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Towards a 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) successfully collaborates 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 of research and applications, it has become a challenging task to maintain both the completeness and accuracy of the EXFOR library. Evolution of the library highlighting recent developments is described.

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. Compilation is mandatory for all low and intermediate energy ($\leq$ 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 compiled on a voluntary basis.

Currently the fourteen data centers shown in Table I participate in the International Network of Nuclear Reaction Data Centres (NRDC) [1] and collaborate 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). After introduction to the current EXFOR compilation procedure, we summarize recent efforts to make the contents of the EXFOR library more complete and accu-

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TABLE I. Scope of compilation and EXFOR web retrieval service (ND/CPND/PhND: neutron/charged-particle/photonuclear 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), http://cdfe.sinp.msu.ru/exfor/
CJD	ND measured in former USSR (except Ukraine)
CNDC	ND and CPND measured in China, http://www-nds.ciae.ac.cn/exfor/
CNPD	CPND (coordinated with other centers)
JAEA	Evaluation. http://spes.jaea.go.jp/
JCPRG	CPND and PhND measured in Japan, http://www.jcprg.org/exfor/
KNDC	ND, CPND and PhND measured in Korea
NDPCI[a]	ND, CPND and PhND measured in India, http://www-nds.indcentre.org.in/exfor/
NDS	ND, CPND and PhND not covered by other centers, http://www-nds.iaea.org/exfor/
NEA DB	ND and CPND measured in NEA DB countries not covered by other centers, http://www.oecd-nea.org/janisweb/search/exfor/
NNDC	ND, CPND and PhND measured in USA and Canada, http://www.nndc.bnl.gov/exfor/
UkrNDC	ND, CPND and PhND measured in Ukraine

[a] NDPCI: Nuclear Data Physics Centre of India (virtual center)

rate. Readers interested in the history of NRDC activity should consult our previous report [3] and references cited therein.

II. COMPILATION

The first important step in data compilation is to scan the 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 worldwide [4], and EXFOR compilers used this as the complete and independent list of experimental work. These CINDA readers are no longer available, and NDS regularly scans more than 60 journals to identify articles for compilation. Articles identified by the 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. Fig. 1 shows the average time for an EXFOR compilation (time difference between publication and inclusion in the EXFOR Master File) for articles that must be compiled from six major journals. Currently, it takes 5 to 10 months on average to release an entry to EXFOR users following its publication.

A set of new and revised EXFOR entries is assembled by the originating center and transmitted to other centers (preliminary transmission). The originating center waits for comments from other centers for a minimum of one month and then transmits again a corrected data entries to other centers (final transmission). Since 2005, a complete set of the latest EXFOR entries has been maintained by NDS as the EXFOR Master File and database.

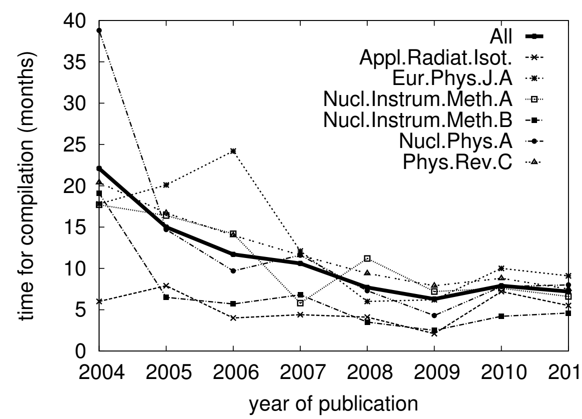

FIG. 1. Average time for compilation of experimental data (time difference between publication and inclusion to the EXFOR Master File).

It is updated on a monthly basis, and the contents are available at the NDS EXFOR web retrieval service [5]. Other data centers providing their own EXFOR retrieval services are 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 EXFOR New by NDS, and distributed to data centers as well as to individual subscribers.

Fig. 2 shows the evolution of the number of EXFOR entries. Only neutron-induced reaction data were compiled at the beginning of the data exchange; compilation of charged-particle and photon-induced reaction data was started in the mid-1970s. The contents of neutron and charged-particle induced reaction data in the EXFOR library are comparable, and more than 20,000 experimental studies are accumulated in the library.

Some data centers are developing compilation tools

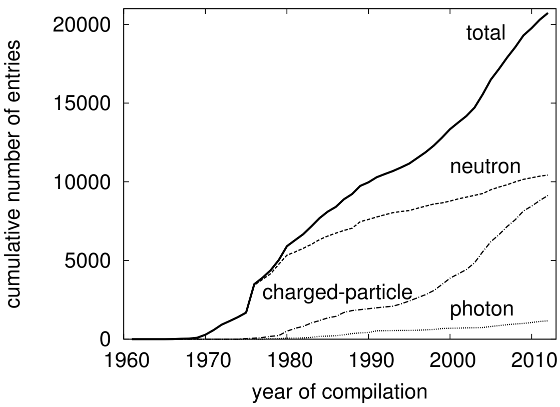

FIG. 2. Cumulative number of EXFOR entries (experimental studies) created in each year of compilation.

(*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) [6] is used for digitization of figure images to extract numerical data that are 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 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 Consultants' Meeting on Neutron Source Spectra for EXFOR [7]. Compilation is ongoing.

2. **Therapeutic radioisotope production cross sections (40)** Data identified within the IAEA CRP on Nuclear Data for Production of Therapeutic Radionuclide [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 ongoing.

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

Another new direction 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 undertaken by NNDC and NDS for the thermal neutron data recommended by Mughabghab [15] and Maxwellian averaged neutron capture cross sections at kT=30 keV recommended by Bao et al. [16]. Similar attempts have been madefor charged-particle induced isotope production cross sections (e.g. [17]) and photoneutron reaction cross sections (e.g. [18]).

Finally, we note that completeness depends strongly on the range of the data types and availability. For example, data in conference proceedings, raw data in arbitrary units and, data not available from authors could be on or beyond the boundary of registrations in EXFOR.

IV. QUALITY ASSURANCE

Quality assurance is another important issue for the EXFOR library. Most of the information in EXFOR entries is typed manually by EXFOR compilers, who sometimes have to type hundreds of numerical data lines not available in electronic form. Even though EXFOR compilers at the originating center take the greatest care during compilation, it is still impossible to eliminate all errors at the compilation stage. However, EXFOR users have more opportunity to compare different EXFOR data sets with their own experimental or theoretical data set for a particular range of reactions and quantities, and they are in a good position to detect errors. Unfortunately, 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 of 1000 larger than the normal values because of the coding of barn instead of millibarn) were submitted by Koning (NRG) and Forrest (UKAEA) and discussed in the NRDC 2006 meeting [19]. In order to improve the quality of the EXFOR contents by means of a collaboration between EXFOR users and NRDC, a new WPEC subgroup "Quality Improvement of the EXFOR Database (SG30)" [20] was coordinated by Koning between 2007 and 2010, and the detection and correction of errors were performed in a systematic manner. The initial important step was translation of the contents of the EXFOR database to the extended Computational Format (XC4) at NDS using the X4toC4 code [21]. Suspicious EXFOR data sets were then mainly detected by two methods: (1) detection of outliers by intercomparison of data points in XC4, and (2) comparison of data points in XC4 with predictions 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 procedures 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. The following 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), reactions violating charge or mass conservation (17), and partial data without specification of excitation level (288).

Checking codes (ZCHEX, JANIS TRANS Checker) also assist EXFOR compilers in eliminating format and physical errors before submission of their EXFOR entries. Various other inspections (e.g. formatting, bibliographic information) are also carried out regularly by NEA DB. All comments from EXFOR users and data centers are registered on 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 in determining the quality of numerical data published in old articles. NDS has organised the IAEA Consultants' 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 does not normally provide enough information to evaluators. 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 absolute units (i.e. neutrons/energy/fission), and the coding method was not fully standardised. Motivated by the ongoing IAEA CRP on Prompt Fission Neutron Spectra of Actinides [31], all PFNS EXFOR entries were upgraded by data centers. In addition, PFNS for Pu, Am and Cm measured by Khlopin Radium Institute within the ISTC project were compiled by JAEA/NDC and NDS. Such improvements identified with IAEA CRPs are also expected for data related to β-delayed neutron [32] and IRDFF library validation [33]. In order to improve accessibility to English translations of articles in Russian, systematic addition of English translation information to EXFOR entries is ongoing, led by CAJaD.

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

VI. CONCLUSIONS

The demand and needs for experimental reaction data is always increasing. Also more and more information in the EXFOR library is expected to be machine readable because of the development of various processing tools. NRDC is continually seeking approaches to maintain EXFOR as a complete and error-free library. Feedback from EXFOR users is extremely important for achieving this goal.

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