Toward More Complete and Accurate Experimental Nuclear Reaction Data Library (EXFOR) - International Collaboration Between Nuclear Reaction Data Centres (NRDC)

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The International Network of Nuclear Reaction Data Centres (NRDC) coordinated by the IAEA Nuclear Data Section (NDS) is successfully collaborating in the maintenance and development of the EXFOR library. As the scope of published data expands (e.g., to higher energy, to heavier projectile) to meet the needs from the frontier of sciences and applications, it becomes nowadays a hard and challenging task to maintain both completeness and accuracy of the whole EXFOR library. The paper describes evolution of the library with highlights on recent developments.

I. INTRODUCTION

The EXFOR library has become the most comprehensive compilation of experimental nuclear reaction data. It contains cross sections and other nuclear reaction quantities induced by neutron, charged-particle and photon beams. Currently compilation is mandatory for all low and intermediate energy (< 1 GeV) neutron and light charged-particle (A ≤ 12) induced reaction data. Heavy-ion (A ≥ 13) and photon induced reaction data are also additionally compiled on a voluntary basis.

Currently fourteen data centers shown in Table I are participating in the International Network of Nuclear Reaction Data Centres (NRDC) [1] and are collaborating mainly for compilation and exchange of experimental data by using the common Exchange Format (EXFOR format) [2] under the auspices of the IAEA Nuclear Data Section (NDS). Following an introduction to the current EXFOR compilation procedure, this paper summarizes various recent efforts to make the contents of the EXFOR library more complete and accurate. Readers interested in the history of the NRDC activity are guided to our previous report [3] and references therein.

II. COMPILATION

The first important step of data compilation is to scan literature and identify articles reporting experimental data for EXFOR compilation. For many decades, neutron-induced reaction measurement publications were indexed for CINDA (Computer Index for Neutron Data) by “CINDA readers” world-wide [4], and EXFOR compilers could use it as the complete and independent list of experimental works. These

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TABLE I. Scope of compilation and EXFOR web retrieval service (ND/CPND/PhND: neutron/charged-particle/phononuclear data).

| Center | Scope and URL                                                                 |
|--------|-----------------------------------------------------------------------------|
| ATOMKI | CPND measured in collaboration with ATOMKI                                  |
| CAJaD | CPND measured in former USSR (except for Ukraine)                           |
| CDFE  | PhND (coordinated with other centers)                                        |
| CJD   | ND measured in former USSR (except Ukraine)                                 |
| CNDC  | ND and CPND measured in China                                                |
| CNPD  | CPND (coordinated with other centers)                                        |
| JAEA  | Evaluation, [http://spes.jaea.go.jp/](http://spes.jaea.go.jp/)              |
| JCPRG | CPND and PhND measured in Japan                                              |
| KNDC  | ND, CPND and PhND measured in Korea                                          |
| NDPCI | ND, CPND and PhND not measured in India                                      |
| NDS   | ND, CPND and PhND not covered by other centers                               |
| NEA DB| ND and CPND measured in NEA DB countries not covered by other centers        |
| NNDC  | ND, CPND and PhND measured in USA and Canada                                 |
| UkrNDC| ND, CPND and PhND measured in Ukraine                                        |

* NDPCI: Nuclear Data Physics Centre of India (virtual center)

CINDA readers are no longer available, and NDS is regularly scanning more than 60 journals to identify articles for compilation. Articles identified by NDS and other data centers are registered to an internal database for assignment of an EXFOR entry number by the responsible center (e.g., NNDC for data measured in USA and Canada). Progress in compilation and distribution of compilation responsibility are periodically reviewed and discussed in annual NRDC meetings. Figure 1 shows the average time for EXFOR compilation (time difference between publication and inclusion to the EXFOR Master File) for articles that must be compiled from six major journals. We observe that it takes 5 to 10 months on average to release an entry to EXFOR users since publication.

A set of new and revised EXFOR entries is assembled to a “tape” by the originating center, and transmitted to other centers (preliminary transmission). The originating center waits for comments from other centers for one month at minimum, and transmits again a corrected tape to other centers (final transmission). Since 2005, a complete set of the latest EXFOR entries is maintained by NDS as the EXFOR Master File and database. It is updated on a monthly basis, and its contents are available at the NDS EXFOR web retrieval service [3]. Other data centers providing their own EXFOR retrieval services are also encouraged to adopt the EXFOR Master File in order to provide the same contents to users. The newly released EXFOR data sets are also indexed in the “EXFOR News” by NDS, and distributed to data centers as well as individual subscribers.

Figure 2 shows time evolution of the number of EXFOR entries. Only neutron-induced reaction data were compiled at the beginning of data exchange, while compilation of charged-particle and photon induced reaction data was started in the middle of 1970s. Now the contents of neutron and charged-particle induced reaction data in the EXFOR library are comparable, and more than 20000 experimental works are accumulated in the library.

Some data centers are developing compilation tools (e.g., editors, digitizers). For example, an editor developed by CNPD (EXFOR Editor) is used by EXFOR compilers for input of information in the EXFOR format. Also a Java based digitizer developed by JCPRG (GSYS) [4] is used for digitization of figure images to extract numerical data not available from experimentalists. In order to utilize these compilation tools, NDS periodically organises workshops for EXFOR compilers in Vienna. Similar workshops are also organised at regional and country levels. For example, four Asian data centers (CNDC, JCPRG, KNDC, NDPCI) organised three workshops (2010 in Sapporo, 2011 in Beijing, 2012 in Pohang) to stimulate EXFOR compilation and other nuclear reaction database developments. The Indian center (NDPCI) also or-
organises EXFOR compilation workshops regularly (2006 and 2007 in Mumbai, 2009 in Jaipur, 2011 in Chandigarh, 2013 in Varanasi), and many experimental data measured in India have been compiled by the participants from Indian universities and institutes.

III. COMPLETENESS

The EXFOR library is expected to be complete for low and intermediate energy neutron and light charged-particle induced reaction data. However, the coverage of light charged-particle induced reaction data (especially differential cross sections) is not as good as that of neutron induced reaction data because compilation of charged-particle induced reaction data was started later.

Some examples of recent attempts to improve the coverage of the EXFOR library are summarized below with the number of articles missed in EXFOR in parentheses:

1 Neutron source spectra (30): Data reporting neutron source spectra (e.g., neutron spectra from $^9$Be+d). The compilation rules were also discussed in the IAEA Consultant Meeting on “Neutron Source Spectra for EXFOR” [7]. Compilation is on-going.

2 Therapeutic radioisotope production cross sections (40): Data identified within the IAEA CRP on “Nuclear Data for Production of Therapeutic Radionuclides” [8]. All articles were compiled by 2008.

3 Isotope production cross sections (300): Data for light-charged particle (p, d, t, $^3$He, α) induced isotope production in Landolt-Börnstein compilation [9]. Compilation is on-going.

4 Proton-induced total reaction cross sections (10): Proton-induced total reaction cross section data in Carlson’s compilation [10]. Compilation was completed by 2012 except for one article.

5 Nuclear resonance fluorescence (NRF) data (10): Properties of resonances excited by γ-ray scattering and relevant to nondestructive assay (NDA) of fissile materials. All articles were compiled by 2012 [11].

Similar checking was also done for other types of data (e.g., data used in the IAEA Spallation Model Benchmarking [12], super-heavy elements production cross sections).

Another new direction of extension is compilation of evaluated or recommended reaction data not distributed in the ENDF-6 format [13]. Initially such an attempt was made by NDS for the EXFOR-VIEN (Various International Evaluated Neutron Data) file [14]. In 2012, compilation was done by NNDC and NDS for the thermal neutron data recommended by S. Mughabghab [15] and Maxwellian averaged neutron capture cross sections at $kT=30$ keV recommended by Z.Y. Bao et al. [16]. There are also similar attempts for charged-particle induced isotope production cross sections (e.g., [17]) and photonuclear reaction cross sections (e.g., [18]).

Finally we would like to note that the completeness depends strongly on the range of the data types and availability. For example, data in conference proceedings, raw data in arbitrary unit, data not available from authors could be on the boundary of the scope.

IV. QUALITY ASSURANCE

Quality assurance is another important issue for the EXFOR library. The entire information of EXFOR entries is mostly typed by EXFOR compilers manually, and sometimes they have to type hundreds of numerical data lines not available in an electronic form. Even though the EXFOR compiler of the originating center takes the greatest care during compilation, it is still impossible to eliminate all errors at the stage of compilation. On the other hand, EXFOR users have more opportunity to compare different EXFOR data sets with their own experimental or theoretical data set for a certain range of reactions and quantities, and they are in a good position to detect errors. However, there was no well-established means of communication between EXFOR users and NRDC.

A turning point came when two valuable lists of suspicious EXFOR entries (e.g., a factor 1000 larger than usual values due to coding of barn instead of millibarn) were submitted by A.J. Koning (NRG) and R.A. Forrest (UKAEA) and discussed in the NRDC 2006 Meeting [19]. In order to improve the quality of the EXFOR contents in collaboration between the EXFOR users and NRDC, a new WPEC subgroup “Quality Improvement of the EXFOR Database (SG30)” [20] was coordinated by A.J. Koning from 2007 to 2010, and detection of errors and their corrections were performed in a systematic manner. The initial important step was translation of contents of the EXFOR database to the extended Computational Format (XC4) at NDS using the X4toC4 code [21]. The detection of suspicious EXFOR data sets were then mainly done by two methods: (1) detection of outliers by intercomparison of data points in XC4, and (2) comparison of data points in XC4 with prediction by TALYS [22]. The suspicious entries were further filtered by visual inspection using the JANIS display software [23] at NEA DB, and then checked against the original articles at NDS. Finally about 100 erroneous EXFOR data sets were confirmed, and were corrected by the originating data centers. More details of these approaches are reported elsewhere [24].

The development of such systematic and semi-automatic detection is continuing at NEA DB (in collaboration with NRG) [25] involving data types not covered by the WPEC SG30 activity. Here are examples of additional inspections performed by NDS (with the number of detected erroneous data sets in parentheses): incident energy coded in MeV instead of in keV (29), level energies higher than 20 MeV or lower than 10 keV (59), reaction violating charge or mass conservation (17), partial data without specification of excitation level (288).

Checking codes (ZCHEX, JANIS TRANS Checker) also support EXFOR compilers to eliminate format and physical errors before submission of their EXFOR entries. Various
other inspections (e.g., formatting, bibliographic information) are also being done regularly by NEA DB. All comments from EXFOR users and data centers are registered to the EXFOR Feedback List (http://www-nds.iaea.org/nrdc/error), and the correction process is monitored by NDS. Digitization is also a key process to determine the quality of numerical data published in old articles. NDS has organised the IAEA Consultant Meeting on “Benchmarking of Digitization Software” in 2012[26] to improve this process.

V. OTHER IMPROVEMENTS

Various other efforts are being made to improve the contents and accessibility of the EXFOR library. One of the most important issues is the detailed documentation of uncertainties and covariances to support evaluation with minimum assumption. The error propagation described in articles is not satisfactory to provide enough information to evaluators in the most cases. Recently the EXFOR format was extended to accommodate correlation properties and covariance matrices in computer readable form, and guides were published to promote submission of detailed information by experimentalists[27, 28]. Archiving of time-of-flight spectra is also important when one needs to evaluate covariances between resonance parameters by error propagation from the primary measurable[29]. NDS is working for compilation and documentation of time-of-flight spectra in collaboration with EC-JRC IRMM[30].

Another advance is seen in EXFOR entries for prompt fission neutron spectra (PFNS). They are very rarely given in the absolute unit (i.e., neutrons/energy/fission), and the coding method was not well standardised. Motivated by the currently on-going IAEA CRP on “Prompt Fission Neutron Spectra of Actinides”[31], all PFNS EXFOR entries were upgraded thoroughly by data centers. In addition, PFNS for Pu, Am and Cm measured by Khlopin Radium Institute within the ISTC project were compiled by IAEA/NDC and NDS. Such improvements related to IAEA CRPs are also foreseen for data related to β−delayed neutron[32] and IRDFF library validation[33]. In order to improve accessibility to English translation of articles in Russian, systematic addition of English translation information to EXFOR entries are on-going, led by CAJaD.

Further improvement of formats is also discussed to make the contents of EXFOR entries more understandable[34, 35].

VI. CONCLUSIONS

The needs for experimental reaction data are always growing. Also more and more information in the EXFOR library is expected to be machine readable according to development of various processing tools. NRDC is always trying to take various approaches to maintain EXFOR as a very complete and error-free library. Feedback from EXFOR users is also extremely important to achieve this goal.

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