How to search on EXFOR

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Abstract. The experimental nuclear reaction data compiled in the EXFOR library are loaded to databases and accessed by users. The EXFOR library covers not only the cross section but also various other nuclear reaction quantities such as fission yield and thick target yield. It is not always trivial to find an appropriate set of keywords extracting the data sets of interest neither too many or too few. Sometimes users are too specific in their queries, and find nothing in the database. This article presents some examples of EXFOR retrievals for better access to the databases.

1. Introduction

The EXFOR library [1] is a large collection of experimental cross sections and other nuclear reaction data from more than 23,000 experimental works. It is maintained by the International Network of Nuclear Reaction Data Centres (NRDC) [2] under the auspices of the International Atomic Energy Agency. The data compiled by the centres in the EXFOR format are transmitted to other centres after review, and included in the databases for dissemination to end users. Various codes (e.g., SIG for cross section) are defined in the EXFOR system to make the information machine-retrievable, and the reaction and quantity codes are frequently used coded information for retrieval. They are expressed in EXFOR by a REACTION code string. For example, (92-U-238(N,G)92-U-239,,SIG) stands for the neutron capture cross section of 238U. More than one thousand quantities are defined in the EXFOR/CINDA dictionary to cover the wide scope of EXFOR. They are often cryptic, and also their spells are sometimes different from the usual nuclear physics notations. Under this situation, it is very important to know how to construct a query to extract an appropriate range of the data sets from the database. The aim of this short article is to introduce some “tips” for an efficient retrieval from the EXFOR databases.

2. Specification of reaction and quantity

Table 1 summarizes Web retrieval systems developed by data centres, and Fig. 1 shows the input forms of three Web retrieval systems developed by the IAEA Nuclear Data Section (NDS) [3], OECD NEA Data Bank (NEA DB) [4] and Hokkaido University Nuclear Reaction Data Centre (JCPPG) [5]. The input form of the Web retrieval system developed by the Centre for Photonuclear Experiments Data (CDFE) [6] is similar to NEA DB’s one. Apart from the incident energy range, the target, projectile (incident particle), process (emission), product (residual) and quantity are important keywords. Table 2 shows an example of specification of these keywords in the three Web retrieval systems. Currently the NDS and JCPPG Web retrieval systems support use of a wildcard *, which matches any character zero or more times, and is useful to make the query not too specific.
Table 1. EXFOR Web retrieval systems maintained by Nuclear Reaction Data Centres (NRDC).

| Data Centre     | URL                                                                 |
|-----------------|----------------------------------------------------------------------|
| NDS (IAEA)      | http://www-nds.iaea.org/exfor/                                        |
| Mirror          | http://www.ndc.bnl.gov/exfor/ (USA)                                   |
|                 | http://www-nds.ciae.ac.cn/exfor/ (China)                              |
|                 | http://www-nds.indcentre.org.in/exfor/ (India)                        |
|                 | http://www-nds.atomstandard.ru/exfor/ (Russia)                        |
| NEA DB (OECD)   | http://www.oecd-nea.org/janisweb/                                    |
| JCPRG (Japan)   | http://www.jcprg.org/exfor/                                           |
| CDFE (Russia)   | http://cdfe.sinp.msu.ru/exfor/                                        |

Table 2. Submission of a query to EXFOR databases for Mo + p $^{99}$Mo production cross section.

|          | NDS                  | NEA DB                              | JCPRG                                    |
|----------|----------------------|-------------------------------------|------------------------------------------|
| Target   | target=Mo-*          | target Z=42; A=blank                | target=Mo-*                              |
| Reaction | reaction=P, *        | incident projectile=P               | projectile=P                             |
|          | process=blank        | process=blank                       | emission=blank                           |
| Product  | product=Mo-99        | product Z=42; A=99                  | residual=Mo-99                           |
| Quantity | quantity=CS          | quantity (general)=CS               | quantity=CS                              |

Figure 1. Query forms of EXFOR Web retrieval systems (as of November 2019).
2.1. Reaction specification

EXFOR expresses the target and product by the atomic number, element symbol and mass number connected by hyphens (e.g., 6–C–12 for $^{12}\text{C}$). $A=0$ denotes a target of natural isotopic abundance (e.g., 74–W–0). If the data set is for an isomer product (ground state, or another level living longer than 0.1 sec), it is expressed by an isomeric flag such as $-G$ for the ground state and $-M$ for the metastable state (e.g., 94–AM–242–M). Table 2 shows the atomic number or element symbol may be omitted in the input form, and the atomic number will be omitted in the query examples through this article.

Table 3 shows typical codes for processes and particles with $A \leq 4$. Note that these particles must be expressed in the $Z$–$S$–$A$ form when they appear as the product, and special nuclide codes such as $0-G-0$ ($\gamma$) and $0-NN-1$ (neutron) are defined for this purpose. If there are several outgoing particles, they are ordered starting with the lightest (lowest $Z$, then lowest $A$), and the heaviest one becomes the product, for example 2–HE–3(\text{N,} 2n+P)1–H–1 for $^3\text{He}(\text{n,} 2n+2p)$. If only one particle/nuclide is specified in the exit channel, it is coded as the product with $X$ as the process, for example 82–PB–0(\text{P,} X)0–NN–1 for $^{nat}\text{Pb}(\text{p,} n+x)$.

| Table 3. Examples of process and particle codes. |
|------------------------------------------------|
| **Process** | **Particle** |
| ABS | absorption | NON | nonelastic | A | $\alpha$ | N | neutron |
| EL | elastic scattering | TOT | total | D | deuteron | P | proton |
| F | fission | X | process unspecified | G | $\gamma$ | T | triton |
| INL | inelastic scattering | | | HE3 | $^3\text{He}$ |

2.2. Quantity specification

EXFOR expresses each quantity by four fields separated by commas: (branch, parameter, particle considered, modifier). A code always presents in the parameter field. If a field is blank, the separating comma is included, except that trailing commas are omitted.

**Examples**

- PAR, SIG Partial cross section, where ”partial” means the quantity is characterized by a secondary energy but not energy differential (e.g., for a reaction leaving the product to its ground state)
- PAR, DA, G Angular differential cross section of $\gamma$-rays at an energy ($G$ must be added since it does not appear in the process field except for the capture reaction)
- , DA, RTH Angular differential cross section relative to the Rutherford scattering cross section

All EXFOR quantity codes are grouped to about 15 ”Web quantities” (Table 4), which are usually enough for EXFOR retrieval unless the user gets too many results. For example, the three quantities PAR, SIG, PAR, DA, G and , DA, RTH can be retrieved by using the Web quantities CSP, DAP and DA, respectively.

3. Cross section queries

3.1. Cross section for a specific process

The cross section for a specific process can be retrieved with the Web quantity CS or CSP and the process code.
Table 4. Examples of Web quantities (Web q.) w.r.t. = with respect to.

| Web q. | Explanation                        | Web q. | Explanation                        |
|--------|------------------------------------|--------|------------------------------------|
| CS     | Cross section data                 | MFQ    | Differential fission neutron multiplicities |
| CSP    | Partial cross section data         | NU     | Fission neutron multiplicities      |
| DA     | Differential data w.r.t. angle     | POL    | Polarization data                  |
| DAE    | Differential data w.r.t. angle and energy | RI     | Resonance integrals                |
| DAP    | Partial differential data w.r.t. angle | RP     | Resonance parameters               |
| DE     | Differential data w.r.t. energy    | TT     | Thick target yields                |
| E      | Kinetic energies                   | TTD    | Differential thick target yields   |
| FY     | Fission product yields             | TTP    | Partial thick target yields        |

Examples

| Target | Reaction | Product | Web q. |
|--------|----------|---------|--------|
| C-12   | N, TOT   | CS      | $^{12}$C+n total cross section |
| U-238  | N, 2N    | CS      | $^{238}$U(n,2n)$^{237}$U cross section |
| FE-~   | P, INL   | CS*     | Fe(p,p')Fe inelastic scattering cross section (incl. partial) |

The third query may return quantities including cross sections of

- (26-FE-56(P, INL)26-FE-56, PAR, SIG): inelastic scattering leaving $^{56}$Fe in a specific level, or leaving the proton in a energy group,
- (26-FE-56(P, INL)26-FE-56, PAR, SIG, G): inelastic scattering emitting a γ-ray at an energy.

3.2. Cross section for a specific product (Activation cross section)

The cross section for a specific the product can be retrieved by the Web quantity CS and the product. The process should not be specified since the product may be from several processes (e.g., neutron+proton emission and deuteron emission).

Examples

| Target | Reaction | Product | Web q. |
|--------|----------|---------|--------|
| Al-27  | D, ~     | NA-24   | CS     | $^{27}$Al(d,x)$^{24}$Na cross section |
| MO-~   | A, ~     | TC-95*  | CS     | Mo($\alpha$,x)$^{95}$Tc cross section (incl. isomer production) |

The second query may return quantities including

- (42-MO-0(A, X)TC-95*, , SIG): $^{nat}$Mo($\alpha$,x)$^{95}$Tc cross section,
- (42-MO-0(A, X)TC-95-G, , SIG): $^{nat}$Mo($\alpha$,x)$^{95g}$Tc cross section,
- (42-MO-0(A, X)TC-95-M, , SIG): $^{nat}$Mo($\alpha$,x)$^{95m}$Tc cross section,
- (42-MO-0(A, X)TC-95-M/G, , SIG/RAT): $^{nat}$Mo($\alpha$,x)$^{95m/g}$Tc cross section ratio.

3.3. Angular differential cross section

The angular differential cross section is typically partial (except for elastic scattering), and it is always better to use the Web quantity DA~.
Examples

| Target | Reaction | Product | Web q. |
|--------|----------|---------|--------|
| Fe-56  | N, INL   | DA*     | $^{56}$Fe(n,n')$^{56}$Fe angular differential cross section (incl. partial) |
| Ti-*  | P, A     | DA*     | Ti(p,$\alpha$)Sc angular differential cross section |
| Ti-*  | P, X     | HE-4    | DA*     | Ti(p,$\alpha$+x) angular differential cross section |

The first query may return quantities including

- (26-Fe-56(N, INL)26-Fe-56, PAR, DA): $^{56}$Fe(n,n')$^{56}$Fe partial neutron angular differential cross section,
- (26-Fe-56(N, INL)26-Fe-56, PAR, DA, G): $^{56}$Fe(n,n' + $\gamma$)$^{56}$Fe partial $\gamma$ angular differential cross section.

The second and third queries are for the same outgoing particle ($\alpha$) but for exclusive and inclusive, respectively. They may return quantities including

- (22-Ti-46(P, A)21-Sc-43, PAR, DA): $^{46}$Ti(p,$\alpha$)$^{43}$Sc $\alpha$ partial angular differential cross section, and
- (22-Ti-0(P, X)2-He-4, , DA): $^{nat}$Ti(p,$\alpha$+x) angular differential cross section, respectively. Additionally the third query may return
- (22-Ti-0(P, X)2-He-4, , DA/DE): $^{nat}$Ti(p,$\alpha$+x) double differential cross section because DAE also matches DA*.

3.4. Double differential cross section

The double differential cross section is always retrieved with the Web quantity DAE. This quantity is usually defined for an inclusive reaction (process code X), and the outgoing particle of interest must be specified not as the outgoing particle but as the product.

Example

| Target | Reaction | Product | Web q. |
|--------|----------|---------|--------|
| Li-7   | P, X     | NN-1    | DAE    | $^7$Li(p,n+x) double differential cross section |

4. Fission quantity queries

The process code is always F. The spontaneous fission is expressed by (0, F).

4.1. Fission neutron quantity

The fission neutron multiplicities ($\bar{\nu}$) and related quantities (e.g., emission probability $P_n$) are typically retrieved by the Web quantity NU. Other fission neutron quantities (e.g., prompt fission neutron spectrum) are retrieved by the Web quantity MFQ (with some exceptions, e.g., E for kinetic energy).

Examples

| Target | Reaction | Product | Web q. |
|--------|----------|---------|--------|
| U-238  | N, F     | NU      | $^{238}$U(n,f) $\bar{\nu}$ |
| Cf-252 | 0, F     | MFQ     | $^{252}$Cf(sf) differential $\bar{\nu}$ etc. |
| U-235  | N, F     | MASS    | NU     | $^{238}$U(n,f) $\bar{\nu}$ characterized by a fragment mass |

The first query may return quantities including
• \((92\text{-U-}238\text{(N,F), PR, NU})\): \(238\text{U(n,f)}\) prompt neutron multiplicity \((\bar{\nu}_p)\),
• \((92\text{-U-}238\text{(N,F), DL, NU})\): \(238\text{U(n,f)}\) delayed neutron multiplicity \((\bar{\nu}_d)\),
• \((92\text{-U-}238\text{(N,F), DL/GRP, NU})\): \(238\text{U(n,f)}\) delayed neutron multiplicity for a half-life group.

The second query may return quantities including
• \((98\text{-CF-}252\text{(N,F), PR, NU/DE})\): \(252\text{Cf(sf)}\) prompt neutron spectrum,
• \((98\text{-CF-}252\text{(N,F), PR, NU/DE, , MXD})\): \(252\text{Cf(sf)}\) prompt neutron spectrum relative to Maxwellian.

In the third query, \textit{MASS} is used for extraction of quantities for a mass, and may include
• \((95\text{-U-}235\text{(N,F)MASS, PR, NU})\): \(235\text{U(n,f)}\) \(\bar{\nu}_p\) for fissions leaving a fragment having a specific mass,
• \((95\text{-U-}235\text{(N,F)MASS, PR/FRG, NU})\): \(252\text{U(n,f)}\) \(\bar{\nu}_p\) for neutrons emitted from the fragment having a specific mass.

The fission fragment mass is given in the data table under the data heading \textit{MASS}.

4.2. Fission yield

The fission yield is expressed by the Web quantity \textit{FY}, which includes the multiplicity of particles released during fission other than neutrons (e.g., prompt gammas, light charged particles).

\begin{tabular}{llll}
\textbf{Target} & \textbf{Reaction} & \textbf{Product} & \textbf{Web q.} \\
\hline
PU-239 & N,F & FY & \(239\text{Pu(n,f)}\) fission yield \\
CF-252 & 0,F & MASS & \(252\text{Cf(sf)}\) yield of a fragment having a specific mass \\
\hline
\end{tabular}

The first query may return quantities including
• \((94\text{-PU-}239\text{(N,F)ELEM/MASS, CUM, FY})\): \(239\text{Pu(n,f)}\) cumulative fission product yield,
• \((94\text{-PU-}239\text{(N,F)ELEM/MASS, IND, FY})\): \(239\text{Pu(n,f)}\) independent fission product yield,
• \((94\text{-PU-}239\text{(N,F)MASS, CHN, FY})\): \(239\text{Pu(n,f)}\) chain yield,
• \((94\text{-PU-}239\text{(N,F)MASS, PRE, FY})\): \(239\text{Pu(n,f)}\) pre-neutron emission mass yield,
• \((94\text{-PU-}239\text{(N,F)MASS, SEC, FY})\): \(239\text{Pu(n,f)}\) post-neutron emission mass yield,
• \((94\text{-PU-}239\text{(N,F)0-G-0, PR/PAR, FY})\): \(239\text{Pu(n,f)}\) prompt fission partial \(\gamma\) yield.

The fission product yield is typically compiled with \textit{ELEM/MASS} as the product, which means the charge and mass of each fragment are in the data table under the data headings \textit{ELEMENT} and \textit{MASS}. For example, a data table compiling \(235\text{U(n,f)}^{135}\text{Cs}\) cumulative yield is usually not coded as \(92\text{-U-}235\text{(N,F)55-CS-135, CUM, FY}\) but as \(92\text{-U-}235\text{(N,F)ELEM/MASS, CUM, FY}\) with the yields of other products. The next coding sample shows the \(235\text{U(n,f)}^{135}\text{Cs}\) cumulative yield is 6.41%.

\begin{tabular}{lll}
\textbf{REACTION} & \(92\text{-U-}235\text{(N,F)ELEM/MASS, CUM, FY, , MXW})\) & \\
\hline
\textbf{MASS} & \textbf{ELEMENT} & \textbf{DATA} \\
\hline
& NO-DIM & NO-DIM & PC/FIS \\
135 & 55. & 6.41 \\
137 & 55. & 6.10 \\
\hline
\end{tabular}
5. Thick target yield queries

5.1. Thick target yield of a stable product

The thick target yield of a stable product (typically neutron or $\gamma$) is expressed by the number of products per incident particle or charge, and the latter is expressed by a modifier code $CH$.

**Examples**

| Target | Reaction | Product | Web q. |
|--------|----------|---------|--------|
| PB-0   | P, *     | NN-1    | TTP $^{nat}$Pb(p,n+x) partial thick target yield |
| LI-7   | P, *     | NN-1    | TTD $^{7}$Li(p,n+x) differential thick target yield |

The first query may return quantities including
- $(82$–PB–$0(P,X)0$–NN–$1,PAR, PY, , TT)$: $^{82}$Pb(p,n+x) partial thick target yield (per incident particle),

while the second query may return quantities including
- $(3$–LI–$7(P,X)0$–NN–$1, , PY/DA, , TT)$: $^{7}$Li(p,n+x) angular differential thick target yield (per incident particle),
- $(3$–LI–$7(P,X)0$–NN–$1, , PY/DA/DE, , TT/CH)$: $^{7}$Li(p,n+x) double differential thick target yield (per incident charge).

5.2. Thick target yield of radioactive product

This quantity is expressed as the radioactivity of the product per incident charge (e.g., $\mu$C, $\mu$A-hr) or beam current (e.g., $\mu$A).

**Example**

| Target | Reaction | Product | Web q. |
|--------|----------|---------|--------|
| CR–0   | P, *     | CR–51   | TT $^{nat}$Cr(p,x)$^{51}$Cr thick target yield. |

This example may return quantities including
- $(24$–CR–$0(P,X)24$–CR–51, TTY, , PHY)$: $^{nat}$Cr(p,x)$^{51}$Cr physical thick target yield

See Ref. [8] for the definitions and quantity codes of the thick target yields of radioactive products.

6. Summary

The reaction and quantity specifications for EXFOR retrieval were briefly summarized. Users are recommended to construct their queries not too specific. This description is not comprehensive, and there are also many exceptions. The users should not hesitate to ask the data centre covering your geographical area (see [2]) or the IAEA Nuclear Data Section for any help on your data request and its result. EXFOR Basics [7] is a manual for users who would like to know more details about EXFOR.

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