron (use pico)

μs ---------- microseconds

ν ---------- frequency (wave motion quantum theory); neutrino

ρ density, general or vapor

σ ---------- area; barn (cross section) theoretical standard deviation; Compton collision coefficient

σ_a ---------- absorption cross section in barns; Compton absorption coefficient

σ_{ac} ---------- activation cross section in barns

σ_{eff} ---------- effective cross section in barns

σ_s ---------- Compton scatter coefficient; scattering cross section in barns

σ_t ---------- total cross section in barns

τ ---------- resolving time; photoelectric coefficient

ϕ ---------- work function; time increment

Ω ---------- ohm

χ ---------- concentration, air

Prefixes

d	deci	$(= 10^{-1})$	da	deka	$(= 10)$
c	centi	$(= 10^{-2})$	h	hecto	$(= 10^{2})$
m	milli	$(= 10^{-3})$	k	kilo	$(= 10^{3})$
μ	micro	$(= 10^{-6})$	M	mega	$(= 10^{6})$
n	nano	$(= 10^{-9})$	G	giga	$(= 10^{9})$
p	pico	$(= 10^{-12})$	T	tera	$(= 10^{12})$
f	femto	$(= 10^{-15})$			
a	atto	$(= 10^{-18})$			

CONSTANTS

Quantity		Value (±)	MKSA	CGS
speed of light	c =	2.997 925 3	10^{8} m s^{-1}	10^{10} cm s^{-1}
Boltzmann constant	k =	1.380 54 18	10^{-23} J $^{\circ}K^{-1}$	10^{-16} erg $^{\circ}K^{-1}$
mass hydrogen atom	m_H =	1.673 43 8	10^{-27} kg	10^{-24} g
proton mass	m_p =	1.672 52 8	10^{-27} kg	10^{-24} g
		1.007 276 62 8	u	u
neutron	m_n =	1.674 82 8	10^{-27} kg	10^{-24} g
		1.008 665 20 10	u	u
electron mass	m_e =	9.109 1 4	10^{-31} kg	10^{-28} g
		5.485 97 3	10^{-4} u	10^{-4} u
	m_p/m_e =	1.836 10 3	10^{3}	10^{3}
charge of positron	e =	1.602 10 7	10^{-19} C	
	e =	4.802 98 20		10^{-10} esu
	e/c =	1.602 10 7		10^{-20} emu
charge to mass ratio	e/m =	1.758 796 19	10^{11} C kg^{-1}	
	e/m =	5.272 74 6		10^{17} esu g^{-1}
	e/mc =	1.758 796 19		10^{7} emu g^{-1}
electron radius	r_e =	2.817 77 11	10^{-15} m	10^{-13} cm
Thomson cross section	$(8\pi/3)r_e^2$ =	6.651 6 5	10^{-29} m^2	10^{-25} cm^2
Zeeman splitting constant	$e/4\pi mc$ =	4.668 58 4	10^{1} $m^{-1}T^{-1}$	
	$e/4\pi mc^2$ =	4.668 58 4		10^{-5} $cm^{-1}G^{-1}$

Quantity		Value (±)	MKSA	CGS
Planck constant	h =	6.625 6 5	10^{-34} J s	10^{-27} erg s
	$h/2\pi = \hbar$ =	1.054 50 7	10^{-34} J s	10^{-27} erg s
	h/e =	4.135 56 12	10^{-15} J s C^{-1}	
	h/e =	1.397 47 4		10^{-17} erg s esu^{-1}
	hc/e =	4.135 56 12		10^{-7} erg s emu^{-1}
	h/k =	4.799 3 6	10^{-11} s °K	10^{-11} s °K
1st radiation constant	$c_1 = 2\pi hc^2$ =	3.741 5 3	10^{-16} W m^2	10^{-5} erg $cm^2 s^{-1}$
2nd radiation constant	$c_2 = hc/k$ =	1.438 79 19	10^{-2} m °K	cm °K
Wien's radiation law	$\lambda_{max} T = c_2/4.965\ 114\ 23$ =	2.897 8 4	10^{-3} m °K	10^{-1} cm °K
Stefan-Boltzmann constant	σ =	5.669 7 2 9	10^{-8} W m^{-2} $°K^{-4}$	10^{-5} erg $cm^{-2} s^{-1}$ $°K^{-4}$
fine structure constant	α =	7.297 20 10	10^{-3}	10^{-3}
	α^{-1} =	1.370 388 19	10^{2}	10^{2}
	α^2 =	5.324 92 14	10^{-5}	10^{-5}
Bohr radius	a_0 =	5.291 67 7	10^{-11} m	10^{-9} cm
Rydberg constant	R_∞ =	1.097 373 1 3	10^{7} m^{-1}	10^{5} cm^{-1}
	R_H =	1.096 775 8 3	10^{7} m^{-1}	10^{5} cm^{-1}
	$R_\infty c$ =	3.289 842 4	10^{15} s^{-1}	10^{15} s^{-1}
	$R_\infty hc$ =	2.179 72 17	10^{-18} J	10^{-11} erg