Overview of Nuclear Data

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Abstract

For many years, nuclear structure and decay data have been compiled and disseminated by an International Network of Nuclear Structure and Decay Data (NSDD) evaluators under the auspices of the International Nuclear Data Committee (INDC) of the International Atomic Energy Agency (IAEA). In this lecture I will discuss the kinds of data that are available and describe various ways to obtain this information. We will learn about some of the publications that are available and Internet sources of nuclear data. You will be introduced to Isotope Explorer software for retrieving and displaying nuclear structure and radioactive decay data. The on-line resources *Table of Radioactive Isotopes*, *PGAA Database Viewer*, *Nuclear Science Reference Search*, *Table of Isotopes Educational Website*, and other information sources will be discussed. Exercises will be provided to increase you ability to understand, access, and use nuclear data.

Contents

1   Introduction to Nuclear Structure and Decay Data

Nuclear structure and decay data have been compiled and evaluated for nearly seventy years. Indeed it is interesting that the first *Tabelle Riassuntive E Bibliografia delle Trasmutazioni Artificiali*[Fea35], shown if figure 1, was published here in Italy by Giorgio Fea in Nuovo Cimento in 1935. A later compilation was published by Livingston and Bethe [Liv37] and the *Table of Induced Radioactivites* was published by Livingood and Seaborg [Liv40] on 1940. Nuclear information increased rapidly in the following years, and many organizations involving dozens of compilers and evaluators were formed to analyze, organize, and disseminate a flood of information. Among these efforts were the *Nuclear Data Sheets* (Oak Ridge, Brookhaven) [NDS], *Table of Isotopes* (Berkeley) [Sea44, Sea48, Hol53, Str58, Led67, Led78, Fir96], *A=3-20* (University of Pennsylvania, Triangle Universities Nuclear Laboratory) and *A=21-44* (University of Utrecht) [NPA]. These and other efforts were united into the International Network of Nuclear Structure and Decay Data Evaluators (NSDD) under the auspices of the International Atomic Energy Agency Nuclear Data Section (IAEA/NDS).

When I published the 8th *edition of the Table of Isotopes* in 1996 [Fir96] the publication had grown to 3000 pages. Following the emergence of the Internet, nuclear data is now readily available on-line from many sources including the IAEA/NDS, National Nuclear Data Center (NNDC) at Brookhaven National Laboratory, and the Isotopes Project at Berkeley. I will discuss how to access these information and describe some utilities that are available to search and display data.

2   What is (are) Nuclear Data?

Each of us has a different definition of nuclear data. Traditionally, the nuclear reactor community thinks of nuclear data mainly in terms of cross sections and related information. The nuclear structure community looks on nuclear data as information about nuclear levels and their properties. Radiochemists are most often concerned with alpha-, beta-, and gamma-radiation energies and emission probabilities. Nuclear medicine and health physics want dosimetry data. Other nuclear data users want only one quantity such as half-lives, atomic masses, or nuclear moments. My nuclear research interests have spanned several fields including nuclear structure, radioactive decay, environmental nuclear tracers, archaeology, and prompt and delayed neutron activation analysis. In this lecture I will concentrate on nuclear structure and decay data. Nuclear reaction data will be discussed later in this workshop. I hope to provide you with a broad overview of nuclear data so that you come away with a broader understanding of the information that are available, and a greater ability to find what you need for your application. Before we begin, let us start with a brief refresher course about where the nuclear properties come from.

Although many of you are not primarily interested in nuclear structure, a knowledge of nuclear level schemes will help you understand the physical source of radiations we observe. Figure 2 shows the well known level scheme for ^{99}Mo decay.

The ground (lowest energy) state of ^{99}Mo emits beta minus (electron) particles and neutrinos to three possible final states in ^{99}Tc. Since the neutrino and the electron share the decay energy, the beta spectrum is continuous. Levels are populated randomly by decay, but each state receives a fixed feeding percentage after many decays. Note that all of the levels

Ligne

GIORGIO FEA

TABELLE RIASSUNTIVE E BIBLIOGRAFIA
DELLE TRASMUTAZIONI ARTIFICIALI

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NICOLA ZANICHELLI, EDITORE

BOLOGNA 1935-XIII

Figure 1: The first Table of Isotopes.
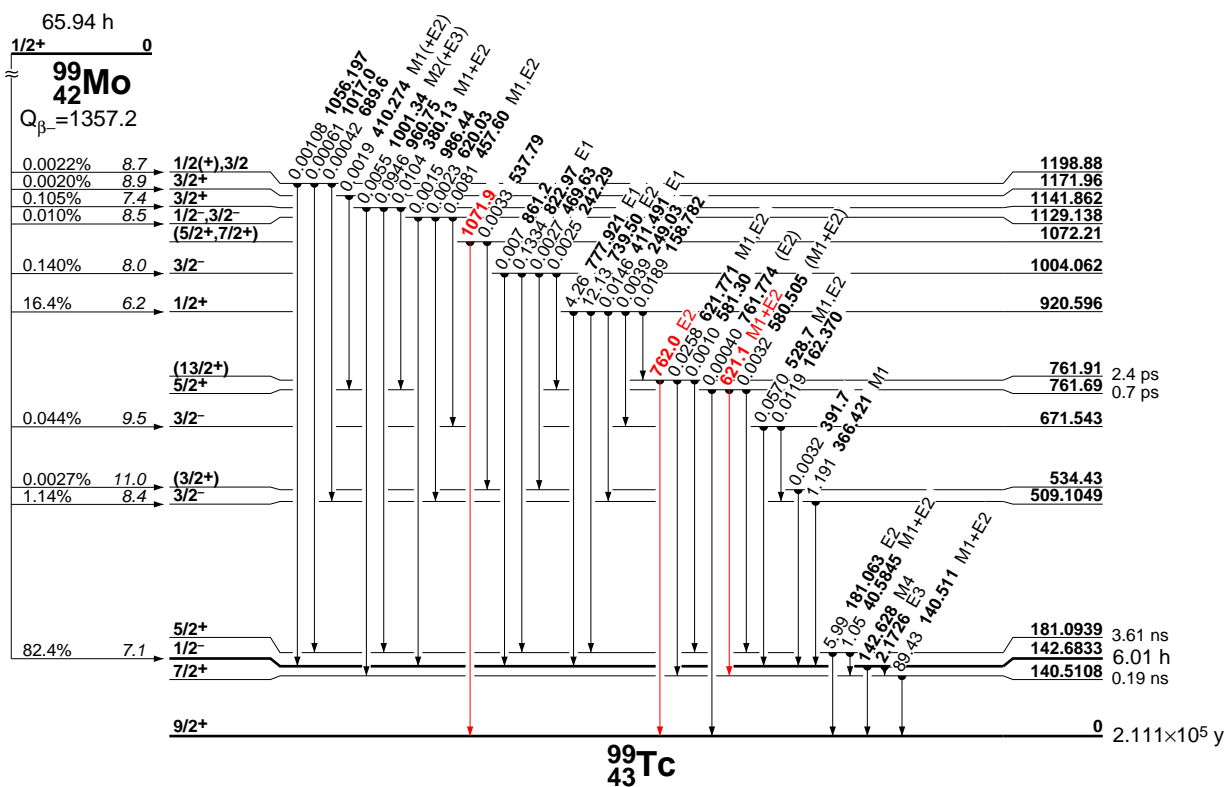
Figure 2: Level scheme for ^{99}Mo decay.

have properties called spin and parity, shown on the left. Not all levels are populated by beta decay because only when the spin change is small can decay occur rapidly. Also, only those levels that exist below the Q-value energy can be fed. When a level is populated by beta decay it may subsequently decay by the emission of gamma rays to lower-energy levels. Again, the gamma ray path is random, but after many decays the gamma-ray intensities will be distributed as shown. Note that the gamma rays are denoted with a "multipolarity" which may be M1, E1, E2 or something else. The multipolarity can be used to describe the angular distribution of gamma rays with respect to the nucleus or each other. Usually gamma-rays are not emitted isotropically.

Whenever a level can decay by gamma ray emission, it can also decay by conversion electron emission. In that case an atomic electron is ejected from the atom leaving an atomic vacancy which is quickly filled by other electronic transitions which in turn emit x-rays and Auger electrons. Conversion electron, x-ray, and Auger electron energies and intensities can be calculated if the transition multipolarities are known.

Most nuclear levels are very short lived, so the decay gamma rays follow the half-life of the parent level. Some nuclear levels are long lived isomers like the 142.6833 keV level in ^{99}Tc with a 6.01 h half-life. In that case the gamma intensity will vary with time. Since ^{99}Mo (65.94 h) is much longer lived than ^{99m}Tc, the daughter gamma rays will be in "equilibrium" for several hours.

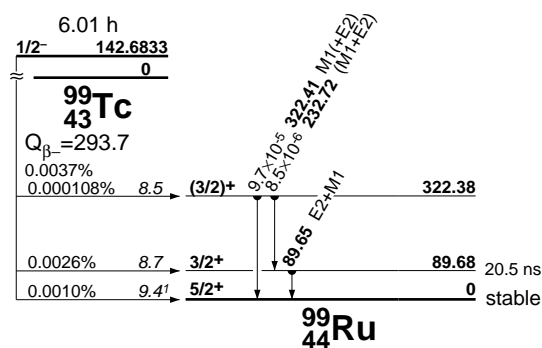Figure 3: Level scheme for ^{99m}Tc decay.

Many isomers de-excite by beta or alpha decay in addition to gamma ray emission. The gamma ray decay of ^{99m}Tc is shown in figure 2, and the beta decay is shown in figure 3. Exotic decay modes also exist including spontaneous fission, proton or neutron emission (prompt or delayed), and even light isotope emission.

We will also discuss prompt gamma ray data from thermal neutron capture. When an isotope captures a thermal neutron, it exists in an excited neutron capture state of well defined energy as shown in figure 4. This state immediately de-excites by the emission of prompt gamma rays which can be detected for Prompt Gamma-ray Activation Analysis (PGAA). If an isomer is populated, or the ground state is radioactive, subsequent delayed gamma rays may be detected for Neutron Activation Analysis (NAA).

3   Printed Sources of Nuclear Data

Despite the growth and convenience of the Internet, printed sources of information are still widely used because they are convenient and familiar. In some laboratories access to the Internet is limited making published sources of information essential. Many laboratories and authors have published nuclear information and it would be impossible for me to mention all of them. The following publications are among my favorites.

3.1 8th edition of the Table of Isotopes [Fir96]

This 2-volume, 3000 page book includes comprehensive nuclear structure and radioactive decay information for nearly all known isotopes. Summary "skeleton scheme" drawings for each mass chain, detailed decay scheme drawings, and recommended decay gamma-ray energies and intensities make this book especially useful. The book comes with a CD-ROM containing an Acrobat PDF version with convenient links between related material and indexes. Additional local Internet resources and Isotope Explorer software, which will be discussed later in this lecture, are included. The 1998 update consists of an updated CD-ROM and a 138 page booklet containing the Isotope Explorer manual, isotope summary tables, and energy ordered table of radioactive decay gamma-rays and alpha particles. The 1999 update
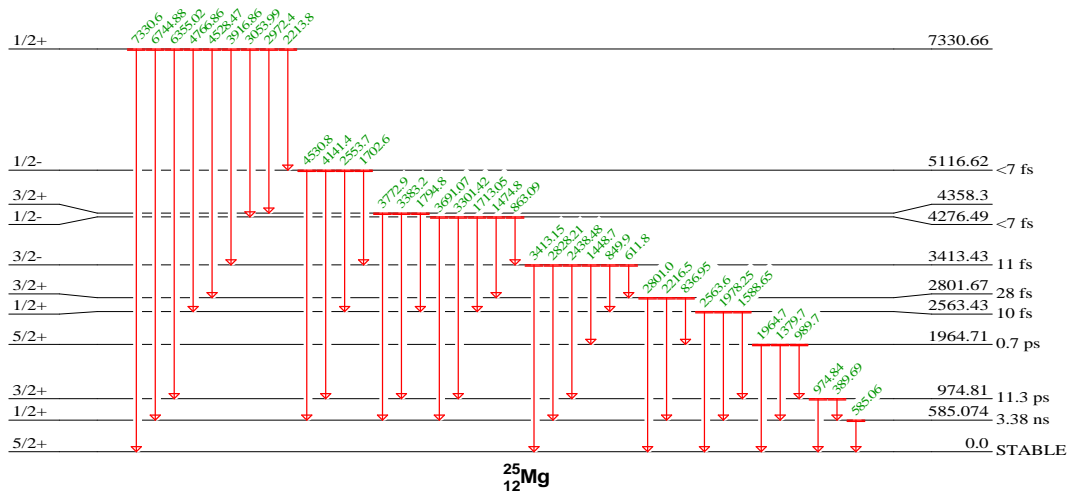
Figure 4: Level scheme for ^{24}Mg(n,γ) thermal neutron capture.

also contains an updated CD-ROM and summary nuclear structure tables. Many appendices of chemical, physical, and atomic properties, and information about standard radiation sources, interaction of radiation with matter, and nuclear physics are provided.

3.2 Table of Radioactive Isotopes, [Bro86]

This book was designed for the applied user of nuclear data. It contains summary "skeleton scheme" drawings for each mass chain, specific activities, production modes, tables of x-ray, gamma-ray, alpha particle, and other radiation energies and absolute transition probabilities, and beta and internal bremsstrahlung spectral data. A major advantage of this book is that nearly complete radiation energies and emission probabilities are provided for nearly all isotopes for the applied user.

3.3 Energy Levels of Light Nuclei, A=3-20 [NPA]

Nuclear structure information and level energy diagrams for nuclei with A=3-20 published in Nuclear Physics A [NPA] by evaluators and the University of Pennsylvania and Triangle Universities National Laboratory.

3.4 Nuclear Data Sheets [NDS]

This journal publishes nuclear structure data evaluations from the Evaluated Nuclear Structure Data File [ENSDF] for A$\leq$44 and is available in many libraries. The evaluations include the best experimental results for various radioactive decays and nuclear reaction studies. The adopted nuclear properties include level schemes and excitation energies, Half-lives, decay modes, spin-parity values and their basis, magnetic dipole moments, electric quadrupole

moments, disintegration energies, radiations, transition probabilities, and band structure. Decay schemes, level schemes, and isobaric chains are displayed. If you want a detailed discussion about nuclear data, and your main interest is in nuclear structure physics, then the Nuclear Data Sheets are the place to go.

3.5   Nuclear Wallet Cards [Tul00]

This pocket summary of isotope spins, parities, mass excesses, half-lives, natural abundances, and decay modes is available at no charge from the National Nuclear Data Center, Department of Energy Sciences and Technology Brookhaven National Laboratory P.O. Box 5000 Upton, NY 11973-5000. Copies are available for the participants in this workshop.

3.6   Chart of the Nuclides [Knoll]

The Chart presents a plot of all known elements and radioactive nuclides. The nuclides are arranged with atomic number Z (number of protons) along the vertical axis and neutron number N along the horizontal axis. Each horizontal row on the Chart represents one element; entries along that row show all of the isotopes of that element. Data presented for each nuclide include atomic mass, relative abundance, half-life and modes of decay, as well as a variety of other nuclear properties. The Chart is available as a 32" x 54" single sheet or a bound 65-page booklet containing both the Chart and explanatory information. It can be ordered at a cost of 25 dollars, and student discounts and quantity discounts are available. This chart belongs on the wall of your laboratory, but hang a magnifying glass next to it if you want to read the compact detailed information it offers.

3.7   IAEA Technical and Scientific Reports [IAEA]

A variety of authoritative nuclear data publications are available from the International Atomic Energy Agency, Nuclear Data Section, at no charge. For more information, find them on the Internet at http://www.iaea.or.at/programmes/ripc/nd/publications.htm.

4   Websites Providing Nuclear Data

Most people can find the nuclear data that they need on the Internet. You can even write your own reference book by printing the data that you need. Many websites provide a wide variety of nuclear data. The following list is by no means complete, but it includes some of my favorites.

4.1   LBNL Isotopes Project Nuclear Dissemination Home Page (Berkeley)

Most of the nuclear data resources we will discuss in this lecture are found on my website at http://ie.lbl.gov/toi.html. Of course I am biased when I say this is the first place you should go, but over 150,000 people from every corner of the world use this website annually.

4.2 Atomic Mass Data Center (Orsay)

You can visit this website at http://csnwww.in2p3.fr/amdc/amdc_en.html for an authoritative source of evaluated experimental atomic mass data. You can download NUBASE which contains experimentaly known nuclear properties, and some that have been estimated from extrapolation, for 3010 nuclides: mass, isomeric excitation energy, half-life, spin, parity, decay modes and intensities.

4.3 Gamma-ray Sectroscopy Center (Idaho Falls)

This center at http://id.inel.gov/gamma/ provides specialized data and technical services in the field of Gamma-ray Spectrometry for radiation measurements in many disciplines. The site includes integrated technical reference material of gamma energies, decay spectra and actual spectral Data in catalog form, history of gamma-ray Spectrometry at the INEEL, and Links to other sources of nuclear data for educating and supporting users who are applying Gamma-ray Spectrometry to an expanding experimental and application based environment. You can see experimental gamma ray spectra here.

4.4 IAEA Nuclear Data Services (Vienna)

Go to http://www-nds.iaea.org/ for a variety of information and services that are products of the Network of Nuclear Reaction Data Centres, the Network of Nuclear Structure and Decay Data Evaluators, and the Data development programme of the Nuclear Data Section, IAEA. We wouldn't have much to talk about without the IAEA nuclear data efforts.

4.5 National Nuclear Data Center (Brookhaven)

Visit http://www.nndc.bnl.gov/, for the main US repository for the Evaluated Nuclear Structure Data File [ENSDF] and nuclear reaction databases including NSR, ENDF, CINDA, and CSISRS. Many nuclear data utilities and services are available here and mirrored at the IAEA website in Vienna.

4.6 National Institute of Standards and Technology (NIST, US)

Standard data physical reference data at http://physics.nist.gov/PhysRefData/contents.html. Physical constants, atomic and molecular spectroscopic, ionization, x-ray and gamma ray, dosimetry, nuclear physics and other data.

4.7 Nuclear Data for Charged Particle Activation (Belgium)

At http://allserv.rug.ac.be/ kstrykmn/nuclear/#Q-value you will find links to decay and cross section data.

4.8   Particle Data Group (Berkeley)

My neighbors at http://pdg.lbl.gov/ are the principal source for elementary particle data for $A \leq 1$.

4.9   Reaction Rates for Stellar Nuclear Synthesis (Livermore)

Astrophysicists go to http://www-phys.llnl.gov/Research/RRSN/ for the compilation of stellar nuclear reaction rates for light, intermediate mass, and heavy nuclei used in calculations of stellar nucleosynthesis. Most of these data are calculated because these data are beyond our current means of measurement.

4.10   SigmaBase (Idaho State University)

Try the http://www.physics.isu.edu/sigmabase/ database and data server that provides programs, data (cross sections), and documents that are of interest to the Ion Beam Analysis community.

4.11   T2 Nuclear Information Service (Los Alamos)

An excellent website at http://t2.lanl.gov/data/data.html for reaction data, Q-values, photonuclear data, and astrophysics data. They offer a lot of cross section data too.

4.12   TUNL Nuclear Data Evaluation Group (North Carolina)

A fine website at http://www.tunl.duke.edu/nucldata/ showcasing their nuclear structure evaluations for $A \leq 20$ which are published in Nuclear Physics A [NPA].

5   Internet Nuclear Data Resources

These are some of the websites I will discuss where you can actually find the data that you need. If you visit the websites described in the previous sections, you will find even more information.

5.1   Nuclear Science References Server

At http://ie.lbl.gov:6023/welcome.htm you can perform literature searches using the Nuclear Science Reference [NSR] that contains approximately 170,000 literature references on nuclear physics from 1910 and forward. This database can be searched by any combination of cutoff year; nuclide; even/odd mass, atomic number, or neutron number; reference keynumber; author(s); reaction (e.g. $^{12}C(n,\gamma)$), or keyword (e.g. fission). The result of a search is a list of references with author(s), title, and an abstract of the contents. In some cases the reference is linked to the publisher's website where the article can be downloaded.

5.2   Elemental Data

Elemental data can be found at http://ie.lbl.gov/elem/elem.htm. Here you can download a periodic table of the elements displaying the electronic structure, boiling and melting points, oxidation states, atomic weights, and abundance in the solar system for each element. There is also a table of chemical properties including atomic weight, density, melting point, boiling point, critical point, ionization potential, and specific heat. Additional tables show elemental abundances in the solar system, earth's crust, and the sea, and IUPAC recommended isotopic abundances. Finally, there is a table of physical constants. Tables of recommended mass excesses, binding energies, decay Q-values, and neutron or proton separation energies are available here.

5.3   Atomic Masses

Experimental and theoretical atomic mass data are found at the Isotopes Project Atomic Mass Data Home Page at http://ie.lbl.gov/toimass.html. A convenient reaction Q-value calculator is available from the Lund Nuclear Data WWW Service at http://nucleardata.nuclear.lu.se/database/masses/.

5.4   Atomic Data

Atomic data are found at the Isotopes Project Atomic Data website at http://ie.lbl.gov/atomic/atom.htm. Tables and graphs of internal conversion coefficients are provided here. Also, atomic binding energies, fluorescence and Koster-Cronig yields are available. Finally, a detailed table of x-ray and Auger electron energies and intensities for vacancies in K, L_1, L_2, and L_3 atomic subshells is presented.

5.5   Exploring the Table of Isotopes

Exploring the Table of Isotopes at http://ie.lbl.gov/education/isotopes.htm provides a periodic table with each element linked to a table of the know isotopes and their half-lives, spin, parity, decay modes, and natural abundances. Each isotope in the table is linked to more detailed information from the WWW Table of Radioactive Isotopes which is discussed below. Exploring the Table of Isotopes also provides general information about isotopes including an animated glossary guaranteed to both edify and amuse.

5.6   Isotopes Project Decay Data Home Page

Summary decay scheme drawings (skeleton schemes) and nuclear charts from the *8th edition of the Table of Isotopes* [Fir96] are available here. Energy-ordered tables of gamma-rays and alpha particles are also provided. Standard alpha and gamma-ray source information have been tabulated, and the database from the 1986 *Table of Radioactive Isotopes* [Bro86] can be downloaded here.

5.7   WWW Table of Radioactive Isotopes

The WWW Table of Radioactive Isotopes was developed in collaboration with Dr. L.P. Ekstrom of Lund University and is available at http://ie.lbl.gov/toi/. It provides comprehensive access to radioactive decay data from the *8th edition of the Table of Isotopes* [Fir96]. These data can be accessed either by a radiation or nuclide search.

The radiation search allows the user to search the gamma ray or alpha particle databases by energy and parent half-life, mass number, element atomic number, and/or neutron number. The result of the radiation search is a table of energies, disintegration probabilities, and associated parent information including decay mode, half-life, and a link to other data for that parent.

The nuclide search allows the selection of a range of mass numbers, an atomic number or element, the neutron number, and/or a range of half-lives. It returns a list of the nuclides that meet these criteria and their decay modes, half-lives, excitation energies, spins, parities, and a link to other data for each parent. Alternately, periodic table is provided with links to the isotopes of each element.

Selection of an isotope opens a series of tables and links to drawings for that isotope. The first table provides the half-life, spin and parity, neutron and proton separation energies, production modes, and reference information. The second table lists all of the decay modes, branching intensities, Q-values, and references for the isotope.

The third table provides links to interactive HTML radiation tables, the original ENSDF format datasets, and applets to display level scheme drawings and beta spectra. It is important to note that the beta spectrum applets can be downloaded into a text editor where the spectrum can be extracted for use in other utilities. Additional tables of gamma-ray, x-ray, alpha particle and beta decay branching energies and transition probabilities are provided as needed.

5.8   Gamma-ray Spectra

It is often useful to see gamma-ray spectra. Go to the periodic table menu for the INEEL Gamma-ray Spectrum Catalogue of Isotope Spectral Data at http://id.inel.gov/gamma/actinide.html. Take a look at the ^{57}Co spectrum.

5.9   Fission Data

The evaluation of fission yields by England and Rider [Eng94] is available on the Isotopes Project Fission Data Home Page at http://ie.lbl.gov/fission.html. Tables of independent and cumulative yields of isotopes from spontaneous, thermal neutron induced, fast pooled neutron induced, and high energy neutron induced fission of a variety of isotopes are provided. ^{252}Cf spontaneous and ^{238}U(n,γ) induced fission prompt gamma-ray data are also provided.

5.10   Neutron Capture Data

The Isotopes Project Thermal Neutron Capture Home Page is found at http://ie.lbl.gov/ng.html. Currently thermal neutron capture data from the ENSDF file, including energy-ordered gamma-ray tables, and radiative cross section by Mughabghab et

al [Mug81, Mug84] are available. These pages are in the process of being updated to include the recent results of the IAEA Coordinated Research Project to produce a *Database of Prompt Gamma-rays from Slow Neutron Capture for Elemental Analysis.* The PGAA database viewer will be described later.

5.11 Nuclear Databases

Recent releases of the complete ENSDF, NSR, and Table of Radioactive Isotopes [Bro86] databases can be downloaded at http://ie.lbl.gov/databases/databases.html.

5.12 Nuclear Structure and Decay Systematics

Interesting nuclear charts of nuclear structure and decay systematics are available at http://ie.lbl.gov/systematics.html.

6 Isotope Explorer Software

The LBNL Isotopes Project has developed Isotope Explorer for retrieving and displaying nuclear data from both Internet and local databases. Isotope Explorer 2.2 is a PC Windows program and more information is available at http://ie.lbl.gov/isoexpl/isoexpl.htm. Isotope Explorer 3 is a JAVA/HTML program that can be found at http://ie.lbl.gov/ensdf/.

You were provided with copies of Isotope Explorer 2.2, which has the more features than the JAVA/HTML version, and will be described in this lecture. The accompanying manual will also be distributed. I assume that you have Isotope Explorer 2.2 installed on your computers. For convenience, create a shortcut for c:/isoexpl/isoexpl.exe on your desktop. When you start the program you will see three options, "Chart", "Nucleus", and "Ref", that display nuclear charts, data, and reference information respectively. These features will be discussed in the following sections.

6.1 Configuration

Before we begin, look at the configuration options on the menu bar. Here you have a choice of the Internet of local database. If you choose the Internet, you will receive data directly from the Berkeley server. If you choose local database, you will receive data from a local copy of the database. Choose "local" and you will be prompted to find the file "catalog.log". Normally this file is in the folder c:/isoexpl. Database updates are provided twice a year from the Berkeley server. You can choose to work from either source during this lecture.

6.2 Nucleus

Selecting the nucleus button allows you to search for data about a nucleus as a decay parent, reaction product or decay daughter, or superdeformed nuclear band (structure item). Choose the nucleus ^{60}Ni for our first example. The Adopted Levels, Gammas level scheme for ^{60}Ni is displayed showing all of the nuclear structure information from ENSDF for that nucleus. Note that the level scheme is compressed, so use the $\pm$ scale keys to expand the display so

that it is more readable. Also notice that only the lowest few gamma-rays are displayed. You can see successively higher tiers of gammas with the arrow keys. Look at the three arrows at the bottom of the level scheme. If you grab them with the mouse, you can change the gamma-ray and label plotting areas to show more information.

Select a gamma ray by clicking on its arrow with your mouse. Note that it has changed color. Similarly, select another gamma ray that is in coincidence with the first. Now click on the COIN button to see all gamma rays that are in coincidence with your selection. A dialogue box asks you for the time interval for the coincidence, defaulted to 100 ns. Remember that coincidences can only occur if the gamma rays come from levels with short enough lifetimes. Choose a coincidence time and select OK. Now, you see only gamma rays with the chosen coincidence relationships. Click any where on the drawing to reset the display.

Choose the menubar Operation option and select "set energy gate". Select G1 and the energy range 1100 to 1200. After you say OK, all gamma rays with energy between 1100 and 1200 keV are displayed. This is how you can find gamma rays in a complicated level scheme drawing. Now, go to the menubar and select the configuration option. There you can select the text font size. Choose a size that is pleasing to you.

There are many different kinds of datasets in ENDSF for nuclear reaction, neutron capture, and other applications. On the menubar choose "Data" and "select a dataset". Choose "60CO B- Decay (1925.3 d)". The level scheme for ^{60}Co $\beta-$ decay is shown. Select "P" to see the parent information and select "L" to see the legend. You can perform coincidence operations here too.

Now, in the menubar item AddView, select table. The level table for the current level scheme drawing will appear. Select the GC button to see the general comments associated with the table, and choose the "foot" button to see the footnotes. Now go to the table option in the menubar and select "Gamma". You are given the option to choose which columns to display. Select OK to see the table. Comments and footnotes are displayed as before. Click on the gamma energy column header, and you can sort the table in the reverse energy order. A second click reverses the sorting order again. Click on other column headers to see how you can sort the table. Sorting can also be done by chosing "Sorting" on the menubar. Now select a footnote on the column header the display the associated comment.

Isotope Explorer 2 also supports printing and print preview of the windows you have prepared. These features are available from the File menu. Close all windows. If you downloaded data from the Internet, you will be asked if you want to keep in on your disk. You can save data for future reference.

You can also create and display your own data with Isotope Explorer. First you must generate a dataset in ENSDF format, and then you can open it in Isotope Explorer. The ENSDF formats are simple and the ENSDF manual is available at http://www.nndc.bnl.gov/nndcscr/documents/ensdf/#ensdf. ENSDF data is provided at many places on the Internet with the file extensions .ENS or .ENX. You can associate these file extensions with Isotope Explorer so that they open automatically.

6.3   Chart

Isotope Explorer comes with experimental and theoretical data for creating nuclear charts. Select the Chart button. You will see a menu of .chr files that include both blank and

pre-formatted charts. Choose the chart `toi_saved.chr` which displays the chart of isotopes colored by half-life. Two windows appear. The navigator window shows you the entire chart and lets you choose a region to display in the second window. Move the box in the navigator to display different regions. The chart title and legend are greyed on the navigator box. Move the box over them to display in the second window. The "set scale" and + or - buttons allow you to change the size of the chart boxes.

If you select a box in the main window, you will see the data for that isotope. You can click on the legend boxes to bring up a menu of colors for each box. Clicking on the legend text will let you change the range of values represented by that legend color. Try making all of the boxes except one white. Now you only see the isotopes that satisfy that selection. Narrow the selection even further by editing the legend text and you will see fewer isotopes.

Now, go to the Chart menu and select the blank.chr. This chart contains experimental data. Another chart called blankm.dat contains calculated nuclear data by Peter Moller of Los Alamos National Laboratory [Mol95]. Initially the chart is blank, waiting for you to add data. Go to the Select Field button an choose some quantities that you wish to display. In this exercise we will choose the decay mode EC (Electron capture + beta plus decay). When you say OK, the Select Color Scheme window opens where you can choose which data to color your chart with. Choose equal ranges, and 10 bins and say OK. Go to the chart legend and make the undefined selection white. Now you see all nuclides that decay by electron capture.

The charts can be programmed to display selected data. This can be complicated but is explained in detail in the Isotope Explorer manual. One chart allows you to look for all nuclides with gamma rays in a certain energy range. Open the chart file `findgam_saved.chr`. This chart displays all isotopes with gamma rays between 1200 and 1250 keV. Now open the chart findgam.chr. On the menubar choose the Chart option and select open editor. You will see the short program that controls the selection of data for this chart. Change some of the parameters and save the file by closing the window. Now select the Build button and the new chart is created with your criterion. Learn to make charts by looking at the many samples, reading the manual, and looking at the programs.

6.4   Ref

This function has been superseded by the NSR reference search service on the Internet discussed earlier. The current function has been disabled here.

6.5   Isotope Explorer 3

Isotope Explorer 3 is being developed for interactive searching of nuclear data on the Internet. You can try it at http://ie.lbl.gov/ensdf/. You will see a window called the LBNL/Lund ENSDF Viewer where you can select an Isotope, database, and dataset type. Enter the nucleus ^{60}Ni and choose the Get List button. In the index of data sets select 60CO B- Decay (1925.3 d). Choose a table from the display list and hit the display button. The corresponding table will appear. The footnotes are linked to their comments and the references are linked to the keyword abstracts.

Now select Level Drawing from the display index and select the display button. The level scheme drawing should appear in the display window. Display features, including coincidence
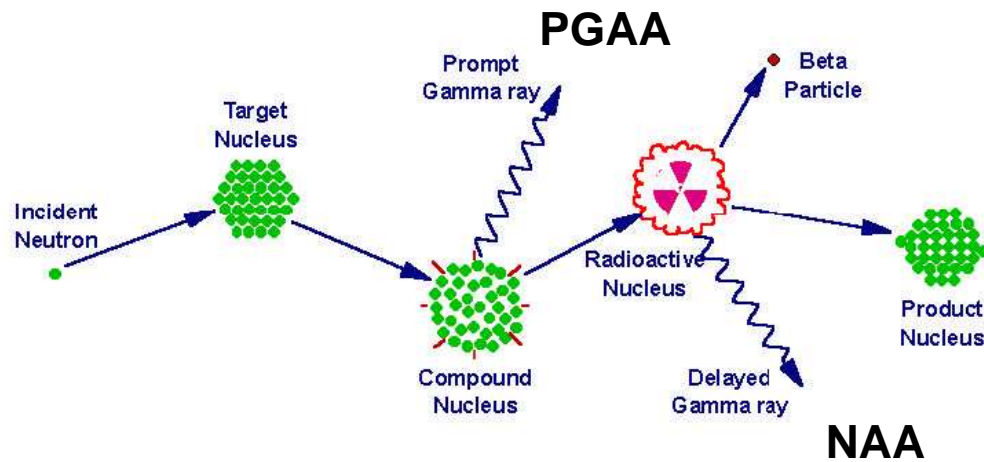
Figure 5: Schematic of PGAA and NAA.

gating, are similar to those in Isotope Explorer 2. A filter is also provided to select data for display by level or gamma ray properties.

7   PGAA/NAA Database

Neutron Activation Analysis (NAA) and Prompt Gamma-ray Activation Analysis (PGAA) are commonly used, related methods of elemental analysis. Although, there is no widely accepted, complete electronic database for NAA, a database of over 35,000 gamma rays suitable for PGAA and short-lived NAA analysis was recently completed. This database was developed as part of a Coordinated Research Project for the Development of a Database for Prompt Gamma-ray Neutron Activation Analysis sponsored by the International Atomic Energy Agency (IAEA). The data are derived from the isotopic measurements compiled in the Evaluated Nuclear Structure Data File (ENSDF), updated when necessary, and from elemental measurements performed at the Budapest Reactor Centre.

7.1   PGAA/NAA Overview

A schematic showing the process by which PGAA/NAA occurs is shown in figure 5. The incident neutron strikes the target nucleus leaving it in an excited state called the compound nucleus. It immediately de-excites to the ground or isomeric state emitting prompt gamma rays that are characteristic of that nucleus. The prompt gamma rays are measured in PGAA. If the final nucleus is radioactive, then it may emit slowly additional gamma rays that are characteristic of the decay. These delayed gamma rays are measured in NAA. Often NAA gamma rays are observed during PGAA measurements.

Three quantities are important for PGAA and NAA. These are the gamma-ray energies, their thermal neutron capture production cross sections (the probability that a neutron can find the target), and the k_0 factors which are the ratios of the cross sections to a standard cross section. PGAA and NAA will be discussed in greater detail in other lectures.

7.2   The PGAA Viewer

The PGAA Viewer was developed for interactive searching of the PGAA database by isotope, energy, or cross section. The viewer was developed by Viktor Zerkin (IAEA, NDS). This viewer is not yet released, but you will be able to obtain if from the Nuclear Data Section of the IAEA. I will preview its capabilities here.

When you open the viewer you will see two windows. One window contains a periodic table with links on each element to tables containing the atomic weight, elemental cross section, and isotopic data properties including abundance, cross section, Westcott g-factor, and the number of PGAA gamma rays available. A plot of the gamma-ray energies and cross sections is given for each isotope.

The second table contains a list of the isotopes for the most recently selected element. Each isotope is linked to tables of isotopic abundance, total thermal neutron capture cross section, number of observed gamma rays, Westcott g-factor, and a list of all of the gamma-ray energies, cross sections, k_0 values, indication as to whether they are prompt (PGAA) or delayed (NAA), and the half-life associated with NAA gammas. The plot of gamma-ray energy versus cross section is displayed after the table.

Gamma-ray search capability is also available with the PGAA Viewer. Gamma rays can be selected on the basis of energy, atomic number, mass number, cross section, and/or whether they are prompt (PGAA) or delayed (NAA). Each search returns a table of results, as described in the previous paragraph, extracted from the entire database.

8   Conclusions

We have covered a lot of information about the sources of nuclear data. I apologize to providers of the many data sources that I have failed to mention. I hope that you have found this lecture both enjoyable and useful. Please feel free to discuss nuclear data with me during the workshop. Now that we are acquainted, you can contact me at any time by email at rbf@lbl.gov or by mail. Be sure to visit me whenever you are in Berkeley.

Acknowledgments

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