Table of Isotopes

SEVENTH EDITION

Edited by

C. Michael Lederer

and Virginia S. Shirley

Principal Authors

Edgardo Browne

Janis M. Dairiki

Raymond E. Doebler

Authors

Adnan A. Shihab-Eldin

Leslie J. Jardine

Jagdish K. Tuli

Audrey B. Buyrn

Table of Isotopes

SEVENTH EDITION

Edited by
C. Michael Lederer
and Virginia S. Shirley

Principal Authors
Edgardo Browne
Janis M. Dairiki
Raymond E. Doebler

Authors
Adnan A. Shihab-Eldin
Leslie J. Jardine
Jagdish K. Tuli
Audrey B. Buyrn

Lawrence Berkeley Laboratory
University of California, Berkeley

A Wiley-Interscience Publication
JOHN WILEY & SONS, INC., New York · Chichester · Brisbane · Toronto

1-5 • 101-105 • 201-205

6-10 • 106-110 • 206-210

11-15 • 111-115 • 211-215

16-20 • 116-120 • 216-220

21-25 • 121-125 • 221-225

26-30 • 126-130 • 226-230

31-35 • 131-135 • 231-235

36-40 • 136-140 • 236-240

41-45 • 141-145 • 241-245

46-50 • 146-150 • 246-250

51-55 • 151-155 • 251-255

56-60 • 156-160 • 256-260

61-65 • 161-165 • 261-263

66-70 • 166-170

71-75 • 171-175

76-80 • 176-180

81-85 • 181-185

86-90 • 186-190

91-95 • 191-195

96-100 • 196-200

To
Claudette, Laura, and Mark Lederer
Dave, David, Diane, Michael, Eric, and Gail Shirley
Magdalena, Guillermo, Ernesto, and Gerardo Browne
Ned and Geoffrey Dairiki
Kathleen, Matthew, and Jennifer Doebler

who struggled with us throughout the compilation of this book, and rejoiced with us upon its completion.

Preface

Data compilers, like news reporters, succumb to an occasional impulse to identify with the events they chronicle. For our pioneers, among them the founders and early authors of the *Table of Isotopes*, the identity was no aberration; significant discoveries recorded in the early editions often bore their own names. These were Sunday compilers whose work has a special, archival significance. Among the scientific findings they tabulated are the alpha-decay fine structure that stimulated Bohr and Mottelson to develop the model of a deformed, rotating nucleus, and the discovery of a number of isotopes of immense practical value to mankind.

The present, 7th edition includes findings of comparable scientific import, if not of equal drama. The discovery and exploration of shape isomers have added a new dimension to the understanding of nuclear structure; this dimension in turn provides the framework for computational methods that predict the stability of nuclei many particles beyond those currently known. We are unable to resist the impulse to mark these events with the use of a new symbol "f" (as in ^{242f}Am) for the fission isomers. As to the predicted "island of stability" populated by the elusive superheavy elements, future compilers may hopefully share in the excitement of their discovery. Despite extensive and imaginative experimental efforts in a number of laboratories, all findings to date must be considered inconclusive, negative, or disproved.

No less significant is the exploration of the nucleus at high angular momentum, including the observation of individual states with spins up to $32\hbar$. Notwithstanding certain opinions (Rutherford commented that the atomic emission spectrum of iron resembled "a grand piano falling down the stairs"; the remarks of some contemporary physicists about complex decay schemes are unprintable), we believe that the complexity and sheer mass of the data are sometimes unavoidable if one aspires to an understanding of the underlying phenomena. This is most obviously true in the case of nuclear rotation.

The data explosion has also created the professional compilation project, if not the professional compiler. The computer assumes a new and significant role in the process; most of the 7th edition, including everything on this page, was entered, edited, stored, checked for form and consistency, formatted, and finally typeset or drawn by a computer. The result has been gratifying to the compiler, who is spared some disagreeable tasks (repetitive proofreading of the same material, for example). It should benefit the reader by reduction of the number of mistakes that inevitably occur when so many numbers are handled. We have tried to educate the computer to spot most errors of form or consistency and violations of the laws, conventions, and probabilities of physics. We have also attempted to achieve a production quality closer to that of traditional composition and illustration than to that of computer printout. However, the function of the computer has been limited to exclude the generation of any information, with the exception of computed log ft values and α decay hindrance factors. Overall, we believe that the extent to which the reader is *unaware* of the role of the computer is a good measure of our success in using it.

The tasks of data selection, adoption of best values, and the synthesis of level schemes ("data evaluation") remain as the unautomated skills of the trade. The evaluation process, though not significantly different in philosophy from that developed by G.T. Seaborg and collaborators, has grown in magnitude even more rapidly than the data themselves, necessitating an "edited" 7th edition with many authors. Each mass number is headed by the initials of the compiler(s) who did the evaluation, followed (after a semicolon) by the initials of the reviewer who checked the data and, in most cases, did some last-minute updating. Although we have attempted to maintain uniformity of scope and style, the evaluations are still very much the product of the individual authors.

The editors and authors are grateful to the many talented individuals who devoted time and effort to the production of the 7th edition. The data handling and reference management were done principally by Janice Chong and Maureen Whalley. Traudel Prussin, Silva Newton, and Monika Rinneberg did extensive editing and computer processing of level schemes, with Silva also doing the pencil originals of the mass-chain decay schemes. Ave Maria Nichol, Donna Kadel, Eileen Leon, and David N. Shirley assisted with data handling.

The design and final layout are the work of Douglas Kreitz. Melba Sharp assisted with the layout and typeset many of the appendix tables. Mirriam Schwartz drew the final mass-chain illustrations.

Gerry Litton, Ed Romascan, Ardith Kinney, and Bill Greiman assisted with computer program development. Some of their work is based on prototype systems developed by Loren Meissner and Manny Clinnick. In the early phases of computerization, additional contributions came from Leo Vardas and Art Habbeger.

Many persons not connected directly with the project assisted us in our work. The LBL Library staff gave us extensive help in locating obscure references during compilation of the 6th edition as well as the 7th edition; omission of an acknowledgment in the last edition was an unfortunate oversight. The staff of the LBL Computer Center provided excellent service continuously throughout the project. The Computer Science and Applied Mathematics Department was the source of most of the programming assistance. The LBL Technical Information Department provided extensive service in the production stage, most notably in the manufacture of the final negatives from which the book was printed. On behalf of many individuals in these groups, we thank Roy Nielsen, Dave Stevens, Carl Quong, Ted Kirksey, George Kagawa, and Ray Wakerling.

Final typography and drawing were done by photocomposition at Lawrence Livermore Laboratory (LLL). Credit is due to Bill Nay and George Michael for development and operation of the system, to Viktor Hampel for the arrangements which made it possible to use the facilities, and to Ned Dairiki for providing courier service between LLL and LBL.

Advice, helpful criticism, and encouragement were provided by Bernard Harvey, director of the LBL Nuclear Science Division, and by our program managers in the funding agencies: George Rogosa of the U.S. Department of Energy and Lewis Gevantman of the U.S. National Bureau of Standards.

A 3-month visit by George Vasiliu (the GV associated with mass numbers 27, 28, 65, 88, and 89) was initiated by S. Râpeanu of the Roumanian State Committee for Nuclear Energy, and was supported by the U.S. National Academy of Sciences. The arrangements were handled by Alan Campbell of the Academy.

Jack Hollander helped guide the evolution of the *Table of Isotopes* for almost 20 years. He took part in the studies and decisions which gave form and character to the 7th edition, until his duties as father of the LBL energy and environment program precluded continued participation in the project. The editors of the 7th edition are indebted to him for their education in data compilation.

As in previous editions of the *Table of Isotopes*, frequent references to other compilations are testimony to the importance of contributions from other evaluators. Contributions are from members of the Nuclear Data Group and NIRA fellows for mass chains A≥45, from P.M. Endt and C. Van der Leun for 21≤A≤44, and from F. Ajzenberg–Selove for A≤20. Most masses and Q–values are from the recent adjustment by A.H. Wapstra and K. Bos. Isotopic abundances and neutron cross–sections were compiled by N. Holden. For the scanning and indexing of all literature from 1970 onward, we are indebted to the Nuclear Data Group.

It is expected that the 7th edition of the *Table of Isotopes* will be the last in the series* started in 1940. On behalf of ourselves and previous authors, we thank the many readers who have offered support and encouragement for our work. The project will continue to serve the basic and applied nuclear science community by participation in the new U.S. and international program for nuclear data compilation. At the same time, the experience embodied in the *Table of Isotopes* has spawned new information projects at LBL that will address the data requirements for dealing with the all–important energy problem. We look forward with enthusiasm to the new tasks that lie ahead.

C.M. Lederer
V.S. Shirley

Berkeley, California
April, 1978

---

* Previous editions: (1) J.J. Livingood and G.T. Seaborg, *Reviews of Modern Physics* 12, 30 (1940); (2) G.T. Seaborg, *ibid.* 16, 1 (1944); (3) G.T. Seaborg and I. Perlman, *ibid.* 20, 585 (1948); (4) J.M. Hollander, I. Perlman, and G.T. Seaborg, *ibid.* 25, 469 (1953); (5) D. Strominger, J.M. Hollander, and G.T. Seaborg, *ibid.* 30, 585 (1958); (6) C.M. Lederer, J.M. Hollander, and I. Perlman, *Table of Isotopes*, John Wiley and Sons, Inc., New York (1967)

Introduction

I. Changes Introduced in the 7th Edition

The following list of changes provides a quick introduction to readers already familiar with the 6th edition. More significant changes are listed first. Numbers in square brackets refer to following sections of the introduction which discuss the new features in detail:

Data are given in a single table, consisting of an abbreviated mass-chain decay scheme for each mass, plus a tabular data entry for each isotope (and isomer). Detailed level schemes are included for each isotope (A,Z) for which there is information beyond that shown on the mass-chain decay scheme; levels populated by radioactive decay are shown in one drawing, levels observed in nuclear reactions in a separate one. The tabular sections replace both "Table I" and the tabular part of "Table II" of the 6th edition. The mass-chain decay scheme and detailed level schemes replace the single "decay scheme" of the 6th edition. An Isotope Index, ordered by atomic number, precedes the main table [II.A].

Reported uncertainties are given for all tabulated data [II.B].

Most levels observed in nuclear reactions are included in the detailed level schemes, regardless of whether it is energetically possible for the levels to be populated by a known decay parent. When it is necessary to omit levels, this is noted in a comment. As in the 6th edition, all levels established in radioactive decay studies are included [III.C].

An improved reference-code format and a "reference-code" list replace the former "author" codes and bibliography [II.D].

"Major radiations" are no longer tabulated separately from the detailed spectral listings [II.A]. Information on absolute normalization and measured data on x-rays, annihilation radiation, and Auger electrons are included in the detailed listings [II.A, III.B].

Additional, model-dependent quantum numbers $K[Nn_z\Lambda]$, $\Delta\ell$, and T are included on the detailed level schemes [III.C].

Isotope labels that head each tabular data section include the half-life only when relative positions of several isomers are unknown. The new isomer designation "f" is used for fission isomers. Mass numbers are written to the left of the element symbol [III.B].

Radiation identifier labels are given in terms of energy rather than serial order of the radiation [II.F, III.B].

Nuclear magnetic and quadrupole moments are listed in a separate table in APPENDIX VII. Methods for nuclear moments and spins are given in a new form that more accurately describes the experiments [III.B and APPENDIX VII].

A new class "R" designates nuclei observed by particle identification or observation of their level structure, but whose decay has not been characterized [III.B].

Genetic relations are listed only to show parentage of isomeric states [III.B].

Radiation spectral data from a paper that contains information on additional transitions, or additional properties of transitions, are sometimes *quoted in part* to show only those data not covered by other listings [II.F, III.B].

Half-lives of excited states are given in a modified format; a single list of "others" references is given for all levels of a nucleus [III.B].

Short half-lives are expressed in sub-second units, e.g., 3.1 μs for 3.1×10^{-6} s.

Atomic subshells in γ-ray listings are denoted by Arabic rather than Roman numerals – i.e., $L_1/L_2/L_3$ instead of $L_I/L_{II}/L_{III}$.

Polarization measurements are designated by a new set of categories that more accurately describes the quantity measured in terms of polarization type and dependence on coincidence angle [III.B].

Methods of measurement include several new methods and minor changes in the nomenclature [II.E, III.B]. The superfluous word *spect*, as in *mag spect*, *scint spect*, is omitted. Detector types are included in the methods for coincidence measurements [III.B].

Neutron cross sections other than true "thermal" (2200 m/s) values are explicitly noted as such [III.B].

Q-values for β or α decay derived from nuclear reaction Q-values and/or mass doublets are no longer designated "calc" [III.A].

"Others" references and references to angular and polarization correlations are listed in reverse chronological order [II.F].

An energy scale is shown alongside the mass-chain decay schemes and detailed level schemes, with scale changes noted [III.A, III.C].

II. General Features of the *Table of Isotopes*

II.A. *Layout:* An Isotope Index, ordered by atomic number (Z) and subordered by mass number (A), precedes the main table. It contains all stable nuclei, radioisotopes, and isomers that appear in the *Table of Isotopes*. (R-rated isotopes – those identified only in nuclear reactions – do not appear in the Isotope Index.) In addition to the isotope designation, the index includes the natural abundance, half-life, class (certainty of identification), and the number of the page on which the tabular data entry is found in the main table.

The main table is ordered by mass number and subordered by atomic number. For each mass number there is an abbreviated mass-chain decay scheme, showing the adopted half-lives, spin-parity assignments, and decay energies (Q-values) for the isobars, and the decay relationships between them. Noted near this scheme are the initials of the compiler(s) and, following a semicolon, those of the reviewer.

Following the mass-chain decay scheme, tabulated data and detailed nuclear level schemes are given for individual isotopes. Tabulated data entries are included for each ground state or isomer with half-life ≳1 s. A few shorter-lived isomeric species are also included – e.g., fission isomers and a few "historic" isomers, such as ^{24m}Na. The data include natural abundance, mass excess, nuclear spin, thermal neutron cross sections, all categories of data on radioactive decay, and excited-state half-lives. Data categories are shown to the left in **bold serif** type. The data are printed in sans-serif (plain) type. Each entry under a given data category concludes with the reference code or codes in braces {}. Longer data entries (radiation data in particular) begin on a new line, indented to the left of any continuation lines.

Detailed level schemes are given for each isotope (A,Z) for which there is information beyond that shown on the mass-chain decay scheme. The schemes are separated into a "decay-level" scheme, showing levels and transitions observed in the decay of all parent isotopes and isomeric states, and a "reaction" scheme, summarizing the information derived from nuclear reaction studies. Absence of a decay-level scheme, a reaction scheme, or both, means that excited levels have not been observed or that the scheme is not well established.

Decay–level schemes include all levels established in radioactive decay studies. Reaction schemes include most levels observed in nuclear reactions; when it is necessary to omit levels because of space limitations, the number of omitted levels, the energy cutoff above which they occur, and (usually) the reactions which populate them are noted in a comment. Not included are most neutron–capture resonances and other unbound states (e.g., giant resonances); these states are generally outside the scope of the present compilation, with a few exceptions in the light–element region. Some references to unbound levels other than neutron resonances are included under "other reactions" or "others".

II.B. *Uncertainties:* Uncertainties are included in tabular data listings whenever they were given in the original literature. Smaller italic numbers following any value represent the uncertainty in the last place or places. For example, 37.2 *22* stands for 37.2 ± 2.2, 15.7^{+17}_{-5} for $15.7^{+1.7}_{-0.5}$, $4.3\ 2\times10^{-4}$ for $(4.3 \pm 0.2)\times10^{-4}$.

In general, the author's original data are quoted exactly (to the same number of significant digits in the value and uncertainty). Where the author has stated that the same uncertainty or fractional uncertainty applies to a series of values (e.g., to radiation energies or intensities), this fact is noted by a comment, rather than by attaching an uncertainty to each value. (See section III.B for a further explanation of these comments.)

II.C. *Energies:* All energy quantities in the main table, except in "final–state labels" for alpha transitions, are in units of MeV. These include radiation energies, level energies, Q–values, and "energy labels" for γ, β, proton, and neutron transitions. Transition energies and level energies are shown in boldface type, both in the tabulated listings and on the level schemes.

II.D. *References:* References to journals or serial reports are coded in the form "journal volume page(year)" or "report number page(year)"; for example, NP A169 449(71) stands for *Nuclear Physics*, volume A169, page 449 (1971). These codes permit the reader to look up the original paper directly, without reference to a bibliography. A complete list of the journal and report codes follows the main table; many of the codes will be obvious, or will be quickly learned through frequent use. It should be noted that the "volume" may contain additional designators for series (s), issue number (n), part (p), division (d), or class (c). For example, 17n3 stands for volume 17, issue 3 and s2v25 stands for series 2, volume 25. (The issue number is included only when required for uniqueness.) Page numbers are omitted for monographs and other single–author sources.

Conferences are coded by year and (usually) location; e.g., Cf69 Nashv 27 for page 27 of a 1969 conference in Nashville. Books, private communications, theses, and non–serial annual or progress reports are coded in a similar manner; for example, Bk65 Siegbn, PC75 Hoff, Th72 Clark, AR70 IKO. A complete description of each conference, book, etc. is included in the reference–code list, along with the journals and reports.

For a few tabulated data entries that represent selection, normalization, or averaging of data from several sources, the individual reference codes are followed by the initials of the compiler(s). The compilers' initials appear also where the data from a single reference were subjected to non–trivial reinterpretation or recalculation by the compiler. As implied by the initials, responsibility is accepted for any abuse of the original data.

II.E. *Methods of measurement:* Methods for spins, half–lives, and all radiation data are listed after the data, just before the reference code, in *plain italics* type. A definition of each method applicable to a given data category is contained in section III.B under the appropriate data category. Occasionally, a reference code is appended to a method to indicate that data from another source were incorporated. For example, the method *Ge(Li), mag conv(NP A235 47(74))* typically would indicate that the author (rather than the compiler) utilized conversion–electron intensities from the cited reference, in addition to his own γ–ray data, in deriving the conversion coefficients he reported. The comment *method not given* indicates that experimental details were not reported in the paper.

II.F. *Data evaluation:* As in the 6th edition, each tabulated entry consists of a critical selection of reported data, chosen so as to give the reader a concise summary of what is known about the isotope, including at least one value for each measured quantity. Typically, "single–quantity" data categories will contain the one or few "best" measurements, with the most reliable values listed first. When there are many comparably accurate measurements or unresolved disagreements, more values may be listed. Unless otherwise noted, all tabulated data are *reported* values.

Radiation data are treated somewhat differently. Because a single entry may include many different quantities, it is seldom possible to select and order the entries by accuracy alone. For example, one reference may contain the best energies for low–energy transitions, a second the best energies for high–energy transitions, a third the best intensities, a fourth conversion coefficients, etc. In general, enough data are included to give the best measured values for all spectral properties, with the best energy measurements listed first, intensities next, and conversion data last. (This ordering is necessarily very approximate.)

A few numbers in the tabular entries may be treated (in most cases) as adopted values; these include the first–listed branching ratios under decay mode (☢) and the γ–ray normalizations. These quantities are discussed more fully in section III.B.

In some cases, only part of the data has been extracted from a paper: e.g., several transitions not reported by others; or conversion coefficients, but not the energies or photon intensities. The omission of some of the author's data is always noted by a comment such as other data reported or other γ rays observed at the end of the entry, and/or by designation of a transition by an energy label ($\gamma_{0.357}$) in place of the measured energy (0.357). In such cases, it is the compiler's judgement that the quantities omitted are sufficiently well covered by other entries.

A list of references to data not cited is given under the heading **others** for each data category. These listings include references to all measurements of any practical value, as well as data of historical interest on the identification of radioisotopes. "Others" references are listed in reverse chronological order.

Information contained in the level schemes represents the compilers' adopted values or assignments. No uncertainties are given; however, the data (continuous variables) are rounded to show the approximate uncertainty in each quantity (≤5 units in the last digit). Spins and parities are given without parentheses when well established. A more complete discussion of these and other quantum numbers appearing on the level schemes is given in section III.C.

Evaluations by other compilers have been used whenever it was felt advantageous to do so. In such cases the source of the evaluation is referenced instead of, or in addition to, the original papers.

II.G. *Cutoff date:* The compilers have attempted to include all references received by January, 1977. In the course of the final review, which took place during most of 1977, new references were included to the extent possible. Therefore, the cutoff varies from about January, 1977, for the lightest mass chains to about December, 1977, for the heaviest. A few papers available at reviewing time were not used due to time pressure.

III. Detailed Description of the Data Listings and Level Schemes

III.A. *Mass-chain decay schemes:* Each ground-state nucleus is represented by a heavy bar whose vertical position (upper edge) represents the energy of the nucleus relative to the lightest (most beta-stable) isobar. The energy scale is plotted to the left of the scheme, with scale changes noted by small breaks. Isomeric states are represented by lighter bars, plotted above the ground state. The position of an isomer is in some cases slightly above the actual energy, in order to allow room for labels; however, the position of an isomer relative to (above or below) that of a neighboring nucleus is qualitatively correct. Isomers of unknown relative position are shown side-by-side at the same vertical position (heavy bars). Dashed bars represent probable isotopes or isomers. A few rather uncertain isotopes have been omitted from the mass-chain decay schemes. Isotope labels, with the notation ${}^{A}_{Z}$El, appear immediately below the ground-state bar.

Alpha-decay parents are shown at the top of the mass-chain decay scheme, directly above their respective daughters. Their vertical positions are not related to the energy scale.

Half-lives are printed alongside the isotopes or on the bars, in large type. Units are the same as in the tabular data (see III.B. $t_{1/2}$). Spin-parity assignments are printed immediately above the bars on the left side, with the spin in bold type. Energies of isomeric states are printed to the right, also in bold type.

Decay of an isotope is indicated by an arrow, labeled by the decay mode. When several decay processes compete, percentage branchings are given if known. Symbols and conventions are the same as those described in section III.B. ☢.

Q-values for β^-, EC, and α decay are printed below each isotope; Q_α values are given also for α-decay parents. Q_{EC}, rather than Q_{β^+} (= $Q_{EC} - 2m_ec^2$), is given for all positive β-decay processes: positron emission (β^+), orbital electron capture (EC), and EC+β^+ decay. Thus, all stated Q-values represent the actual energy or mass difference, in units of MeV, between neutral atoms. Unless otherwise noted, the Q-values are taken from the reference ANDT 19 175(77). They are derived from a least-squares fit to measured Q-values for decay and nuclear reactions and data on mass doublets. The notation syst indicates that a Q-value was calculated with the aid of semi-empirical estimates. The uncertainties of systematic values vary from several tenths of an MeV to several MeV (for nuclei farthest from stability).

III.B. *Tabulated experimental data:* Each block of data on an isotope (or isomeric species) is headed by the *isotope label*. Isomeric states of known relative position are designated in the conventional way, for example: ${}^{166}_{67}$Ho, ${}^{166m}_{67}$Ho; ${}^{166}_{71}$Lu, ${}^{166m_1}_{71}$Lu, ${}^{166m_2}_{71}$Lu. Probable position is denoted by parentheses: ${}^{180(g)}_{73}$Ta, ${}^{180(m)}_{73}$Ta. Isomers of unknown relative position are designated by half-life: ${}^{90}_{43}$Tc(50 s), ${}^{90}_{43}$Tc(7.9 s). Fission isomers are denoted by an "f": ${}^{240f}_{94}$Pu, ${}^{237f_1}_{94}$Pu, ${}^{237f_2}_{94}$Pu.

Immediately below the label, there may be a ***general comment*** about the isotope. Most often the comment is a cross-reference to another isotope. Following the isotope heading and any general comment, the data are listed by data category (labeled to the left in **bold serif** type). A description of each data category and its associated data, in order of appearance in the listings, follows:

%: *Natural isotopic abundance* (atom percent basis) for elements as they occur on earth. The values are taken from a compilation by N. Holden (BNL-NCS-50605(77)). For elements whose composition displays variations outside experimental uncertainty, comments and/or values for specific sources are also included.

Δ: *Mass excess* (≡ M-A), on the unified mass scale ($\Delta(^{12}C) \equiv 0$), in units of MeV. All values refer to masses of the neutral atoms. Like the Q-values for decay, they are derived from a least-squares fit to Q-value and mass doublet data. Values dependent on semi-empirical estimates have the comment from systematics appended; the meaning is the same as the abbreviated comment syst on Q-values, and similar uncertainty (≈0.2 to 2 MeV) is implied (see section III.A). Most of the values are taken from ANDT 19 175(77). The mass excess of an isomer has been calculated by the compiler by addition of the level energy and/or the use of measured Q-values for the isomer; uncertain isomeric assignments were checked against the input mass data for correct correspondence between the stated mass and one (or more) of the isomers. (A systematic estimate for isomers of uncertain relative position refers arbitrarily to either of the isomers; the same estimate is given for each.)

I: *Nuclear spin* (angular momentum), in units of ħ. Only directly measured spins of ground or isomeric states are tabulated. Adopted spin assignments for all levels, including values deduced from nuclear spectroscopic measurements, are given on the detailed level schemes.

Methods for spin measurements are the same as those for magnetic and quadrupole measurements; refer to the *Table of Nuclear Moments* (Appendix VII) for a description.

σ: *Thermal neutron cross sections* include values for σ_c ($\equiv \sigma(n,\gamma)$, the capture cross section), σ_f (fission), σ_{abs} (total absorption), $\sigma(n,\alpha)$, and $\sigma(n,p)$. The notation σ_c(to *isotope*) [e.g., σ_c(to ^{188m}Re)] refers to capture to one of several isomeric states. The value quoted is for direct capture (independent yield) unless otherwise specified, although the underlying measurements may involve both independent and total yields. All cross sections were compiled and evaluated by N. Holden (PC77 Holden), and are given in units of barns (10^{-24} cm^2). Unless otherwise noted, they refer to neutrons with a velocity of 2200 m/s (E=0.0253 eV, or T=293°K). The comment reactor spectrum indicates that the neutrons have an energy spectrum that is not well defined, but that is approximately characteristic of a "thermal" irradiation position in a reactor. The comment subcadmium refers to neutrons to which a cadmium absorber is "opaque" - roughly, to neutrons of energy ≲0.5 eV.

The reader is cautioned that many nuclei have strong epithermal resonances, and that "thermal" reactors contain epithermal neutrons in the irradiation positions. Consequently, the effective cross section in a given experiment can be larger than a thermal (2200 m/s) value, and may be either smaller or larger than a "reactor spectrum" or "subcadmium" value. A more detailed source of neutron data, such as BNL–325(73), may be useful to readers familiar with neutron physics.

❦: *Decay mode.* Modes and percentage branchings are given with the following symbols:

β^-	Negative β–particle (negatron) emission.
β^+	Positive β–particle (positron) emission.
EC	Orbital electron capture.
α	α–particle emission.
IT	Isomeric transition (electromagnetic decay from an excited state).
SF	Spontaneous fission. (Listed only if the branching is $\gtrsim$1%. When the branching is smaller, the partial half–life is listed under $t_{1/2}$(SF).)
p	Proton emission (^{53m}Co).
β^-n	Neutron emission from excited states promptly following β decay to those states. Entry is made in conjunction with the β emitter.
β^+p, ECp, (EC+β^+)p	Proton emission from excited states promptly following β decay to those states. Entry is made in conjunction with the β emitter.
$\beta^-\alpha$, $\beta^+\alpha$	α–particle emission from excited states promptly following β decay to those states. Entry is made in conjunction with the β emitter.

The notation no... (e.g., no β^+) indicates that a particular decay mode has been searched for but not observed. (For cases in which *no* radioactivity has been observed, limits on the total or partial half–life are given under $t_{1/2}$.)

A question mark (?) means that the decay mode is uncertain. Square brackets occasionally enclose a decay mode that is inferred, or poorly established. (Note – a decay mode may be "observed" in a number of ways: β^+ by the observation of positrons or annihilation quanta ($\gamma^\pm$), IT by the observation of gamma rays or conversion electrons, any mode by the demonstration of a genetic relationship, etc.)

For isotopes that decay by several modes, percentage branchings are given when known. In most cases, the first entry contains an *adopted value* of the decay branchings. Branching ratios are listed occasionally when uncertainty concerning a third mode precludes a statement of absolute values. For example, α/β^+ 4.7 might be listed if that ratio was measured but the ratio EC/β^+ is not known.

The listing of EC and β^+ modes deserves special comment. Electron capture always accompanies positron emission; positron decay accompanies electron capture whenever the transition energy is greater than $2m_ec^2$ (=1.022 MeV). The ratio β^+/EC increases rapidly with increasing transition energy and decreasing atomic number (see Appendix V). In many cases experimental evidence for one or the other mode is lacking due to its weakness or to experimental limitations. In other cases, decay by some combination of EC and β^+ may be reliably established by genetic relationships, although direct evidence for either mode is absent. The following convention has been adopted:

EC, β^+ β^+, EC	Both EC and β^+ decay have been shown *experimentally* to occur. The probable larger branching is listed first. Percentage branchings are given when known (e.g., EC 90%, β^+ 10%).
EC	EC has been observed or inferred from genetic relationships; β^+ is either energetically forbidden, or is expected to be $\lesssim$1% from theoretical considerations.
β^+	β^+ has been observed or inferred from genetic relationships; EC is probably $\lesssim$1% from theoretical considerations.
EC+β^+ β^++EC	The first–named mode has been observed or inferred from genetic relationships; the second mode is probably $\gtrsim$1% from theoretical considerations.

Detailed data on measured EC and β^+ decay properties – EC subshell ratios for total decay, subshell and EC/β^+ ratios for individual transitions – are given under the data category EC (see below).

The comment β^- unstable, EC unstable, or β stable is sometimes included under ❦ to indicate whether an unobserved decay mode is energetically possible. Such notes are included only when the stability is not obvious from other data (e.g., a limit under $t_{1/2}$(...)) or from the mass–chain decay scheme.

genet: *Parentage of isomeric states in the decay daughter.* As noted, these data are often derived from the level scheme. Quantitative data are given when known. Genetic relations are *not* given unless the decay daughter has an isomeric state, even though the information may be relevant to the identification of the isotope, or of its descendants or antecedents.

$t_{1/2}$: *Half–life.* Whenever possible, the total half–life ($t_{1/2}$) is given. Conventional units are employed – y=year, d=day, h=hour, m=minute, s=second, ms=millisecond (10^{-3} s), μs=microsecond (10^{-6} s), ns=nanosecond (10^{-9} s), ps=picosecond (10^{-12} s), fs=femtosecond (10^{-15} s), as=attosecond (10^{-18} s). Partial half–lives, denoted $t_{1/2}(\beta^-)$, $t_{1/2}(\alpha)$, etc., are given when the total half–life is unknown or poorly known, most commonly when a lower limit for decay of a long–lived isotope by a specified mode has been determined. The partial half–life for spontaneous fission ($t_{1/2}$(SF)), rather than the percentage branching, is given when the branching is small ($\lesssim$1%). Partial half–lives or limits for double negatron decay ($t_{1/2}(\beta\beta)$) or double electron capture ($t_{1/2}$(ECEC)) are given for the few cases in which these have been measured.

Methods for half–life: When no method is listed, the half–life has been determined directly by measurement of the time–decay of emitted radiation. "Direct" determination also includes measurement of the growth from a parent activity, as well as the analysis of complex growth–decay curves. Other methods are denoted as follows:

mass spect Direct determination of the decay rate by measurement of the decrease in the number of atoms (or the increase in the number of atoms of a daughter isotope), relative to another isotope of the same element, in a mass spectrometer.

sp act (+ *mass spect*) Determination of the disintegration rate of a sample containing a known mass of the active substance. (Mass spectrometric analysis of the sample to correct for other isotopes present.)

calorim Determination of the rate of heat production from a known mass of an active substance.

genet (+ *mass spect*) Measurement of the decay rate of a parent substance by periodic removal and radioassay (or mass spectrometric assay) of a decay product.

geochem Specific activity determination by chemical and/or isotopic analysis of natural samples, involving assumptions about the sample history (age, chemical or isotopic fractionation, etc.).

yield Measurement of radioactivity from a sample containing a number of atoms calculated from the expected yield of the reaction by which it was produced.

est Estimation based on decay energy, level structure, and theoretical considerations. Usually this method refers to alpha emitters, for which half-lives can often be predicted from the measured α-particle energy to within an order of magnitude or better.

delay coinc, nuclear recoil See methods for $t_{1/2}$(levels). These methods apply to a few very short-lived ground states and to most fission isomers.

Class, Ident: *Class and means of identification.* Class defines the degree of certainty with which an isotope has been identified. With one exception noted below, the class and identification refer to the decay properties of radioisotopes – that is, to the attribution of a half-life and/or radiation characteristics to a specific element and mass number. Class is defined as follows:

A Element and mass number certain.
B Element certain and mass number probable.
C Element probable and mass number certain or probable.
D Element certain but mass number not well established.
E Element probable and mass number not well established.
F Insufficient evidence.
G Probably in error.
R Nucleus or excited levels identified in a nuclear reaction; radioactive decay has not been observed (see below).

G-rated isotopes are included to alert the reader to the probable incorrectness of assignments that appear in the literature, but were later refuted. Other data (type of decay, half-life, means of production) are included only for the purpose of identification. Isotopes rated G in the 6th edition have been omitted unless subsequent evidence in support of their existence has been given.

These "ratings" should not be read as levels of confidence in the experiments but rather as an indication of the limitations of the experiments as they relate isotopic assignments to the observed decay properties. In some instances a simple cross bombardment results in an unambiguous assignment. In others, much more elaborate experiments are insufficient. Among the factors that can limit the certainty of an assignment based on the means of production are targets of mixed isotopic composition, low cross sections, the possibility of isomerism, similarity of properties to other isotopes, and absence of knowledge of neighboring isotopes.

The class R describes nuclides characterized by "particle identification" of A and Z, by mass determination (from a reaction Q-value), or by observation of excited states by in-beam γ-ray spectroscopy. Light nuclei that have been proved to be unstable against particle emission (with a very short lifetime) have also been included with an R rating and the notation *particle-unstable* under **Ident**. The R rating does not convey the degree of certainty; however, most nuclei so designated can be considered well-established in the sense that the observed properties are associated with definite atomic and mass numbers.

The means by which the isotopic assignments were established (Ident) are listed immediately following the class. In general, the first entry refers to the discovery (except for the classical natural radioactivities); subsequent entries reference measurements which increased the certainty of the assignment. In some cases, the original observation of an activity resulted in an incomplete assignment; the activity may have been shown subsequently to consist of several isotopes or isomers that decay with similar properties or in equilibrium. In such cases, the "discovery" may be credited to several authors referenced in the first few entries.

Means of identification are denoted by the following abbreviations:

chem Assignment of the element (atomic number) based on chemical separations.

genet Evidence obtained (by chemical or other means) for the existence of a decay relationship with another isotope whose assignment is known or probable.

excit Refers broadly to energy considerations in the production of the isotope, including:
(1) excitation-function or yield experiments to establish the nuclear reaction that produced the isotope;
(2) limitation of products formed by limiting the energy of bombarding particles;
(3) use of a calculated Q-value;
(4) use of fission-yield data to limit mass assignments.

cross bomb Arrival at an assignment by attempts to produce the isotope in different ways.

n-capt Key evidence supplied by production with slow neutrons, from which it is usually inferred that the (n,γ) reaction was observed.

resonance neutron activation Demonstration that several isomers belong to the same nucleus (A and Z) by the observation that they are produced (with filtered or monoenergetic neutrons) at the same resonances in the (n,γ) reaction.

sep isotopes The use of target elements enriched or depleted in a particular isotope.

mass spect Mass number determined by mass spectrometry.

decay charac Identification of predicted decay properties such as the decay energy or the general pattern of levels in the decay daughter.

genet energy levels Energy levels of the daughter nucleus agree with those from decay of another parent whose isotopic assignment and mode of decay are known, or with levels observed in a nuclear reaction.

atomic level spacing Atomic number of the daughter nucleus assigned by measurement of the characteristic energies of x-rays or energy differences between internal-conversion electron lines from a particular γ transition converted in different shells.

critical abs Assignment of the atomic number of the daughter nucleus by critical absorption of x-rays accompanying the decay process.

fission fragment range Determination of the approximate mass number by measurement of the range of fission fragments.

recoil angular distrib Production by a fusion-evaporation type reaction inferred from the narrow angular distribution of the recoiling product nuclei.

For G-rated isotopes, the first entry(ies) under

Ident gives the reason for rejection of the assignment and/or the probable reassignment; subsequent entries refer to the original assignment.

R-rated isotopes are identified only by the reaction(s) in which the nucleus was observed.

Prod: *Principal means of production.* For each isotope, the methods of production selected for inclusion are those that have given the highest yield and those that permit greatest isotopic purity. These listings serve principally as references to the original literature in which important aspects of the preparation, such as experimental conditions, yields, and purity of product, are discussed.

Most commonly, the means of production is given in standard reaction format – for example, $^{59}Co(p,3n)$, where ^{59}Co, p and 3n refer to the target, projectile, and emitted particles, respectively. The emission of γ rays is not noted except in the conventional notation (n,γ) and (p,γ) for neutron and proton capture. Multi-step processes, involving both reactions and radioactive decay, are given in a similar "extended reaction" format – e.g., $^{144}Sm(\alpha,2n)^{146}Gd(EC+\beta^+)$, $^{197}Au(n,\gamma)^{198}Au(n,\gamma)$. For many transuranic isotopes that can be produced by a series of neutron captures and intervening β decays, starting from several different materials, the notation multiple n-capt from... stands for a similar, multi-step process, in which several different paths can sometimes compete.

The production method fission most often refers to fission induced by thermal neutrons on ^{235}U or ^{239}Pu, but may include fission induced by neutrons or charged particles of low to moderate energies on targets of thorium or heavier elements, as well as the spontaneous fission of ^{252}Cf. Although a given fission product is produced to some extent in all such reactions, the yield can depend strongly on the reaction and bombardment energy; the reader is referred to the original references for details.

Notations such as protons on Ta, ^{12}C on ^{197}Au, etc. refer to means of production involving several possible reactions, or to high-energy reactions (including fission in lighter targets) whose mechanisms are complex or obscure. Means of production for isotopes whose assignments are very uncertain or probably incorrect are also given in this form.

The notation daughter... or descendant... means that the activity was separated from a parent or ancestor in order to take advantage of its longer half-life, or to obtain a product of higher purity. This production method implies that the parent substance was first isolated from other reaction products; otherwise, the "extended reaction" format is used.

The notation natural source refers to the long-lived naturally occurring radioisotopes and their descendants.

Radiation spectra (α, β^-, β^+, p, n, γ): The data entries are often complex, since each entry may describe all or part of the spectrum consisting of numerous transitions. Although the heart of an entry is a list of transition energies and intensities, important comments often precede and follow the list. Aspects of these comments (and of the transition list itself) that are common to all radiation types are discussed in this section; features that are specific to a particular radiation type are described below, under the appropriate heading.

Most generally, an entry may include (1) an absolute normalization comment (optional, for γ rays only), (2) an uncertainty comment and/or other comments (optional), (3) the list of transition energies, intensities, and other properties, (4) additional comments on omitted or unobserved radiations (optional), and (5) the method of measurement and reference code(s). Each of these is discussed below, in order of occurrence in a data entry:

(1) *Comment on the absolute normalization of measured relative intensities:* The normalization comment is easily recognized by the notation ⟨norm:...⟩ at the beginning of an entry. It is included for γ-ray spectra for which absolute intensities have not been measured directly, or are known less precisely than the quoted relative intensities. (Normalization of other radiations is generally indicated under decay mode (☢).) A typical comment, $\gamma_{0.570}$ (γ 10.5 7%), from level scheme, means that the photon (γ) intensity of the 0.570-MeV transition is 10.5 ± 0.7 per 100 decays of the parent substance and further, that this normalization was deduced from analysis of the level scheme. A reference code in place of from level scheme would indicate that the normalization was derived from a measurement reported in that reference.

The normalization comment is included in at least one γ-ray entry for each isotope, except when absolute intensities have been quoted explicitly, or when the normalization is not well established. *The value represents the compiler's choice for the "best" or recommended number.* For a few isotopes, normalizations are included with several of the γ-ray listings to emphasize that the preferred value depends on a choice between different measurements of comparable accuracy, or that there is an unresolved disagreement.

(2) *Uncertainty comment, etc.:* Whenever the author has stated that a fixed or fractional uncertainty(ies) applies to the data, this uncertainty is noted in parentheses. As an example, (ΔE=0.001, $\Delta †_\gamma$=5% if $†_\gamma \geq 10$, 10% if $†_\gamma < 10$) means that the energies are uncertain by 0.001 MeV, and that a relative γ-ray intensity is uncertain by 5% of the value if the value is ≥10, or by 10% if the value is <10.

Occasionally other comments are included (within parentheses) just before the energy-intensity listing. Most often these describe normalization relative to another radiation that is not part of the listing: for example, a γ ray belonging to a daughter activity that decays in equilibrium.

(3) *Energies, intensities, and other properties of the transitions:* Energies, in MeV, are shown as boldface numbers. An "energy label" in place of the measured energy denotes a transition (whose properties follow) without implying a *measured* value for the energy. Either the energy was not reported by the author, or (more commonly) the compiler has suppressed it in favor of more accurate values in other entries. Energy labels consist of the radiation symbol subscripted by the energy (in MeV, rounded to the nearest keV), e.g., $\beta_{3.12}$, $\gamma_{0.357}$. Note that α-particle transitions are labeled by the final-state energy (in keV), rather than by the α-particle energy (see under α). A question mark (?) following the energy or energy label means that the existence of the transition or its assignment to the isotope is questionable. The notation no... (e.g., no $\gamma_{1.44}$) indicates that the transition has been searched for but not found.

Intensities and other properties (in parentheses) follow the energy or energy label.

Intensities are denoted by the symbols % for absolute intensity (transitions per 100 decays of the parent substance), or † for relative intensity. The symbol ‡ refers to a separate set of relative intensities; the use of this symbol and the further designation of intensities for photons or conversion electrons is discussed below under γ. The ratio of an intensity to the intensity of another type of radiation is occasionally given. For example, $\gamma_{0.057}$ (γ/α 0.35) means that the intensity of the 0.057–MeV γ ray is 0.35 times that of all α particles; $\beta_{1.32}$ ($\beta/\gamma_{0.832}$ 0.4) means that the 1.32–MeV β transition is 0.4 times as intense as the 0.832–MeV γ ray.

Comments on individual transitions are occasionally given. Most common are comments that indicate a radiation is complex, or that refer to coincidence measurements – e.g., $\beta_{1.32}$ (27%, coinc $\gamma_{0.832}$). Coincidences are noted *only* when the placement of a transition in the decay scheme is uncertain or unknown. Although the more numerous coincidence observations used to construct the decay schemes are not listed explicitly, the fact that coincidences were measured is always noted in the method of measurement.

(4) *Additional comments:* Comments such as other data reported or other γ rays observed occur at the end of the transition listing. Usually they indicate that *the compiler has listed only part of the data from the reference*, although the latter comment may mean (rarely) that the author noted the existence of other transitions but did not give any numeric data. Comments such as no other α transitions observed (lim 0.1%) also appear at the end of the listing.

(5) *Method(s) of measurement (in italics) and the reference code(s) (in braces {})*: These conclude each entry. Methods applicable to measurement of a specific radiation type are described below under the radiation in question.

Unless otherwise noted, the radiation entries are associated with the decay of a single isotope or isomer. In some cases, in which a short–lived daughter substance decays in equilibrium with a parent, the measurements reported refer to the equilibrium mixture. This is noted in the data category – for example, **β^+ with ^{160m}Ho and ^{160}Ho in equilibrium**. The data are listed under one of the isotopes, with a cross–reference under the other. In a few cases radiations from a mixture of several isotopes or isomers not in equilibrium, but with similar half–lives, are treated in the same way.

α: *Alpha–particle spectrum*. α transitions are denoted by both the final–state energy in keV, and the α–particle energy in MeV. For example, α_{32} 5.071 *3* stands for an α group of energy 5.071 ± 0.003 MeV populating a state at 32 keV in the daughter nucleus. The α–particle energy is sometimes omitted when a more accurate energy is cited in another entry or (rarely) when it was not stated by the author. The final–state label contains the adopted level energy (rounded to the nearest keV), not necessarily the value derived from the measured α energy. It is omitted if the excited–state energy (i.e., the decay scheme) is not known, or if the assignment is in question (transition not shown on decay scheme). Transitions are listed in order of decreasing α–particle (increasing excited–state) energy.

The α–particle energy always refers to the energy of the emitted particle, not the Q–value (which includes the energy of the recoil nucleus). All energies have been corrected to the new Rytz standard [see Metr 7 65(71) and ANDT 12 479(73)], except when low precision of the measurement does not warrant such an adjustment.

The data category **long range α** refers to α transitions from excited states of ^{212}Po and ^{214}Po which follow promptly the β^- decay of ^{212}Bi and ^{214}Bi. By convention these are listed under the respective polonium isotopes. "Delayed" α transitions that depopulate excited states of lighter nuclei following β decay are listed with the β–decay parents (^{8}B, ^{12}B, ^{12}N, ^{16}N, ^{20}Na, ^{24}Al) under the data category **α**. These and "long–range" α spectra are ordered by increasing α energy.

Methods for α spectra include:

mag Magnetic spectrometer with photographic or counter detector.
semicond Diffused–junction or surface–barrier semiconductor detector.
Si(Li) or *Si* Lithium–drifted or intrinsic silicon detector.
scint Scintillation detector.
ion ch Ionization chamber or proportional counter.
range emuls Measurement of the lengths of α–particle tracks in a photographic emulsion.
abs Absorption methods.
cl ch Cloud chamber with magnetic deflection.
$\alpha\gamma$ coinc, αe coinc Measurement of coincidences between α particles and γ rays or conversion electrons. Detectors are usually given, e.g., *semicond–scint $\alpha\gamma$ coinc*, where the first and second detectors refer to α particles and γ rays, respectively. (Refer also to methods for γ.)

β^-, β^+: *Beta–particle spectrum*. The listed energies refer to the endpoint of the continuous beta spectrum. These and the listed intensities are values derived from analysis of the beta spectrum itself (and/or $\beta\gamma$ coincidence spectra). In a few cases intensities of β^+ transitions have been derived from coincidences between annihilation radiation and nuclear γ rays. Note that for many beta emitters a more complete spectrum and more accurate values can be inferred from independent measurements of Q_β and the level feeding (intensity balance); consequently, the reader who is interested in "best" values should consult the decay scheme. Transitions are listed in order of decreasing β–particle energy.

Methods for β spectra include:

mag Magnetic spectrometer with counter or photographic detector.
electrostatic Electrostatic spectrometer. *electrostatic, mag* refers to a hybrid spectometer.
scint Scintillation detector (solid or liquid).
Si(Li), Si, Ge(Li), Ge Lithium–drifted or intrinsic silicon or germanium detector.
semicond Surface–barrier or diffused–junction semiconductor detector.
ion ch Ionization chamber or proportional counter.
abs Absorption methods.
cl ch Cloud chamber with magnetic deflection.
range emuls Measurement of the lengths of β–particle tracks in a photographic emulsion.
recoil mag, recoil electrostatic Measurement of the energies of recoiling atoms by electromagnetic and electrostatic deflection.
calorim Calorimetric determination of the average β–particle energy.
$\beta\gamma$ coinc, βe coinc Measurement of coincidences between β particles and γ rays or conversion electrons. Detection methods are usually given, e.g., *mag–scint $\beta\gamma$ coinc*. (Refer also to methods

for γ.)

βγγ coinc, βγ±γ± coinc, β(γγ sum) coinc Triple coincidence methods. A single preceding detector type refers to the β spectrum, as in *Si(Li) βγγ coinc*. Two preceding detectors refer to β particles and γ rays, respectively, as in *Si(Li) scint βγγ coinc*.

γγ± coinc, γγ±γ± coinc Double or triple coincidence method to determine the intensities of β^+ transitions. (See methods for γ for detector types.)

sum (βγ) scint Sum spectrum of coincident β particles and γ rays from an internal source within a scintillator.

p: *Proton spectrum*. With the exception of the direct proton emitter ^{53m}Co, this data category refers to "delayed" protons – protons emitted promptly from excited states of the daughter nucleus following beta decay to these states. The listed energies, in increasing order, refer to the energies of the emitted protons, not the transition energies (which include the energies of the recoil nuclei). Approximate energy ranges are noted for heavier (A≳100) delayed–proton emitters, for which the spectra have not been resolved into individual lines.

Methods for proton spectra include *semicond*, *Si(Li)*, *Si*, *scint*, *ion ch*, *mag*, *range emuls*, and *pγ coinc*. The definitions are the same as those given for α–particle methods.

n: *Delayed neutron spectrum*. This data category refers to neutrons emitted promptly from excited states following β^- decay to these states. Transitions are listed in order of increasing energy. Approximate energy ranges are given for some isotopes for which individual transitions have not been resolved.

Methods for delayed–neutron spectra include:

³He(n,p) ion ch Measurement of the energies of protons from the ^{3}He(n,p) reaction in an ion chamber.

time of fl Measurement of the time of flight of neutrons in coincidence with β^- particles.

proton recoil in ion ch, proton recoil in cl ch, recoil scint Measurement of elastically scattered protons in an ion chamber, cloud chamber, or scintillation detector.

abs paraffin, abs polyethylene Measurement of the absorption (and/or scattering) in paraffin or polyethylene.

nγ coinc Measurement of coincidences with γ rays. Detection methods are usually given, as in *³He(n,p) ion ch–scint nγ coinc*. (Refer also to methods for γ.)

γ: *Electromagnetic spectrum*. Included in this category are measured data on nuclear γ rays, conversion electrons, atomic transitions (x–rays and Auger electrons), and annihilation radiation. (Note: atomic transitions and annihilation radiation are normally listed only if their intensities relative to the intensities of nuclear transitions were reported. The reader is cautioned that in many cases authors have not measured or reported the intensities of these non–nuclear radiations, even when they are prominent in the spectrum. Intense x–rays always accompany electron capture decay or intense, highly converted γ–ray transitions. Annihilation radiation is prominent in the spectra of β^+ emitters.)

Energies: Transitions are listed by the γ–ray (photon) energy, even when conversion electrons were measured. They *do not* include the energy of the recoil nucleus ($\equiv E_\gamma^2/(2M_{recoil}c^2)$), which is significant only for high–energy transitions in light nuclei. Derived *level* energies shown on the level schemes have been corrected for the recoil energy.

Nuclear transitions are ordered by increasing energy. Atomic transitions *precede* nuclear transitions; if both x–rays and Auger electrons are reported in a single reference, the Auger electrons are listed first. X–rays are designated by the conventional "Siegbahn" notation rather than by energy; for example, Ta $K_{\alpha2}$ X for the $L_2 \rightarrow K$ transition in tantalum. (See Appendix III, Table 10 for a more detailed description of x–ray designations and a table of energies.) Auger electrons are designated by the shells involved (e.g., Th KL_1L_2 Auger). The energies are *approximately* equal to the binding–energy difference $B_1-B_2-B_3$ [$B(K) - B(L_1) - B(L_2)$ in the above example]; binding energies are listed in Appendix III, Table 9. The notations may include complex, unresolved transitions such as K_α X [$\equiv (K_{\alpha2} + K_{\alpha1})$ X], $K_{\beta2}'$ X [$\equiv (K_{\beta2} + K_{\beta4})$ X], KLL Auger [$\equiv (KL_1L_1 + KL_1L_2 + ... + KL_3L_3)$ Auger]. Annihilation radiation, designated by the symbol $\gamma^\pm$ rather than by its energy (0.511 MeV), is included among the nuclear transitions.

The subject of high–precision γ–ray energies deserves special comment. During compilation of the 7th edition, the accepted energies of commonly–used calibration sources changed frequently. Due to the manner in which most energy measurements are made and reported it is difficult, if not impossible, to correct earlier measurements to the present "best" set of standard energies. Furthermore, the absolute energy scale was uncertain by an amount that is large (17 ppm) compared to the precision of the best relative measurements. Consequently γ–ray energies in the main table are quoted as they appear in the original literature; no attempt has been made to apply corrections. More recent values have been selected in preference to earlier ones of comparable precision when it was evident that the latter are subject to calibration errors or other problems. In general, listed energies with uncertainties from ≈10 eV at low energies to ≈100 eV at 1 MeV are unlikely to require significant corrections. For many applications this level of accuracy will be entirely adequate.

The situation changed dramatically in 1978 with the measurement of the "gold standard" (the 411–keV transition in ^{198}Au decay) to an accuracy of 0.4 ppm. It is now possible to correct a few measurements to the new standard. In Appendix II, energies are tabulated for a number of standard sources, based on this new standard.

Intensities: The traditional symbols for absolute (%) and relative (†) intensity are used. For electromagnetic transitions, additional symbols indicate whether reference is made to γ rays (photons) or to conversion electrons (of a particular atomic shell). For example, γ 7% stands for an absolute γ–ray intensity of 7%, $\dagger_\gamma$ 67 for a relative γ–ray intensity of 67. Similarly, K...% and $\dagger_K$... refer to absolute and relative K–conversion electron intensities, respectively. The symbol e, as in e...%, or $\dagger_e$..., refers to the (absolute or relative) total conversion electron intensity (e ≡ K+L+...).

The symbol ‡ is sometimes used to denote a separate set of relative intensities, not normalized to those denoted by †. For example 0.33 ($\dagger_\gamma$100, $\ddagger_K$100), 0.44 ($\dagger_\gamma$*72*, $\ddagger_K$15*3*) indicates that the intensity ratio of 0.44–MeV photons to 0.33–MeV photons is 0.07 ± 0.02 and that the ratio of respective K–conversion line intensities is 0.15 ± 0.03; no relationship between the photon and K–line intensities is implied.

Intensities for annihilation radiation ($\gamma^\pm$) refer to the broadened photon peak at the energy m_ec^2 (0.511 MeV). The presence of this peak implies the existence of a continuum, extending to higher energies, whose integrated intensity (which is dependent on the positron energy) is of the order of 5% of the intensity of the peak. The total annihilation intensity (including the continuum) is twice the intensity of positrons arising from β^+ decay and internal pair conversion, where the former contribution is usually dominant. Further caution should be exercised in the interpretation of the annihilation intensity (particularly when β^+ decay is weak or absent), due to the fact that its measurement is complicated by natural background and by the *external* pair conversion of γ rays from the source in surrounding materials. Appropriate comments have been provided when the authors themselves noted the possibility of such experimental problems.

Internal conversion coefficients: These are denoted by e/γ, e_K/γ, e_L/γ, e_{L1}/γ... for the total, K, L, L_1... conversion coefficients. In many cases a theoretical conversion coefficient for one transition has been used in order to derive coefficients for others; this is indicated by the word *assumed* preceding the theoretical value. Measured shell and subshell ratios are listed as simple or compound ratios – for example, K/L 5 or $L_1/L_2/L_3$ 100/12 *2*/1.7 *3*. Subshell ratios are normally quoted only for the innermost shell; for example, M–subshell ratios are usually omitted if the L–subshell ratios are reported. Exceptions are made in the cases of some accurate measurements of particular interest for comparison with theory. When several absolute conversion coefficients are known, these are usually given in terms of the coefficient for the innermost shell and a ratio, e.g., e_K/γ and $K/L_1/L_2$ rather than e_K/γ, e_{L1}/γ, and e_{L2}/γ.

Additional symbols: A few rather specialized symbols are used occasionally to denote less common electromagnetic processes. The symbol $e^\pm$ stands for internal pair conversion, usually stated in terms of the ratio to γ–ray emission ($e^\pm/\gamma$) or to internal conversion (e.g., $e^\pm/K$). The symbol e_K^+ refers to conversion by emission of a positron with simultaneous transfer of an electron to a vacant K orbit. Double–quantum emission is denoted by $\gamma\gamma$ (two–photon emission), KK (two–K–electron emission), etc.; typical measured quantities are the intensity ratios for double– to single–quantum emission, e.g., $I_{\gamma\gamma}/I_\gamma$, I_{KK}/I_γ.

Decay by several modes: In general, electromagnetic transitions that occur with each decay mode and each isotope are listed separately. This is indicated by the data category heading: for example, **γ with IT**, **γ with β⁻**. The normalization of relative intensities between listings for different modes may be noted in comments at the beginning of one or more of the entries. If some or all of the transitions have not been assigned to a definite mode, these may be listed under a heading such as **γ with IT or β⁻**. In a few instances the assignments are well known, but decomposition of the spectrum is complicated by the presence of short–lived daughter isotopes. For example, most spectra of 5–hour ^{160m}Ho, which decays by IT and EC+β^+, were measured with 26–minute ^{160}Ho in equilibrium. Since some transitions occur in the EC+β^+ decay of both isotopes, data are listed under ^{160m}Ho with the heading **γ with EC+β⁺ and ¹⁶⁰Ho in equilibrium**. (A cross–reference is provided under ^{160}Ho.)

Note that the intensity of a daughter radiation in equilibrium always refers to the instantaneous decay rate, which is larger than the "decay–scheme" value by a factor

$$\frac{t_{1/2}\,(\text{parent})}{t_{1/2}(\text{parent})-t_{1/2}(\text{daughter})},$$

and may exceed 100%. For example, an isomeric transition from a 1–hour state populated by a 100% beta transition from a 10–hour parent would have an "apparent" transition (γ+e) intensity of 111% (1/0.9).

Methods of measurement are described below. Unless otherwise noted, they refer to the detection of γ rays; the same methods with the term *conv* appended (e.g., *scint conv*) refer to the detection of conversion electrons.

Ge(Li), *Ge*, *Si(Li)*, *Si* Lithium–drifted or intrinsic germanium or silicon detector. These methods (with *conv*) may include the use of magnetic fields to separate the conversion electrons from other radiations.

Ge(Li) anti–Compt, *Ge anti–Compt*, etc. Ge(Li) or other detector in anti–coincidence with a surrounding scintillation detector (γ rays only).

Ge(Li) pair, *scint pair*, etc. Ge(Li) or other detector in coincidence with surrounding scintillation detectors to record the "double–escape" spectrum resulting from pair conversion in the central detector (γ rays only). [Includes measurements designated by "3 cryst pair spect" in the 6th edition.]

semicond conv Diffused–junction or surface–barrier semiconductor detector for conversion electrons.

scint Scintillation detector (usually NaI(Tl)).

scint sum, *Ge(Li) sum*, etc. Scintillation or other detector; observation of sum peaks.

cryst Bent–crystal diffraction spectrometer (γ rays only).

mag Magnetic spectrometer with counter or photographic detection. *mag conv* refers to the measurement of internal–conversion electrons, *mag* to the measurement of γ rays via the production of secondary electrons in an external converter. *mag, mag conv* usually refers to the "internal–external conversion" (IEC) method, in which use of a common geometry permits the direct calculation of conversion coefficients.

electrostatic conv Electrostatic spectrometer.

ion ch Ionization chamber or proportional counter.

mag e$^\pm$, *Si(Li) e*$^\pm$, *mag–Si(Li) e*$^\pm$, etc. Coincidence measurement of the energies of the electron and positron produced by external pair conversion of a γ ray, or by internal pair conversion (with *conv*). (*Si(Li) e*$^\pm$ *conv* implies the use of magnetic fields to separate electrons from positrons.)

critical abs E_γ bracketed by demonstration that the energy lies between the K–absorption edges of adjacent elements (γ rays only).

range emuls conv Measurement of the lengths of tracks produced by conversion electrons in a photographic emulsion.

γγ coinc, *γe coinc*, *eγ coinc*, *ee coinc* γ–γ, γ–conversion electron, etc. coincidence measurement. Usually the two detectors are given, as in *scint–scint γγ coinc*, *Si(Li)–Ge(Li) eγ coinc*.

γX coinc, *eX coinc* [$X = \beta$, α, p, or n] Coincidences between γ rays or conversion electrons and other radiations. Detectors are usually given, as in *Ge(Li)–semicond γα coinc*.

γγγ coinc, *eγγ coinc*, *γγ*$^\pm$*γ*$^\pm$ *coinc*, etc. Triple coincidence method. Detectors are usually given: e.g., *scint γγγ coinc* (3 scintillation detectors), *Ge(Li) scint γγγ coinc* (2 Ge(Li) and 1 scintillation or 1 Ge(Li) and 2 scintillation detectors).

γγ sum coinc Coincidence measurements between γ rays whose energies sum to a given value. Detector is usually given, as in *scint γγ sum coinc*.

Ge(Li) scint γγβ coinc, *$\gamma^{\pm}\gamma^{\pm}\gamma^{\pm}\gamma^{\pm}$ coinc*, etc. Miscellaneous triple and higher-order coincidence measurements.

ion ch–scint 4πβγ coinc, *scint–scint 4πβγ coinc*, *sum scint 4πβγ* Singles and coincidence (or sum) measurement, employing 4π geometry for β particles, to determine absolute γ-ray intensity.

Mössbauer Mössbauer spectroscopy (determination of e/γ from resonance integral).

Average radiation energies: When measured directly (rather than calculated from the spectrum), average energies are given under the data categories **avg. β^- energy**, **avg. neutron energy**, etc. These entries follow any detailed spectra for the respective radiation type.

Angular correlations, alignment, polarization: References to these measurements are listed in reverse chronological order. Angular correlations are denoted by $XY(\theta)$, where X and Y refer to the radiations [$X,Y = \gamma$, e, β, α, p, n, or IB (internal bremsstrahlung)]. **Align** refers to static alignment – measurement of the angular distribution of a radiation emitted from nuclei aligned at low temperatures by magnetic fields. Polarization measurements are denoted by the radiation symbol, subscripted by the type of polarization measured. The following abbreviations are used:

lin p	linear polarization
lon p	longitudinal polarization
cp	circular polarization
tp	transverse polarization
pp	plane polarization

When the dependence of polarization on coincidence angle was measured, this is noted. For example, γ_{cp} refers to the circular polarization of γ rays; $\beta\gamma_{cp}(\theta)$ refers to the circular polarization of γ rays as a function of angle between the γ ray and a coincident β particle.

$t_{1/2}$**(levels)**: *Half-lives of excited states*. These are listed with tabular entries for the ground state of the nucleus. The energy of each state (rounded to the nearest keV) is printed in boldface type, followed by the measured half-life values, methods, and references. When a half-life has been reported only for a single level of the nucleus, the energy is included in the heading: for example, $t_{1/2}$**(0.087)**. A combined list of "others" references follows the data on all levels.

All states for which a half-life has been determined (either in a decay or in a nuclear reaction experiment) are included. Values are reported using the conventional time units defined in III.B. $t_{1/2}$. (Half-lives of isomeric states for which there is a separate tabular data section will be found in that section under the data catagory $t_{1/2}$.)

The *method* by which a half-life was determined is "direct" unless otherwise noted. Direct determination includes multiscaling. There is often a marginal distinction between a direct (multiscaler) and a delayed coincidence measurement; those methods by which it is possible to observe more than one event following the production of nuclei in the excited state (e.g., by a single beam burst) are considered direct.

Methods (other than direct) are denoted by the following abbreviations:

delay coinc Measurement of the time-interval distribution between the emission of two radiations, or between a beam burst and a radiation, by use of a time-to-amplitude converter or variable delay.

delay coinc sum Analysis of the line shape of a distorted sum peak resulting from γ rays populating and depopulating the state. (See PR C15 431(77).)

recoil dist Doppler Determination of the fraction of moving nuclei that decay within a known distance between a target and a stopping foil from the ratio of Doppler-shifted to unshifted γ rays emitted ("stopper" or "plunger" method).

nuclear recoil Determination, by mechanical (geometric) or electrostatic means, of the distance that a moving nucleus travels before decaying.

channeling effect Determination, by use of the channeling effect, of the distance that a moving nucleus travels before decaying.

Doppler Determination of the half-life of a nucleus moving through a stopping medium, by measurement of the broadening or shifting of emitted γ rays. (Includes "Doppler shift attenuation method".)

Coulomb excit, *e^- Coulomb excit* Determination of the half-life from the cross section for electromagnetic excitation by nuclei or electrons.

nucl res fluor Determination of the half-life from the resonant scattering cross section for γ rays.

level width Direct determination of the width, e.g., by Mössbauer spectroscopy.

hf deflection Determination of the delay between two coincident conversion-electron transitions by acceleration of one or both in a high-frequency electric field and measurement of the resulting energy shifts.

Various methods for particle-emitting levels, involving reaction cross sections; e.g., *from $\Gamma_p\Gamma_\gamma/\Gamma$ and Γ_p*.

$t_{1/2}$**(isomeric state)**, **γ(isomeric state)**: Data included under these headings describe a few short-lived (<<1 s) isomers for which no decay scheme is established (i.e., the energy of the state is unknown). Data formats, nomenclature, and methods of measurement are similar to those described for $t_{1/2}$**(levels)** and **γ**, respectively. If several such isomers occur in the same nucleus, they are designated by $t_{1/2}$**(isomeric state 1)**, $t_{1/2}$**(isomeric state 2)**, etc.

EC: *Electron-capture transitions*. Included are such properties as shell and subshell capture ratios (e.g., EC(K)/EC(L)), and ratios to β^+ decay (e.g., EC(K)/β^+). Data for transitions to specific levels in the daughter nucleus are given with the heading **EC(*E*)** [E = the level energy].

Internal bremsstrahlung endpoint: *Photon continuum accompanying EC or β^- decay*. Unless otherwise specified, the value listed refers to the endpoint of the entire spectrum. The heading may alternatively refer to the endpoint for a transition to a specified final level, the endpoint for (electron capture from) a specified shell, or both.

III.C. *Detailed level schemes*: Nuclear levels populated by radioactive decay are shown on a *detailed decay scheme*. A single decay scheme for each nucleus summarizes its level structure as observed in the decay of all parent isotopes and isomeric states. Unless otherwise noted, only levels and transitions that have been observed in radioactive decay are shown on a decay scheme. Some of the *numeric quantities* on decay schemes may be derived, totally or in part, from nuclear reaction experiments. In particular, the energies, spin-parity assignments, and half-lives on decay schemes are *adopted values* derived from all methods of measurement. γ-ray multipolarities and (occasionally) branching ratios may also be based on information from reaction studies.

The following is a description of the properties shown on decay schemes:

Levels are represented by horizontal bars, *transitions* by vertical arrows. Heavy bars denote ground states, and moderately heavy bars are used for long-lived isomeric states. Uncertain levels or transitions are represented by dashed bars or arrows. When the space between several levels immediately above (below) a transition arrow is inked in, the transition originates (terminates) at one or more of the initial (final) levels so grouped.

Level energies (MeV), in bold type, are located near the right end of a level. Superscript c or (c) appended to the energy means that the level is complex or probably complex.

Spins, parities, and other quantum assignments, also in bold type, are located near the left end of the level. Values given without parentheses are considered certain, values with parentheses only probable. For example, (1/2)+ means that the spin (1/2) is probable and the parity (+) is definite; 2,3(−) would indicate a spin of either 2 or 3, with probable odd parity.

Other model-dependent quantum numbers are given when appropriate. In deformed nuclei, K-quantum numbers are indicated implicitly by vertical alignment of the spins for members of the same band. Nilsson quantum numbers $K[Nn_Z\Lambda]$ are given for single-quasiparticle states. Isotopic spin is given, where appropriate, under the heading T. (Typically, T is given only for the lowest level with $T>T_Z[\equiv N-Z]$ and higher-lying states.)

Half-lives, in large type, are located to the left or right of level bars, or on the bar. (Most of the half-life limits that are tabulated have been omitted from the level schemes.)

Relative intensities of γ rays are located immediately above the transition arrow. These branchings represent *photon* intensities, normalized to a sum of 100 for transitions from each level.

γ-ray energies (MeV), in bold type, are located above the arrow (following the relative intensity if given). Only energies measured in radioactive decay are included.

The multipolarity of a γ ray is located on (to the left of) the transition arrow, near the initial level. (If there is no room on the arrow, the multipolarity is located above the transition, following the energy.) Parentheses mean that the multipolarity is probable rather than certain. For transitions of mixed multipolarity, percentage admixtures are given when known. The largest component is given first, without its admixture; for example, M1+7% E2 (≡ 93% M1+7% E2).

Absolute intensities of the γ rays are located on (to the left of) the transition arrow, near the final level. (If there is insufficient room on the arrow, the absolute intensity is located above the transition, following the energy and multipolarity.) Absolute γ-ray intensities are denoted by the *percent sign* (%); they always represent *photons per 100 decays of the parent isotope*. They are most commonly given on decay schemes that have only a single parent isotope. Whenever ambiguity is possible because of multiple parents or isomeric states, a comment is included, e.g., Absolute γ intensities refer to ^{230}U decay.

Particle emission from excited states is indicated by vertical arrows, above which the decay mode is printed in large type. These transitions are located to the left of any γ-ray transitions on the decay scheme. In cases where "delayed" neutron, proton, or α-particle transitions are known to populate specific levels of the daughter nucleus, relevant levels of that nucleus and the transitions are shown in detail. The positions of relative and absolute transition intensities with respect to the transition arrows and the interpretation of these quantities are the same as described above for γ-ray transitions.

β (and α) transitions from isomeric states are shown as short arrows from the isomer; details of the levels populated by these transitions will be found on the decay scheme for levels of the *daughter* nucleus. The absolute intensity located above the transition arrow represents β (α) transitions *per 100 decays of the isomeric state*.

Parent isotopes are located in the upper corners of the decay scheme: β^- parents to the left, EC+β^+ parents to the right, α parents on either side. The parent half-life, spin assignment, decay mode, and branching (if <100%) are given. A small half-dot on the decay arrow below the isotope bar marks the energy (Q-value) of the parent. Absence of the half-dot implies that the Q-value is larger than the highest level (of the daughter) shown. Q-values are given explicitly on the mass-chain decay scheme. Feeding of levels by β or α decay is given in transitions per 100 decays of the parent (%). An exception is made in the case of partial α emitters, for which the α feedings (denoted by † rather than %) sum to 100. (The total α branching is given with the decay mode, below the parent isotope.) In rare cases where absolute β branchings to levels are unknown, relative values (†) may be given.

Log ft values for β decay are given in italics, to the right of the feeding intensity. (When separate intensities are quoted for an EC and a β^+ transition to the same level, the average *log ft* is given, unless the two *log ft* values differ by >0.3 units. For first-forbidden unique transitions (ΔI=2, parity change), *log f_1t* is given (e.g., *9.3^{1}*).

α-decay hindrance factors are likewise given in italics following the α-group intensity. The values are based on the one-body theory (PR 71 865(47)), with the nuclear radius parameter adjusted to yield HF≡1 for the ground-state transitions of even-even nuclei.

A separate *reaction level scheme* is given for each nucleus whose levels have been characterized in nuclear reaction experiments. Levels, level properties, and transitions shown are those measured in reaction studies, except that the values of level half-lives are those adopted from all sources of measurement.

Spins and other quantum numbers have the same interpretation as on decay schemes. ℓ-transfer values are sometimes given, especially when they add significant information not contained in the spin-parity assignment, or when they encompass all that is known about the assignment. (In the latter case, the ℓ value is often given and the spin-parity omitted.)

γ-ray transitions are shown in one of two abbreviated forms. In the most common form, all transitions to a given final level are represented by a single arrow