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A Compilation of Modern Nuclear Decay Data
for High Resolution Gamma Spectroscopy*

F. F. Dyer and L. C. Bate
Analytical Chemistry Division
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830 USA

ABSTRACT

Recently published radionuclide decay data necessary for interpreting and quantifying high-resolution gamma spectra were collected and tabulated. The data, consisting of gamma energies and intensities and other information, e.g. half lives, fission yields, neutron cross section, etc, for over 500 radionuclides, were computer processed to yield a tabular form highly useful to gamma spectroscopists and activation analysts. The collection is unique in that many short-lived radionuclides, e.g. fission gases are included that are not found in similar data tables. Basically two computer listings are produced. The first table lists all data for each radioisotope arranged according to increasing atomic number (with increasing mass number for isotopes of the same atomic number). The source of reference for each nuclide is documented. The second table consists of a list of sorted gamma energies arranged according to increasing energy. Opposite each gamma energy is the contributing radionuclide symbol, its mass number and half life, a classification of nuclide type (e.g. fission product), several associated gamma energies and their intensities and a cross reference to the nuclide's entry in Table I. By careful attention to the elimination of non-prominent gamma rays Table II is kept manageably small yet sufficiently complete to permit spectroscopists to rapidly identify the lines of gamma spectra and/or check the results of spectral analysis codes. The data on magnetic tape along with a program to make listings are available to users on request to the ORNL Radiation Shielding Information Center. The organization of the tables, applications of the data to gamma spectral studies of reactor components and activation analysis and additional data needs will be discussed.

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1. Introduction

Large lithium-drifted germanium, Ge(Li) detectors have revolutionized the measurement of gamma-ray emitting radionuclides. These detectors can now be obtained with a counting efficiency of about one-fourth that of 3 in. x 3 in. sodium iodide detectors, and many laboratories are using Ge(Li) detectors with efficiencies greater than one-tenth that of NaI. These new larger detectors have resolutions as good as or better than the very small earlier ones. Thus one can have, for example, a detector with a relative counting efficiency* of 13% with a resolution of 2.1 KeV (FWHM) or better. Although these larger detectors are expensive, they have expanded the role of Ge(Li) from a research-only tool to one of analytical applications.

To effectively use Ge(Li) detectors in a wide variety of applications one must be able both to collect pulse-height spectra of several thousand channels and resolve the spectra by computers. Many laboratories combine these two functions with computers that function as pulse height analyzers. Ge(Li) gamma spectra are "resolved" by measuring the net areas of full energy peaks (total area minus underlying base line), calculating peak centroids and their corresponding energies, and computing photon emission rates for each peak. These arrays of energies and photon emission rates are then compared to entries of energies and intensities in radionuclide tables to determine likely isotopes responsible for the peaks. When candidates are found, photon emission rates are divided by appropriate fractional absolute intensities to obtain disintegration rates. Thus we see the need for extensive accurate nuclear data.

We began our collection of data about three years ago during a study of fission product distribution in a molten salt nuclear reactor. Early in that study we began to collect gamma spectra with one to three hundred full energy peaks. Many of the radionuclides measured were rather short lived and because of the great number of peaks it was difficult to assign many of them to known radioisotopes. Except for the table by Gunnink et al [1] for some of the relatively long lived radionuclides, there were no lists of sorted accurate gamma energies that we could use to identify spectral lines. We thus began a systematic collection from the literature of fission product energy and intensity data and eventually processed about 1000 of these complex spectra [2]. Since that time we have expanded our data collection to all types of radionuclides and have included all data necessary for absolute neutron activation analysis. The collection now includes data for 513 radionuclides. The data are stored and edited on a master card file from which we generate listings and duplicate files on magnetic tape.

2. Criteria for Selection of Data

Where possible we have selected for inclusion in our data collection gamma energy and intensity data from critically evaluated publications such as the one by Martin and Blichert-Toft [3]. We have also relied heavily on the well founded experimental studies of Gunnink et al [1]. In the case of those radionuclides

*Relative counting efficiency is derived by counting a ⁶⁰Co source with both a Ge(Li) and a 3 in. x 3 in. NaI detector with the source placed 25 cm from both detectors. 100 times the ratio of that count rate of the 1332 KeV line obtained with Ge(Li) to the corresponding count rate for NaI is the relative counting efficiency.

that have been studied by two or more investigators in the past few years, we normally select the most recent reference provided that the investigator:

(1) has used the best modern experimental techniques, (2) was aware of the existing data for the radioisotope, and (3) gave adequate explanations for any large differences or unexpected results obtained (if any) compared to the existing data. In some instances we have been unable to choose between two or more references and have included separate entries for both references in our collection. Some radionuclides, of course, have been studied very little (for example, many short-lived fission products); and for these we tabulate whatever we can find. We do not, however, tabulate older values of gamma energies that have been determined by NaI spectroscopy and which may be uncertain by 10 KeV or more. We have used some of the older gamma intensity values where no recent study exists.

3. Data Editing Program

A computer program (NUCDAT) is used to read the data either from punched cards or magnetic tape, prepare new tapes from a master card file or copy existing tapes. NUCDAT makes listings of the data either from tape or cards as desired. The program will also generate radionuclide data libraries for both large and small computer programs that are used to process Ge(Li) gamma-ray spectra at Oak Ridge National Laboratory.

4. Content and Organization of Tables

Principally two tables are listed by NUCDAT. Table 1 consists of card images of the input data edited to be easily read. An example of a slightly abridged entry in Table 1 for the radionuclide ^{103}Ru is shown on page 4. One line (card) is used for all data such as half lives, cross sections, fission yield, etc. as shown in the example. Two lines are used for references and other notes; and the remainder of the entry consists of gamma energies and intensities. Energies are given in KeV, and are punched on cards with as many significant digits as given in the reference. Two digits after the decimal are printed; usually only one is significant. Intensities are expressed as photons emitted per 100 decays (absolute percentage, status A) if such values are available. In many instances only relative intensities are available (status R). We occasionally classify the intensity status as "D" when it appears, but we are not completely sure, that the intensities are expressed in absolute percentages.

To aid in identifying lines in gamma spectra, we classify radionuclides into categories according to the manner in which they are normally produced. As shown in the example of ^{103}Ru — class 0 denotes a neutron capture product, 1 a fission product, 2 a radionuclide formed both by fission and neutron capture, 3 a neutron deficient radionuclide formed by charged particle bombardment, 4 a natural radionuclide, 5 a special "catch all" category, and 6 represents a fission gas. We have just recently classified fission gases in a separate class to cause our computer to reject identifications of fission gas daughters when we are interested only in the gases. More will be said later about the uses of a radionuclide classification system.

Table II, whose listing by NUCDAT is optional, consists of a sorted list of gamma energies, arranged by increasing energy, with several items of associated information given with each gamma energy. This table was designed for use by gamma spectroscopists and activation analysts to aid in identifying lines in gamma spectra. A spectroscopist may know the energies of the lines in a spectrum and wish to identify their radionuclide sources or more typically may wish to confirm (or deny) an identification made by a computer program. Because there are

EXAMPLE OF RADIONUCLIDE DATA ENTRY IN TABLE 1

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
217	RU123	44	39.6	D	B-	RU122	51.51	1.40	2	3.6	7	A	4.2			

REF. F.J. MARTIN AND P.M. BLICHERT-TOFT RADIOACTIVE ATOMS,
 INT. NUCLEAR DATA TABLES, SEC. A, VOL. 2 (1977).
 ENERGY Z INT. ENERGY Z INT. ENERGY Z INT. ENERGY Z INT.
 39.55 0.056 53.11 0.34 204.58 2.217 443.85 0.360
 406.80 79.2 556.90 0.80 612.23 5.40

WHERE THE HEADINGS DENOTE:

- A=TABLE 1 ENTRY NUMBER
- B=ISOTOPE SYMBOL
- C=MASS NUMBER
- D=STATE:CLANK=GROUND STATE,N=METASTABLE STATE
- E=ATOMIC NUMBER
- F=HALF LIFE
- G=TIME UNIT OF HALF LIFE
- H=MODE OF DECAY: EC=ELECTRON CAPTURE,B-=NEGATRON DECAY,
 B+=POSITRON DECAY
- I=PRECURSOR SYMBOL FOR NEUTRON CAPTURE PRODUCT
- J=PRECURSOR MASS NUMBER
- K=NATURAL ABUNDANCE IN PERCENT OF PRECURSOR
- L=2200 M/SEC NEUTRON CAPTURE CROSS SECTION OF PRECURSOR
- M=CLASS OF RADIONUCLIDE:1=NEUTRON CAPTURE PRODUCT
 1=FISSION PRODUCT,2=BOTH NEUTRON CAPTURE AND FISSION
 PRODUCT,3=NEUTRON DEFICIENT RADIONUCLIDE,4=NATURAL
 RADIONUCLIDE,5=SPECIAL RADIONUCLIDE CLASS,6=FISSION
 GAS.
- N=FISSION YIELD IN PERCENT
- O=NUMBER OF GAMMA RAY ENERGIES TABULATED
- P=INTENSITY STATUS OF GAMMA RAYS:A=ABSOLUTE PERCENT
 (GAMMAS PER 100 DECAYS),R=RELATIVE,D=POSSIBLY ABSOLUTE
- Q=NEUTRON CAPTURE RESONANCE INTEGRAL

many thousands of gamma rays (many of which have nearly the same energies) emitted by radioisotopes, it is impossible to design a "fool proof" identification algorithm. Because computer programs frequently make mistakes in identifications it is necessary for spectroscopists to check their identifications.

Considerable effort was devoted to obtaining an arrangement of Table II that would permit the table to be used easily and efficiently. Typical entries for gamma rays of ^{56}Mn and ^{134}I are on page 6. For ease of reference, sorted energies are listed down the left margin. The items associated with each energy are listed across the page in what we have found to be an order of decreasing importance with respect to the identification of spectral lines. Normally the information of Table II is more than enough to identify all the radionuclides that produce a gamma spectrum. Adjacent to each energy is the radionuclide symbol and mass number followed by the radionuclide class, half life, the number of gamma energies tabulated in Table I and a cross reference to the radionuclide's entry in Table I. The class and half life are quantities that normally are the most important ones in rejecting invalid radionuclide candidates for spectral lines. The spectroscopist normally knows if a specimen that he is attempting to analyze can possibly contain fission products, neutron capture products, etc. He rejects candidates of the wrong class. He also rejects candidates whose half lives are incompatible with the specimen's decay time. For ease of application half lives are listed in their conventional units rather than a standardized unit. If, after these rejections, there still are two or more candidates from the sorted gamma energy list other associated energies may be examined. If they exist we list in Table II up to 12 associated gamma energies. These energies are again sorted and listed in order of decreasing intensity. Thus to make a spectral line identification it is normally only necessary to refer to the first two or three energies. Although normally two or three energies are sufficient to identify a radionuclide, we want to have the energies of the most intense gamma rays listed in Table II so that most of the lines in a spectrum can be easily identified. Listing too few would permit isotopes to go unidentified as well as cause a too frequent reference to Table I to get the "complete picture." Listing too many energies would make Table II too large to be manageable (if a radionuclide has 5 sorted energies it appears 5 times in Table II). We have found that the most useful version of Table II is produced if we sort either 12 gamma rays or up to that gamma ray whose intensity is one percent of the most intense one. Since most of our work does not involve neutron deficient radionuclides we find it useful to leave these radionuclides out of Table II. In this way we produce a compact but highly useful aid to our efforts in spectral line identifications.

The program NUCDAT will sort and list in Table II any one class or combination of classes desired. Thus it is possible for the user to produce any version of Table II that meets his needs.

5. Applications of this Data Collection

As previously mentioned we generate, from this collection of data, files that are used in computer programs to identify and measure peaks in gamma ray spectra. Currently most of our efforts are devoted to small computer applications. We have two Nuclear Data 50/50 systems each consisting of a 4096-24-bit word hardwired analyzer and an 8192-18-bit word PDP-15 computer. Program MONSTR [4] is used to identify and measure peaks, calculate disintegration rates and parts per million for activation analysis problems. Identifications are made from a magnetic tape file of sorted gamma energies arranged with increasing energy. All of the energy entries of Table II are recorded in this file. Each energy has associated with it the mass and atomic

Energy	Nuclide	Type	Half Life	NGT	ISO	Energy	Intensity	Energy	Intensity	Energy	Intensity	Energy	Intensity
846.60	Mn 56	0	2.57H	3	185	846.60	99.00	1811.20	30.00	2112.6	15.5		
847.03	I 134	1	53.00M	29	308	847.03	96.0	884.08	66.00	1072.53	14.30	595.40	11.20
						621.75	10.90	1136.12	9.15	540.80	8.60	677.34	8.20
						405.44	7.35	857.28	6.60	1806.90	5.60	974.63	4.93

Example of Typical Entries in Table II for Gamma Rays of ^{56}Mn and ^{134}I

where the Headings Denote:

TYPE = Radionuclide class as previously defined.

NGT = Total number of gamma energies tabulated in Table I.

ISC = Cross reference to Table I where data for Radionuclides are tabulated.

numbers, the nuclide type, and the half-life in seconds. Candidates for the lines of a spectrum are selected by comparing spectrum and tape energies, nuclide types with a preset list of the nuclide types that may be present, and half-lives with the decay time. Candidates may also be entered manually in the candidate list.

During the search for candidates, a list of unidentified peaks is produced. Subsequently a radionuclide file is read with all information necessary to compute disintegration rates or elemental concentrations for activation analysis problems. Because the computer's memory is small, we read the radionuclide file one entry at a time until computations for all candidates were finished.

We are using these systems and this collection of data to carry out a wide range of work in absolute neutron activation analysis, and radionuclide measurements. We have just begun to test our scheme of absolute neutron activation analysis on standard samples whose trace element content has been well established and documented by comparative neutron activation analysis and other reliable methods. Using this approach, we hope to critically evaluate much of the data we have collected for neutron capture radionuclides.

We are also using high resolution gamma spectroscopy to study the release of fission products from the fuel of high-temperature gas cooled reactors and in-pile experiments. Although our reactor experiments are carried out to further our understanding of reactor components, they sometimes yield approximate values for absolute values of gamma-ray intensities. Recently, for example, an in-pile fission gas release study indicated that the absolute intensity of the 258 KeV gamma-ray of ^{138}X is 30 percent -- a value closely approximating 32.5 percent as reported by Monnard [5].

6. Availability of Data to Users

Individuals or organizations who wish to obtain copies of these data can do so by sending a 1200 foot reel of industry compatible magnetic tape to the Radiation Shielding Information Center, Oak Ridge National Laboratory, and requesting data file DECAYGAM. A copy of the editing program NUCDAT written in FORTRAN IV and user's instructions will be supplied with the data.

7. Some Final Observations

Undoubtedly special problems will always arise in which radiochemical and/or comparative methods of radionuclide analysis will be required. Nevertheless it seems inevitable that the current trend in instrumental absolute methods of neutron activation analysis and gamma spectroscopy using Ge(Li) detectors supplemented by coincidence and anticoincidence techniques will continue. This trend is due not only to investigator's research interests but also to the simplicity and power of these methods as well as economic realities. For most organizations it has become economically infeasible to obtain by comparative activation analysis the large number of analytical results required in such studies as trace element surveys of ecological and biological materials. In other areas of work such as gamma-ray scanning of nuclear fuel elements and other nuclear reactor components, the instrumental techniques are the only ones applicable.

In our current tabulation of data for 513 radionuclides, 164 have only relative gamma-ray intensities. Since the data for those radionuclides that are listed with absolute intensities were gathered from publications of reputable investigators, the data are presumably reliable. We, however, have tested

the reliability of only a few. It is therefore evident then that much of the task remains in determining, evaluating and compiling a complete, reliable radionuclide data file for applied gamma spectroscopy.

There are also significant needs for data in other areas of applied nuclear technology. An example is the requirement of fission yields as a function of neutron energy for fission of ^{235}U , ^{239}Pu and other heavy nuclides to permit fission-product inventory calculations for the newer types of nuclear reactors such as the high temperature gas cooled reactor. It appears that much of this data has not been measured. Other examples of data needs can be found in the areas of shielding and dose-rate calculations.

At the present time there is no unified collection of nuclear data for applied nuclear technology. Although the applied nuclear scientists must use the variety of data that has been mentioned (radionuclide decay data, cross sections, etc), he must search for it in sources that are too diverse. We therefore believe that there is a place for specialists who would be responsible for evaluating and compiling complete nuclear data files that the user could apply easily and efficiently. The compiler should maintain communication with users to determine areas where additional data are needed. He should also assist in publicizing these needs. If such an effort were made with care, the extreme duplication of efforts now occurring in this endeavor would be reduced and the life of the applied nuclear scientist would be easier.

8. Acknowledgements

Although the sources of data are given for each radionuclide in our data file, we wish to acknowledge four specific sources. We especially thank the Nuclear Data Group of the Oak Ridge National Laboratory for the use of their splendid reference files which led us to much of the information collected. Our gratitude also goes to the Radiation Shielding Information Center of ORNL for their cooperation in making the data available to the scientific community. We wish to thank Ray Gunnink of the Lawrence Radiation Laboratory for his permission to include in our collection results from much of his experimental measurements [1]. Finally, we reference the papers of Adams and Dams [6,7] from which we have drawn heavily.

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