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## Production of innovative radionuclides for therapy or diagnostic: nuclear data measurements and comparison with TALYS code

Arnaud Guertin, Etienne Nigron, Mateusz Sitarz, Charlotte Duchemin, Ferid Haddad, Vincent Métivier

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**Production of innovative radionuclides  
for therapy or diagnostic: nuclear data measurements  
and comparison with TALYS code**

**A. Guertin et al.**

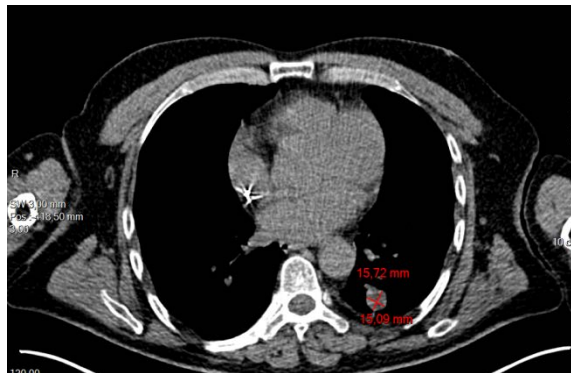
# Conventional imaging in oncology

**Visualize and localize tumors, measure them  
and evaluate the response to treatments**



*Centre François Baclesse*

Radiography



*Centre René Gauducheau*

Computerized Tomography  
Scanner



*Institut Roi Albert II*

Magnetic Resonance  
Imaging

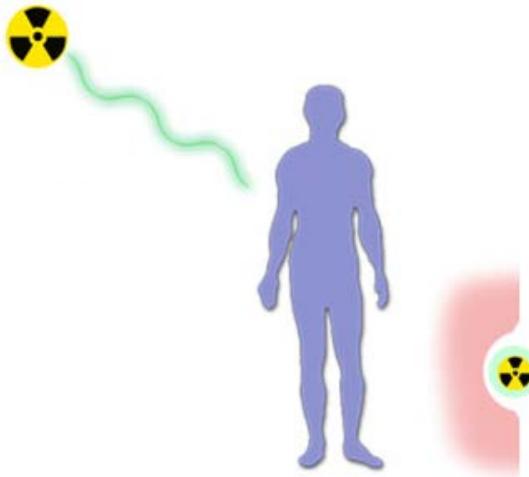
**These techniques allow to get accurate information on the morphology  
but give limited information on the metabolism**

**A gain can be obtain by coupling them with nuclear medicine  
technique ( SPECT or PET) which gives these information**

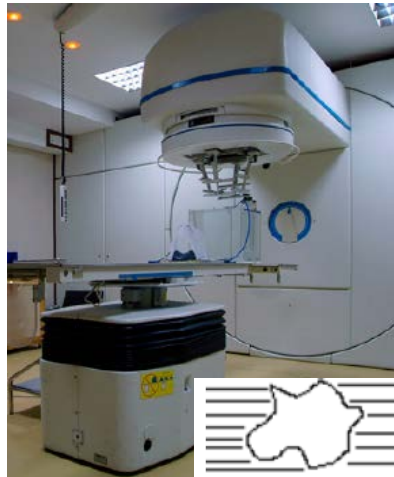
# Conventional radiotherapy

External beam radiotherapy:

- X rays, gamma, electrons
- Hadrontherapy



Brachytherapy  
 Curietherapy



*Institut de cancérologie de l'Ouest*



*ProteusOne, IBA*



*Institut de cancérologie de l'Ouest*

**These techniques are very efficient to treat a localized disease**

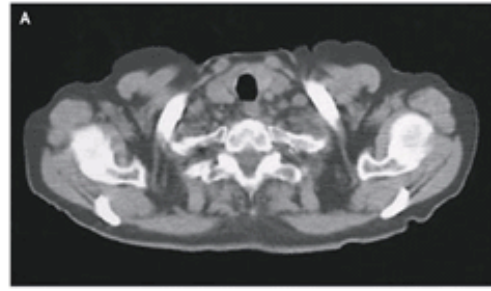
**Limit:** does not target disseminated disease or residual disease

**This can be address by nuclear medicine techniques**

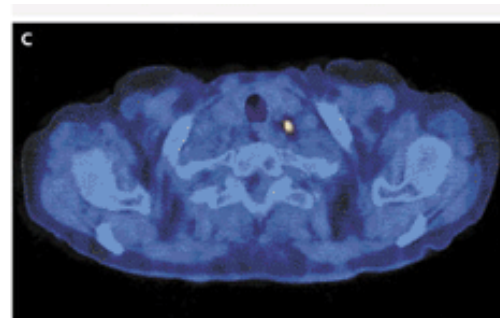
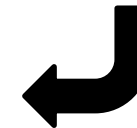
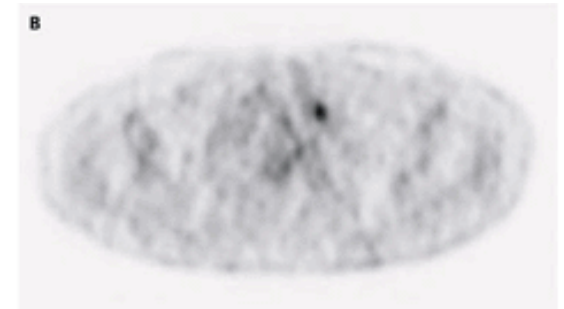
# Great progress in the last ten years

**Multimodality:** SPECT/CT, PET/CT then PET/MR

**Morphology**



**Metabolism**



**New targets, tracers and radionuclides (béta+, béta-, Auger and alpha)**

## Nuclear medicine

Many useful / potentially useful isotopes identified for applications in **nuclear medicine**

Cyclotrons and accelerators being used **in an increasing number** of countries along with reactors

- Diagnosis ( $\gamma$ ,  $\beta^+$ )
- Therapy ( $\beta^-$ ,  $\alpha$ ,  $e_{\text{Auger}}$ )

## Nuclear data

- **Accurate and reliable** sets of data
- Well defined **production routes and decay properties**
- **Optimum production** of specific radionuclides, minimization / elimination of **impurities**, realistic dose calculations

**Nuclear data needs** addressed by successive:

- Experimental physicist generations
- IAEA Coordinated Research Projects initiated in the 90's, European FPs, national programs

## Nuclear codes

Provide a **large set of nuclear data** in terms of targets, projectiles and energy range **to constrain and develop** predictive simulation tools of nuclear reactions

## A large set of radioisotopes with very different characteristics is suitable:

- **Radiation type** for the different applications
- Half-life to match the **bio-distribution** time
- Chemical properties to attach to the **vector molecule**
- Production yields to get the **purest product**
- Prod. capacities to envisaged **large scale use**

## The nuclear physicist could have crucial contribution:

- Identify production route and define production process (spallation, fission or activation)
- Identify and quantify contaminants
- Define waste management process
- Discuss with physicians to promote its use

## Over the last years, several radionuclides have emerged:

- $\beta^+$ : Cu-64, Ga-68, Zr-89 ...
- $\beta^-$ : Ho-166, Lu-177 ...
- **Theranostic**: Sc-44/Sc-47, Cu-64/Cu-67, Ga-68/Lu-177 ...
- **Auger**: Sn-117m, Tb-155 (at the research level for the moment)
- $\gamma$ : Sn-117m ...
- $\alpha$ : At-211, Bi-212, Bi-213, Ra-223, Ac-225 ...
- Terbium quadruplet: Tb-149, 152, 155, 161

**To do so, we possess facility (will possess) available for irradiations equipped with experimental techniques**



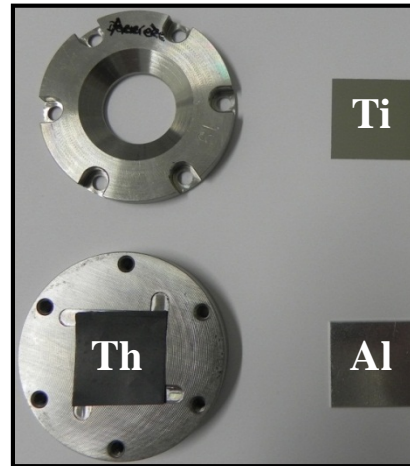
# Stacked-foil technique

## Stacked-foil technique:

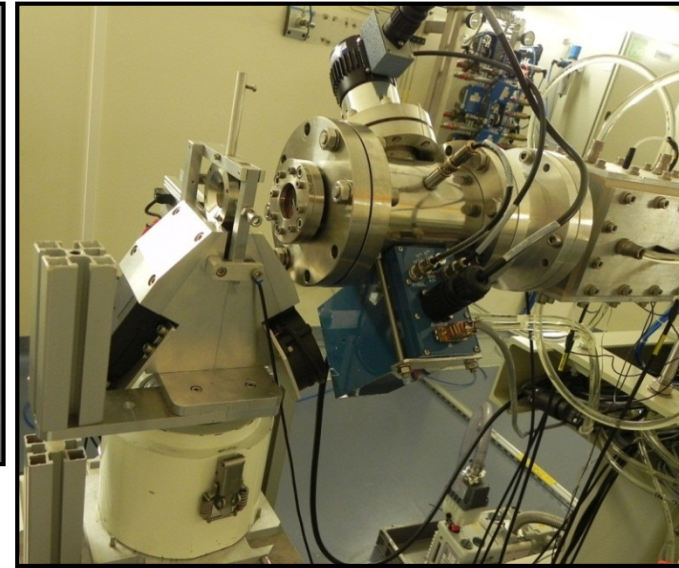
- Target/monitor/degrader **pattern**
- **Thin** foils:  
E loss small and constant
- One cross section value per foil

## Activity and cross section:

$$\sigma = \frac{\text{Act} \cdot A}{\chi \cdot \Phi \cdot \mathcal{N}_A \cdot \rho \cdot e \cdot (1 - e^{-\lambda \cdot t})}$$



Capsule and foils



Irradiation station and beam line

## Use of a Faraday cup:

- Beam dump placed at the end of the stack to control the intensity during the irradiation

## Use of a monitor foil:

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

- error on e, e':  $\leq 1\%$
- error on t: negligible

## IAEA recommended cross sections:

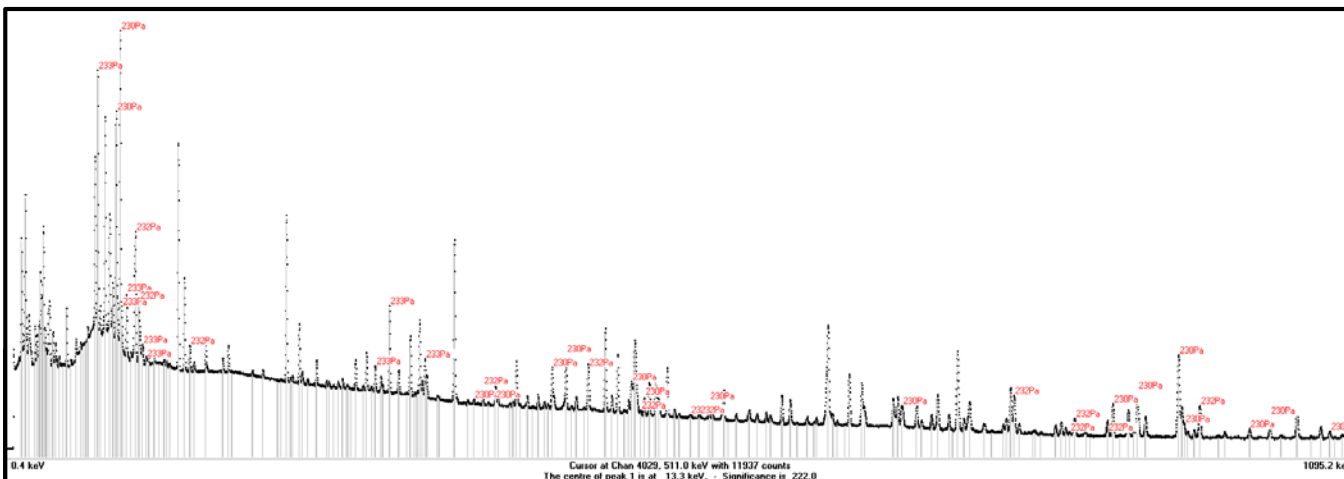
- 11 reactions available for protons  
 $^{27}\text{Al}$  (2),  $^{\text{nat}}\text{Ni}$ ,  $^{\text{nat}}\text{Ti}$  (2),  $^{\text{nat}}\text{Cu}$  (5),  $^{\text{nat}}\text{Mo}$
- 11 reactions available for deuterons  
 $^{27}\text{Al}$  (2),  $^{\text{nat}}\text{Fe}$ ,  $^{\text{nat}}\text{Ni}$ (3),  $^{\text{nat}}\text{Cu}$  (5),  $^{\text{nat}}\text{Ti}$ (2)
- 6 reactions available for alpha-particles  
 $^{27}\text{Al}$  (2),  $^{\text{nat}}\text{Ti}$  and  $^{\text{nat}}\text{Cu}$  (3)



# Stacked-foil technique

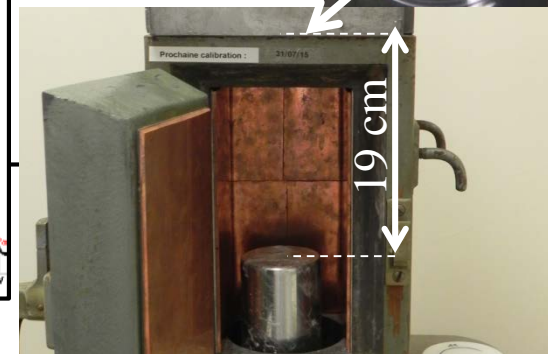
## Off line gamma spectroscopy

- **HPGe** coaxial detector
- Dead time: < 10% (sum peak)
- Activity values: FitzPeaks
- $T_{1/2}$ ,  $E_\gamma$ ,  $I_\gamma$ : Lund/LBNL, NNDC
- $\gamma$  spectra recorded on **8192 channels**
- FWHM: 1.04 keV at 122 keV ( $^{57}\text{Co}$ )
- 1.97 keV at 1332 keV ( $^{60}\text{Co}$ )
- Energy and efficiency calibrations: Co and Eu

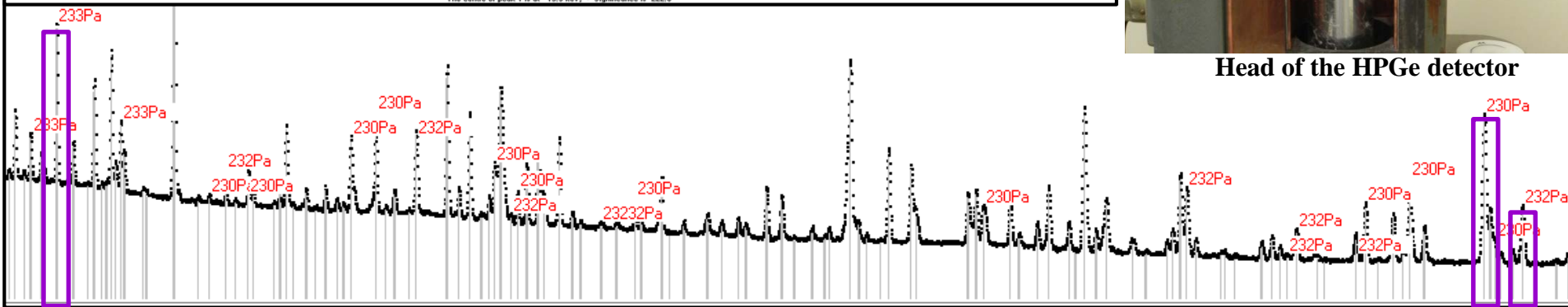


**Target and monitor:**

- ✓ counted twice
- ✓ during > 24 hrs
- ✓ 2 week delay



Head of the HPGe detector



$\gamma$  rays used to extract production cross section of  $^{230,232,233}\text{Pa}$

## Proton induced reactions:

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

C. Duchemin et al, Phys Med Biol **60** (2015) **931-946**

C. Duchemin et al, Phys Med Biol **60** (2015) **931-946**

V. Métivier et al, EPJ Web of Conf. **146** (2017) **08008**

E. Garrido et al., Nucl Instr Meth Phys Res B **383** (2016) **191-212**

## 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) **6847-6864**

C. Duchemin et al, Appl Radiat Isot **118** (2016) **281-289**

C. Duchemin et al, Appl Radiat Isot **97** (2015) **52-58**

V. Métivier et al, EPJ Web of Conf. **146** (2017) **08008**

C. Duchemin et al, Appl Radiat Isot **103** (2015) **160-165**

**“Production cross section of  $^{197m}\text{Hg}$  induced by deuterons on natural gold target”,  
Etienne Nigrón, Friday morning, deuteron induced reaction**

## Alpha induced reactions:

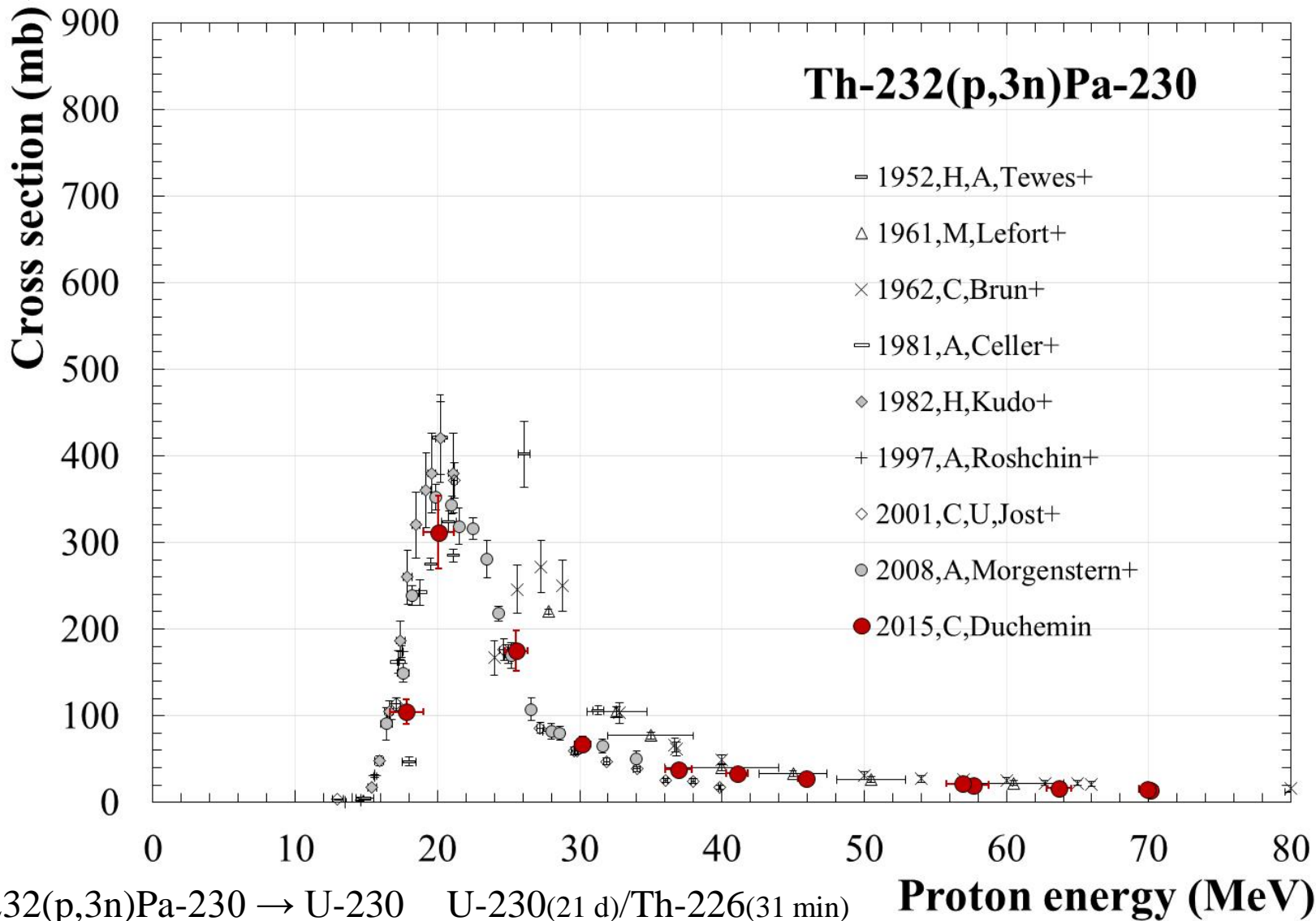
Sn-117m from Cd-116( $\alpha$ ,x)

Monitor reactions on Cu, Ti, Ni

C. Duchemin et al, Appl Radiat Isot **115** (2016) **113-124**

**“Production of medically interesting  $^{97}\text{Ru}$  via  $^{\text{nat}}\text{Mo}(\alpha, x)$  above 40 MeV at ARRONAX”,  
Mateusz Sitarz, today, in this session medical radioisotopes**

# Pa-230 as a precursor of an $\alpha$ generator



$\alpha$  RIT for leukaemia treatment

4  $\alpha$  cascade of 27.7 MeV

*C. Duchemin et al., Phys. Med. Biol. 60 (2015) 931-946*

Code for the simulation of nuclear reactions

Projectiles : n, p, d, t, He-3,  $\alpha$  particles

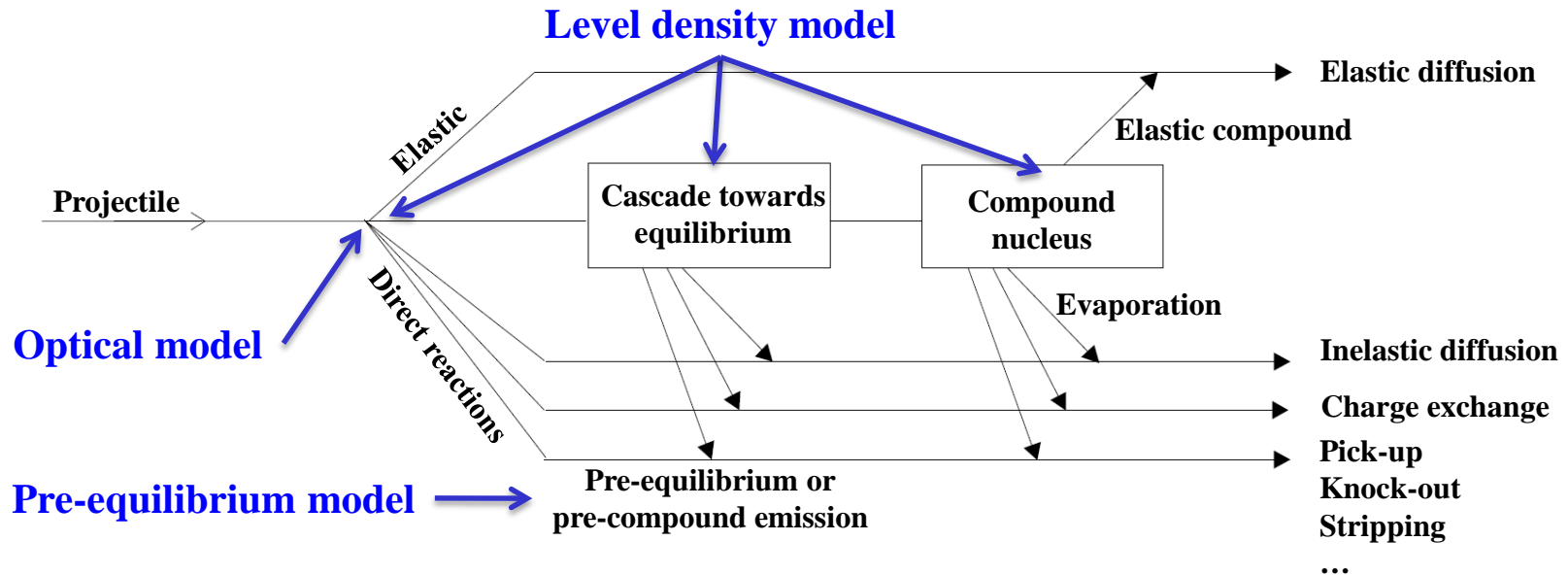
Many state-of-the-art nuclear models

Energy : 1 keV to 1 GeV

Provide a complete description of all reactions channels and observables

Targets :  $Z = 3$  to 110

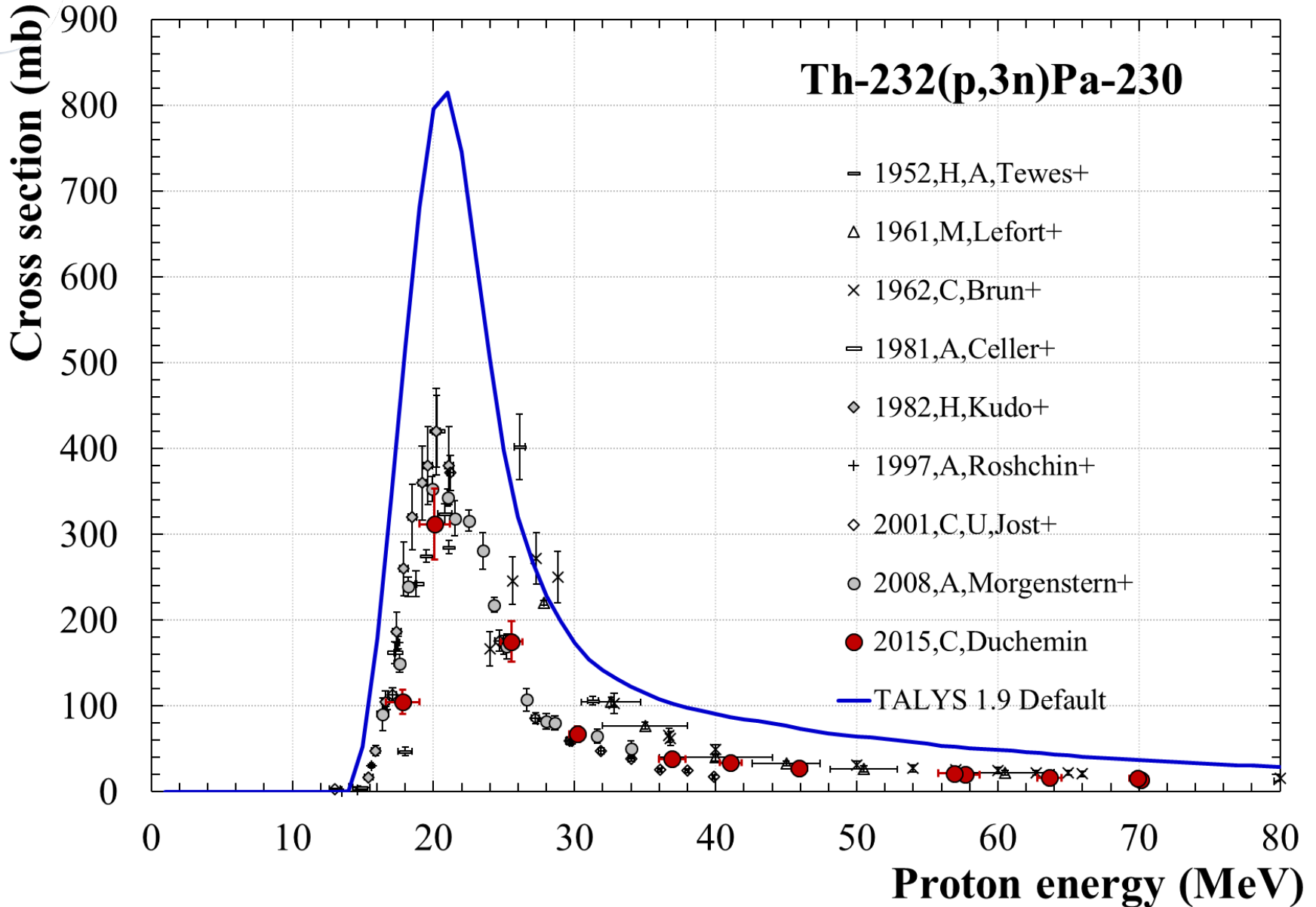
## Nuclear reactions



Adapted from S. Benck, PhD thesis, 1999

⇒ Influence on the calculated production cross section values

# Pa-230 as a precursor of an $\alpha$ generator



## TENDL2015

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



By A.J. Koning<sup>1</sup>, D. Rochman<sup>2</sup>, J. Kopecky<sup>3</sup>, J.Ch. Sublet<sup>4</sup>, M. Fleming<sup>4</sup>, E. Bauge<sup>7</sup>, S. Hilaire<sup>7</sup>, P. Romain<sup>7</sup>, B. Morillon<sup>7</sup>, H. Duarte<sup>7</sup>, S.C van der Marck<sup>6</sup>, S. Pomp<sup>5</sup>, H. Sjostrand<sup>5</sup>, R. Forrest<sup>1</sup>, H. Henriksson<sup>8</sup>, O. Cabellos<sup>9</sup>, S. Goriely<sup>10</sup>, J. Leppanen<sup>11</sup>, H. Leeb<sup>12</sup>, A. Plompen<sup>13</sup>, and R. Mills<sup>14</sup>

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

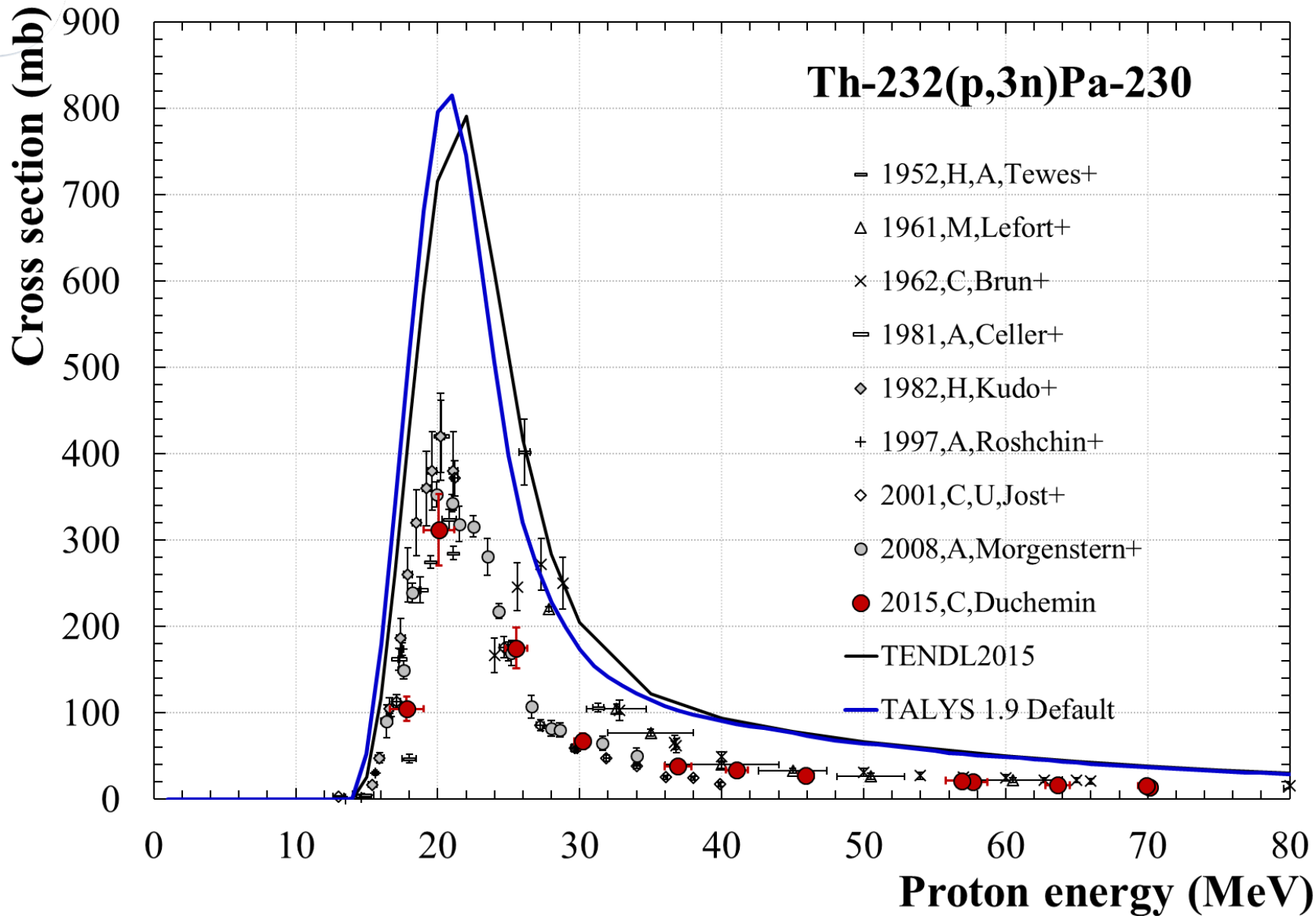
all files are original except 15 (natural carbon from JENDL-4.0, <sup>1,2,3</sup>H, <sup>2,3</sup>He, <sup>6,7</sup>Li, <sup>10,11</sup>B, <sup>9</sup>Be, <sup>14,15</sup>N, <sup>16</sup>O and <sup>19</sup>F from ENDF/B-VII.1)

Koning A.J. et al., [https://tendl.web.psi.ch/tendl\\_2015/tendl2015.html](https://tendl.web.psi.ch/tendl_2015/tendl2015.html)

Koning A.J. and Rochman D., Nucl. Data Sheets, 113, 2012



# Pa-230 as a precursor of an $\alpha$ generator



## TALYS default and adjusted calculations

TALYS code version 1.9

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

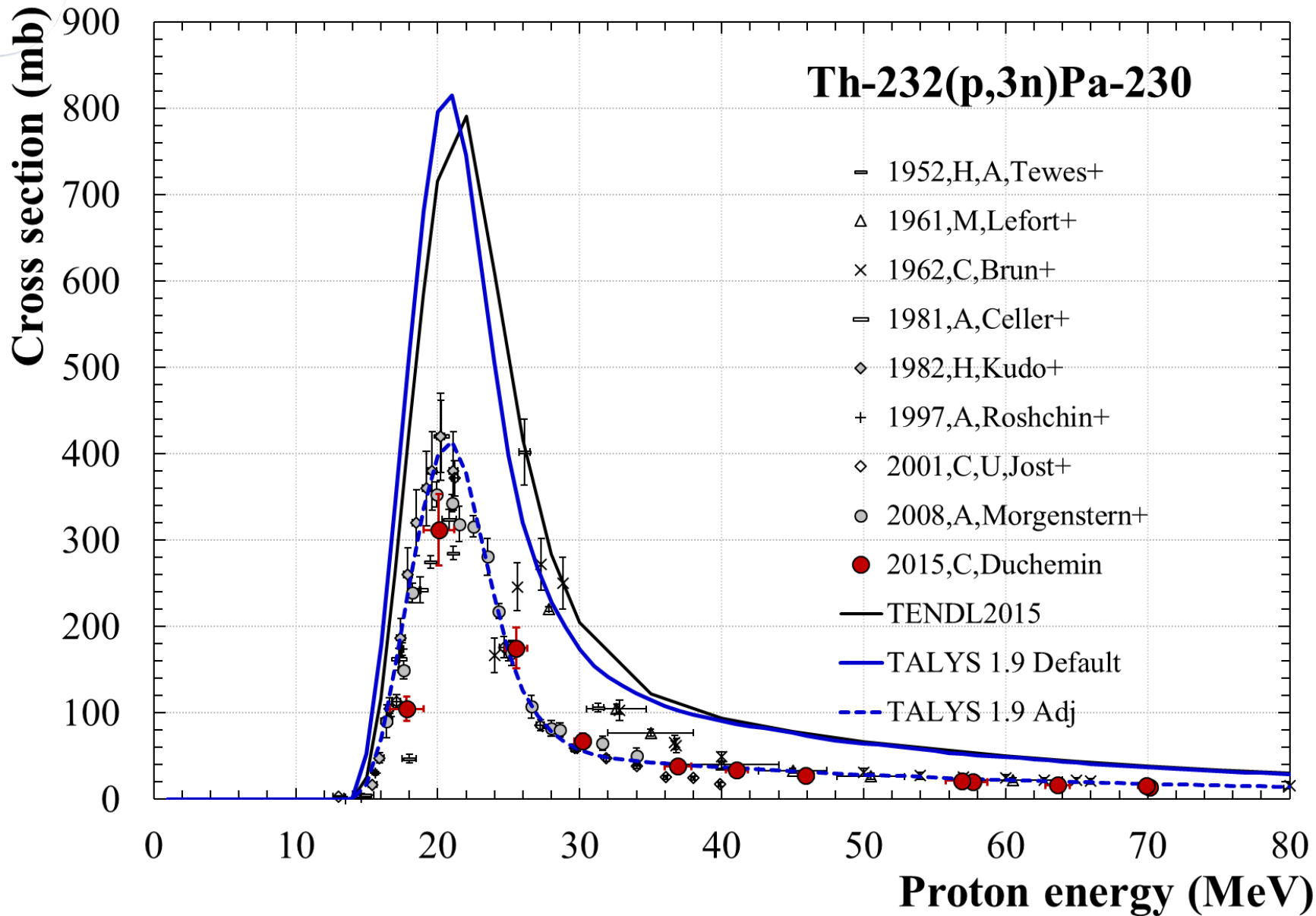
⇒ TALYS 1.9 Default

One combination of models that best describes our whole set of data for proton, deuteron, alpha particles as projectile (and also some literature data) has been defined by A. Guertin et al.

⇒ TALYS 1.9 Adj.

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)
	$\alpha$ (8)	V. Avrigeanu et al. (2014)	Demetriou et al. (2002)
Pre-equilibrium	All (4)	Two-component exciton model Numerical transition rates with E-dependent matrix element A.J. Koning and M.C. Duijvestijn (2004)	Two –component exciton model Numerical transition rates with optical model for collision probabilities A.J. Koning and M.C. Duijvestijn (2004)
Level density	All (6)	Constant temperature and Fermi gas model A.J. Koning et al. (2008)	Microscopic level density (Skyrme force) from Hilaire’s combinatorial tables Goriely et al. (2008)

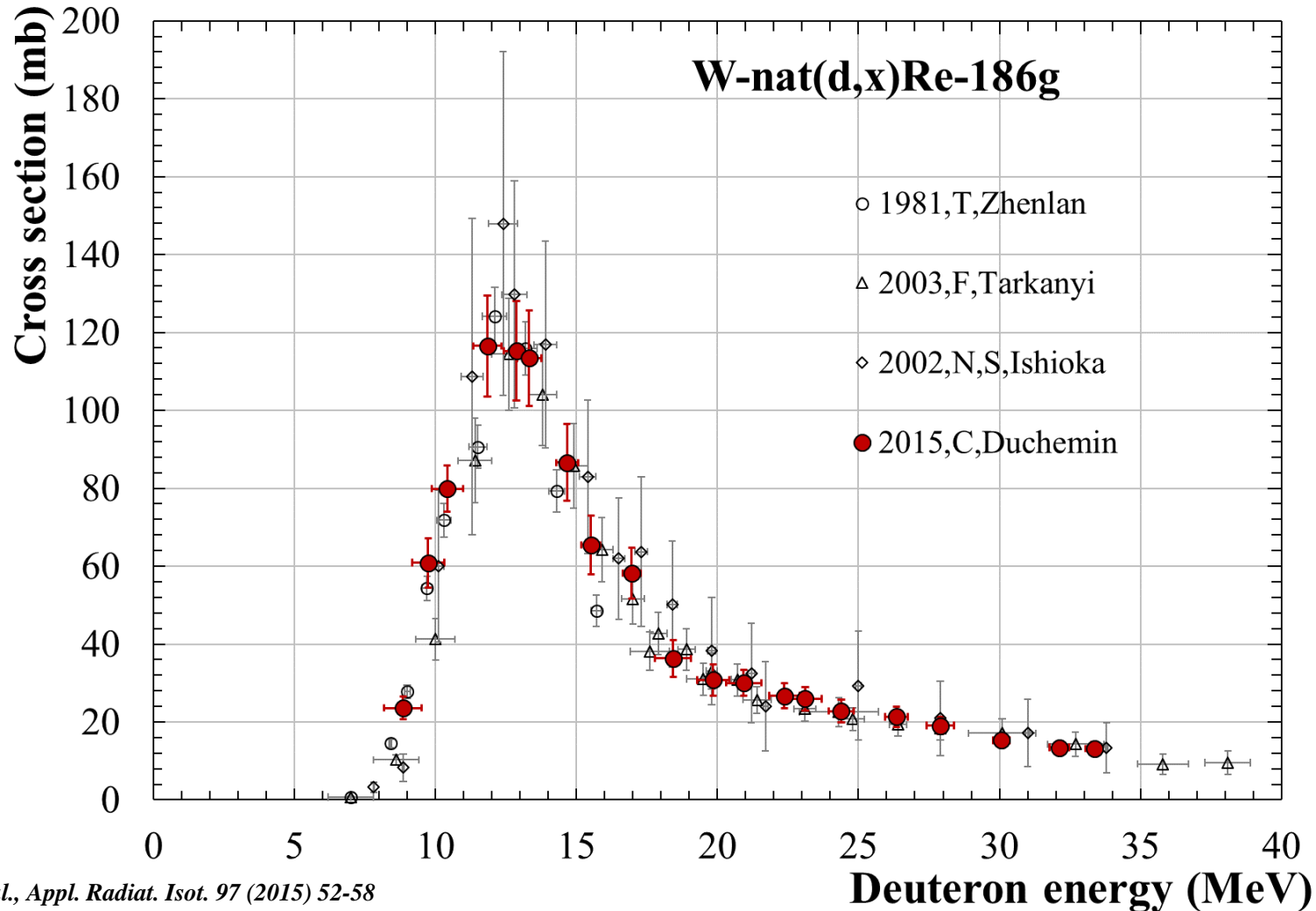
# Pa-230 as a precursor of an $\alpha$ generator



# Re-186g: proton/deuteron production route

**Re-186g ( $T_{1/2} = 3.7$  d)**

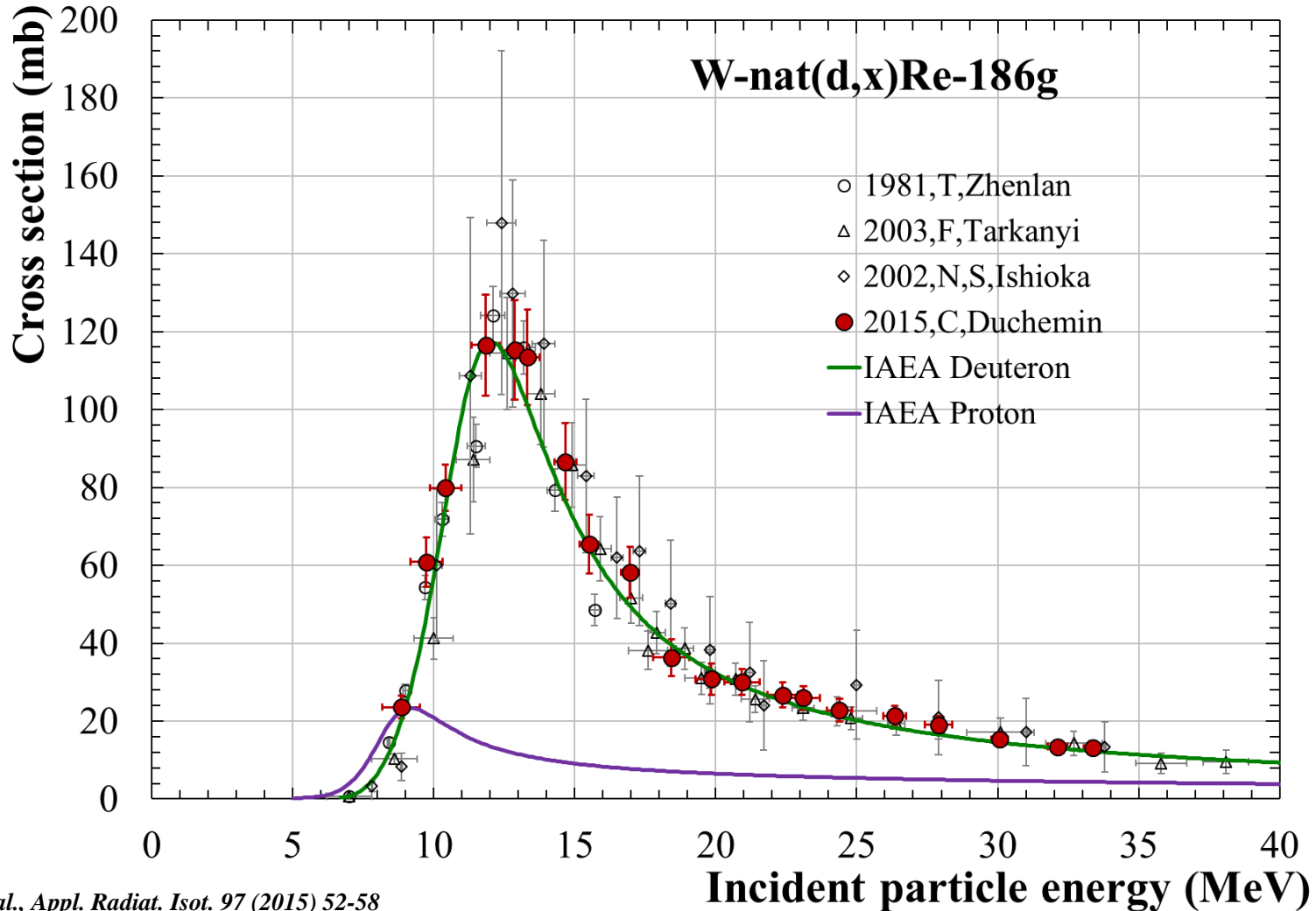
$\beta^-$ - emitter used in clinical trials for the palliation of painful bone metastases resulting from prostate and breast cancer



# Re-186g: proton/deuteron production route

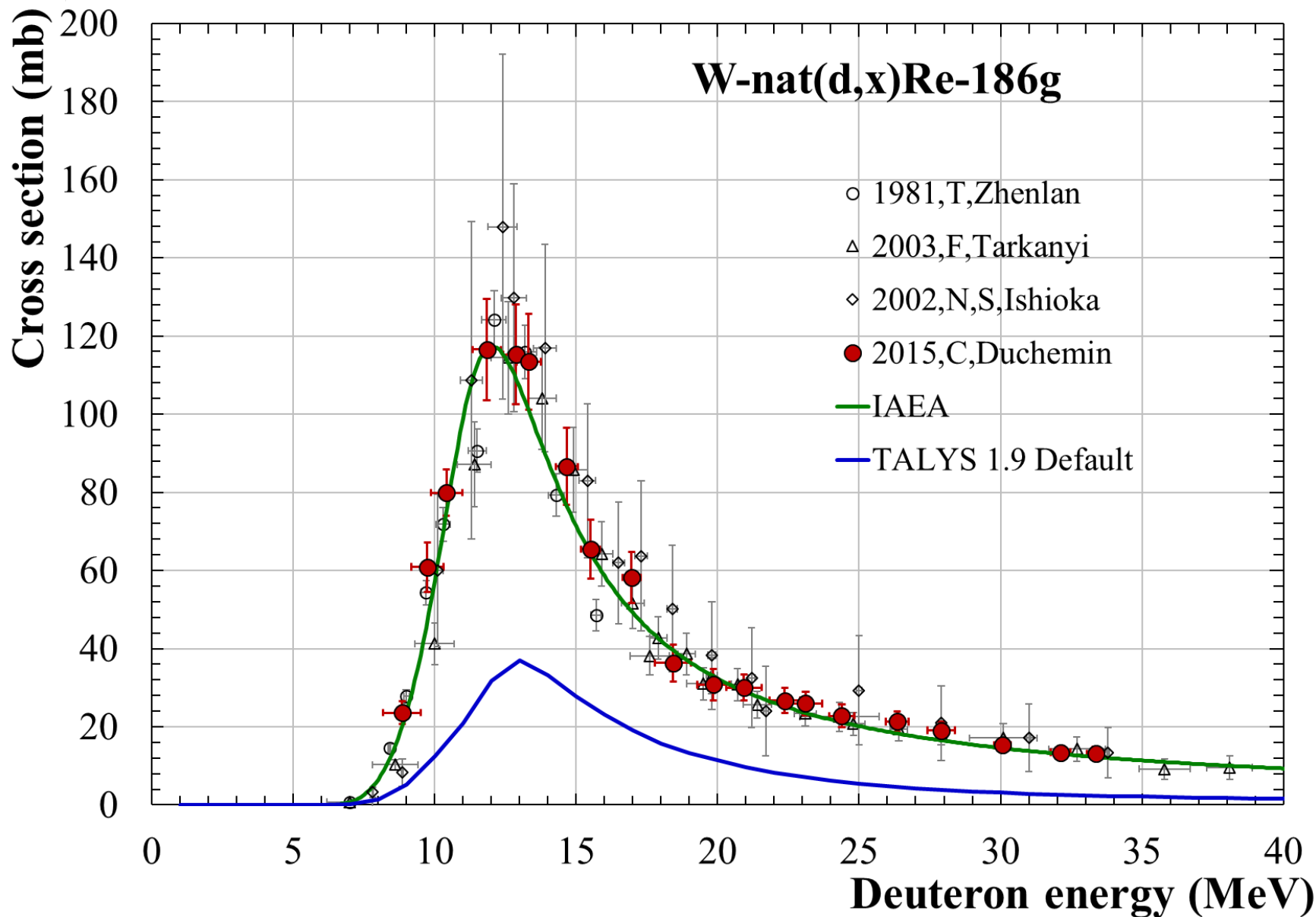
**Re-186g ( $T_{1/2} = 3.7$  d)**

Deuteron induced reaction has clearly a highest Re-186g production cross section



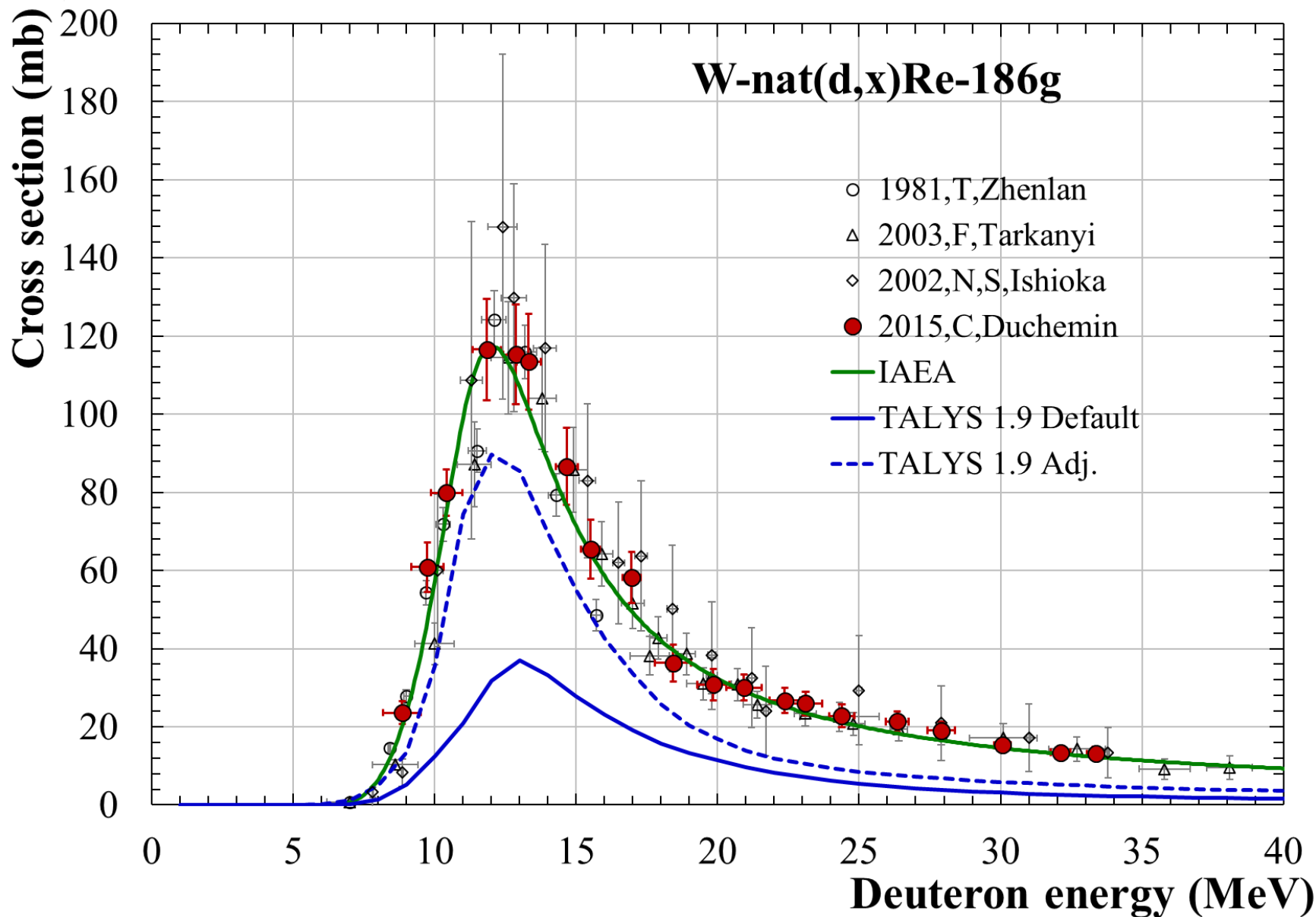
C. Duchemin et al., *Appl. Radiat. Isot.* 97 (2015) 52-58

# Re-186g: deuteron production route





# Re-186g: deuteron production route

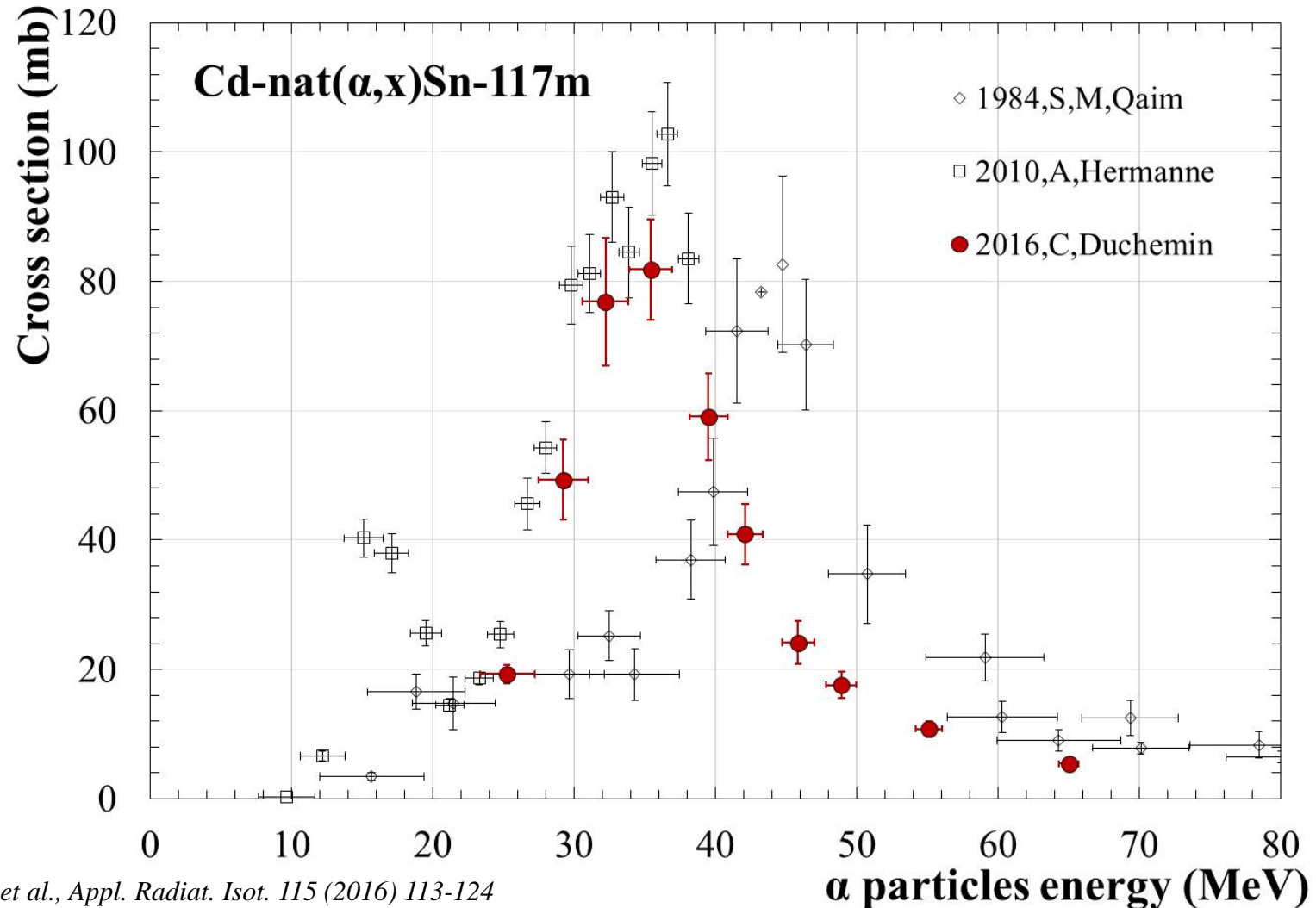


# Novel therapeutic and imaging nuclide

**Sn-117m ( $T_{1/2} = 13.6$  d)**

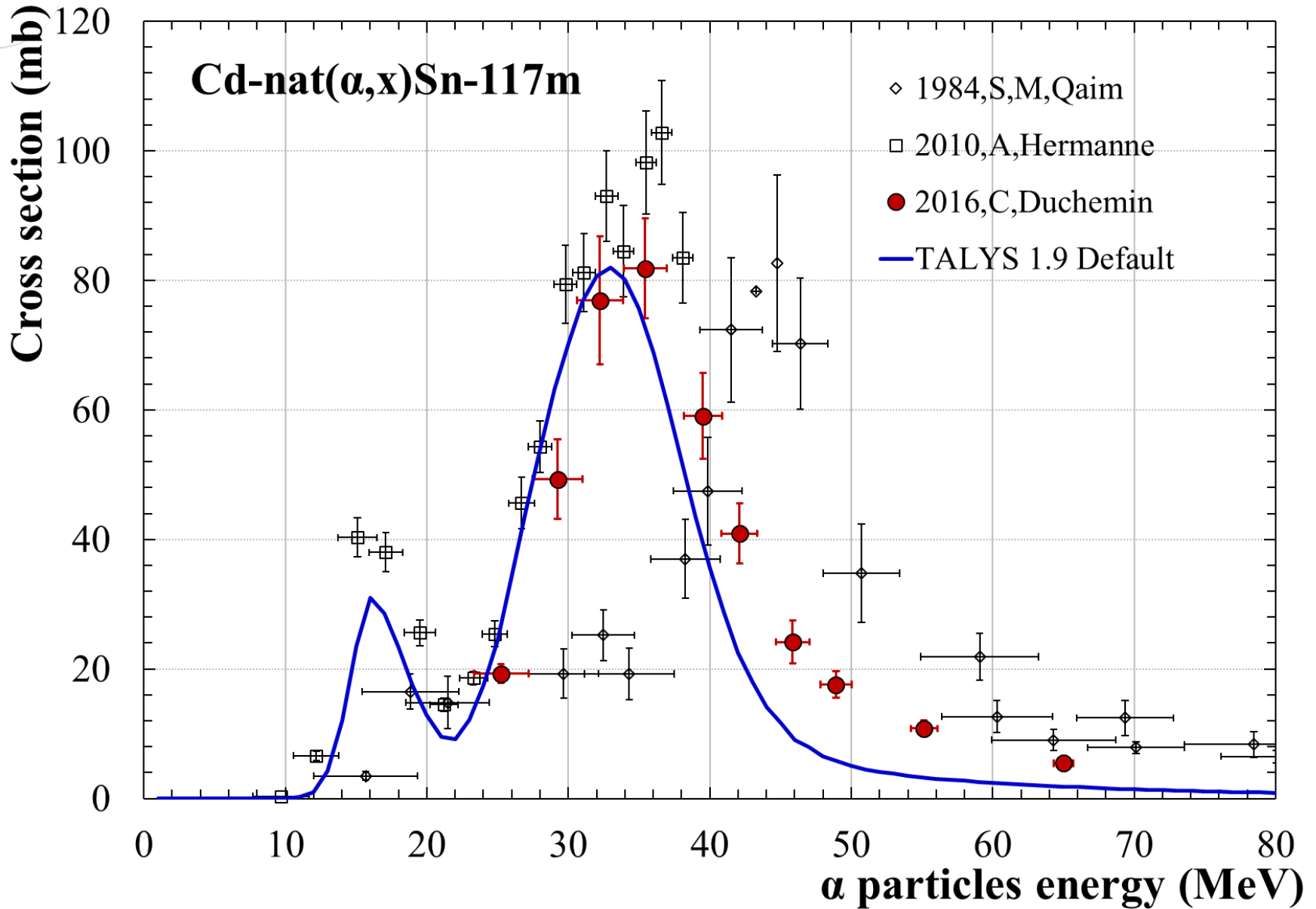
Conversion e- emitter used for the palliation of painful bone metastases

158 keV gamma ray suitable for SPECT imaging

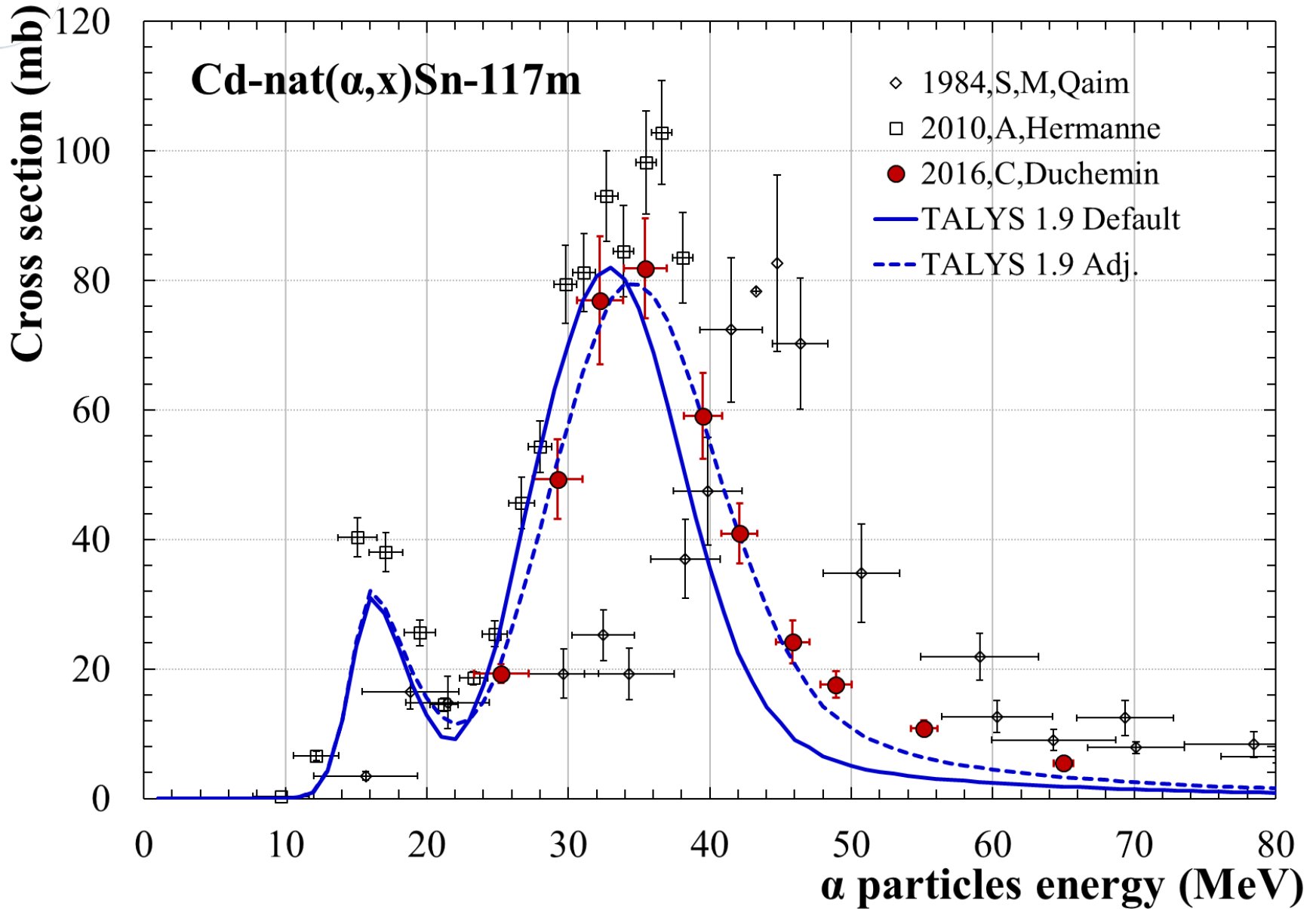


C. Duchemin et al., *Appl. Radiat. Isot.* 115 (2016) 113-124

# Novel therapeutic and imaging nuclide



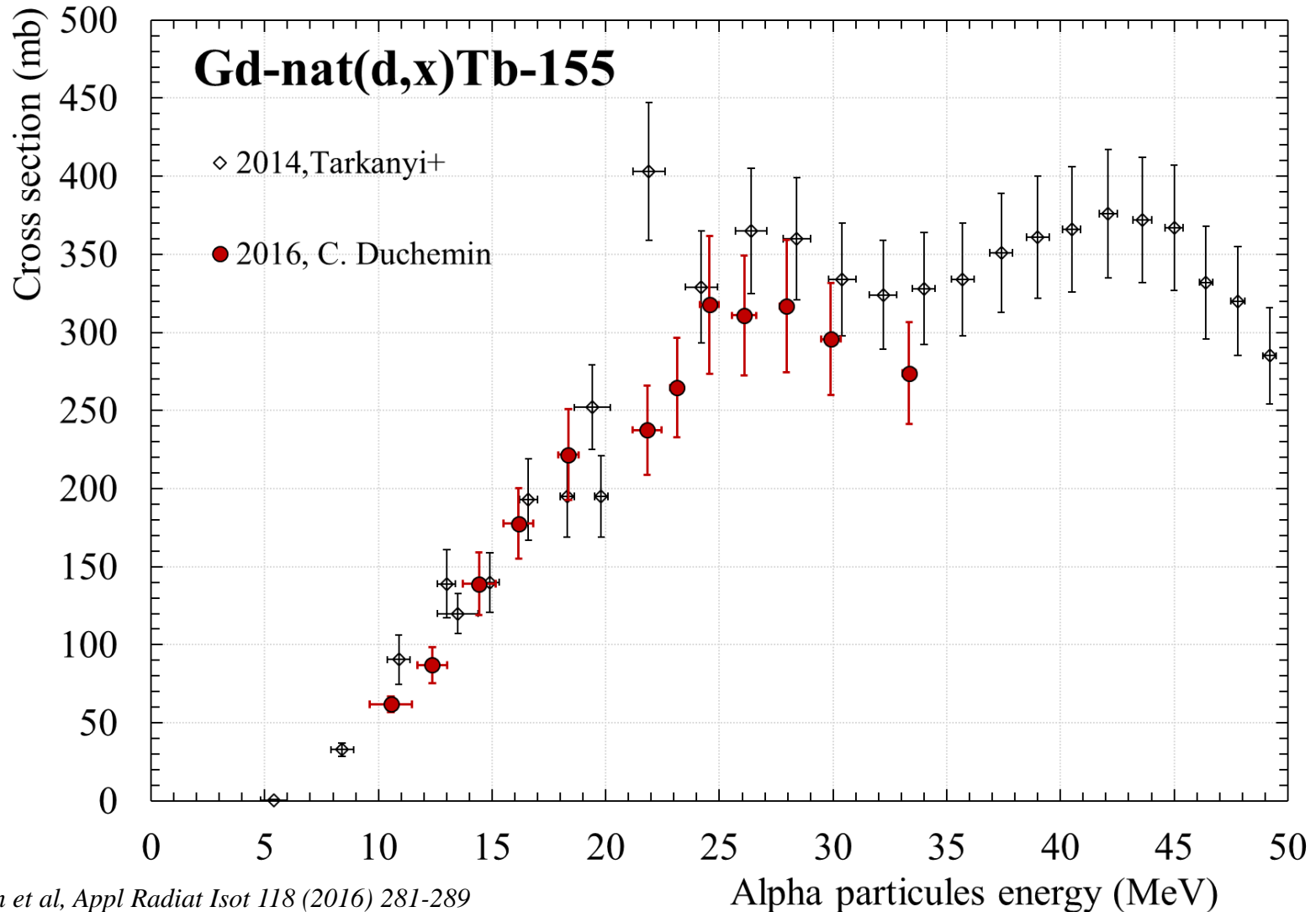
# Novel therapeutic and imaging nuclide



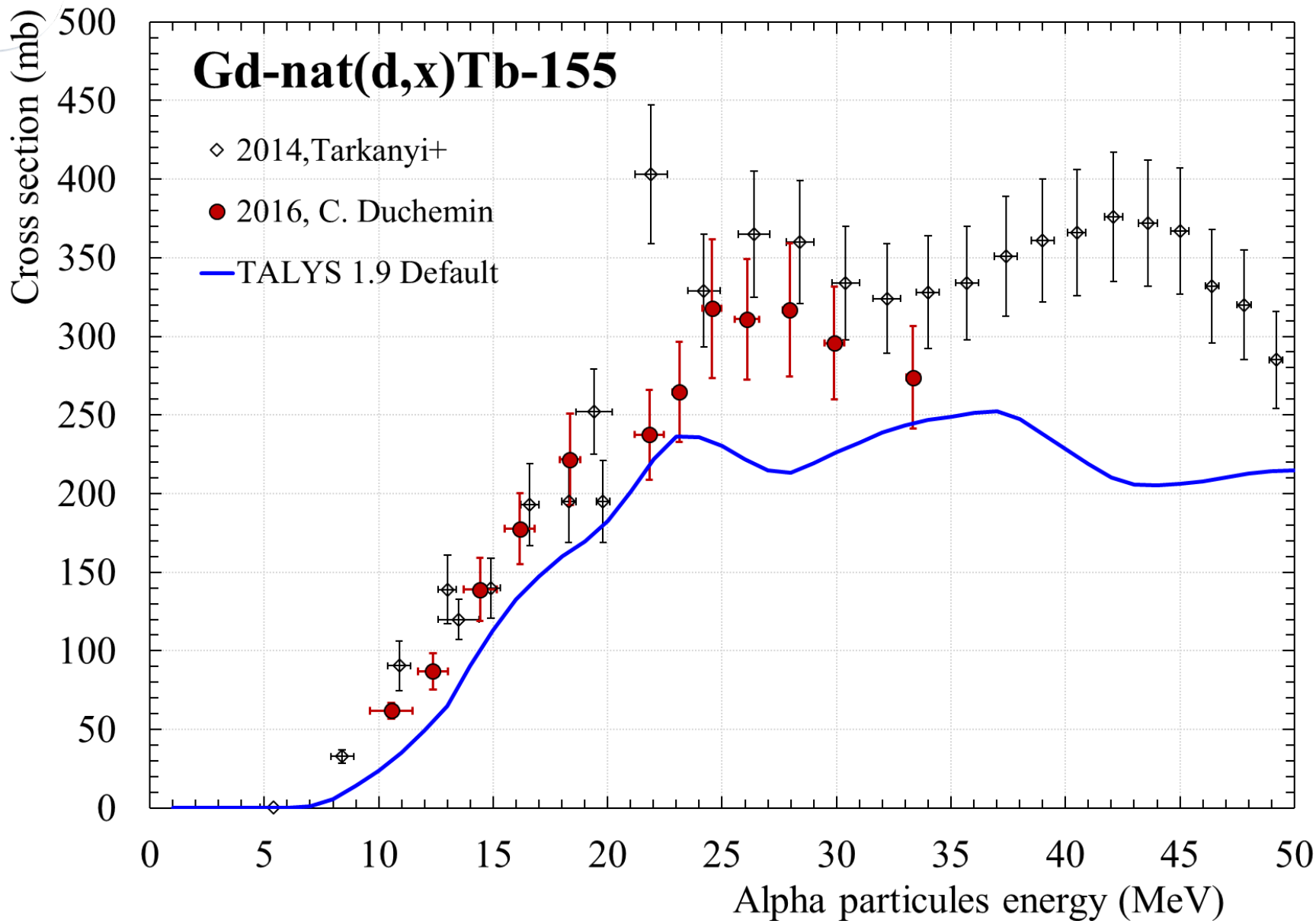
# Terbium 155: theranostic isotope

**Tb-155 ( $T_{1/2} = 5.3$  d)**

a theranostic isotope for SPECT imaging and Auger therapy

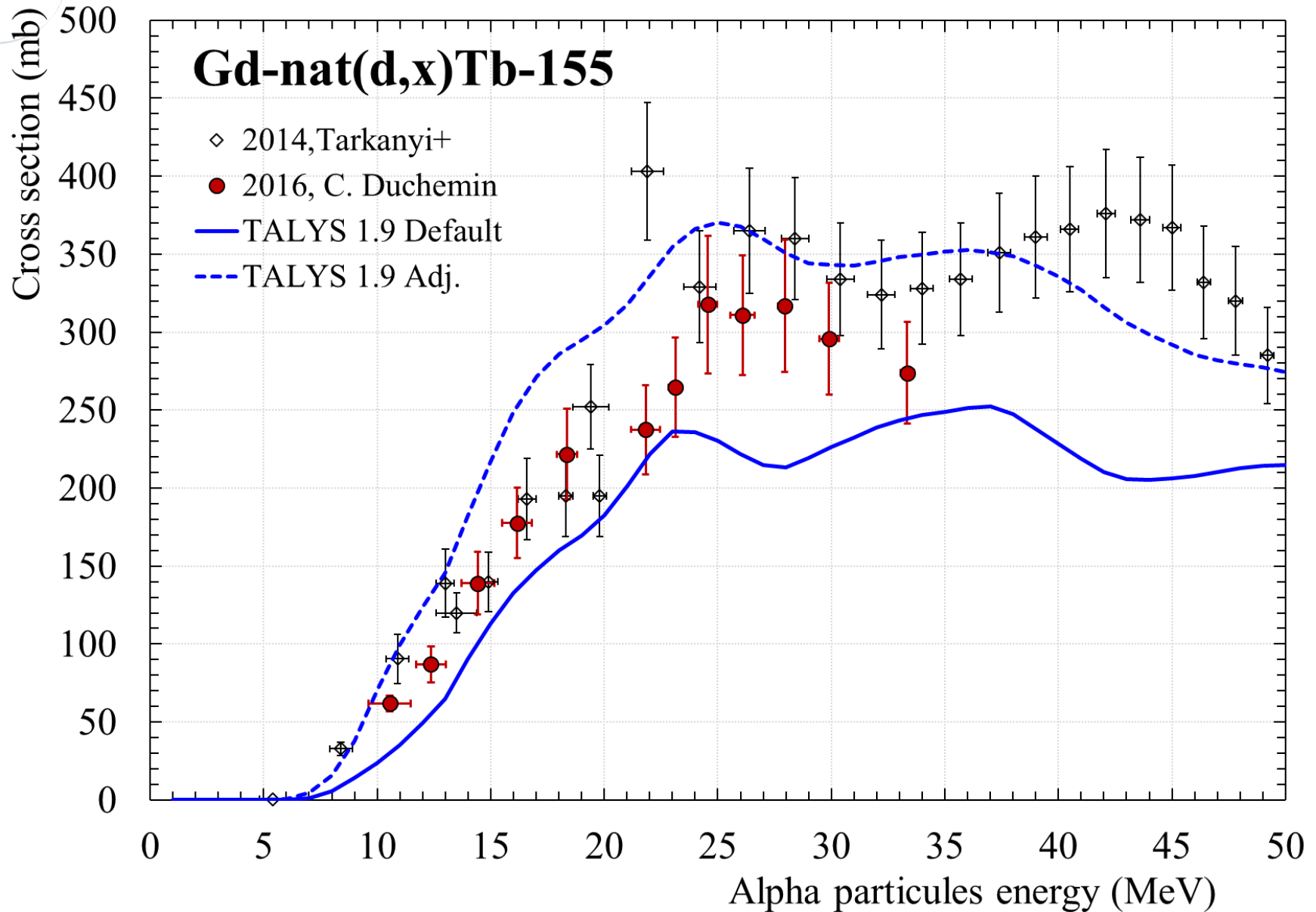


# Terbium 155





# Terbium 155

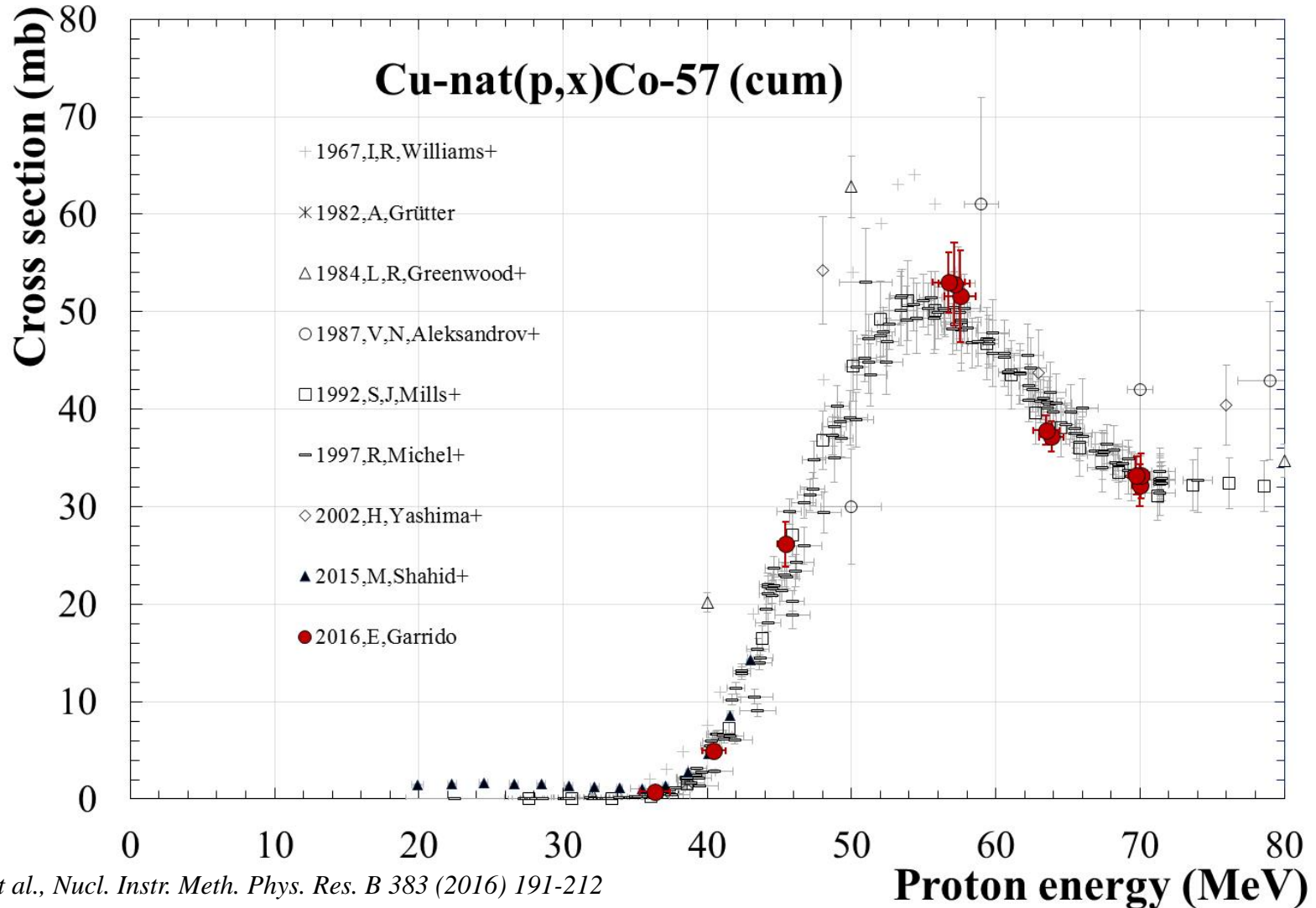


# Monitor reaction

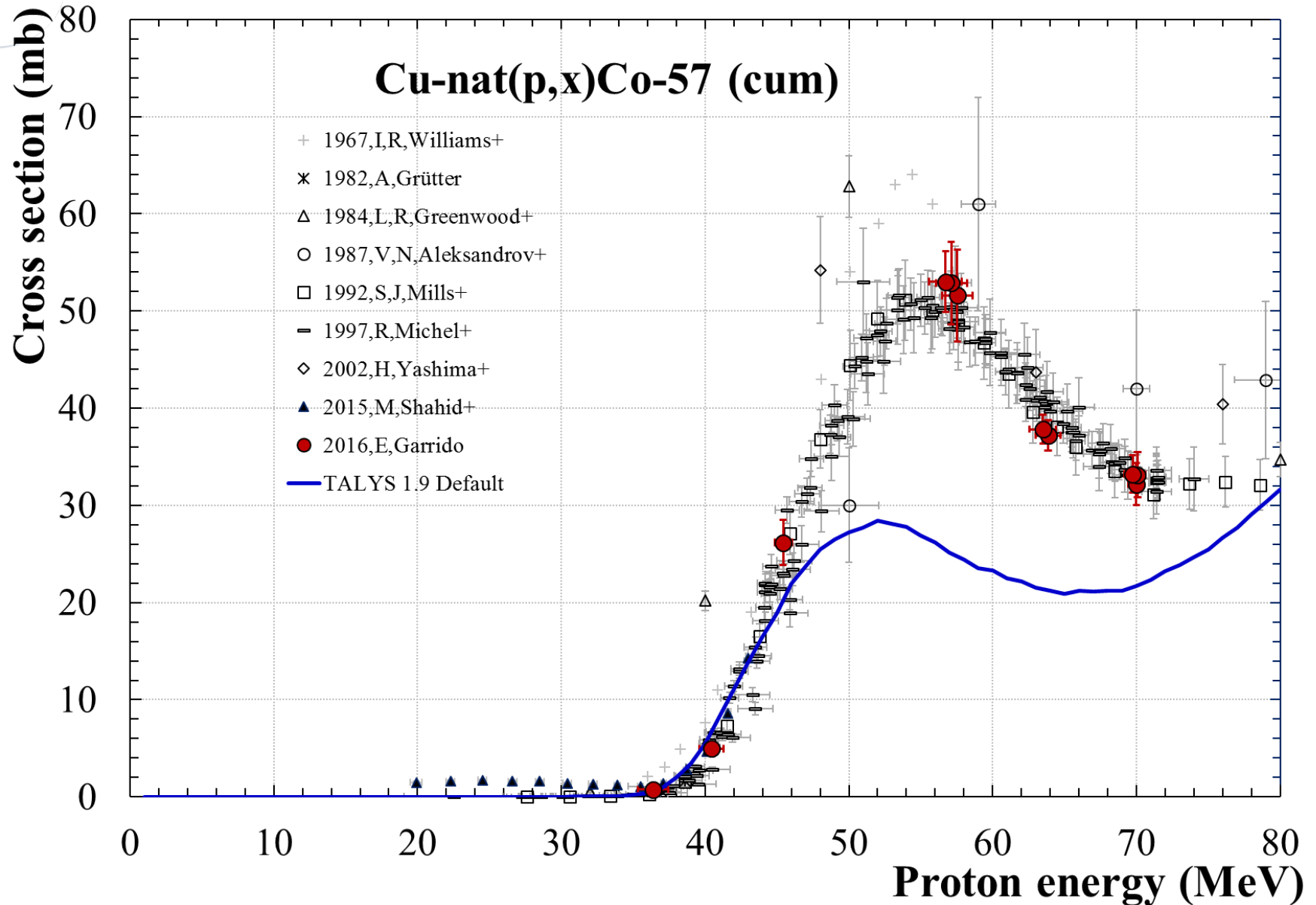
**Co-57 ( $T_{1/2} = 271.79$  d)**

EC process (100%) to stable Fe-57

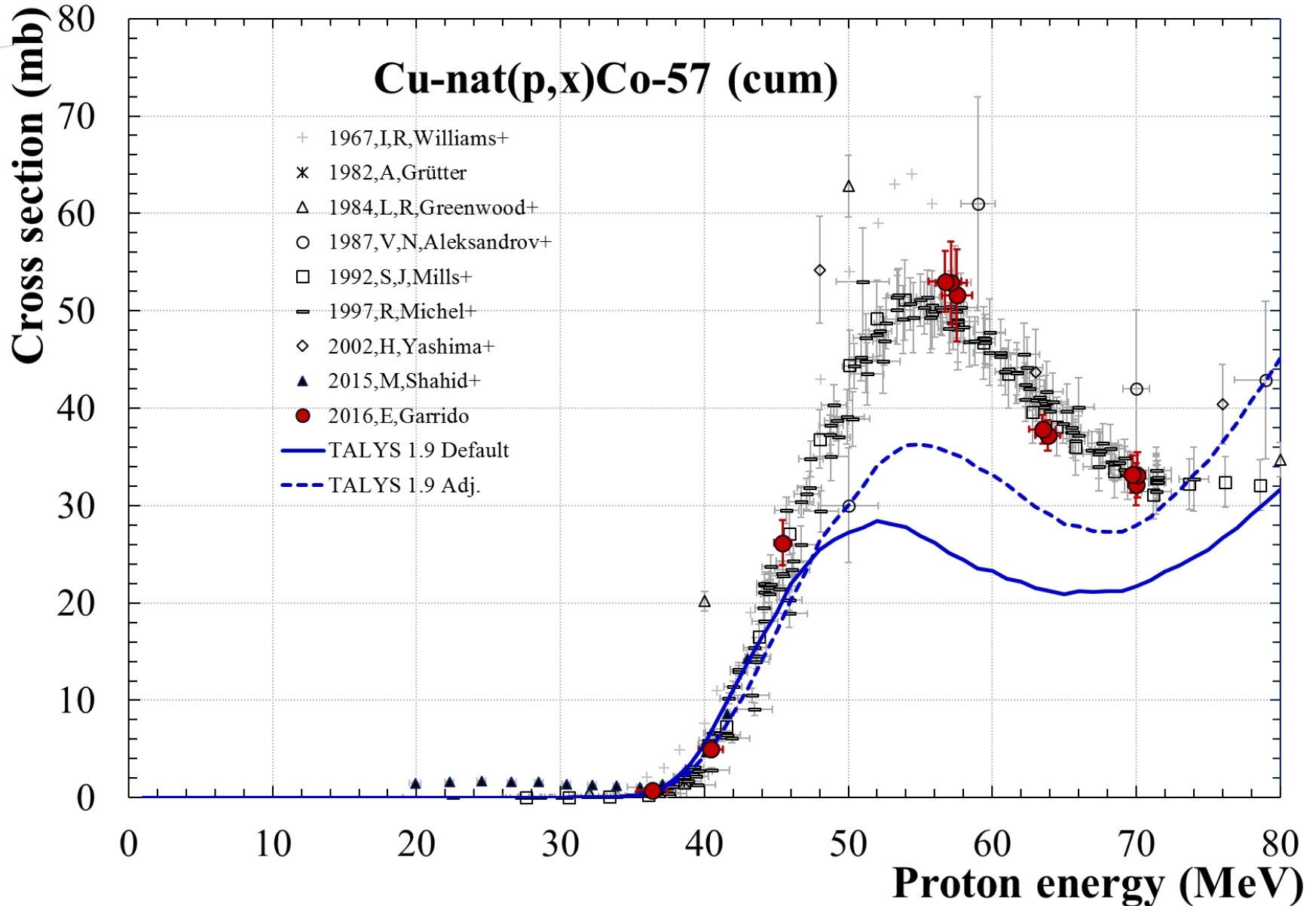
Suitable for proton monitor reaction



# Monitor reaction



# Monitor reaction

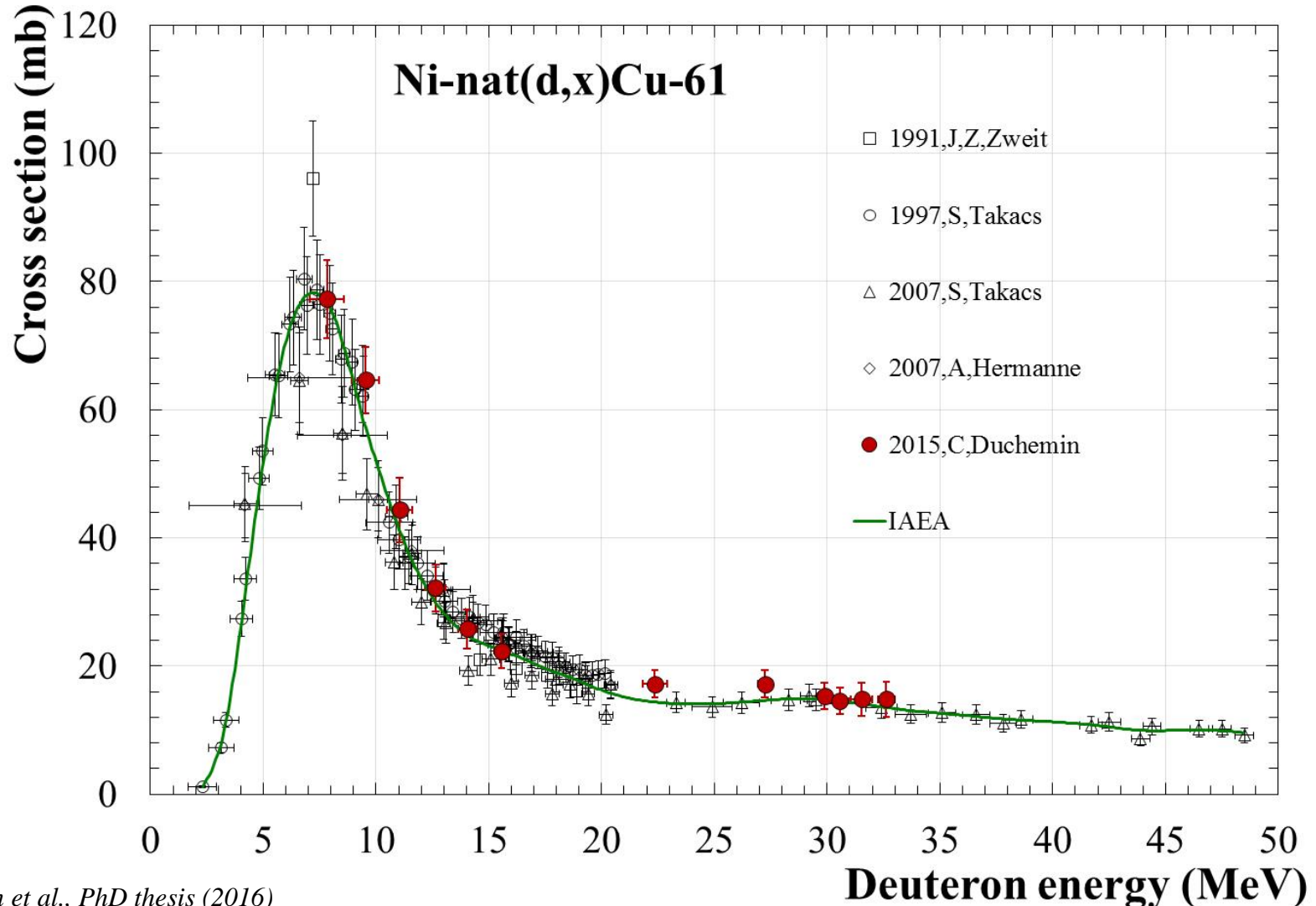


# Monitor reaction

**Cu-61 ( $T_{1/2} = 3.333$  h)**

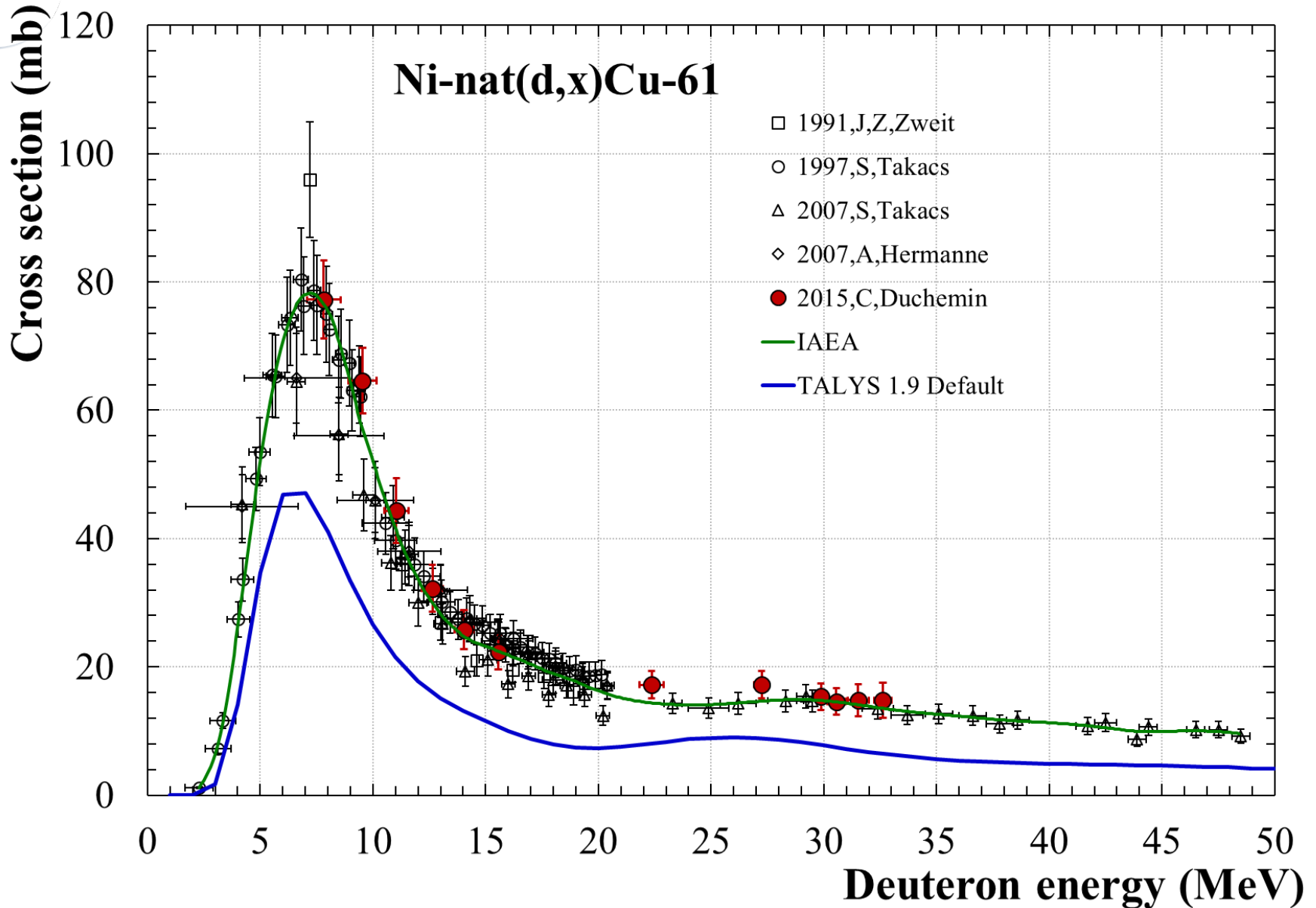
EC  $\beta^+$  processes to stable Ni-61

Suitable for PET imaging



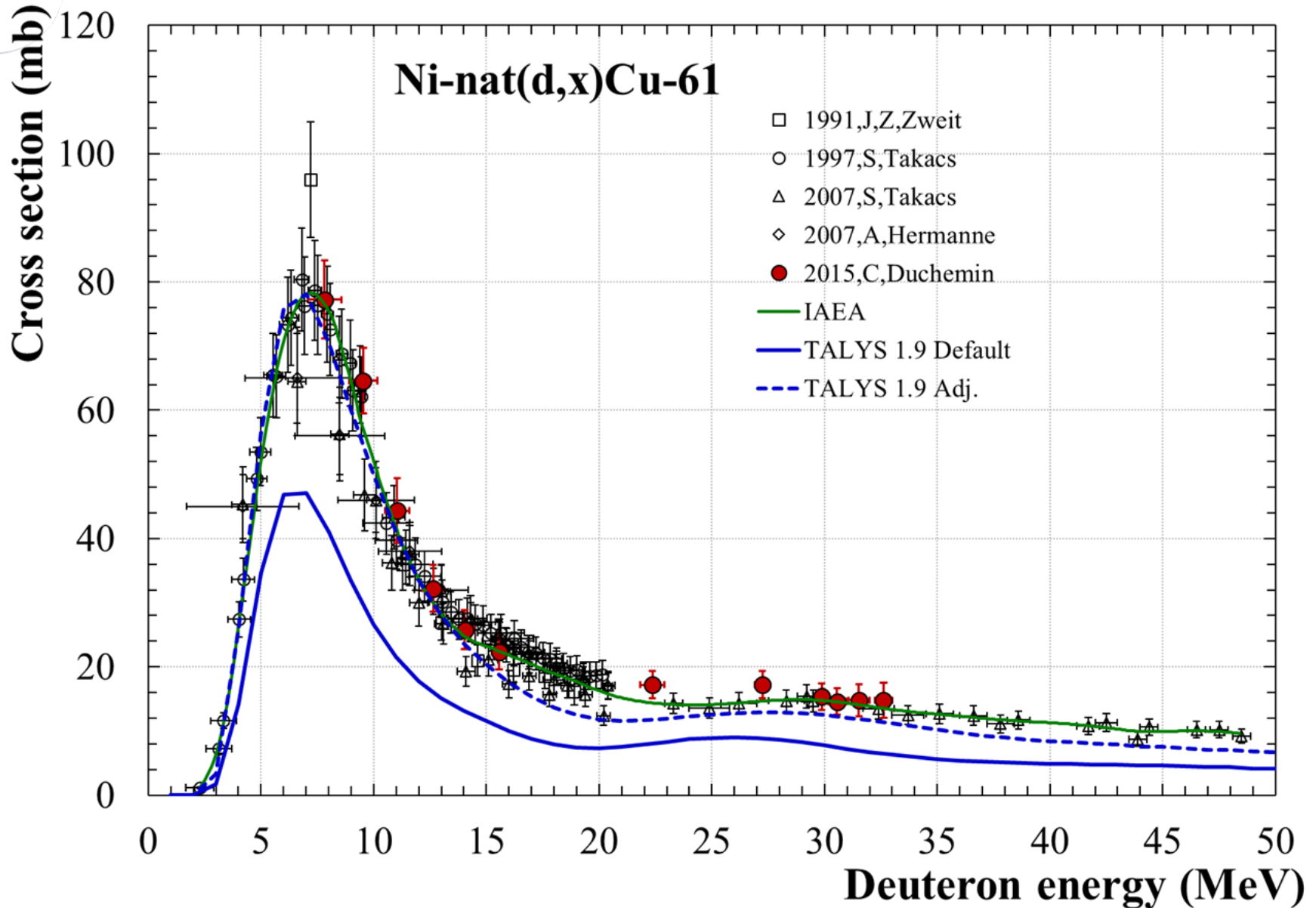
*C. Duchemin et al., PhD thesis (2016)*

# Monitor reaction





# Monitor reaction

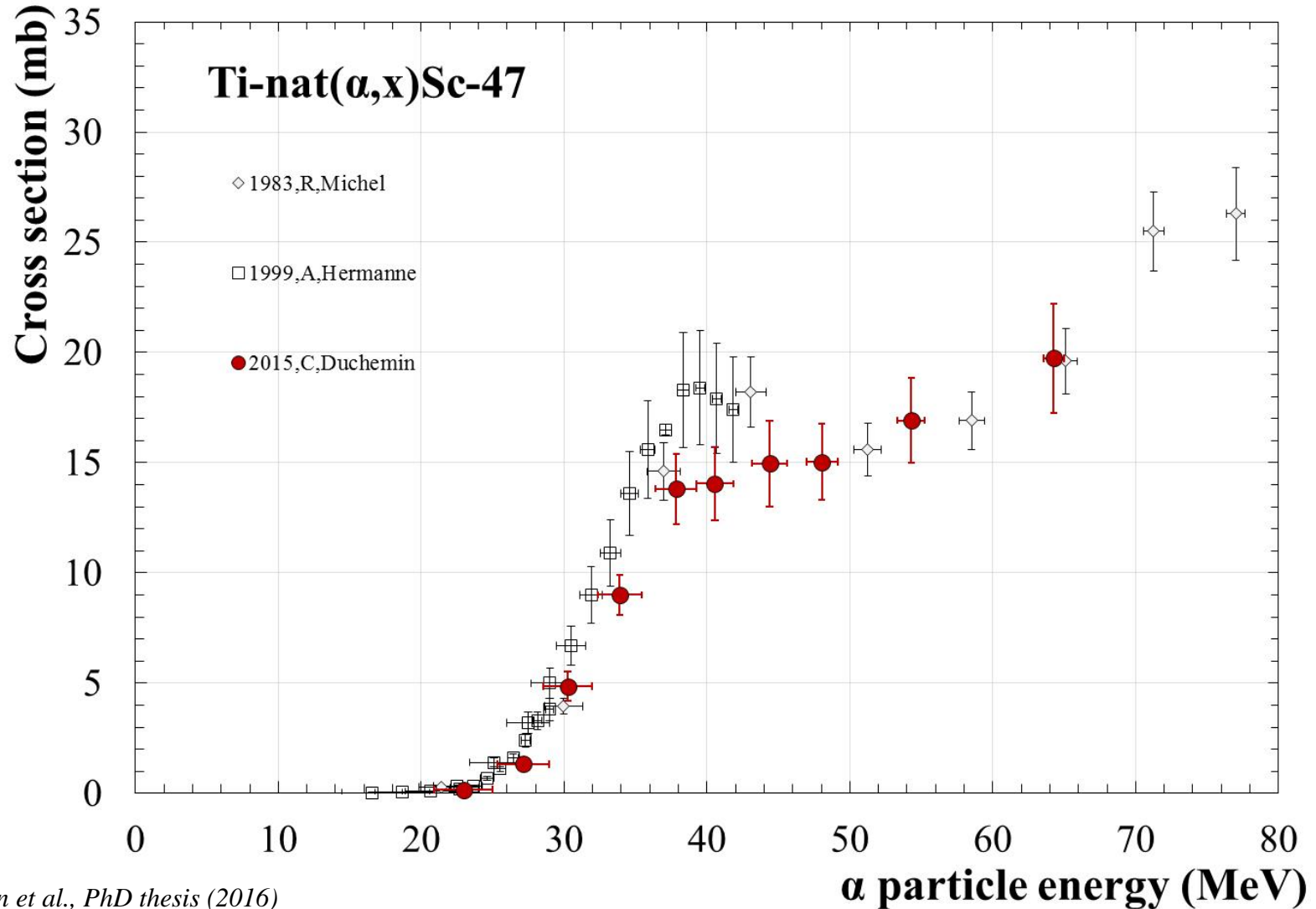


# Monitor reaction

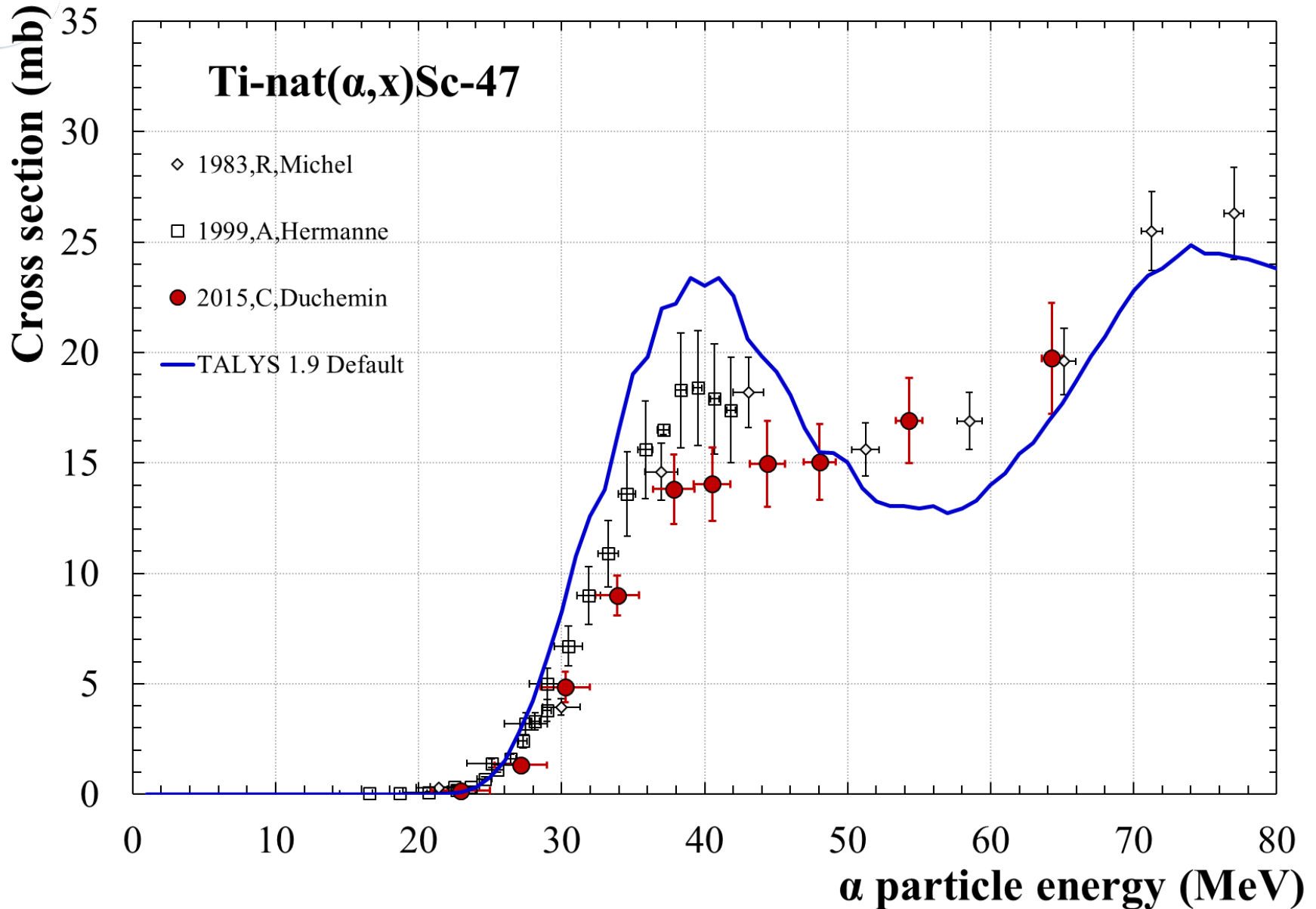
**Sc-47 ( $T_{1/2} = 3.3492$  d)**

$\beta^-$  (100%) to stable Ti-47

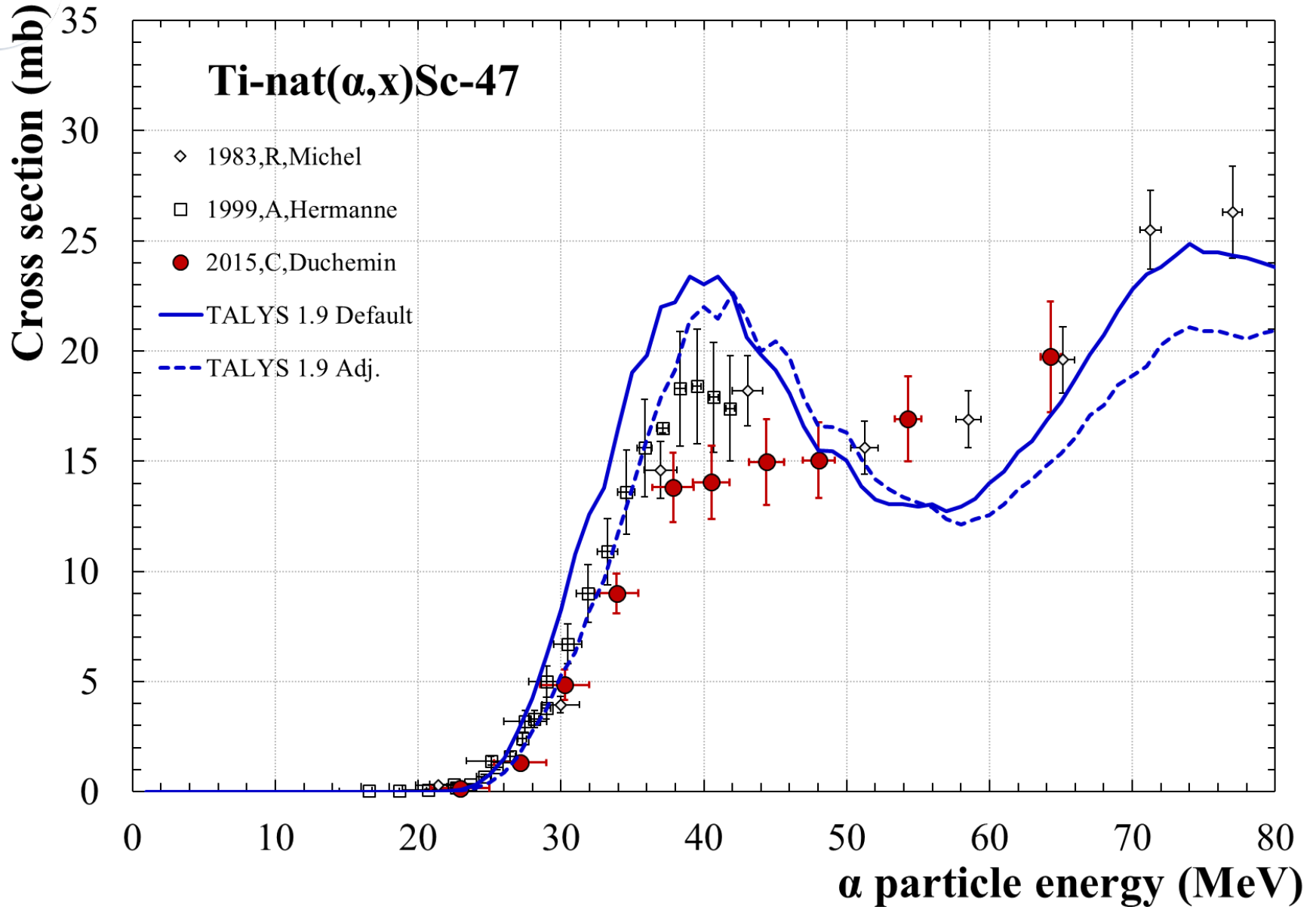
Suitable for theranostic approach with the Sc-44



# Monitor reaction



# Monitor reaction



## Nuclear medicine

**Many useful / potentially useful isotopes identified** for applications in **nuclear medicine**

- Personalized medicine

**The Right Drug To The Right Patient For The Right Disease  
At The Right Time With The Right Dosage**

## Nuclear data

**A large set of data have been collected** using the stacked-foil technique at ARRONAX

- with different type of projectiles (proton, deuteron and alpha particles)
- for materials all over the mass range
- for diagnosis and therapy purposes in nuclear medicine

To achieve:

- optimum production of specific radionuclides
- minimization or elimination of impurities
- realistic dose calculations

Comparisons have been performed systematically with the **TALYS 1.9 code**

- state of the art models included
- possibility to combine models to better describe data
- a set of models have been found to allow a **good description of all our collected data**

# Medical radioisotopes session

Thank you for your attention

Acknowledgments to the 15<sup>th</sup> Varenna International Conference  
organization committee

**“Production of innovative radionuclides for therapy or diagnostic:  
nuclear data measurements and comparison with TALYS code”**

Guertin A.<sup>1</sup>, Nigrón E.<sup>1</sup>, Sitarz M.<sup>2,3</sup>, Duchemin C.<sup>1</sup>, Haddad F.<sup>1,2</sup>, Métivier V.<sup>1</sup>

1 SUBATECH, CNRS/IN2P3, IMT Atlantique, Université de Nantes, Nantes, France

2 GIP ARRONAX, 1 rue Aronnax, 44817 Saint-Herblain cedex – France

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