



International Atomic Energy Agency

The 4th DAE-BRNS Theme Meeting on
EXFOR Compilation of Nuclear Data
Department of Physics, Panjab University, Chandigarh, India
4–8 April 2011

Introduction to EXFOR

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Nuclear Data Section
Department of Nuclear Sciences and Applications



Outline

- Why nuclear data library?
- Experimental data and evaluated data
- Nuclear Reaction Data Centres (NRDC)
- Scope of EXFOR
- EXFOR entry
- EXFOR Formats
- REACTION code
- Uncertainty in EXFOR – for future evaluation
- EXFOR cross section plot (incl. exercise)
- EXFOR compilation (incl. exercise)
- Utilities for EXFOR compilation
- Summary



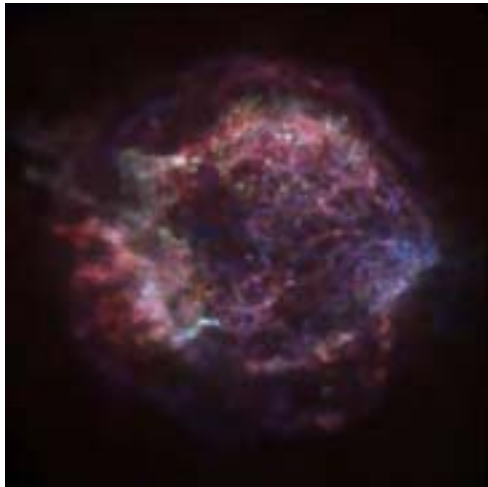
Why nuclear data library?

Nuclear Reaction Network in Science

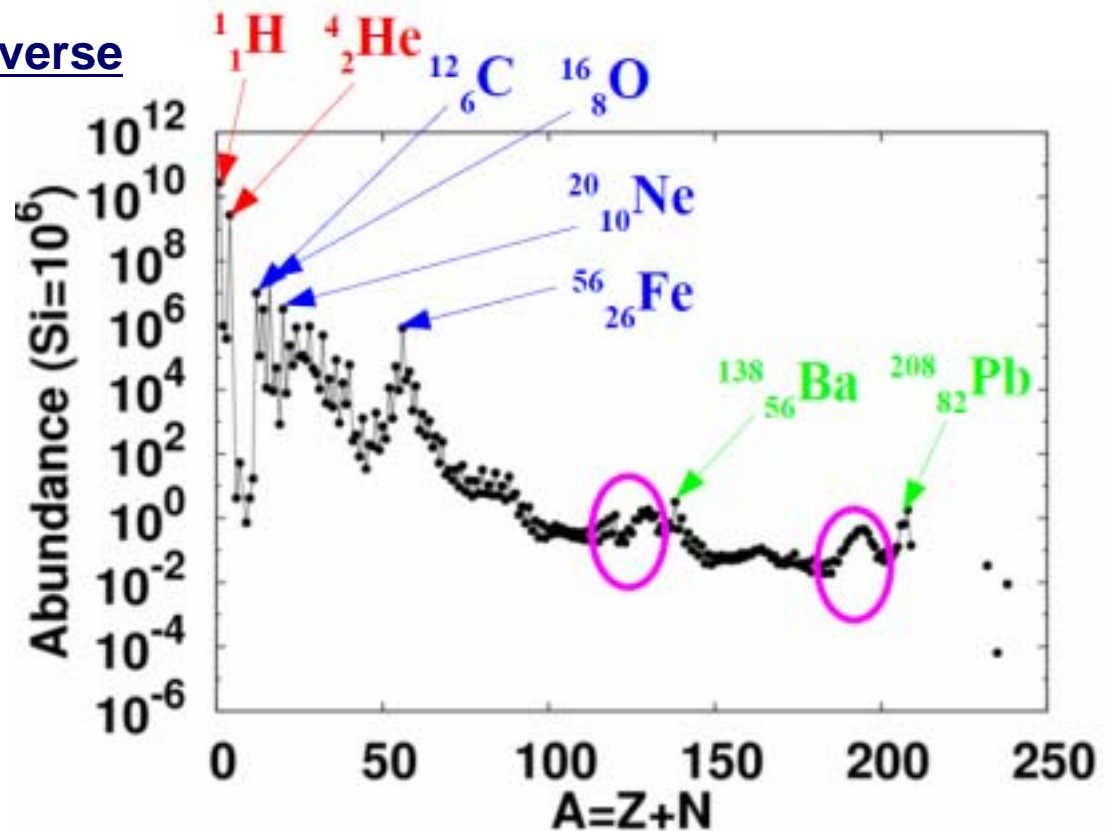
Nucleosynthesis

How do we understand isotopic abundances?

Isotopic abundances in the universe



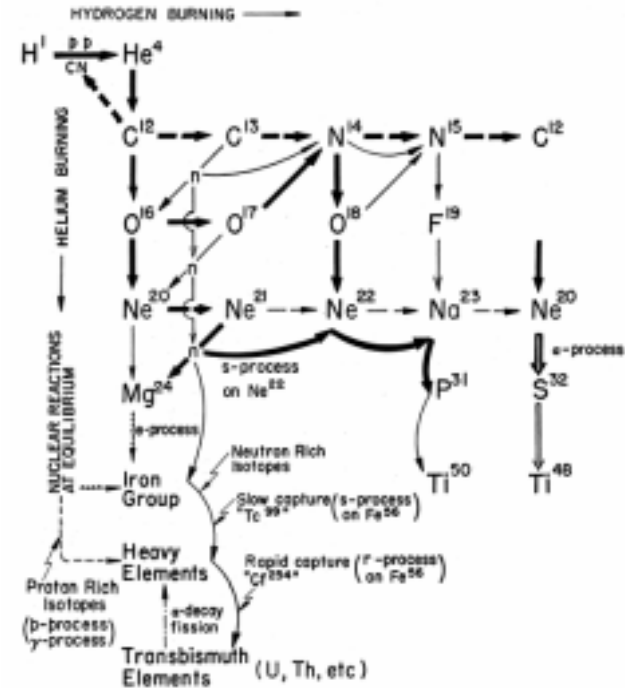
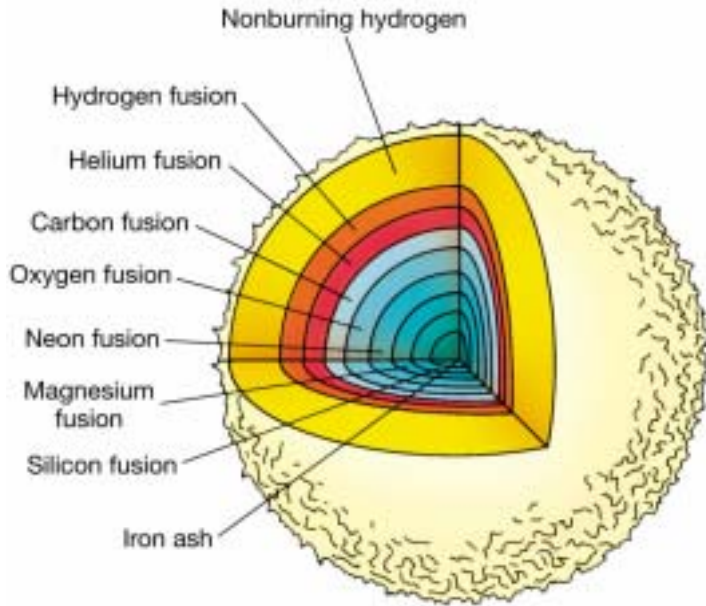
Cassiopeia A (Cas A).
Source: Chandra X-ray Observatory,
NASA/CXC/SAO/Rutgers/J.Hughes



Why nuclear data library?

Nuclear Reaction Network in Science (cont)

Nuclear reaction network in high mass stars



E. M. Burbidge et al., (B²FH) Rev.Mod.Phys.29(1957)

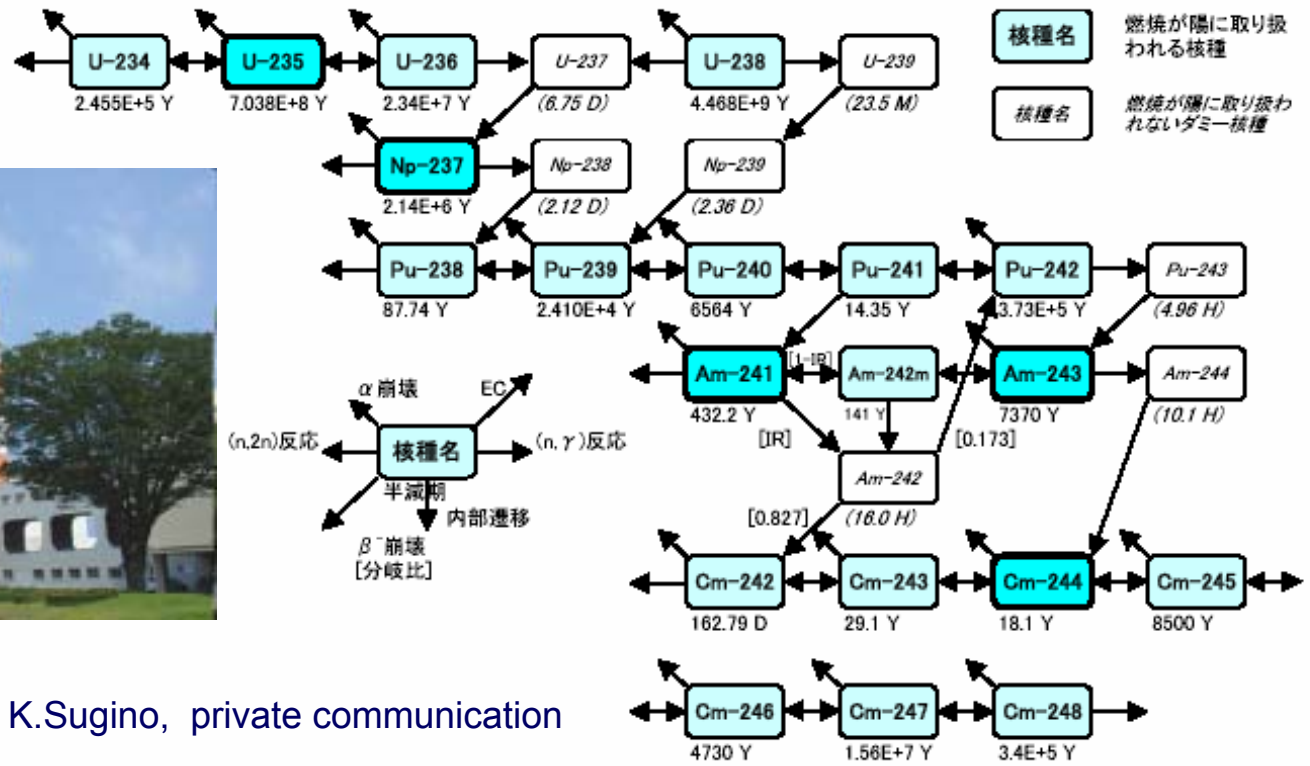
(Note: Heavy elements are also created in supernovae.)

Why nuclear data library?

Nuclear Reaction Network in Application

Another example of reaction network:

Burning chain model in a **fast reactor** (JOYO, Japan)



K.Sugino, private communication

Why nuclear data library?

Nuclear Data in Nuclear System

Growth of the number of the i -th isotope per unit time/volume $N_i(t)$

$$\frac{dN_i(t)}{dt} = -\lambda_i N_i(t) - \sigma_i \phi N_i(t) + \sum_j f_{j \rightarrow i} \lambda_j N_j(t) + \sum_k g_{k \rightarrow i} \sigma_k N_k(t)$$

Decrease by decay of the i -th isotope

Decrease by reaction from the i -th isotope

Increase by decay into the i -th isotope

Increase by reaction from the i -th isotope

Various nuclear data (λ , σ) for each isotope as input parameters!

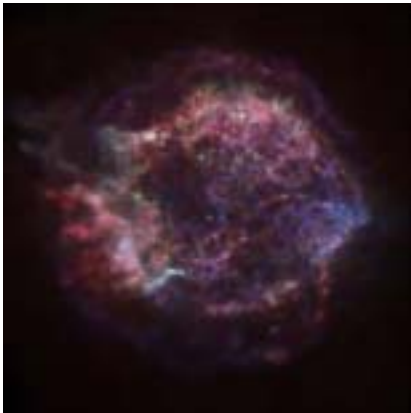


Why nuclear data library?

Nuclear Data in Science and Technology

Science

- Nuclear physics
- Astrophysics
- etc.



Technology

- Fission and fusion energies
- Material analysis
- Medical application
- etc.



Why nuclear data library?

Structure Data and Reaction Data

Nuclear Data:

Data which **characterize properties and phenomena of nucleus** (e.g., mass, spin-parity, half-life, cross section)

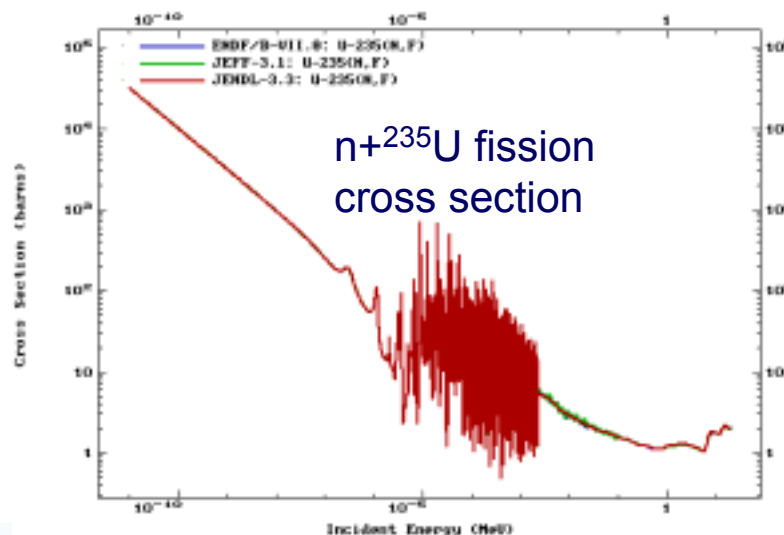
Example: Uranium-235

Mass: 218 942 MeV/c²

Structure

Level energy (MeV)	Spin	Parity	Half-life
0.0	7/2	-1	7.0x10 ⁸ y
0.0765	1/2	+1	~26 min
13.04	3/2	+1	0.50 ns
...

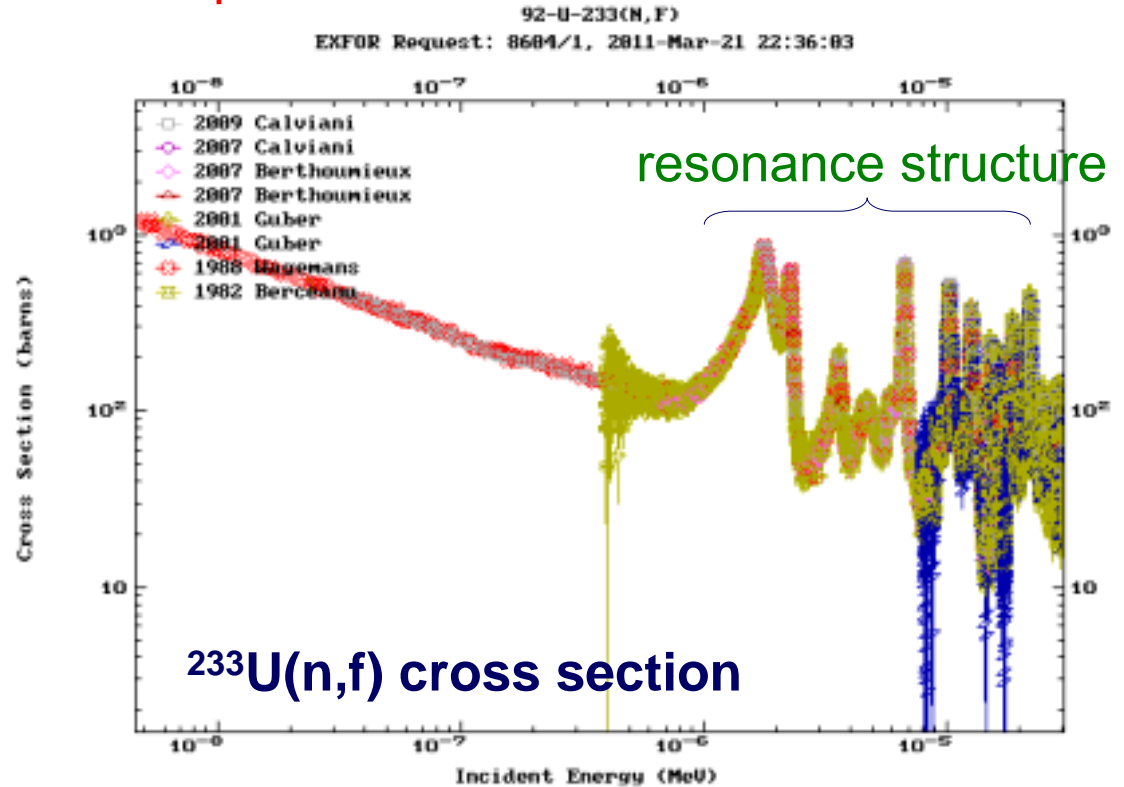
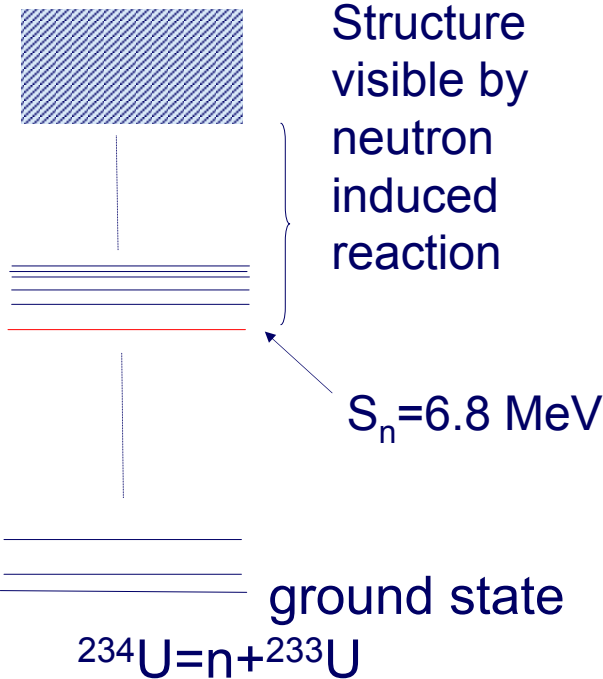
Reaction (incl. EXFOR)



Example of Experimental Data in Library

Fission cross section in resonance region

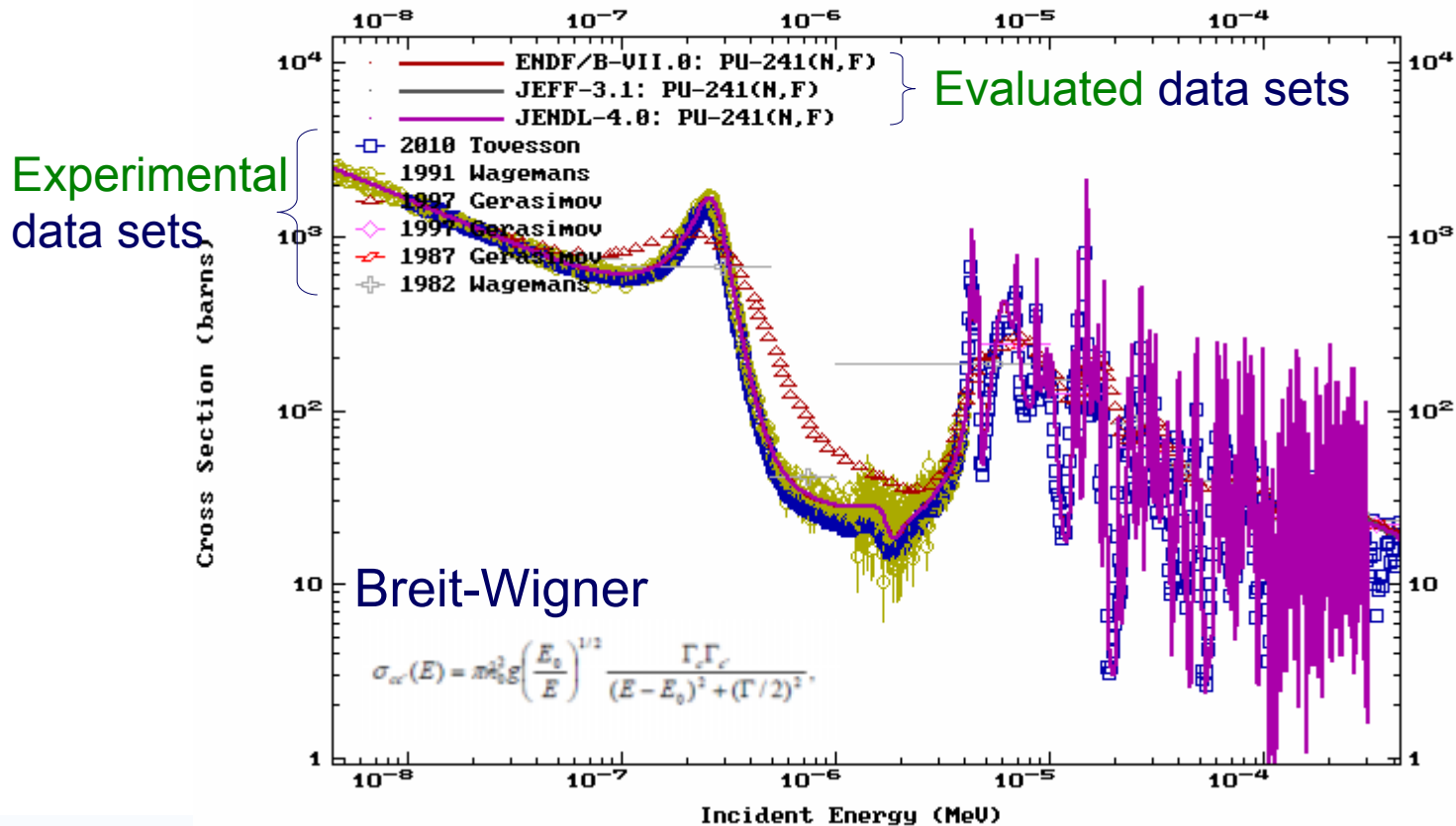
Important for application, theory is not very powerful, but a lot of experimental data points are available.



Experimental and Evaluated Data Libraries

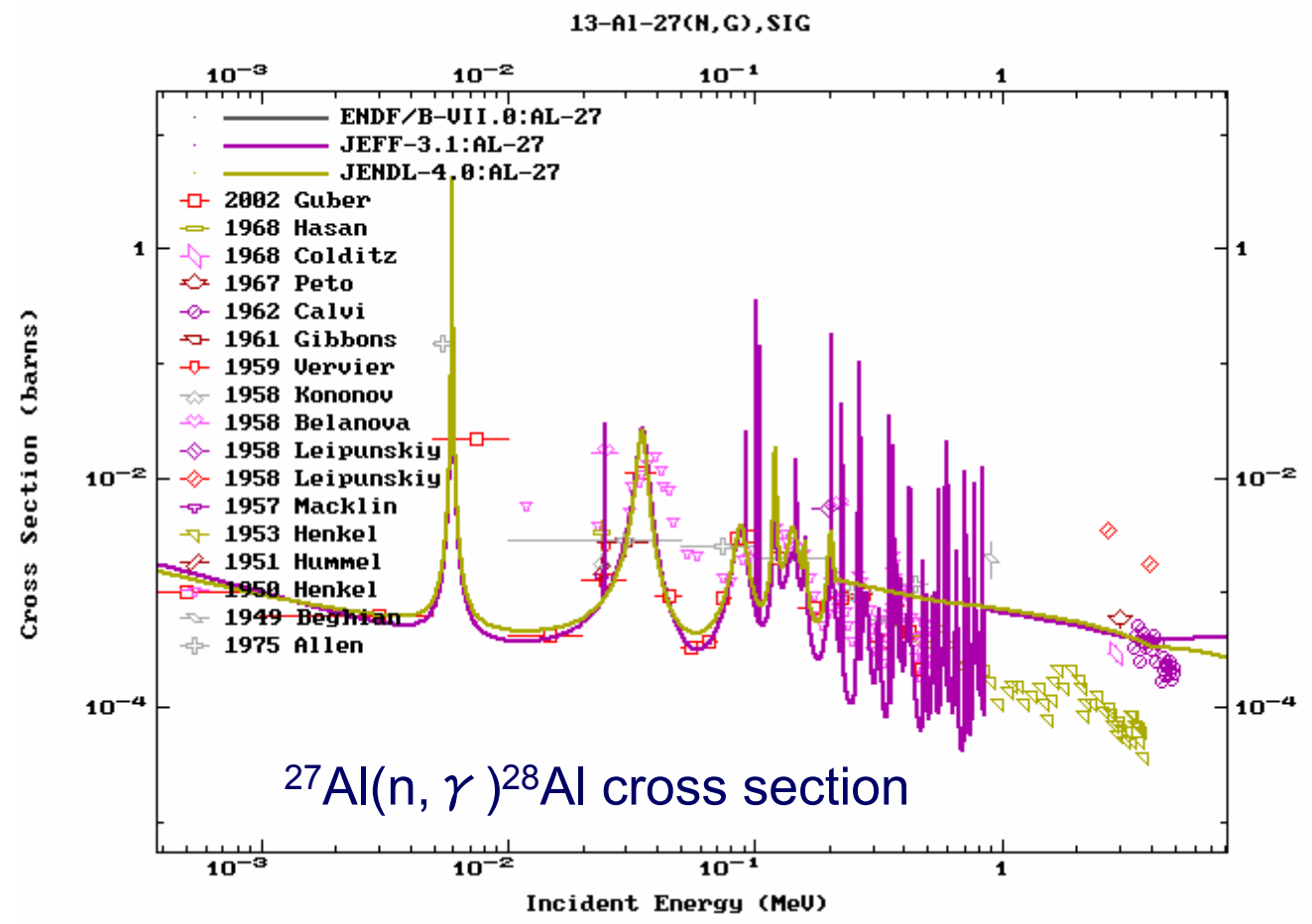
Evaluated data derived from **experimental data** are used as an input for applications (Breit-Wigner, R-matrix).

ENDF Request 3550, 2011-Mar-21, 22:32:58
 EXFOR Request: 8603/1, 2011-Mar-21 22:32:37



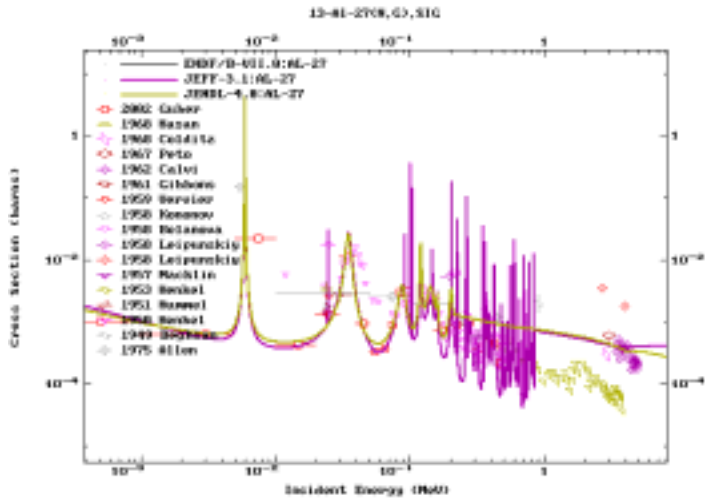
Experimental and Evaluated Data Libraries (cont)

Resonance structure is also important in **astronuclear physics**



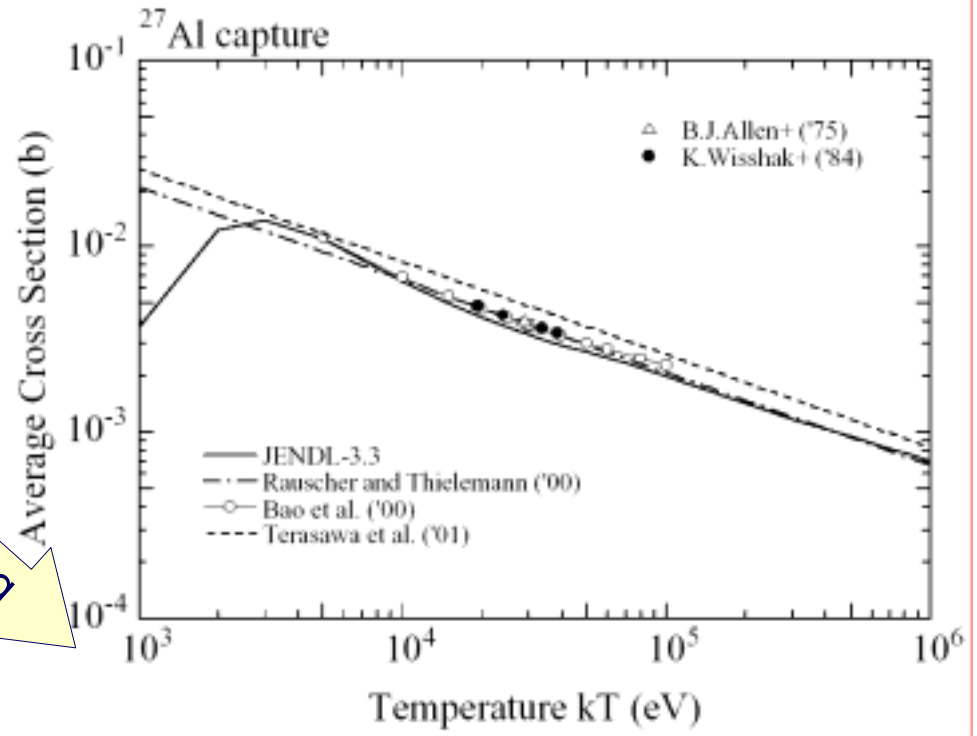
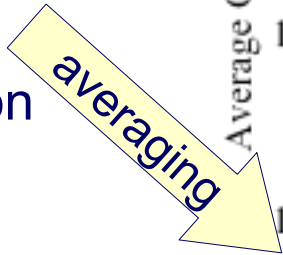
Processed Evaluated Data Library in Science

In stellar environment, Maxwellian averaged cross section (MACS) at a given temperature is important.

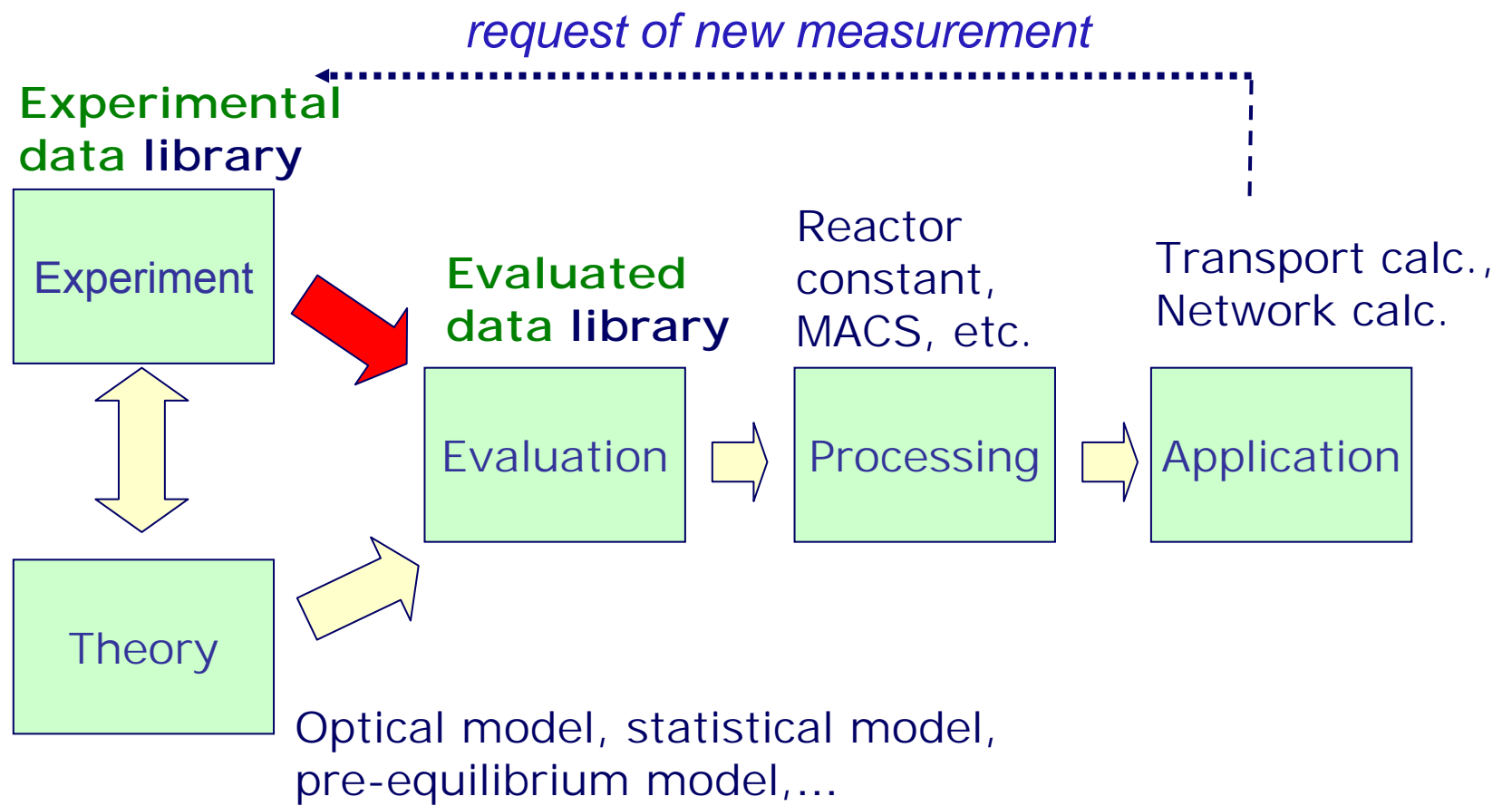


Incident energy

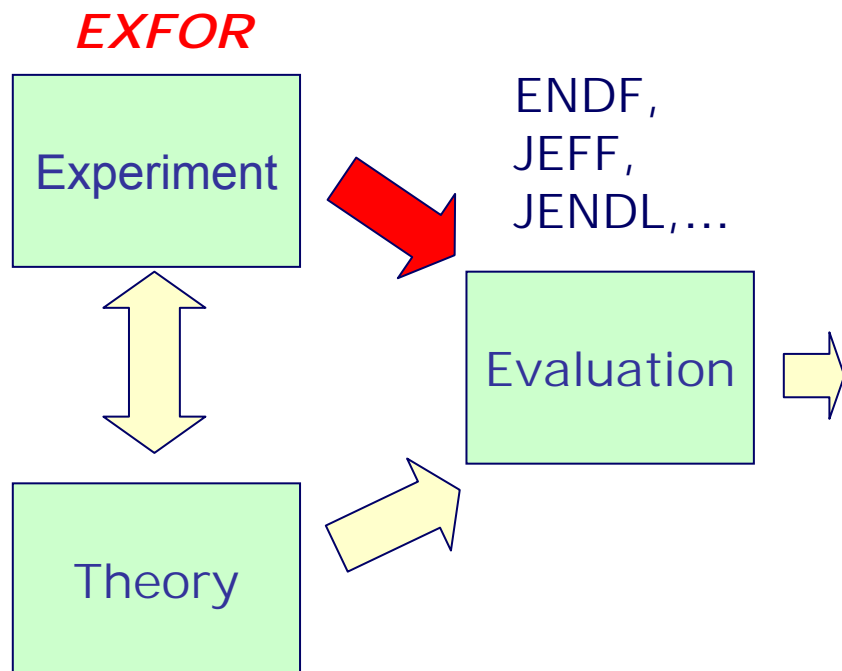
$^{27}\text{Al}(n, \gamma)^{28}\text{Al}$ cross section



From Microscopic Experiment to Application



Major Data Libraries in the World



Experimental data library

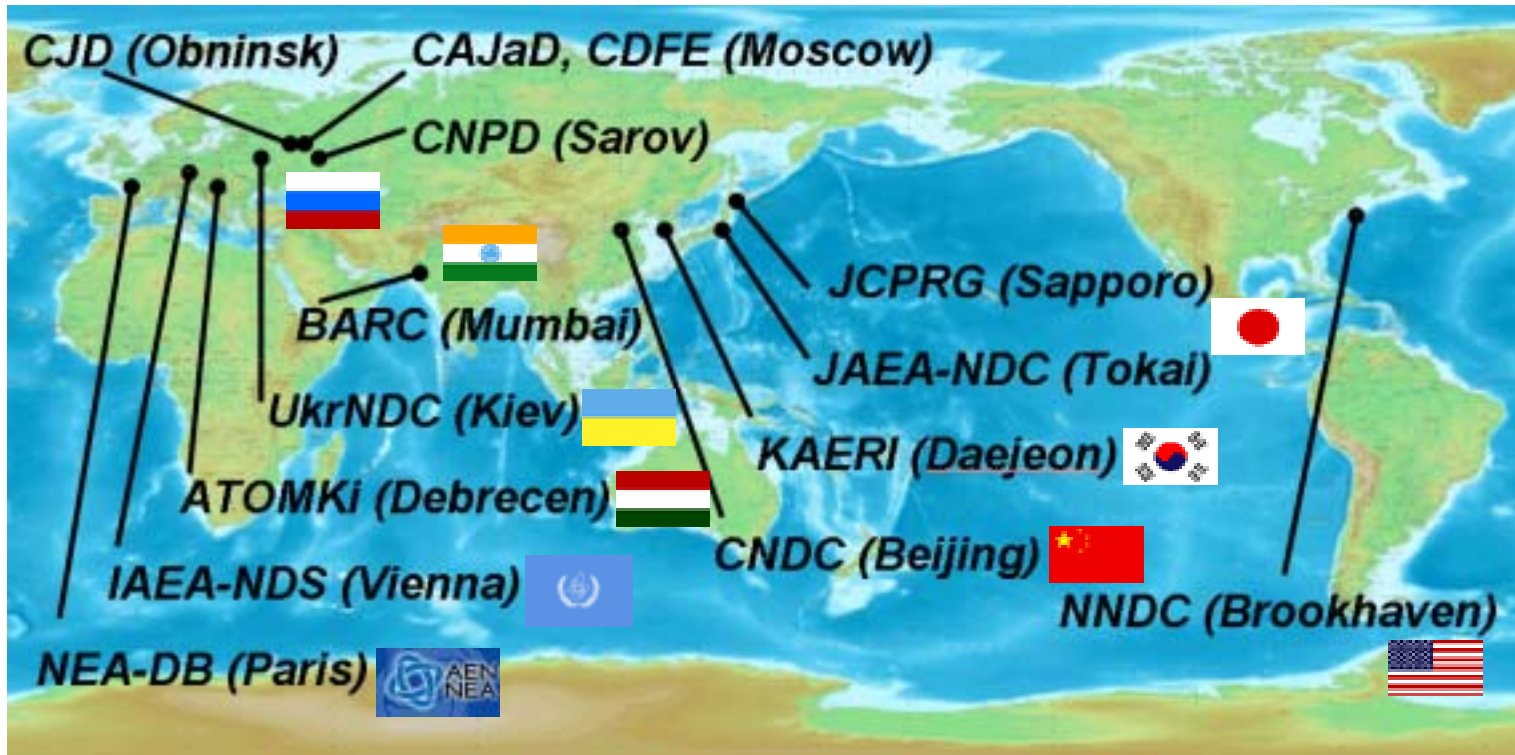
- EXFOR
(Data Centres - NRDC)

Evaluated data libraries

- ENDF (US)
 - JEFF (EU)
 - JENDL (Japan)
 - BROND/ROSFOND
(former USSR)
 - CENDL (China)
- etc.

Nuclear Reaction Data Centres (NRDC)

EXFOR is a product of international collaboration.



14 centres from 8 countries and 2 international organisations
(China, Hungary, India, Japan, Korea, Russia, Ukraine, USA, NEA, IAEA)

Coordinated by IAEA Nuclear Data Section



Brief History

History

1966

- 1st meeting of Four Centres (Brookhaven, Saclay, Obninsk, Vienna)

1969

- EXFOR adopted as official exchange format.

1974

- 1st meeting of Charged-Particle and Photonuclear Data

1979

- 1st meeting of Nuclear Reaction Data Centres



IAEA Headquarters
in Grand Hotel (until **1979**)
(from IAEA Imagebank)

Nuclear Reaction Data Centres

NRDC Meeting

Annual NRDC Meeting (intensive discussion)



IAEA
International Atomic Energy Agency

INDC(NDS)-0536
Dist. G/HNC

INDC International Nuclear Data Committee

Summary Report on
Technical Meeting of the
International Network of Nuclear Reaction Data Centres

IPPE, Obninsk
and
Moscow State University, Moscow
Russian Federation

22 - 25 September 2008

Prepared by
Svetlana Dunauva, Alan L. Nichols
IAEA Nuclear Data Section, Vienna, Austria
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Hans Hentzellon
OECD Nuclear Data Bank, Isy-les-Moulineux, France

December 2008

IAEA Nuclear Data Section, Wagramer Strasse 5, A-1400 Vienna, Austria

Meeting reports are
published as INDC(NDS)
reports

2008 NRDC Meeting (Obninsk)

NRDC Meeting (cont)

EXFOR Workshop (intensive practice)



2009 EXFOR Workshop (Vienna)

Nuclear Reaction Data Centres
NRDC Meeting (cont)

... and intensive communication



Social event (Grinzing, Vienna, 2009)

Role of IAEA Nuclear Data Section

- Maintain central EXFOR storage (EXFOR Master)
- Maintain on- and off-line accesses to EXFOR Master
- Assignment of articles to data centres
- Review EXFOR entries made by other centres
- Maintain EXFOR manuals
- Maintain EXFOR dictionary
- Organize annual NRDC Meeting



V.Semkova



V.Zerkin



S.Simakov



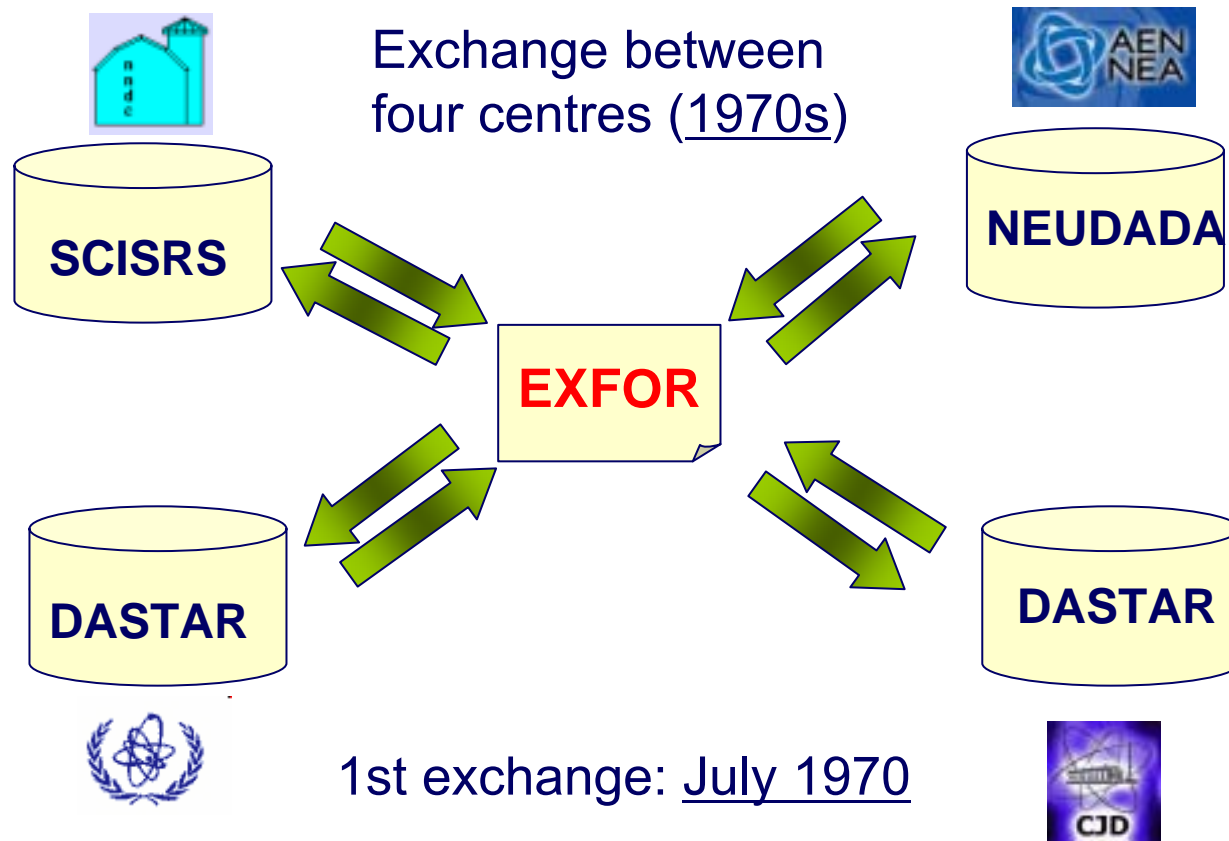
R.Forrest



Nuclear Reaction Data Centres

Data Exchange

EXFOR is an **EX**change **FOR**mat for experimental data.



Reference

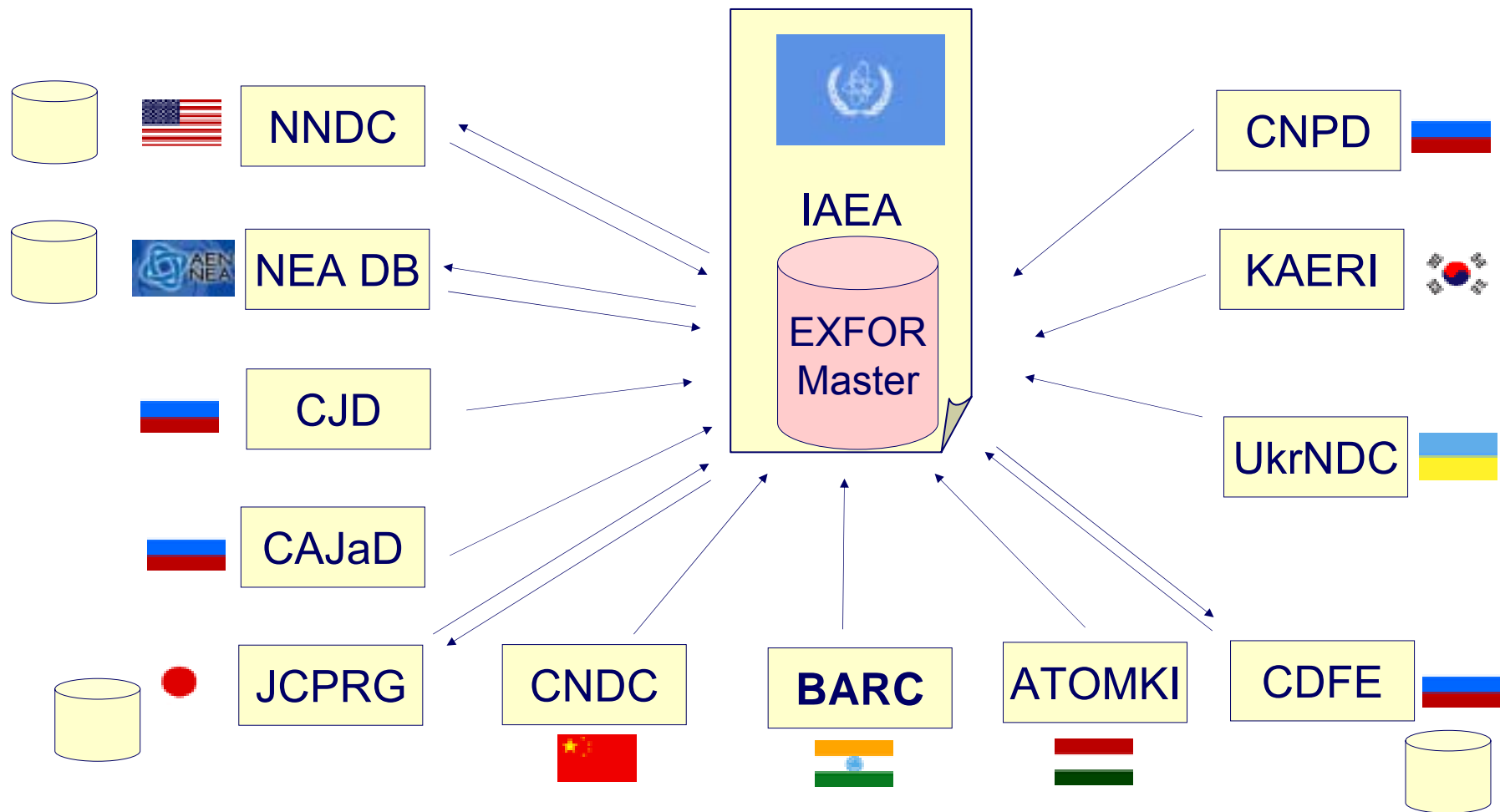
N.E. Holden, *A Short History of CSISRS* (2005)



Nuclear Reaction Data Centres

Data Exchange (cont)

The current exchange structure:

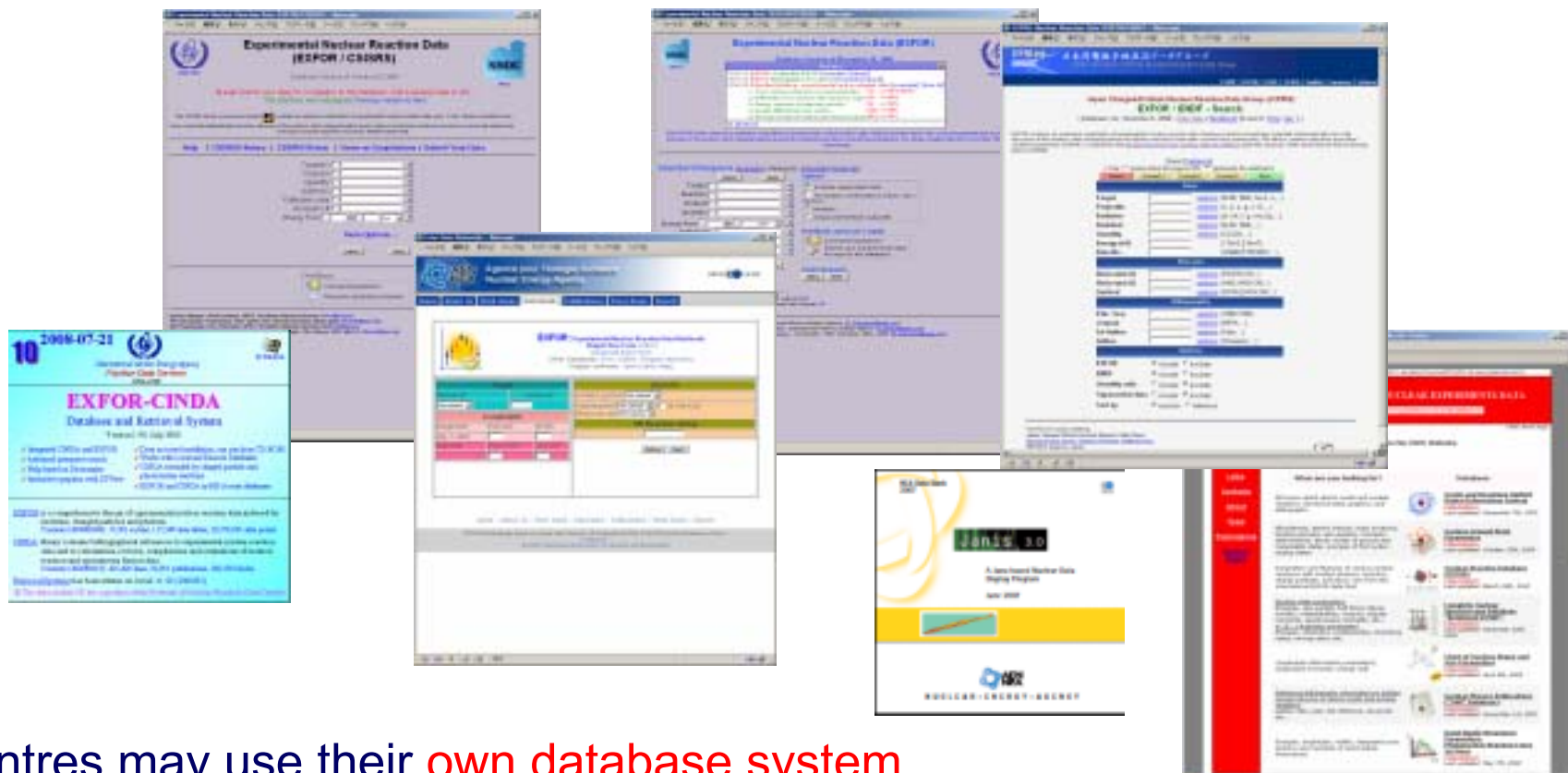


5 centres receive exchanged data and include into their own DB.



Nuclear Reaction Data Centres

EXFOR from Various Centres / Medias



- Centres may use their **own database system**.

Example: CSISRS, SIGMA (NNDC), JANIS (NEA-DB), EXFOR (IAEA-NDS)

- However, all centres (should) use the **latest EXFOR** source files.

(IAEA-NDS maintains “**EXFOR Master File**” 2005~)

EXFOR from Various Centres / Medias (cont)

IAEA Nuclear Data Section maintains EXFOR search system:

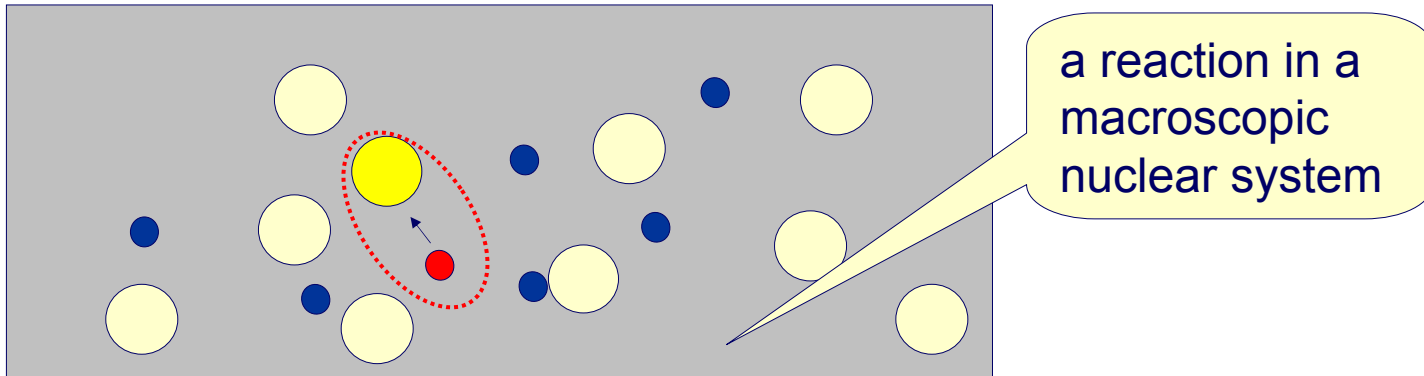
<http://www-nds.iaea.org/exfor/>

(A mirror server is also located in BARC.)

The screenshot shows the EXFOR search interface. At the top, it says 'Experimental Nuclear Reaction Data (EXFOR) Database Version of February 18, 2011'. Below this is a search form with various fields: Target, Reaction, Quantity, Product, Energy from, to, Author(s), Publication year, and Accession #. There are also checkboxes for 'Extended Keywords Expert' and 'Options' such as 'Exclude superseded data', 'No reaction containers (rates...)', 'Enlarged search of Products', 'Retrieve long only', 'Disable Promoted', and 'Sort by' (Reaction, Publication (Entry #)). A 'Request' section at the bottom provides instructions on how to use the search criteria.

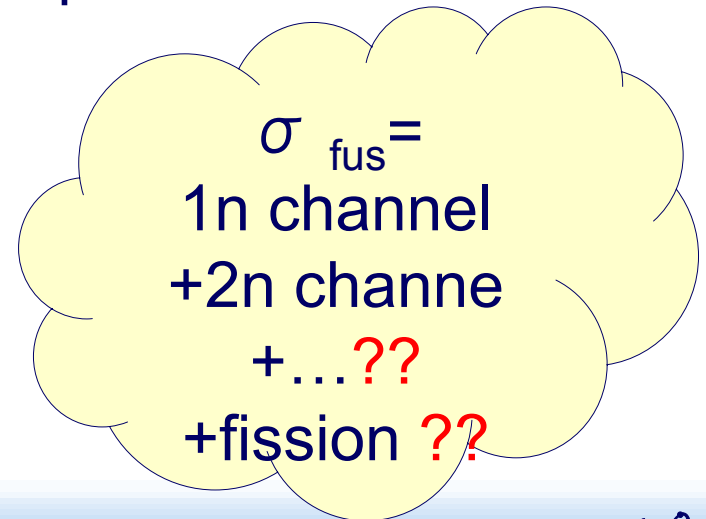
Scope of EXFOR

- EXFOR is a **general purpose** experimental data library.
(c.f. ENDF – evaluated nuclear data libraries – are designed for fission and fusion energy systems. $E_n < 20$ MeV)
- Data describing a **microscopic** nuclear reaction are considered (c.f. “per incident particle” “per reaction”).



Should EXFOR include “all” reaction data?

- An effort should be made for potential users (e.g., quantity defined for a specific theory should be skipped.)
- Clear definition should be given for stored quantities. (e.g., definition of “fusion cross section” depends on authors and not very clear.)



Example of Quantities in EXFOR

- Cross section
- Differential cross section (angular, energy, double, triple, ...)
- Resonance parameter
- Fission quantity (fission yield, fission neutron multiplicity, ...)
- Polarization quantity (analyzing power, ...)
- Thick target yield

etc.

Scope of EXFOR

Projectiles in EXFOR

Beam	Neutron	Light ion ($A \leq 12$)	Heavy ion ($A \geq 13$)	Photon
$E < 1$ GeV	complete	complete	incomplete	incomplete
$E > 1$ GeV	incomplete			

Highest priority is assigned to neutron and light-ion (p, d, ^3He , α , ...) induced reaction data ($E < 1$ GeV).

Note that

n: 45%, p: 25%, d: 6%, α : 5%, γ : 5% (Sum~85%)
in the EXFOR library (March 2011).

Scope of EXFOR

Work Sharing

To maintain completeness of the EXFOR library efficiently, each centre is responsible for specific data type.

Example

NNDC (Brookhaven, US)

neutron, charged-particle, photo-nuclear data from USA+Canada

CJD (Obninsk, Russia)

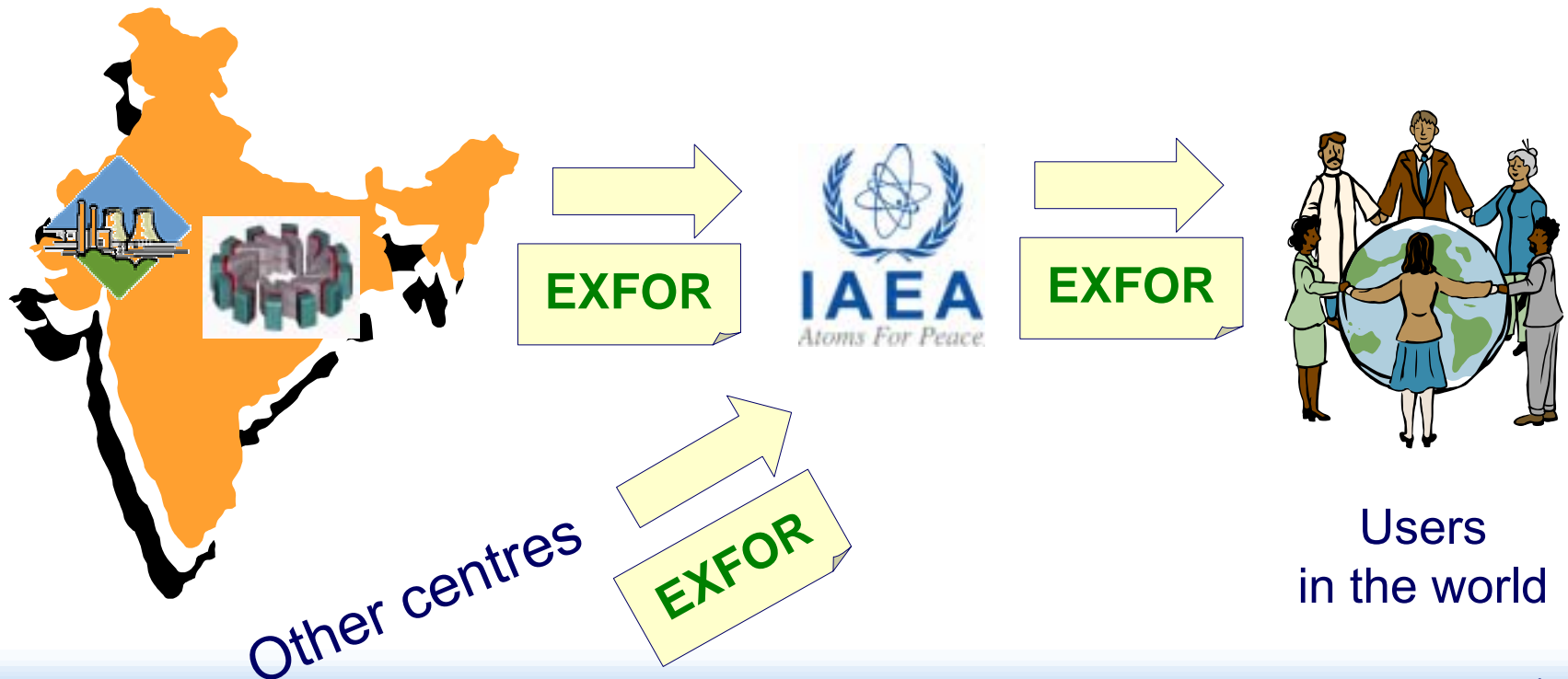
neutron data from former USSR (except for Ukr.)

CAJaD (Moscow, Russia)

charged-particle data from former USSR (except for Ukr.)

Responsibility of Indian Researchers

Indian Group (coordinated by Prof. Ganesan, BARC) is responsible to neutron, charged-particle and photonuclear reaction data **measured in India.**



EXFOR Entry Entry Number

- Each EXFOR Entry is identified by **Entry number (accession number)**.
- Entry number has one area character and 4 digits number.

Example

Entry **41123**: 1123th EXFOR entry from area 4

Entry **C0453**: 453th EXFOR entry from area C

- area 4: Neutron data from former USSR
- area C: charged-particle data from US+Canada

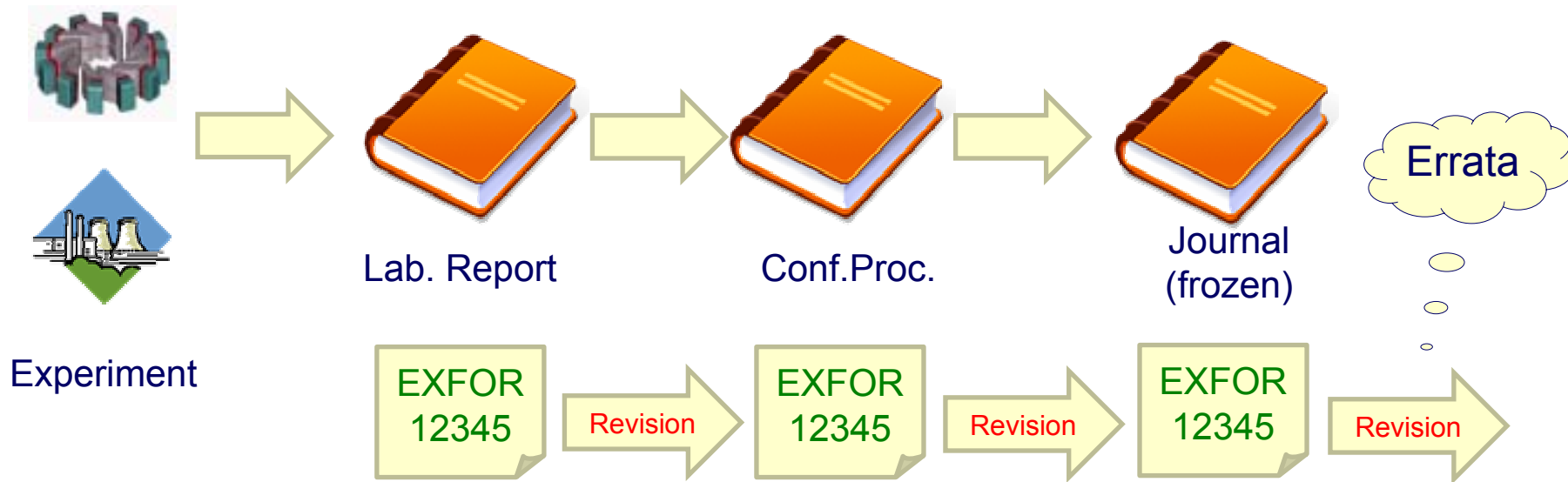
EXFOR Entry Entry Number (cont)

Example of area character

1	Neutron data from US+Canada
2	Neutron data from NEA DB countries
3	Neutron data from rest of the world (incl. India)
4	Neutron data from former USSR
A	Charged-particle data from former USSR
C	Charged-particle data from US+Canada
D	Charged-particle data from rest of the world (incl. India)
E	Charged-particle data from Japan
L	Photo-nuclear data from US+Canada

EXFOR Entry Entry Number (cont)

- 1 EXFOR Entry = 1 Experimental work
≠ 1 Publication



EXFOR entries are alive!

(We can revise them even after final publications)

EXFOR Entry Subentry Number

- One Entry is a set of Subentry.
- Each subentry is characterized by subentry number (subaccession number).
- Subentry 001 is a set of common information applicable to all subentries (e.g., title, authors, institute, experimental facility, detector)
- Subentry 002, 003,... are assigned to data sets.

Subentry Number (cont)

Example:

An Indian neutron EXFOR entry (EXFOR 33023)

(B.K. Nayak et al., Phys.Rev.C78(2008)061602)

33023.001:

Common information (title,author,...)

33023.002:

Data set for $^{233}\text{Pa}(n,f)/^{235}\text{U}(n,f)$ x-section ratio

33023.003:

Data set for $^{233}\text{Pa}(n,f)$ x-section



EXFOR Search by (Sub) entry Number

Each EXFOR entry is searchable by Entry # (Accession #) at <http://www-nds.iaea.org/exfor/>.

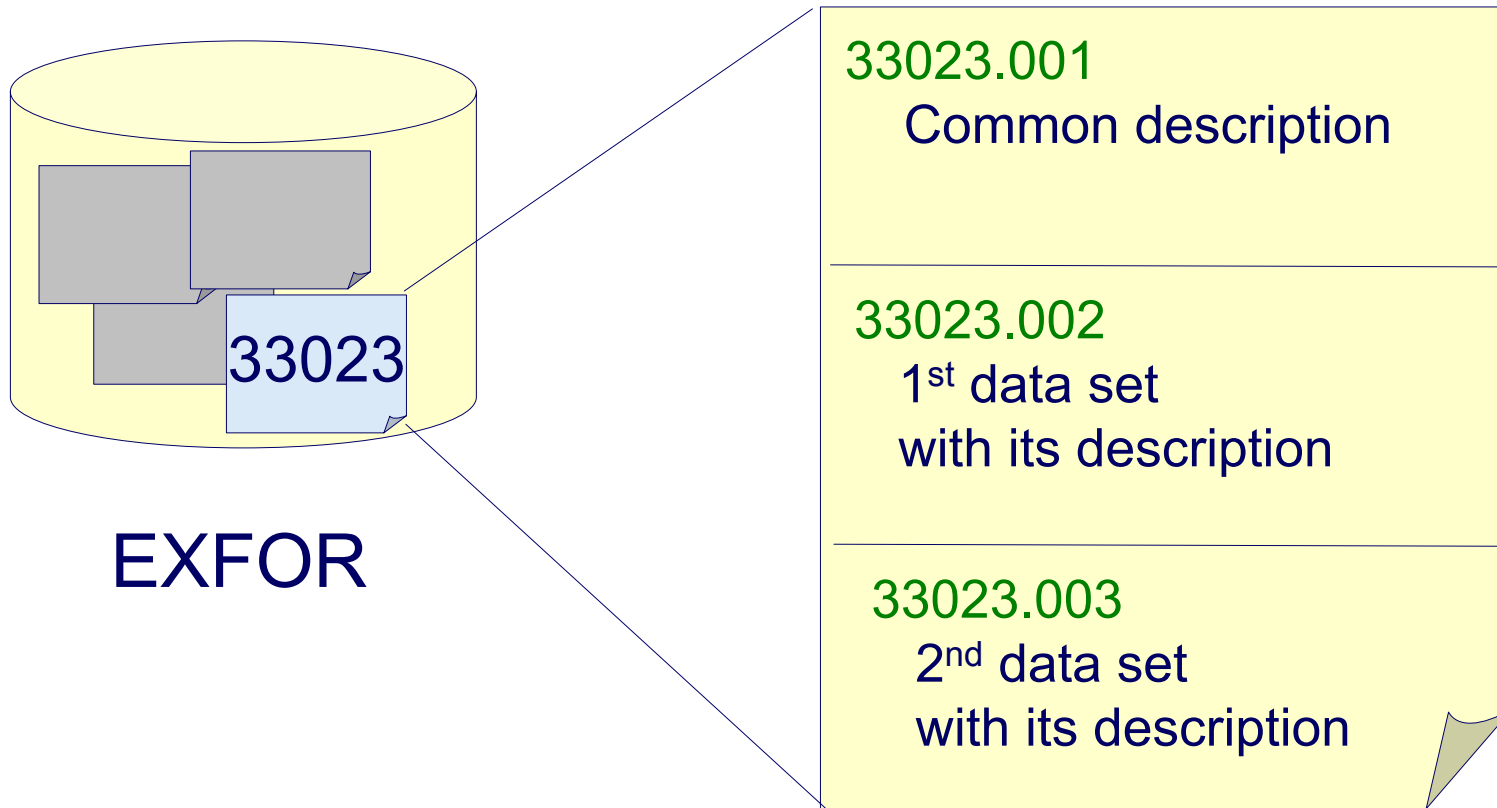
n	Acc#	1st Author	Year	Reference
1)	33023	2008 B.K.Nayak+		J, PR/C, 78, 061602, 2008
Determination of the $^{233}\text{Pa}(n, f)$ reaction cross section from 11.5 to 16.5 MeV neutron energy by the hybrid surrogate ratio approach				
<input type="checkbox"/>	1	33023001		Info X4 X4+ general information
<input type="checkbox"/>	2	33023002		Info X4 X4+ T4 Pt:6 1.18e7 1.69e7 (91-PA-233 (N, F) ,, SIG) // (92-U-235 (N, F) ,, SIG)
<input type="checkbox"/>	3	33023003		Info X4 X4+ T4 Pt:6 1.18e7 1.69e7 (91-PA-233 (N, F) ,, SIG)

subentry #

beam energy (eV)

reaction+quantity

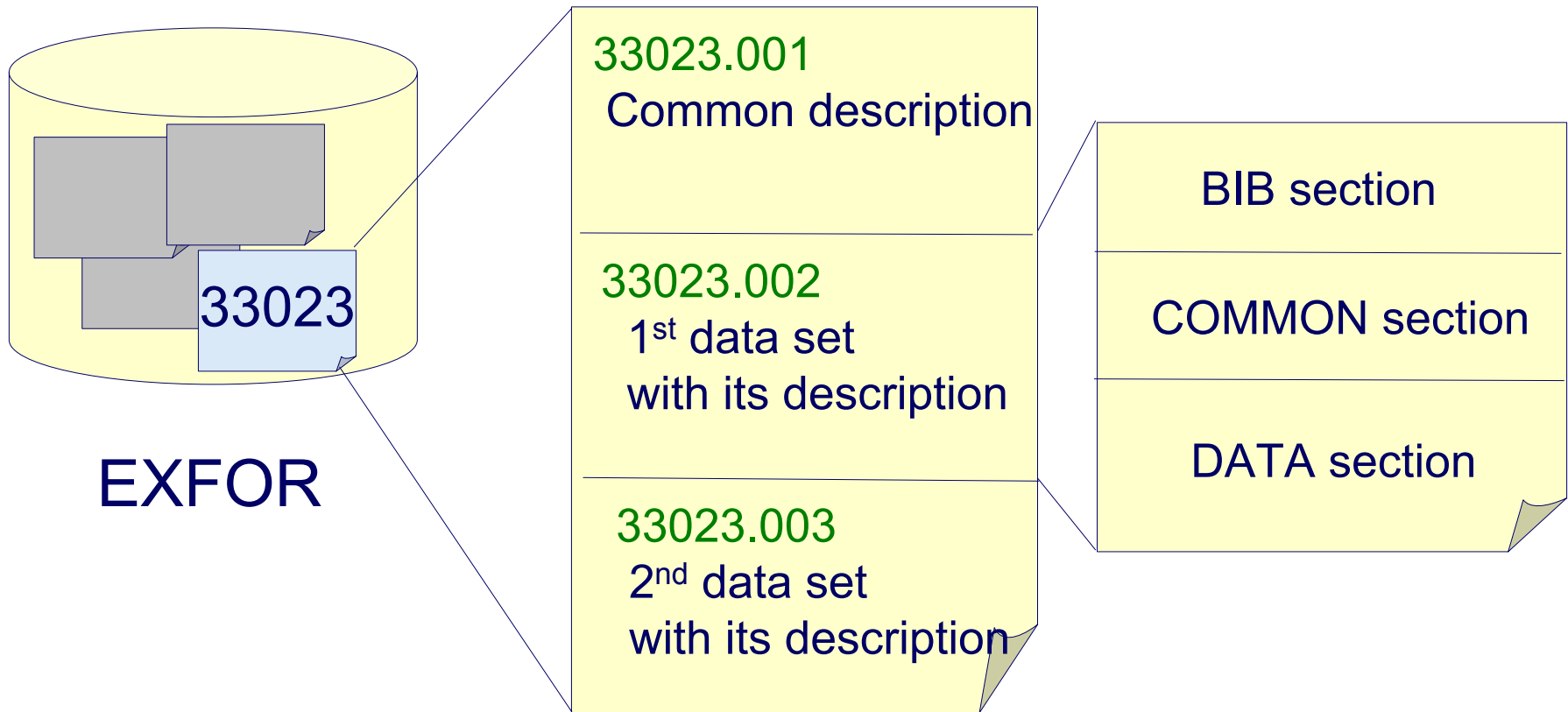
Subentry number (cont)



EXFOR Formats

- Each EXFOR entry is stored in an **ASCII file**.
- Each line of EXFOR entry has **80 columns**.
(67th-80th columns: Line sequential number)
- Each EXFOR subentry is divided into
 - 1) **BIB** section: Description of the experiment
 - 2) **COMMON** section: numerical data (constants of the data set)
 - 3) **DATA** section: numerical data

BIB, COMMON and DATA Section



Example of Subentry (33023.001)

11 22 33 44 55 66 80

	SUBENT	33023001	20110104			33023001	1
	BIB	14	66			33023001	2
Title	TITLE	Determination of the 233-Pa (n, f) reaction cross section from 11.5 to 16.5 MeV neutron energy by the hybrid surrogate ratio approach				33023001	3
						33023001	4
						33023001	5
Authors	AUTHOR	(B.K.Nayak, A.Saxena, D.C.Biswas, E.T.Mirgule,				33023001	6
	...						
Affiliation	INSTITUTE	(3INDTRM)				33023001	9
Reference	REFERENCE	(J,PR/C,78,061602,2008)				33023001	10
Facility	FACILITY	(VDGT,3INDTAT)				33023001	11
	...						
Definition of error	ERR-ANALYS	(ERR-S) The uncertainties shown in the measured cross section is due to the statistics of coincidence counts in each energy beam.				33023001	59
						33023001	60
						33023001	61
Source of values	STATUS	(TABLE) Data provided by authors				33023001	62
		(APRVD) Entry approved by Drs.B.K.Nayak and A.Saxena				33023001	63
History of the entry	HISTORY	(20090803C)Compiled by Mr.Paresh Prajapati of The				33023001	64
	...						
	ENDBIB	66				33023001	69
	NOCOMMON	0	0			33023001	70
	ENDSUBENT	69				33023001999999	

Example of Subentry (33023.003)

11 22 33 44 55 66 80

SUBENT	33023003	20110104					
BIB	4	4					
REACTION	(91-PA-233(N,F),,SIG)			← REACTION code (reaction + quantity given)			
MONITOR	((MONIT)92-U-235(N,F),,SIG) ENDF-B/VII				33023003	4	
MONIT-REF	,,3,ENDF-B/VII.0,,2006)				33023003	5	
STATUS	(DEP,33023002) 233Pa(n,f)/235U(n,f) data @ given E*				33023003	6	
ENDBIB	4				33023003	7	
NOCOMMON	0	0			33023003	8	
DATA	5	6			33023003	9	
EN	DATA	ERR-S	EN-NRM	MONIT		33023003	10
MEV	B	B	MEV	B		33023003	11
11.83	0.8832	0.076	10.50	1.703		33023003	12
12.83	0.8754	0.076	11.50	1.799		33023003	13
13.84	0.8986	0.066	12.51	1.988		33023003	14
14.84	0.9444	0.071	13.51	2.091		33023003	15
15.85	1.1347	0.077	14.52	2.151		33023003	16
16.85	1.4780	0.1	15.52	2.122		33023003	17
ENDDATA	8					33023003	18
ENDSUBENT	17					3302300399999	

BIB section

DATA section

EXFOR Formats

Structure of BIB Section

	11	66	80
TITLE	Determination of the 233-Pa (n,f) reaction cross	33023001	3
..			
AUTHOR	(B.K.Nayak, A.Saxena, D.C.Biswas, E.T.Mirgule,	33023001	6
...			
INSTITUTE	(3INDTRM)	33023001	9
REFERENCE	(J,PR/C,78,061602,2008)	33023001	10
FACILITY	(VDGT,3INDTAT)	33023001	11
...			
STATUS	(TABLE) Data provided by authors	33023001	62
	(APRVD) Entry approved by Drs.B.K.Nayak and A.Saxena	33023001	63
HISTORY	(20090803C)Compiled by Mr.Paresh Prajapati of The	33023001	64
...			

keyword

information

Parenthesized coded information
and/or free text information



Coded Information in BIB Section

	11	66	80
..			
AUTHOR	(B.K.Nayak , A.Saxena , D.C.Biswas , E.T.Mirgule ,	33023001	6
...			
INSTITUTE	(3INDTRM)	33023001	9
REFERENCE	(J,PR/C,78,061602,2008)	33023001	10
...			

- Coded information is designed for database search.
- Many abbreviations are defined in Dictionary.

(See, <http://nds121.iaea.org/ndsx4/trans/dicts/trans.9101>)

Example

3INDPUC: Punjab University, Chandigarh (Institute code)

PRM: Pramana (Journal code)

,SIG: Cross section (Quantity code)



EXFOR Formats

EXFOR Formats Manual

All details of EXFOR Formats are described in the **EXFOR Formats Manual**. A pdf copy is available on NRDC web page (<http://www-nds.iaea.org/nrdc/>).



INTERNATIONAL ATOMIC ENERGY AGENCY

NUCLEAR DATA SERVICES

DOCUMENTATION SERIES OF THE IAEA NUCLEAR DATA SECTION

IAEA-NDS-207
February 2008

EXFOR Exchange Formats Manual

Revision 2008 edited by

Otto Scherer
IAEA Nuclear Data Section
Vienna, Austria

based on earlier work by

Victoria McLane
National Nuclear Data Center
Brookhaven National Laboratory, USA

Issued on behalf of the
Nuclear Reaction Data Centres Network

Abstract: EXFOR is the exchange format for the transmission of experimental nuclear reaction data between national and international nuclear data centers for the benefit of nuclear data users in all countries. This report contains the agreed coding rules and a description of the format.

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fax: (43-1)26007
telephone: (43-1)2600-21710
web: <http://www-nds.iaea.org>

Example of EXFOR Formats Manual

DECAY-DATA Gives the decay data for any nuclide occurring in the reaction measured as assumed or measured by the author for obtaining the data given¹. See also **LEXFOR, Decay Data**.

1. If the keyword RAD-DET is used, an entry should also be made for DECAY-DATA. Also, if decay flags appear in the data section, they must be linked to an entry under DECAY-DATA, see below. Otherwise, its presence is optional, and free text or coded information, with or without free text, may be given.

If the keyword DECAY-DATA is present, the keyword HALF-LIFE may not be used. See also **LEXFOR, Half-Lives**.

2. The general format of the coding string consists of three major fields which may be preceded by a decay flag:

((flag)nuclide, half-life, radiation).

Embedded blanks are permitted in the code only at the beginning of a field or subfield. A code string may be broken for continuation onto the next record, but the break must come at the end of a field or subfield, *i.e.*, the comma separating the subfields should be the last character on the line.

Flag. The general format of the code is (*n*), where *n* has a numerical value that also appears in the data section under the data heading DECAY-FLAG. The flag may be omitted, in which case its parentheses are also omitted. See also **LEXFOR, Flags**.

Nuclide field. The general format of the code is *Z-S-A-Y*, except that when the ground state of a nuclide is given, the use of the extension *G* is optional, see page 6.2.

Half-life field. Contains the actual half-life of the nuclide specified, coded as a number, readable in an E11.4 format (see page 4.2, no blanks are allowed), followed by a unit which consists of a code from Dictionary 25 with the dimension TIME; no embedded blanks are allowed.

REACTION Code

REACTION code is the most important coded information in EXFOR. It defines quantity given in the subentry.

...

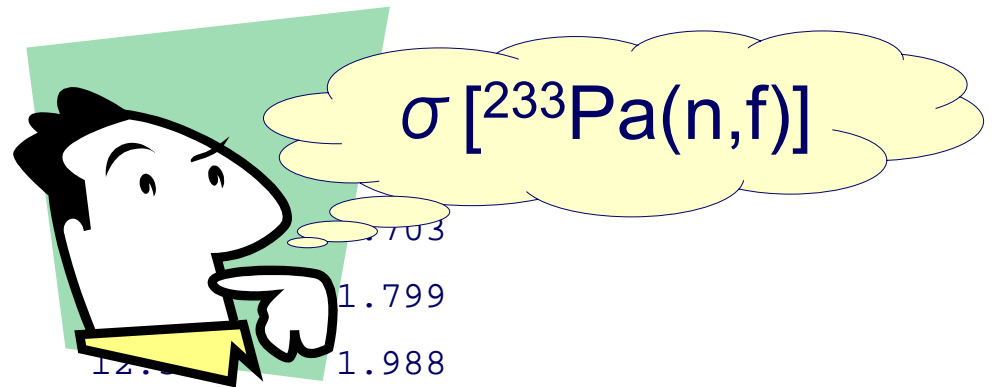
REACTION (91-PA-233(N,F),,SIG)

...

EN DATA ERR-S

MEV B B

11.83	0.8832	0.076		
12.83	0.8754	0.076		
13.84	0.8986	0.066	12.83	1.988
14.84	0.9444	0.071	13.51	2.091
15.85	1.1347	0.077	14.52	2.151
16.85	1.4780	0.1	15.52	2.122



Sub Fields (SF) in REACTION Code

(\$SF1(\$SF2,\$SF3)\$SF4,\$SF5,\$SF6,\$SF7,\$SF8,\$SF9)



Reaction field

Quantity field

Example

(30-ZN-67(N,P)29-CU-67,,SIG)

= Cross section of $^{67}\text{Zn}(n,p)^{67}\text{Cu}$

(\$SF7,\$SF8,\$SF9 are omitted)



Sub Fields (SF) in REACTION Code (Cont)

More Example

(30-ZN-67(N,P)29-CU-67,,DA)

= (Proton) angular distribution in $^{67}\text{Zn}(n,p)^{67}\text{Cu}$ [mb/sr]

(30-ZN-67(N,N+P)29-CU-66,,DA,P)

= Proton angular distribution in $^{67}\text{Zn}(n,np+pn)^{66}\text{Cu}$ [mb/sr]

(30-ZN-67(N,P)29-CU-67,PAR,DA)

= (Proton) partial angular distribution in $^{67}\text{Zn}(n,p)^{67}\text{Cu}$ [mb/sr]

“*partial*” = data for a specific secondary (level, kinetic) energy

Sub Fields (SF) in REACTION Code (Cont)

More Example

(30-ZN-67(N,X)29-CU-66,,SIG)

= ^{66}Cu production cross section from $^{67}\text{Zn}(n,x)^{66}\text{Cu}$ [mb]

(Outgoing particle unknown - n+p? d?)

(30-ZN-67(N,X)1-H-1,,DA/DE)

= Proton double diff. cross section in $^{67}\text{Zn}(n,p+x)$ [mb/sr/MeV]

(30-ZN-67(P,EL)30-ZN-67,,DA,,RTH)

= (Proton) Rutherford ratio in $^{67}\text{Zn}(p,p_0)^{67}\text{Zn}$ [no dimension]

Sub Fields (SF) in REACTION Code (Cont)

More Example

(92-U-233(N,F)53-I-131,IND,FY)

= ¹³¹I independent fission yield from ²³³U(n,f) [nuclides/fission]
 (“independent” = contribution of decay to ¹³¹I excluded)

(98-CF-252(0,F),PR,NU)

= Prompt fission neutron multiplicity in ²⁵²Cf spontaneous
 fission [neutrons/fission]

(92-U-235(N,F),PR,NU/DE)

= Prompt fission neutron spectrum in ²³⁵U(n,f)
 [neutrons/fission/MeV]

Sub Fields (SF) in REACTION Code (Cont)

More Example

(95-AM-241(N,G)95-AM-242-M,,SIG)

= Cross section for $^{241}\text{Am}(n, \gamma)^{242\text{m}}\text{Am}$ [mb]

(91-PA-233(N,F),,SIG)/(92-U-235(N,F),,SIG)

= Cross section ratio for $^{233}\text{Pa}(n,f)/^{235}\text{U}(n,f)$ [no dimension]

(91-PA-233(N,G)91-PA-234,,SIG,,MXW)

= Cross section for $^{233}\text{Pa}(n, \gamma)^{234}\text{Pa}$ averaged for Maxwellian spectrum [mb]

REACTION Code LEXFOR

- Major quantities defined in the EXFOR Formats are explained in **LEXFOR** (EXFOR Compiler's Manual) with corresponding REACTION code.
- A pdf copy is available on NRDC web page:
<http://www-nds.iaea.org/nrdc/>



INTERNATIONAL ATOMIC ENERGY AGENCY

NUCLEAR DATA SERVICES

DOCUMENTATION SERIES OF THE IAEA NUCLEAR DATA SECTION

IAEA-NDS-208
February 2008

LEXFOR
(EXFOR Compiler's Manual)

Revision 2008 edited by

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Issued on behalf of the
Nuclear Reaction Data Center: Network

Abstract: EXFOR is the exchange format for the transmission of experimental nuclear reaction data between national and international nuclear data centers for the benefit of nuclear data users in all countries. This report contains the compiler's section of the manual, including physics definitions, background information and practical examples. For a description of the format and coding rules see the EXFOR Systems Manual (IAEA-NDS-207).

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REACTION Code

Example of LEXFOR

Astrophysical S-factor

(See also Thermonuclear Reaction Rate).

For non-resonant reactions between low-energy charged particles, the steepest dependence of $\sigma(E)$ is contained in the penetration factor for the Coulomb and angular momentum barrier. For incident energies that are small compared to the height of these barriers, it is convenient to factor out the energy dependence and an additional factor of $1/E$. The cross section can then be written:

in terms of the Coulomb parameter

$$\sigma(E) = \frac{S(E)}{E} \exp(-2\pi\eta)$$

$$\eta = Z_1 Z_2 e^2 / h v$$

where v = relative velocity
 Z_1, Z_2 = charge of incident ion and target, respectively

or in terms of the Gamow energy:

$$\sigma(E) = \frac{S(E)}{E} \exp\left[-\beta/\sqrt{E}\right]$$

$$\beta = 0.98948 Z_1 Z_2 m^{1/2}$$

where E = center-of-mass incident energy (MeV)
 Z_1, Z_2 = charge of incident ion and target, respectively
 m = reduced mass of system: $m = m_1 m_2 / (m_1 + m_2)$

REACTION Coding: (..., SIG, , SFC)

Units: a code from Dictionary 25 with the dimension E*B (e.g., B(EV)).

S-factor as a function of angle.

Occasionally, the S-factor may be given as a function of angle: $S(E, \theta)$.

REACTION coding: (..., DA, , SFC)

Units: a code from Dictionary 25 with the dimension EDA (e.g., B*MEV/SR)

Definition by
an equation

EXFOR
REACTION code

EXFOR Search by REACTION

Each EXFOR entry is searchable by Target, Projectile etc. at <http://www-nds.iaea.org/exfor/>.

The screenshot shows the EXFOR search interface. At the top, there is a 'Request' dropdown menu with 'Examples: 1|2|3|4|5|6|7...' and buttons for 'Submit', 'Reset', and 'Help'. Below this are several search criteria, each with a checkbox and a text input field, and a right-pointing arrow button:

- Target [] >
- Reaction [] >
- Quantity [] >
- Product [] >
- Energy from [] to [] eV >
- Author(s) [] >
- Publication year [] >
- Accession # [] >

 At the bottom, there are three expandable sections: 'Extended', 'Keywords', and 'Expert', each with a right-pointing arrow. Below these are 'Submit' and 'Reset' buttons.

Keyword	Example
Target	O-18
Reaction	"p,n"
Quantity	"CS" (cross section)
Product	F-18

REACTION Code

EXFOR Search by REACTION (cont)

Target O-18 >>

Reaction p,n >>

Quantity cs >>

Product F-18 >>

Energy from to eV >>

Author(s) >>

Publication year >>

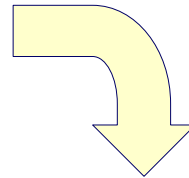
Accession # >>

Target: O-18

Reaction: p,n

Quantity: cs

Product: F-18



n	Display	Year	Author-1	Energy range, eV	Points	Reference	Accession#
1)	8-O-18 (P,N)9-F-18,,SIG C4: MF3 MT4						
	Quantity: [CS] Cross section						
1	Info X4 X4+ X4± T4	2001	E.Hess+	2.43e6 3.00e7	110	J,RCA,89,357,2001	D4095002
2	Info X4 X4+ X4± T4	1990	S.W.Kitwanga+	1.09e7 2.98e7	7	J,PR/C,42,748,1990	O0916004
3	Info X4 X4+ X4± T4	1973	J.K.Bair	2.52e6 3.87e6	295	J,PR/C,8,120,1973	C1010004
4	Info X4 X4+ X4± T4	1967	G.Amsel+	2.70e6	1	J,AC,39,1689,1967	D0104009
5	Info X4 X4+ X4± T4	1960	J.M.Blair+	2.63e6 2.96e6	30	J,PR,118,495,1960	O0454005
6	Info X4 X4+ X4± T4	1952	L.Marquez	4.20e8	1	J,PR,86,405,52	C0250003
7	Info X4 X4+ X4± T4	1952	J.P.Blaser+	2.08e6 6.79e6	60	J,HPA,24,465,1952	D0095004
2)	8-O-18 (P,N)9-F-18,,SIG,,RECOM C4: MF3 MT4						
	Quantity: [CS] Cross section						
8	Info X4 X4+ X4± T4	2003	S.Takacs+	2.50e6 2.98e7	274	J,NIM/B,211,169,2003	D41110061
3)	8-O-18 (P,N)9-F-18,IND,SIG,,EXP C4: MF=3 MT=?						
	Quantity: [CS] Independent cross section						
9	Info X4 X4+ X4± T4	1979	T.J.Ruth+	2.30e6 1.47e7	35	J,RCA,26,21,79	A0235002

1st author beam energy (eV) reference subent #

Uncertainty – for Future Use of EXFOR data

Let us consider a quantity Q which depends on the capture cross sections at two neutron energy points a and b :

$$Q(\sigma^a_{(n,\gamma)}, \sigma^b_{(n,\gamma)}).$$

Error propagation from σ to Q :

$$(\Delta Q)^2 = \left(\frac{\partial Q}{\partial \sigma^a}\right)^2 (\Delta \sigma^a)^2 + \left(\frac{\partial Q}{\partial \sigma^b}\right)^2 (\Delta \sigma^b)^2 + \left(\frac{\partial Q}{\partial \sigma^a}\right) V^{ab} \left(\frac{\partial Q}{\partial \sigma^b}\right)$$

Total uncertainty of σ^a

Total uncertainty of σ^b

Covariance between σ^a and σ^b

Not only total uncertainty, but also covariance may play an important role in error propagation.



Covariance

$$(\Delta Q)^2 = \left(\frac{\partial Q}{\partial \sigma^a}\right)^2 (\Delta \sigma^a)^2 + \left(\frac{\partial Q}{\partial \sigma^b}\right)^2 (\Delta \sigma^b)^2 + \left(\frac{\partial Q}{\partial \sigma^a}\right) \underline{V^{ab}} \left(\frac{\partial Q}{\partial \sigma^b}\right)$$

V^{ab} : covariance between σ^a and σ^b

If σ is a function of parameter set (x_1, x_2, \dots) :

$$V^{ab} = \sum_i \frac{\partial \sigma^a}{\partial x_i^a} V_i^{ab} \frac{\partial \sigma^b}{\partial x_i^b} = \sum_i \Delta \sigma_i^a \underline{c_i^{ab}} \Delta \sigma_i^b$$

correlation coefficient $|c| \leq 1$

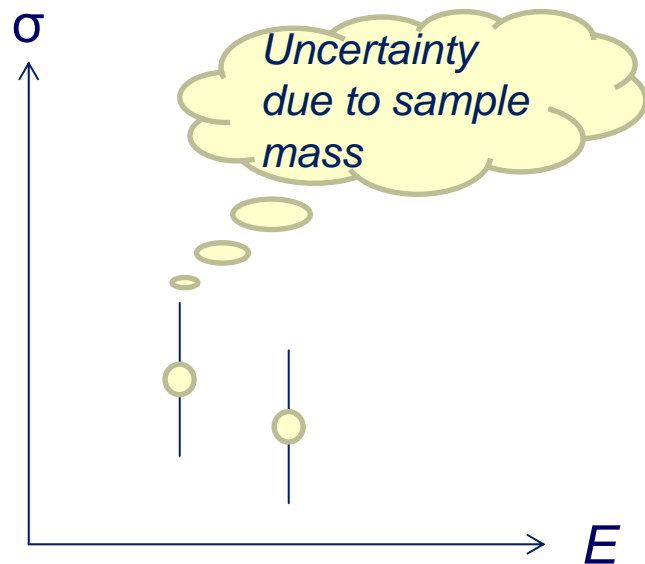
partial uncertainty due to i -th parameter

partial covariance due to i -th parameter



Uncertainty – for Future Use of EXFOR data

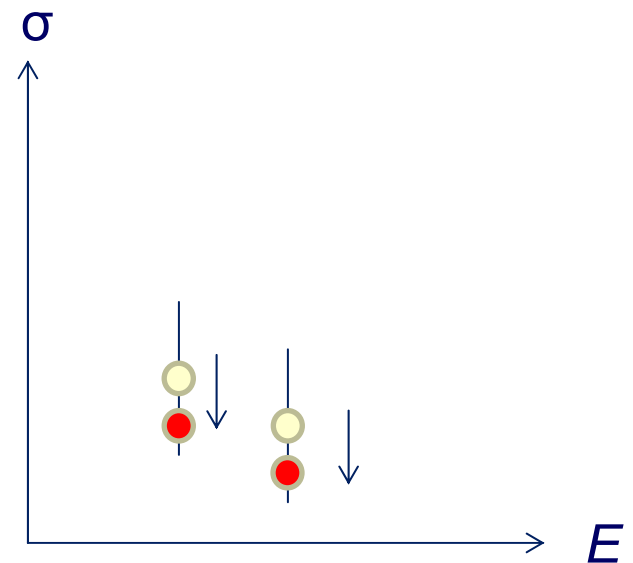
Example of Correlations



Two cross section points measured with same sample



If the *sample mass* is revised to higher value...



Two cross section points measured with same sample

No such a relation for uncorrelated source (e.g., counting statistics)

Partial Uncertainty and Correlation Coefficient

$$V^{ab} = \sum_i \frac{\partial \sigma^a}{\partial x_i^a} V_i^{ab} \frac{\partial \sigma^b}{\partial x_i^b} = \sum_i \underbrace{\Delta \sigma_i^a}_{\text{partial uncertainty due to } i\text{-th parameter}} \underbrace{c_i^{ab}}_{\text{correlation coeff. } |c| \leq 1} \Delta \sigma_i^b$$

partial uncertainty due to i -th parameter

- In order to obtain the covariance V^{ab} , both **partial uncertainties** and **correlation coefficients** for each i -th component should be known.
- Partial uncertainties (or their ranges) are often reported. But correlation properties are rarely reported.



Example of Correlation Coefficient

$$V^{ab} = \sum_i \frac{\partial \sigma^a}{\partial x_i^a} V_i^{ab} \frac{\partial \sigma^b}{\partial x_i^b} = \sum_i \Delta \sigma_i^a \underline{c_i^{ab}} \Delta \sigma_i^b$$

Example of correlation coefficient in activation formula discussed in M. Afzal Ansari et al., Ann. Nucl. Energy 11(1984)173:

$$\sigma_{(n,\gamma)} = \frac{A_{(n,\gamma)}}{A_{\text{monit}}} (\lambda_{(n,\gamma)}, \theta_{(n,\gamma)}, \lambda_{\text{monit}}, \theta_{\text{monit}}, N_{(n,\gamma)}, N_{\text{monit}}, \varepsilon_{(n,\gamma)}, \varepsilon_{\text{monit}}, t_1, t_2, t_3) \sigma_{\text{monit}}$$

- Count A: $c = 1$ ($a=b$) or $=0$ ($a \neq b$) - “uncorrelated”
- Atom number N: $c = 1$ for any (a,b) – “fully correlated” (assuming that the sample is used at all neutron energies)
- Decay data (e.g., gamma intensity) – “fully correlated”



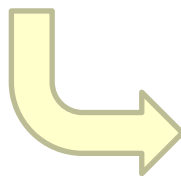
Uncertainty – for Future Use of EXFOR data

Covariance – EXFOR Coding Sample

C. Sage et al., Phys.Rev.C81(2010)064604 – $^{243}\text{Am}(n,2n)$ cross section.

TABLE VI. Uncertainties (in %) for the most significant contributions in Eq. (1) at each neutron energy. Only the diagonal elements are given. The full matrix for each component is not given here but was used to obtain the correlation matrix in Table V.

Neutron energy (MeV)	σ_{Al}	S_{Am}	S_{Al}	I_{Am}	n_{Al}	n_{Am}	$\epsilon_{Al}/\epsilon_{Am}$	$(f_{\Sigma}, f_r)_{Am}$	$\frac{C_{Am}}{C_{Al}}$
8.34	1.9	5.0	1.0	1.2	0.1	0.3	3.0	0.9	
9.15	1.9	4.0	1.0	1.2	0.1	0.3	3.0	0.6	
13.33	1.6	2.5	1.0	1.2	0.1	0.3	3.0	0.4	0.3
16.1	2	2.1	1.0	1.2	0.1	0.3	3.0	0.6	0.3
17.16	2	1.5	1.0	1.2	0.1	0.3	3.0	0.6	0.3
17.9	2.2	1.3	0.7	1.2	0.1	0.3	3.0	0.7	0.3
19.36	3.1	6.3	2.0	1.2	0.1	0.3	3.0	0.6	1.3
19.95	4.1	1.4	1.0	1.2	0.1	0.3	3.0	0.6	1.4
20.61	5.4	5.7	1.6	1.2	0.1	0.3	3.0	0.6	1.4



```

BIB
REACTION (94-AM-241(N,2N)94-AM-240,,SIG)
...
ERR-ANALYS (ERR-T,,,P) Total uncertainty
(MONIT-ERR,,,P) Monitor cross section
(ERR-1,,,U) Number of counts (Am)
(ERR-2,,,U) Number of counts (Al)
(ERR-3,,,F) Gamma intensity (Am)
(ERR-4,,,U) Sample mass (Al)
(ERR-5,,,P) Sample mass (Am)
(ERR-6,,,F) Efficiency ratio (Al/Am)
(ERR-7,,,F) Decay correction (Am)
(ERR-8,,,U) Secondary neutron correction (Am/Al)
...
COMMON
ERR-3 ERR-4 ERR-5 ERR-6
PER-CENT PER-CENT PER-CENT PER-CENT
1.2 0.1 0.3 3.0
ENDCOMMON
DATA
EN DATA ERR-T MONIT-ERR ERR-1 ERR-2 ERR-7 ERR-8
MEV MB PER-CENT PER-CENT PER-CENT PER-CENT PER-CENT PER-CENT
8.34 96.8 6.5 1.9 5.0 1.0 0.9
9.15 162.9 5.7 1.9 4.0 1.0 0.6
13.33 241.8 4.6 1.6 2.5 1.0 0.4 0.3
16.1 152.4 4.6 2. 2.1 1.0 0.6 0.3
17.16 116.1 4.4 2. 1.5 1.0 0.6 0.3
17.9 105.7 4.4 2.2 1.3 0.7 0.7 0.3
19.36 89.5 8.2 3.1 6.3 2.0 0.6 1.3
19.95 102.1 5.8 4.1 1.4 1.0 0.6 1.4
20.61 77.9 8.8 5.4 5.7 1.6 0.6 1.4
ENDDATA
    
```

Correlation Property
U: uncorrelated
F: fully correlated
P: partly correlated
 (for approval in May.)

Partial uncertainty values

Covariance – EXFOR Coding Sample (cont)

C. Sage et al., Phys.Rev.C81(2010)064604 – $^{243}\text{Am}(n,2n)$ cross section.

```
BIB
REACTION (94-AM-241(N,2N)94-AM-240,,SIG)
...
ERR-ANALYS (ERR-T,,,P) Total uncertainty
(MONIT-ERR,,,P) Monitor cross section
...
(ERR-5,,,P) Sample mass (Am)
...
COVARIANCE (EN,MEV)
8.34 9.15 13.33 16.1 17.16 17.9 19.36 19.95 20.61
(COR,ERR-T,PER-CENT) Total correlation
100
35 100
37 42 100
38 43 53 100
...
(COR,MONIT-ERR,PER-CENT) Partial correlation due to standard
100
43 100
0 0 100
0 0 6 100
...
(COR,ERR-5,PER-CENT) Partial correlation due to sample mass
100
0 100
0 100 100
0 100 100 100
...
```

Not only partial uncertainties, correlation coefficients are also reported for all partly correlated uncertainties. (for approval in May)



Covariance - Summary

$$(\Delta Q)^2 = \left(\frac{\partial Q}{\partial \sigma^a} \right)^2 (\Delta \sigma^a)^2 + \left(\frac{\partial Q}{\partial \sigma^b} \right)^2 (\Delta \sigma^b)^2 + \left(\frac{\partial Q}{\partial \sigma^a} \right) \underline{V^{ab}} \left(\frac{\partial Q}{\partial \sigma^b} \right)$$

V^{ab} : covariance between σ^a and σ^b

$$V^{ab} = \sum_i \frac{\partial \sigma^a}{\partial x_i^a} V_i^{ab} \frac{\partial \sigma^b}{\partial x_i^b} = \sum_i \Delta \sigma_i^a \underline{c_i^{ab}} \Delta \sigma_i^b$$

correlation coefficient $|c| \leq 1$

partial uncertainty due to i -th parameter

- Covariance V^{ab} may be important when we consider a quantity depending on two or more data points.
- Partial uncertainties $\Delta \sigma_i^a$ propagated to the total uncertainty must be reported and compiled
(Experimentalists should be able to provide them!)
- Pay also attention to correlation properties c_i^{ab} for each source of uncertainty.



EXFOR Cross Section Plot

Selected
 Unselected
 All

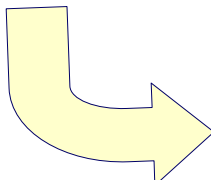
Output: EXFOR EXFOR+ Bibliography TAB

Plot: Quick-plot (cross-sections only) Advanced plot

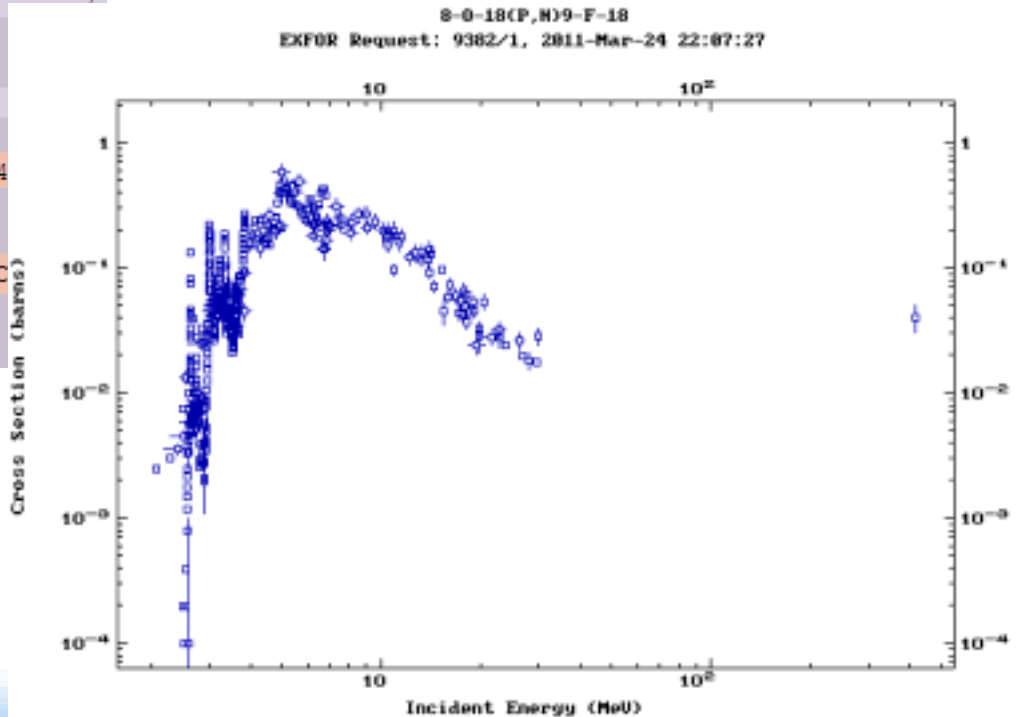
Narrow Energy (optional), eV: Min: Max:

Advanced data modifications

n	Display	Year	Author-1	Ene
1	8-O-18 (P,N) 9-F-18,,SIG C4: MF3 MT4			
Quantity: [CS] Cross section				
1	<input checked="" type="checkbox"/> Info X4 X4+ X4± T4	2001	E.Hess+	2.
2	<input checked="" type="checkbox"/> Info X4 X4+ X4± T4	1990	S.W.Kitwanga+	1.
3	<input checked="" type="checkbox"/> Info X4 X4+ X4± T4	1973	J.K.Bair	0.
4	<input checked="" type="checkbox"/> Info X4 X4+ X4± T4	1967	G.Amsel+	
5	<input checked="" type="checkbox"/> Info X4 X4+ X4± T4	1960	J.M.Blair+	
6	<input checked="" type="checkbox"/> Info X4 X4+ X4± T4	1952	L.Marquez	
7	<input checked="" type="checkbox"/> Info X4 X4+ X4± T4	1952	J.P.Blaser+	
2	8-O-18 (P,N) 9-F-18,,SIG,,,RECOM C4			
Quantity: [CS] Cross section				
8	<input type="checkbox"/> Info X4 X4+ X4± T4	2003	S.Takacs+	
3	8-O-18 (P,N) 9-F-18,IND,SIG,,,EXP C4			
Quantity: [CS] Independent cross section				
9	<input type="checkbox"/> Info X4 X4+ X4± T4	1979	T.J.Ruth+	

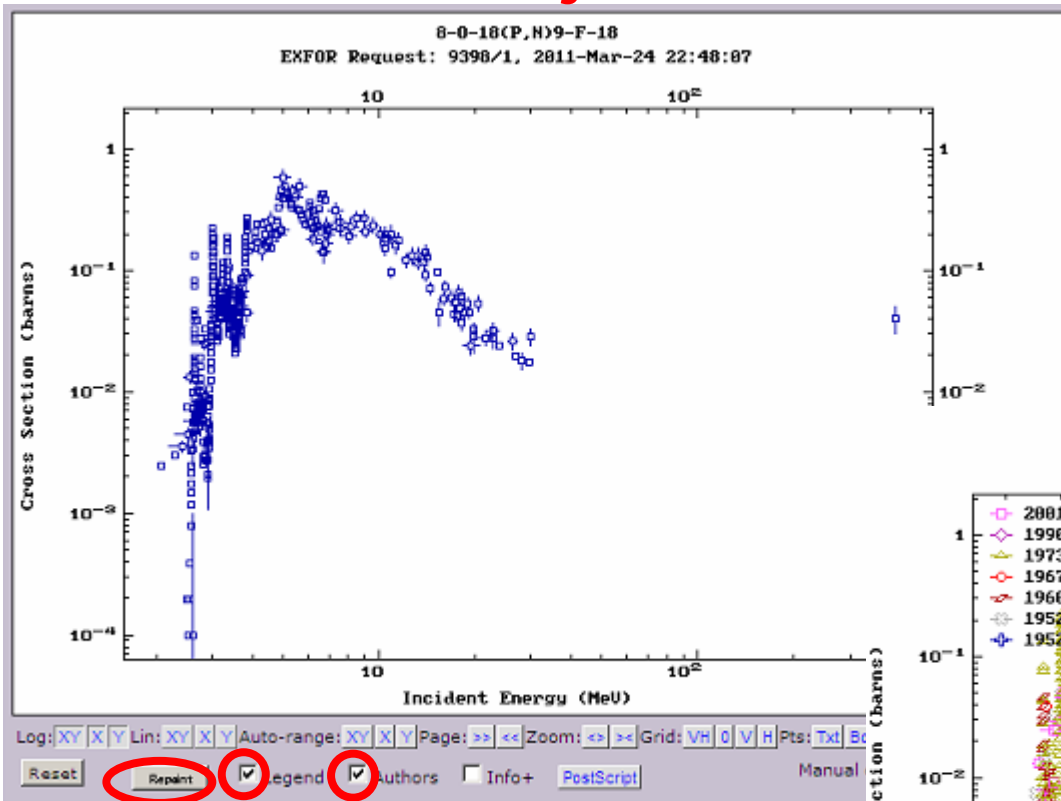


Plot of cross section is very easy! (Quick-plot)

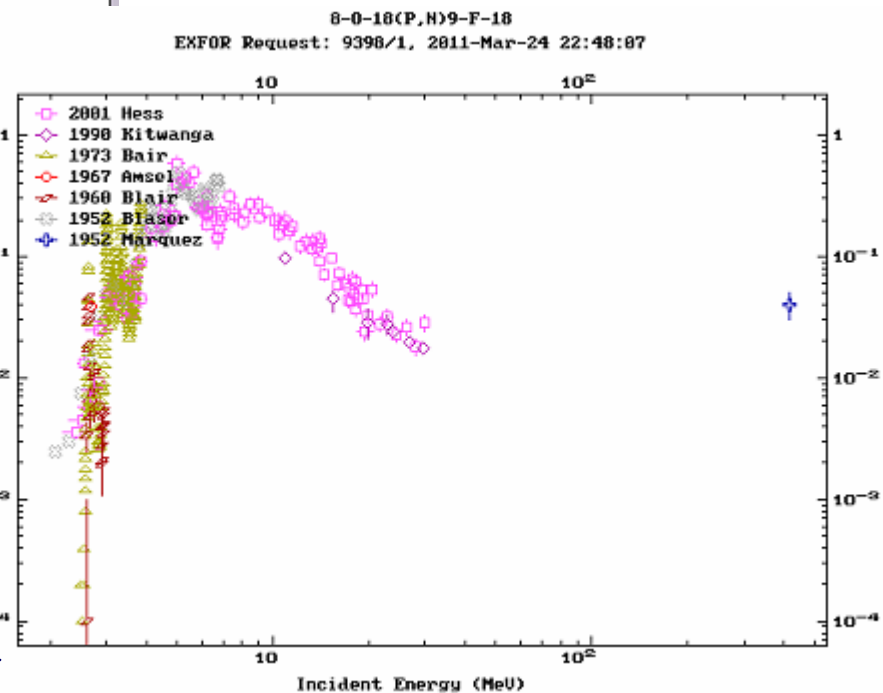
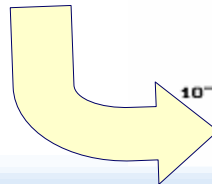


EXFOR Cross Section Plot

Adjustment of Plot on Web

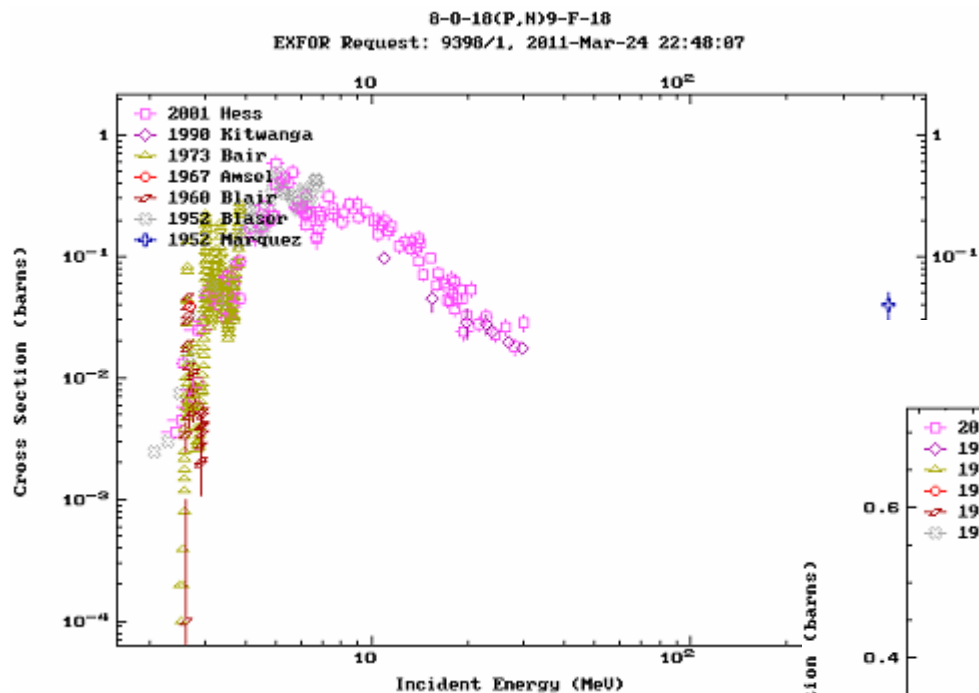


Check “Legend” and “Authors”
and click “Repaint”.

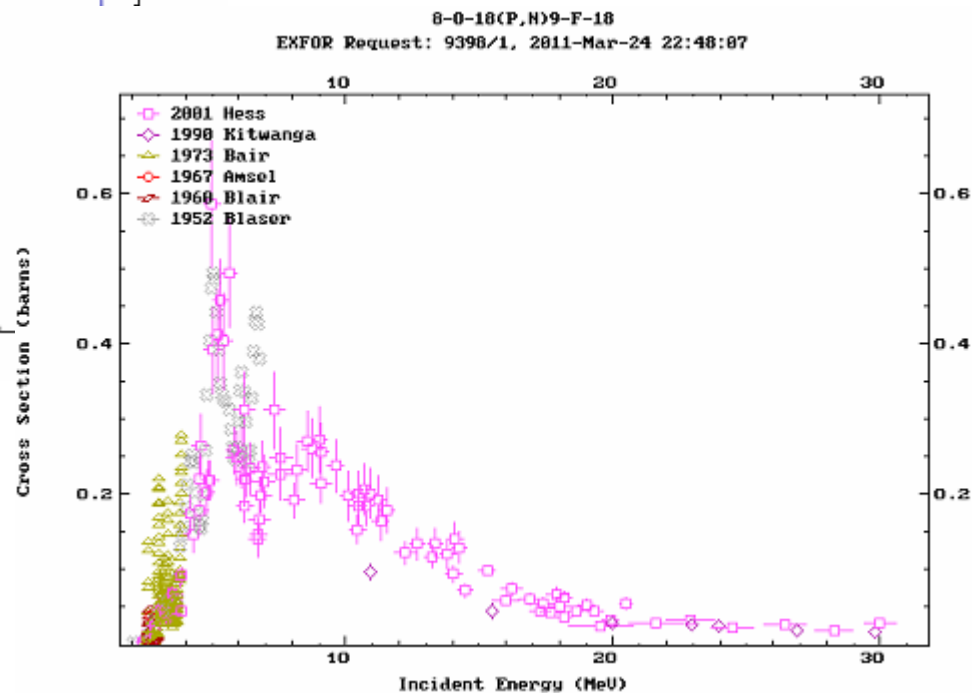
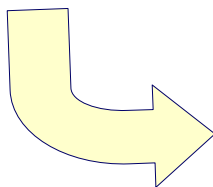


EXFOR Cross Section Plot

Adjustment of Plot on Web (cont)



Select area,
Click "Lin:XY"
and click "Repaint".



Exercise: $^{67}\text{Zn}(n,p)^{67}\text{Cu}$

Exercise:

$^{67}\text{Zn}(n,p)^{67}\text{Cu}$ cross section

- Search $^{67}\text{Zn}(n,p)^{67}\text{Cu}$ cross sections in EXFOR by <http://www-nds.iaea.org/exfor/>

Target: Zn-67

Reaction: n,p

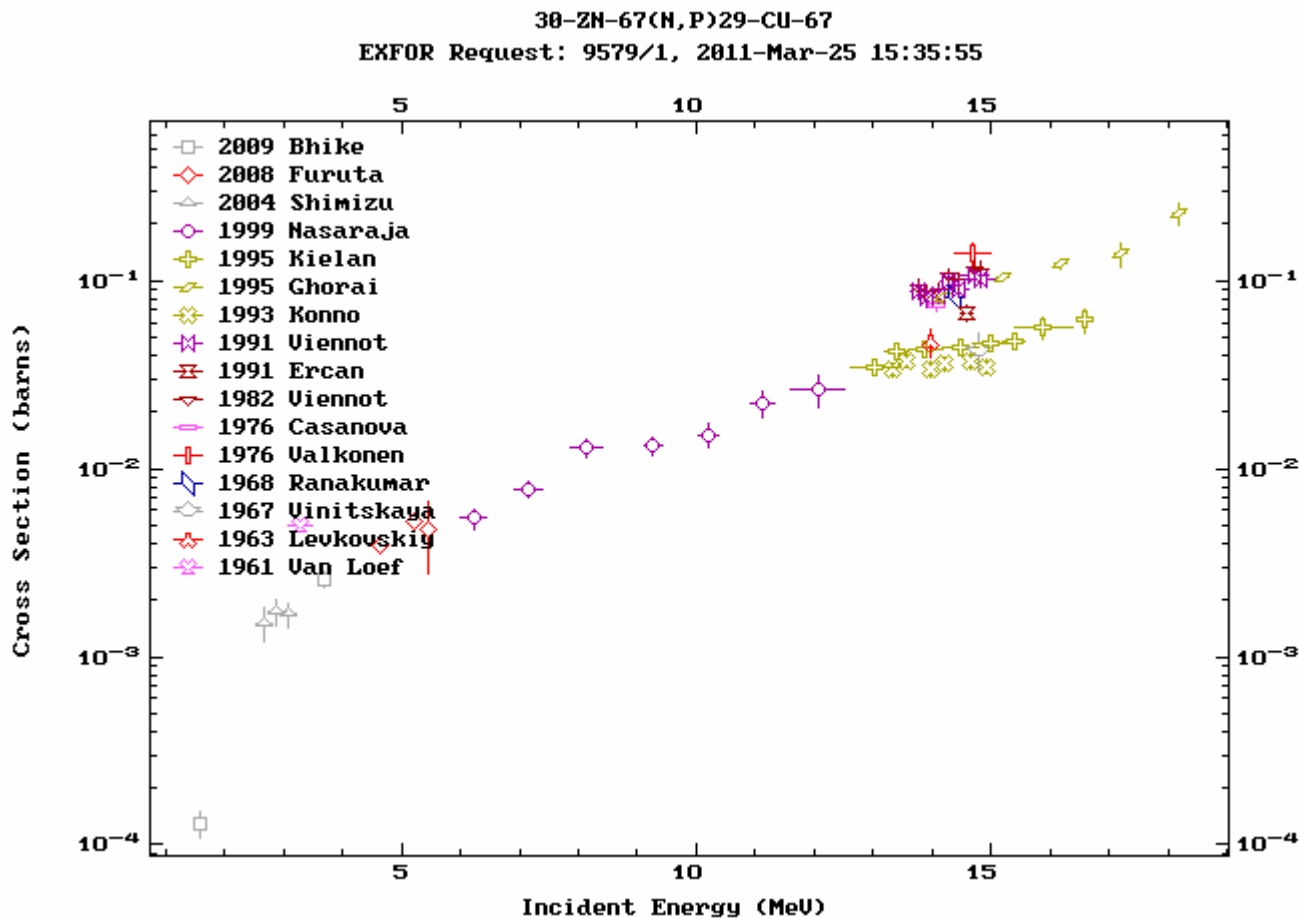
Quantity: cs

- Select all relevant data
- (Quick-)Plot all data sets in (x,y)=(lin-log)



EXFOR Cross Section Plot

Exercise: $^{67}\text{Zn}(n,p)^{67}\text{Cu}$ (cont)



2 options (Legends, Authors) were selected and repainted.)

EXFOR Cross Section Plot
Exercise: $^{233}\text{Pa}(n,f)$

Exercise:

^{233}Pa neutron-induced fission cross section

- Search $^{233}\text{Pa}(n,f)$ cross sections in EXFOR by <http://www-nds.iaea.org/exfor/>

Target: Pa-233

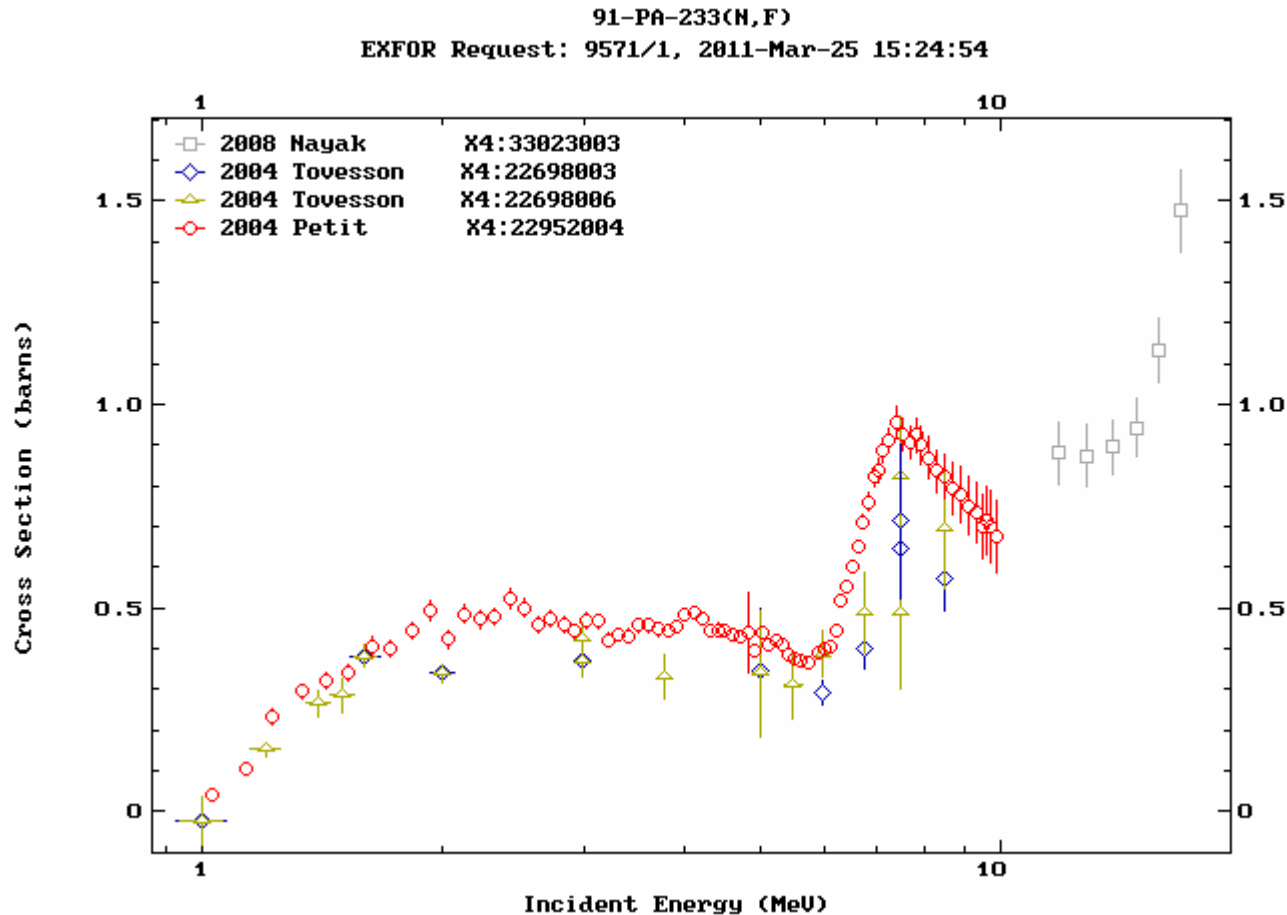
Reaction: n,f

Quantity: cs

- Select 3 data sets (Nayak, Tovesson, Petit)
- (Quick-)Plot all data sets in (x,y)=(log-lin)

EXFOR Cross Section Plot

Exercise: $^{233}\text{Pa}(n,f)$ (cont)



3 options (Legends, Authors, Info+) were selected and repainted)

Exercise: $^{232}\text{Th}(n, \gamma)^{233}\text{Th}$

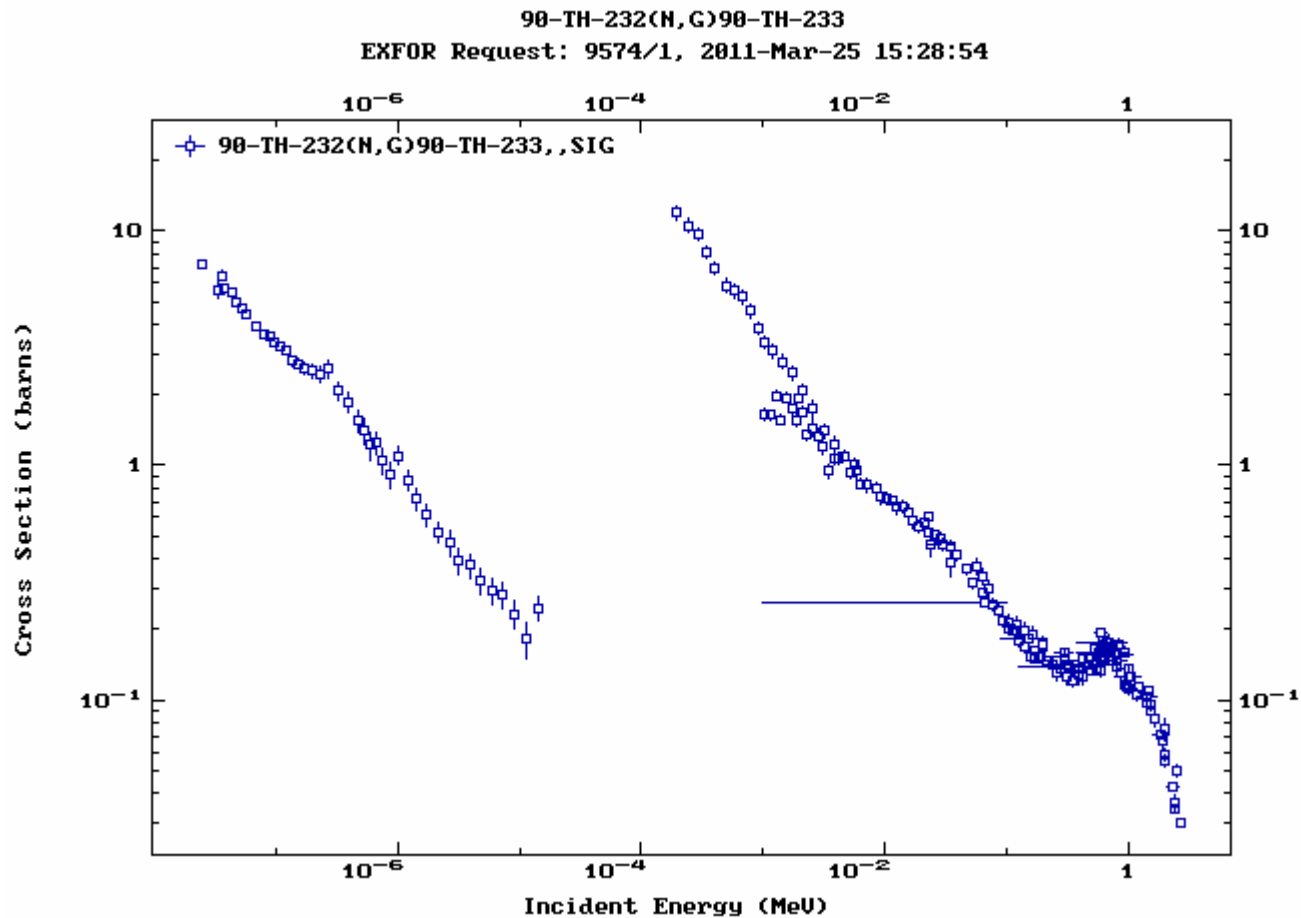
Exercise: neutron capture by ^{232}Th

- Search $^{232}\text{Th}(n, \gamma)^{233}\text{Th}$ cross sections in EXFOR by <http://www-nds.iaea.org/exfor/>
Target: Th-232
Reaction: n,g
Quantity: cs
Publication year: 1970-2010
- Select all relevant data (about 40 data sets)
- Plot all data sets in $(x,y)=(\log\text{-}\log)$



EXFOR Cross Section Plot

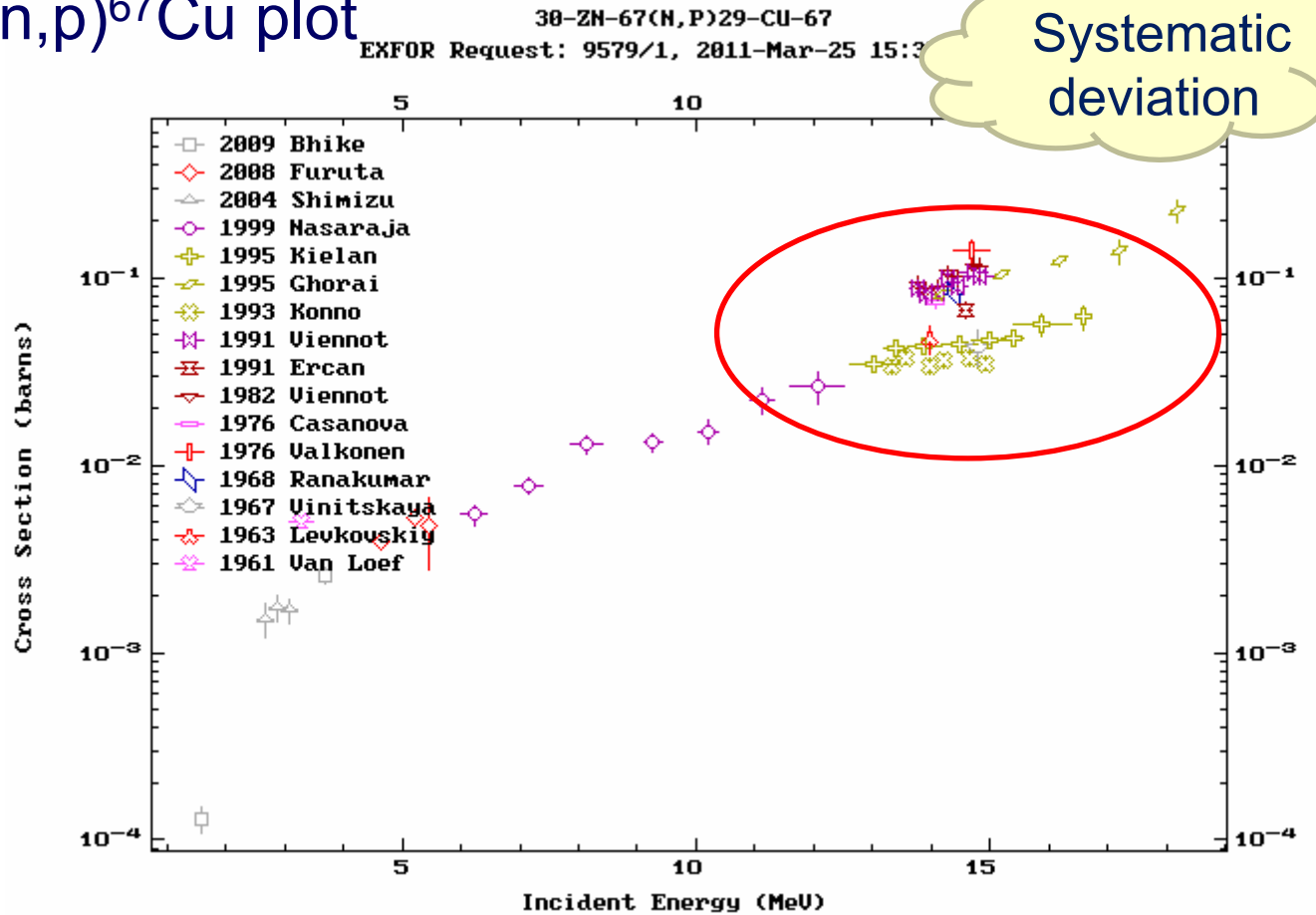
Exercise: $^{232}\text{Th}(n, \gamma)^{233}\text{Th}$



1 options (Legends) was selected, and repainted.

Plot of EXFOR Data with Theoretical Data

Revisit $^{67}\text{Zn}(n,p)^{67}\text{Cu}$ plot



Let us compare EXFOR data with theoretical prediction.

Plot of EXFOR Data with Theoretical Data (cont)

Major nuclear reaction calculation codes:

- **EMPIRE**

M. Herman et al., Nucl. Data Sheets 108(2007)2655
(<http://www.nndc.bnl.gov/empire219/>)

- **TALYS**

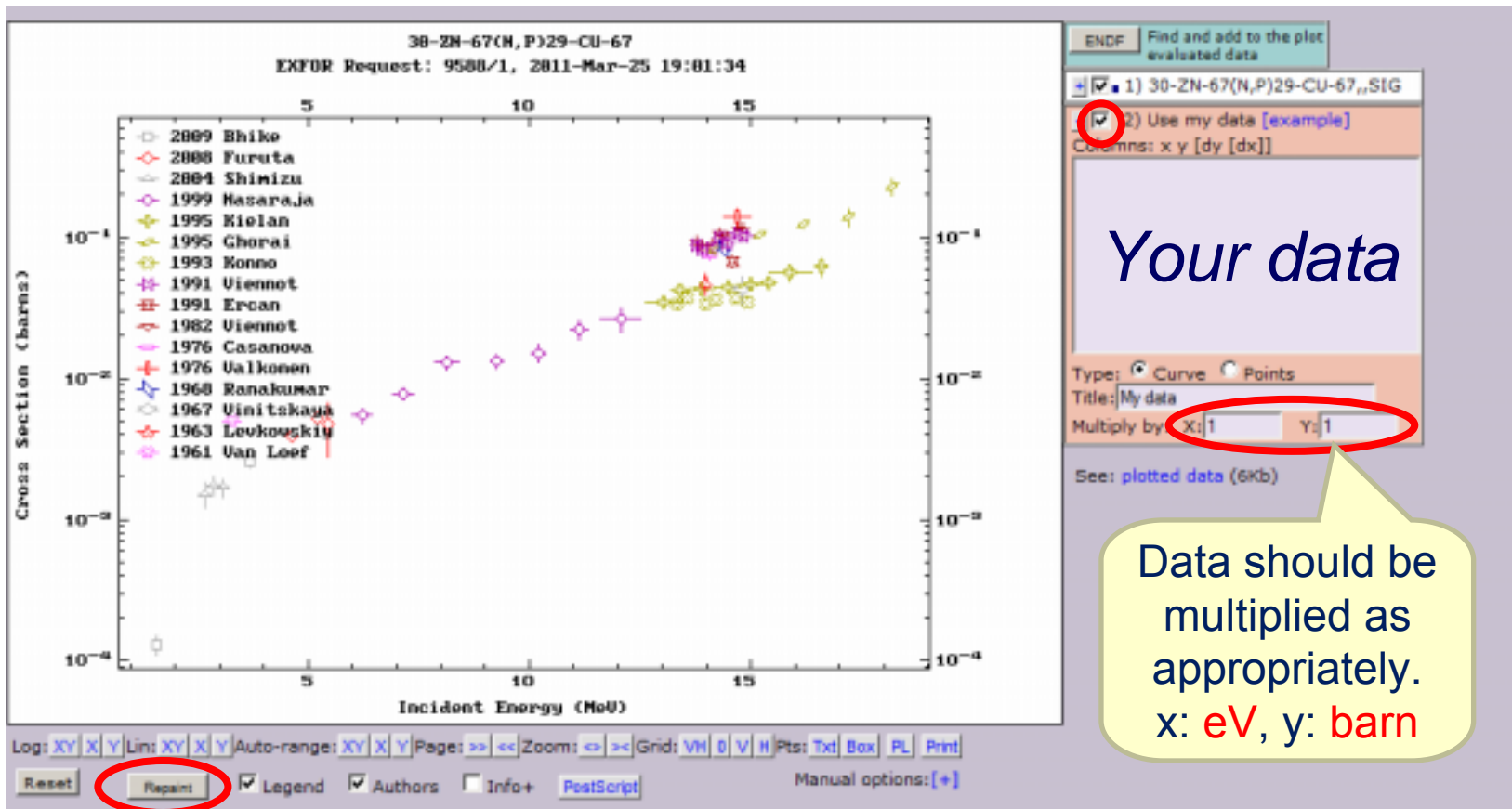
A. Koning et al., Proc. Conf. Nucl.Data Sci. Technol.,
April 22-27, 2007, Nice, p211
(<http://www.talys.eu/>)

I prepared some TALYS outputs for our practice:

http://www-nds.iaea.org/nrdc/wsin_2011/

EXFOR Cross Section Plot

Plot of EXFOR Data with Theoretical Data (cont)

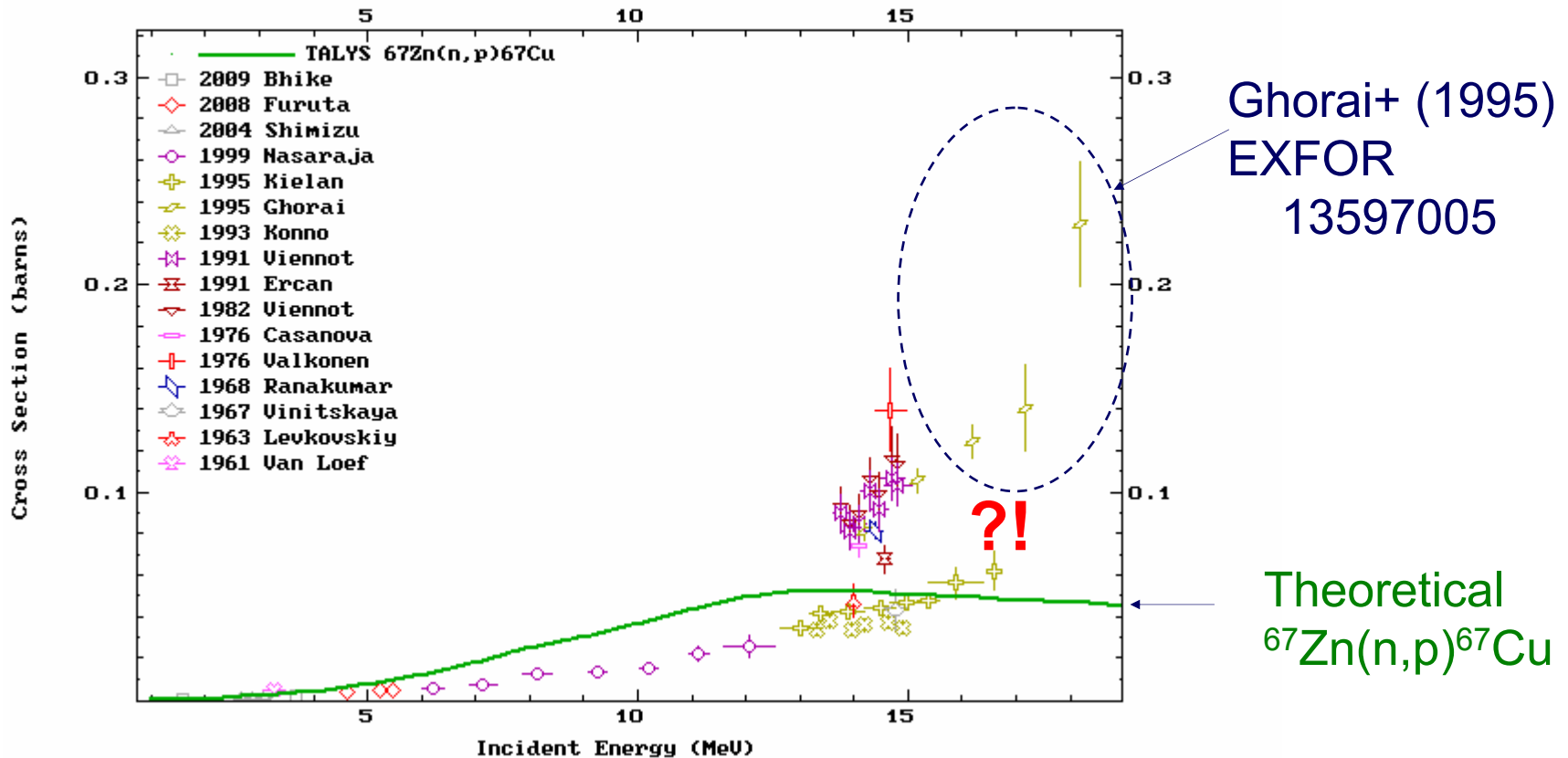


Exercise: Plot $^{67}\text{Zn}(n,p)^{67}\text{Cu}$ TALYS data (Material #1) with EXFOR data. (Get TALYS data from http://www-nds.iaea.org/nrdc/wsin_2011/)

EXFOR Cross Section Plot

Exercise: $^{67}\text{Zn}(n,p)^{67}\text{Cu}$

30-ZN-67(N,P)29-CU-67
EXFOR Request: 9588/1, 2011-Mar-25 19:01:34



Why we see such deviation?

EXFOR Cross Section Plot

Experimental Condition in BIB Section

```
SUBENT      13597001      950822
BIB          15          27
...
AUTHOR      (S.K.GHORAI,P.M.SYLVA,J.R.WILLIAMS,W.L.ALFORD)
TITLE       Partial neutron cross sections for 64Zn, 66Zn, 67Zn
            and 68Zn between 14.2 and 18.2 MeV
FACILITY    (DYNAM)
INC-SOURCE  (D-T) deuterons on titanium tritide.
SAMPLE    Natural zinc sample. ←
METHOD  (ACTIV,MOMIX) ←
...
ENDSUBENT   34
SUBENT      13597005      950217
BIB          2            2
REACTION  (30-ZN-67(N,P)29-CU-67,,SIG)
DECAY-DATA (29-CU-67,62.01HR,DG,185.,0.470) ←
ENDBIB      2
NOCOMMON    0            0
DATA        5            5
EN          DATA        DATA-ERR  MONIT      MONIT-ERR
MEV         MB           MB         MB         MB
14.2        82.          5.          122.0      0.65
15.2        106.         6.          108.0      1.96
16.2        125.         8.          90.0       1.75
17.2        141.         21.         72.0       1.41
18.2        230.         30.         59.5       1.26
ENDDATA     7
ENDSUBENT   14
```

Natural Zn
was irradiated.

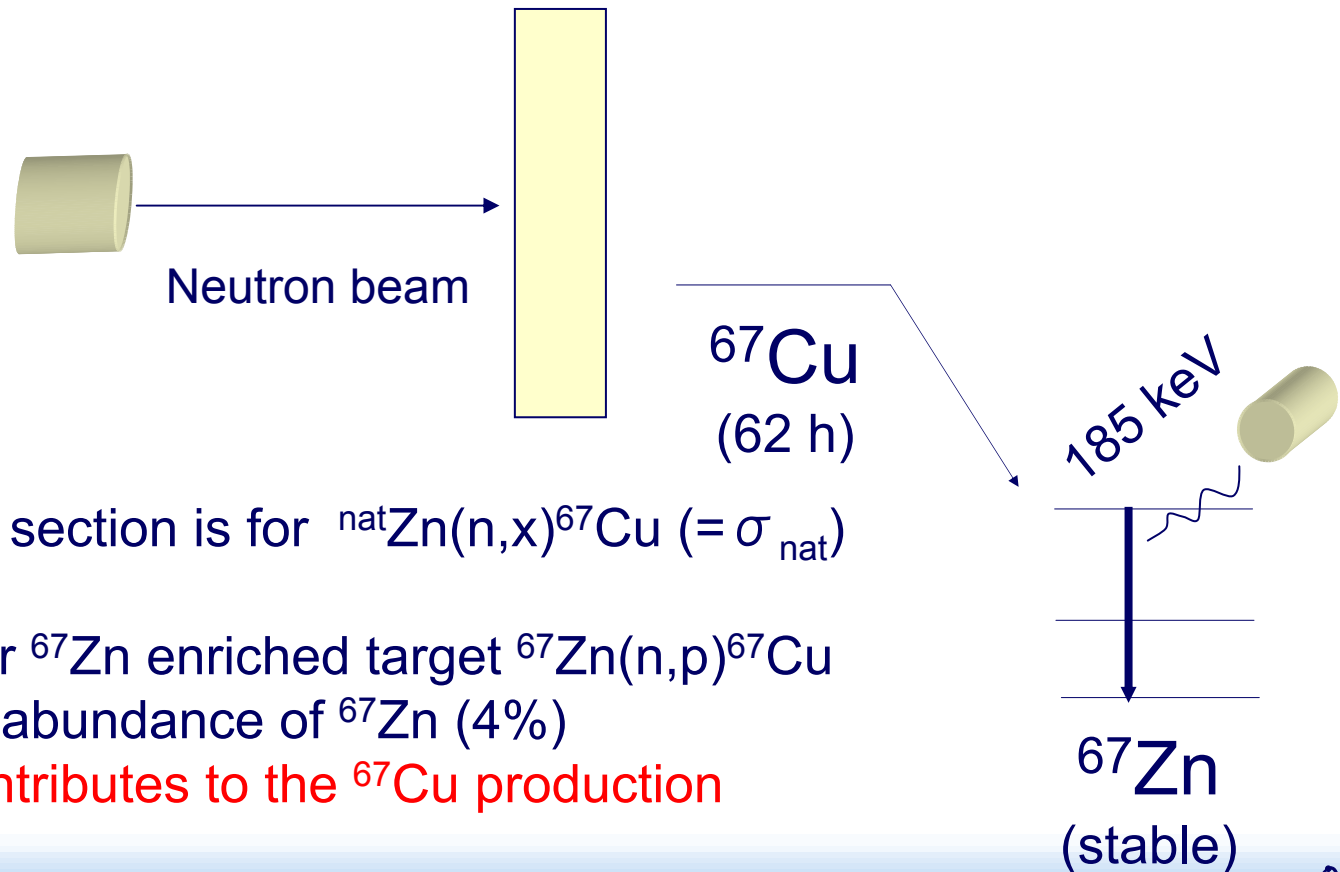
Activation
method was
used.

185 keV γ -ray
($I_{\gamma}=47\%$) used.

Experimental Condition in BIB Section (cont)

Natural Zinc

(^{64}Zn : 49%, ^{66}Zn : 28%,
 ^{67}Zn : 4%, ^{68}Zn : 19%)



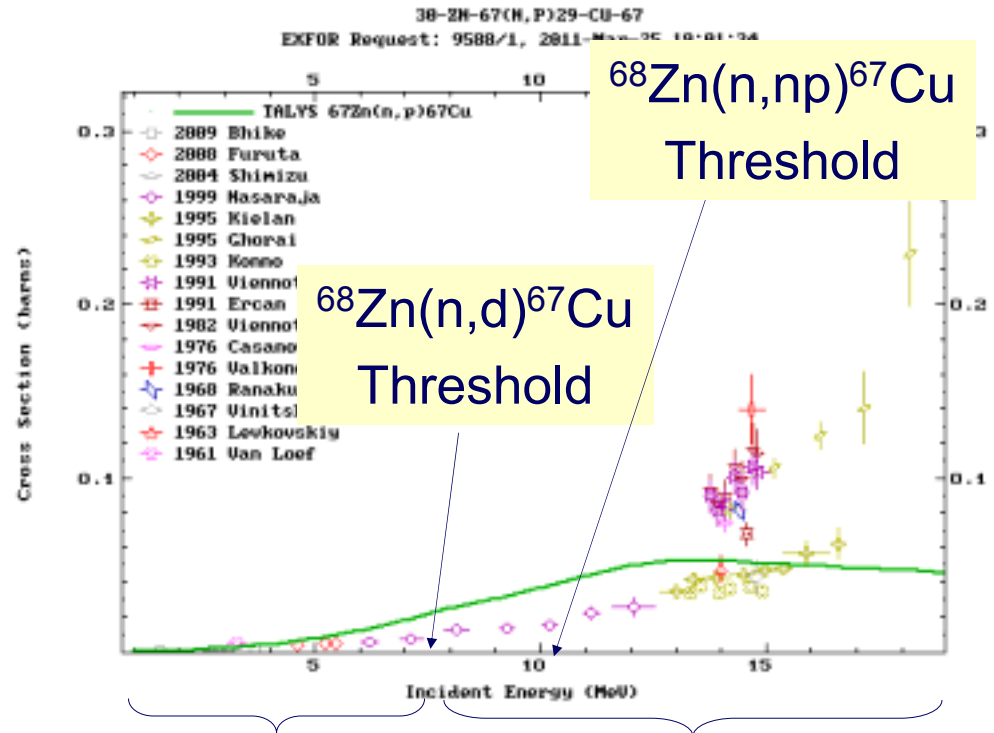
Measured cross section is for $^{\text{nat}}\text{Zn}(n,x)^{67}\text{Cu}$ ($= \sigma_{\text{nat}}$)

→
Cross section for ^{67}Zn enriched target $^{67}\text{Zn}(n,p)^{67}\text{Cu}$
 $= \sigma_{\text{nat}} / \text{Isotopic abundance of } ^{67}\text{Zn} (4\%)$
if only ^{67}Zn contributes to the ^{67}Cu production

Exercise: $^{67}\text{Zn}(n,p)^{67}\text{Cu}$ (cont)

Q-value is easily calculated by
 QCalc: <http://www.nndc.bnl.gov/qcalc/>

^{67}Cu production reaction	Threshold energy (MeV)
$^{67}\text{Zn}(n,p)$	0
$^{68}\text{Zn}(n,d)$	7.868
$^{68}\text{Zn}(n,np)$	10.125

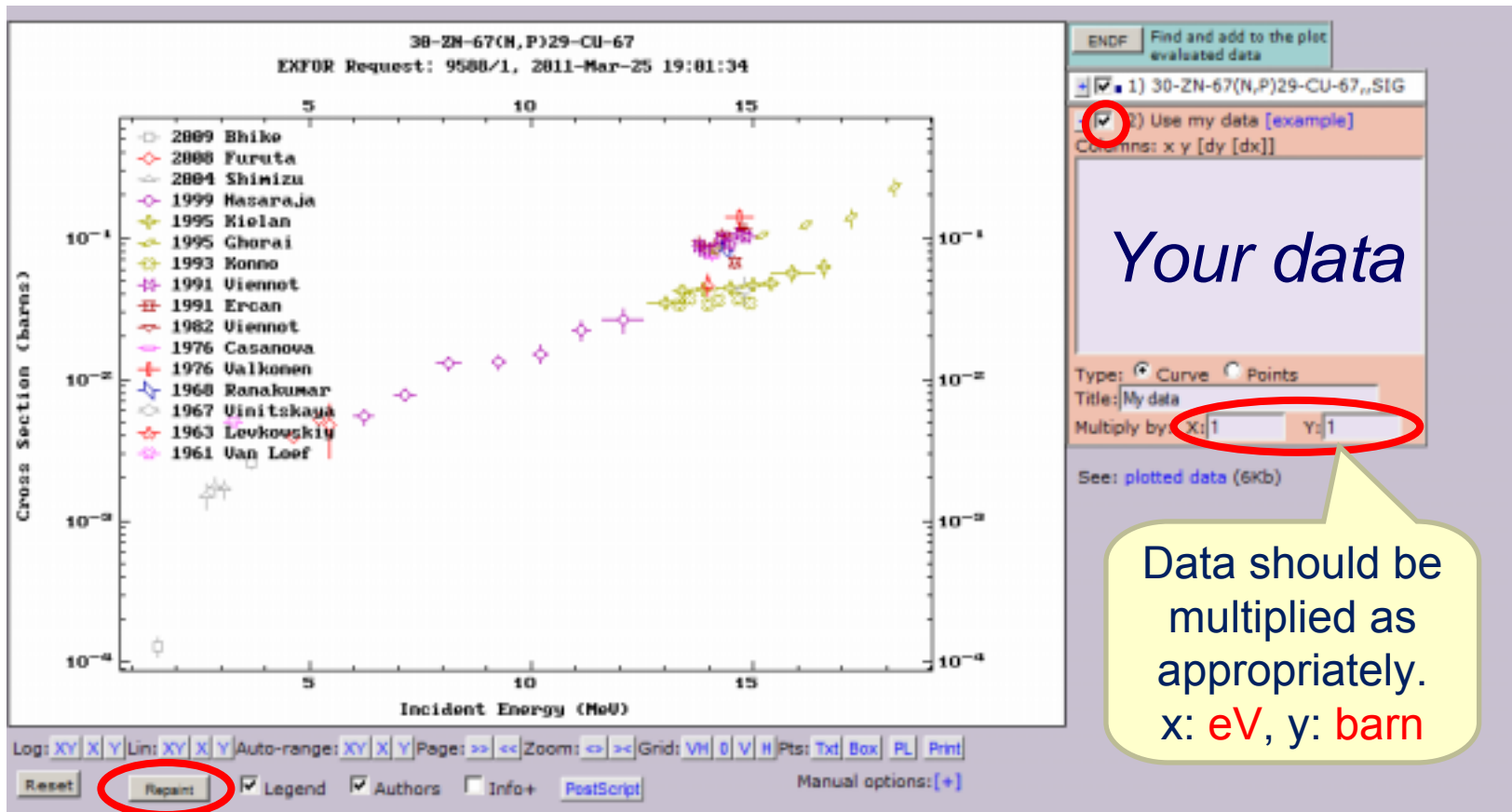


Only ^{67}Zn contributes to ^{67}Cu production

Both ^{67}Zn and ^{68}Zn contributes to ^{67}Cu production

EXFOR Cross Section Plot

Exercise: $^{67}\text{Zn}(n,p)^{67}\text{Cu}$ (cont)



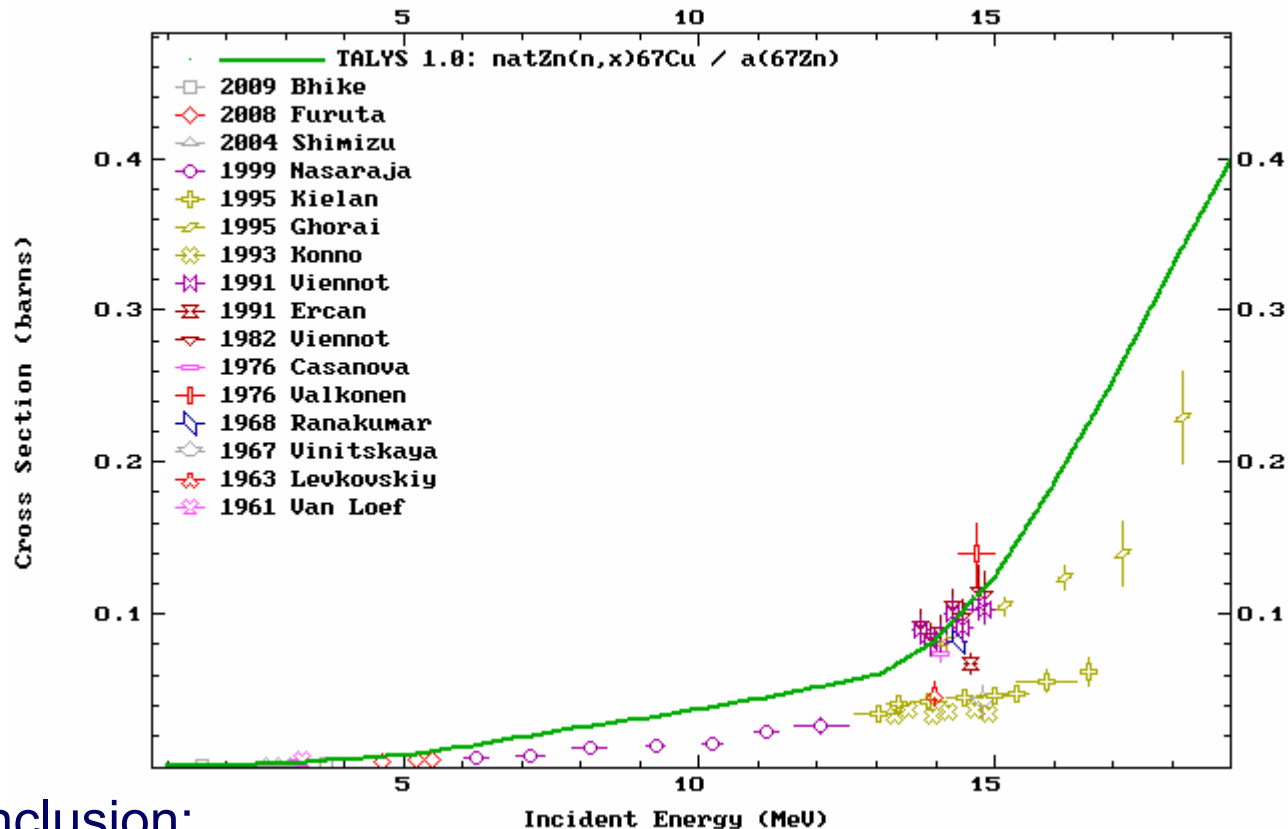
Exercise: Plot $^{nat}\text{Zn}(n,p)^{67}\text{Cu}/a(^{67}\text{Cu})$ TALYS data (Material #2) with EXFOR data. (TALYS data available on http://www-nds.iaea.org/nrdc/wsin_2011/)

EXFOR Cross Section Plot

Exercise: $^{67}\text{Zn}(n,p)^{67}\text{Cu}$ (cont)

30-ZN-67(N,P)29-CU-67

EXFOR Request: 9593/1, 2011-Mar-25 22:52:21



Conclusion:

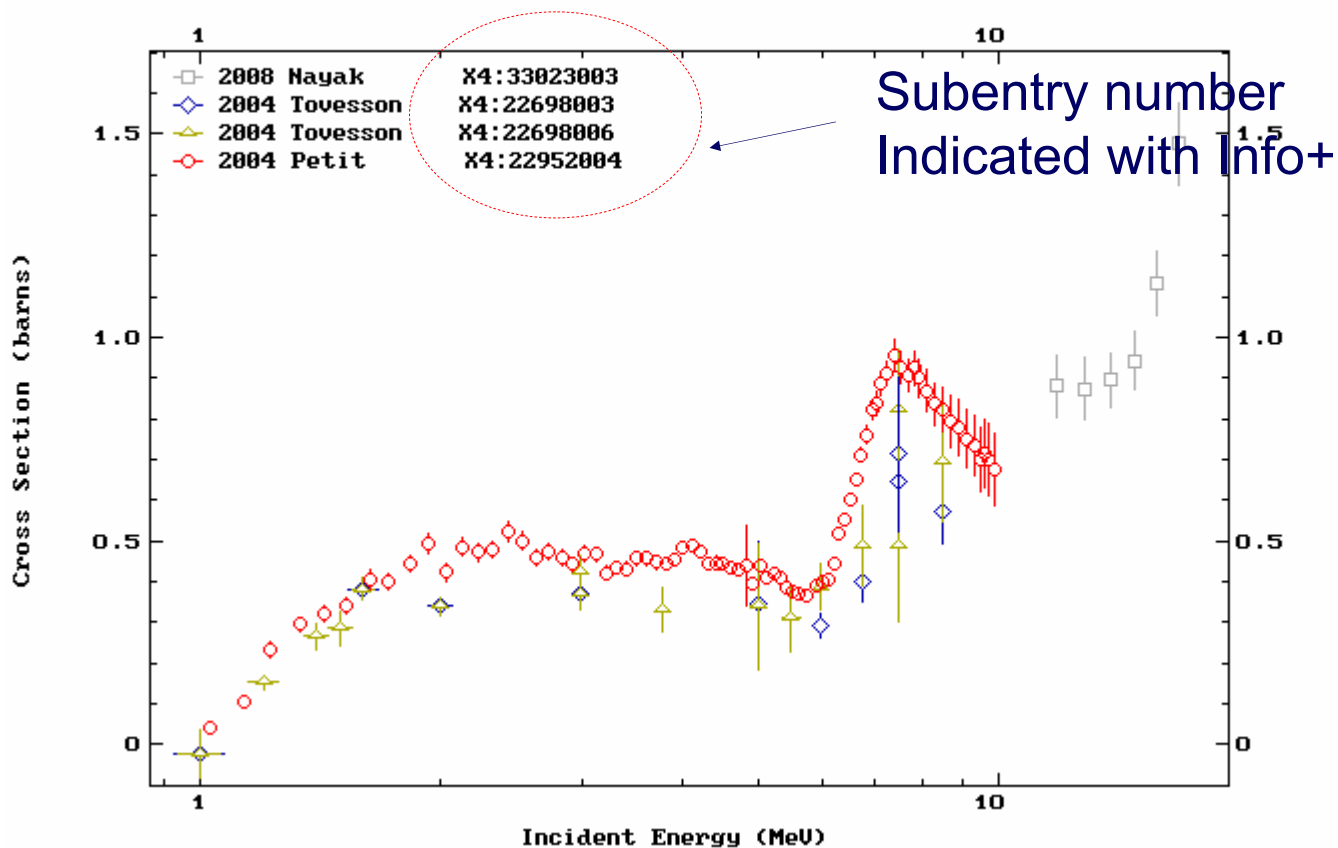
BIB information (SAMPLE, METHOD etc.) carefully extracted from articles by good compilers helps us to interpret data measured by authors.

EXFOR Cross Section Plot

Exercise: $^{233}\text{Pa}(n,f)$

91-PA-233(N,F)

EXFOR Request: 9571/1, 2011-Mar-25 15:24:54

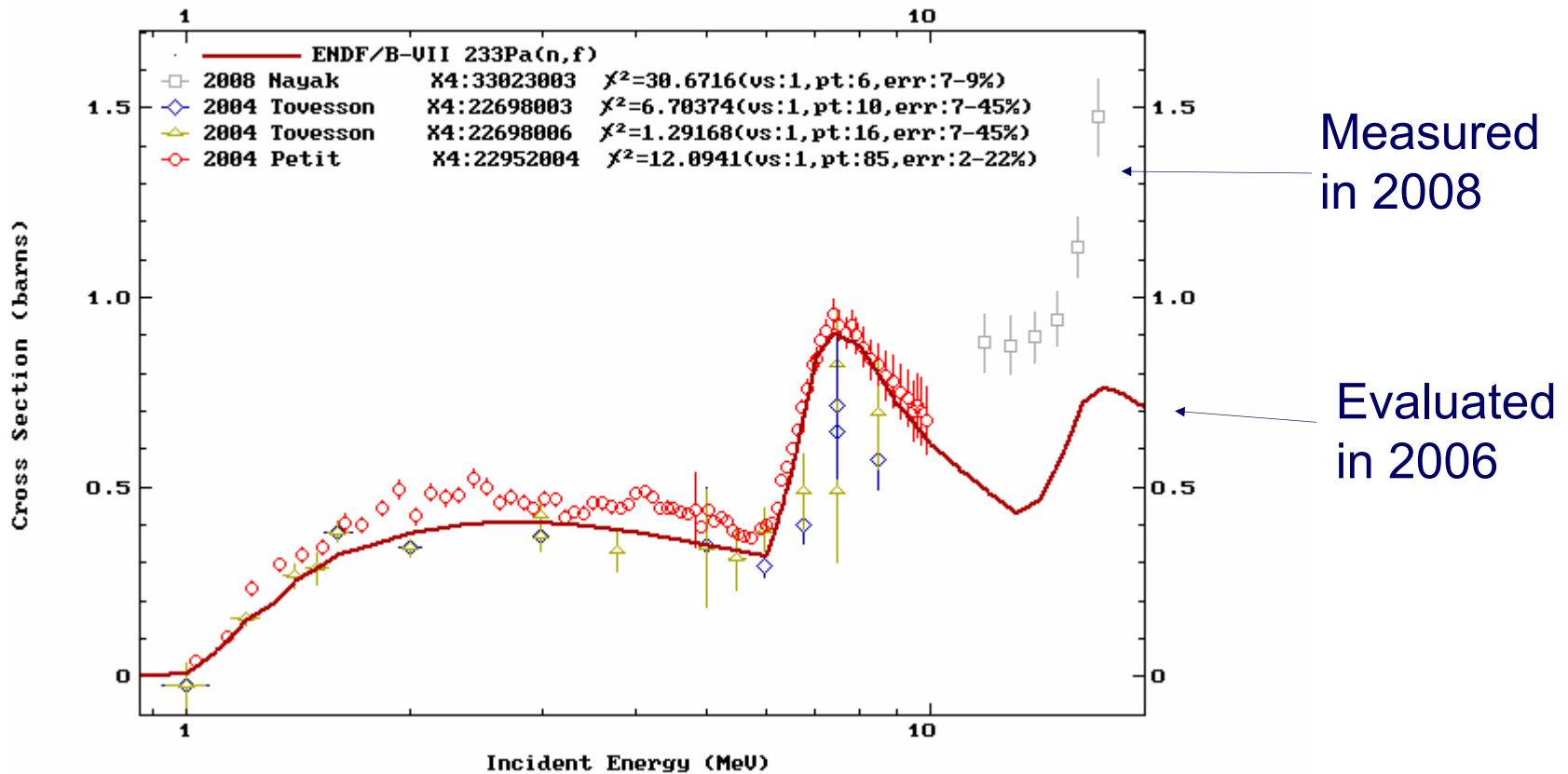


Exercise: Plot EXFOR data (Nayak, Tovesson, Petit) with ENDF/B-VII data (Material #3). ENDF/B-VII data available on http://www-nds.iaea.org/nrdc/wsin_2011/.

EXFOR Cross Section Plot

Exercise: $^{233}\text{Pa}(n,f)$ (cont)

91-PA-233(N,F)
EXFOR Request: 9612/1, 2011-Mar-26 06:49:13



Exercise: ^{233}Pa target is unstable (~27 days)

What reaction Nayak and Petit measured to derive $^{233}\text{Pa}(n,f)$? Check BIB section.

Exercise: $^{233}\text{Pa}(n,f)$ (cont)

Excitation of compound (^{234}Pa) by different reactions (surrogate reaction method)

Nayak 2008 (33023.001)

```
SUBENT      33023001   20110104
BIB          14         66
TITLE       Determination of the  $^{233}\text{Pa}(n, f)$  reaction cross
            section from 11.5 to 16.5 MeV neutron energy by the
            hybrid surrogate ratio approach
...
ANALYSIS    (SURGT) The  $^{234}\text{Pa}$  and  $^{236}\text{U}$  compound systems have
            been populated at overlapping excitation energies in
            the same experiment through  $^{232}\text{Th}(^6\text{Li},A)$   $^{234}\text{Pa}$  and
             $^{232}\text{Th}(^6\text{Li},D)$   $^{236}\text{U}$  transfer channels at  $E(\text{lab}) = 38$ 
            MeV, and the absolute surrogate method is used to
            determine fission decay probabilities of the above
            compound nuclei by dividing the number of PLF-fission
            coincidences by the associated PLF-singles data. The
            experimental values of fission decay probability
            ratios of  $^{234}\text{Pa}$  and  $^{236}\text{U}$  compound nuclei at the same
            excitation energies have been used to deduce the  $^{233}\text{Pa}$ 
            ( $n,f$ ) cross-section using a surrogate ratio approach.
```

Measured: $^{232}\text{Th}(^6\text{Li}, \alpha)^{234}\text{Pa} \rightarrow \text{fission}$

Conclusion:

BIB should gives essential information *shortly and precisely!!*
 (Edit free text after “copy and paste”)

Petit 2004 (22952.004)

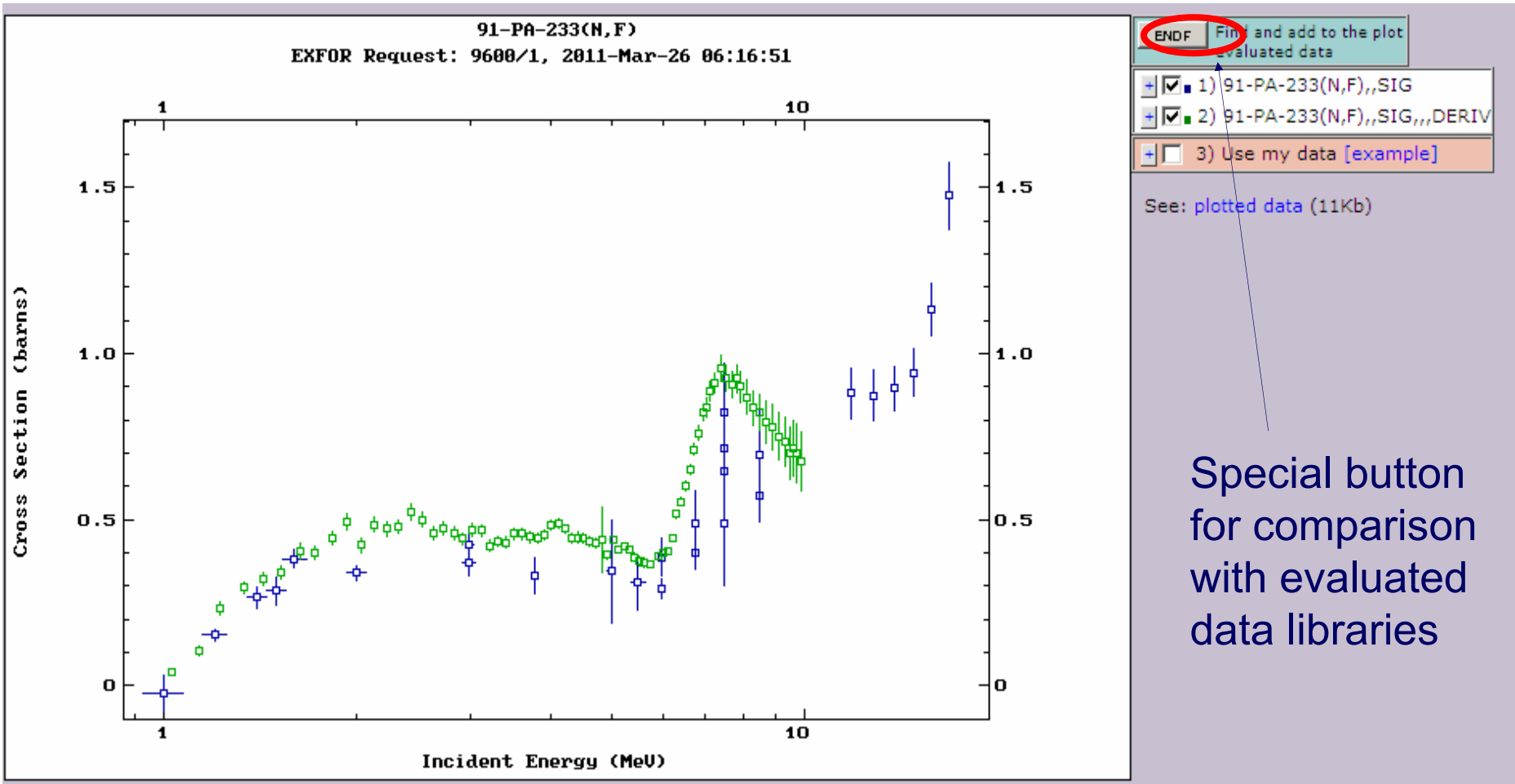
```
SUBENT      22952004   20070117
BIB          4         10
REACTION    (91-PA-233(N,F),,SIG,,,DERIV)
            Fission c-s deduced via the product of measured
            fission probability distribution of Pa-234 using
            the transfer reaction Th-232(He-3,p)Pa-234exc
STATUS      (CURVE) Digitized data of Fig. 13 ,Main Reference.
ERR-ANALYS (EN-ERR-DIG) Error of EN Digitizing
            (ERR-DIG) Error of DATA Digitizing
COMMENT     Of compiler. Several data points in Fig.13 has
            no error bars and these lines has no DATA-ERR in
DATA        section.
ENDBIB      10
```

Measured: $^{232}\text{Th}(^3\text{He},p)^{234}\text{Pa} \rightarrow \text{fission}$



EXFOR Cross Section Plot

Comparison with Evaluated Data Libraries



Comparison with Evaluated Data Libraries (cont)

Request #4086
ENDF Data Selection (Plot for EXFOR Request #9610)
 Retrieve **Plot** Selected Unselected All Reset
 Plotting options: Quick plot (cross-sections only: σ)

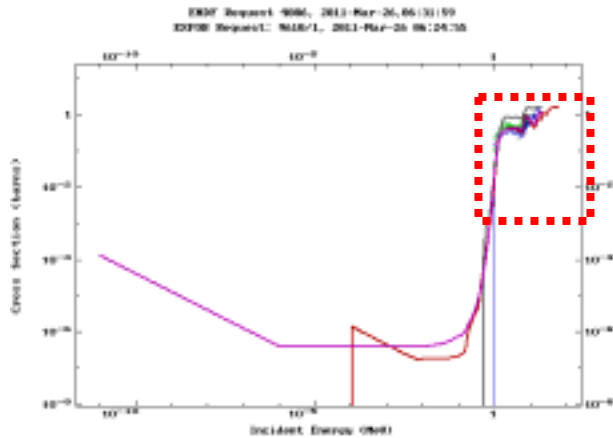
Sorted by: [Reactions] Reorder by: [Libraries] View: basic extended

	1)	PA-233(N,F),SIG	MT=18 MF=3 NSUB=10
		MF3 [SIG] Cross sections	MT18: [N,F] Total fission.
1	<input checked="" type="checkbox"/>	ENDF-6	Interpreted σ Plot
2	<input checked="" type="checkbox"/>	ENDF-6	Interpreted σ Plot
3	<input checked="" type="checkbox"/>	ENDF-6	Interpreted σ Plot
4	<input type="checkbox"/>	ENDF-6	Interpreted σ Plot
5	<input type="checkbox"/>	ENDF-6	Interpreted σ Plot

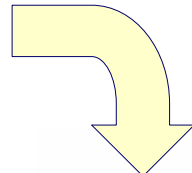
Evaluated data library selector appearing on another tab.

EXFOR Cross Section Plot

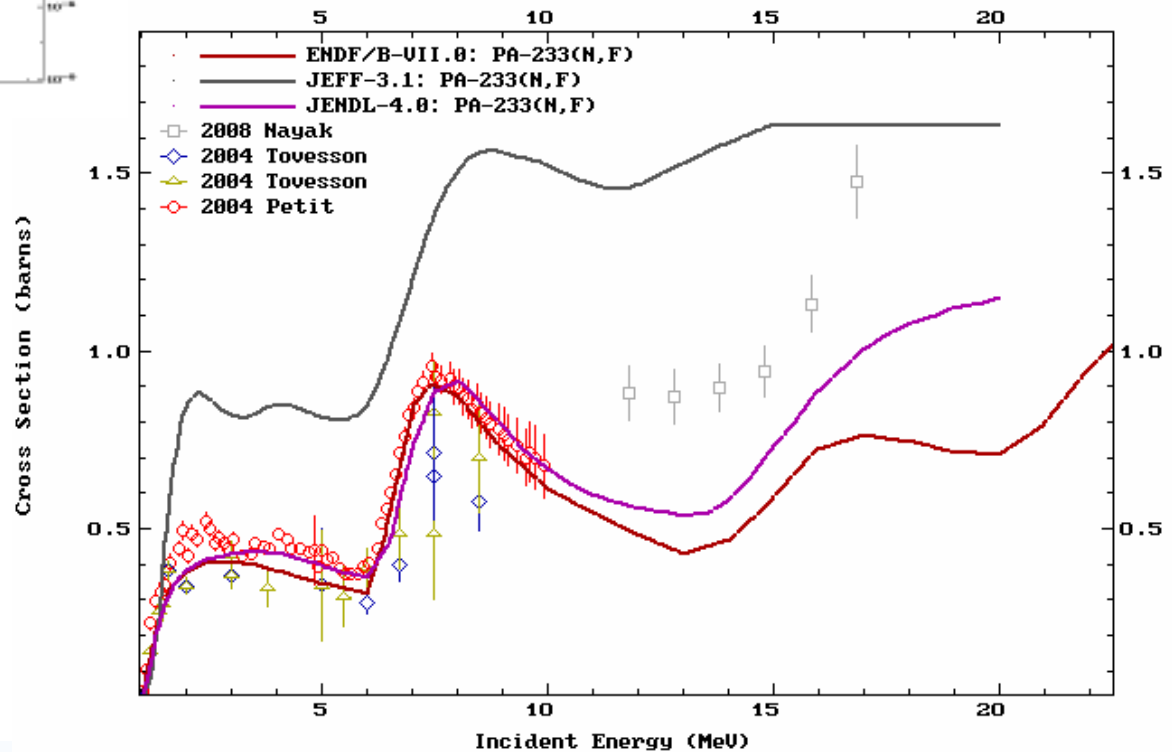
Comparison with Evaluated Data Libraries (cont)



Select area and use
(x,y)=(lin,lin) scale



ENDF Request 4086, 2011-Mar-26,06:31:59
EXFOR Request: 9610/1, 2011-Mar-26 06:24:55



ENDF-B/VII: 2006
JEFF-3.1: 2009
JENDL-4.0: 2010

Advanced plot (Diff. Cross Section etc.)

Data Selection

Review Selected Unselected All

Output: EXFOR EXFOR+ Bibliography TAB C4 Plot

Plot: Quick-plot (cross-sections only) **Advanced plot [how-to]**

Narrow Energy (optional), eV: Min: Max:

Advanced data modifications

n	Display	Year	Author-1
1	83-BI-209(5-B-11,EL)83-BI-209	2003	P.K.Sahu
2	1998 A.Shri...	1998	A.Shri...

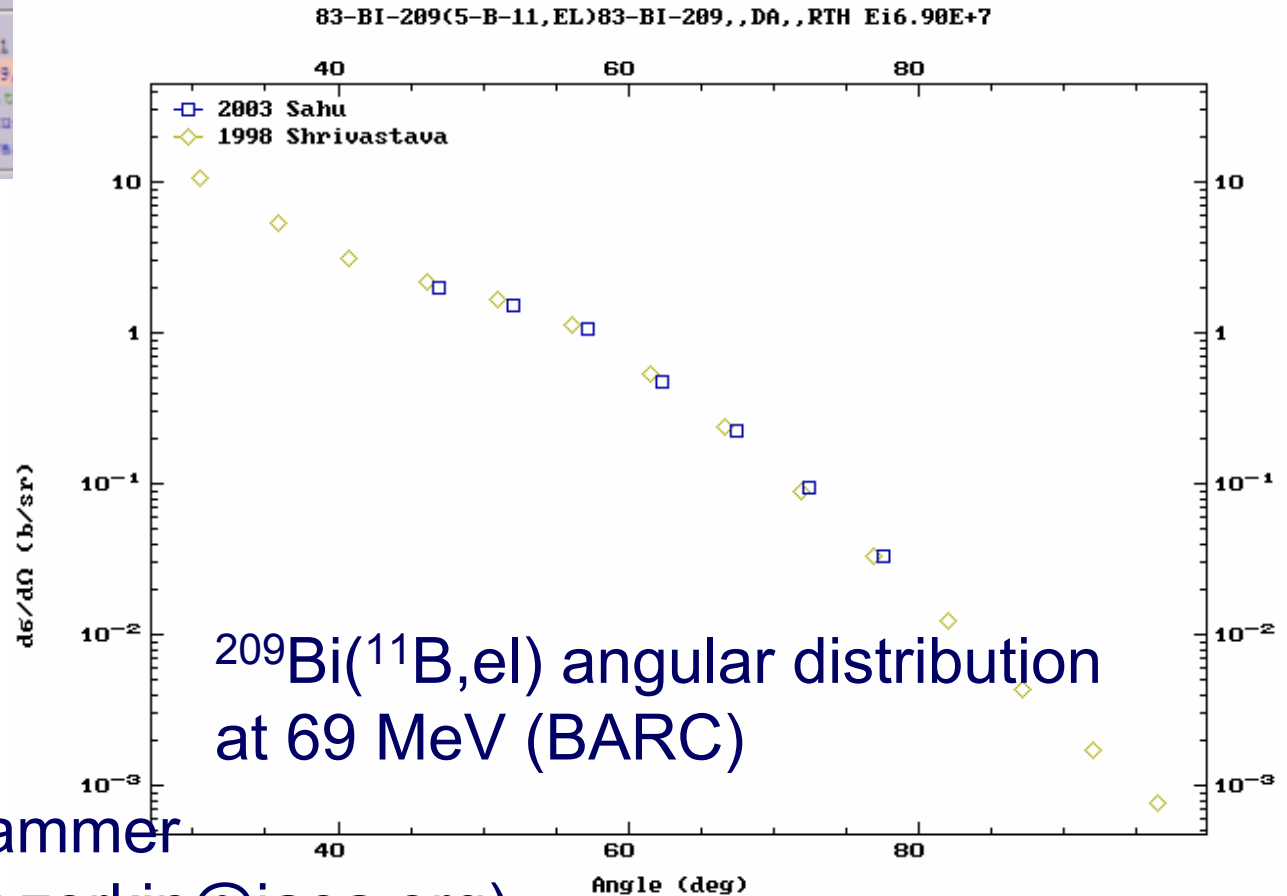
Quantity: [DA] Differential cs d/dA rel.t

1 Info X4 X4+ X4z T4

2 Info X4 X4+ X4z T4



Send your question to the NDS programmer
 Dr. V. Zerkin (v.zerkin@iaea.org)



EXFOR Compilation

What must be done by EXFOR compilers?

- Identification of articles for EXFOR
(Should be in EXFOR, but missing in EXFOR):
- Allocation of an EXFOR entry number to the article;
- Extraction of key information for BIB section
(bibliography, facility, detector, method);
- Define each data set by REACTION code;
- Preparation of numerical data (digitization if original data are not available);
- Checking by ZCHEX (checking code), proof-read by authors;
- Transmission to other data centres through IAEA-NDS



Extraction of Key Information for BIB section

- Description is given by code(s) and/or free text under an appropriate keyword.
- Keyword is given in 1st to 11th columns.
- Code(s) follow an open parenthesis at the 12th column.
- Free text is given between 12th to 66th column

Example

	11	22	33	44	55	66	Free text only
	-----+-----+-----+-----+-----+-----+						
TITLE	The 4th DAE-BRNS Theme Meeting on EXFOR Compilation of Nuclear Data						←
AUTHOR	(B.R.Behera, A.Kumar, A.Saxena)						←
INSTITUTE	(3INDPUC) Department of Physics						} ←
	(3INDTRM) Nuclear Physics Division						

coded information only (points to AUTHOR and INSTITUTE lines)

coded info.+free text (points to INSTITUTE line)

Major keywords (Bibliography)

Keyword	Contents
TITLE	Title of the experimental work
AUTHOR	Researchers contributes to the work
INSTITUTE	Institutes of authors
REFERENCE	Articles used for compilations

Example

	11	22	33	44	55	66
	-----+-----+-----+-----+-----+-----+					
TITLE	Radiative capture cross-sections of isotopes of Gd, Sm and V between 1 and 3 MeV					
AUTHOR	(M.Afzal Ansari, R.K.Yasikul Singh, M.L.Sehgal, V.K.Mittal, D.K.Avasthi, I.M.Govil)					
INSTITUTE	(3INDMUA, 3INDPUC)		<i>Aligarh Muslim Univ.+Punjab Univ.</i>			
REFERENCE	(J,ANE,11,173,1984)		<i>Ann.Nucl.Energy 11(1984)173</i>			



Major keywords (Experimental description)

Keyword	Contents
FACILITY	Experimental facility (reactor, accelerator etc.)
INC-SOURCE	Source of beam (for neutron and photon beam)
INC-SPECT	Spectrum of beam (for neutron and photon beam)

Example

11 22 33 44 55 66
 -----+-----+-----+-----+-----+-----+
 FACILITY (CYCLO, 3INDPUC) *Cyclotron at Punjab University*
 INC-SOURCE (P-T) *³H(p,n)³He neutron source*



Major keywords (Parameters)

Keyword	Contents
MONITOR	Standard reaction for normalization
DECAY-DATA	Decay property of reaction product
DECAY-MON	Decay property of standard reaction product
LEVEL-PROP	Level of reaction product (spin, parity)

Example

	11	22	33	44	55	66
	-----+					-----+
MONITOR	(53-I-127(N,G)53-I-128,,SIG)					<i>$^{127}\text{I}(n, \gamma)^{128}\text{I}$ used as reference reaction</i>
DECAY-DATA	(64-GD-161,3.7MIN,DG,315.,0.229)					<i>315 keV decay gamma (I_{γ}=22.9%) from ^{161}Gd measured</i>
DECAY-MON	(53-I-128,24.9MIN,DG,443.,0.160)					<i>443 keV decay gamma (I_{γ}=16.0%) from ^{128}I measured</i>



Major keywords (Data Specification)

Keyword	Contents
REACTION	Reaction and quantity in the DATA section

Example

11 22 33 44 55 66
 -----+-----+-----+-----+-----+-----+
REACTION (64-GD-160(N,G)64-GD-161,,SIG) *¹⁶⁰Gd(n, γ)¹⁶¹Gd cross section is given*



Major keywords (Correction and Error)

Keyword	Contents
CORRECTION	Correction applied to the raw data
ERR-ANALYS	Specification of uncertainties (e.g. statistical)
COVARIANCE	Covariance or correlation information

Example

```

      11          22          33          44          55          66
-----+-----+-----+-----+-----+-----+
CORRECTION Corrected for self-absorption of neutrons in the sample
ERR-ANALYS (ERR-T) Total uncertainty
            (ERR-S) Statistical uncertainty
            (ERR-1) Uncertainty in sample mass
COVARIANCE Uncertainty in sample mass is fully correlated

```



Major keywords (Bookkeeping)

Keyword	Contents
STATUS	Status of data (source, approval, cross reference)
HISTORY	History of the EXFOR entry

Example

```

      11          22          33          44          55          66
-----+-----+-----+-----+-----+
STATUS      (TABLE) Table 2 of Ann. Nucl. Energy 11(1984)173
            (APRVD) Approved by S.Ganesan (2010-03-30)
HISTORY     (20100321C) Compiled by Paresh M. Prajapati
            (20110411A) Corrected by Megha Bhike
  
```



COMMON and DATA Section

- Constants of the data table → COMMON section
- Variables of data table → Data section
- 11 columns are used for each data field

Example (of data section)

11	22	33	44	55	66	
EN	EN-RSL	DATA	ERR-T	MONIT	MONIT-ERR	<i>Heading</i>
MEV	MEV	MB	MB	MB	MB	<i>Unit</i>
1.07	0.20	25.4	3.0	78.	6.	<i>Value</i>
1.48	0.18	19.7	1.8	69.	5.	
1.89	0.17	18.7	1.9	62.	4.	

...



First Exercise of EXFOR Compilation

M. Afzal Ansari *et al.*, Ann. Nucl. Energy 11(1984)173
(give good description for nuclear data)

Ann. nucl. Energy, Vol. 11, No. 4, pp. 173-176, 1984
Printed in Great Britain. All rights reserved

0306-4549/84 \$3.00 + 0.00
Copyright © 1984 Pergamon Press Ltd

RADIATIVE CAPTURE CROSS-SECTIONS OF ISOTOPES OF Gd, Sm AND V BETWEEN 1 AND 3 MeV

M. AFZAL ANSARI, R. K. YASKUL SINGH and M. L. SEHGAL
Department of Physics, Aligarh Muslim University, Aligarh 202 001, India
V. K. MITTAL, D. K. AVASTHI and I. M. GOVIL
Department of Physics, Punjab University, Chandigarh 160 014, India

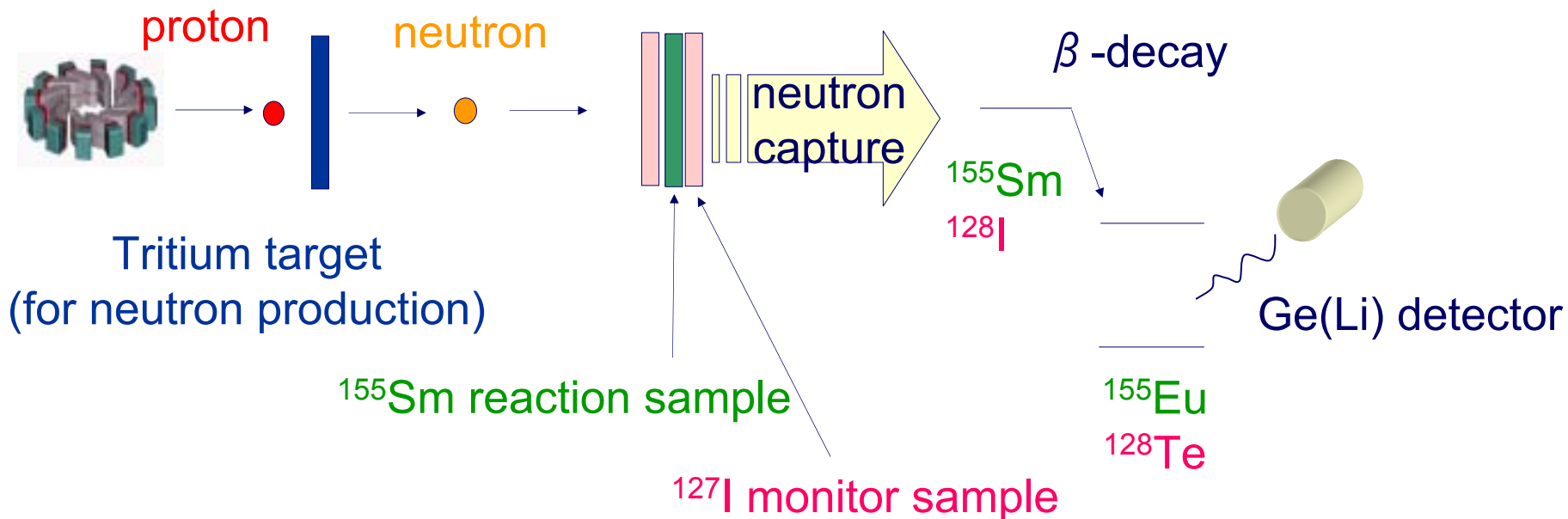
Keyword:

TITLE, AUTHOR, INSTITUTE, REFERENCE

Experimental situation under BIB

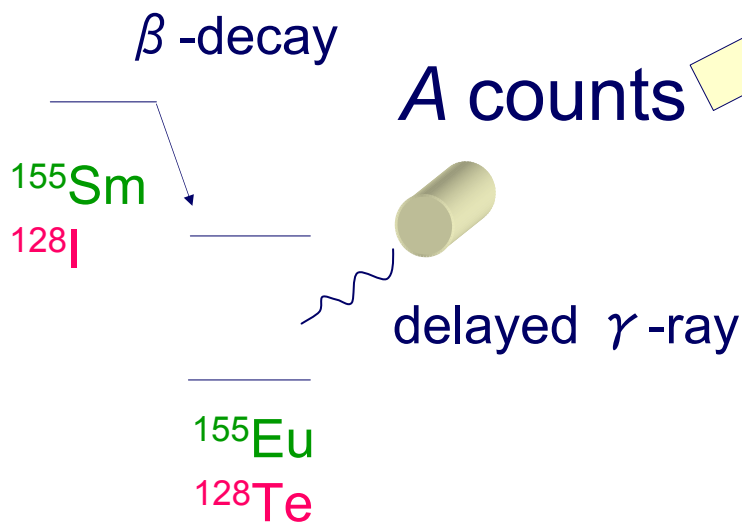
Keyword:

FACILITY, INC-SOURCE, SAMPLE, MONITOR, DETECTOR



Experimental situation under BIB (cont)

Keyword:
METHOD



Activation formula
(θ , λ : Decay data)

$$\sigma_{(n,\gamma)} = \frac{A\lambda \exp(\lambda t_2)}{N_0(\phi G)_{\text{av.}} \varepsilon \theta K [1 - \exp(-\lambda t_1)][1 - \exp(-\lambda t_3)]} \quad (1)$$

where A is the total counts under the photopeak of the characteristic γ -ray, λ is the decay constant of the product nucleus, N_0 is the number of nuclei of the isotope under investigation, ε is the effective photopeak detection efficiency of the Ge(Li) detector, $(\phi G)_{\text{av.}}$ is the average neutron flux, θ is the absolute intensity of the characteristic γ -ray, K is the self-absorption correction factor for the γ -ray in the sample, t_1 is the irradiation time, t_2 is the time elapsed between the end of the irradiation and the start of counting and t_3 is the counting time. The ranges of t_1 , t_2 and t_3 are 1000–2000, 20–2000 and 200–2000 s, respectively.

Experimental situation under BIB (cont)

$$\sigma_{(n,\gamma)} =$$

$$\frac{A\lambda \exp(\lambda t_2)}{N_0(\phi G)_{av} \varepsilon \theta K [1 - \exp(-\lambda t_1)][1 - \exp(-\lambda t_3)]}$$

Keyword:

DECAY-DATA, DECAY-MON

Decay data (λ or $T_{1/2}$, θ) used for derivation of cross sections must be kept (Table 1 of the article). Note that cross section values are proportional to the inverse of gamma intensity θ .

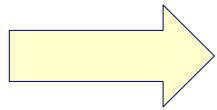
$$\sigma_{(n,\gamma)} = \frac{A_{(n,\gamma)}}{A_{\text{monit}}} (\lambda_{(n,\gamma)}, \theta_{(n,\gamma)}, \lambda_{\text{monit}}, \theta_{\text{monit}}, N_{(n,\gamma)}, N_{\text{monit}}, \varepsilon_{(n,\gamma)}, \varepsilon_{\text{monit}}, t_1, t_2, t_3) \sigma_{\text{monit}}$$

ratio of counts \uparrow Decay data \uparrow Sample atom numbers \uparrow Detection efficiency \uparrow Irradiation condition \uparrow

Experimental situation under BIB (cont)

Keyword:
ERR-ANALYS

$$\sigma_{(n,\gamma)} = \frac{A_{(n,\gamma)}}{A_{\text{monit}}} (\lambda_{(n,\gamma)}, \theta_{(n,\gamma)}, \lambda_{\text{monit}}, \theta_{\text{monit}}, N_{(n,\gamma)}, N_{\text{monit}}, \varepsilon_{(n,\gamma)}, \varepsilon_{\text{monit}}, t_1, t_2, t_3) \sigma_{\text{monit}}$$



Partial uncertainties propagated to total uncertainties must be preserved.

$$(\Delta\sigma_{(n,\gamma)})^2 = \left(\frac{\partial\sigma_{(n,\gamma)}}{\partial A_{(n,\gamma)}} \Delta A_{(n,\gamma)} \right)^2 + \left(\frac{\partial\sigma_{(n,\gamma)}}{\partial A_{\text{monit}}} \Delta A_{\text{monit}} \right)^2 + \dots + \left(\frac{\partial\sigma_{(n,\gamma)}}{\partial \sigma_{\text{monit}}} \Delta\sigma_{\text{monit}} \right)^2$$

$$\left(\frac{\Delta\sigma_{(n,\gamma)}}{\sigma_{(n,\gamma)}} \right)^2 = \left(\frac{\Delta A_{(n,\gamma)}}{A_{(n,\gamma)}} \right)^2 + \left(\frac{\Delta A_{\text{monit}}}{A_{\text{monit}}} \right)^2 + \dots + \left(\frac{\Delta\sigma_{\text{monit}}}{\sigma_{\text{monit}}} \right)^2$$

Summary of BIB compilation

- Information on experimental condition and data reduction.
- Users should be able to follow **the logic of data reduction** from BIB section.
- **Key parameters and partial uncertainties** must be given. They are useful for future evaluation.
(But these are not always available...)

Preparation of EXFOR Entry from “Skeleton”

- Copy “skeleton” of Entry 34567 (Material #4a) from http://www-nds.iaea.org/nrdc/wsin_2011/
- Replace \$.... by real information by **EXFOR Editor**.
 - *\$text*: replace by free text
 - *\$author*: replace by an author name
 - *\$DICT3*: replace by a dictionary 3 code
(Dictionary is also available on the web page. Material #4b)
 - *\$i*: replace by an integer
 - *\$r*: replace by a real number
 - *\$nucl*: replace by a nuclear symbol (e.g. 8-O-16)
- See “EXFOR Formats Manual” Chapter ? for coding rule.



Utilities for EXFOR Compilation

Today

- *ZORDER* (IAEA NDS)
 - addition of line numbers etc. (compulsory)
- *ZCHEX* (IAEA NDS)
 - checking of EXFOR entries (compulsory)



Tomorrow

- *ExforEdit* (CNPD)
 - assistance of EXFOR formatting (optional)
- *InpGraph* (CNPD)
 - digitization of data from images (optional)
- *GSYS* (JCPRG)
 - digitization of data from images (optional)
- *JANIS Trans-Checker* (NEA Data Bank)
 - Checking of EXFOR entries (optional)

ZORDER


- Originally developed by V. McLane (NNDC)
- Now maintained by V. Zerkin (IAEA NDS)
- What does ZORDER do for us?
 - ▶ Addition of line sequential number (col.67-80)
 - ▶ Addition of “N1” and “N2” parameters
- Only entries checked by ZORDER are accepted by NDS.

Utilities for EXFOR Compilation

What are Modified by ZORDER?

```
ENTRY          34567   20110404
SUBENT         34567001 20110404
BIB
TITLE          Radiative capture cross-sections of isotopes of Gd, Sm,
                and V between 1 and 3 MeV
AUTHOR         (M.Afzal Ansari, R.K.Yaiskul Singh, M.L.Sehgal,
                V.K.Mital, D.K.Avasthi, I.M.Govil)
INSTITUTE      (3INDMUA,3INDPUC)
REFERENCE      (J,ANE,11,173,1984)
FACILITY       (CYCLO,3INDPUC)
INC-SOURCE     (P-T)
DETECTOR       (GELI)
METHOD         (ACTIV)
MONITOR        (53-I-127(N,G)53-I-128,,SIG)
DECAY-MON      (53-I-128,24.9MIN,DG,443.,0.160)
ERR-ANALYS    (ERR-T) Total uncertainty
                Uncertainties in decay data are not considered.
                (ERR-S,1.,10.) Counts under photopeak      (1-10%)
```

You do not need to
add these numbers
manually.
ZORDER will do it
for you!




```
ENTRY          34567   20110404   3456700000001
SUBENT         34567001 20110404   3456700100001
BIB            13                20   3456700100002
TITLE          Radiative capture cross-sections of isotopes of Gd, Sm, 3456700100003
                and V between 1 and 3 MeV 3456700100004
AUTHOR         (M.Afzal Ansari, R.K.Yaiskul Singh, M.L.Sehgal, 3456700100005
                V.K.Mital, D.K.Avasthi, I.M.Govil) 3456700100006
INSTITUTE      (3INDMUA,3INDPUC) 3456700100007
REFERENCE      (J,ANE,11,173,1984) 3456700100008
FACILITY       (CYCLO,3INDPUC) 3456700100009
INC-SOURCE     (P-T) 3456700100010
DETECTOR       (GELI) 3456700100011
METHOD         (ACTIV) 3456700100012
MONITOR        (53-I-127(N,G)53-I-128,,SIG) 3456700100013
DECAY-MON      (53-I-128,24.9MIN,DG,443.,0.160) 3456700100014
ERR-ANALYS    (ERR-T) Total uncertainty 3456700100015
                Uncertainties in decay data are not considered. 3456700100016
                (ERR-S,1.,10.) Counts under photopeak      (1-10%) 3456700100017
```



Utilities for EXFOR Compilation

ZCHEX

- Originally developed by V. McLane (NNDC)
- Now extended+maintained by V. Zerkin (IAEA NDS)
(e.g., porting from VMS to Windows, Linux, Mac)
- Checking items:
 - ✓ Format checking (e.g., position of column)
 - ✓ Code checking (e.g., existence of the code in dictionary)
 - ✓ Dimension checking (e.g., b, mb etc. for cross section)
 - ✓ Enough and necessary set of independent variables
(e.g., angle and incident energy for angular distribution)
 - ✓ Charge and mass conservation in REACTION
etc.
- Only entries checked by ZCHEX are accepted by NDS. 

What are Checked by ZCHEX?

```

ENTRY          01061    20051028
SUBENT         01061001  20051028
BIB            12        25
TITLE          Inelastic scattering of 28.0 MeV protons on Fe-56.
AUTHOR         (A.Kumar, D.K.Avasthi, A.Tripathi, S.K.Datta,
                I.M.Govil)
INSTITUTE      (3INDPUC) ←
                (3INDNSD) Nuclear Science Centre
    
```

Defined in dictionary?

```

...
ENDBIB         25
COMMON         1        3
    
```

EN
MEV

Matching of heading and (unit dimension)

```

ENDCOMMON     3
ENDSUBENT     32
SUBENT         01061002  20040321
BIB            2        3
REACTION      (26-FE-56(P,EL)26-FE-56(,DA,,RTH)
    
```

Rutherford ratio

- Incident energy and angle required
- Dimension: no-dimension

```

...
DATA          2        15
ANG-CM        DATA
ADEG          NO-DIM
                28.28    0.225
                33.16    0.1268
    
```

Utilities for EXFOR Compilation

Example of ZCHEX Output

ZCHEX (Version 2011-01-07) run on 30-Mar-2011

Input file: ../../exfor/tool/trans-65a.txt

File labeled: TRANS 20110330

ENTRY 03018

First pass completed with no fatal errors

1

- Second pass checking -

ENTRY 03018

** <u>Illegal code field</u>		03018001
DETECTOR (HPGF) Hyperpure Ge detector		0301800100013
^^^^		
** <u>Illegal code in</u>	field 4	
REACTION (80-HG-196(N,2N)79-HG-195,,SIG)		0301800200003
	^^^^^^^^^^	
** <u>Missing independent variable</u>	NUCLIDE	03018002

Tape statistics

# of records----->	43
# of entries----->	1
# of subentries----->	2
# of new data subentries->	1

Utilities for EXFOR Compilation After Checking by ZCHEX ...

- Send your EXFOR entry to authors for approval (with questions to authors if any).
- If it is approved by authors, indicate it by the following coded information under STATUS:

Example

```

11          22          33          44          55          66
-----+-----+-----+-----+-----+
STATUS      (TABLE) Table 2 of Ann. Nucl. Energy 11(1984)173
            (APRVD) Approved by S.Ganesan (2010-04-04)
```

ZORDER/ZCHEX Exercise (1)

- Copy “bad entry” (Entry 01234 Material #5) from http://www-nds.iaea.org/nrdc/wsin_2011/
- Process this entry by ZORDER+ZCHEX (upload the entry to <http://www.jcprg.org/exfor/tool/>)
- Correct your Entry 01234 and repeat ZORDER+ZCHEX so that all error messages are disappeared.
(You may find one additional wrong coded information which is *not* detected by ZCHEX.)

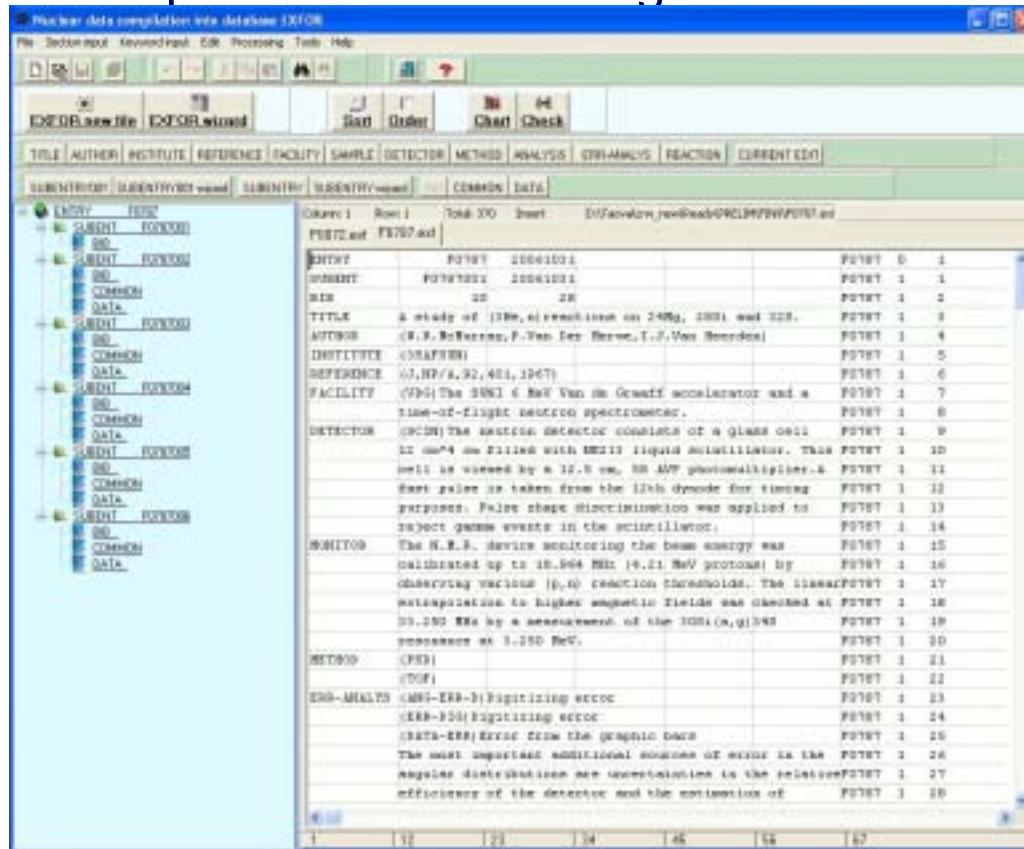
ZORDER/ZCHEX Exercise (2)

- Process your entry 34567 by ZORDER+ZCHEX
(upload the entry to <http://www.jcprg.org/exfor/tool/>)
- Correct your entry 34567 and repeat ZORDER+ZCHEX so that all error messages are disappeared.

More Utilities

ExforEdit (to edit ascii files in the EXFOR Formats on Windows)

Download it from http://www-nds.iaea.org/nrdc/nrdc_sft/



See details in the lecture by Dr. Svetlana Dunaeva (tomorrow)

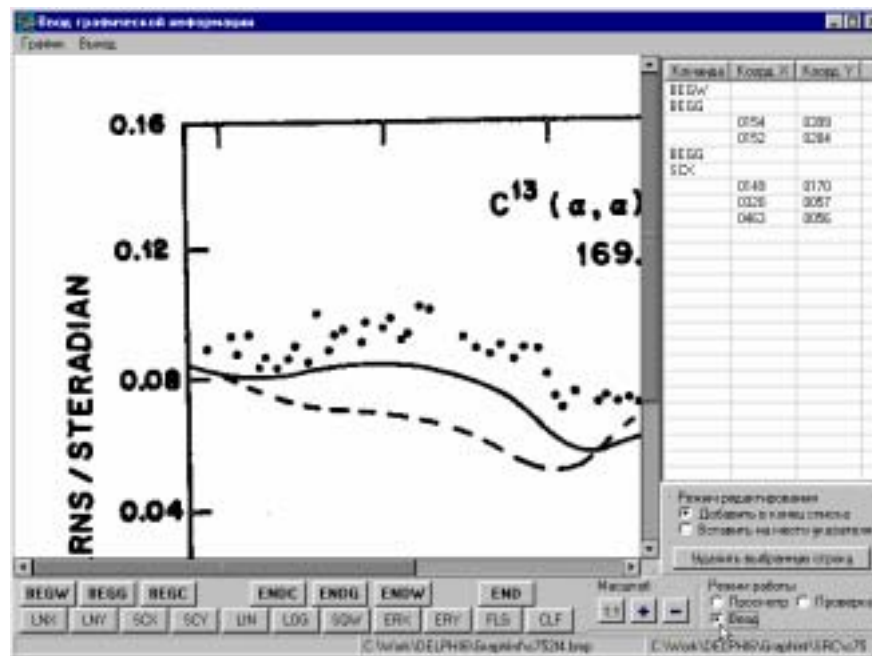


Utilities for EXFOR Compilation

More Utilities (cont)

InpGraph (to digitize numerical data from images on Windows)

Download it from http://www-nds.iaea.org/nrdc/nrdc_sft/

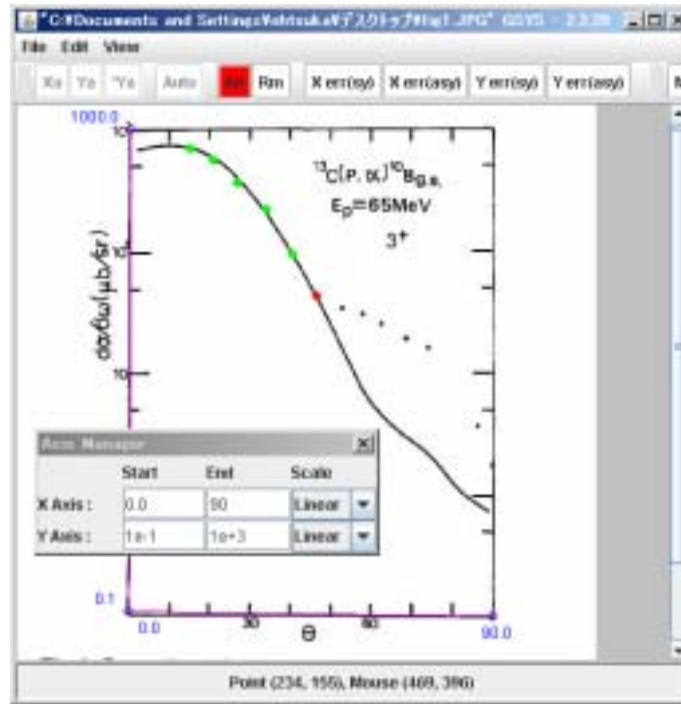


See details in the lecture by Dr. Svetlana Dunaeva (tomorrow)

Utilities for EXFOR Compilation

More Utilities (cont)

GSYS (to digitize numerical data from images on Windows, Linux, Mac)
Download it from http://www-nds.iaea.org/nrdc/nrdc_sft/



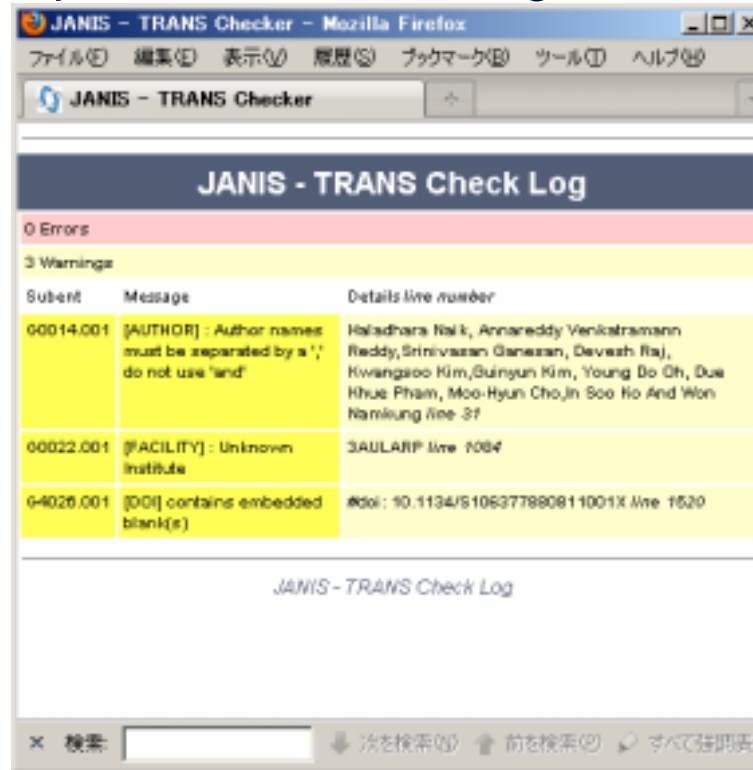
See details in my presentation (tomorrow)

Utilities for EXFOR Compilation

More Utilities (cont)

Janis TRANS Checker (to check EXFOR files on Windows, Linux, Mac)

Download it from http://www-nds.iaea.org/nrdc/nrdc_sft/



Ask Dr. Emmeric Dupont (NEA Data Bank) for details.

Summary

- Evaluated data **verified by experimental data** are essential input parameters to solve nuclear system problems.
- EXFOR Library is a **collection of comprehensive (microscopic) nuclear reaction experimental data** maintained by Nuclear Reaction Data Centres.
- Each experimental work is compiled as an **EXFOR entry**.
- BIB section of EXFOR entry should explain **the flow from experimental set to compiled values** (incl. key parameters used in data reduction).
- **REACTION code** is the most important BIB code. It defines measured quantities compiled in each subentry.
- Compilation of **partial uncertainties** (and their correlation properties) propagated to the total uncertainty are desired by evaluators.