2484-22

ICTP-IAEA Joint Workshop on Nuclear Data for Science and Technology: Medical Applications

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EMPIRE nuclear data modelling

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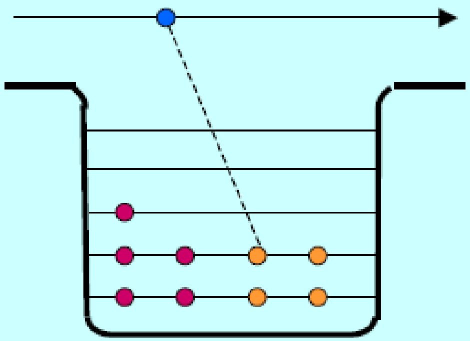
Direct and Compound scattering

At low energies, neutron-nucleus scattering occurs either directly or through the quasi-bound compound nucleus states.

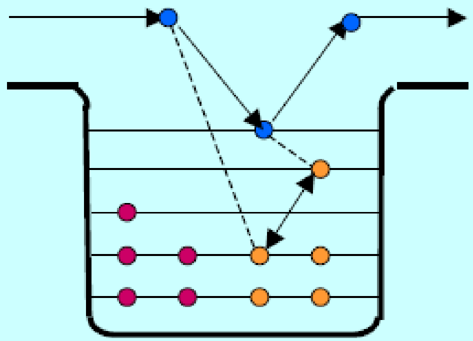
Direct scattering



$\Delta t \sim 10^{-20} - 10^{-22}\,\mathrm{s}$

$\Delta E \Delta t \geq \hbar$

Compound nuclear scattering



$\Delta t \sim 10^{-12} - 10^{-20}\,\mathrm{s}$

In a direct scattering, the incident neutron interacts with the average field of the nucleus. The duration of the collision is approximately the time it takes the neutron to cross the nucleus.

In a compound nuclear scattering, the incident neutron loses energy upon colliding with the nucleus and is trapped. After a fairly long interval, enough energy is again concentrated on one neutron to allow it to escape.

The Bohr Hypothesis

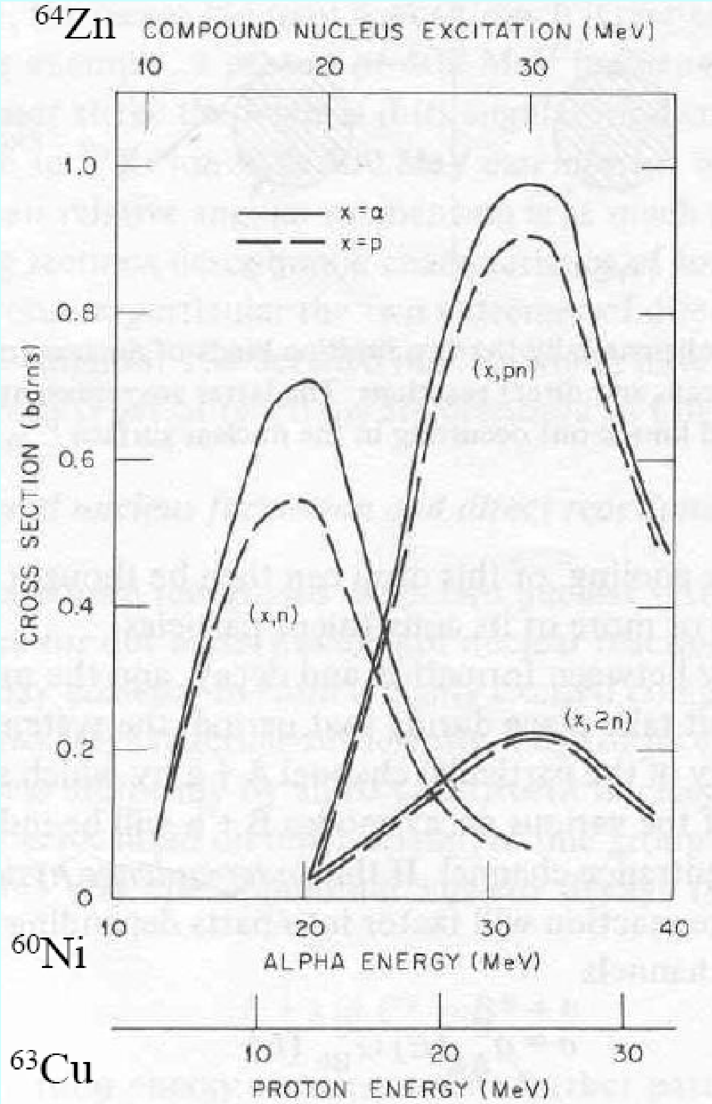
The average cross section has the form

$$\sigma_{ab} = w_{ab}\sigma_a^C \frac{\Gamma_b^C}{\Gamma^C},$$

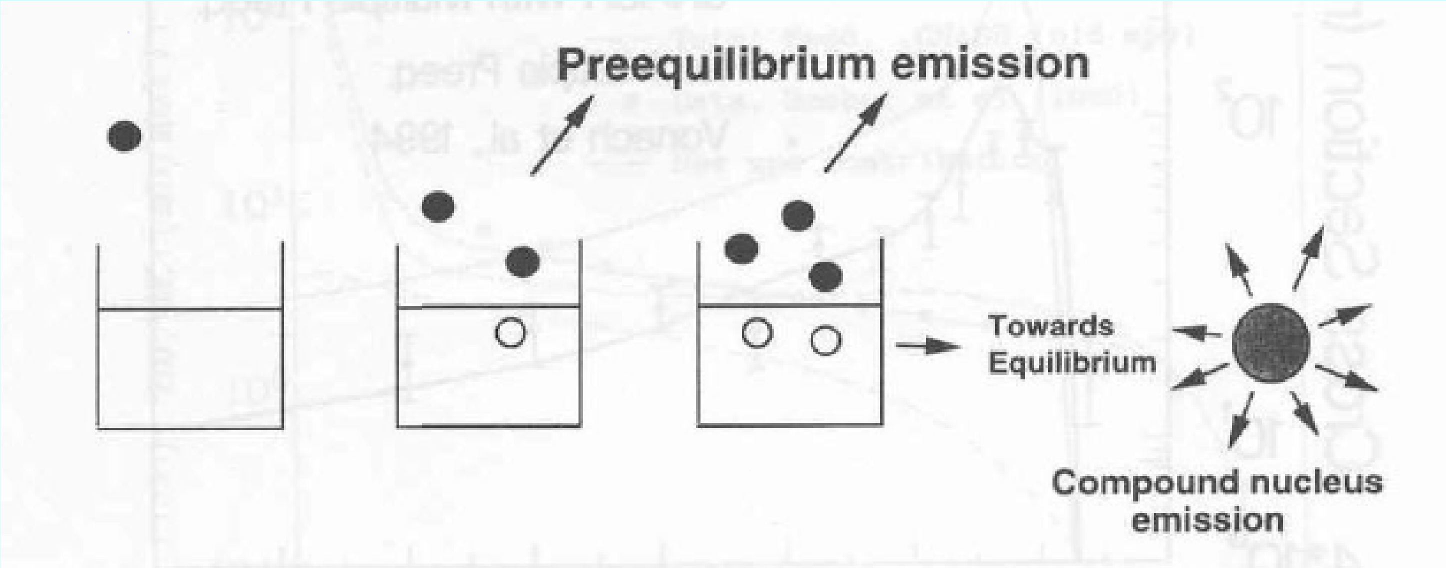
where σ_a^C is the cross section for compound nucleus formation from channel a, Γ_b^C is the partial width for decaying into channel b, with the total width being

$$\Gamma^C = \sum_b \Gamma_b^C.$$

The width fluctuation factor w_{ab} varies between 2 and 3 for the elastic channel. For other channels, it is close to one, except at very low energies. If we neglect it here, we satisfy the Bohr hypothesis, which states that the formation and decay of the compound nucleus are independent processes. This was tested experimentally by Goshal in 1950.



Pre-equilibrium emission



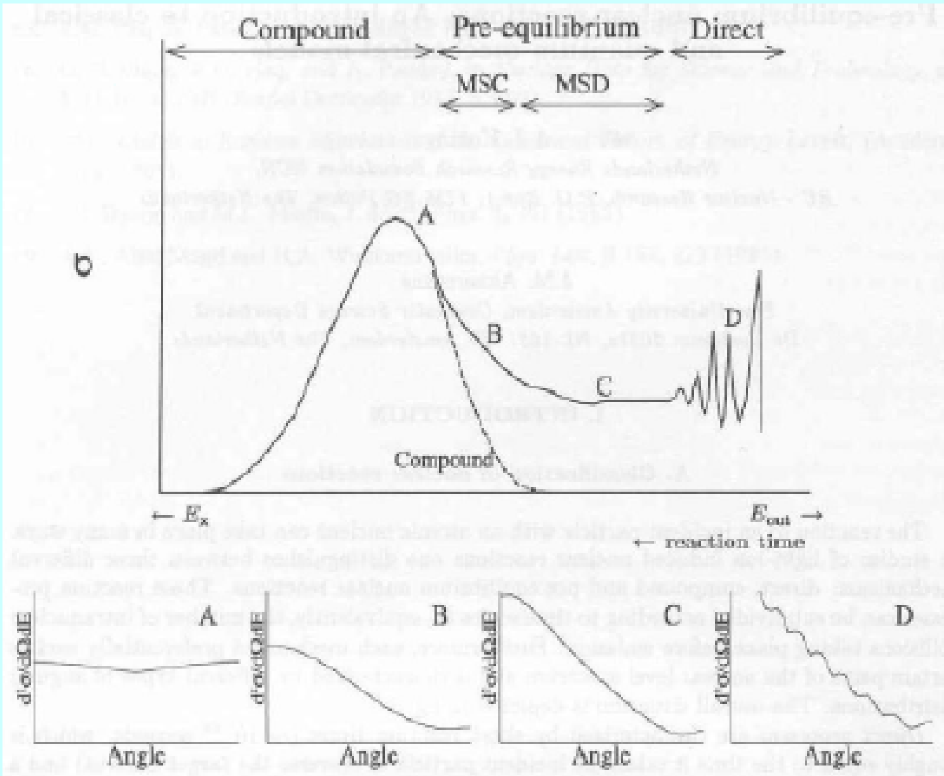
Compound nucleus models assume that the nucleus reaches an equilibrium (all states are equally probable) before emission occurs. Physically, the equilibration process proceeds through a series of nucleon-nucleon reactions. As the incident energy increases, it becomes more and more likely that one of the nucleons still retains a large fraction of the incident energy after the first one or two collisions, which favors its emission from a preequilibrium configuration.

Combining Reaction Models

At low incident energies, nucleon-induced reactions occur on two distinct time scales. Direct reactions, in which the incident particle remains in the continuum, occur quickly. Compound nucleus reactions, in which the projectile is trapped in a quasi-bound state, occur much more slowly.

The corresponding differential cross sections are consistent with their time scales: direct reactions tend to be forward peaked while compound nucleus ones are symmetric about 90°.

Preequilibrium processes corresponding to intermediate time scales arise and become ever more important as the incident energy increases.



Nuclear scattering and reactions

- Elastic scattering – (n, n), (p, p), (α ,α), ...
- Inelastic Scattering -- (n, n′), (p, p′), (α ,α'), ...
- Knockout/emission – (n, 2n), (n, np), (p, pn), (p, 2p), ...
- Stripping – (d, p), (d, n), (t, d), ...
- Pickup – (p, d), (n, d), (d, t), ...
- Charge exchange – (n,p), (p,n), (t,^{3}He), (^{3}He, t), ...
- Fission – (n,f), (p,f), (α,f), ...

Depending on the incident energy and the combination of projectile and target, some or many of these reactions can occur in a nuclear collision.

We will find that they usually occur through two very different mechanisms – a fast, direct one and a slower, composite nucleus one.

INTRODUCTION to EMPIRE

EMPIRE **belongs to a new generation of model codes to be used in basic research and nuclear data evaluation over a broad range of incident energies and projectiles.**

EMPIRE **is an open source project.**

M. Herman, R. Capote, M. Sin, A. Trkov, B.V. Carlson, V. Zerkin

and many other contributors

EMPIRE code & RIPL database

Extension of the nuclear reaction model code
EMPIRE
to actinides' nuclear data evaluation

@NNDC: http://www.nndc.bnl.gov/empire219/ @IAEA: http://www-nds.iaea.org/empire/

ELSEVIER

Available online at www.sciencedirect.com

ScienceDirect

Nuclear Data Sheets

Nuclear Data Sheets 110 (2009) 3107–3214

www.elsevier.com/locate/nds

EMPIRE v3.2 (Malta), May 2013

RIPL – Reference Input Parameter Library for Calculation of Nuclear Reactions and Nuclear Data Evaluations

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$^{169}Tm(p,n)^{169}Yb$

```
  5.                 ;INCIDENT ENERGY (IN LAB)
169.   69.           ;TARGET  A , Z
  1     1            ;PROJECTILE A, Z
3                    ;NUMBER OF NEUTRONS  TO BE EMITTED
1                    ;NUMBER OF PROTONS   TO BE EMITTED
0                    ;NUMBER OF ALPHAS    TO BE EMITTED
1                    ;NUMBER OF DEUTERONS TO BE EMITTED
0                    ;NUMBER OF TRITONS   TO BE EMITTED
0                    ;NUMBER OF He-3      TO BE EMITTED
0  0. 0.             ; reserved
***************************************************************************************************************
@ Tm-169(p,n) calculation : ICTP workshop
IOUT       3.
NEX      080.                    Number of points in the outgoing energy grid
ENDF       0.                    No ENDF formatting by default (much faster runs)
RECOIL     0.                    No recoils are calculated. Sizeable speed-up if no ENDF file is required
* HAUSER-FESHBACH INPUT
*
FITLEV     0.                    FITLEV>0 is recommended for 1st run to compare vs NLD exp.data
LEVDEN     0.                    EMPIRE NLD (EGSM RIPL-3) as default
*LEVDEN     1.                   Refitted GSM model (Ignatyuk) NLD (future option)
HRTW       0.                    Width fluctuations considered up to 3 MeV (for neutron induced)
GSTRFN     1.                    Default gamma ray strength function (Plujko MLO RIPL-2)
***
* DEFAULT OPTICAL MODEL INPUT
*OMPOT   2405.       1           OMP for the inverse neutron channel   - Koning & Delaroche
*OMPOT   5405.       2           OMP for the inverse proton channel    - Koning & Delaroche
*OMPOT   9600.       3           OMP for the inverse alpha channel     - Avrigeanu et al
*OMPOT   6200.       4           OMP for the inverse deuteron channel  - Haixia et al
*OMPOT   7100.       5           OMP for the inverse triton channel    - Becchetti & Greenless
*OMPOT   8100.       6           OMP for the inverse He-3 channel      - Becchetti & Greenless
*
DIRECT     0.                   Spherical optical model by default for A>220
***
* Prequilibrium models
MSD        0.                    Quantum statistical Multi-Step-Direct model
MSC        0.                    Quantum statistical Multi-Step-Compound model
PCROSS    1.5                    Exciton model with default 1.5 MFP parameter
HMS        0.                    Monte Carlo Hybrid (DDHMS)preequilibrium model
GO
5.5
6.
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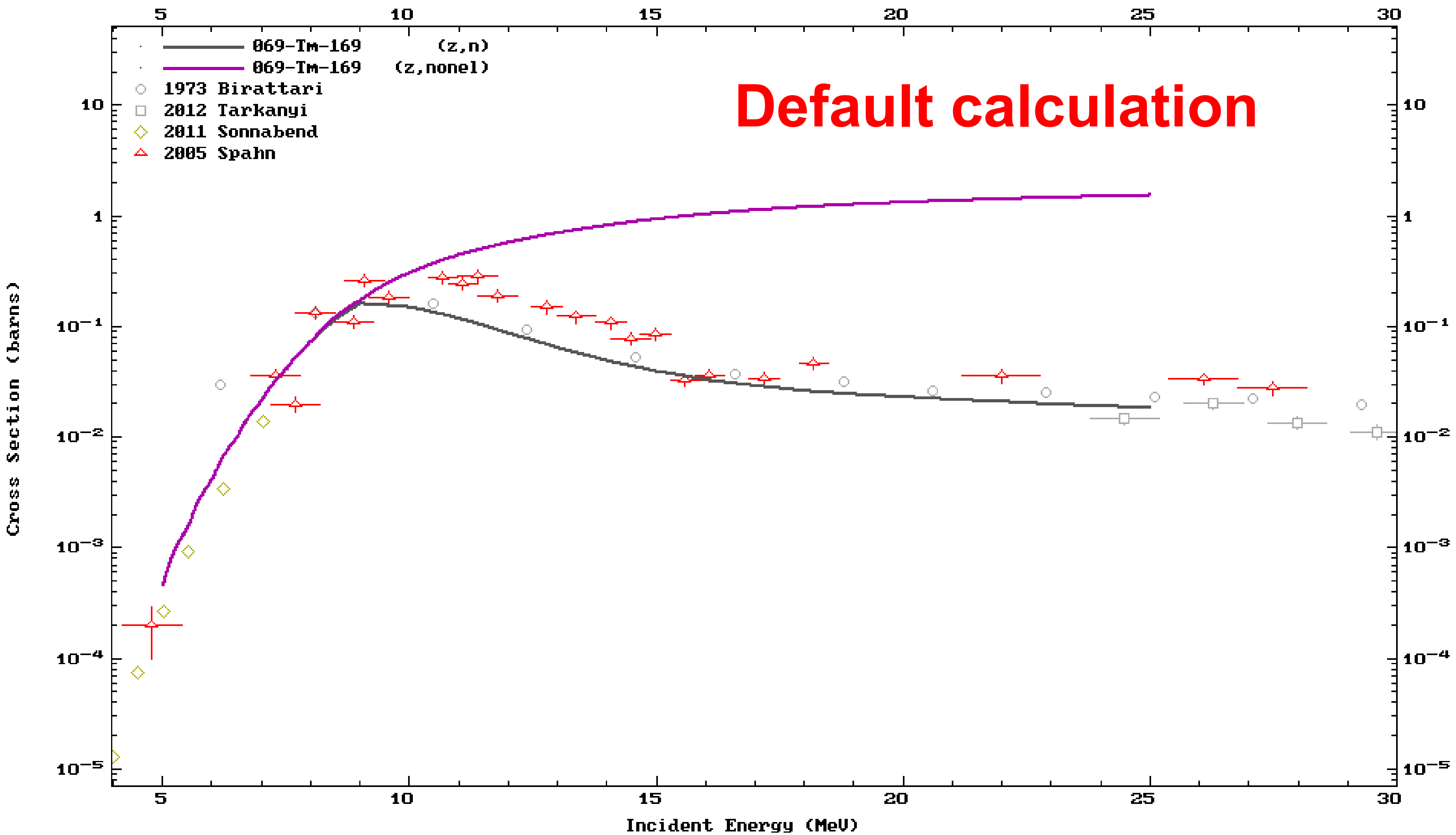
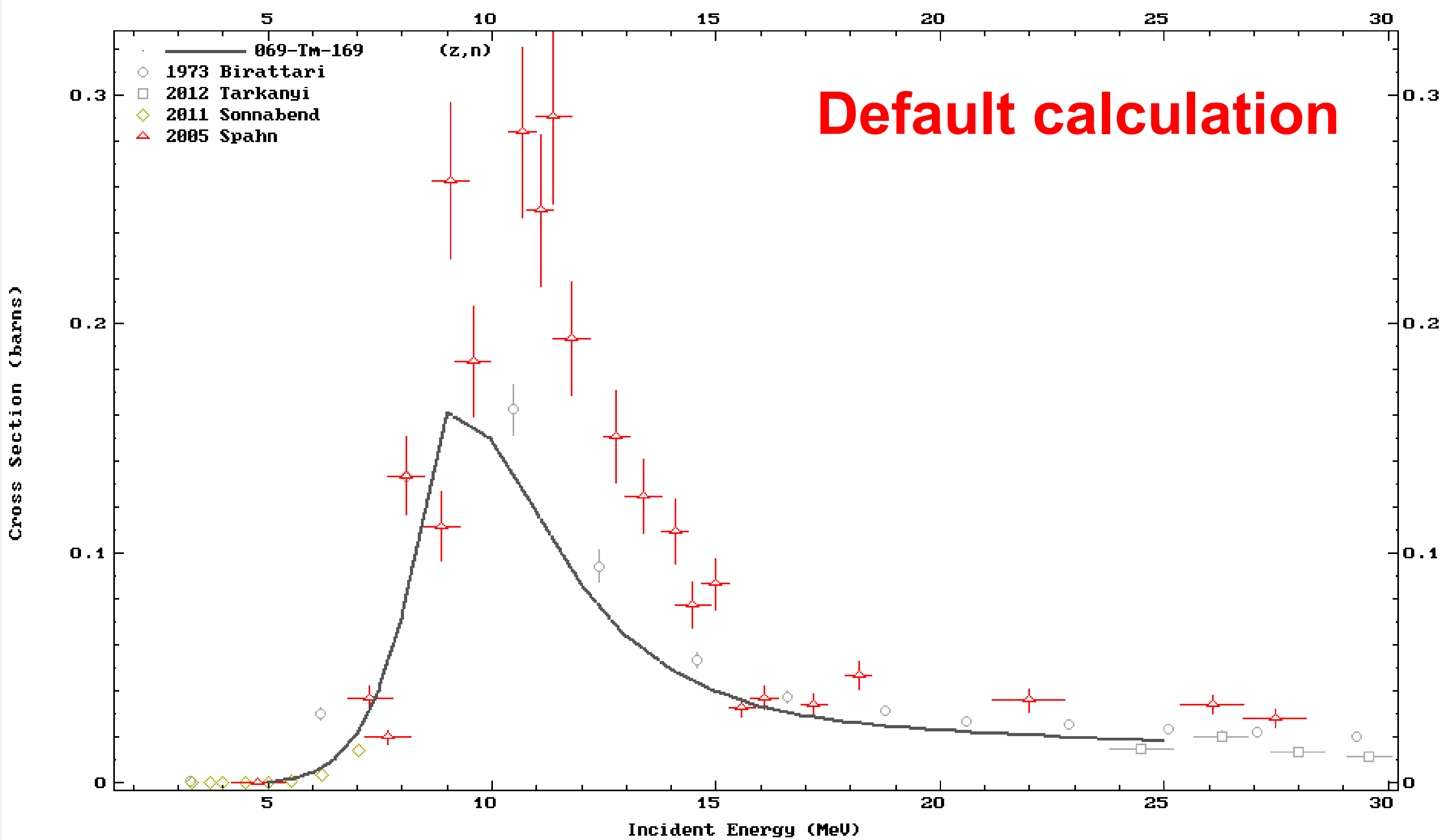
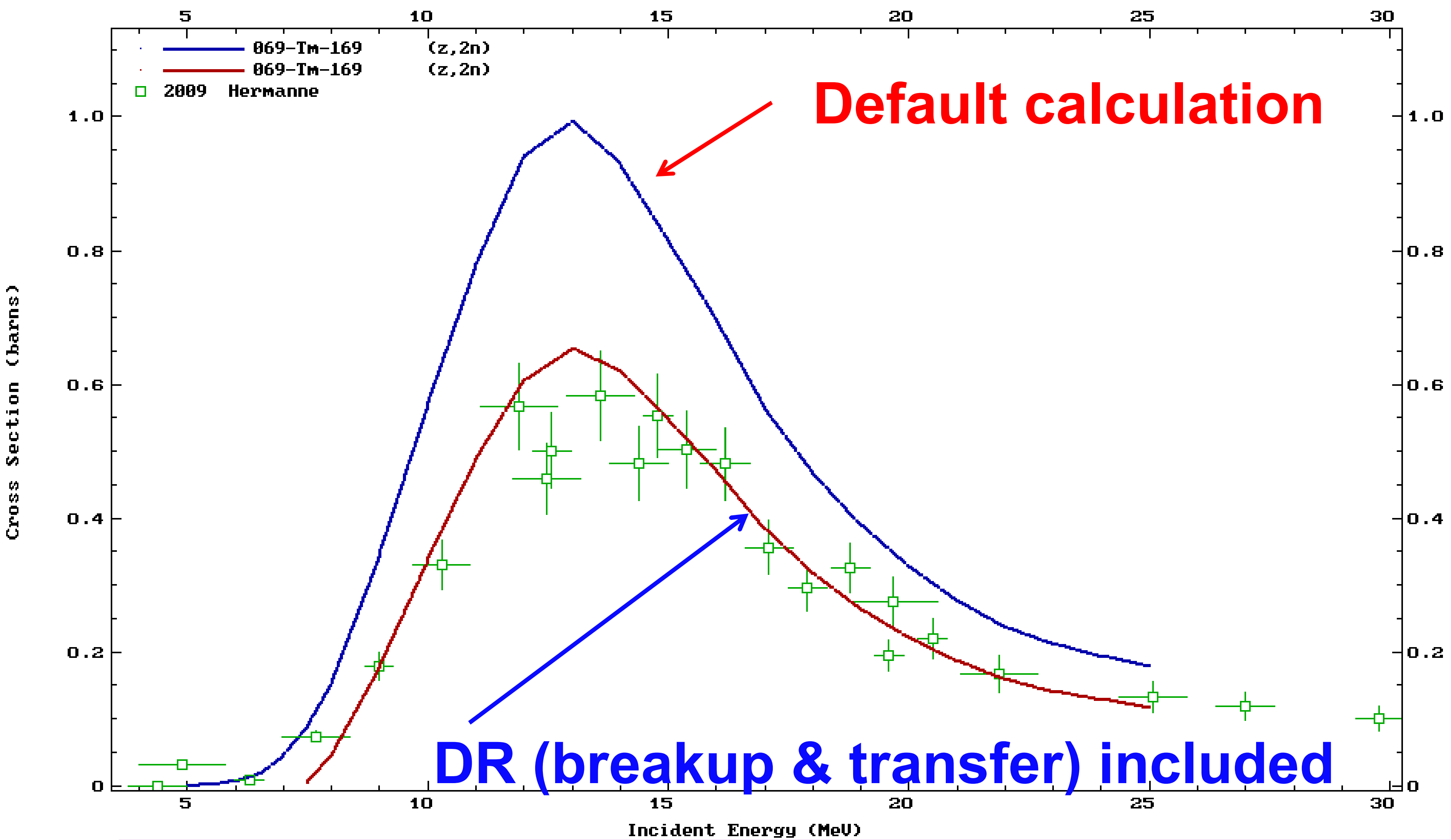
$^{169}Tm(p,n)^{169}Yb$



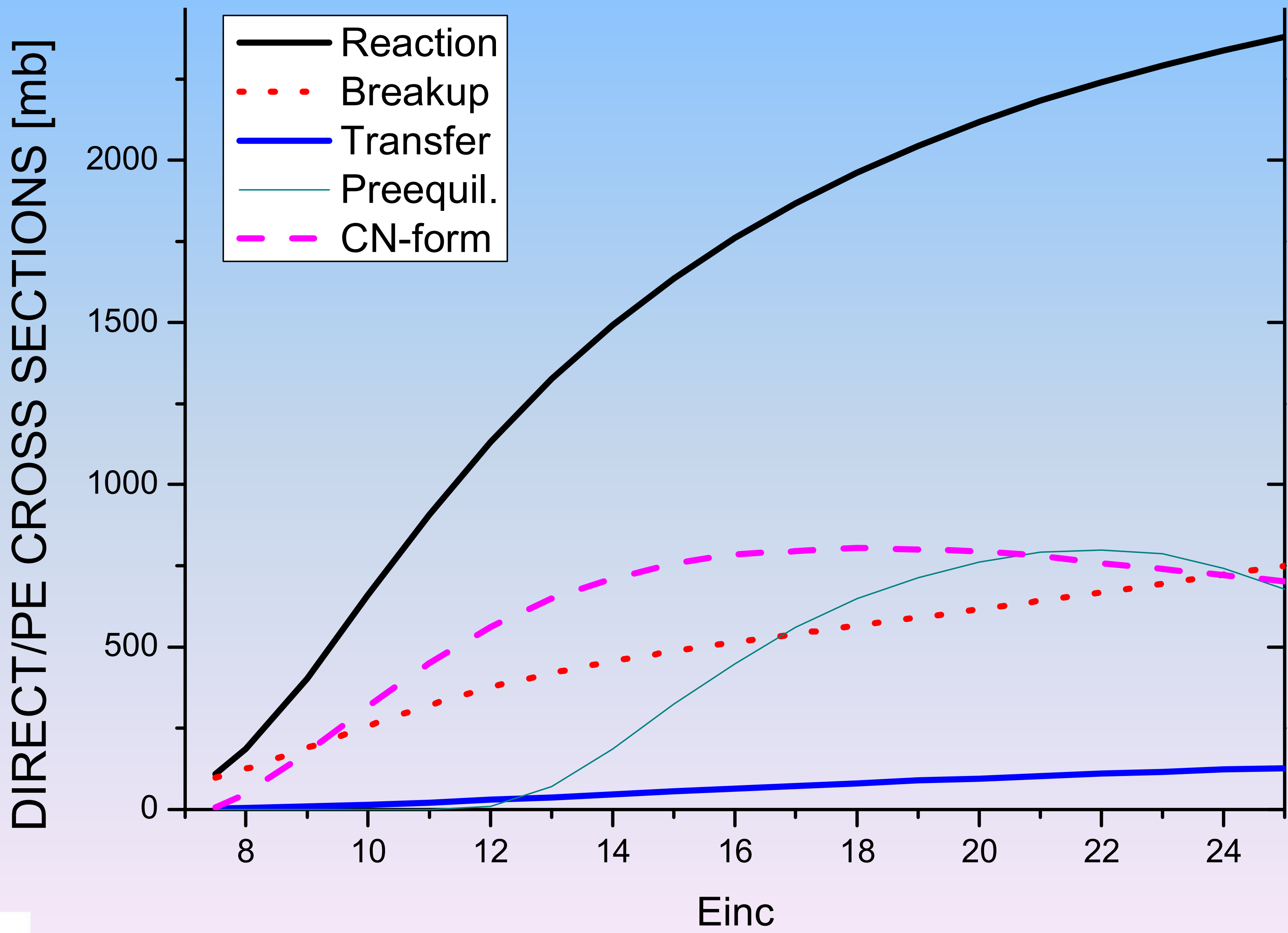
$^{169}Tm(p,n)^{169}Yb$



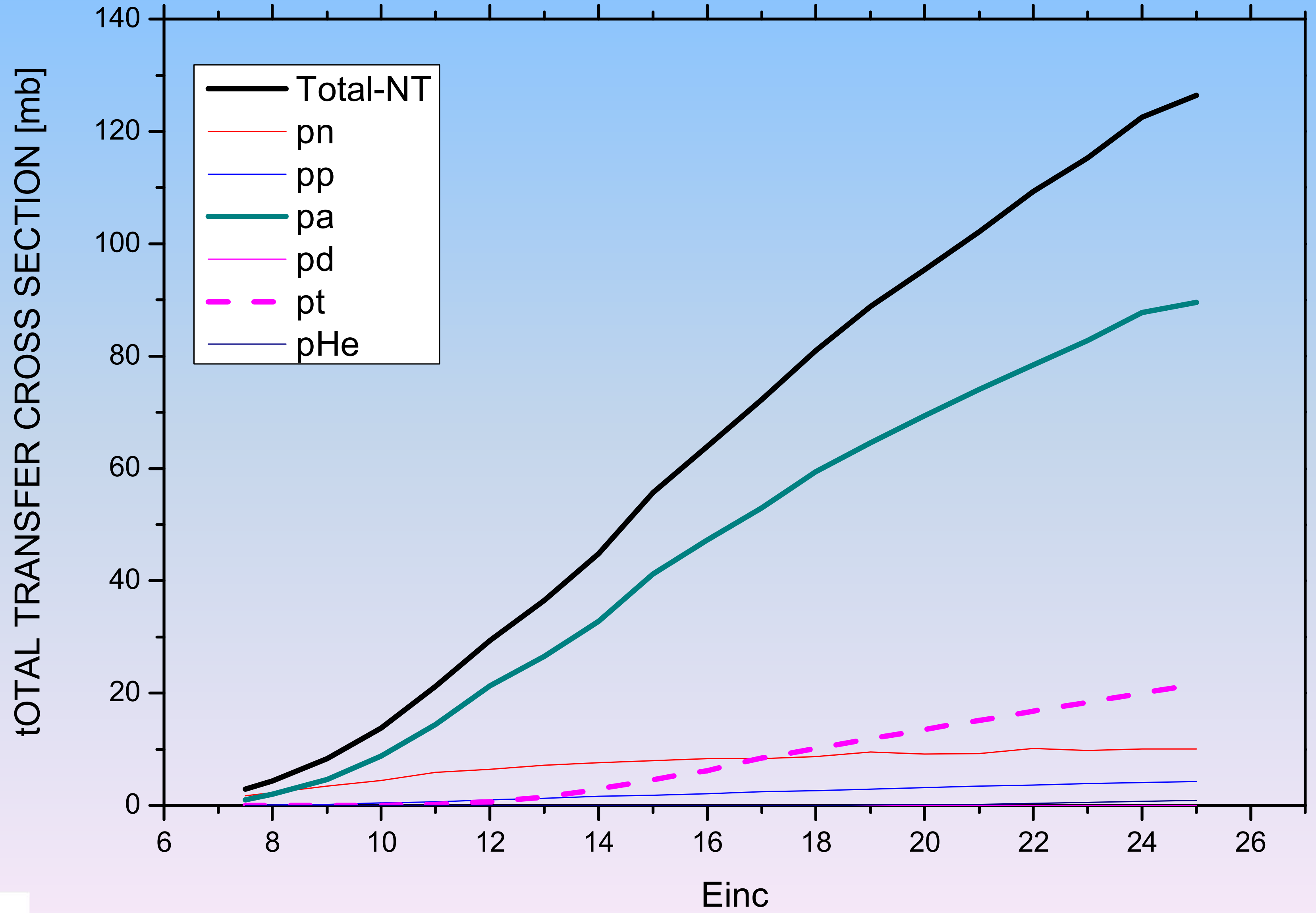
$^{169}Tm(d,2n)^{169}Yb$



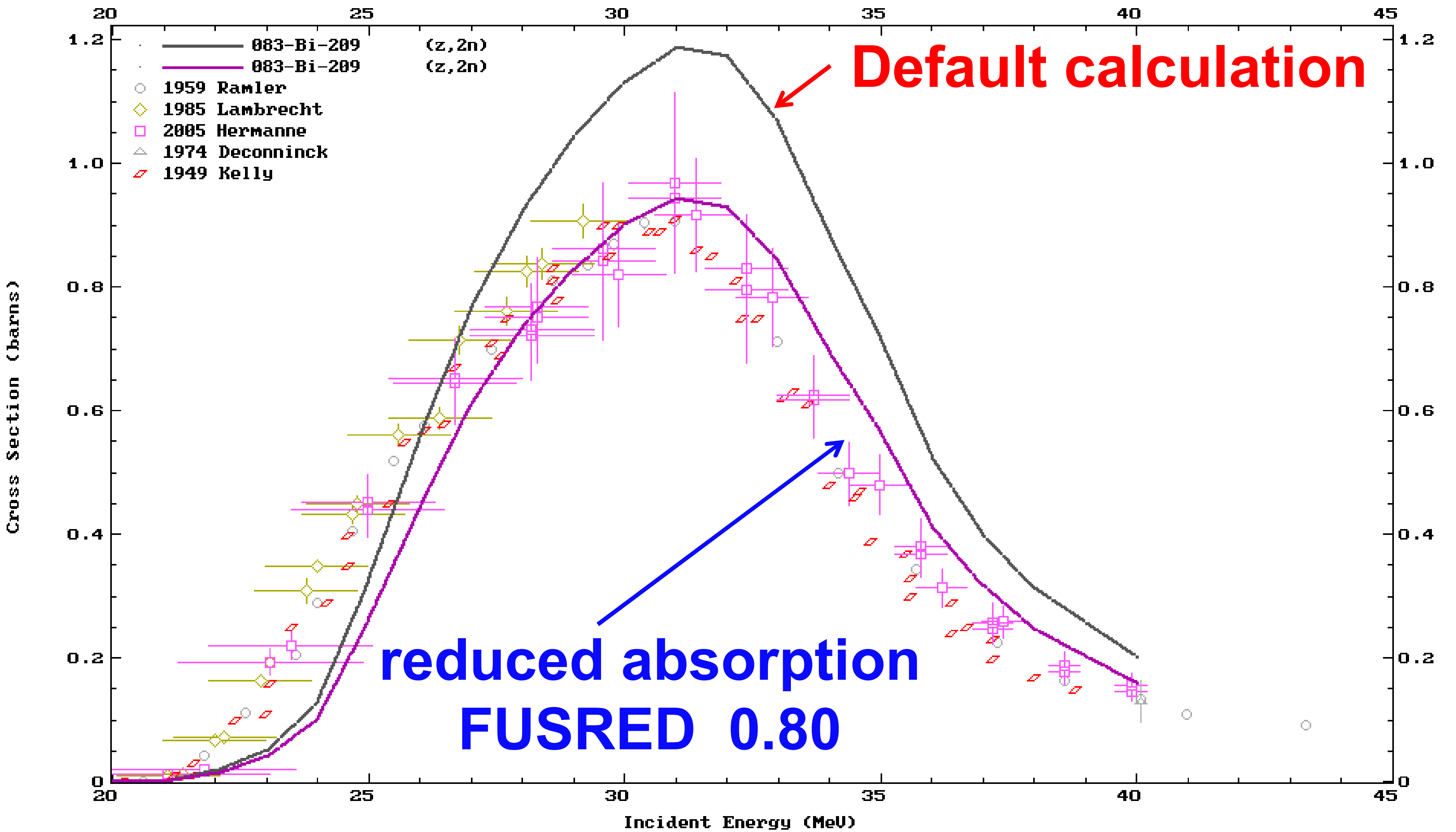
$^{169}Tm(d,2n)^{169}Yb$: non-eq. reactions



$^{169}Tm(d,2n)^{169}Yb$: transfer



$^{209}Bi(a,2n)^{211}At$



EMPIRE summary

Experimental data: masses, discrete levels, deformations
Model parameters: OMP, NLD, gamma, fission,etc.

RIPL

EMPIRE

Nuclear Reaction Model Code

EMPIRE v3.2 (Malta)
May 2013

www-nds.iaea.org/empire

- **Easy DEFAULT calculations**
- **Powerful tool for reaction modelling (beyond DEFAULT)**