Computer Tools for Nuclear Physics

Introduction to EXFOR Nuclear Database

Krzysztof Piasecki

Introduction to EXFOR

- **EXFOR** (**EX**change **FOR**mat, **X4**) – is the large database on nuclear reactions, written in a specific format.

You can retrieve (and/or plot) data on e.g. :

σ (total cross section) for a given AA and nA reaction,
$d\sigma/d\Omega$ (angular differential cross section)
Yields and energies of Fission fragments
Gamma spectra, etc. within a given range of beam energies.

EXFOR is coordinated by **IAEA**, and maintained by the international network of Nuclear Reaction Data Centres (**NRDC**), nowadays: 13 institutes worldwide.

The service started in 1970. Since 1980 it was accessible via telnet, and since 1997 – on the web.

- **Manual**: interactive and in pdf.

- **Papers**: N. Otuka et al., "Towards a More Complete and Accurate Experimental Nuclear Reaction Data Library (EXFOR): Intl. Collaboration Between Nuclear Reaction Data Centres (NRDC)" Nucl. Data Sheets 120, 272 (2014) , [arXiv]

  V.V. Zerkin, B. Pritychenko, "The experimental nuclear reaction data (EXFOR): Extended computer database and Web retrieval system", Nuclear Instruments and Methods A 888, 31 (2018) , [arXiv]

- **Projectiles**: (regular compilation for $E_{Kin} < 1$ GeV. For $E_{Kin} > 1$ GeV only selected data available)

  - neutrons
  - charged particles (thoroughly up to A = 12)
  - heavy ions (A > 12) : selected data
  - photons

EXFOR: basic nomenclature

- A basic unit is called: **ENTRY** .
  It corresponds to one nuclear experiment, resulting in ≥ 1 literature source (paper, lab report, etc.)

- An ENTRY may carry 1 or more experimental result (or data table).
  It may collect results from more than 1 collision type.
  Therefore, entries are divided into **SUBENTRIES** , numbered in ascending order (1, 2, 3, ...)

  However, **subentry 1** is special. It always stores a human-readable meta info :

  title, author, reference, institute, sample, detector etc.

  Experimental data starts from **subentry 2**.

- Each entry has a unique **accession number** (e.g. C1582).

  Original EXFOR queries and printouts are very raw. Queres are facilitated by the **Web Interface** .
  Convenient commentaries ("**interpretations**") on data ⊕ plotting tools are available
  ⇨ don't feel stuck by first impression :)

- One subentry carries a given reaction and given observable. It is identified in a field called **REACTION** .
  To understand this field, let's learn step by step how the basic bricks of reactions are encoded by EXFOR.

- We will learn how to specify:
  - beam and target nucleus
  - outgoing particle(s) (or subgroup, or total)
  - type of reaction process
  - physics quantity we look for (e.g. cross section, angular distribution etc)

Encoding the particle type

- **Particle**: it can be either a nucleus, hadron or elementary particle.

  A general nucleus-oriented notation is: **`Z-S-A`** (**Z** = atomic number, **S** = symbol, **A** = mass number)

  e.g. `6-C-12`, `13-AL-27`

  But 1: for natural isotope mixture, *A* = 0 e.g. `28-NI-0` means ^{nat}Ni

  But 2: if the nucleus has isomeric states, then **`Z-S-A-X`** where **X** = M (if only 1 isomeric state exists)
  M1, M2, … (if more – point to yours)
  T (if you mean: sum of all isom. states)

- **Codes** for specific **particles** (see here) :

CODE	TYPE	CODE	TYPE	CODE	TYPE	CODE	TYPE
A	α	ETA	η meson	K	Kaon (any)	PI	Pion (any)
AN	$\overline{n}$	G	γ (photon)	KN	K^-	PI0	π^0
AP	$\overline{p}$	HE2	^{2}He	KP	K^+	PIN	π^-
D	deuteron	HE3	^{3}He	N	n	PIP	π^+
E	electron	HE6	^{6}He	P	p	T	triton

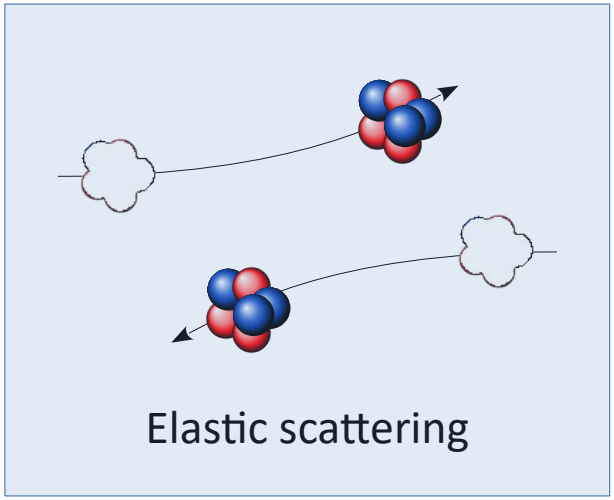
- **Codes** for groups of particles and/or playing a special role in some process (see here) :

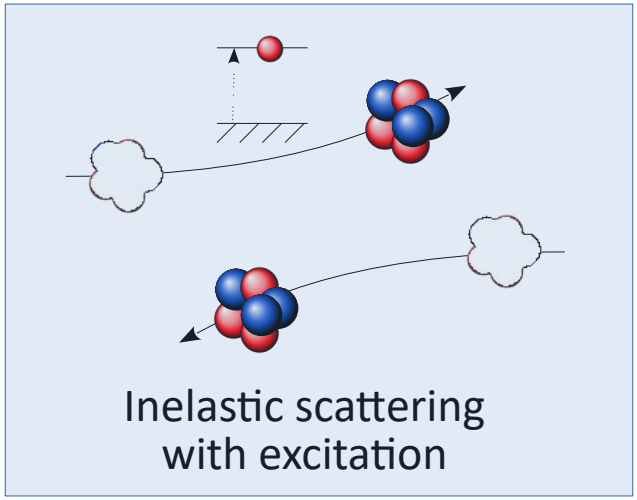
CODE	TYPE	CODE	TYPE	CODE	TYPE
AR	annihilation radiation	EC	Electron capture	LCP	light charged particle
B	Decay β	ER	evaporation residues	LF	light fragment
B+	Decay β^+	FF	fission fragments	PN	Prompt neutron
B-	Decay β^-	HCP	heavy charged particle	RSD	Residual nucleus
DG	Decay γ	HF	heavy fragment	SF	fragments from spontan. fission
DN	Delayed neutrons	ICE	Internal-conversion electr.	XR	X-rays

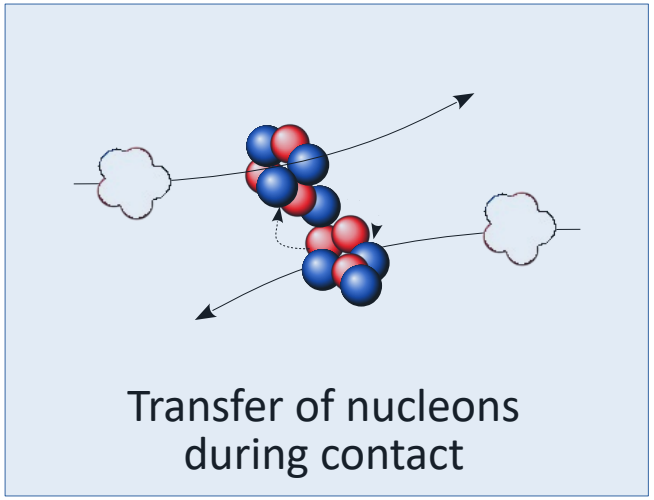
- A process can have **NO** incoming or outgoing particle. Then symbol **0** (zero) is used.
- **www query form**: using asterisk * means: please accept any outgoing particle

Scattering and reactions of two nuclei (lower energies)

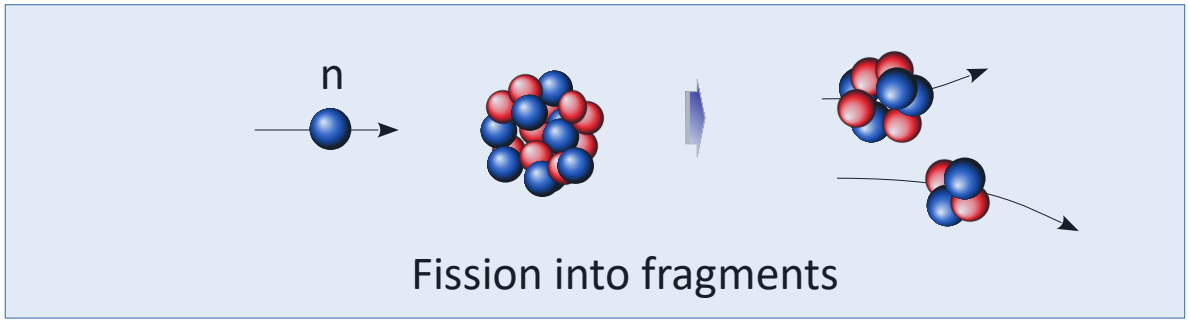
- Two nuclei in the outgoing channel


Elastic scattering

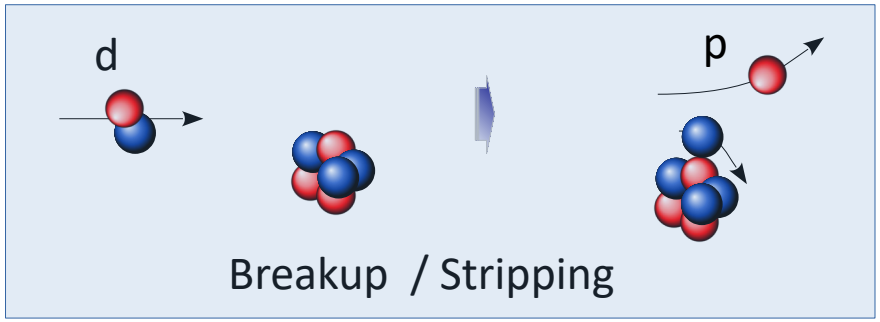

Inelastic scattering
with excitation


Transfer of nucleons
during contact

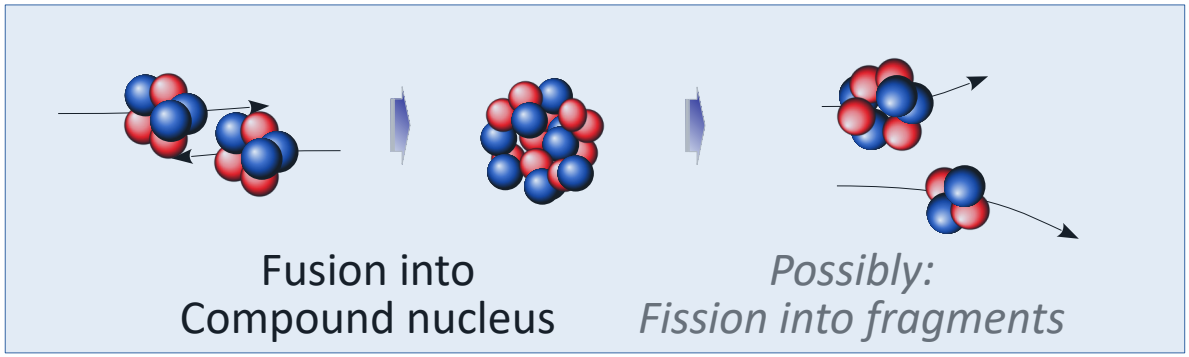
- Two / more nuclei in the outgoing channel + possible further emission of γ / n



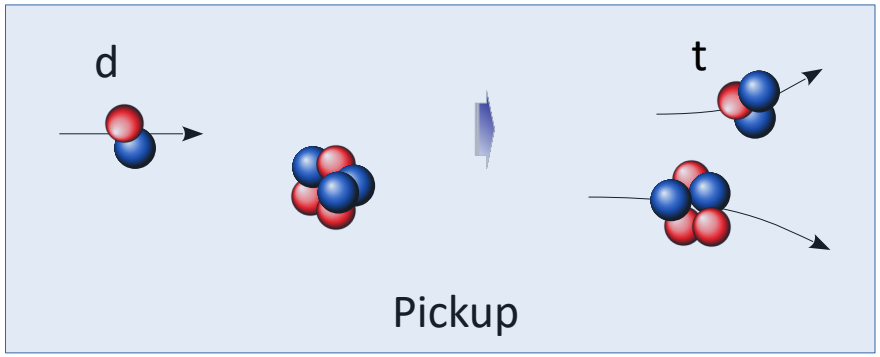
Fission into fragments



Breakup / Stripping


Fusion into
Compound nucleus

Possibly:
Fission into fragments



Pickup

Encoding the reaction

- **Process**: an interaction of two specific nuclei / particles with a given result (scattering included).

  Full notation of a reaction follows the "compact notation", i.e. **A(b,c)D** for the process A + b → c + D .
  It fills **subfields 1 - 4** of the REACTION field in a given SUBENTRY.

- The process can be either specified by: ① the incoming and outgoing projectile-like fragment,
  or ② an abbreviation of the process type.

Examples of ① :

`1-H-1(N,G)1-H-2`	means	$^{1}H(n,\gamma)^{2}H$	or	$p + n \rightarrow d + \gamma$
`5-B-10(N,A+T)2-HE-4`	means	$^{10}B(n,\alpha+t)^{4}He$	or	$n + {}^{10}B \rightarrow \alpha + \alpha + t$

- Ad ② – list of process types (see also here) :

CODE	REACTION TYPE	CODE	REACTION TYPE
ABS	Absorption	PAI	Pair production (for photonuclear reactions)
EL	Elastic scattering	SCT	Total scattering (elastic + inelastic)
F	Fission	TCC	Total charge changing
FUS	Total fusion	THS	Thermal neutron scattering
INL	Inelastic scattering	TOT	Total
NON	Nonelastic (= total minus elastic)	X	Process unspecified

Examples of ② :

`92-U-235(N,F)`	means	$^{235}U + n \rightarrow$	fission of ^{236}U
`26-FE-56(N,INL)26-FE-56`	means	$^{56}Fe(n,n')^{56}Fe$	(inelastic scattering of neutron)
`28-NI-0(P,X)11-NA-24`	means	$^{nat}Ni(p,X)^{24}Na$	(production of ^{24}Ni, possibly + anything)

Encoding the quantity

- **Quantity**: is a requested physics observable.

  A dictionary of quantities is enormous (see here). Here – only some basic ones.

CODE	QUANTITY	
SIG	σ	(Integrated) cross section
DA	$d\sigma/d\Omega = f(\theta)$	Differential cross section with respect to angle
DAP	$d\sigma/d\Omega = f(\theta)$	Partial differential cross section with respect to angle "Partial" means: a given initial state has more final states than ours.
PY/DA	$dN/d\Omega$	Differential product yield
PY/DA/DE	$d2N/d\Omega dE$	Double differential product yield

  This symbol is placed in the **subfield 6** of the REACTION field (for a given SUBENTRY).

  Most usually other subfields (5, 7, 8, 9) are empty.
  Sometimes they report an auxiliary information, e.g. PAR in field 5 means "partial"

- Examples of full REACTION field:

`(92-U-235(N,F),,SIG)`	means	Cross section for $^{235}U + n \rightarrow$ fission of ^{236}U
`(28-NI-60(N,P)29-CU-26,,DA)`	means	$d\sigma/d\Omega = f(\theta)$ for $^{60}Ni(n,p)^{60}Cu$ reaction
`(3-LI-7(3-Li-7,A)4-BE-10,PAR,DA)`	means	partial $d\sigma/d\Omega = f(\theta)$ for $^{7}Li(^{7}Li,\alpha)^{10}Be$ reaction

Web interface: examples of querying

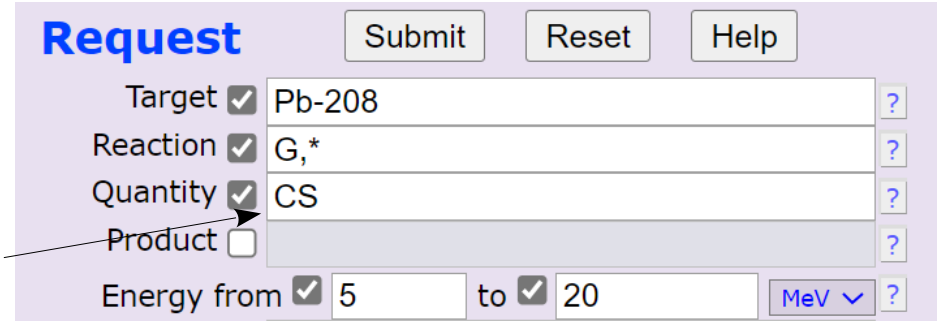
☞ **EXFOR web interface: [HERE] .**

- **Example 1.** $\gamma + {}^{208}Pb \rightarrow$ Anything

We search for $\sigma = f(E)$ within $E \in [1, 25]$ MeV.

Caution: within interface, CS instead SIG!

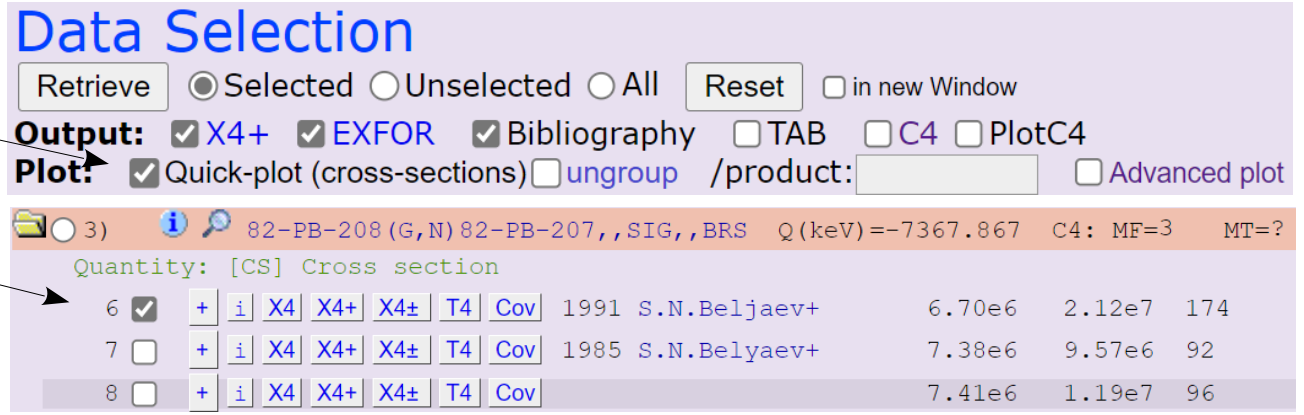
Now, click [**Submit**].



Check “Quick-plot” (cross-sections)

Let’s try “1991 S.N.Beljaev+”

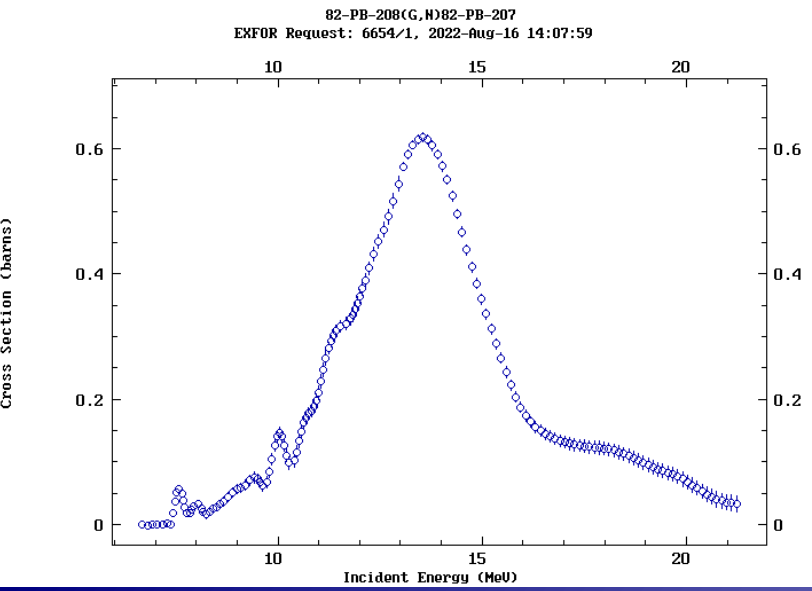
Now, click [**Retrieve**].
You should get this plot:



Raw / Interpretted EXFOR entries

Energies [eV]

No. of points in dataset



Below the plot: plotting options. You can click [+] to enhance.
Click [**Repaint**] to update the plot.

At the RHS, find out this:

See: plotted data (19Kb) out: e6 json: + plotly2

Printout of data in table

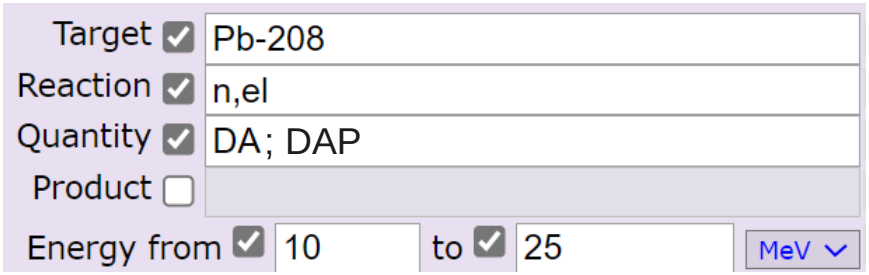
Nicer form of graph

Web interface: examples of querying

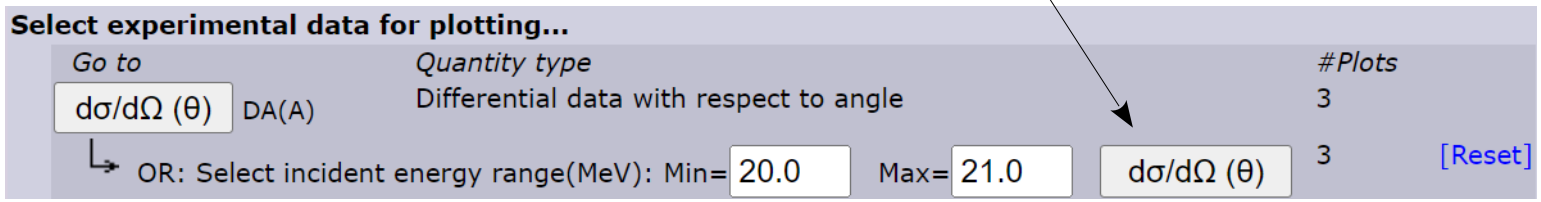
- **Example 2.** **Elastic scattering of n + ^{208}Pb**

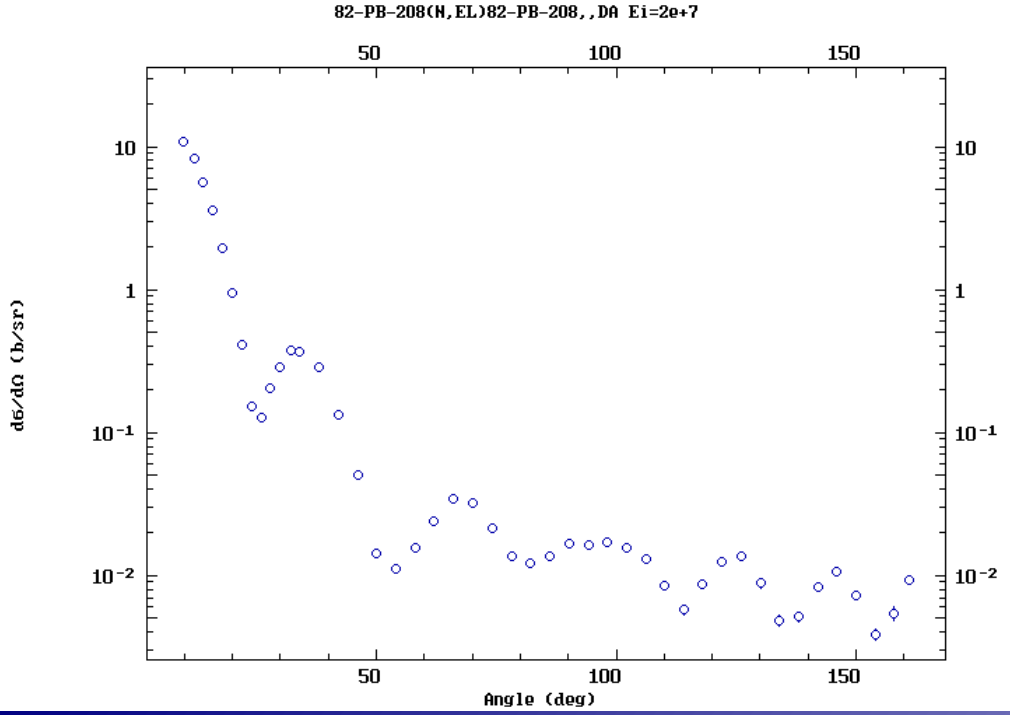
We search for **dσ/dΩ = f(θ)** within ***E* ∈ [10, 25] MeV**.

Let's try "1984 R.W.Finlay+" dataset covering [20, 24] MeV.
Check "Advanced plot" and click [**Retrieve**].



Nearly done, but we need to pinpoint the energy.
Let's take that for 20 MeV ⇨ select [20, 21] MeV. Now click [**dσ/dΩ (θ)**] :





- RHS : print data or run plotly2 (nicer plot)
  Btw. in plotly2's legend you can look up the datasets.

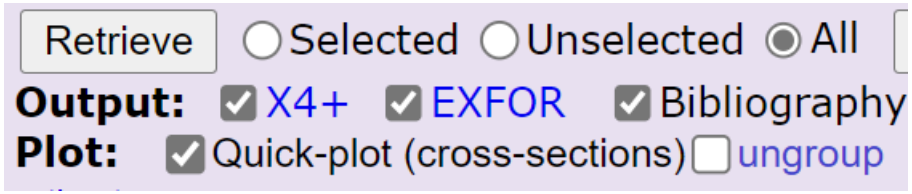
- Below the plot: plotting options
  (don't forget to [**Repaint**])

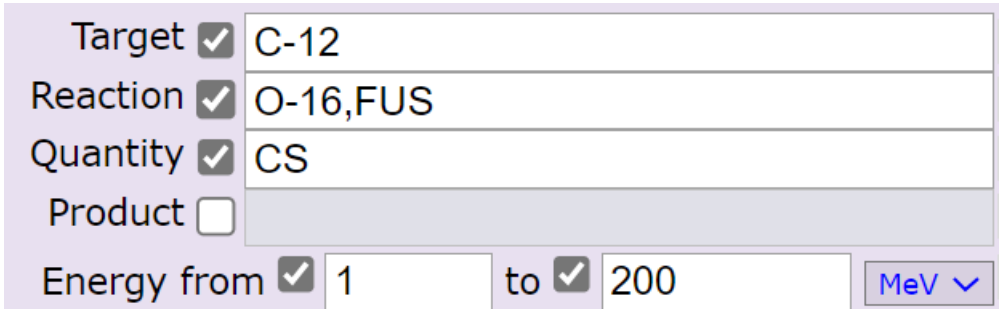
Web interface: examples of querying

- **Example 3.** **Fusion of $^{12}C+ ^{16}O$**

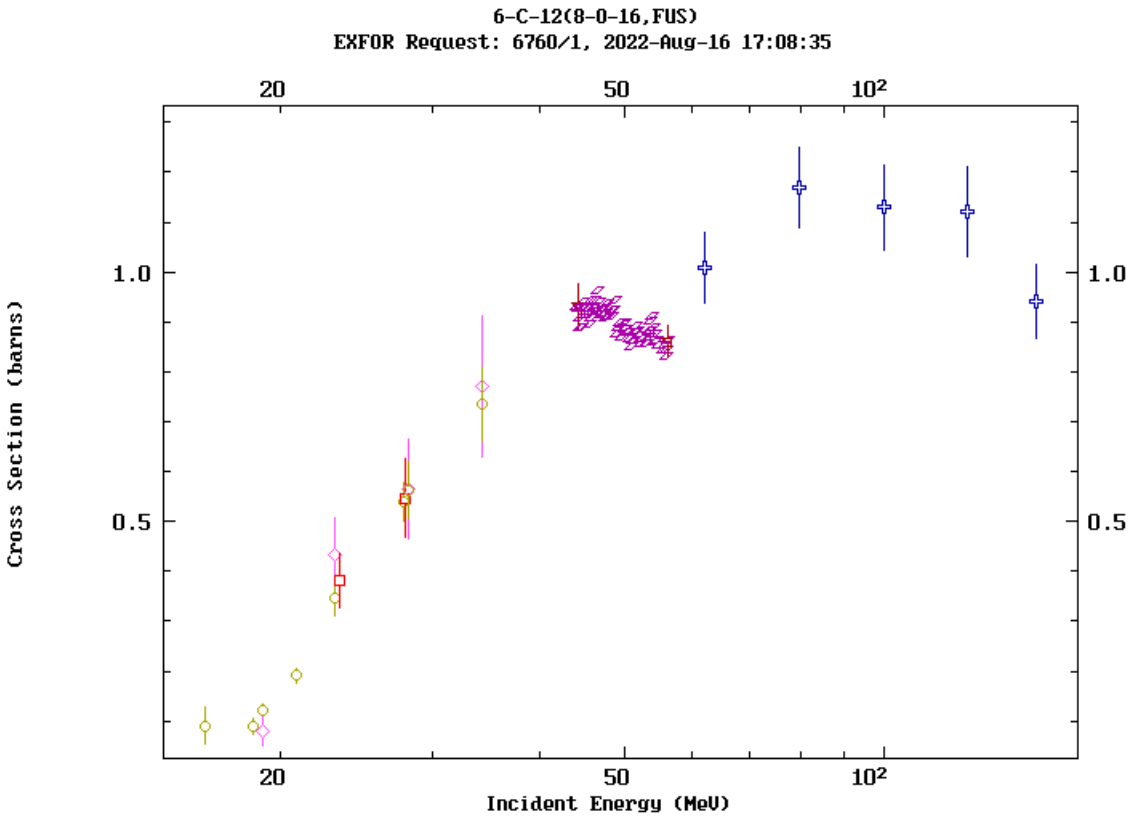
We search for $\sigma = f(E)$ within $E \in [1, 250]$ MeV.

This time let's accept all the data sets – check [All] :





Choose "Quick plot", then [**Retrieve**] .



Notice: **plotly2** offers an informative legend
(colors are bug-free wrt **quick plot**)

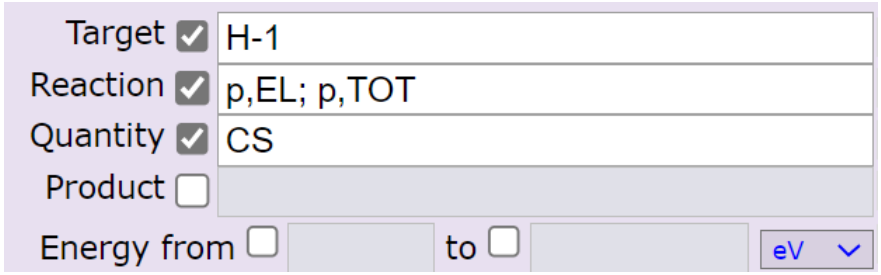
Web interface: examples of querying

- **Example 4.** **p+p collisions : elastic and total σ = f(*E*).**

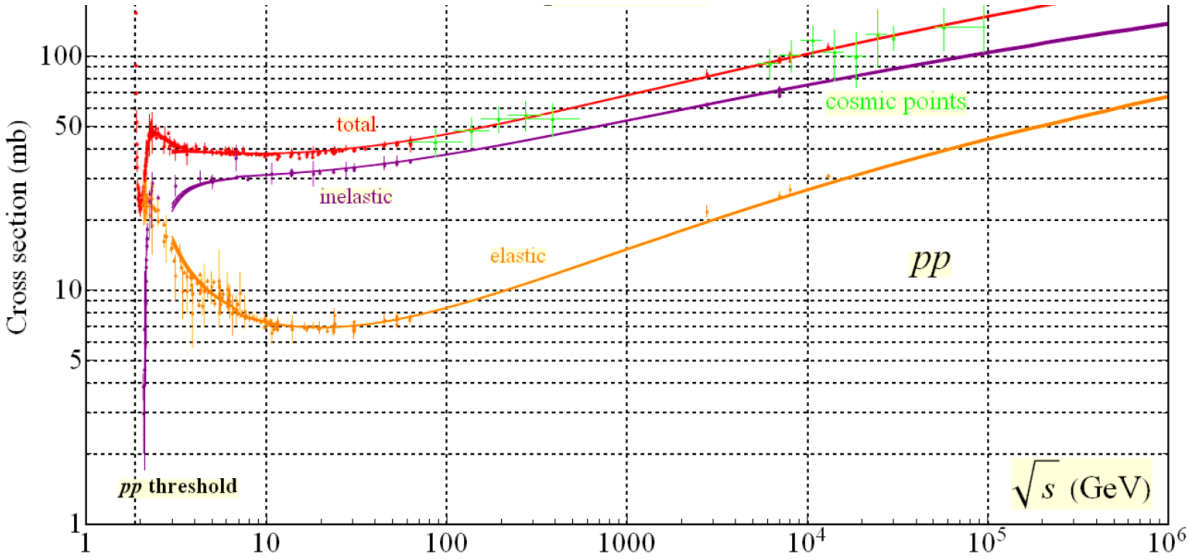
Let's take all the energies. With **;** more cases are accepted.
Click [**Submit**].

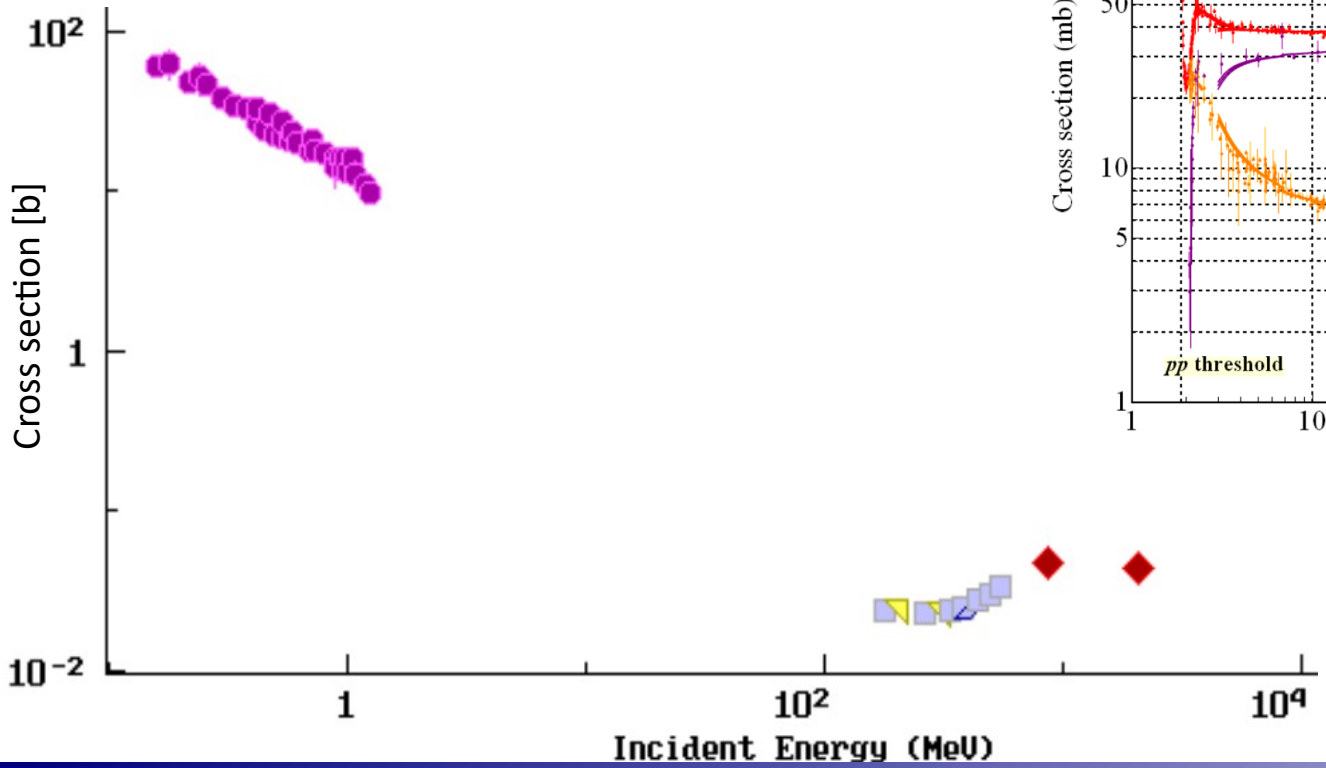
Next, choose [All] and [Quick plot] , then [Retrieve].

Below the plot, click [Log: Y].
Click Plotting options: [+] , then unzoom Y axis.



For comparison: σ = f($\sqrt{s}$) from PDG . $\sqrt{s_{NN}} = \sqrt{2m_N\left(2m_n + T_B\right)}$





T_{Beam} = 1 GeV ↔ √s = 2.3 GeV.

➡ Clearly, EXFOR is designed for lower energies!