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ANNOTATED AND INDEXED BIBLIOGRAPHY OF EXPERIMENTAL PHOTON-ATTENUATION COEFFICIENTS FOR COMPOUNDS

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ABSTRACT

This report presents a bibliography of 106 papers reporting absolute measurements of photon (XUV, x-ray, gamma-ray, bremsstrahlung) total interaction cross sections or attenuation coefficients for molecular or ionic chemical compounds. The energy range covered extends from 10 eV to above 10 GeV. The time period covered extends from 1921 to 1989. Included with each reference are annotations specifying the substances studied and the energy range covered. An index, alphabetized by chemical symbols, is provided. The validity of applying the "mixture rule" for use of theoretical neutral-atom data for deriving data for chemical compounds is discussed.

KEY WORDS: attenuation coefficient, bibliography, compounds, cross section, gamma rays, mixture rule, photons, x rays.

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TABLE OF CONTENTS

I. Introduction; Definitions

Values of the photon (extreme ultraviolet (XUV), x-ray, gamma-ray, bremsstrahlung) mass attenuation coefficient are required in a variety of medical, industrial, defense and scientific applications, as discussed, for example in reference [1]. The symbolic notation for the photon mass attenuation coefficient is μ/ρ, in units of $m^2\ kg^{-1}$, or more customarily in $cm^2\ g^{-1}$, where μ is the linear attenuation coefficient in m^{-1} or more customarily in cm^{-1}, and ρ is the substance density in $kg\ m^{-3}$ or more customarily in $g\ cm^{-3}$.

For any homogeneous material the photon mass attenuation coefficient is defined (see, e.g., reference [2]) for monoenergetic photons in terms of the attenuation I/I_0 of a narrowly-collimated photon beam incident normally on a plane-parallel slab of the material of thickness t where I_0 is the incident intensity and I is the transmitted intensity, according to

$$I/I_0 = \exp\ (-(\mu/\rho)t) \qquad (1)$$

in which t is in units reciprocal to μ/ρ, e.g., $kg\ m^{-2}$ or $g\ cm^{-2}$. Hence, from the above type of measurement μ/ρ can be obtained as

$$\mu/\rho = (-\ell n(I/I_0))/t \quad . \qquad (2)$$

The available theoretical information on μ/ρ, derived from probabilities for the principal interaction processes of photons with atoms: atomic photoeffect, Compton and Rayleigh scattering, pair and triplet production, is for isolated atoms. Hence standard compilations of μ/ρ developed at NIST [2-14] and elsewhere, e.g., [15-20] are for isolated atoms, or for compounds ignoring the effects, if any, of chemical binding on the probabilities for the above photon-atom interaction processes.

II. Compilation of the Bibliography

An invaluable aid in preparing this report was the extensive collection of μ/ρ research results, both published and unpublished, made available to the author of this report. This unique internationally recognized resource reference collection has been accumulated at NBS/NIST from the early 1950's to the present (1990) as a result of systematic search and surveillance of the published and unpublished literature, and by promotion of new μ/ρ measurements where gaps in the reliable information become evident from the vantage point of such a systematic data collection project over the extensive photon energy range 10 eV to 100 GeV and for all elements, compounds, and other substances of technological or medical interest. Unsolicited research results also continue to be received by NIST from all parts of the globe in recognition of the NBS/NIST historically dominant national [21-23] and international [24] role in critical evaluation, compilation and dissemination of μ/ρ data required in such diverse technological applications as design optimization and safety assessment in air cargo x-ray surveillance systems [25].

The literature reporting available absolute measured μ/ρ data for the time period 1909 to 1971 for elements (some data were deduced from measurements or compounds) was reviewed by and indexed by Hubbell in 1971 [26]. This material was updated and extended to include compounds and other substances by Hubbell et al. in 1986 [27]. The present bibliography and index focuses only on those references which report absolute μ/ρ measurement for compounds, and draws heavily on reference [27] as a resource, extending the time coverage of that report up to 1989.

In the annotations and indexing in reference [27], which focused primarily on elemental data, compounds were identified either by name or by chemical-symbol formula, in most cases not by both. In the present bibliography the chemical-symbol formulas are used consistently throughout the annotations and the index, so that all the available references for a given compound will be found in the same place in the index, instead of in two places as in reference [27].

III. Description of the Bibliography

The annotated bibliography in Section VI uses the same six-character reference symbols as were used in references [26] and [27]. The first two characters are the last two digits of the year of publication (or report). The next two characters are the first two letters of the first author's last name. The final two digits (usually 01) are added to insure uniqueness. The references are arranged in increasing order of year of publication and within each year alphabetically by first author. For each item the reference symbol is at the left margin. Next comes a complete listing of all authors, the journal title, volume number, pagination and year (or alternate referencing if not a journal article). The title of the article is given on the lines following. On the last line, enclosed in parenthesis, is the photon energy range studied, then a listing of (a) the elements measured in order of increasing atomic number, (b) chemical-symbol formulas for the compounds measured, which are the focus of the present report, and (c) additional substances measured but not characterizable by a chemical formula.

Section VII is a substance index to the above annotated bibliography, alphabetized by chemical symbol. In the right hand column the number of references containing information on a given compound is indicated.

IV. Discussion, Including Mixture Rule

Theoretical predictions of μ/ρ, and the primary experimental databases of μ/ρ, are almost universally for isolated neutral atoms, whereas real substances, except for the noble gases He, Ne, Ar, Kr, Xe, and Rn are almost never encountered in this state. To obtain μ/ρ values for compounds, the "mixture rule" is generally applied, summing over the contributions of μ/ρ from each constituent element multiplied by its fraction by weight in the compound.

A definitive discussion of the mixture rule has been given by Deslattes in 1969 [28], particularly for the photon energy regions just above the atomic photoeffect absorption edges. In these atomic electron subshell threshold regions, the ejected photoelectrons are of low energy. Hence the atomic photoeffect process here is sensitive to chemical and solid state effects on the valence electrons, and to a lesser extent to such effects on inner-shell electrons.

These chemical and solid-state effects are manifested strikingly in the extended x-ray absorption fine structure (EXAFS), to the extent that these oscillatory variations in μ/ρ, with spectral peaks and valleys of the order of 10 eV in width, are now used extensively as an analytical technique. The history of EXAFS from its origins up through 1975, with some references up through 1988, is the subject of a recent (1989) excellent review by von Bordwehr [29]. An additional review of EXAFS as a modern structural tool in materials science has been given by Wong [30].

In addition to chemically-dependent fine structure just above μ/ρ absorption edges, with oscillations typically as much as 10 to 15% of μ/ρ from peak to valley, smooth monotonic curves drawn through this fine structure (such as would be seen by a detector with wide-band energy discrimination) depart systematically from theory [31] by as much as 10%, usually exceeding theory, but sometimes the reverse. The latter systematic effects have been observed and discussed by Del Grande et al. [32,33].

Both the EXAFS features and the systematic (Del Grande effect) discrepancies are generally confined to the photon energy regions within 1 keV above absorption edges. Outside these edge regions the chemical effects are expected to be negligible (less than 2%), allowing general use of the mixture rule. However, further experimental and theoretical studies, questioning the validity of the mixture rule outside the EXAFS regions, including the pair and triplet production region above 1 MeV where theoretical cross section calculations also utilize atomic structure data, would be useful.

Also, to maintain the NIST unique μ/ρ national and international resource data base as up-to-date and comprehensive as possible, the author, in behalf of NIST, would appreciate receiving any corrections, additions, and comments on this work. In particular, any new papers containing photon absorption cross section data, for elements, compounds, and other substances, will be welcomed.

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VII. Substance Index to Bibliography, Alphabetized by Chemical Symbol

CCl_4 3 REFERENCES

30Wo01 32Cr01 67He01

$CdCl_2$ 1 REFERENCE

84Ra01

CdI_2 1 REFERENCE

81Um01

CdSb 1 REFERENCE

58Bo01

CeO_2 3 REFERENCES

39Wr01 82Um01 84Um01

Ce_2O_3 1 REFERENCE

70Ha02

CF_2 2 REFERENCES

64Te01 70Ma01

CF_2Cl_2 1 REFERENCE

79Wu01

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77Le01

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74Mi01 77Le01

C_2F_2 1 REFERENCE

67He01

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77Le01

CH 1 REFERENCE

69De02

$CHCl_2$ 1 REFERENCE

32Cr01

CHF_3 1 REFERENCE

33St01

CHI_3 1 REFERENCE

39Wr01

CH_2 2 REFERENCES

32Cr01 62Fi01

$(CH_2)n$ 5 REFERENCES

34Gr01 34Ha01 69We01 70Ma01 71Go01

CH_2Cl_2 1 REFERENCE

39HaO2

$CH_2(OCH_3)_2$ 2 REFERENCES

64LuO1 66LuO1

CH_3Cl 1 REFERENCE

79WuO1

$(CH_3CoO)_2*CO_4*H_2O$ 1 REFERENCE

84RaO1

CH_3F 1 REFERENCE

79WuO1

CH_3I 3 REFERENCES

22BuO1 32CrO1 39HaO2

CH_3OH 1 REFERENCE

75DaO1

CH_4 11 REFERENCES

33MeO1 64LuO1 64RuO1 70DeO1 70DeO3 71BeO1
72StO1 73LeO1 75DaO1 75LoO1 77LeO1

CH_4O 1 REFERENCE

70HaO2

C_2H_2 2 REFERENCES

33MeO1 85WuO1

C_2H_4 7 REFERENCES

32CrO1 33MeO1 61WiO1 73LeO1 74MiO1 78PeO1
86BrO1

C_2H_5Br 3 REFERENCES

32CrO1 32StO1 39HaO2

C_2H_5Cl 1 REFERENCE

32CrO1

$(C_2H_5)_2*O$ 1 REFERENCE

32CrO1

C_2H_5OH 2 REFERENCES

66LuO1 75DaO1

$(C_2H_5)_3*PO_4$ 1 REFERENCE

74MiO1

C_2H_6 5 REFERENCES

28KuO1 33MeO1 67HeO1 73LeO1 81DaO1

C_2H_6O 3 REFERENCES

35Ma01 66Lu01 71Be01

C_3H_6 1 REFERENCE

70De02

C_3H_6O 2 REFERENCES

22Ta01 59Ma01

$C_3H_6O_2$ 1 REFERENCE

22Ta01

C_3H_7O 1 REFERENCE

71Be01

C_3H_7OH 1 REFERENCE

75Da01

C_3H_8 1 REFERENCE

33Me01

C_3H_8O 3 REFERENCES

22Ta01 64Lu01 66Lu01

$C_3H_8O_2$ 1 REFERENCE

22Ta01

C_4H_8O 1 REFERENCE

22Ta01

C_4H_{10} 1 REFERENCE

73Le01

$C_4H_{10}O$ 1 REFERENCE

71Be01

$C_5H_8O_2$ 4 REFERENCES

58Sa01 65Th01 70Ma01 78Pe01

C_5H_{12} 2 REFERENCES

30Wo01 32Cr01

C_6H_2 1 REFERENCE

71Go01

$C_6H_3(CH_3)_3$ 1 REFERENCE

23Ol01

$C_6H_4(CH_3)_2$ 1 REFERENCE

23Ol01

$C_6H_5CH_3$ 1 REFERENCE

23Ol01

C_6H_6 3 REFERENCES

22Ta01 220101 71Go01

$C_6H_{12}O$ 1 REFERENCE

230101

C_6H_{14} 1 REFERENCE

32Cr01

C_7H_8 2 REFERENCE

22Ta01 71Go01

C_7H_8O 1 REFERENCE

71Go01

C_7H_{16} 1 REFERENCE

230101

$(C_8H_8)_n$ 4 REFERENCES

58Ba01 65Th01 67Er01 67Er02

C_8H_{10} 1 REFERENCE

71Go01

$C_{10}H_{14}$ 1 REFERENCE

71Go01

$C_{10}H_{16}$ 1 REFERENCE

22Ta01

$C_{10}H_{18}$ 1 REFERENCE

71Go01

CO 7 REFERENCES

28Ku01 33Me01 71Be01 71De03 73Le01 75Da01
79Ba01

CO_2 11 REFERENCES

22Bu01 28Ku01 31De01 32Cr01 33Me01 62Bu01
71Be01 71De03 72St01 74Mi01 79Ba01

$[(CO_2)_2*Fe+2H_2O]$ 1 REFERENCE

39Wr01

$CoCO_3$ 1 REFERENCE

39Wr01

$CoSO_4*7H_2O$ 1 REFERENCE

84Ra01

CrO_3 1 REFERENCE

81Um01

Cr_2O_3 1 REFERENCE
39Wr01

CsCl 1 REFERENCE
70Br01

CsF 1 REFERENCE
71Ot01

CsI 2 REFERENCES
69Fu01 70Br01

CS_2 1 REFERENCE
39Ha02

CuCl 1 REFERENCE
81Um01

CuO 1 REFERENCE
81Um01

CuO_3 1 REFERENCE
81Um01

$CuSO_4*5H_2O$ 1 REFERENCE
84Ra01

D 3 REFERENCES
64Co04 69No01 72Ra01

D_2O 4 REFERENCES
35Ma01 47Ma01 73Ka01 77Ph01

Dy_2O_3 2 REFERENCES
82Um01 84Um01

Er_2O_3 2 REFERENCES
82Um01 84Um01

$FeSO_4*7H_2O$ 1 REFERENCE
84Ra01

GaAs 2 REFERENCES
70Ca01 84Ra01

GaP 1 REFERENCE
70Ca01

GaSb 1 REFERENCE
70Ca01

Gd_2O_3 2 REFERENCES
82Um01 84Um01

$GeBr_4$ 1 REFERENCE

51Gl01

GeCl 1 REFERENCE

51Gl01

GeH_4 1 REFERENCE

51Gl01

Ge_2H_6 1 REFERENCE

51Gl01

HCl 2 REFERENCES

72Ha01 74Mi01

$(HCoO)_2$*Pb 3 REFERENCES

63Ch01 82Um01 84Um01

HF 2 REFERENCES

69Be01 69Be02

HgI_2 1 REFERENCE

84Ra01

H_2O(Water) 36 REFERENCES

21He01	22Ta01	23Ol01	32Ch01	35Ge02	35Ma01
47Ma01	52Wy01	53Gh01	54Pa01	57Ma01	58Wo01
60Wy01	62Ba02	63Sc01	64Te01	65Th01	67Ka01
69Be01	69Be02	69We01	70De03	71Be01	73Ka01
74Jo01	74Su01	75Ah01	75Ph01	75Ra01	77Ph01
78Pe01	83Sh02	84Ra01	85Bi01	86Br01	86Ha01

H_2S 7 REFERENCES

32Cr01	67He01	69La01	72Ha01	72St01	74Mi01
75Da01					

Ho_2O_3 2 REFERENCES

82Um01 84Um01

InAs 1 REFERENCE

70Ca01

InP 1 REFERENCE

70Ca01

InSb 2 REFERENCES

70Ca01 84Ra01

KBr 2 REFERENCES

70Br01 81Um01

$KBrO_3$ 1 REFERENCE

84Ra01

KCl 1 REFERENCE
81Um01

KH_2PO_4 2 REFERENCES
81Um01 84Ra01

KI 4 REFERENCES
69Fu01 70Br01 81Um01 84Um01

KNO_3 1 REFERENCE
84Ra01

$K_2Cr_2O_7$ 1 REFERENCE
84Ra01

K_2TeO_3 1 REFERENCE
39Wr01

La_2O_3 2 REFERENCES
82Um01 84Um01

LiD 1 REFERENCE
65Pr01

LiF 3 REFERENCES
39Wr01 76Cr01 76La01

LiF:Mg,Ti(TLD 600) 1 REFERENCE
82Ba01

LiF:Mg,Ti(TLD 700) 1 REFERENCE
82Ba01

LiF-7(Teledyne) 1 REFERENCE
82Ba01

LiH 2 REFERENCES
65Pr01 69De02

LiOH 1 REFERENCE
81Um01

$Li_2B_4O_7$:Mn(TLD 800) 1 REFERENCE
82Ba01

MgO 1 REFERENCE
81Um01

MnO_2 2 REFERENCES
39Wr01 81Um01

$MnSO_4*H_2O$ 1 REFERENCE
84Ra01

NaCl 4 REFERENCES
59BaO1 76CrO1 81UmO1 84RaO1

NaF 2 REFERENCES
76CrO1 81UmO1

$NaHCO_3$ 1 REFERENCE
81UmO1

NaI 5 REFERENCES
54HoO1 54PaO1 63ScO1 69FuO1 76MaO1

$NaNO_2$ 1 REFERENCE
81UmO1

$NaNO_3$ 2 REFERENCES
81UmO1 84RaO1

$NaWO_4*2H_2O$ 1 REFERENCE
84RaO1

$Na_2B_4O_7*10H_2O$ 1 REFERENCE
84RaO1

Na_2CO_3 1 REFERENCE
81UmO1

Na_2SO_4 1 REFERENCE
81UmO1

Nd_2O_3 2 REFERENCES
82UmO1 84UmO1

NH_3 4 REFERENCES
70De03 72StO1 75DaO1 87SaO1

NH_4Br 1 REFERENCE
39WrO1

NH_4Cl 1 REFERENCE
39WrO1

NH_4NO_3 1 REFERENCE
84RaO1

NH_4VO_3 1 REFERENCE
39WrO1

N_2H_4 2 REFERENCES
69BeO1 69BeO2

NiO 1 REFERENCE
81UmO1

NO 7 REFERENCES

72St01 71Be01 71De03 72St01 73Le01 75Da01 85Sa02

N_2O 7 REFERENCES

72St01 71Be01 71De03 72St01 73Le01 75Da01 79Ba01

PbTe 2 REFERENCES

58Bo01 66Lu02

PH_3 1 REFERENCE

72Ha01

PrO_2 1 REFERENCE

82Um01

RbCl 2 REFERENCES

70Br01 81Um01

Sb_2O_3 1 REFERENCE

39Wr01

SeH_2 1 REFERENCE

73Hr01

SF_6 1 REFERENCE

77Le01

SiF_4 1 REFERENCE

72Ha01

SiH_4 1 REFERENCE

72Ha01

SiO_2 4 REFERENCES

66Er01 67Er01 67Er02 74Mi01

Sm_2O_3 2 REFERENCES

82Um01 84Um01

SnTe 1 REFERENCE

66Lu02

SO_2 4 REFERENCES

22Bu01 30Co01 30Wo01 32St01

SrF_2 1 REFERENCE

81Um01

$Sr(NO_3)_2$ 1 REFERENCE

84Ra01

SrO — 1 REFERENCE
39WrO1

Ta_2O_5 — 2 REFERENCES
82UmO1 84UmO1

ThO_2 — 1 REFERENCE
84RaO1

TiO_2 — 2 REFERENCES
81UmO1 84RaO1

UCl_4 — 1 REFERENCE
89GuO1

UO_2 — 2 REFERENCES
70MaO1 89GuO1

$UO_2(CoO)_2*3H_2O$ — 1 REFERENCE
84RaO1

VB_2 — 1 REFERENCE
70FiO1

VC — 1 REFERENCE
70FiO1

VN — 1 REFERENCE
70FiO1

V_2O_3 — 1 REFERENCE
70FiO1

V_2O_4 — 1 REFERENCE
70FiO1

V_2O_5 — 1 REFERENCE
70FiO1

ZnO — 1 REFERENCE
84RaO1

ZnTe — 1 REFERENCE
84RaO1

$Zr(CH_3)_2$ — 1 REFERENCE
32CrO1

ZrO_2 — 2 REFERENCES
39WrO1 81UmO1

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11. ABSTRACT (A 200-WORD OR LESS FACTUAL SUMMARY OF MOST SIGNIFICANT INFORMATION. IF DOCUMENT INCLUDES A SIGNIFICANT BIBLIOGRAPHY OR LITERATURE SURVEY, MENTION IT HERE.)

This report presents a bibliography of 106 papers reporting absolute measurements of photon (XUV, x-ray, gamma-ray, bremsstrahlung) total interaction cross sections or attenuation coefficients for molecular or ionic chemical compounds. The energy range covered extends from 10 eV to above 10 GeV. The time period covered extends from 1921 to 1989. Included with each reference are annotations specifying the substances studied and the energy range covered. An index, alphabetized by chemical symbols, is provided. The validity of applying the "mixture rule" for use of theoretical neutral-atom data for deriving data for chemical compounds is discussed.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

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