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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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EXFOR – International Experimental Nuclear Reaction Data Library

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[x]…

(Revised 13 January 2013)

This paper has been written to provide nuclear science and engineering researchers with practical guidance on search and use of experimental microscopic nuclear reaction data compiled in the EXFOR library maintained and developed by the International Network of Nuclear Reaction Data Centres (NRDC) under the auspices of the International Atomic Energy Agency Nuclear Data Section (IAEA NDS). Following the introduction and overview, the paper outlines cross sections and other major quantities compiled in the EXFOR library. Emphasis is placed on effective search of data sets (EXFOR entries) required by individual EXFOR users, and interpretation of the definitions of quantities expressed by `REACTION` codes given in each EXFOR entry. Mechanisms to ensure the EXFOR library as a complete and correct library are discussed. In addition to compilation, dissemination of EXFOR entries is an important task of the Network, and some data retrieval and processing systems developed by the IAEA NDS and other centres are briefly introduced.

Contents

C. Dictionary
D. ^{252}Cf spectrum averaged cross sections (?)
E. (etc.)

I. INTRODUCTION

The main goal of nuclear data physics is to determine the best estimate of data describing microscopic nuclear phenomena (nuclear data), and provide them to a wide range of researchers who utilise nuclear phenomena in their daily works in sciences and applications. The current achievement of nuclear physics is still far from unified description of bounding states (structure) and scattering states (reaction) evolved by strong interaction based on its fundamental theory (*i.e.*, quantum chromodynamics), and it has been a realistic approach to use a phonological model which describe various experimental facts widely with a set of parameters. These models and parameters must be continuously validated against newly obtained experimental data so that the researchers can use the nuclear data determined based on the latest knowledge of the experimental facts complemented by various state-of-the-art theoretical approach. Collection of all experimental is therefore always the starting point for nuclear data physicists and other researchers. This quite essential step is however a time-consuming part if researchers individually should going through citation lists of earlier works and collect all experimental publications, and the situation is drastically improved if all experimental data are accumulated in a central storage as a common resource of researchers. This is the idea of experimental nuclear data libraries, and the EXFOR library is the best known experimental nuclear reaction data library maintained by the International Network of Nuclear Reaction Data Centres (NRDC).

Among various nuclear reaction data, low-energy neutron induced reaction data have been recognized as most widely used reaction data for both fission and fusion energy applications, and Four Centres, namely NNCSC (National Neutron Cross Section Center, NY, USA), CCDN (ENEA Centre de Compilation Donnes Neutroniques, Saclay, France), NDU (IAEA Nuclear Data Unit) and CJD (Center Jadernykh Dannykh, Obninsk USSR) systematically collected the relevant data for data libraries like SCISRS (Sigma Center Information Storage and Retrieval System) [NEH2005], NEUDADA (Neutron Data Direct Access System) [ENEA69] and DASTAR (Data Storage and Retrieval) [HDL68] in their own formats. More details of this period are described elsewhere [NEH2005, NO2011]. After discussion in the 1st Four Centres Meeting (1966) and following several annual Four-Centre Meetings, these Four Centres agreed upon the EXFOR (Exchange Format) as a common format to exchange neutron-induced reaction data compiled and stored by the Four Centres in 1969 [AL69], and the first data exchange was done on July 1970.

Meanwhile, there were also activities for compilation of charged-particle and photon induced reaction data. Non differential cross sections for charged particle induced reaction compiled by McGowan et al. (Oak Ridge National Laboratory) in 1960s [] and published after checking and corrections by KaChaPaG (Charged Particle Nuclear Data Group, Karlsruhe) [] is known as CPX. The Japanese Study Group also compiled differential cross sections for charged particle induced reaction data in their own library NRDF (Nuclear Reaction Data File) [MT82]. B. L. Berman (Lawrence Livermore Laboratory) also compiled photoneutron cross sections measured with monoenergetic photons in 1970s [BLB76]. These non neutron induced reaction data became important as needs of nuclear data grew in non energy fields. Two closely related meetings held in IAEA Headquarter in 1976 (The 12th Four Centre Meeting, 26-27 April 1976 [FC76] and 2nd Consultants' Meeting on Charged Particle Nuclear Data Compilation, 28-30 April 1976 [OS76]) are recognised as the 1st NRDC Meeting, and three centres specialized for charged-particle induced reaction data compilation (CAJaD, JCPRG and KaChaPaG) started the EXFOR compilation activity, and efforts were also made for translation of existing libraries to the EXFOR Formats (*e.g.*, translation of NRDF to EXFOR by the NTX system []).

Since the 1st NRDC Meeting, many other data centres (ATOMKI, CDFE, CNDC, CNPD, JAEA, KAERI, NDPCI, RIKEN, UkrNDC) joined in the NRDC Network, and actively collaborating in EXFOR compilation and related activities to meet the needs of nuclear data in energy (fission, fusion) and non energy applications (*e.g.*, medical application, material analysis, safeguards) as well as basic sciences (*e.g.*, nuclear physics, nuclear chemistry, astrophysics). More than 19000 experimental works have been compiled in the EXFOR library, and the number is increasing as shown in F**ig. I.1**.

The EXFOR library has been maintained as comprehensive. As a result, retrieval of a specific type of data in the EXFOR library and interpretation of the search result are not always trivial task for EXFOR users. The purpose of this paper is to introduce important concepts of the EXFOR library, so that the library becomes more accessible and understandable for EXFOR users. Physical quantities are always defined by the `REACTION` codes, and they play a crucial role in search and interpretation of the contents. Therefore many practical examples of `REACTION` codes are given in the paper.

The paper is organized as follows: Section II provides the overview of the EXFOR library. Following the scope and data source, EXFOR entry is introduced. Mechanism for creation and exchange of EXFOR entries within the NRDC Network is also described. Section III introduces `REACTION`

codes for various quantities and also explain how to reach a specific type of data efficiently.

II. OVERVIEW

A. Scope

The EXFOR library is a data library for experimental data describing microscopic (*i.e.*, a projectile on a target) nuclear reactions evolved by strong interaction. In order to satisfy the needs of data users on limited human resource available at data centres, the NRDC Protocols [NO11a] classifies data types into the three categories (A, B and C):

A. Compulsory compilation: Neutrons and light ($A \leq 12$) charged particles induced reaction data as well as photo-neutron and photo-fission reaction data at the incident energies less than 1 GeV.
B. Voluntary compilation: Neutrons and light ($A \leq 12$) charged particles induced reaction data as well as photo-neutron and photo-fission reaction data at the incident energies higher than 1 GeV; Heavy ($A \geq 13$) charged particles induced reaction data and other photonuclear reaction data.
C. Separate transmission: Other data types additionally compiled according to the interests of data centres (*e.g.*, meson-induced reaction data).

Data centres have to maintain EXFOR complete for data belonged to the Category A while data belong to the Categories B and C are compiled according to their interests and available human resource.

There is no official agreement about the physical quantities for which EXFOR must be complete. **Table IIA.1** shows the list of physical quantities for brief search of the EXFOR contents by quantities with the corresponding codes (Web Quantity codes). This list may give EXFOR users what are compiled in the EXFOR library. Obviously cross section data (CS) are most important among these physical quantities. Some quantities (*e.g.*, tensor analyzing powers, kerma factors) are explicitly excluded from the Category A in the NRDC Protocol.

TABLE IIA.1: Lists of quantities and their web quantity codes defined in the EXFOR system. The parenthesized number shows the relative abundance of the EXFOR entries providing the quantity (as of January 2013).

Quantities	Code
Cross section data (50)	CS
Differential data with respect to angle (20)	DA
Partial differential data with respect to angle (20)	DAP
Partial cross section data (10)	CSP
Differential data with respect to angle and energy (5)	DAE
Fission product yields (5)	FY
Polarization data (5)	POL
Differential data with respect to energy (2)	DE
Miscellaneous fission quantities (2)	MFQ
Thick target yields (2)	TT
Resonance integrals (2)	RI
Gamma spectra (2)	SP
Product yields (1)	PY
Kinetic energy (1)	E
Cross section integral over incident energy (1)	INT
Scattering amplitudes (1)	L
Nuclear quantities (1)	NQ
Temperature dependent cross section data (0)	CST
Partial differential data with respect to energy (0)	DEP
Outgoing particle multiplicities (0)	MLT
Resonance parameters (0)	RP
Special quantities (0)	SQ
Differential thick target yields (0)	TTD
Partial thick target yields (0)	TTP

Nucleon-nucleon reaction data are on the boundary between nuclear physics and hadron physics, and the EXFOR users are encouraged to assess more specialized compilation, for example databases maintained by the Particle Data Group (PDG) [PDG12] as well as the Theoretical High Energy Physics Group of the Radbound University of Nijmegen [NNON]. A part of PDG compilation is taken from the EXFOR library [VE12].

B. Data Source

Any numerical data tabulated or plotted by the researchers who performed the experiment (hereafter experimentalists) may be included into the EXFOR library. Data tabulated in scientific publications (*e.g.*, journal articles, conference proceedings, laboratory reports, theses) are most typical and useful sources of numerical data for inclusion to the EXFOR library. EXFOR compilers make an attempt to receive the corresponding numerical data from the authors when data are reported on figures without corresponding data tables in the publications. If the final data are not available despite their efforts, EXFOR compilers occasionally adopt the data digitized from the figures by using software ("digitizer"). Data provided by the authors and extracted by digitizer are most typical data sources, and they are indicated by codes TABLE and CURVE under the keyword STATUS in the EXFOR entry. Numerical data are often readily lost from the experimentalists, and receiving of numerical data from the experimentalists is a quite important role of the EXFOR compilers. Sometimes a data set was outside the scope of the EXFOR library, then it became within the scope as needs arise. Sometimes we

luckily found numerical data. An example is seen in thick target neutron yields for 113 and 256 MeV protons accelerated at the Los Alamos National Laboratory [MMM89, MMM90]. When these neutron yields became important in the relation with the IAEA Coordinated Research Project "xxx" in 2012, the corresponding author have left the field more than 20 years ago and formally retired and he lost track of the data sets. Fortunately IAEA NDS could receive tabulated data from L. Greenwood. (Pacific Northwest Laboratories) who received the tabulated data received from the corresponding author privately, and NNDC could successfully add these original numerical data to the EXFOR entries more than 30 years since their publications. This is an exceptional case, and mostly EXFOR compilers are enforced to perform digitization in this situation.

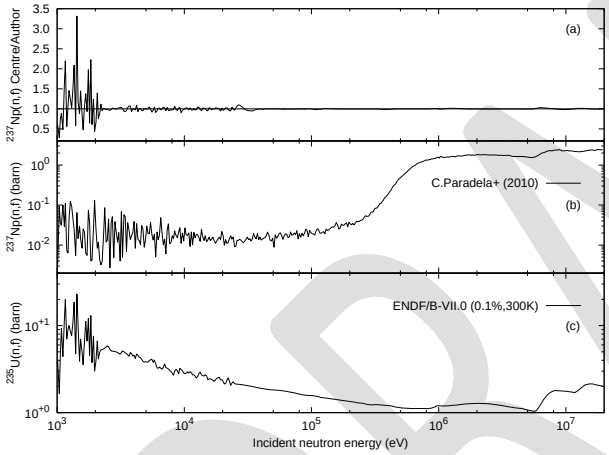


FIG. IIA.1: Normalization of ^{237}Np(n,f) cross section ratio measured by the CERN n_TOF Collaboration [CP10]. (a) Ratio of absolute cross sections normalized by the data centre tool to those normalized by the authors. (b) Absolute ^{237}Np(n,f) cross section obtained by the authors. (c) ENDF/B-VII.0 ^{235}U(n,f) cross section [VP07,MC08] for normalization.

It is sometimes not avoidable to keep numerical data in the EXFOR library even if their sources are unknown. The most typical situation is seen in data originally collected by four neutron centres for their own libraries (*e.g.*, SCISRS, NEUDADA, DASTAR) and then converted into the EXFOR library later. For these data, we cannot know whether the data were originally provided by the authors. For example, there are many data points read from curves in the SCISRS library [VM08]. Such data are indicated with special status codes (*e.g.*, `SCSRS`, `NDD`, `DASTR`) under the keyword `STATUS`. When the same data are found in a publication prepared by the experimentalists, these codes are exchanged with `TABLE`.

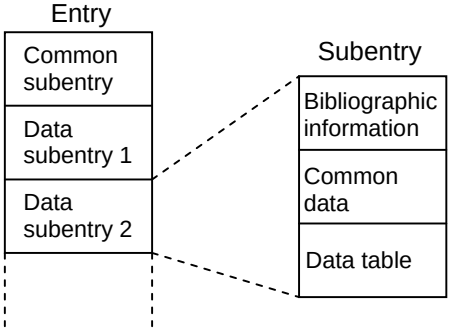
In general, EXFOR compilers are allowed to compile numerical data provided by the authors in general. Exceptionally data renormalized by other than authors may be included (*e.g.*, renormalization due to change in the standard cross section) with a status code `RNORM`. However data centres should store data normalized by the experimentalists in general because renormalization is not always very trivial. The cross section ratio σ [^{237}Np(n,f)]/ σ [^{235}U(n,f)] measured at n_TOF [CP10] normalized to the absolute cross section σ [^{237}Np(n,f)] by the experimentalists and data centre is compared in **Fig.IIA.1**. Though both the authors and data centre normalize the cross section ratio by the ENDF/B-VII.0 cross section [VP07,ADC09], difference between two normalized cross sections is visible below the upper boundary of the resolved resonance region (2.25 keV).

C. An EXFOR Entry

The EXFOR library is a set of *entries*. Each entry is identified by an EXFOR entry number (accession number) and it is corresponding to a set of data sets (data tables) obtained from an experimental *work*. Each entry is divided to the number of *subentries*, and each subentry is divided to Bibliographic information section (BIB section), common data section (COMMON section) and data table section (DATA section). The first subentry is reserved for information commonly applied to all data tables. **Figure IIC.1** shows this structure schematically with a sample EXFOR entry (EXFOR O2053). This sample EXFOR entry is divided to three subentries. In this paper, "O2053.002" means the 2nd subentry of the EXFOR entry O2053.

The BIB section of the first subentry (common subentry) gives the description of the experimental work commonly applied to all data tables. Each BIB section give coded and/or free text information following a keyword. For example, the coded information `(J,PL/B,36,331,1971)` under the keyword `REFERENCE` shows that the reference of the experimental work is Phys. Lett. B **36**, 331 (1971). Another coded information `((MONIT)6-C-12(A,X)4-BE-7,,SIG)` under the keyword `MONITOR` shows that the measured data were normalized by the ^{12}C(α,x)^{7}Be monitor cross section and the monitor cross section is given under the heading `MONIT`. The COMMON section of the first subentry also gives three parameters applied to all data subentries. The set of the heading, unit and value {`EN,MEV,800`} shows that all data tables in this entry are for incident energy at 800 MeV.

(a)



(b)

```
ENTRY           O2053   20121003
SUBENT       O2053001   20121003
BIB                13         16
TITLE      Cross sections for the production of berylium isotopes
           from the 880 MeV alpha-particle bombardment of carbon.
AUTHOR     (J.Lestringuez, G.M.Raisbeck, F.Yiou, R.Bernas)
INSTITUTE  (2FR PAR)
REFERENCE  (J,PL/B,36,331,1971)
…
MONITOR    ((MONIT)6-C-12(A,X)4-BE-7,,SIG)
ENDBIB              16          0
COMMON               3          3
EN          MONIT      MONIT-ERR
MEV         MB         MB
880.        20.2        1.1
ENDCOMMON            3          0
ENDSUBENT           23          0
SUBENT       O2053002   20121003
BIB                  1          2
REACTION   1(6-C-12(A,X)4-BE-9,,SIG)
           2((6-C-12(A,X)4-BE-9,,SIG)/(6-C-12(A,X)4-BE-7,,SIG))
ENDBIB               2          0
NOCOMMON             0          0
DATA                 4          1
DATA       1DATA-ERR  1DATA      2DATA-ERR  2
MB          MB         NO-DIM     NO-DIM
10.6        1.7        0.53       0.08
ENDDATA              3          0
ENDSUBENT           10          0
SUBENT       O2053003   20121003
BIB                  1          2
REACTION   1(6-C-12(A,X)4-BE-10,,SIG)
           2((6-C-12(A,X)4-BE-10,,SIG)/(6-C-12(A,X)4-BE-7,,SIG))
ENDBIB               2          0
NOCOMMON             0          0
DATA                 4          1
DATA       1DATA-ERR  1DATA      2DATA-ERR  2
MB          MB         NO-DIM     NO-DIM
6.5         1.4        0.32       0.07
ENDDATA              3          0
ENDSUBENT           10          0
ENDENTRY             3          0
```

FIG. IIC.1: (a) Structure of one entry. (b) An example of one EXFOR entry (EXFOR O2053).

The second and third subentry gives data tables for the reaction and quantity defined under the keyword REACTION. For example, the second subentry (1st data subentry) gives $^{12}C(\alpha,x)^{9}Be$ cross section (10.6 ± 1.7 mb) and its ratio to the $^{12}C(\alpha,x)^{7}Be$ monitor cross section (0.53 ± 0.08). The REACTION code is given in every data subentry. It describes the reaction and quantity, and plays an essential role to define the data compiled in the DATA section.

One experimental *work* is often reported in more than one publication. For example, a preliminary result could be published in a progress report, conference proceedings etc. before publication of the finalized data in a journal. Information for a given combination of reaction and physical quantity (*i.e.*, REACTION) in all these publications must be compiled in one entry. For example, the $^{40}Ca(n,\alpha_0)^{37}Ar$ cross sections (234 ± 23 mb at E_n = 5 MeV) published in 7 publications [TG92, TG93, YMG93a, YMG93b, TG94, TG96, YMG96] are compiled in the same entry (EXFOR 32609). Before creation of a new EXFOR entry, EXFOR compilers always have to check if the same experimental work has been already seen in an existing EXFOR entry. This principle helps us to avoid compilation of similar data sets twice (*e.g.*, preliminary and final data) in a several EXFOR entries separately. As a result of this principle ("one EXFOR entry for one experimental work"), more than two publications are often coded under the keyword REFERENCE. The information given under the keywords TITLE and AUTHOR are usually taken from the primary reference coded under the keyword REFERENCE.

Sometimes a published data set is revised, and published again. In order to avoid unexpected weight to a measurement, the superseded data set is overwritten, deleted, or flagged by SPSDD under the keyword STATUS. For example,

```
STATUS     (SPSDD,41013004)
```

means the data set is superseded by another data set compiled in EXFOR subentry 41013.004. Some EXFOR search systems (*e.g.*, IAEA NDS web system) provide an option to exclude such superseded data from the search result. It is not always trivial to identify the two data sets originating from the same experimental work. An example is the determination of $^{235}U(n,f)$ cross section absolutely by detection of the recoil charged particles from the D-T and D-D neutron source reaction in coincidence (associated particle method) measured at the Khlopin Radium Institute (Leningrad, KRI), Technical University of Dresden (Dresden, TUD) and Central Institute for Nuclear Study (Rossendorf, ZFK). The related cross section values compiled in EXFOR entries are summarised in **TABLE IIC.1**. It is an important task of EXFOR compilers to trace the history of each data set in collaboration with experimentalists, and to exclude duplication.

The concept of *work* is quite similar the concept of *block* in CINDA. A same block number was assigned to publications belong to the same experimental work. Some CINDA search systems (e.g., IAEA NDS web system) provide an option to extract all publications belong to one experimental work (block). Assignment of a block number (blocking) was one of the most important task of data centres when CINDA was compiled manually.

TABLE IIC.1: $^{235}U(n,f)$ cross sections (barns) between 1.9 and 18.8 MeV measured at the tandem accelerator at Central Institute for Nuclear Study (ZFK) as well as the Cockcroft-Walton accelerators at the Technical University of Dresden (TUD) and Kholpin Radioum Institute (KRI). Italicised data sets are flagged by SPSDD under the keyword SAMPLE in the EXFOR entry.

Author	Year	Ref	EXFOR	Lab.	1.9	2.4	2.6	4.5	8.5	14.7	18.8
I. D. Alkhazov et al.	1983	[ID83]	40911.002	?			*1.214*		*1.801*	*2.086*	
S. S. Kovalenko et al.	1985	[SSK85a]	30706.002	ZFK				*1.057*			
C. M. Herbaoh et al.	1985	[CMH85]	30706.003	ZFK				*1.057*			*1.999*
S. S. Kovalenko et al.	1985	[SSK85c]	30558.002	ZFK					1.801		
S. S. Kovalenko et al.	1985	[SSK85b]	30559.002	TUD			1.215				
V. I. Shpakov	1986	[VIS86]	40927.003	?				*1.057*			*1.999*
V. I. Shpakov	1986	[VIS86]	40927.003	?	*1.26*						
I. D. Alkhazov et al.	1988	[IDA88]	41013.003	KRI			1.215	1.057	1.801	2.085	1.999
I. D. Alkhazov et al.	1988	[IDA88]	41013.004	KRI			1.238	1.093	1.853	2.094	2.065
K. Merla et al.	1991	[KM91]	22304.002	ZFK				1.094	1.855		2.068
K. Merla et al.	1991	[KM91]	22304.006	ZFK			1.24			2.096	
V. A. Kalinin et al.	1991	[VAK91]	41112.002	KRI	1.28	1.27					

D. EXFOR Compilation and Data Centres

Each EXFOR compiler is belonging to one data centres. Currently 14 nuclear data centres from 8 countries and two international organisation (**Table IID.1**) are participating in the International Network of Nuclear Reaction Data Centres (NRDC) [NO11b], and collaborating for maintenance and development of the EXFOR library under the auspices of the IAEA Nuclear Data Section. Each data centre is responsible for completeness of experimental data of specific data types (e.g., projectile) measured in a geographical area. For example, the US National Nuclear Data Center (NNDC) is responsible for compilation of neutron, charged particle and photon induced reaction data measured in USA and Canada.

IAEA NDS is scanning all major journals and register all EXFOR related articles to an internal database (EXFOR Compilation Control System) to ensure the completeness of the EXFOR library. For each publication reporting experimental data within the scope of the EXFOR library, the responsible data centre checks the database and decide if a new EXFOR entry number is created or an existing EXFOR entry is revised based on the new publication. When a similar data set is seen in the database but the relation with the data set in the new publication is not very clear, the data centre must inquire of authors about the relation. This step is still before starting compilation, but an important step to avoid duplication and save a limited human resource available to EXFOR compilation.

Following the conclusion of the assessment described above, EXFOR compilers start compilation of information in the new publication for a new or existing EXFOR entry following several manuals describing the formatting rule [NO11c] and definition of the quantity codes in the EXFOR library [NO11d]. The information given in the publication is often insufficient to archive information satisfactory for future uses. In addition to numerical data shown in figures only in the publication, definition of the quantity, definition of the uncertainty provided by the author, parameters to derive the data to be compiled (*e.g.*, decay data, standard cross sections), and a relation with a similar publication by the same experimentalists in the past are typical questions to the authors at this stage.

When a data centre accumulates a number of new and revised entries, they are assembled into a tape identified by a TRANS number, and it is submitted to other data centres (preliminary transmission). Then the data centre corrects the tape as per comments from the data centres, and submit a finalized tape to other data centres. A complete set of the EXFOR entries (EXFOR Master File) is regularly updated by IAEA NDS, and distributed to data centres.

The data centre members meet together once a year in the NRDC Meeting organized by IAEA NDS in order to review the progress in EXFOR compilation and to discuss revision to the coding rule and actions to the data centres. IAEA NDS also occasionally organize Consultants' Meeting for intensive discussion of a specific subject relevant to EXFOR [SS11, DB12, NO13].

In addition to these meeting, IAEA NDS also organises Workshops to learn the frontier of the nuclear data physics and also new versions of software (*e.g.*, editors, digitizers) useful for EXFOR compilation. Also some NRDC centres are collaborating for improvement of EXFOR entries. For example, Asian Centres (CNDC, JCPRG, KAERI, NDPCI) have organized several workshops to discuss EXFOR compilation and relevant subjects [KA08]. A series of domestic workshop for Indian nuclear physicists is also periodically organized by NDPCI.

TABLE IID,1: Members of the International Network of Nuclear Reaction Data Centres (NRDC). Type: projectile of data compiled in the centre. N: neutron, C: charged-particle, P: photon. KaChaPag and RIKEN have contributed in the past, but are no longer compiling data.

Country	Centre	Type

China	Chinese Nuclear Data Centre (CNDC), Beijing	N, C
Germany	Charged Particle Nuclear Data Group (KaChaPaG), Karlsruhe	C
Hungary	Institute of Nuclear Research (ATOMKI), Debrecen	C
India	Nuclear Data Physics Centre of India (NDPCI), Mumbai	N, C, P
Japan	Hokkaido Univ. Nuclear Reaction Data Centre (JCPRG), Sapporo	C, P
	Institute of Physical and Chemical Research (RIKEN), Wako	C
	Japan Atomic Energy Agency Nuclear Data Center, (JAEA/NDC) Tokai-mura	(eval.)
Korea	Korea Nuclear Data Center (KNDC), Daejeon	N, C, P
Russia	Centre for Nuclear Physics Data (CNPD), Sarov	C
	Centre for Nuclear Structure and Reaction Data (CAJaD), Moscow	C
	Centre for Photonuclear Experiments Data (CDFE), Moscow	P
	Russian Nuclear Data Centre (CJD), Obninsk	N
Ukraine	Ukrainian Nuclear Data Centre (UkrNDC), Kyiv	N, C
USA	US National Nuclear Data Center (NNDC), Upton, NY	N, C, P
NEA	OECD NEA Data Bank (NEA DB), Issy-les-Moulineaux	N, C
IAEA	IAEA Nuclear Data Section (NDS), Vienna	N, C, P

E. Statistics

III. MAJOR QUANTITIES IN EXFOR

A. REACTION Codes

1. Interpretation of REACTION codes

Each column of data tables in EXFOR entries is explained by a combination of a data heading code. Independent variables (*e.g.*, incident energy, outgoing particle angle) are given under their own heading codes (e.g., `EN`, `ANG`) while the measured quantity is given under a generic heading (*e.g.*, `DATA`) and its definition is given under the keyword `REACTION`. The coded information under this keyword is the most essential to understand the data table. It is advantageous for EXFOR users to know basics of the `REACTION` code.

The `REACTION` code is divided to the reaction ("target", "projectile", "process", "product") field, quantity field and data type field. The combination of projectile and process is also called as "reaction" in systems maintained by some centres (*e.g.*, IAEA NDS). The quantity field is divided to four subfields ("branch", "parameter", "particle considered", "modifier") separated by a comma. A parameter code (*e.g.*, `SIG`) is always given while other subfields are optional. For example,

Cross section (`SIG`) for ^{93}Nb(n,2n)^{92m}Nb
`(41-NB-93(N,2N)41-NB-92-M,,SIG)`
Cross section (`SIG`) for ^{3}He photo disintegration
`(2-HE-3(G,N+P)1-H-1,,SIG)`
Cumulative ^{137}Cs yield (`CUM,FY`) ^{235}U neutron fission
`(92-U-135(N,F)55-CS-137,CUM,FY)`
Prompt fission neutron spectrum (`PR,NU/DE`) for ^{252}Cf(sf)
`(98-CF-252(0,F),PR,NU/DE)`
Rutherford ratio (`,DA,,RTH`) for p+^{197}Au elastic scattering
`(79-AU-197(P,EL)79-AU-197,,DA,,RTH)`
Double differential cross section (`,DA/DE`) for ^{nat}Pb(p,n+x)
`(82-PB-0(P,X)0-NN-1,,DA/DE)`

Some remarks on the reaction field:

1. Nuclides are expressed by the atomic number (*Z*), symbol (*S*), mass number (*A*) and isomeric flag (*X*) as *Z*-*S*-*A*-*X*. Special codes are defined for non nuclides (*e.g.*, `0-G-0` for photon, `1-PN-0` for π^- meson, `1-PP-0` for π^+ meson).
2. For natural sample *Z*=0 is used. An isomeric flag (*e.g.*, `G`, `M`, `M1`) is used for products for which a metastable state exists.
3. Codes in the final state are sorted by their mass and charge number. The nuclide having the highest mass and charge among the nuclides is the *product* of the reaction.
4. Light nuclides ($A \leq 4$) are expressed by short their forms when they are projectile or process. Neutron and proton are expressed by `N` and `P` (short form) when they are projectile or process, while `0-NN-1` and `1-H-1` (long form) when they are target or product.
5. There are special codes defined for the process field. (*e.g.*, `EL`: elastic scattering, `INL`: inelastic scattering, `SCT`: scattering, `TOT`: total, `NON`: non elastic, `ABS`: absorption, `F`: fission). The process field never becomes repetition of the projectile field. For example, `(N,EL)`, `(N,INL)` or `(N,SCT)` is used instead of `(N,N)`.

Below are sum rules for some processes:
scattering = elastic scattering + inelastic scattering,
non elastic = total – elastic scattering,
absorption = total – scattering.
When two or more process codes are applicable, the process code having the narrowest definition is applied, for example,

- Process EL for scattering when the inelastic scattering channel does not open.
- Process G for absorption when only the capture channel opens in addition to scattering.

In EXFOR, nuclear states which half-lives are longer than 0.1 sec are treated as *isomers*. States having shorter half-lives may be treated as "quasi-isomeric states" and indicated by an isomeric flag -L. Below are examples of isomeric flags for three states of ^{242}Am:

^{242}Am (16 hour): 95-AM-242-G
^{242}Am (141 year): 95-AM-242-M
^{242}Am (14 msec): 95-AM-242-L

The reaction field is usually human-readable, while the quantity field is cryptic. Data centres are expected to display the full description of the quantity code (*e.g.*, ,DA,,RTH → "Rutherford ratio") so that EXFOR users do not need to interpret each quantity code by themselves.

The data type field is usually empty, but it also may take

DERIV (derived data)
CALC (calculated data)
EVAL (evaluated data)
RECOM (recommended data)

. The derived data is an experimental data set derived by not most straightforward method, for example, data measured by surrogate reaction, non-elastic cross section derived through optical potential parameters. Calculated, evaluated and recommended data are not experimental data, and usually not in general. However some useful evaluated or recommended data not compiled in ENDF-6 format (e.g., kT=30 keV Maxwellian averaged neutron capture cross section recommended by Z. Y. Bao et al. [ZYB00] thermal cross sections recommended by S. Mughabghab [SM]

2. Search a quantity in EXFOR

Search of a quantity in an EXFOR database is typically done by specifying reaction (target, projectile, process, product) and quantity. Normal EXFOR users are expected to search a specific quantity by the web quantity code (Table IIA.1) instead of the codes in the quantity field. Below is an example of quantity codes with their corresponding web quantity codes:

Cross section ,SIG → CS
Cumulative fission yield CUM,FY → FY
Prompt fission neutron spectrum PR,NU/DE → MFQ
Rutherford ratio ,DA,,RTH → DA
Double differential cross section ,DA/DE → DAE

The relation between web quantity codes and quantity code sis one-to-many. Therefore various quantity codes will appear in the result of search for a given web quantity code.

A hint for successful search is *not to be too specific*. For example, it is not recommendable to search a set of data for carbon-12 target by target = 6-C-12 because some data sets may be given for natural carbon targets, and coded as target = 6-C-0 in their REACTION codes. Therefore experienced EXFOR users search carbon-12 target data by target = 6-C-*, where * (asterisk) is a wild card, namely means "any". Another example of search with a wild card is (projectile, process) = (N,*) to search data for production of an isotope because the process field is redundant if the product is specified, and several processes (*e.g.*, n+p and d) may produce the same product isotope. Note that some search systems (*e.g.*, IAEA NDS) allow users to specify nuclides without their atomic numbers (e.g., C-0 instead of 6-C-0).

The rest of this section is devoted to search and interpret major quantities compiled in the EXFOR library. Readers will find an example of search query for various quantities.

B. Cross Sections

1. Double differential cross sections

Double differential cross section is usually given for a product (outgoing particle) q emitted to specific angle θ and with outgoing (secondary) energy E', and given as the sum of cross sections for reactions emitting a specific product q weighted by its multiplicity

$$d^2\sigma(n,q+x)=d^2\sigma(n,q)+2d^2\sigma(n,2q)+3d^2\sigma(n,3q)+\ldots + d^2\sigma(n,q+r)+2d^2\sigma(n,2q+r)+ \quad \text{(IIIB1.1)}$$

($d^2\sigma = d^2\sigma/d\Omega dE'$). It may be searched by specifying a combination of target, projectile, product, and web quantity.

Example IIIB1.1
Search of ^{93}Nb(n,n+x) double differential cross section by
target = 41-NB-93; projectile, process = N,X;
web quantity = DAE. product = 0-NN-1;

Almost all search results belong to the following two REACTION codes:

(41-NB-93(N,X)0-NN-1,,DA/DE),
(41-NB-93(N,X)0-NN-1,EM,DA/DE).

The branch code EM means that the elastic scattering contribution is excluded. An example of comparison between data without and with the branch code EM is shown

in **Fig. IIIB1.1**, where experimental data [AT92,OAS71] are compiled with REACTION codes without and with EM, respectively in their EXFOR entries.

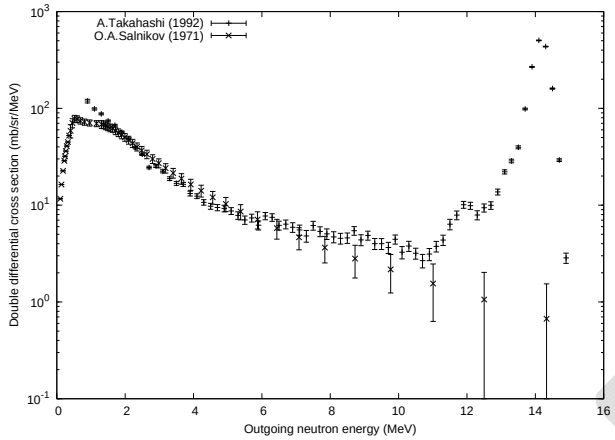


FIG. IIIB1.1 ^{93}Nb(n,n+x) double differential cross sections for incident neutrons at 14.1 MeV (θ_{lab}=30 deg) [AT89, AT92] and 14.4 MeV at θ_{lab}=31 deg. [OAS71].

Below is search for emission of various products q for p+^{181}Ta reaction:

Example IIIB1.2
Search of ^{181}Ta(p,q+x) double differential cross section by

target = 73-TA-181; projectile, process = P,X;
web quantity = DAE.

Then the following various emission double differential cross sections are found:

(73-TA-181(P,X)0-NN-1,DA/DE) for (p,n+x) emission
(73-TA-181(P,X)1-H-1,,DA/DE) for (p,p+x) emission
(73-TA-181(P,X)1-H-2,,DA/DE) for (p,d+x) emission
(73-TA-181(P,X)1-H-3,,DA/DE) for (p,t+x) emission
(73-TA-181(P,X)2-HE-4,,DA/DE) for (p,α+x) emission
(73-TA-181(P,X)1-PN-0,,DA/DE) for (p,π^-+x) emission
(73-TA-181(P,X)1-PP-0,,DA/DE) for (p,π^++x) emission

It would be unfriendly to treat the outgoing neutron as a reaction product (0-NN-1) rather than process (N), however the EXFOR library treat any particle or nuclide as the product of the reaction when it appears in the REACTION code without process specified (*i.e.*, X) or fission (F). The outgoing particle or process is explicitly coded as process when only one process (*e.g.*, SCT: scattering, INL: inelastic) contributes. For example, double differential cross section ^{93}Nb(n,n+x) with and without elastic contribution lower than the ^{93}Nb(n,n+p) ^{92}Zr threshold (~6 MeV) are coded as follows:

41-NB-93(N,SCT)41-NB-93,,DA/DE,
41-NB-93(N,INL)41-NB-93,,DA/DE.

2. *Single differential cross sections*

Several web quantity codes (DA, DAP, DE, DEP) in Table IIA.1 are defined for search of single differential cross section. The last character P in DAP and DEP stands for *partial*, which is an important concept of the EXFOR library and means that the data set is characterized by a secondary energy (*e.g.*, level energy of the product, *Q*-value of the reaction, emission energy of the outgoing particle). Exceptionally data for elastic scattering are not treated as partial even if they are characterised by $Q = 0$. There could be several expressions of secondary energies for the same quantity (*e.g.*, partial inelastic scattering characterized by the level energy E_x coded under the heading E-LVL or Q=-E_x coded under the heading Q-VAL), and they are not distinguished in the REACTION code. Below we will mainly discuss angular differential cross sections DA and DAP.

Example IIIB2.1
Search of angular differential cross sections for neutron scattering in n+^{93}Nb reaction by

target = 41-NB-93; projectile, process = N,*;
web quantity = DA*. product = 41-NB-93;

Excluding double differential cross sections (DAE), majorities of search results are labelled by the following REACTION codes:

(41-NB-93(N,EL)41-NB-93,,DA),
(41-NB-93(N,INL)41-NB-93,PAR,DA)
(41-NB-93(N,EL)41-NB-93,,DA,,LEG)
(41-NB-93(N,INL)41-NB-93,PAR,DA,G)

The 1st REACTION code is angular differential cross section for neutrons from elastic scattering while the 2nd one is for neutrons from inelastic scattering for specific secondary energies (*e.g.*, leaving the residual ^{93}Nb to the $7/2^+$ state at 744 keV). When the J^π is regarded as important to identify the state observed, the EXFOR compiler adds the information under the keyword LEVEL-PROP, for example,

(41-NB-93,E-LVL=0.744,SPIN=3.5,PARITY=+1.)

for the 744 keV level. When the level energy is not explicitly given by the author, the level is tagged by the heading LVL-NUMB, *e.g.*,

(41-NB-93,LVL-NUMB=3.,SPIN=3.5,PARITY=+1.)

for (n,n$_3$) scattering. Note that the product 41-NB-93 is coded without the isomeric flag -G even for elastic

scattering because isomeric flags are used only when the data are summed over the all products .decayed into the isomeric states promptly.

The 3rd `REACTION` code means that the angular differential cross sections are given by a set of Legendre coefficients $\{a_l\}$:

$$d\sigma/d\Omega = a_0 + \Sigma_{l=1,n}\ a_l\ P_l(\cos\theta) \qquad \text{(IIIB2.1)}$$

In addition to this simple Legendre expansion, EXFOR users may find various expansion formulae in LEXFOR "fitting coefficients". The 4th `REACTION` code is for the angular differential cross section of discrete gammas (`G`) characterised by secondary energy (*e.g.*, $E_\gamma(7/2^+ \rightarrow$ g.s.) = 744 keV) instead of outgoing neutrons.

The EXFOR users should aware that the data for the ground state of an intermediate to heavy nuclide may include contribution of the low-lying levels when the ground state was identified by detection of outgoing neutrons depending the energy resolution of the neutron detector [AP11]. For example, the first excitation level of ^{93}Nb ($1/2^-$) is separated from its ground state only by 31 keV, and transition to the level is not separable from transition to the ground state as seen in **Fig. IIIB1.1**, which spectrum was separated to contributions of elastic, "1.08 MeV state" and the sum-peaks of "2.18-2.98 MeV states" by the experimentalists [AT89]. When secondary energy characterizing transition to the "ground state" (*e.g.*, upper boundary of the level energy included in the "ground state"), it is treated as partial scattering, for example,

```
(41-NB-93(N,SCT)41-NB-93,PAR,DA)
```

when data include elastic scattering and inelastic scattering to some low-lying levels inseparable from the ground state.

Deviation of the angular distribution from isotropic distribution (anisotropy) is sometimes expressed by the ratio of the angular differential cross sections normalized to 1 at a reference angle θ_0, i.e., $[d\sigma(\theta)/d\Omega] / [d\sigma(\theta_0)/d\Omega]$. This ratio is expressed by modifiers `RSD` (θ_0=90 deg) and `RS0` (θ_0=0 deg). Study of non isotropic angular distribution of the fission fragments observed for the first time from photofission of ^{232}Th [EJW51, EJW52] is a typical example. The `REACTION` code for the fission fragments of ^{232}Th (γ,f) normalized to 1 at 90 deg is

```
(90-TH-232(N,F),,DA,FF,RSD)
```

, where `FF` indicates that the data are not for a specific product (isotope) but for all fission fragments (`FF`).

Angular distribution is often reported with polarization quantities, for example the vector analyzing power for a spin 1/2 projectile

$$A_y = (1/p_y)\ (N_u - N_d) / (N_u + N_d) \qquad \text{(IIIB2.1)}$$

($-1 \le A_y \le 1$) where p_y is the beam polarization, and N_u and N_d are the numbers of outgoing particles detected at the same angle by using the same number of projectile polarized to the up- and down-direction. Various polarization quantities are defined in LEXFOR "Polarization", and can be searched by the web quantity code `POL`.

3. Cross sections

Cross section is the most fundamental quantity defined in the EXFOR library. Cross sections for particle production and radioisotope production will be discussed separately. Cross sections are searched by the web quantity code `CS`.

Example IIIB3.1

Search of neutron-induced fission cross sections of ^{235}U by
target = `92-U-235`; projectile, process = `N,F`;
web quantity = `CS`.

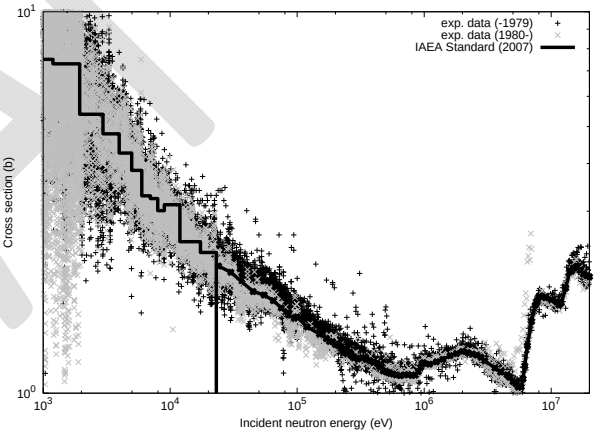


FIG IIIB3.1 Experimental ^{235}U(n,f) cross sections between 1 keV and 20 MeV extracted from the EXFOR library with IAEA standard evaluated cross section.

All ^{235}U(n,f) cross sections between 1 keV and 20 MeV extracted in this example are plotted in **Fig. IIIB3.1** with the IAEA standard evaluated cross section. Since old two experimental works in 1944 at Los Alamos National Laboratory [GAL44, CLB44] more than 100 experimental works have been reported and compiled in the EXFOR library. From the complete archiving of the experimental data reproduced in this figure, we recognize that the absolute cross sections have become slightly lower over 70 years. Even if some old experimental data sets are discarded, there are still a plenty number of experimental data points, and the least squares approach would be a

better option than model calculation (*e.g.*, Hill-Wheller model [DLH53]) to evaluate this important cross section.

It is also possible to obtain the uncertainties and covariances associated to the evaluation performed by the least squares approach if the documentation and compilation are done properly for all partial uncertainties propagated to the total uncertainties with their correlation properties (*e.g.*, correlated or uncorrelated). These are described under the keyword `ERR-ANALYS` and `COVARIANCE` in the EXFOR library. Evaluation of cross sections with their uncertainties and covariances is increasingly-demanded for comparison with the target accuracies required in development of innovative nuclear energy systems [MS08] as well as comparison with the various benchmark problems of the integral nuclear systems through the sensitivity analysis. The EXFOR formats were improved in 2012 to accommodate more detailed descriptions of uncertainties and their correlation properties [DLS12]. Note that the evaluated uncertainty becomes smaller when the number of data points is increased (*i.e.*, better statistics) and the evaluator knows only the uncorrelated uncertainties (*e.g.*, counting statistics). In response to this situation, experimentalists are strongly urged to study guides to error analysis specially prepared for nuclear reaction measurements [WM11, DLS12], and submit detailed description of uncertainties to data centres for compilation in the EXFOR library.

The cross section for the reaction of interest σ_{reac} is often measured with a monitor reaction by irradiating the reaction and standard (monitor) reaction sample simultaneously. Under an ideal condition, σ_{reac} is related to the standard cross section σ_{std} by

$$\sigma_{reac} = (n_{std}/n_{reac})(N_{reac}/N_{std})\,\sigma_{std}, \qquad \text{(IIIB3.1)}$$

where n is the number of atoms in the reaction and standard reaction sample. The ^{235}U(n,f) reaction is a typical standard reaction for measurement of neutron-induced fission cross sections, and its standard data library was prepared by the IAEA Coordinated Research Project "Improvement of standards cross-sections for light elements" and its extension to heavy elements [VP07, ADC09]. The information on the standard reaction and the reference to the standard data adopted by the experimentalists are recorded under the keyword `MONITOR` and `MONIT-REF`, for example,

```
MONITOR    (92-U-235(N,F),,SIG)
MONIT-REF  (,A.D.Carlson+,J,NDS 110,3215,2009),
```

and the standard values are coded under the heading `MONIT` if the values are available to the EXFOR compiler.

Eq. (IIIB3.1) implies that the cross section ratio $\sigma_{reac}/\sigma_{std}$ is more primary measurable quantity than σ_{reac}. Cross section ratios are useful because they can be normalized to the absolute cross sections by using the latest available standard cross section values. Figure IIA.1 shows that this approach could be successful when the standard cross section is a smooth function of the incident energy. Note that the absolute ratio may be obtained only when all parameters having suffixes "std" and "reac" in Eq. (IIIB.3.1) except for σ_{std} are determined well. If some parameters (*e.g.*, the number of atoms) cannot be determined accurately but they are constant of the incident energy, the obtained ratio may be treated as the ratio in the arbitrary units (*i.e.*, shape ratio). An interesting example is seen in neutron-induced fission experiments where samples were prepared by Kholpin Radium Institute (St. Petersburg) while irradiations were done at the Petersburg Institute for Nuclear Physics (Gatchina). The recorded detector signals were analysed and published by the Gatchina group [AL04,AL07] and Petersburg group [AVF04,AVF05] independently. Though the Gatchina group has recognized the obtained cross section ratios as shape ratios [AL06] due to insufficient information on sample masses, the ratios reported by the Gatchina group have been compiled as absolute ratios, and the EXFOR entry lead to a misunderstanding by EXFOR users (*e.g.*, Ref. [MC10] for ^{243}Am(n,f) cross sections). The situation is plotted in **Fig. IIIB3.2**. Extensive discussion with A. Laptev and S. Mashnik (Los Alamos National Laboratory) in 2011 concluded that both data sets are not for superseding. This is a good example of *interdependent data*, namely different results for the same quantity obtained in the same experiment by two different methods of analysis. Such pairs are cross referenced each other by `COREL` under the keyword `STATUS`. For example two interdependent data sets in these two EXFOR entries are cross-referenced by

```
STATUS     (COREL,41487001)
STATUS     (COREL,41444001)
```

in EXFOR 41444.001, and EXFOR 41487.001, respectively.

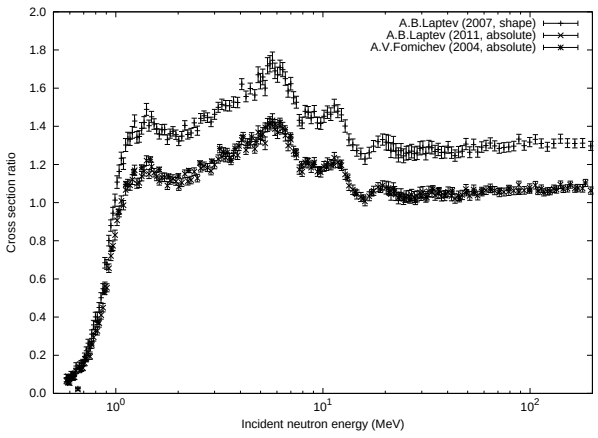


FIG. IIIB3.2. ^{243}Am(n,f) cross section ratios to ^{235}U(n,f) cross sections. Absolute ratios for A. B. Laptev et al. (received in 2011, normalized to ENDF/BII.0 [MBC06] at 1, 5 and 10 MeV) and A. V. Fomichev et al. (received in 2004, cross section integral normalized to ENDF/B-VI at 8.0-15.0 MeV) and shape ratios for A. B. Laptev et al. (received in 2007).

4. Particle production cross sections

Cross sections for reactions leaving a stable nuclide (or particle) as the product is defined as particle production cross section in this paper. Usually we are interested in the sum of all processes leaving the same product, and therefore we use a wild card `*` instead of a process code.

Example IIIB4.1
Search of neutron productions for p+Fe reactions by
target = `26-FE-*`; projectile, process = `P,*`;
product = `0-NN-1`; web quantity = `CS*`.

Then we obtain data sets defined by the following `REACTION` codes for neutron productions:

```
26-FE-0(P,X)0-NN-1,,SIG
26-FE-56(P,X)0-NN-1,,SIG
26-FE-56(P,X)0-NN-1,PAR,SIG
```

The 3rd `REACTION` code is for neutrons within an energy range specified, and it is an example of partial cross sections which web quantity code is `CSP`. A typical secondary energy given for particle productions are lower energy boundary coded under the heading `E-MIN` due to the detector characteristics. Another example is transition energy coded under the heading `E` for for gamma production cross sections, and it will be discussed later.

Production cross sections for various outgoing particles are similar to `REACTION` codes seen in Example IIIB1.2.

Example IIIB4.2
Search of various partial production cross sections for p+^{209}Bi reactions by
Target = `83-BI-209`; projectile, process = `P,*`;
web quantity = `CSP`.

Then we obtain data sets defined by the following REACITION code:

`83-BI-209(P,X)1-H-1,EM/PAR,SIG` for (p,p'+x) emission
`83-BI-209(P,X)1-H-2,PAR,SIG` for (p,d+x) emission
`83-BI-209(P,X)1-H-3,PAR,SIG` for (p,t+x) emission
`83-BI-209(P,X)2-HE-3,PAR,SIG` for (p,^{3}He+x) emission
`83-BI-209(P,X)2-HE-4,PAR,SIG` for (p,α+x) emission

The branch code `EM` of the first `REACTION` indicates that the contribution of the elastic peak is excluded.

As seen in above examples, the particle considered is usually coded as product with `X` in the process field. A major exception is cross sections for production of gammas originating transition of the product from an excitation level.

Example IIIB4.3
Search of various partial production cross sections (`CSP`) for ^{11}B(n,n')^{11}B reactions by
target = `5-B-11`; projectile, process = `N,INL`;
web quantity = `CSP`.

Then there will be following two `REACTION` codes:

```
5-B-11(N,INL)5-B-11,PAR,SIG
5-B-11(N,INL)5-B-11,PAR,SIG,G
```

The 1st `REACTION` code is for ^{11}B(n,n')^{11}B cross section for a specific secondary energy (*e.g.*, leaving ^{11}B to a specific level, outgoing neutrons in a specific energy group), while the 2nd `REACTION` code means the cross section for gamma production following ^{11}B(n,n')^{11}B reaction. **Figure IIIB.4.1** compares cross sections for the ^{11}B(n,n$_1$)^{11}B reaction (E_x=2.1 MeV) and ^{11}B(n,n'γ)^{11}B reaction (E_γ=2.1 MeV). The latest ENSDF evaluation [JHK12] shows the 3rd (E_x=5.0 MeV, 3/2$^-$), 5th (E_x=6.8 MeV, 1/2$^+$) level, and a number of higher levels also contributes to the 2.1 MeV gamma production, that mean (n,n$_1$) data and (n,n'γ$_{2.1MeV}$) data labelled by the two `REACTION` codes are theoretically equivalent below incident energy of 5.0 MeV, and the latter cross section becomes higher above this incident energy. This difference is visible in experimental data in the high (above 10 MeV) energy region in Fig. IIIB.4.1. We also observe two independent evaluation available in the latest major libraries adopt the different sets of experimental data points.

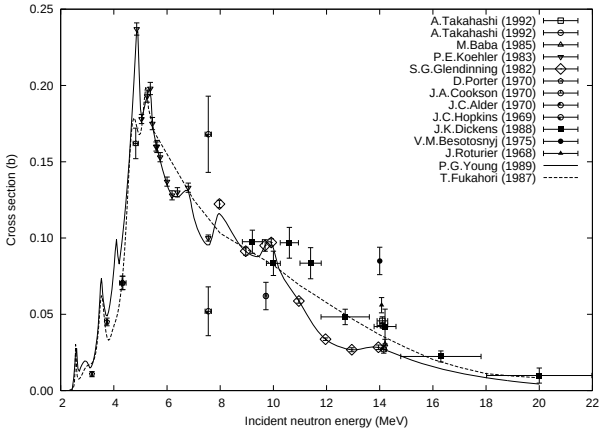


FIG. IIIB.4.1: Comparison of cross sections for transition to 1st excited level (E_x=2.1 MeV) and production of

transition gamma (E_γ(1st→g.s.) = 2.1 MeV) with two evaluated (n,n_1) cross sections. Gamma production cross sections and evaluated cross sections are shown by solid symbols and lines, respectively.

The above example shows that gamma (`G`) is not explicitly coded in the process in gamma production, but in the particle considered field for cross sections. When the transition gamma follows radiative capture reaction, however the gamma is coded in the process field. For example,

```
6-C-12(N,G)6-C-13,PAR,SIG
```

is for ^{12}C(n,γ)^{13}C partial cross section characterised by a specific level (after emission of primary gamma from the capture level), or by a specific transition gamma energy. Note that the sum of the cross section for all possible transition gamma energies is *not* equal to

```
6-C-12(N,G)6-C-13,,SIG
```

(capture cross section).

If the incident energy is high, and we cannot identify the source of gamma production by a specific process (*e.g.*, capture, inelastic), `0-G-0` is coded in SF4, for example.

```
6-C-12(N,X)0-G-0, SIG.
```

5. *Radioisotope production cross sections*

Cross sections for reactions leaving a radioisotope as the product is defined as production cross section in this paper. Similarly to the particle production cross sections, we use a wild card `*` instead of a process code.

Example IIIB5.1

Search of Zn(n,x)^{67}Cu cross section by

Target = `30-ZN-*`; projectile, process = `N,*`;
Product = `29-CU-67`; web quantity = `CS`.

Many of search results belong to the following `REACTION` codes:

```
30-ZN-67(N,P)29-CU-67,,SIG,
30-ZN-67(N,P)29-CU-67,,SIG,,FIS,
30-ZN-67(N,P)29-CU-67,,SIG,,SPA.
```

The 2nd and 3rd `REACTION` codes have an extra code `FIS` and `SPA`, which express that the data were measured under a broad neutron source spectrum (e.g., `FIS`: prompt fission neutron spectrum). Spectrum averaged cross sections compiled in the EXFOR library will be discussed later.

Symbols in **Fig. IIIB4.1** show experimental ^{67}Zn(n,p)^{67}Cu cross sections [MB09, MF08, TS04, CN99, DK95. SKG94, CK93, MV91, AE91, MV82, JLC76, MV76, NR68, GPV67, VNL63] extracted from the EXFOR library. Above 14 MeV, two groups of experimental cross sections are seen. Recent evaluation of ^{67}Zn(n,p)^{67}Cu cross section [NI07] (solid line in Fig. IIIB4.1) supports the lower group, while the energy dependence of the upper group is explained by addition of contribution of ^{68}Zn in the same evaluation

$$\sigma[^{67}\mathrm{Zn(n,p)}^{67}\mathrm{Cu}]+\sigma[^{68}\mathrm{Zn(n,x)}^{67}\mathrm{Cu}]\ [a(^{68}\mathrm{Zn})/a(^{67}\mathrm{Zn})], \quad \text{(IIIB5.1)}$$

(*a*: isotopic abundance) which is plotted by dashed line in Fig. IIIB4.1. Note that "x" stands for the sum of two nucleons (neutron and proton) emission and deuteron emission. Therefore we may conclude that the experimental data belonging to the higher group were measured by the authors with natural zinc samples, and then authors reported the ^{nat}Zn(n,p)^{67}Cu cross sections (*i.e.*, elemental cross sections) divided by the ^{67}Zn isotopic abundance

$$\sigma\ [^{nat}\mathrm{Zn(n,x)}^{67}\mathrm{Cu}]\ /a\ (^{67}\mathrm{Zn}) \quad \text{(IIIB5.2)}$$

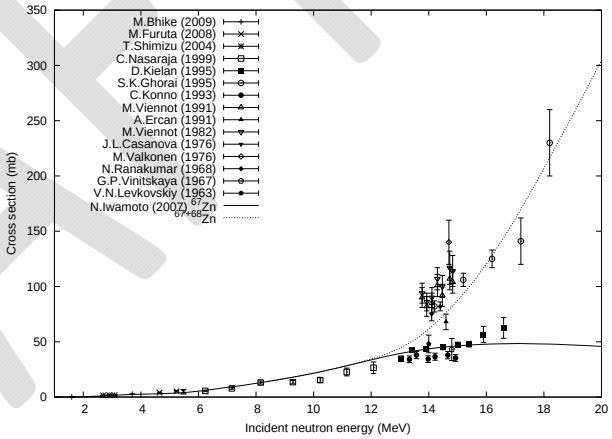


FIG. IIIB4.1: ^{67}Zn(n,p)^{67}Cu cross section. Symbols are experimental data registered as ^{67}Zn(n,p)^{67}Cu cross sections in EXFOR while solid and dashed line are evaluated ^{67}Zn(n,p)^{67}Cu cross sections without and with contributions of ^{68}Zn(n,x)^{67}Cu [NI07].

as the ^{67}Zn(n,p)^{67}Cu cross section (*i.e.*, isotopic cross sections). This is not correct when the neutron energies are above the ^{68}Zn(n,x)^{67}Cu threshold (~8 MeV for deuteron emission and ~10 MeV for two nucleons emission) and the second term of Eq. (IIIB4.1) is not negligible. We have recently a new coding rule for the quantity expressed by Eq. (IIIB5.1)

```
(30-ZN-67(N,P)29-CU-67,,SIG)+
(30-ZN-68(N,X)29-CU-67,,SIG,,RAB),
```

where the code `RAB` means multiplying by the isotopic abundance of the target nuclide and dividing by the isotopic abundance of the target nuclide of the first term. The situation of cross sections belonging to the lower group is understandable for Kielan et al. (1995) [DK95]

and Konno et al. (1993) [CK93] from the description under the keyword CORRECTION and SAMPLE of their EXFOR entries. Kielan et al. corrected the measured data for calculated ^{68}Zn(n,x)^{67}Cu and ^{70}Zn(n,α)^{67}Ni(β$^-$)^{67}Cu contributions, while Konno et al. used an enriched (94.60%) ^{67}Zn sample.

The reported isotopic cross sections are inverse proportion to the isotopic abundance of the target nuclide the experimentalists derived from the elemental cross sections by Eq. (IIIB5.2). Though the isotopic abundance is not significantly revised in general (e.g., a(^{67}Zn)=4.1% in ^{67}Zn(n,p)^{67}Cu experimental work published in 1961 [JJVL61] while it is ??% in 2009 [MB11]. EXFOR compilers are encouraged to keep the isotopic abundance adopted by the experimentalists under the keyword SAMPLE, for example,

```
SAMPLE      (30-ZN-67,NAT=0.041).
```

Radioisotope production cross sections are usually measured by the activation method, namely the cross sections are ideally derived from the counts of decay radiation (typically β or electron capture delayed gamma-rays) by

$$\sigma_{obs} = \lambda N_{rad} / \{\varepsilon I_{rad} n \varphi [1-\exp(-\lambda t_m)]\exp(-\lambda t_c)[1-\exp(-\lambda t_i)]\} \quad \text{(IIIB5.3)},$$

where λ, N_{rad}, ε. I_{rad}, n, φ, t_m, t_c, and t_i are the decay constant, number of the radiation, detector efficiency, intensity of the radiation, number of atoms in the sample, number of projectiles, measuring time, cooling time and irradiation time. The measured cross section depends on decay data λ and I_{rad}, and the decay data adopted by the experimentalists are kept under the keyword DECAY-DATA. For example, Viennot [MV76] adopted the 184.5 keV β$^-$delayed gamma radiation with I_{rad}=47% in derivation of ^{67}Zn(n,p)^{67}Cu cross section. It is recorded in the EXFOR entry as follows:

```
DECAY-DATA (29-CU-67,62.01HR,DG,184.5,.47).
```

The intensity of the 184.5 keV is slightly increased to 48.7% in the latest ENSDF evaluation [HJ05]. The EXFOR compilers do not revise the cross sections reported by the experimentalists in general, however EXFOR users can utilise the information under the keyword DECAY-DATA to renormalize the reported cross sections by the latest evaluation. For example, the above Viennot's cross section may be renormalized by a multiplication factor 47.?/48.7=0.965 based on the latest ENSDF evaluation.

The number of the projectile φ in Eq. (IIIB5.3) is often determined by a standard reaction which role has been already discussed in Section III.B.3. There are some well-established sets of standard cross sections for various monitor reactions (e.g., [] for neutron activation, [] for proton activations). Information about the adopted monitor reactions and references to the standard cross sections is found under the keyword MONITOR and MONIT-REF.

Measurement of the cross sections for production of an isotope ^{A}J (atomic number Z, mass number A) on the β$^+$ side of the stability line is schematically shown in **Fig. 4**. This figure shows that the cross section for production of the ground state of the isotope ^{Ag}J determined by the EC delayed gamma radiation may be influenced by its metastable state ^{Am}J and ^{A}L if they feed ^{Ag}J by isomeric transition (IT) and electron capture (EC).

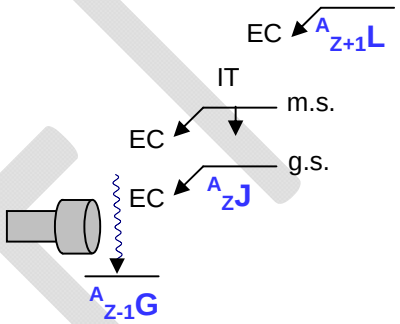


FIG. IIIB5.2: Detection of EC delayed gamma radiation originated by decay of three isotopes ^{Ag}J, ^{Am}J and ^{A}L on the mass chain A. EC: electron capture, IT: isomeric transition.

The observed cross section of ^{Ag}J is expressed by

$$\sigma_{obs}(^{Ag}J) = \sigma(^{Ag}J) + a\,\sigma(^{Am}J) + b\,\sigma(^{A}L) \quad (0 \le a, b \le 1) \quad \text{(IIIB5.4)}$$

where the second and third terms are contribution of the feeding by ^{Am}J and ^{A}L, and the coefficients a and b depend on the decay scheme and measurement conditions (*e.g.*, choose of cooling time).When a~b~0, the measured cross section is called as *independent* cross section, otherwise it is called as *cumulative* cross section. An example of the measured cumulative cross section is shown in **Fig. IIIB5.3**, where ^{nat}Pd(p,x)^{101m}Rh (4.3 day) cross sections determined by counting of EC delayed gamma radiation [MUK10, FD07] are compared with cross sections predicted by TALYS [AK12]. The observed cross section is well reproduced by σ[^{nat}Pd(p,x)^{101m}Rh]+σ[^{nat}Pd(p,x)^{101}Pd] predicted by TALYS (with the default parameter set), and therefore we may interpret that the measured cross section is cumulative. The cumulative cross section of an isotope is, however, usually less than the sum of independent cross sections for precursors. Under a specific condition of measurements and decay scheme, we can obtain this good

agreement seen in Fig. IIIB5.3. These observed cross sections are compiled with the following REACTION code:

```
46-PD-0(P,X)45-RH-101-M,CUM,SIG.
```

Note that the contribution of ^{nat}Pd(p,x)^{101g}Ag (11.1 min) to the observed cumulative cross section is also physically possible. According to the charge conservation, silver is the isotope having the highest Z number produced by p + ^{nat}Pd reaction (below the pion production threshold). If the contribution of ^{101}Pd is subtracted, it can be coded with

```
46-PD-0(P,X)45-RH-101-M,IND,SIG.,
```

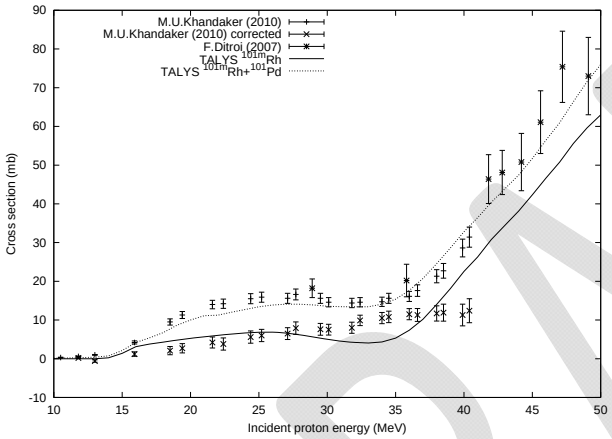


FIG. IIIB5.3: Comparison of observed ^{nat}Pd(p,x)^{101m}Rh (4.3 day) cross sections [MUK10, FD07] with ^{nat}Pd(p,x)^{101m}Rh cross section without (solid) and with (dashed) ^{nat}Pd(p,x)^{101}Pd cross sections predicted by TALYS [AK12]. 'corrected' means ^{nat}Pd(p,x)^{101}Pd cross section measured in the same experimental work is subtracted.

Derivation of the independent cross section is possible by subtraction of the ^{nat}Pd(p,x)^{101}Pd cumulative cross section in Ref. [MUK10] and plotted in Fig. IIIB4.3, though the independent cross section is not reported in the article. The inverse kinematics method is a powerful technique to determine independent cross sections of charged-particle induced reactions by analyzing the products emitted to the forwarded angles. This technique was employed in the systematic study of heavy-ion induced reactions on hydrogen and deuteron targets by using the Fragment Separator (FRS) [HG92] at the Organisation for Heavy-Ion Research (GSI, Darmstadt). Some radioisotope production cross sections measured by the inverse kinematics reaction ^{1}H(^{208}Pb,x) reactions at GSI are compared with those for the normal kinematics ^{208}Pb(p,x) reactions measured by the activation method by the Hanover group in [WW00].

TABLE IIIB5.1. Product and modifier fields for the REACTION code for production cross section of ^{Ag}J shown in Fig. 4. The coefficients a and b are defined in Eq. (4). "?" is applied when the experimentalists do not report the contribution clearly in their publication.

	$a \sim 0$	$0 < a < 1$	$a \sim 1$	a = ?	no ^{Am}J
$b \sim 0$	Z-J-A-G,IND	Z-J-A-G,IND/M+	Z-J-A,IND	Z-J-A-G,IND/(M)	Z-J-A,IND
$0 < b \leq 1$	Z-J-A-G,CUM/M-	Z-J-A-G,CUM	Z-J-A,CUM	Z-J-A-G,CUM/(M)	Z-J-A,CUM
b= ?	(not defined)	Z-J-A-G,(CUM)/M+	Z-J-A,(CUM)	(not defined)	(not defined)
no ^{A}L	Z-J-A-G	Z-J-A-G,M+	Z-J-A	Z-J-A-G,(M)	Z-J-A

All possible combinations of product and modifier for the observed ^{Ag}J production cross sections are listed in **Table IIIB5.1**. The last line (no ^{A}L) is applied when the contribution of ^{A}L does not exist (*e.g.*, due to charge conservation, $Q(^{A}L \rightarrow ^{Ag}J) < 0$) but the feeding by the isomeric transition of ^{Am}J exists, while the last column (no ^{Am}J) is applied when the contribution of ^{Am}J does not exist (*e.g.*, metastable state does not exist, or its isomeric transition probability is zero) and the feeding by ^{A}L exists. Also this Table shows that the isomeric flag is omitted When the cross section is the sum of the ground state and (100%) of the metastable state (*i.e.*, -G+M or -M+G is never coded.). For example, ^{58}Fe(p,n)$^{58g+m}$Co production cross section is coded by

```
26-FE-58(P,N)27-CO-58,,SIG.
```

6. *Resonance parameters*

Resonance parameters are important inputs in description of various low-energy nuclear phenomena. For example, fission energy systems are mainly described by neutron scattering, capture and fission below ~1 MeV (prompt fission neutron energy). Cross sections for charged-particle reactions are very small below the Coulomb barrier in general, but their resonances are essential to describe synthesis of light nuclides in the early universe. Resonances in charged-particle induced reaction are also utilised in ion-beam analysis technique. Despite

theoretical efforts to describe the resonance parameters for applications to nuclear reaction systems (e.g., [CA99] for astronuclear physics), it is not realistic to predict resonance parameters comprehensively, and the realistic and common approach is to extract resonance parameters from experimental data (*e.g.*, fitting of experimental excitation function by the R-matrix formalism). Therefore experimental data play a crucial role in this field.

Experimentally resonances R may be observed as the compound (x+X→R→y+Y) or residual (z+Z→w+R) through nuclear reactions. Recent progress in technologies for radioisotope beam acceleration and coincidence detection has widened the applicability of the second approach, and it is now widely used to estimate the contribution of each compound resonance to the low-energy charged-particle induced reaction rates. The resonance properties derived by the second approach are however outside the scope of the EXFOR library. The nuclear data group of McMaster University is actively working for compilation of such data for XUNDL [XUNDL] in collaboration with other institutions.

Below we will discuss examples of EXFOR entries for compound resonances in low energy neutron-induced reactions which are usually observed by time-of-flight (TOF) measurements. Measurements of compound resonances for low-energy charged-particle induced reactions are also actively done by using thick-target method (e.g., measurement of compound elastic scattering at various depth of the thick sample).

Example IIIB6.1

Search of resonance parameters for n+^{6}Li reaction by
Target = `3-LI-6`; projectile, process = `N,*`;
web quantity = `RP`.

In order to understand the REACTION codes in the search result, let us open the source file of EXFOR 11164.002 [JAF68]:

```
SUBENT        11164002   19800814
BIB                2          4
REACTION  1(3-LI-6(N,0),,EN)
          2(3-LI-6(N,A),,WID)
          3(3-LI-6(N,EL),,WID)
ANALYSIS   (SLA) Single level Breit-Wigner formula
ENDBIB             4
NOCOMMON           0          0
DATA               3          1
DATA      1DATA      2DATA      3
MEV        KEV        KEV
 2.506  -01 84.1       167.2
ENDDATA            3
ENDSUBENT         12
```

It is usual to see more than two REACTION codes are in a subentry for resonance parameters. This subentry gives the following set of resonance parameters:

E_r	Γ_α	Γ_n
MeV	keV	keV
0.2506	84.1	167.2

Below are examples for some other typical resonance parameters for n+^{208}Pb resonance:

`82-PB-208(N,G),,WID,,G`	$g\Gamma_\gamma$
`82-PB-208(N,EL),,WID/STR`	$g\Gamma_n\Gamma_\gamma/\Gamma_{tot}$
`82-PB-208(N,0),,J`	J
`82-PB-208(N,0),,D`	level spacing
`82-PB-208(N,G),,STF`	strength function

There are two general remarks on `REACTION` codes for resonance parameters:

- Product is not explicitly given.
- Process is `0` (zero) when the quantity does not depend on each decay channel theoretically (*e.g.*, resonance energy, spin, parity).

Experimentalists often adopt quantities related to the second remark from another publication to label each resonance. In this case, they are not given under the keyword `REACTION`, but coded under the headings (*e.g.*, `EN-RES` for resonance energy, `SPIN J` for total spin) in the data table.

For neutron-induced reactions, primary measurable in derivation of resonance parameters are usually transmission $T = C_0/\varphi$ and reaction yield $Y_r = C_r/\varphi$ under an ideal condition (C_0: number of neutrons survived from the target without interaction, C_r: number of events for channel r, φ: number of incoming neutrons). In real experiments, however, various corrections (background subtraction, normalization etc.) must be done [PS12]. By their definitions, $T+\Sigma_r Y_r=1$. The transmission is also related with the total cross section σ_{tot}:

$$T = \exp(-n\,\sigma_{tot}) \qquad \text{(IIIB6.1)}$$

Below are examples of `REACTION` codes for transmissions and reaction yields:

```
(79-AU-197(N,TOT),,TRN)
(79-AU-197(N,G)79-AU-198,,RYL)
```

The first one is for n+^{197}Au transmission while the second one is for ^{197}Au(n,γ)^{198}Au reaction yield (capture yield).

Example IIIB6.2

Search of transmission for n+^{233}U by
Target = `92-U-233`; projectile, process = `N,TOT`;
web quantity = `CS`.

Note that the transmission (`,TRN`) belongs to the web quantity code `CS`. Then one may find EXFOR entries for transmissions:

```
(92-U-233(N,TOT),,TRN)
```

in addition to the total cross sections. The transmission obtained at the Oak Ridge Linear Accelerator (ORELA) facility of Oak Ridge National Laboratory [KHG01] is compared with evaluation performed at the same laboratory [LE01] are compared in **Fig. IIIB6.1**. The behaviour of the transmission and its correlation with the total cross section is understandable from Eq. (IIIB6.1).

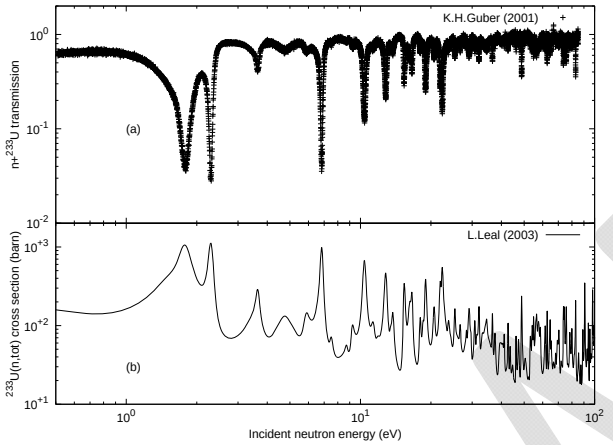


FIG IIIB6.1: Resonance analysis for n+^{233}U. (a) Neutron transmission measured at ORELA [KHG01]. (b) Total cross section evaluated at ORNL [LE01].

The spectra have been regarded as bulky "raw" data (typically ~10^4 data points) by data centres. Correct analysis of spectra for extraction of resonance parameter is possible only when necessary information (*e.g.*, experimental conditions) is available. Under this situation, experimentalists have hesitated submission of there spectra, and EXFOR compilers have compiled only resonance parameters deduced from the spectra though there have been recommendation to improve the situation [PS12]. A limited number of time-of-flight measurement facilities are still in operation, while evaluators urge to use experimental spectra for their own evaluations. Re-analysis of existing time-of-flight spectra is also important when one want to analyze new experimental data (*e.g.*, capture yield) and existing data (*e.g.*, transmission) simultaneously (*e.g.*, [xxx]). Uncertainties and their correlation properties of spectra also become essentialt if one want to evaluate covairances of resonance parameters [BB11]. Under this situation, a new EXFOR format [NO11,DLS12] was agreed for time-of-flight spectra and their covariances in the AGS format [CN92,BB11]. NDS, NEA DB and NNDC have started discussion with experimentalists in major facilities to improve the situation in collaboration with P. Schillbeckx (Institute of Reference Materials and Measurements, Geel).

C. Yields

1. Fission yields

Fission yields are the number of products from fission (fission products) specified by atomic number and/or mass number, or their ranges. They are usually expressed by the number of products per 1 fission (or per 100 fission, often expressed by %). If $\sigma(A,Z)$ and $Y(A,Z)$ are production cross sections and fission yields for a specific product characterised by Z and A from a particle induced fission, $Y(A,Z)=\sigma(A,Z) / \sigma_f$, where σ_f is the fission cross section.

Fission yields are important inputs for calculation (*e.g.*, barn up, decay heat) of fission energy systems for their designing and operation. Also, it is demonstrated that the abundance of a part of the elements synthesized by r-process (A<140) may be sensitive to the fission mass distribution (e.g., symmetric of asymmetric See [SG13]). Model prediction of fission yields is still very challenging, and fitting to existing experimental data sets (*e,g.*, Wahl's systematics [ACW88]) is a realistic approach of evaluation. Therefore the EXFOR library is expected to be a primary source of experimental fission yields for evaluators. At the beginning stage of the EXFOR library, fission yield data were less complete than cross section data because of difficulty to compile fission yield data in the EXFOR formats and rule at that time. The situation has been improved during the IAEA Coordinated Research Project "Compilation and Evaluation of Fission Yield Nuclear Data" [ML00] made a special effort to improve the situation. Fission yield data compiled in the Rider File [BFR81] were converted into the EXFOR library by data centres.

Fission yields compiled in the EXFOR library are usually given for fragments at one of the following fission stage:

1. fragments before prompt neutron emission
2. fragments after prompt neutron emission but before β decay
3. fragments after β decay

On-line analysis (*e.g.*, time of flight, prompt gamma spectroscopy) can observe the fragments on the second stage, while off-line analysis (e.g., β delayed gamma spectroscopy) identifies isotopes at the third stage. The first stage is very short (<10^{-10} to 10^{-15} sec), and accessible only indirectly by kinematical information obtained from on-line measurements with assumptions (*e.g.*, isotropic emission of neutrons, conservation of mass, momentum, energy). The information on fragments before and after prompt neutron emission is often called as *primary* and *secondary*, which fragment yields are usually labelled by mass, namely $Y(A)$. Fission yields $Y(A,Z)$ at the second and third stage are *independent* and *cumulative*, which idea was

discussed in the discussion on radioisotope production cross sections (Section IIIB5**)**. Note that $Y_{ind}(A,Z) \leq Y_{cum}(A,Z)$ for each (A,Z), and

$$Y_{sec}(A)=\Sigma_Z Y_{ind}(A,Z) \leq \Sigma_Z Y_{cum}(A,Z)=Y_{chain}(A) \qquad \text{(IIIB5.1)}$$

, where the cumulative yield summed over Z is defined as the *chain* yield. As discussed for cumulative production cross sections, cumulative yields may depend on the measurement condition (*e.g.*, cooling time). In addition to the precursor of β decay $(A,Z\pm1)$, β delayed neutron emitter $(A+1,Z)$ also may contribute to $Y_{cum}(A,Z)$. For secondary fragment mass yields and independent product yields,

$$\Sigma_A Y_{sec}(A)=\Sigma_{A,Z} Y_{ind}(A,Z) \geq 2 \text{ (or 200\%)} \qquad \text{(IIIB.5.2)}$$

The equal sign is valid when we can ignore ternary fission events (*i.e.*, emission of light charged particles like α as the third fragment).

Example IIIC1.1
Search of ^{235}U(n,f)^{99}Mo fission yield by
Target = `92-U-235`; projectile, process = `N,F`;
web quantity = `FY`.; product = `42-MO-99`.

Then we find the following cumulative yields in the search result:

```
92-U-235(N,F)42-MO-99,CUM,FY
92-U-235(N,F)42-MO-99,CUM,FY,,MXW
92-U-235(N,F)42-MO-99,CUM,FY,,FIS
```

for example. The modifier `MXW` and `FIS` mean the yields were measured under Maxwellian neutron field and fission neutron field, respectively. Also this cumulative yield often appears in denominators of reaction ratios, for example,

```
(92-U-235(N,F)40-ZR-97,CUM,FY)/
(92-U-235(N,F)42-MO-99,CUM,FY)

((92-U-235(N,F)55-CS-136,IND,FY,,FST)/
(92-U-235(N,F)42-MO-99,CUM,FY,,FST))//
((92-U-235(N,F)55-CS-136,IND,FY,,MXW)/
(92-U-235(N,F)42-MO-99,CUM,FY,,MXW))
```

(`FST`: fast reactor neutron field) because the ^{99}Mo yield are recommended as reference (standard) yield. The second type of ratio

$$R=[(Y(Z,A) / Y(Z_s,A_s)]_E / [(Y(Z,A) / Y(Z_s,A_s)]_T$$

(s: standard, E: incident neutron energy of interest, T: thermal neutron energy) is known as "R-value". Advanced search systems also may show some results which have instead of `ELEM/MASS` as a product instead of `42-MO-99`, for example,

```
92-U-235(N,F)ELEM/MASS,CUM,FY
```

, which means the atomic (`ELEM`) and mass number (`MASS`) numbers as variables of the data table. The next example shows fission yields for ^{99}Mo (4.63%), ^{132}Te (3.16%) and ^{140}Ba (7.85%):

```
SUBENT        32663002   20060622
BIB                  1          1
REACTION   (92-U-235(N,F)ELEM/MASS,CUM,FY)
ENDBIB               1
NOCOMMON             0          0
DATA                 3          3
ELEMENT    MASS       DATA
NO-DIM     NO-DIM     PC/FIS
 42.         99.       4.63
 52.        132.       3.16
 56.        140.       7.85
ENDDATA              5
ENDSUBENT           11
```

Fission yields and radioisotope production cross sections are often compiled in one table with atomic and mass numbers as variable in this way. One may expect that various mass yields $Y(A)$ can be found with `MASS` as the product.

Example IIIC1.1
Search of ^{235}U(n,f) chain and secondary mass yield by
Target = `92-U-235`; projectile, process = `N,F`;
web quantity = `FY`.; product = `MASS`.
(If your EXFOR search systems do not recognize this symbolic nuclide code `MASS` as a product and you receive not result, you should try without specification of product).

Then we find the following mass yields in the search result:

```
92-U-235(N,F)MASS,CHN,FY
92-U-235(N,F)MASS,PRE,FY
92-U-235(N,F)MASS,SEC,FY
```

These are for chain yield, primary and secondary fragment mass yields, respectively. In many case, these `REACTION` codes are supplemented by a spectrum modifier (e.g., `MXW` for Maxwellian neutron spectrum, `SPA` for unspecified spectra). These various mass yields for ^{235}U thermal neutron fissions extracted from the EXFOR library is compared in **Fig. IIIC1.1** (a). Many of them are chain yields determined by β delayed gamma spectroscopy. One experimental work [MD70] measured masses of two secondary fragments by time-of-flight with silicon detectors in coincidence. They determined the secondary fragment mass yields, and then derived the primary fragment mass yields. The shift of the mass curve due to the correction for prompt neutron emission is seen in **Fig. IIIC1.1** (b).

Fission yields for light charged particles (e.g., multiplicities for alphas from ternary fission) are expressed by the corresponding nuclide codes in the product field. For example,

```
(92-U-235(N,F)2-HE-4,TER,FY)
```

means ^{235}U(n,f) ternary fission alpha yields.

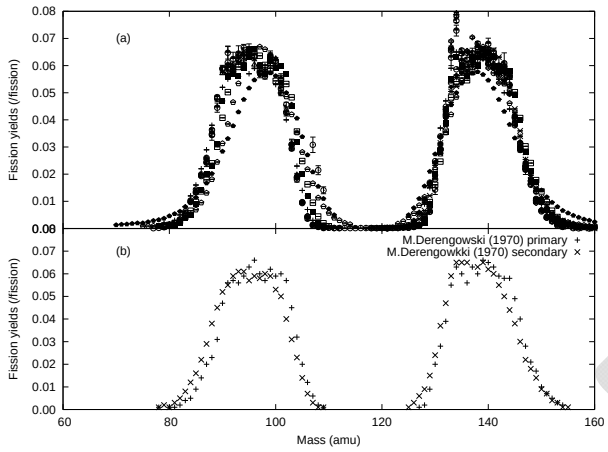


FIG IIIC1.1 (a) Fission mass yields for ^{235}U(n_{th},f) extracted from the EXFOR library. (b) Comparison of the primary and secondary fission fragment mass yields [MD70].

An important exception for the above mentioned rule is applied for fission neutron multiplicities. It is searched by the web quantity MFQ (Miscellaneous fission quantities), which is actually defined for various fission neutron quantities (*e.g.*, multiplicities, spectra). The quantity is *not* coded with `0-NN-1` in the product field.

Example IIIC1.2
Search of ^{239}Pu(n,f) fission neutron multiplicities by,
Target = `94-PU-239`; projectile, process = `N,F`;
web quantity = `MFQ`.

Then you may find various neutron multiplicities, for example.

```
(94-PU-239(N,F),PR,NU)
(94-PU-239(N,F),DL,NU)
```

for prompt and delayed neutron multiplicities. We do not see the nuclide code 0-NN-1 as the product, but see a parameter code specially defined for the neutron multiplicities (`NU`). Prompt fission neutron multiplicities are often given as the ratio to the ^{252}Cf spontaneous fission (sf) prompt neutron multiplicity (~3.8 neutrons / fissions), for example,

```
(94-PU-239(N,F),PR,NU)/(98-CF-252(0,F),PR,NU)
```

for the ratio of the ^{239}Pu(n,f) prompt fission neutron multiplicity to that of ^{252}Cf(sf). This allows EXFOR users conversion to the absolute multiplicity by using the best estimate of ^{252}Cf(sf) prompt fission neutron multiplicities at that time. Above example also shows that quantities for spontaneous fissions are coded with a special code `0` (zero) in the projectile field.

In addition to fission neutron multiplicity, its energy distribution is also important in reactor application. Below are examples of REACTION codes for ^{235}U(n,f) prompt fission neutron spectra:

```
(92-U-235(N,F),PR,NU/DE)
(92-U-235(N,F),PR,NU/DE,,NPD)
(92-U-235(N,F),PR,NU/DE,,REL)
(92-U-235(N,F),PR,NU/DE)/(98-CF-252(0,F),PR,NU/DE)
```

The modifier `NPD` means the energy distribution is normalized to probability distribution (i.e., integration of the spectrum is equal to 1), while REL means the energy distribution is given in arbitrary unit. As see in the last example, the prompt fission neutron spectrum is also often determined relative to that of ^{252}Cf(sf). The measurement of the low energy (<1 MeV) neutron part is challenging due to the low detector efficiency, and experts of experimentalists and theorists are currently collaborating under the IAEA Coordinated Research Project "xxxxx".

In addition to fission yields, some quantities related fission yields are also found by the web quantity `FY`, for example,

```
92-U-235(N,F),PRE,AP,LF
92-U-235(N,F),PRE,AP,HF
```

are for most probable mass for light and heavy fragments (i.e., masses which give the peak in the double-humped mass curves). Various kinetic energies related to fissions are also found by the web quantity `E`, for example,

```
92-U-235(N,F),,AKE,LF+HF
92-U-235(N,F)MASS,KE,LF+HF
```

give the total kinetic energy averaged for all fission fragment and for fragments having a certain mass, respectively.

2. Thick target particle yields

The number of a product from charged-particle induced reaction with a thick sample is defined as thick target particle yields (multiplicities) in this paper. The initial incident energy (beam energy) is reduced in the sample according to the stopping power dE/dx of the sample material, and the projectile is finally stopped if the sample is enough thick. The product is produced at the various depth of the sample x, and therefore the quantity depends on the sample thickness when the thickness is shorter than the stopping length. Under an ideal condition (*e.g.*, no secondary reaction in the sample), the thick target particle yield Y (per one projectile) is related with the production cross sections

$Y = \int_{E_{out}}^{E_{in}} dE\ \sigma(E)\ \rho\ (dE/dx)^{-1}$ (products/projectile), (IIC2.1)

where E_{in} and E_{out} are the projectile energies at the entrance and exit of the sample material, and ρ is the number of the nuclei per unit volume. It is often also expressed by the number of products per unit charge (*e.g.*, per 1 μC). In many cases, the yields are given for the sample having the full stopping length thickness (i.e., E_{out}=0), and does not depend on the sample thickness.

Among various products, thick target neutron yields are most important for various applications (*e.g.*, shielding, neutron source development). In the relation with nucleosynthesis, thick target gamma yields from low energy charged particle induced reactions (*e.g.*, (p,γ) reaction) have been utilized to derive the resonance strength (capture kernel) $\omega\gamma = g\,\Gamma_i\,\Gamma_\gamma/\Gamma_{tot}$ with $g = (2J_R+1) / (2J_p+1)(2J_t+1)$ *R*: resonance, *p*: projectile, *t*: target) [JMD04,WAF48].

Example IIIC2.1

Search of Li(p,n+x) differential thick target neutron yields by,

Target = `3-LI-*`; projectile, process = `P,X`;
web quantity = `TTD`; products = `0-NN-1`

Then we find the following `REACTION` codes in the search result:

```
3-LI-0(P,X)0-NN-1,,PY/DA,,TT
3-LI-0(P,X)0-NN-1,,PY/DA/DE,,TT
```

. The first code means angular differential neutron yields and the second code is for double differential neutron yields. They are given per one incident proton or per a unit induced charge (*e.g.*, μC). Note that the neutron is coded as process (`N`), for example,

```
3-LI-7(P,N)4-BE-7,PAR,MLT/DA,TT
3-LI-7(P,N)4-BE-7,,MLT/DE,,TT
```

This may happen when the level of ^{7}Be is specified, or only (p,n) channel opens. When the yield of the particle in the process field is considered, we see `MLT` instead of `PY`. If we want to have a complete list of Li+p thick target neutron yields, the search performed in Example IIIC2.1 must be complemented by the following search:

Target = `3-LI-*`; projectile, process = `P,N`;
web quantity = `TTD`;

. Low-energy (p,n) thick target neutron energy differential yields (spectra) are often discussed in the relation with neutron sources. As an example, ^{3}H(p,n)^{3}He, ^{7}Li(p,n)^{7}Be and ^{18}O(p,n)^{18}F neutron spectra studied at the Karlsruhe group to simulate *kT* ~ 5 , 25 and 52 keV Maxwelian neutron sources are shown in **Fig. IIIC2.1**, where probability distribution (`,MLT/DE,,TT/NPD`) is plotted instead of the absolute spectra for visibility.

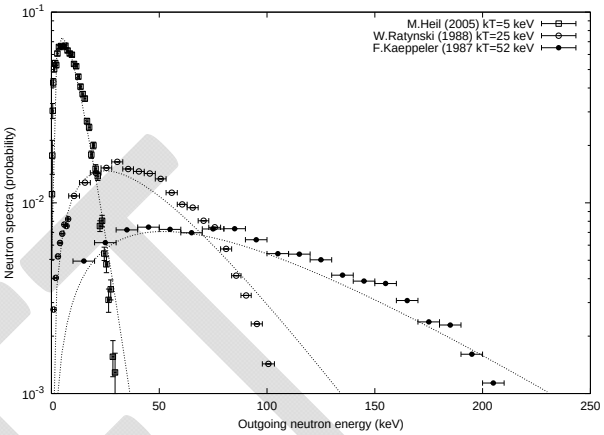


FIG.IIC2.1.: Quasi-Maxwellian neutron spectra simulated by thick target neutron production from ^{3}H(p,n)^{3}He (E_p=1.1 MeV, *kT*~5 keV [MH05], ^{7}Li(p,n)^{7}Be (E_p=1.9 MeV, *kT*~25 keV [WR88]) and ^{18}O(p,n)^{18}F (E_p=2.6 MeV, *kT*~52 keV [FK87]) neutron spectra (probability distribution). Dashed lines show the pure Maxwellian spectra $(kT)^{-2}\ E \exp(-E/kT)$.

3. Thick target radioisotope yields

The basic idea of the thick target radioisotope yields is quite similar to the thick target particle yields. Usually radioisotope yields are expressed in terms of decay rate (*e.g.*, Bq), and therefore one may call it as thick target radioisotope *activities*. The total number of radioisotopes produced after irradiation time *t* with current *I* is $N(t) = Y I t$, where *Y* was defined in Eq.(IIC2.1), and the corresponding activity is $\lambda\ Y I t$. Namely the activity of the sample irradiated per unit current is increased by

$$A_{phys} = \lambda Y \qquad \text{(IIIC3.1)}$$

per unit time. This quantity is defined as *physical* thick target yield in EXFOR. Its unit is MBq/μC (=1 MBq/μA-sec), for example. This quantity does not depend on irradiation time.

If we consider the loss of the product during irradiation due to its decay, the total number of the radioisotope *N* after irradiation time *t* satisfies

$$dN(t)/dt = IY - \lambda N(t). \qquad \text{(IIIC3.2)}$$

The solution of this differential equation is $N(t) = IY\ [1-\exp(-\lambda t)] / \lambda$, and the sample activity per unit current at time *t* is therefore

$A_{prod}(t) = N(t) / I = Y[1\text{-}\exp(-\lambda t)] / \lambda$, (IIIC3.3)

which is defined as *production thick target yield* in EXFOR. Its unit is MBq/μA, for example. The production thick target yield depends on the irradiation time. However

$A_{sat} = A_{prod}(t \rightarrow \infty) = Y / \lambda$, (IIIC3.4)

namely the sample activity becomes a constant when the irradiation time is enough longer than 1 / λ. This activity A_{sat} is defined as saturation thick target yield in EXFOR. The physical thick target is corresponding to the number of radioisotopes produced per unit time, while the production and saturation thick target yields are corresponding to the radioisotopes existing at the irradiation time. The situation is schematically shown in **Fig.IIIC3.1**. The time evolution of $A_{prod}(t)$ is similar to the time evolution of the velocity $v(t)$ of a ball (mass m) falling under the gravity field (a constant acceleration g) with a frictional force proportional to k), because the equation of the motion can be written as

$dv(t)/dt = g - (k/m)\, v(t)$. (IIIC3.5)

This is similar to Eq. (IIIC3.2). We observe that g, $v(t)$ and $v(t \rightarrow \infty)$ and k/m are corresponding to $I\, A_{phys}/\lambda$, A_{prod}, A_{prod} , and λ.

Example IIIC3.1

Search of $^{18}O(p,n)^{18}F$ thick target yields by,

Target = `8-O-18`; projectile, process = `P,N`;
web quantity = `TT`; products = `9-F-18`

…..

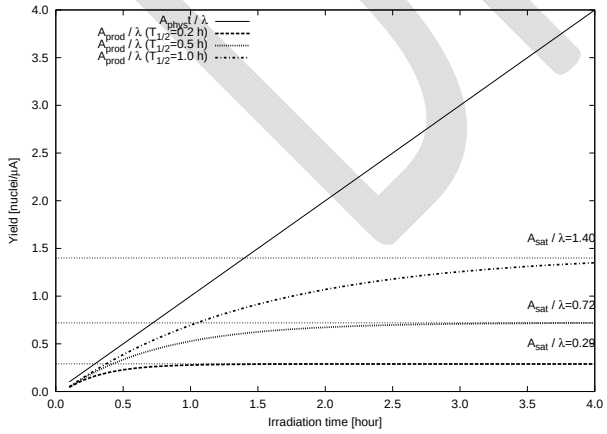


FIG.IIIC3.1. Comparison of physical thick target Aphys, production thick target yield A_{prod} and saturation thick target yield A_{sat} when A_{phys} = 1.0 nuclei / μA-h.

The physical thick target yield is determined by measurement of the irradiated sample activity or integration of the measured excitation function by using Eqs. (IIC2.1) and (IIC3.1). The second derivation is recognized as not most straight forward derivation, and flagged by `DERIV` in the data type field of `REACTION` codes.

D. Spectrum Averaged Data

1 Neutron fields

Except for time-of-flight measurement (i.e., determination of incident neutron energy one by one), neutron induced reaction data are always measured with neutron beam having energy distribution. Unless the measured quantity is a constant under the neutron energy range, the measured quantity should be treated as spectrum averaged data. If the neutron flux distribution is $\varphi(v) = n(v)\, v$ ($n(v)$: velocity distribution, v: neutron velocity), spectrum averaged cross section $\sigma(v)$ is expressed by

$$\langle\sigma\rangle = \int_0^\infty dv\, \sigma(v)\, \varphi(v) \,/\, \int_0^\infty dv\, \varphi(v)$$
$$= \int_0^\infty dE\, \sigma(E)\, n(E) \,/\, \int_0^\infty dE\, n(E) \quad \text{(IIID1.1)}$$

.For example, cross section measured under the fission spectrum $\chi(E)$ is

$$\langle\sigma\rangle = \int_0^\infty dE\, \sigma(E)\, \chi(E) \,/\, \int_0^\infty dE\, \chi(E) \quad \text{(IIID1.2)}$$

, where $E^{1/2}$ is proportional to the neutron velocity v. Prompt fission neutron spectrum for ^{252}Cf(sf) has been recognized as a well-established neutron field, and cross sections measured under this field have been used to validate energy dependence of important cross sections (*e.g.*, dosimetry reaction cross sections). For example, 55Mn(n,2n)54Mn cross section measured under this spectrum is expressed by

`(25-MN-55(N,2N)25-MN-54,,SIG,,FIS).`

From the REACTION code, we cannot know what is the fissionning system providing the incident neutron (*e.g.*, ^{252}Cf(sf), ^{235}U(n,f) etc.), and the details of the spectrum is usually seen under the keyword `INC-SPECT` in free text. For the ^{252}Cf(sf) neutron source case, the code `CF252` is also coded under the keyword `INC-SOURCE`.

One of the following modifier is used for spectrum averaged neutron induced reaction quantities:

`FIS`: fission spectrum average
`FST`: fast reactor neutron spectrum average
`MXW`: Maxwellian average
`SPA`: spectrum average (generic)

The definition of Maxwellian averaged cross section (MACS) is slightly different from (IIID.1.1):

$$\langle\sigma\rangle = 2\,\pi^{-1/2}\ \int_0^\infty dE\ \sigma(E)\ n(E)\ \ /\ \int_0^\infty dE\ n(E) \quad \text{(IIID1.1)}$$

with $n(E) = E \exp(-E/kT)$. This additional factor is due to the Westcott convention [CHW55] where the mean velocity of neutrons $\langle v\rangle = \int_0^\infty dv\ \varphi(v)$ in (IIID1.1) is replaced with the most probable velocity (~2200 m/sec for the room temperature kT~0.0253 eV). In EXFOR, `MXW` means Maxwellian spectrum averaged cross section defined with this factor $2\pi^{-1/2}$. Some authors exclude this factor from the definition of the Mxwellian spectrum averaged cross section (e.g., []) and it is coded as

```
(95-AM-241(N,G)92-AM-242,,MXW/FCT)
```

for example. The additional modifier `FCT` shows that the definition is a constant factor different from the original definition, and the EXFOR users are asked to check the free text explanation of the EXFOR entry to know the factor.

Maxwellian spectrum averaged cross section is typically determined by folding energy dependent cross section measured at time-of-flight facilities by using Eq. (IIID1.1), or more directly, by irradiation under quasi-Maxwellian spectrum neutron field (*e.g.*, Fig. IIC2.1). The Maxwellian averaged cross sections evaluated based on experimental averaged cross sections by the Karlsruhe group [ZYB00] have been utilized to validate energy dependent neutron-induced capture cross sections (*e.g.* ,[NT05,BP10]).

VI. SUMMARY

This paper introduced the brief history of the EXFOR library and international collaboration among data centres. Major quantities compiled in the EXFOR library with various examples of their `REACTION` codes were discussed. Various efforts to ensure completeness and correctness of the EXFOR library was reviewed. Dissemination of the EXFOR contents through the systems maintained by IAEA NDS and other data centres was also explained.

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