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Introduction

Databases of evaluated nuclear data form a cornerstone on which we build academic nuclear structure physics, reaction physics, astrophysics, and many applied nuclear technologies. In basic research, nuclear data are essential for selecting, designing and conducting experiments, and for the development and testing of theoretical models to understand the fundamental properties of atomic nuclei. Likewise, the applied fields of nuclear power, homeland security, stockpile stewardship and nuclear medicine, all have deep roots requiring evaluated nuclear data. Each of these fields requires rapid and easy access to up-to-date, comprehensive and reliable databases. The DOE-funded US Nuclear Data Program is a specific and coordinated effort tasked to compile, evaluate and disseminate nuclear structure and reaction data such that it can be used by the world-wide nuclear physics community.

Overview of Our Databases

Within the US Nuclear Data Program (USNDP), data are filtered into two primary databases; the Evaluated Nuclear Structure Data File (ENSDF) containing nuclear structure and decay data, and the Evaluated Nuclear Data File (ENDF/B) containing nuclear reaction data.

ENSDF [1] contains experimentally determined nuclear structure and decay data for all known nuclei. The results derived following each specific nuclear reaction and decay mode are individually cataloged and then combined in a critical analysis of all measurements to derive recommended properties for each quantum state and its decays. The uncertainties on each derived quantity are carefully evaluated. ENSDF is the only database in the world of this kind and is updated on a monthly basis. The evaluated data from ENSDF are used in a number of tools utilized by the nuclear physics community, including Monte Carlo codes like MCNP and GEANT, medical dosimetry files, Ortec and Canberra isotope identification software, Nuclear Wallet Cards, and more.

The ENDF/B library [2] contains nuclear reaction data mainly for use in nuclear applications, including cross sections, outgoing particle distributions, fission product yields as well as atomic reaction data and decay data. Users of ENDF/B data frequently access the data through application codes and often the users are not even aware that they are using ENDF/B data libraries (such as various application-tailored cross section libraries). The most well-known applications include general particle transport codes used in nuclear reactor, radiation shielding and health physics applications (e.g., MCNP6, SCALE, GEANT4); isotope burn-up codes used for the time-dependent nuclear reactor analyses, nuclear waste managements, and radiochemical applications (e.g., ORIGEN, CINDER); and other application code systems that use covariance data to estimate nuclear data uncertainty in application metrics (e.g., TSUNAMI, WHISPER).

The US Nuclear Data Program supports two additional databases which complement and underpin the primary databases; the Nuclear Science References Database (NSR) [3] and the Exchange FORmat Database (EXFOR) [4]. NSR contains bibliographic information on low- and intermediate-energy nuclear physics articles including more than 220,000 publications and secondary references spanning the 100 years of nuclear physics research. The EXFOR library includes a complete compilation of experimental neutron-induced reactions, selected compilations of charged-particle-induced and photon-induced reactions, and assorted high-energy and heavy-ion reaction data. The EXFOR library is the most comprehensive collection of experimental nuclear reaction data available. The USNDP coordinates compilation of EXFOR data experiments performed in North America.

The newest addition to the supporting databases is XUNDL (eXperimental Unevaluated Nuclear Data List), a database [5] containing critical compilations of current journal articles on experimental nuclear structure and radioactive decay data presented in the same format as ENSDF. It takes, on average, 7-8 years to revisit and re-evaluate all 3,300 nuclei currently contained in ENSDF. XUNDL was developed to complement ENSDF and provide users with data from publications which have not yet been included into ENSDF. Presently, over 15 experimental journals are scanned on a frequent basis and relevant articles incorporated into XUNDL within two months of publication. Supplemental material provided by authors and associated with published papers can also be included. Such additions are highly encouraged, particularly in instances where the publication has a length limitation.

Interacting with Structure Databases

All databases can be quickly and easily searched using web-applications available at the National Nuclear Data Center (NNDC) website at www.nndc.bnl.gov. We are continually developing new tools to make data access and visualization easier. We try to be responsive to user needs and encourage community participation in improving the databases and corresponding software. In 2016, more than four million electronic retrievals were made from the NNDC website, accessing various databases and online applications. By far, the most popular product (at over 60% of the total retrievals) is the application NuDat. NuDat provides users many options for displaying the nuclear structure and decay data in ENSDF, from the entire nuclear chart, to a single nucleus, and from tabular numerical data to sophisticated plotting capabilities. Many nuclear properties can be visualized by selecting from options at the top of the chart; Fig. 1 gives an example using the Q value for beta-delayed neutron emission. The plots have the option for zooming in to smaller regions of the chart or selecting a single nucleus. NuDat also can be used to search all of ENSDF for basic properties of nuclei. The search page is illustrated in Figure 2, where conditions on energy, spin, parity, half-life, transition multipolarity and more can be placed. A particularly useful feature in an experimental setting is the ability to search for gamma-ray transitions which are known to come in coincidence.

Figure 1: Q value for beta-delayed neutron emission for the entire chart of nuclides as plotted using the NuDat application.

New plotting features are currently being incorporated into NuDat. As an example, a common observable used as an indicator of deformation in nuclei is the ratio of the excitation energy of the first 4^+ state to the first 2^+ state (the $R_{4/2}$ ratio) in even-even nuclei. Figure 3 (left) illustrates the previous plotting capabilities of NuDat for the $R_{4/2}$ ratio.

Figure 2: NuDat search page for making queries of specific nuclear properties in ENSDF.

Figure 3: (Left) Previous plotting option in NuDat displaying the $R_{4/2}$ ratio in a region around ^{100}Mo . New plotting options are found in the middle and right panels where the same $R_{4/2}$ ratio will be automatically displayed as a function of both neutron and proton number.

While some trends are evident, such as increasing values as one moves away from closed shells, the finer details are not immediately obvious from the two dimensional plot. A new feature in NuDat now allows observables, like the $R_{4/2}$ ratio, to be automatically plotted as a function of both proton and neutron number. Here is where new physics can be quickly observed, with the large gap in the plot as a function of proton number (right panel) indicating the presence of a sub-shell closure [6]. Such plotting features are available for a number of basic observables. For the future, more extensive plotting capabilities are being explored, including, for example, plotting one measured quantity versus another.

The traditional way of visualizing the levels in a nucleus and their decay has been to use horizontal lines to indicate excited levels and vertical arrows to indicate gamma-ray transitions. Again, in an attempt to provide users with a different perspective, the standard plotting capabilities in NuDat have been expanded to include for each nucleus the option to generate plots of excitation energy as a function of spin. An example of this type of plot is given in Figure 4 for ^{194}Pb . The user will have the option to join individual states by their gamma-decay branching ratio, as done in Figure 4, or by transition strengths (M1, E2, etc). In this example, the changes in shape as a function of angular momentum can be clearly identified.

Figure 4: Plot of excitation energy as a function of angular momentum for levels in ^{194}Pb . States are connected by their branching ratios, with the width of the line proportional to the intensity.

New Release of ENDF/B: ENDF/B-VIII.0

As mentioned above, the ENDF/B library contains nuclear reaction data for transport and other applications. ENDF/B is the product of the Cross Section Evaluation Working Group (CSEWG), a collaboration that has been active since 1967. It has been 50 years since the release of ENDF/B-I. Currently CSEWG is preparing a new release: ENDF/B-VIII.0

This new ENDF/B-VIII.0 Library release incorporates work from across the US and the international nuclear science community over the last six years, most notably with Europe (JEFF), Japan (JENDL), South Korea, and the International Atomic Energy Agency (IAEA). This Library is being issued in the traditional ENDF-6 format, as well as in an alternative new Generalized Nuclear Data (GND) format. ENDF/B-VIII.0 is due late 2017.

Major changes to ENDF/B-VIII.0 include:

- A new Neutron Standards evaluation
- New standards level full evaluations from the CIELO pilot project: $^{235,238}\text{U}$, ^{239}Pu , ^{56}Fe , ^{16}O , and ^1H
- Many new and improved neutron evaluations
- New atomic reaction data
- Many new thermal scattering evaluations
- Improvements to charged particle reactions

ENDF/B-VIII.0 is the best performing ENDF/B library to date. ENDF/B performance is typically measured by the agreement between simulations of small zero power nuclear reactors (critical assemblies) and their experimental realization. The figure of merit in these comparisons is the k_{eff} , namely the ratio of neutron gain to loss. Figure 5 shows the cumulative χ^2 from a series of simulations of these critical assemblies.

Figure 5: Cumulative χ^2 of ENDF/B library performance. Each tick on the x-axis represents one critical assembly case. The y-axis is the cumulative χ^2 comparing performance of the simulation of each critical assembly to the experimental k_{eff} . Lower cumulative χ^2 indicates better performance.

New developments in Nuclear Data Sheets

Traditionally, nuclear structure evaluations are documented and published in Nuclear Data Sheets, a monthly journal published by Elsevier Science. The Nuclear Data Sheets (NDS) journal dates back to 1965 and continues to thrive and be a well-cited resource within the community. However, the format of NDS has remained nearly the same for decades. Based on user input and feedback, the February 2017 issue [7] of Nuclear Data Sheets introduces a new layout and several

improvements to the presentation of data. The most significant change is in the presentation of tabular data. The ENSDF recommended data is presented in two tables, one describing level properties and the other displaying the gamma and E0 transition decays. Previously, these two tables were distinct, linked only by the excitation energy of the initial level. To allow the tables to be used more independently, the gamma-ray table has been expanded, to provide the user with information on the spin of the parent level, as well as the excitation energy and spin and parity of the final level. The font for all tables and text has also been increased for ease in reading. An example of the new gamma table is given in Figure 6. Recently, all of ENSDF was made available for downloading in this new style of pdf and this new format can be obtained at www.nndc.bnl.gov/ensdf.

Improvements have also been made to the presentation of level schemes and band drawings. An example is presented in Figure 7. For the sake of clarity, the requirement of plotting the excitation energies to scale has now been relaxed, and levels are separated such that their decay is legible. Color coding has been added, so that one can easily get an idea for the stronger and/or weaker transitions in the decay. Finally, decay paths involving particle emission are now incorporated into the drawings, for example, in Figure 7, the beta-delayed neutron branch is indicated by the hatched region.

NDS is not limited to publishing just nuclear structure evaluations. Since 2006, the journal has devoted one special issue a year to nuclear reactions, with the aim to provide a venue for publication of key papers on reaction evaluations which are too extensive or detailed for other journals. These issues can have a large impact, the paper detailing the release of ENDF/B-VII.0 [8] has over 1600 citations (Google Scholar), while the ENDF/B-VII.1 paper [2] has over 940 citations (Google Scholar). Submissions relating to nuclear structure or reaction data are welcomed and authors with articles with relevance to Nuclear Data Sheets should contact the editor for additional information.

$\gamma(^{168}\text{Er})$									
$E_i(\text{level})$	J_i^π	E_γ	I_γ	E_f	J_f^π	Mult.	δ	α	Comments
79.804	2 ⁺	79.804	1	0.0	0 ⁺	E2		7.04	B(E2)(W.u.)=213 4
264.0888	4 ⁺	184.285	1	79.804	2 ⁺	E2		0.331	B(E2)(W.u.)=319 9
548.7470	6 ⁺	284.655	2	264.0888	4 ⁺	E2		0.0811	B(E2)(W.u.)=424 18
821.1685	2 ⁺	557.079	3	264.0888	4 ⁺	E2 ^b		0.01252	B(E2)(W.u.)=0.61 4
		741.356	3	79.804	2 ⁺	E2+M1 ^a	>25 ^{a§}	0.00639 9	B(M1)(W.u.)<1.6×10 ⁻⁵ ; B(E2)(W.u.)>8.0
		821.164	5	0.0	0 ⁺	E2		0.00510 8	B(E2)(W.u.)=4.68 16

Figure 6: New format of the gamma-ray table available in the Nuclear Data Sheets journal and on-line through the ENSDF search application. New columns (indicated by the red squares) include the J^π of the initial level, as well as the energy and J^π of the level to which the gamma-ray decays.

Future outlook

The history of nuclear physics has always been data driven and has shown that systematic studies of nuclear properties can lead to major advances in our understanding of how nuclei work. An exciting time is upon us, where new, modern facilities around the world are providing huge amounts of data in a new terrain of the nuclear chart. Vastly increased computing power is enabling more fundamental theoretical models based on real nuclear forces. The internet now allows us to share these new results at unprecedented speed. With these types of advances, the rapid collection, correlation, evaluation and dissemination of data is ever more important. The US nuclear data program is eager to work closely with the nuclear physics community to ensure that all data are promptly and reliably incorporated into the databases in order to pave the way for new scientific breakthroughs. To exploit the full potential for scientific discovery, will also require the development of innovative software tools for display, extraction and manipulation of the evaluated data and feedback from the users on their needs is highly requested.

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Figure 7: Example of new decay drawing available on-line and in the Nuclear Data Sheets journal.

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