

CONSTRAINING THE TALYS CODE USING DATA COLLECTED FOR MEDICAL APPLICATIONS

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Motivations

Nuclear medicine

Need for Accurate and reliable sets of data

To choose between **production routes**

To **optimize production** of specific radionuclides, to minimize/eliminate **impurities**

Arronax has been built to provide innovative radionuclides for medical application.

→ We have constructed and use an experimental set-up to make production cross section measurements

Nuclear data for other applications

Tracers are used in other fields thought monitor reactions

Coordinated Research Projects have been initiated by IAEA over the years

Requirements for **improved and extended excitation functions** for monitor reactions

Our data can also:

→ Provide **a large set of nuclear data** in terms of targets, projectiles and energy range that will allow to **constrain Nuclear code** and develop their predictive power

Experimental facility



All our experiments have been performed at our facility

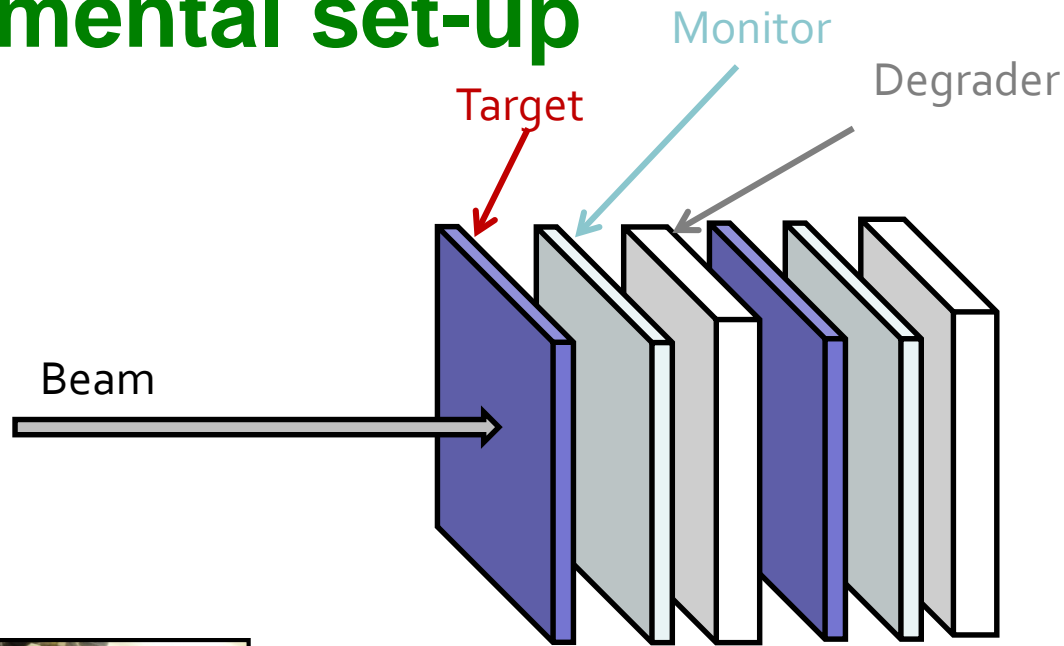
- Access to different types of projectiles
- Large energy range

using the stacked-foils technique

- Cost effective, fast and precise

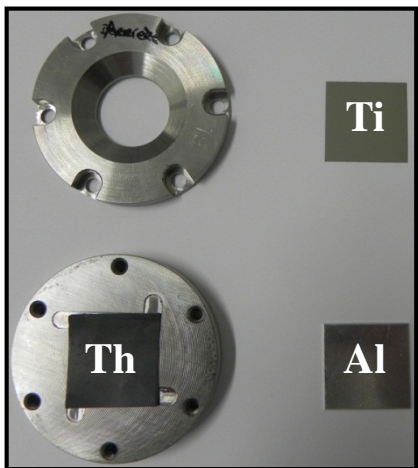
Extracted	Energy (MeV)
Proton	30 – 70
	17
Deuteron	15 – 35
Alpha	68

Experimental set-up

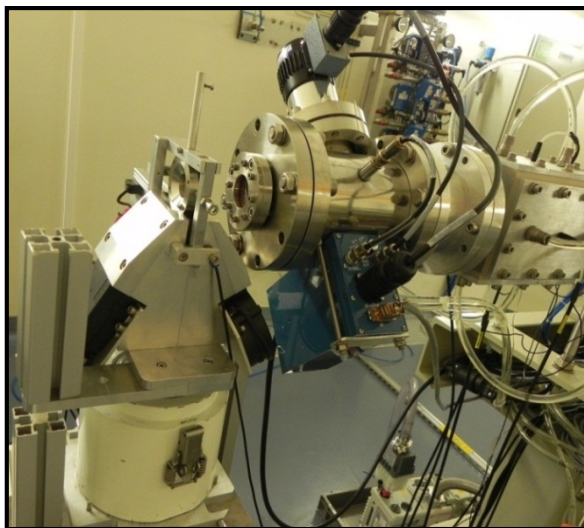


Stacked-foil technique:

- Target/monitor/degrader **pattern**
- **Thin** foils:
- One cross section value per foil



Capsule and foils



Irradiation station and beam line

Using the information of the monitor:

$$\sigma = \sigma' \cdot \frac{\chi' \cdot Act \cdot A \cdot \rho' \cdot e' \cdot (1 - e^{-\lambda' \cdot t})}{\chi \cdot Act' \cdot A' \cdot \rho \cdot e \cdot (1 - e^{-\lambda \cdot t})}$$

Collected data sets

Proton induced reactions:

Cu-67 → New data set from $^{68}\text{Zn}(p,2p)$

Ac-225 → from Th-232(p,x)

Ra-223 → from Th-232(p,x)

Fission fragment distribution → from Th-232(p,x)

Monitor reactions on **Ti, Ni and Cu** → from Th-232(p,x)

- NIMB 415 (2018) 41-47

- Phys. Med. Biol. **60** (2015) **931–946**

- EPJ Web of Conferences 146, 08008 (2017)

- E. Garrido et al., NIM. B 383 (2016) 191

Deuteron induced reactions:

Sc-44 → New data set for Ca-44(d,x)

Tb-155 → New data set for Gd-nat(d,x)

Re-186g → New data set for W-186(d,x)

Th-226 → New data set for Th-232(d,x)

Fission fragment distribution → from Th-232(d,x)

Monitor reactions on **Ti**

- C. Duchemin et al, Phys. Med. Biol. **60** (2015) **6847**

- Submitted to ARI

- C. Duchemin et al, Appl. Rad. And Isot. **97** (2015) **52**

- C. Duchemin et al

Nuclear Data Sheets **119** (2014) **267**

International Journal of Modern Physics **27** (2014)

Phys. Med. Biol. **60** (2015) **931**

- C. Duchemin et al, ARI **103** (2015)**160**

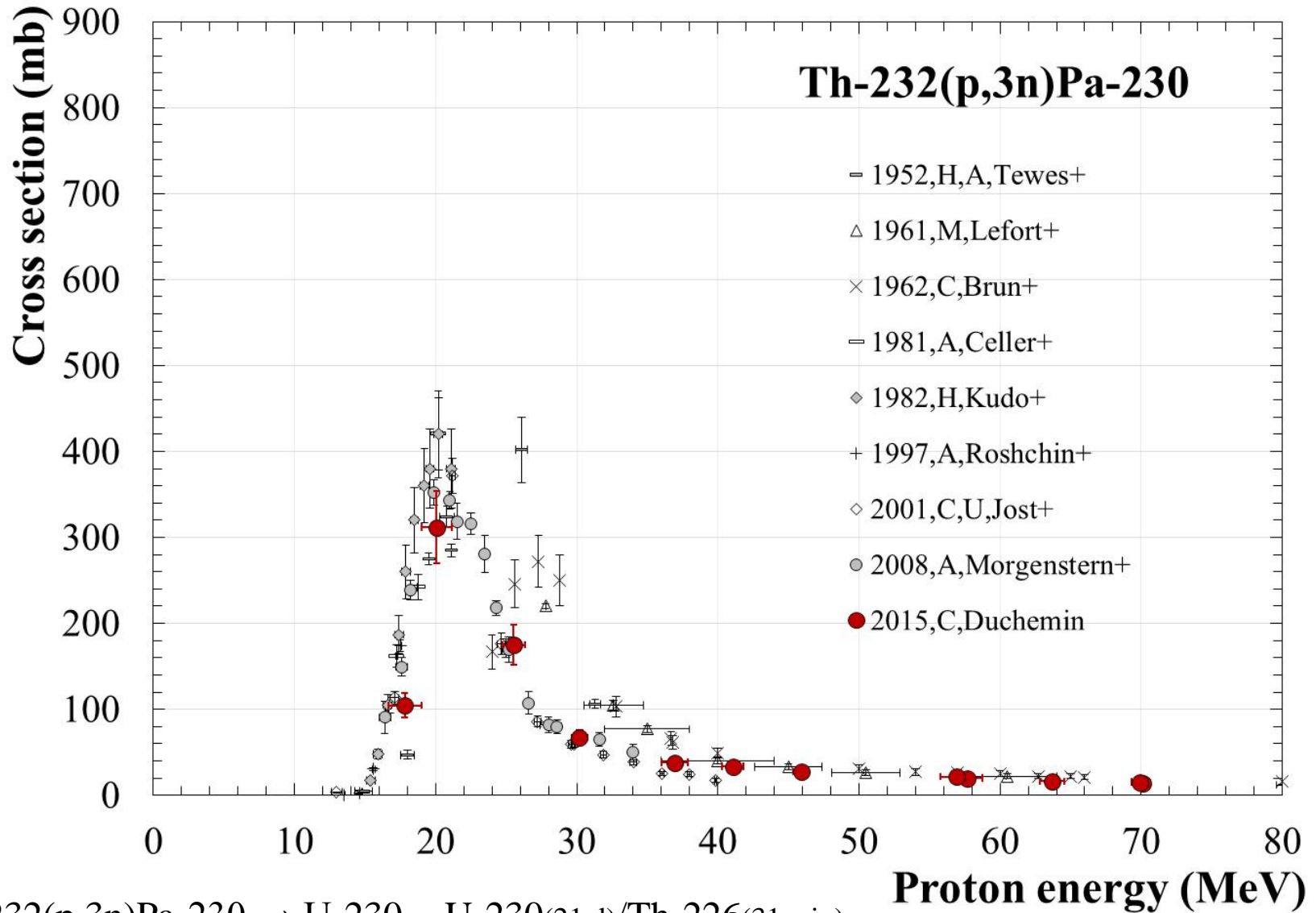
Alpha induced reactions:

Sn-117m → Cd-116(α ,x)

Monitor reactions on **Cu, Ti, Ni:**

- C.Duchemin et al, ARI 115 (2016) 113

An example: Th-232(p,3n)Pa-230



Th-232(p,3n)Pa-230 → U-230 U-230(21 d)/Th-226(31 min)

TENDL2015

TENDL2015

Nuclear data library based on both default and adjusted TALYS calculations and data from other sources



By A.J. Koning¹, D. Rochman², J. Kopecky³, J.Ch. Sublet⁴, M. Fleming⁴, E. Bauge⁷, S. Hilaire⁷, P. Romain⁷, B. Morillon⁷, H. Duarte⁷, S.C van der Marck⁶, S. Pomp⁵, H. Sjostrand⁵, R. Forrest¹, H. Henriksson⁸, O. Cabellos⁹, S. Goriely¹⁰, J. Leppanen¹¹, H. Leeb¹², A. Plompen¹³, and R. Mills¹⁴

¹ IAEA, ² PSI, ³ JUKO Research, ⁴ CCFE, ⁵ Uppsala Univ., ⁶ NRG, ⁷ CEA, ⁸ Vattenfall, ⁹ NEA, ¹⁰ ULB, ¹¹ VTT, ¹² ATI, ¹³ IRMM, ¹⁴ NNLL.

TENDL2015 contains evaluations for :

seven types of incident particles (n, p, d, t, He-3, alpha-particle, gamma ray)

all isotopes living more than 1 second (~ 2800 isotopes)

all files are original except 15 (natural carbon from JENDL-4.0, ^{1,2,3}H, ^{2,3}He, ^{6,7}Li, ^{10,11}B, ⁹Be, ^{14,15}N, ¹⁶O and ¹⁹F from ENDF/B-VII.1)

TALYS

TALYS

Code for the simulation of nuclear reactions

Projectiles : n, p, d, t, He-3, α particles

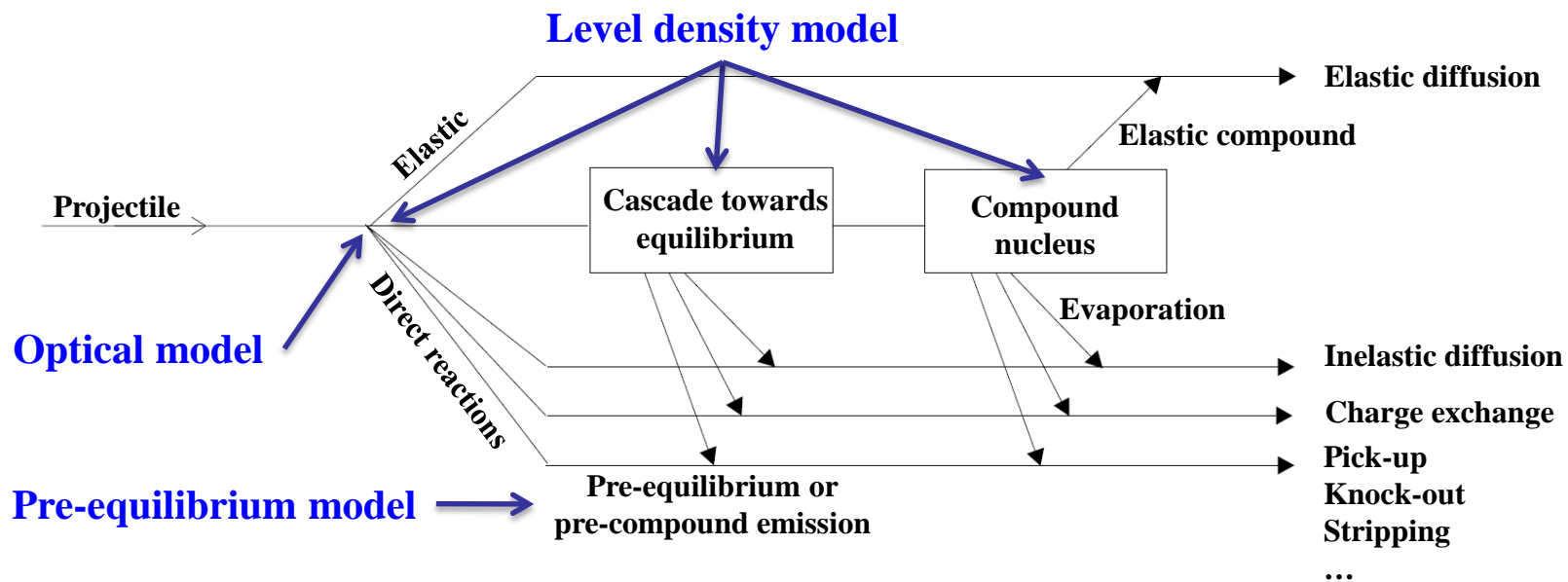
Many state-of-the-art nuclear models

Energy : 1 keV to 1 GeV

Provide a complete description of all reactions channels and observables

Targets : $Z = 3$ to 110

Nuclear reactions

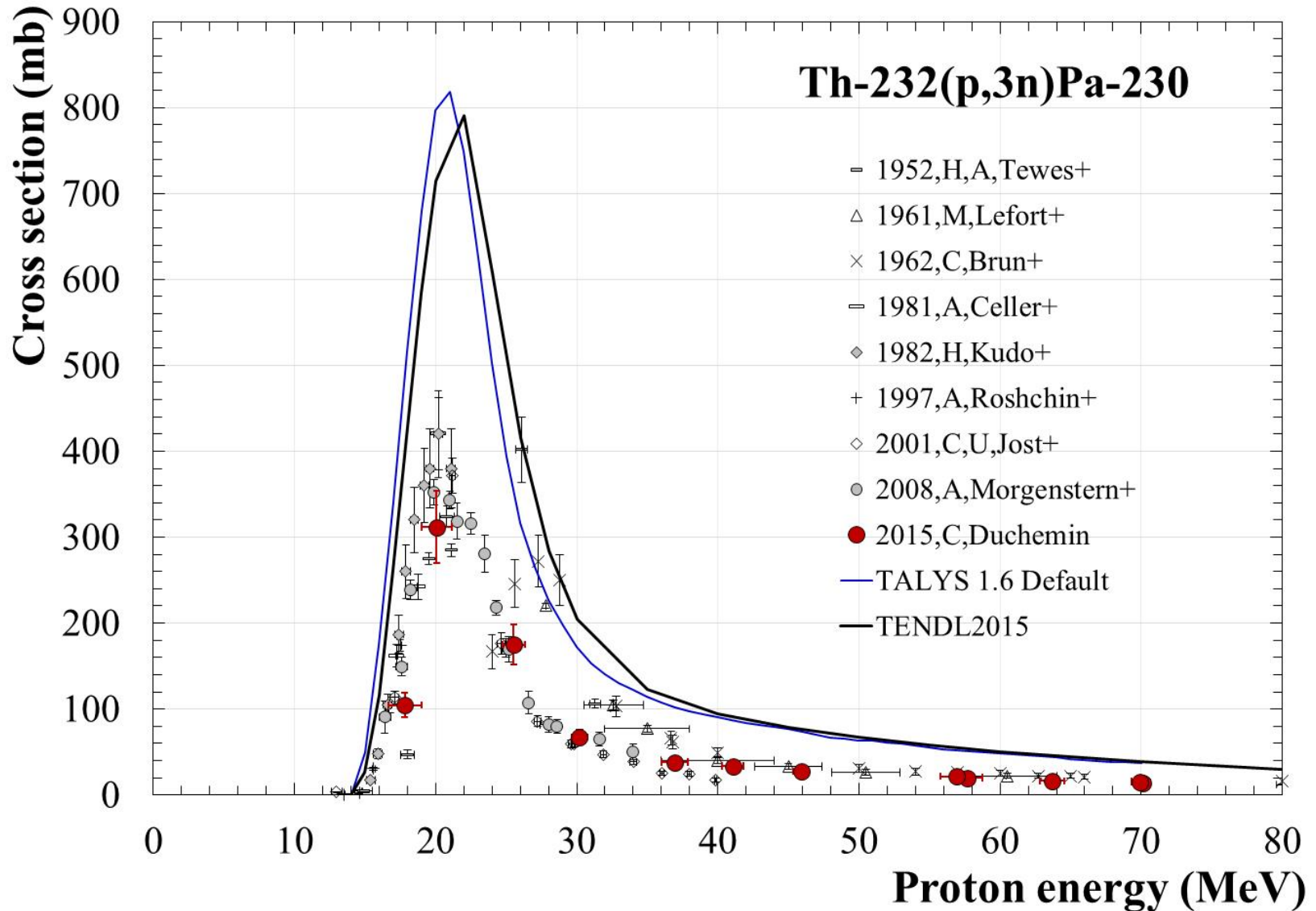


⇒ Influence on the calculated production cross section values

TALYS 1.6 Default: the combination of models that best describes the whole set of available data for all projectiles, targets and incident energies defined by the TALYS authors

Adapted from S. Benck, PhD thesis, 1999

An example: Th-232(p,3n)Pa-230



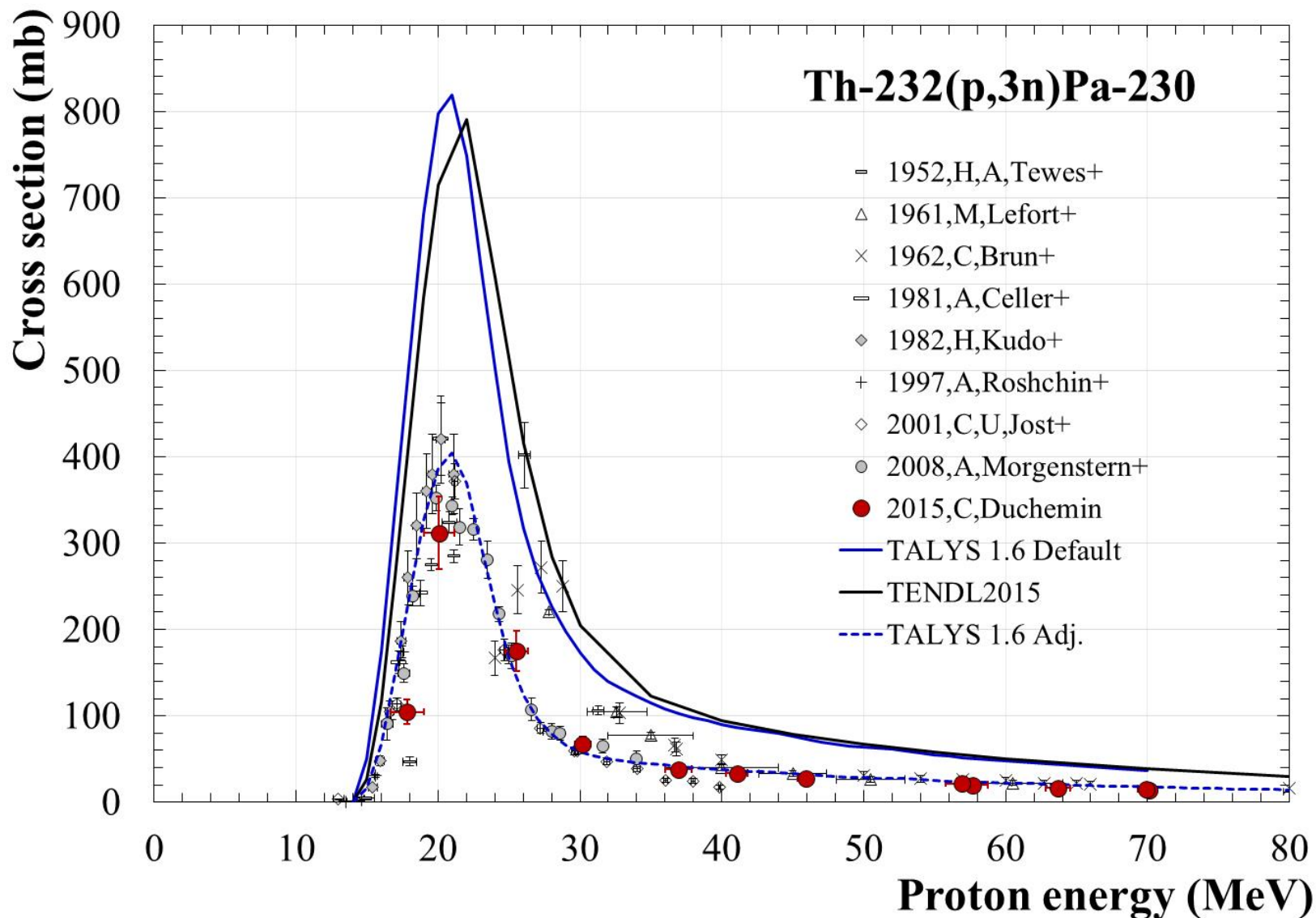
TALYS

TALYS 1.6 Adj:

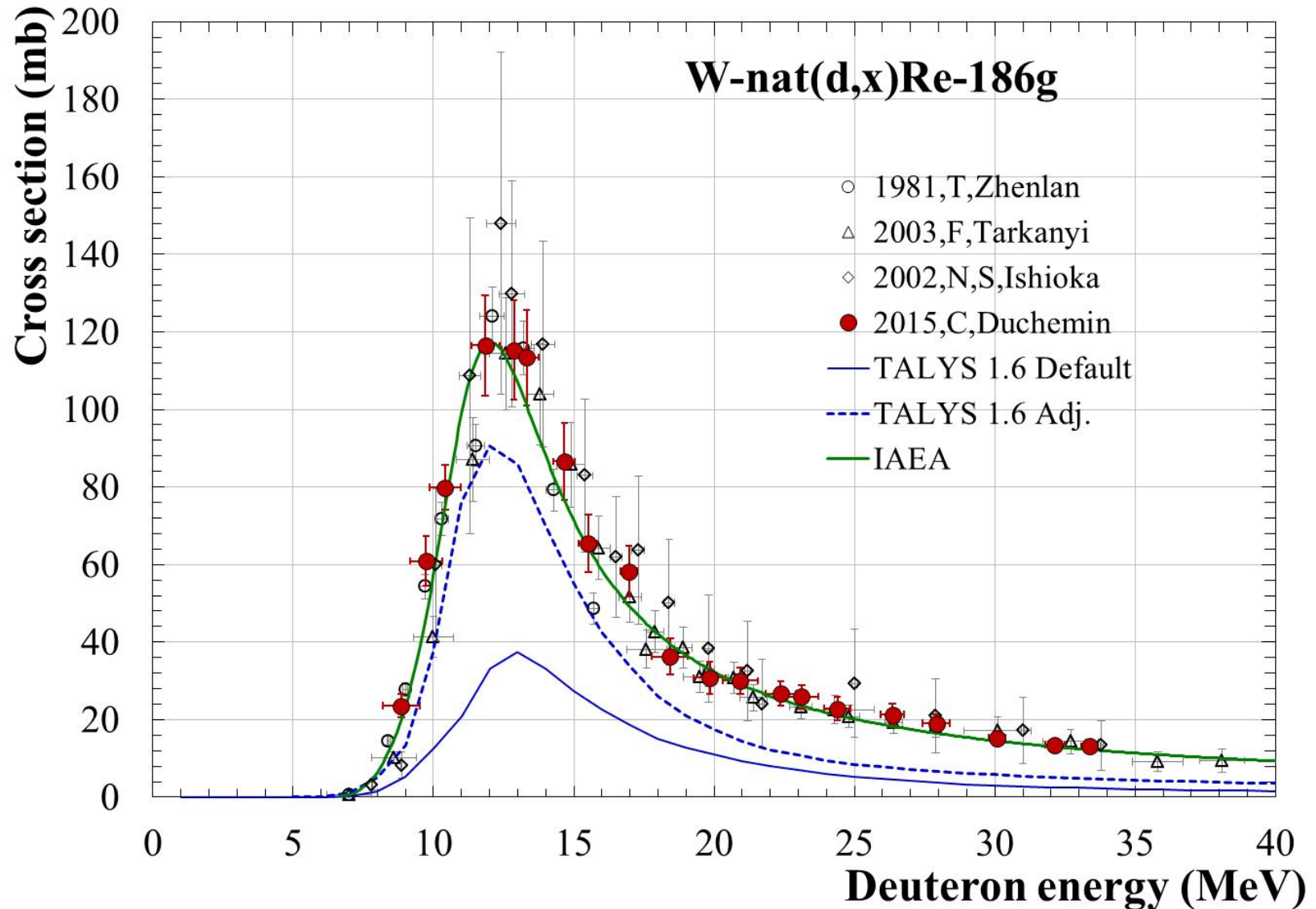
- One combination of models that best describes our whole set of data for proton, deuteron, alpha particles as projectile has been defined.
- We also looked to data available in the literature

Models	Projectile	Default	Adj.
Optical	p (1)	A.J. Koning and J.P. Delaroche (2003)	A.J. Koning and J.P. Delaroche (2003)
	d (5)	S. Watanabe (1958) ...	Y. Han et al. (2006) ...
	α (5)	L. McFadden and G.R. Satchler (1966) ...	Demetriou et al. (2002) ...
Pre-equilibrium	All (4)	2 components exciton A.J. Koning and M.C. Duijvestijn (2004) ...	Exciton model including numerical transition rates for collision probabilities A.J. Koning and M.C. Duijvestijn (2004) ...
Level density	All (6)	Fermi gas A.J. Koning et al. (2008) ...	Hilaire's combinatorial tables Goriely et al. (2008) ...

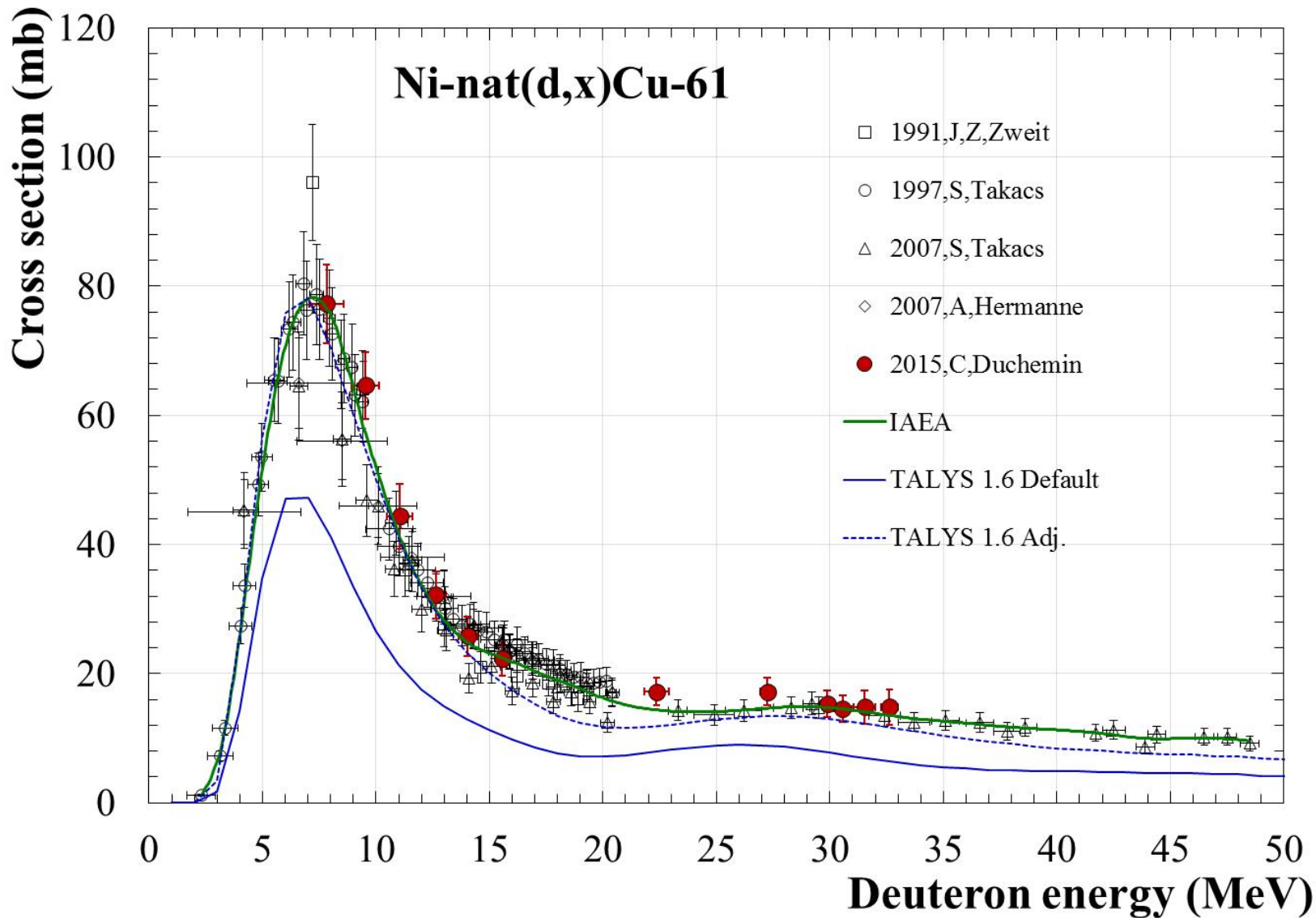
Proton induced reaction



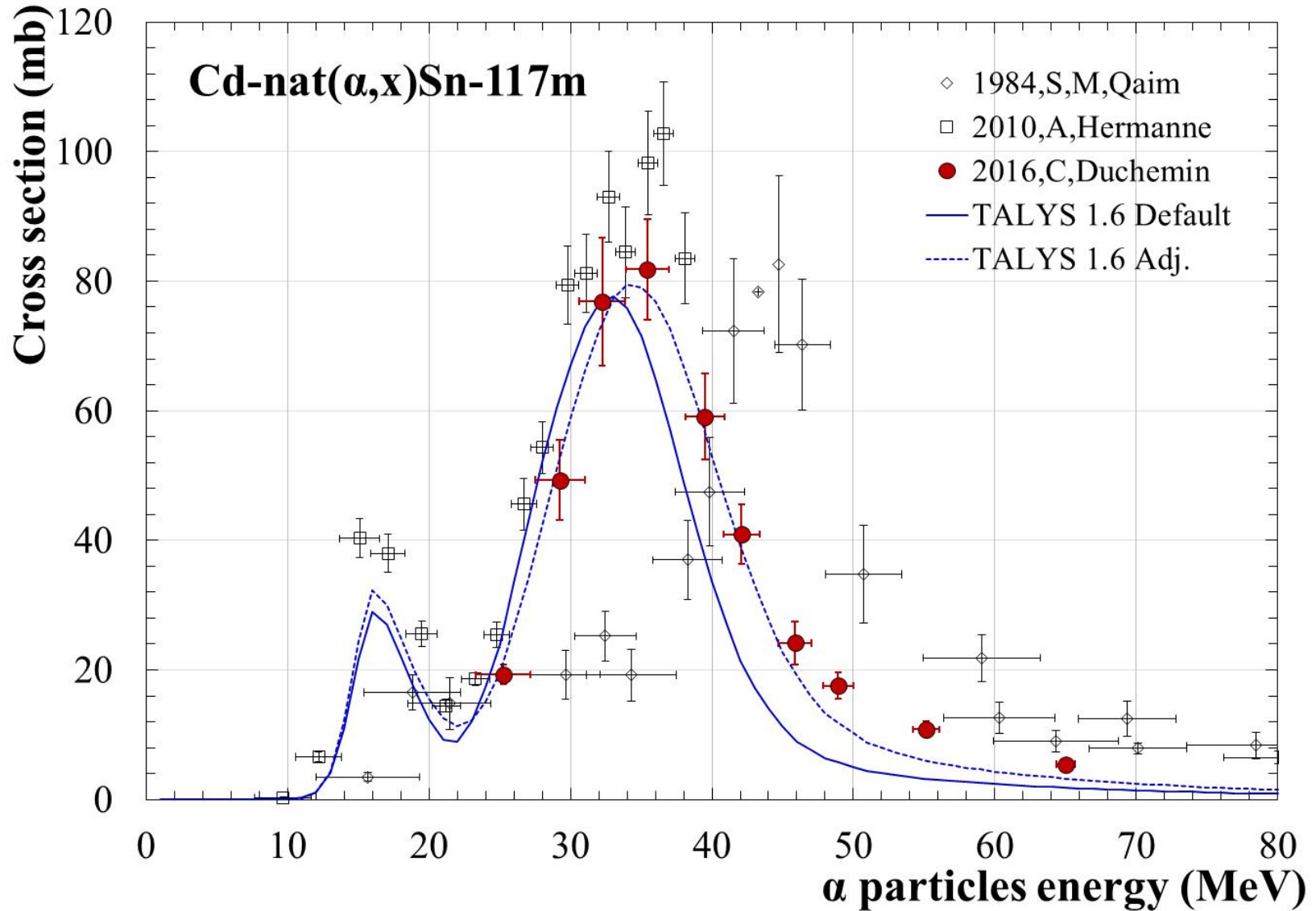
Deuteron induced reaction



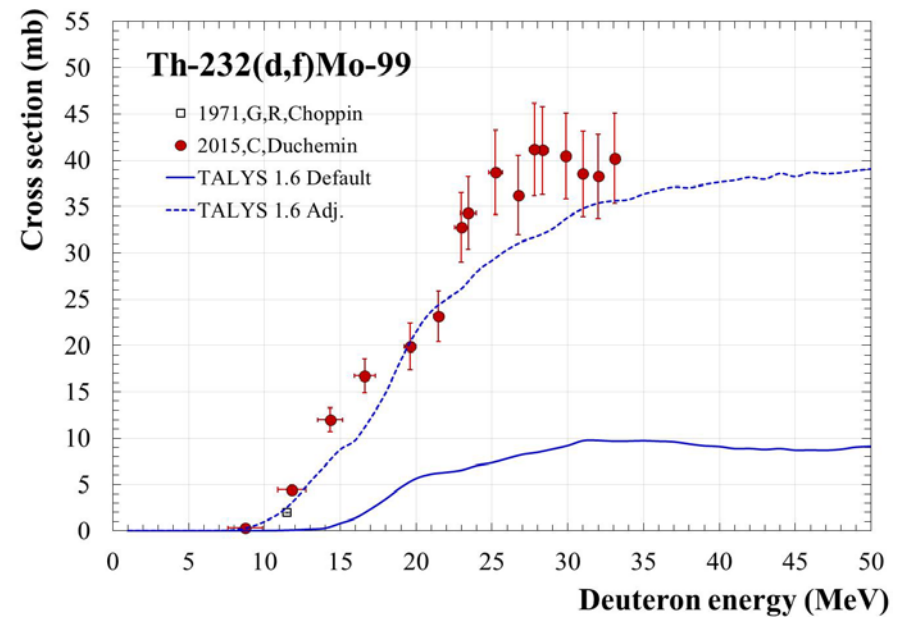
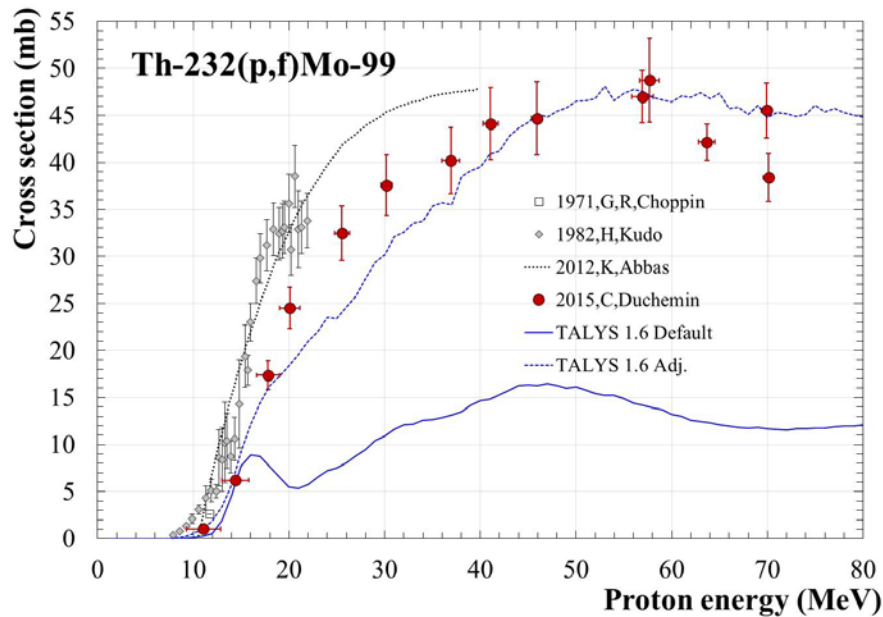
Monitor reaction: Ni-nat(d,x)Cu-61



α induced reaction



Light charged particle induced fission

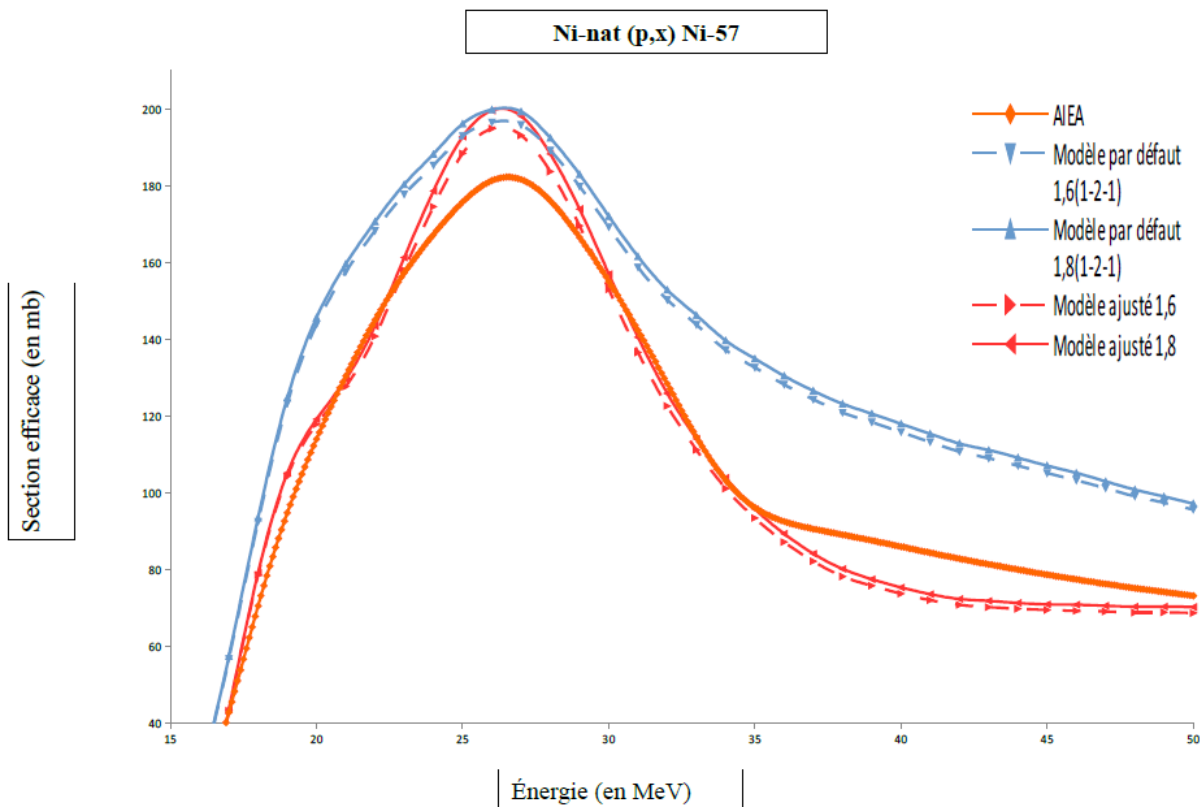


TALYS 1.8

Main differences with TALYS 1.6:

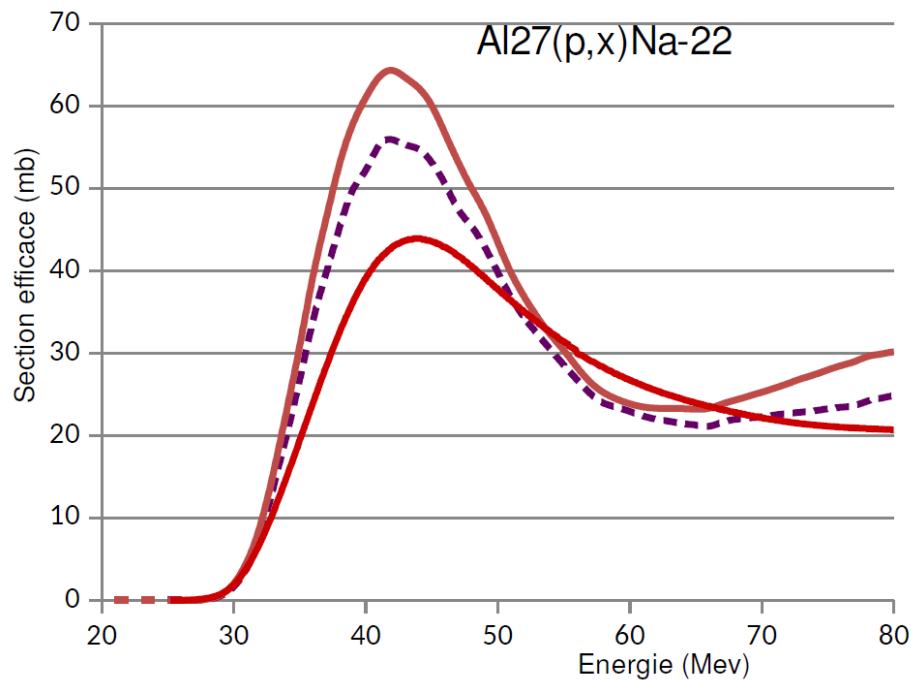
- **Extended mass range (up to $A=124$)**
- **New mass definition file (HFB24)**
- **Additional models (3) for the optical potential of alpha projectile**
- **A new microscopic description of the nuclear level density description**
 - **→ Idmodel 6** is based on temperature-dependent Hartree-Fock-Bogolyubov calculations using the Gogny force

New talys version 1.8

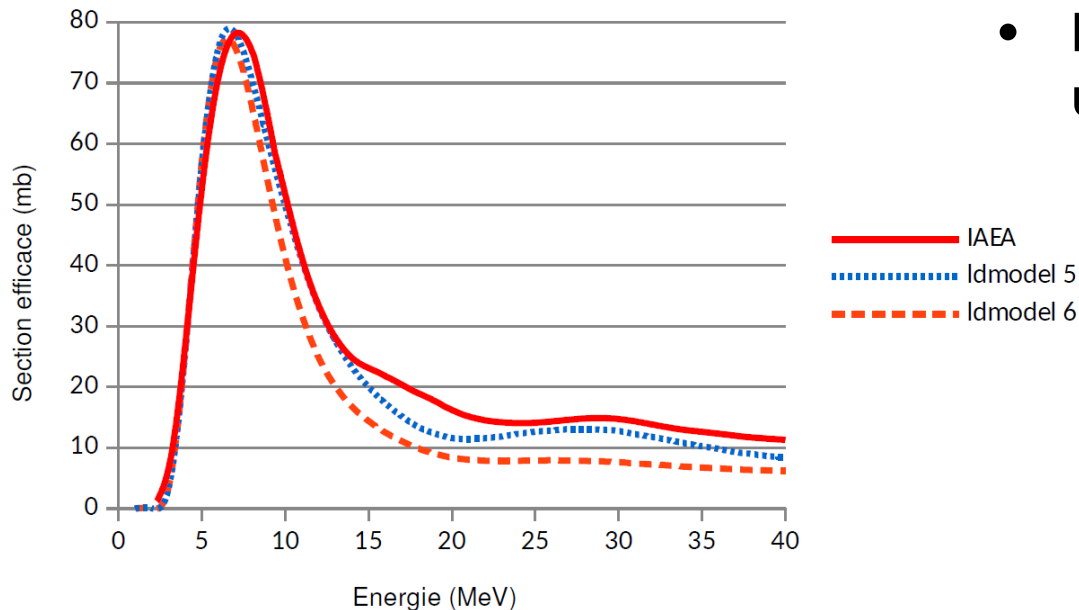


Despite changes in the Mass definition (HFB24) only small differences between the two versions in most cases

Impact of the new level density model



Ni0(d,x)Cr-51



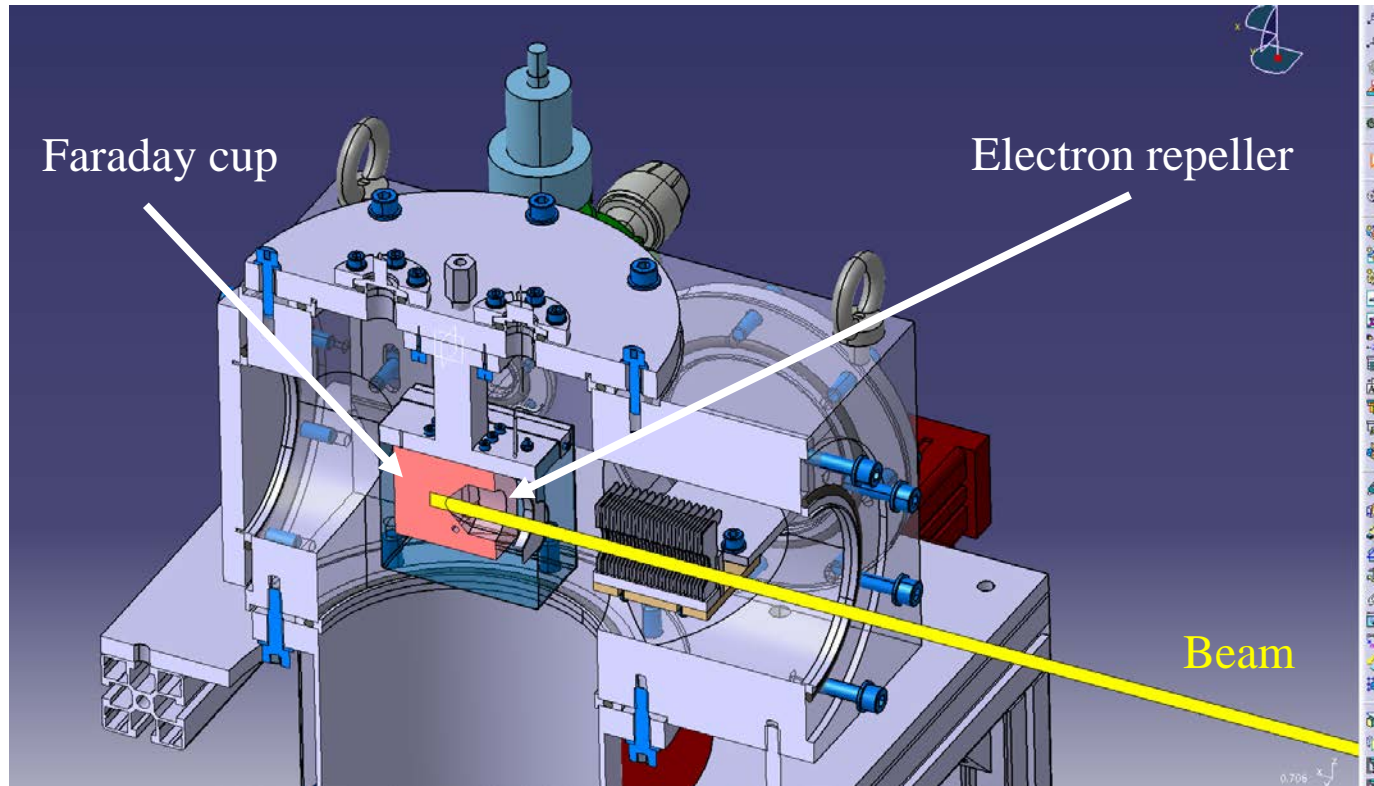
- New model included in the 1.8 version for level density description may give better description for protons
- Little influence found for others up to now

Further studies necessary

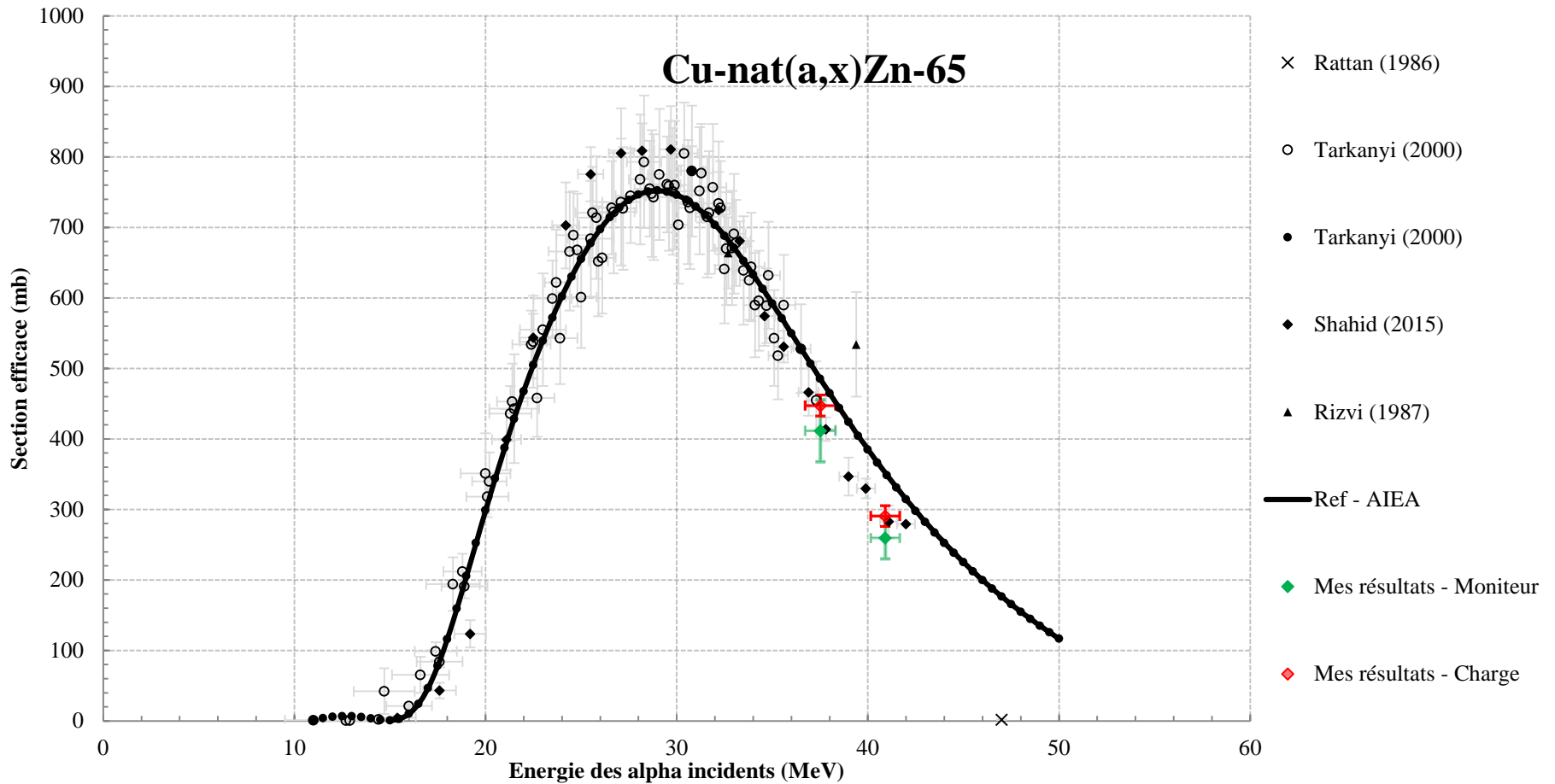
Improvement using a Faraday cup

Main error source with relative measurements \rightarrow the monitor reaction ($\sim 10\%$)

Use of a faraday cup allows for Absolute values with error associate to the Current digitizer use ($\sim 1-2\%$).



First results



Data consistent but reduce error bars

Conclusion and perspectives

A large set of data have been collected @ Arronax using the stacked-foil technique

- with different type of projectiles
- for materials all over the mass range

Comparisons have been performed systematically with the **TALYS 1.6 code**

- State of the art models included
- Possibility to combine models to better describe data
- Strong reactivity of authors

Three main mechanisms have been studied at the moment:

- Optical potential
- Level density description
- Preequilibrium model

A set of models have been found to allow a good description of all our collected data, which is different from the suggested default models.

Version 1.8 show only slight difference with the 1.6 on production cross section induces by light charged particles

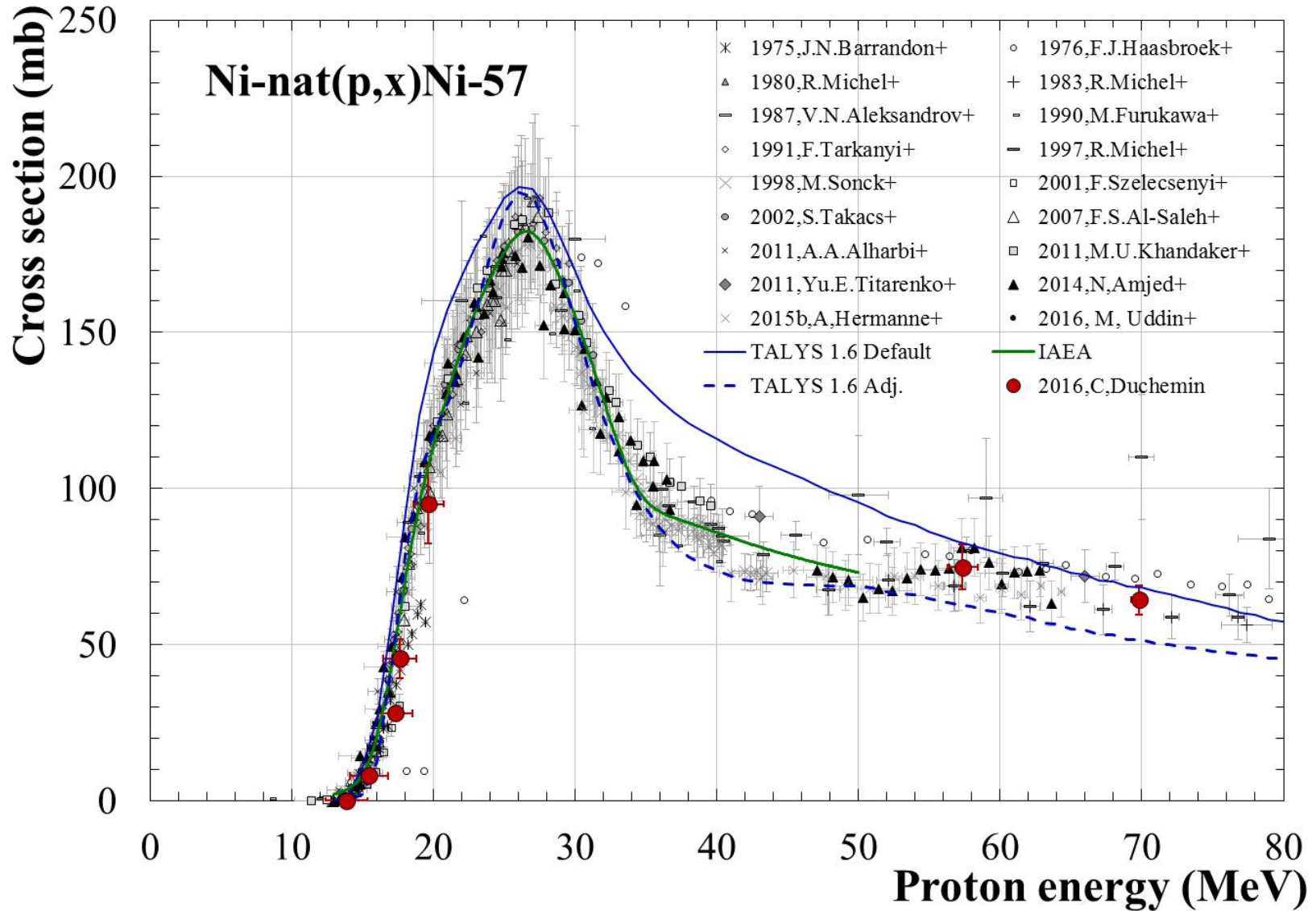
Further investigations will be done on other mechanisms that can affect our observable.

Thank you for your attention

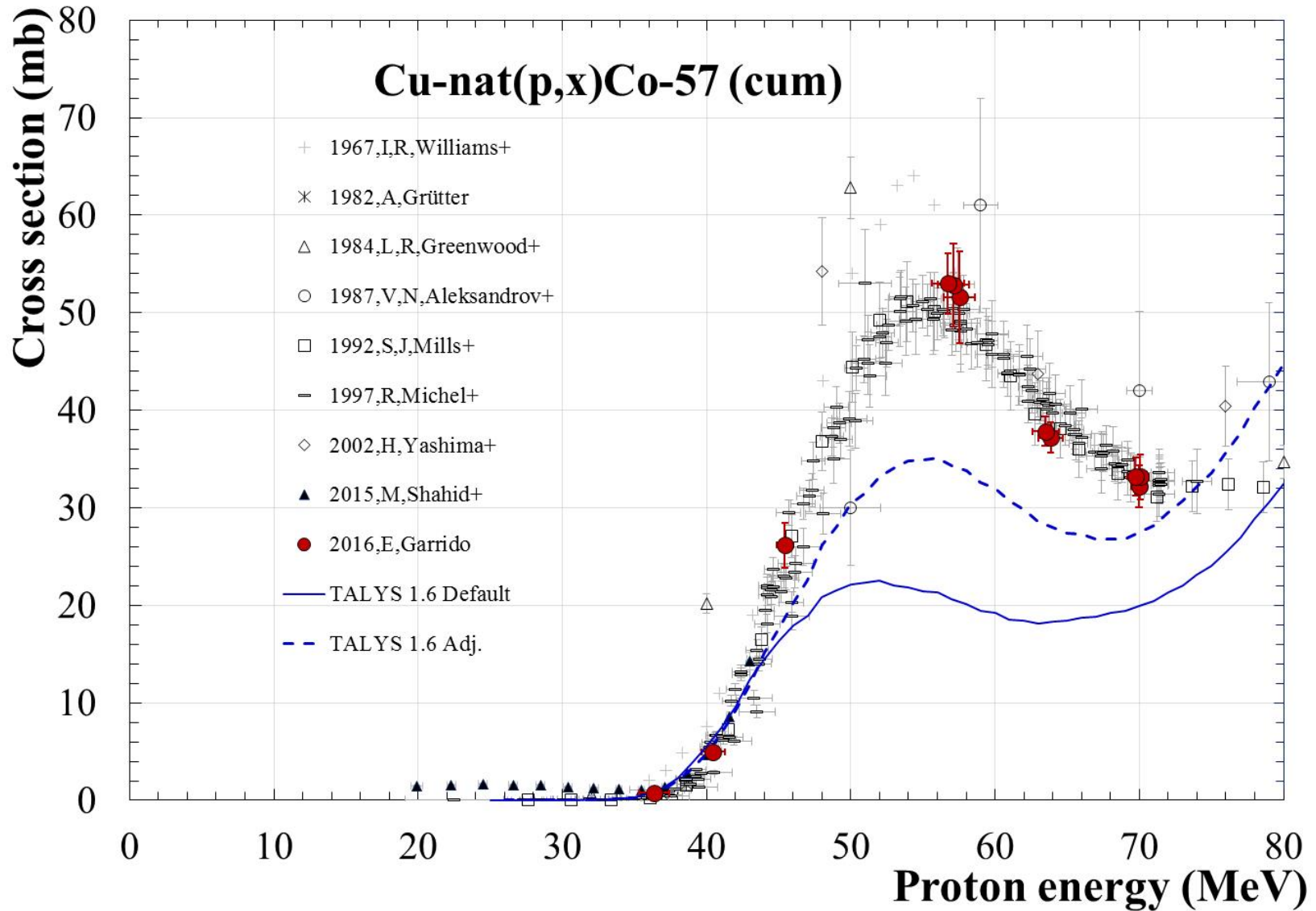
The **ARRONAX** project is supported by:
the **Regional Council of Pays de la Loire**
the **Université de Nantes**
the **French government (CNRS, INSERM)**
the **European Union**.

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Monitor reaction: Ni-nat(p,x)Ni-57



Other reaction: Cu-nat(p,x)Co-57



Other reaction: Ti-nat(α ,x)Sc-47

