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 microscopic 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 ($A \leq 12$) induced reaction data. Heavy-ion ($A \geq 13$) and photon induced reaction data are also additionally compiled on a voluntary basis.

Currently fourteen data centres 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 CINDA readers are no longer available, and NDS is regularly

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TABLE I. Nuclear Reaction Data Centres (NRDC).

Country	Centre and EXFOR web retrieval service
China	China Nuclear Data Centre (CNDC), Beijing
Hungary	Institute of Nuclear Research (ATOMKI), Debrecen
India	Nuclear Data Physics Centre of India (NDPCI), Mumbai http://www-nds.indcentre.org.in/exfor/
Japan	Hokkaido Univ. Nuclear Reaction Data Centre (JCPRG), Sapporo. http://www.jcprg.org/exfor/
	Japan Atomic Energy Agency Nuclear Data Center (JAEA/NDC), Tokai-mura. http://spes.jaea.go.jp/
Korea	Korea Nuclear Data Center (KNDC), Daejeon
Russia	Centre for Nuclear Data (CJD), Obninsk
	Centre of Nuclear Physics Data (CNPD), Sarov
	Centre for Nuclear Structure and Reaction Data (CAJaD), Moscow
	Centre for Photonuclear Experiments Data (CDFE), Moscow. http://cdfe.sinp.msu.ru/exfor/
Ukraine	Ukrainian Nuclear Data Centre (UkrNDC), Kyiv
USA	US National Nuclear Data Center (NNDC), Upton, NY http://www.nndc.bnl.gov/exfor/
NEA	OECD NEA Data Bank (NEA DB), Issy-les-Moulineaux http://www.oecd-nea.org/dbdata/x4/
IAEA	IAEA Nuclear Data Section (NDS), Vienna http://www-nds.iaea.org/exfor/

scanning about 90 journals to identify articles for compilation. Articles identified by NDS and other data centres are registered to an internal database for assignment of an EXFOR entry number by the responsible centre (*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 (the date of inclusion to the EXFOR Master File minus the date of publication) 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 its publication in recent years.

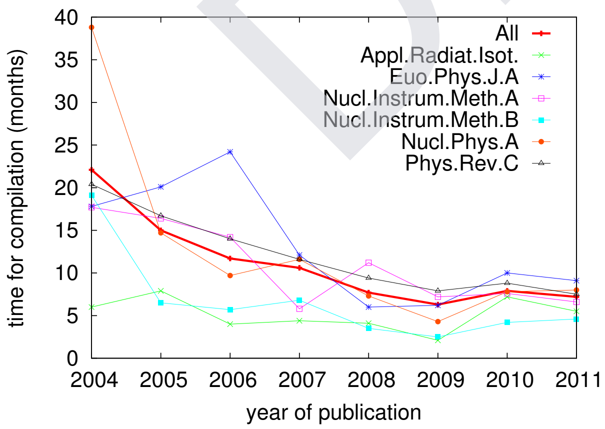

FIG. 1. (Color online) Average time for compilation of experimental data (the date of inclusion to the EXFOR Master File minus the date of publication).

A set of new and revised EXFOR entries is assembled to a "tape" by the originating centre, and transmitted to other centres (preliminary transmission). The originating centre waits for comments on the tape from other centres for one month at minimum, and transmits again a corrected tape to other centres (final transmission). Since 2005, a complete set of the latest EXFOR entries is maintained by NDS as the EXFOR Master File and its database. It is updated on a monthly basis, and its contents are available at the NDS EXFOR web retrieval service [5]. Other data centres providing their own EXFOR retrieval services are also encouraged to adopt the EXFOR Master File in order to provide the same contents to EXFOR users. The newly released EXFOR data sets are also indexed in the "EXFOR News" by NDS, and distributed to data centres 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 about 20000 experimental works are accumulated in the library.

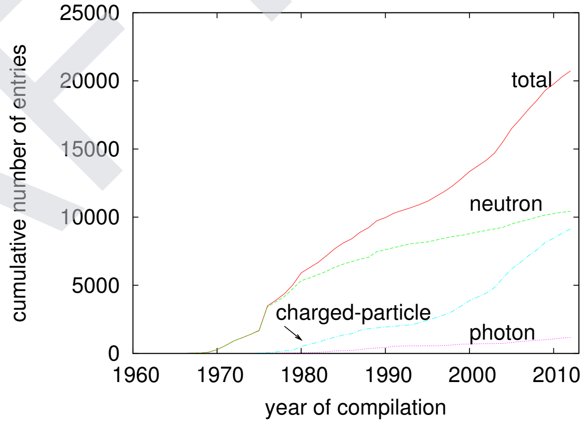

FIG. 2. (Color online) Cumulative number of EXFOR entries (experimental works) created in each year of compilation.

Some data centres 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 EXFOR formats. Also a Java based digitizer developed by JCPRG (GSYS) [6] 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 organized in regional and country levels. For example, four Asian data centres (CNDC, JCPRG, KNDC, NDPCI) organised three workshops (2010 in Sapporo, 2011 in Beijing, 2012 in Pohang) to stimulate activities in EXFOR compilation and other nuclear reaction database developments. The Indian centre (NDPCI) also organises EXFOR compilation workshops (2006 and 2007 in Mumbai, 2009 in Jaipur, 2011 in Chandigarh, 2013 in Varanasi), and many Indian experimental data have been compiled by the participants from various 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 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 ENDF-6 formats [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 thermal neutron data recommended by S. Mughabghab [15] and kT=30 keV Maxwellian averaged neutron capture cross sections recommended by Z.Y. Bao et al. [16, 17]. There are also similar attempts for charged-particle induced isotope production cross sections (*e.g.*, [18]) and photoneutron reaction cross sections (*e.g.*, [19]).

Finally we would like to note that the completeness depends strongly on the range of the data types. For example, data in conference proceedings, 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 EXFOR compilers have to type hundreds of lines of numerical data when they are not available in an electronic form. Even though EXFOR compilers of the originating centre 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) submitted by A.J. Koning (NRG) and R.A. Forrest (UKAEA) were discussed in the NRDC 2006 Meeting [20]. 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)" [21] 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) NDS using the X4toC4 code [22]. 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 [23]. The suspicious entries were further filtered by visual inspection using the JANIS display software [24] at NEA DB, and then checked against the original articles at NDS. Finally about 100 erroneous EXFOR data sets were confirmed, and all of them were corrected by the originating data centres. More details of these approaches are reported elsewhere [25].

The development of such systematic and semi-automatic detection is continuing at NEA DB (in collaboration with NRG) [26] and NDS involving data types not covered by the WPEC SG30 activity. Here are examples done 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), data above threshold of second level excitation without specification of level energy (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 centres are registered to the EXFOR Feedback List (http://www-nds.iaea.org/nrdc/error/). Digitization is also a key process to determine the quality of numerical data published in old articles, and NDS organized the IAEA Consultant Meeting on "Benchmarking of Digitization Software" in 2012 [27] to help 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 could be the detailed documentation of uncertainties and error analysis to support evaluation of uncertainties and covariances 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 Formats were extended to accommodate correlation properties and covariance matrices in computer readable form, and guides were published to promote submission of detailed information by experimentalists [28]. Archiving of time-of-flight spectra is also important when one wants to evaluate covariances between resonance parameters by error propagation from the primary measurable [29], and 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 standardized. 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 centres. In addition, PFNS for Pu, Am and Cm minor actinides measured by KRI within the ISTC project were compiled by JAEA/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].

VI. CONCLUSIONS

The needs for experimental reaction data are always growing. Also more and more information in the EXFOR library are 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 nevertheless also extremely important to achieve this goal.

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