How nuclear data collected for medical radionuclides production at ARRONAX could constrain the TALYS code

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AccApp'17
13th International Topical Meeting on the Nuclear Applications of Accelerators

Motivation: study of the production of innovative radionuclides for nuclear medicine

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Radionuclide →

Diagnosis → to reveale/localize the disease

functional imaging (organs' activity, cells metabolism)

Therapy → to treat the disease

α particle/electron emitters

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I-131 for therapy

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F-18 linked to a glucose analogue for PET imaging

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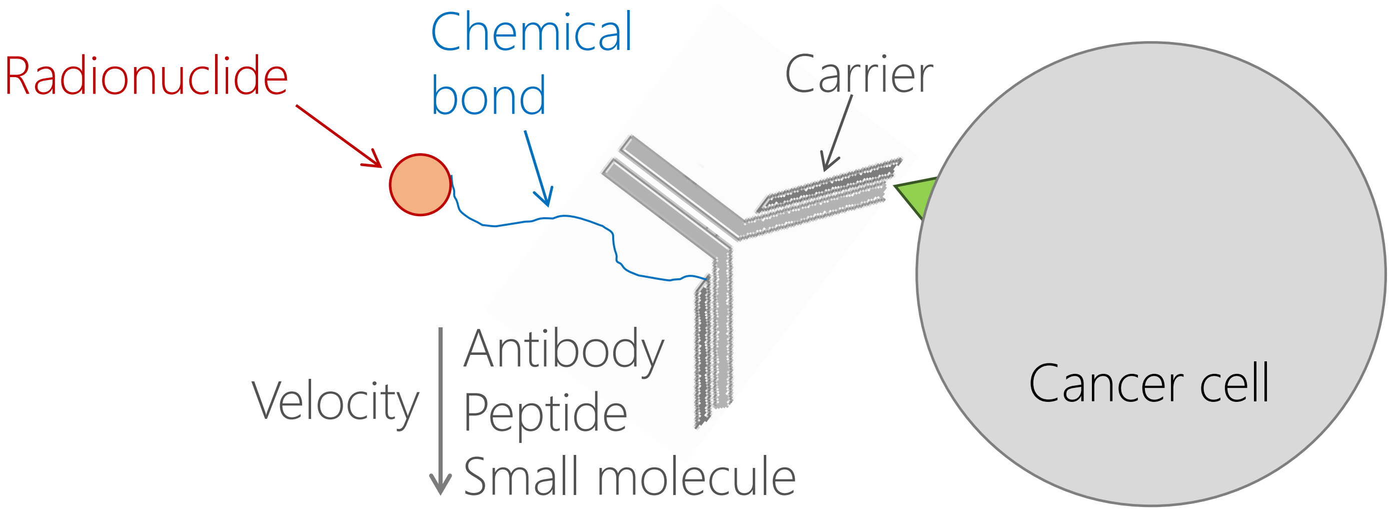

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SUBATECH

Research lab

. Particle physics
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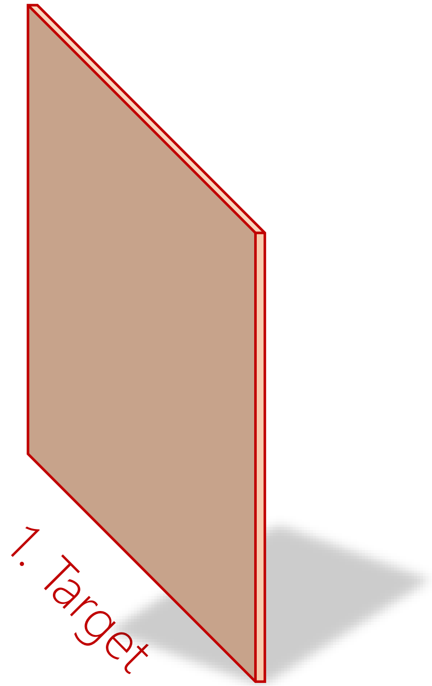
Accelerator for the **R**esearch in **R**adiochemistry and in **O**ncology at **N**antes **A**tlantique **X**

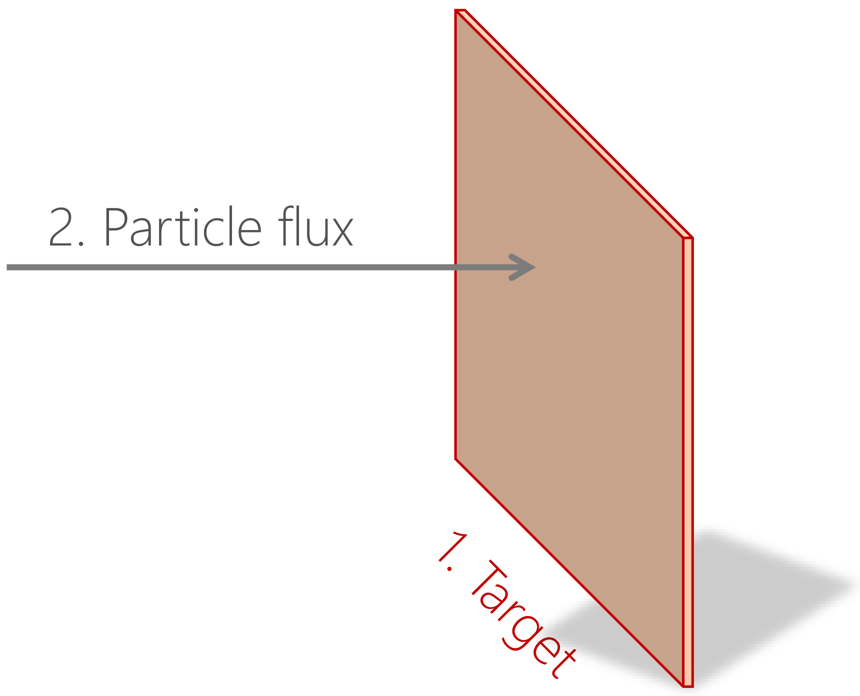
C70 Cyclotron build by IBA:

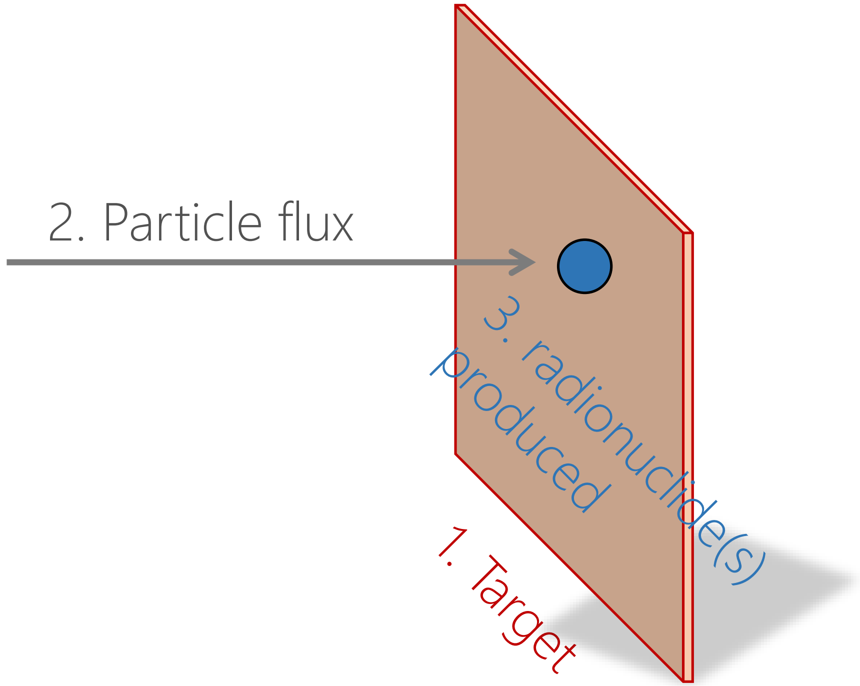
- **4 sectors** isochron **cyclotron**
- **2 extraction methods**: stripper or electrostatic deflector
- **6 beam lines** one vault devoted to experiments

Extracted	Energy (MeV)	Max. current (μA)
H^+	30 – 70	2 x 375
D^+	15 – 35	2 x 50
He^{2+}	68	70
HH^+	17	50

2. Production process


1. Target

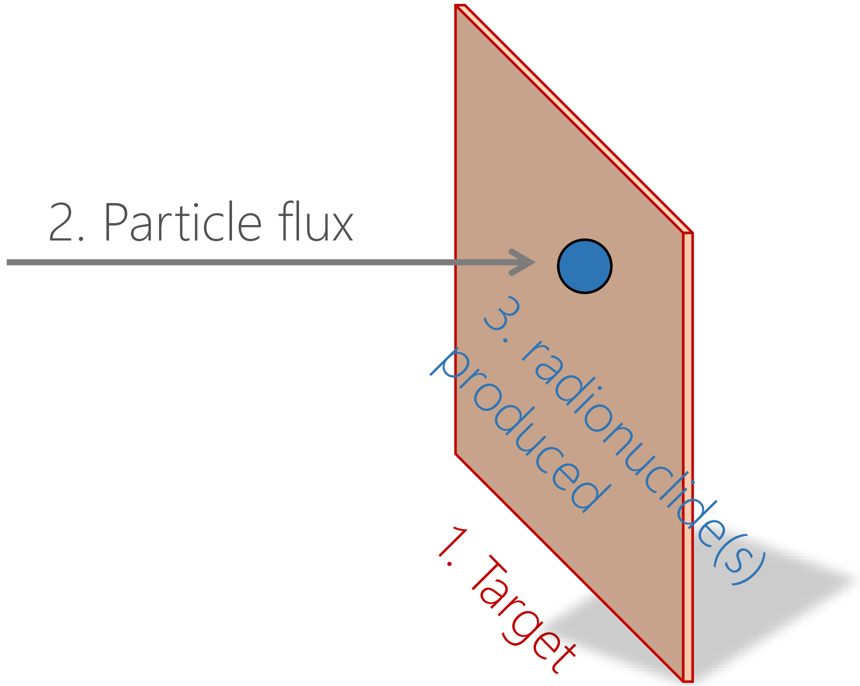

2. Particle flux
1. Target


2. Particle flux
3. radionuclide(s) produced
1. Target

Usual production routes

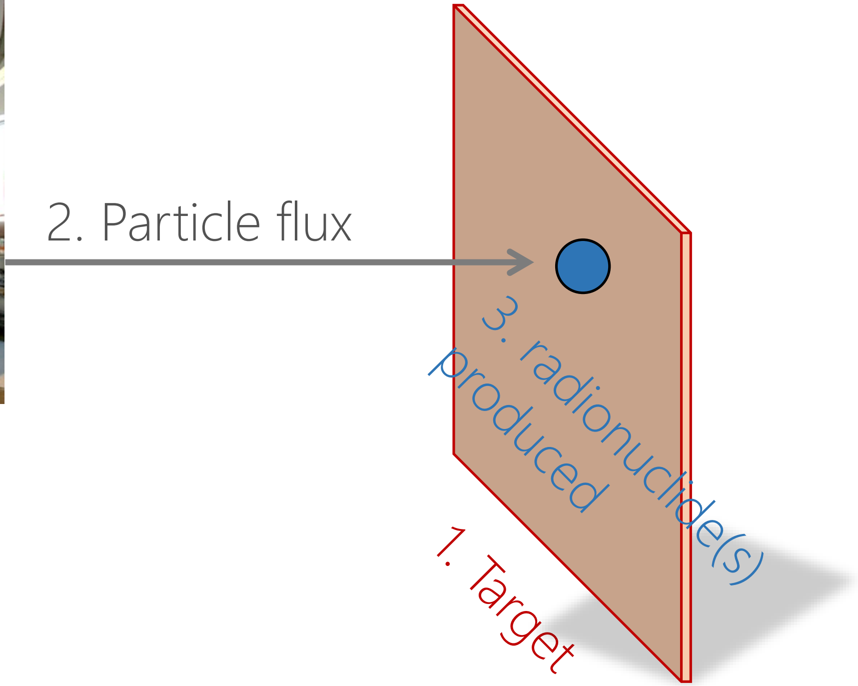
→ Accelerators : low energy protons
F-18

→ Reactors : neutrons
I-131, Mo-99



The production of a limited number of radionuclides can be assessed through these production routes

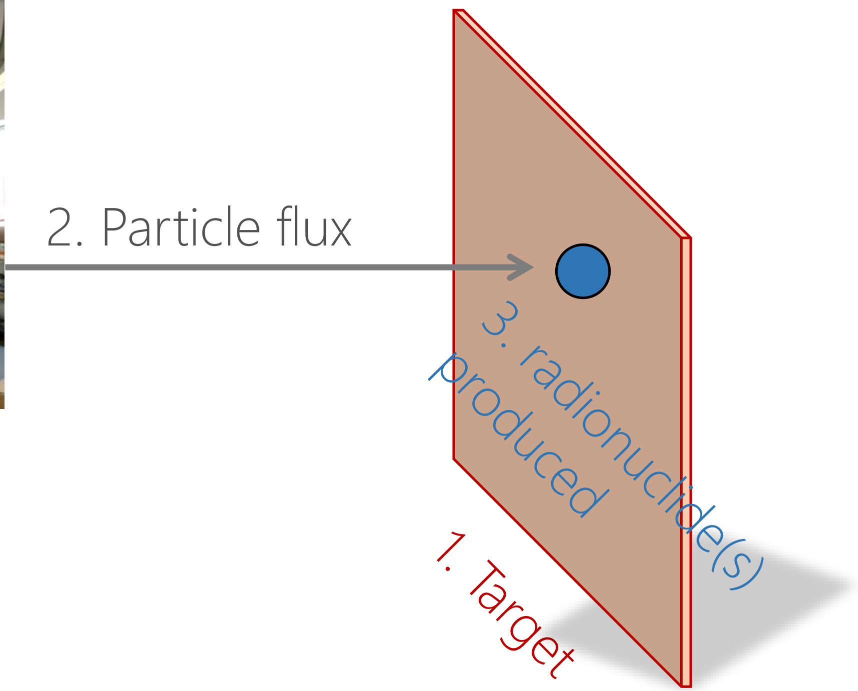
Study of alternative production routes for the production of innovative radionuclides



→ High energy protons
→ Deuterons
→ α particles

→ Fission process

Study of alternative production routes for the production of innovative radionuclides



→ High energy protons
→ Deuterons
→ α particles

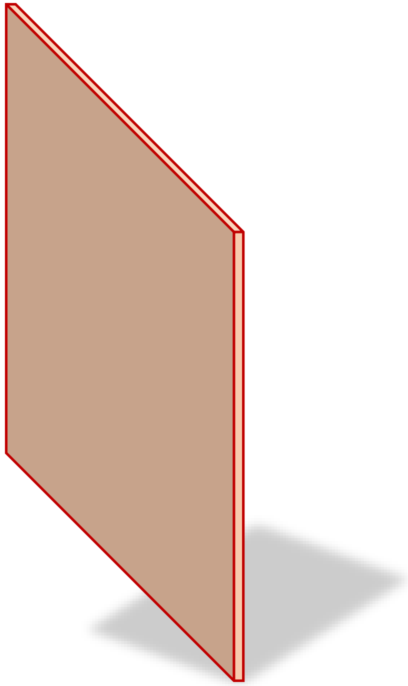
→ Fission process

. The **production cross section** is not known or only few experimental data are available

→ Needed to determine the **best production pathway** and the **best irradiation conditions**

3. Production cross section determination

Thin target approach



Few µm thick

Thin target approach

→ Low energy loss of the projectile through the target

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→ σ slightly changes on this small energy range

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→ Low energy loss of the projectile through the target

→ σ slightly changes on this small energy range

→ for a mean energy value of the projectile crossing the target

=

One experimental σ value

Thin target approach

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→ for a mean energy value of the projectile crossing the target

=

One experimental σ value

$$Act = \sigma(E) . \Phi . \chi . \frac{N_A . \rho . ef}{A} . (1 - \exp(-\lambda . t_{irr}))$$

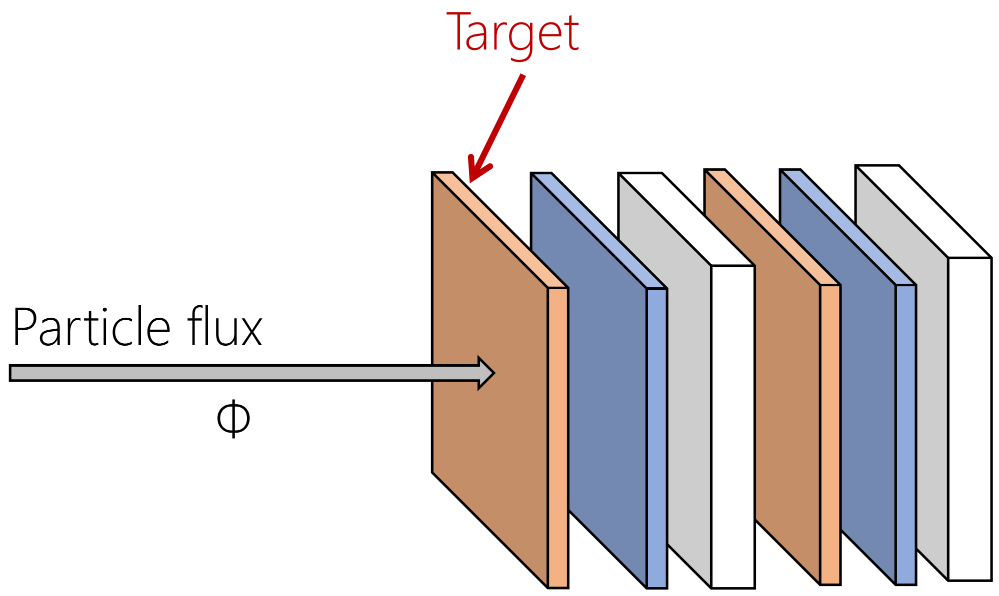
Produced radionuclide

Target

Irradiation conditions

Stack of foils made of a:

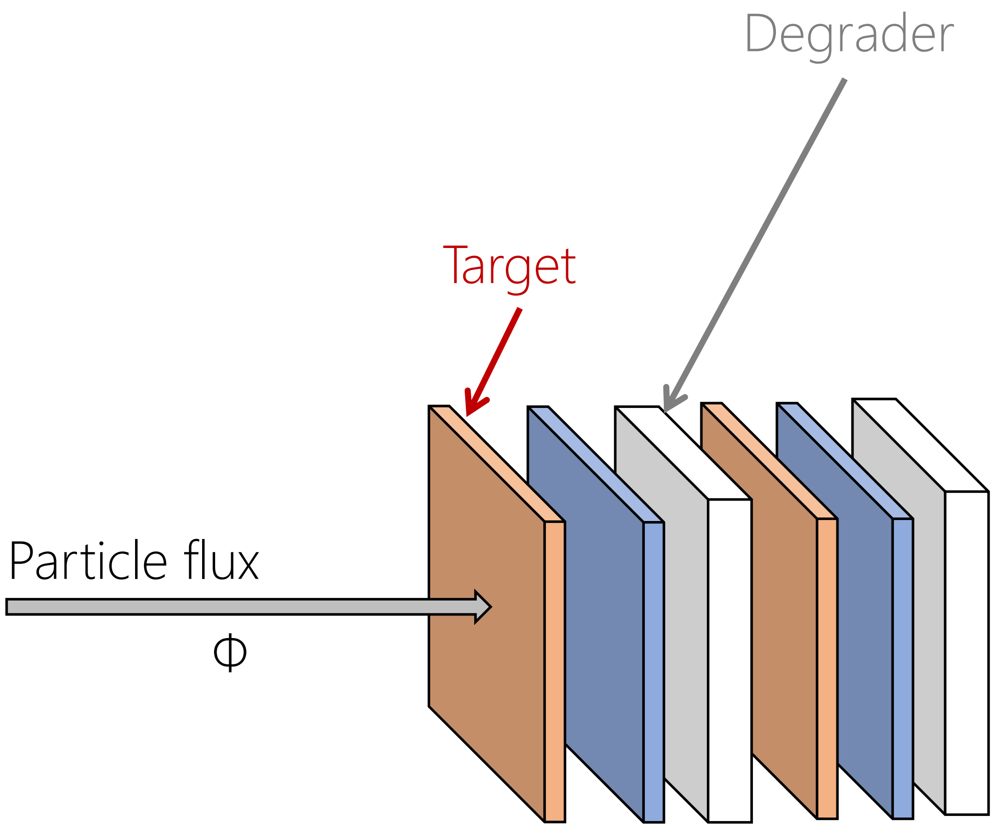
→ Target: to produce the radionuclide
for which the cross section will be determined



Stack of foils made of a:

→ Target: to produce the radionuclide
for which the cross section will be determined

→ Degrader: to decrease the beam energy

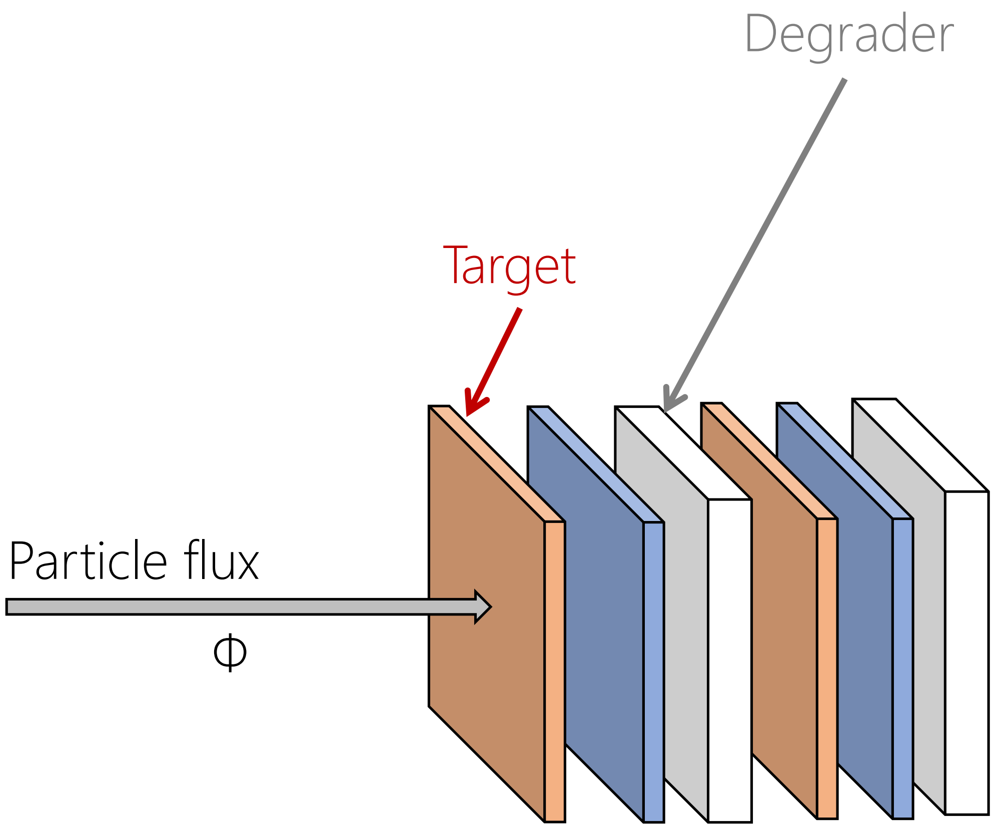


Stack of foils made of a:

→ Target: to produce the radionuclide for which the cross section will be determined

→ Degrader: to decrease the beam energy

!! Particle flux measured at the end of the stack

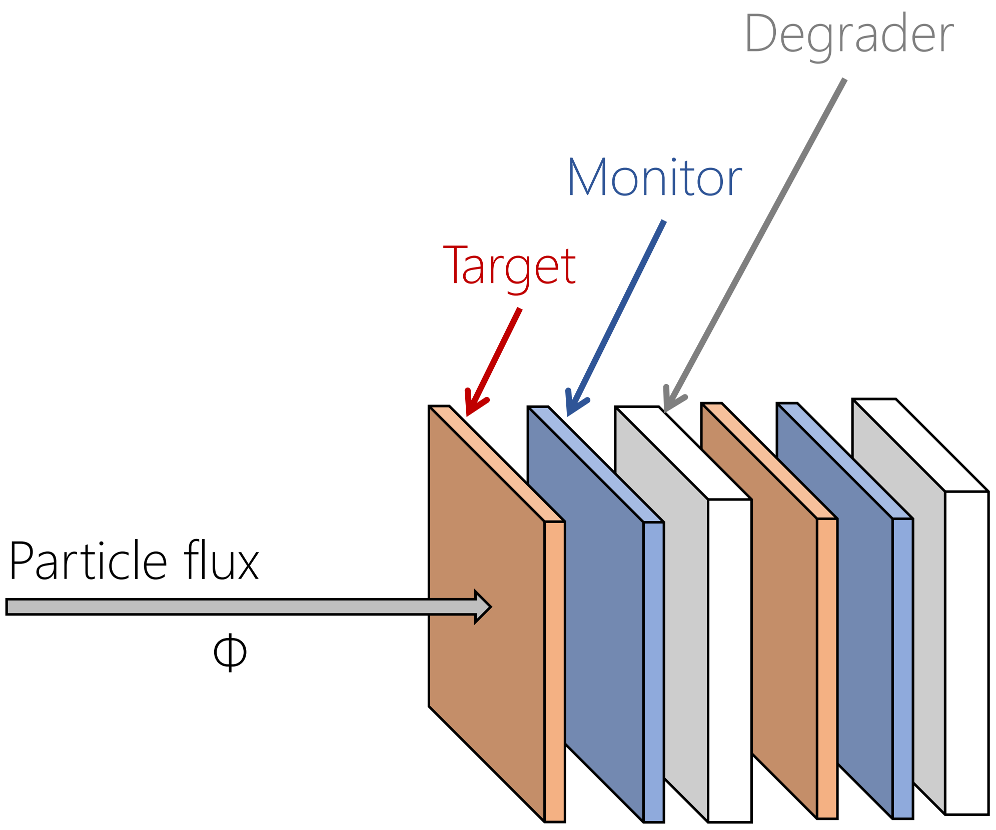


Stack of foils made of a:

→ Target: to produce the radionuclide for which the cross section will be determined

→ Monitor: to produce a radionuclide with a cross section value of reference

→ Degrader: to decrease the beam energy



Monitor reactions

. Defined by the International Atomic Energy Agency (IAEA)
Coordinated Research Project F41029
« Nuclear Data for Charged-particle Monitor Reactions and Medical Isotope Production »

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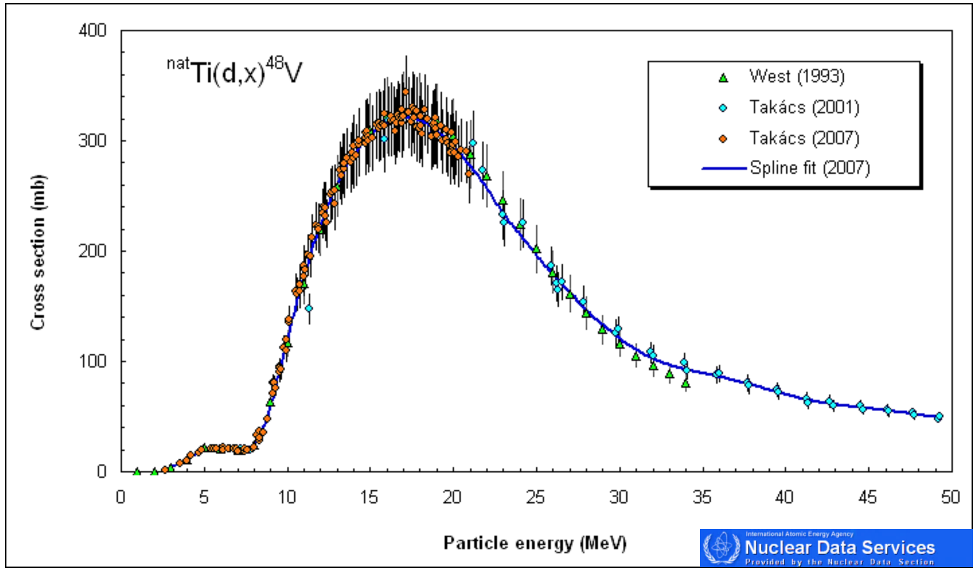
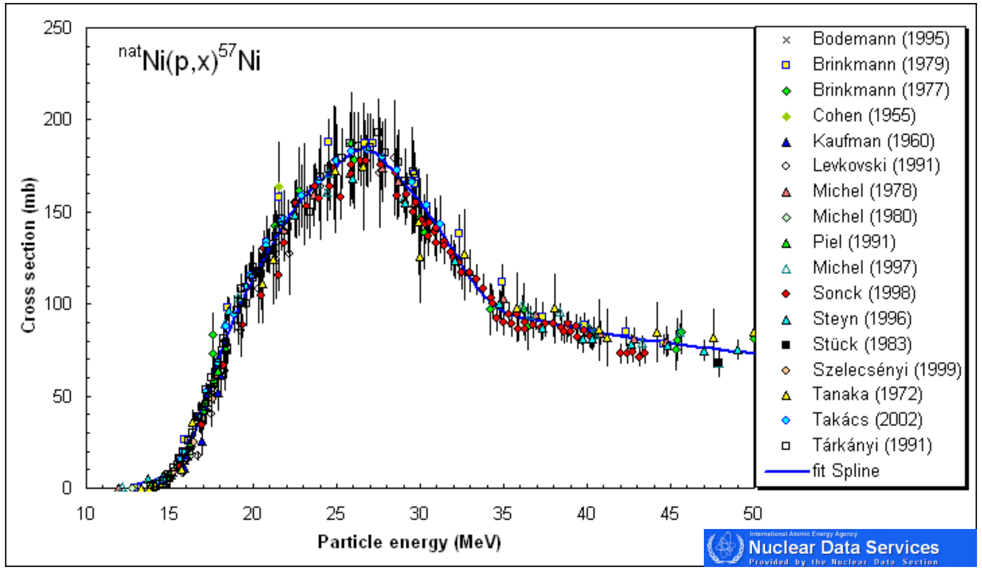
→ Analysis of the σ exp. data and related articles
→ Adjustment of the selected data
→ Determination of recommended/reference values



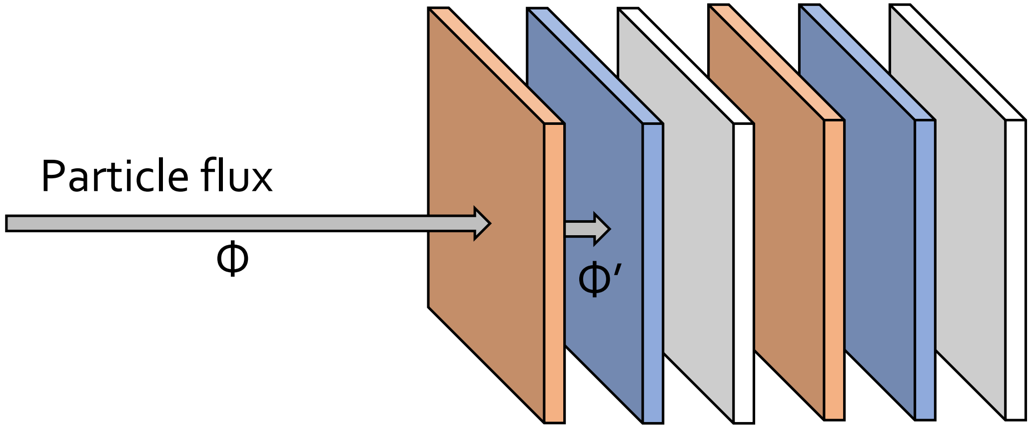


$$Act = \sigma(E).\ \Phi\ .\ \chi\ .\ \frac{N_A.\ \rho.\ ef}{A}\ .\ (1-\exp(-\lambda.t_{irr}))$$

Produced radionuclide

Target

Irradiation conditions



$$Act = \sigma(E) . \Phi . \chi . \frac{N_A . \rho . ef}{A} . (1 - \exp(-\lambda . t_{irr}))$$

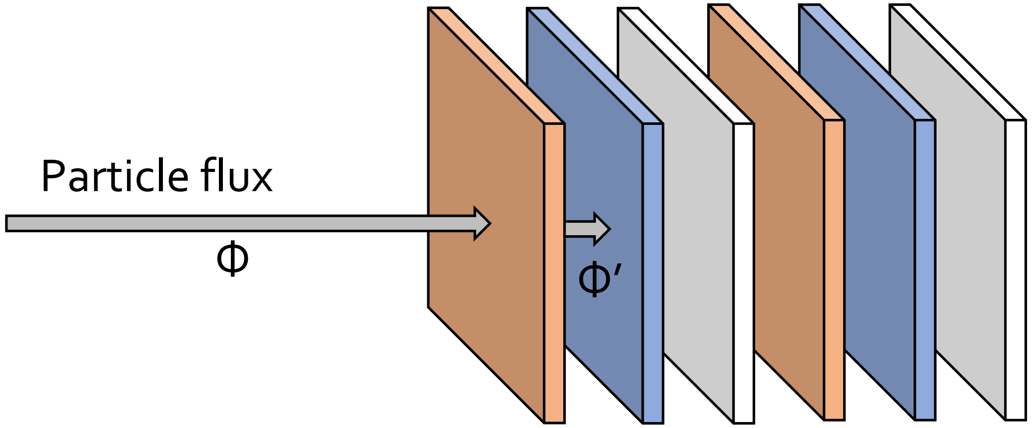
$$\Phi_{Target} = \frac{Act . A}{\sigma(E) . \chi . N_A . \rho . ef . (1 - \exp(-\lambda . t_{irr}))}$$

$$\Phi'_{Monitor} = \frac{Act' . A'}{\sigma'(E') . \chi' . N_A . \rho' . ef' . (1 - \exp(-\lambda' . t_{irr}))}$$

Produced radionuclide

Target

Irradiation conditions



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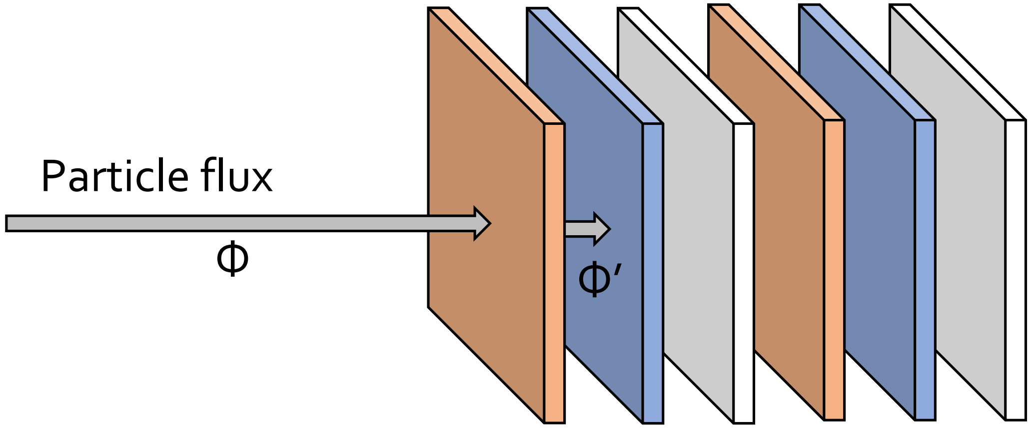
Produced radionuclide

Target

Irradiation conditions

Condition: $\Phi = \Phi'$



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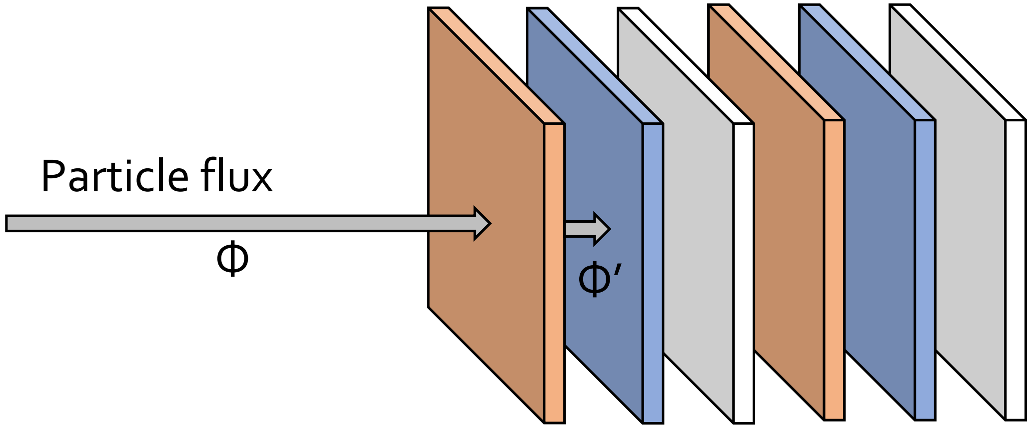
Produced radionuclide

Target

Irradiation conditions

Condition: $\Phi = \Phi'$

$$\sigma(E) = \sigma'(E') \,.\, \frac{Act \,.\, A \,.\, \chi' \,.\, \rho' . ef' \,.\, (1 - \exp(-\lambda' . t_{irr}))}{Act' \,.\, A' \,.\, \chi \,.\, \rho \,.\, ef \,.\, (1 - \exp(-\lambda . t_{irr}))}$$

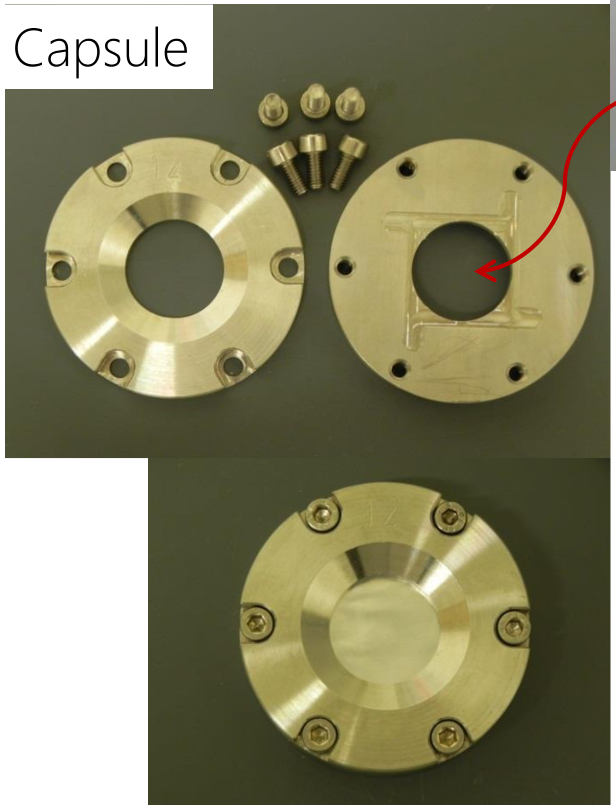


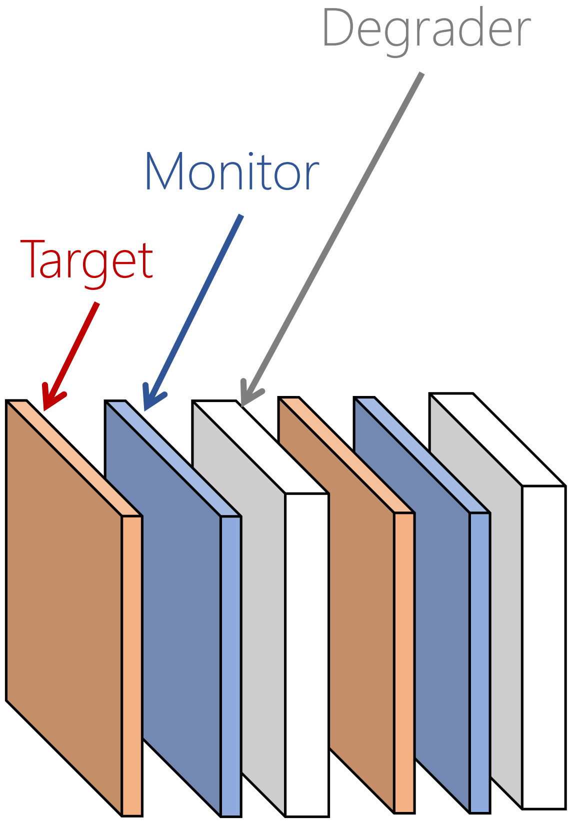
Recommended cross section values from the IAEA

International Atomic Energy Agency
Nuclear Data Services
Provided by the Nuclear Data Section

4. Experimental set-up

Stacked-foils technique





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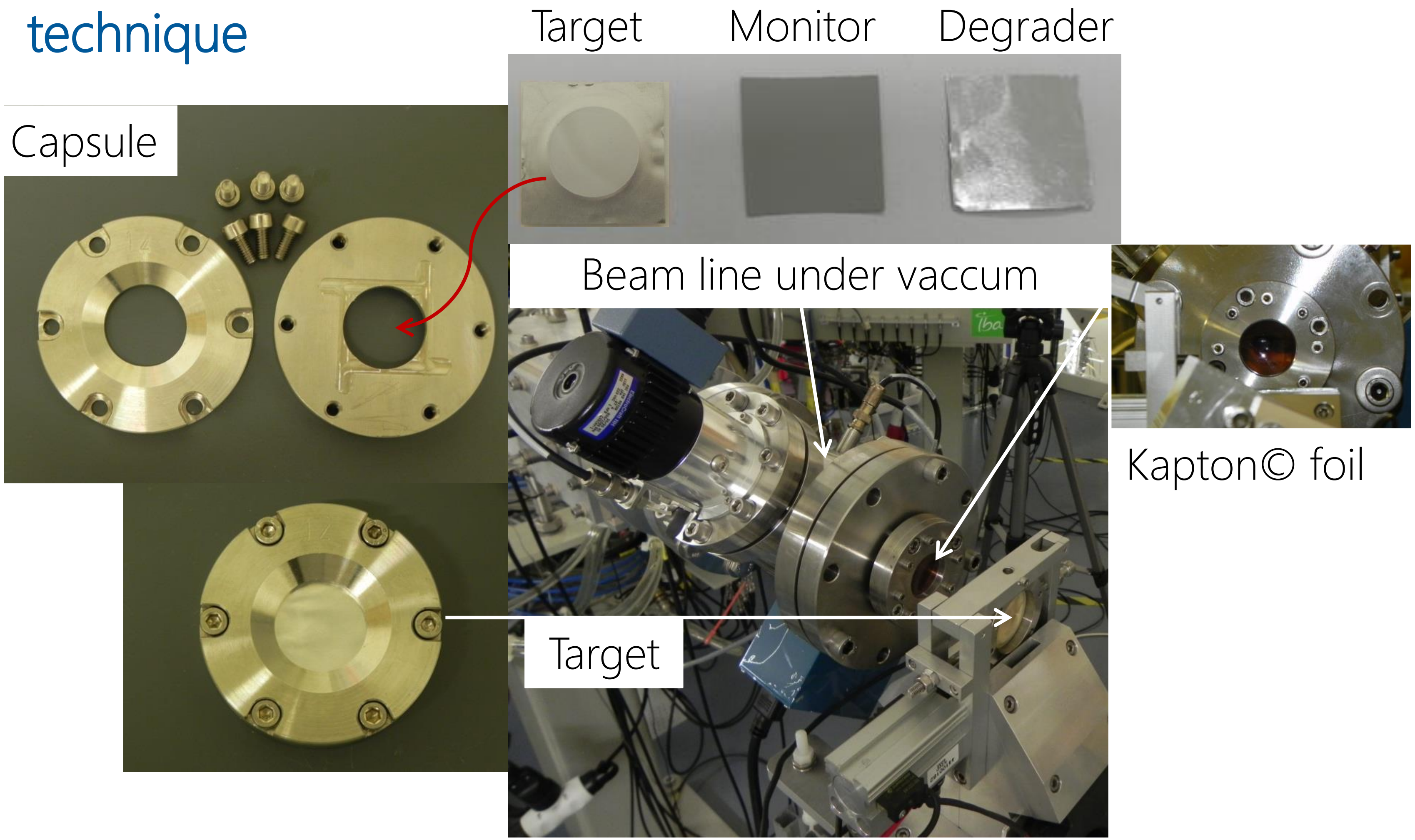
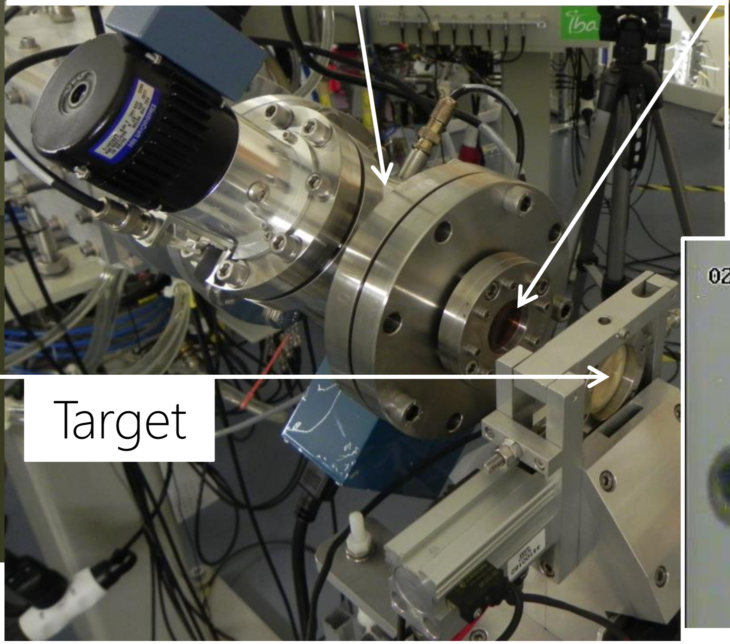
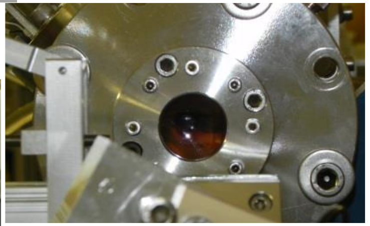


Stacked-foils technique

Target Monitor Degrader

Beam line under vaccum



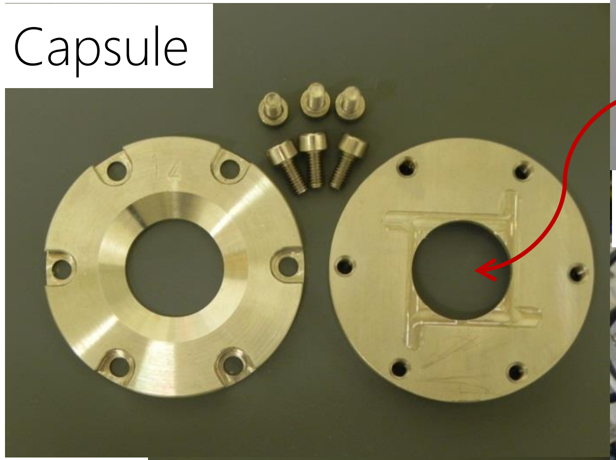


Kapton© foil

Alumina target under irradiation

Stacked-foils technique

Capsule



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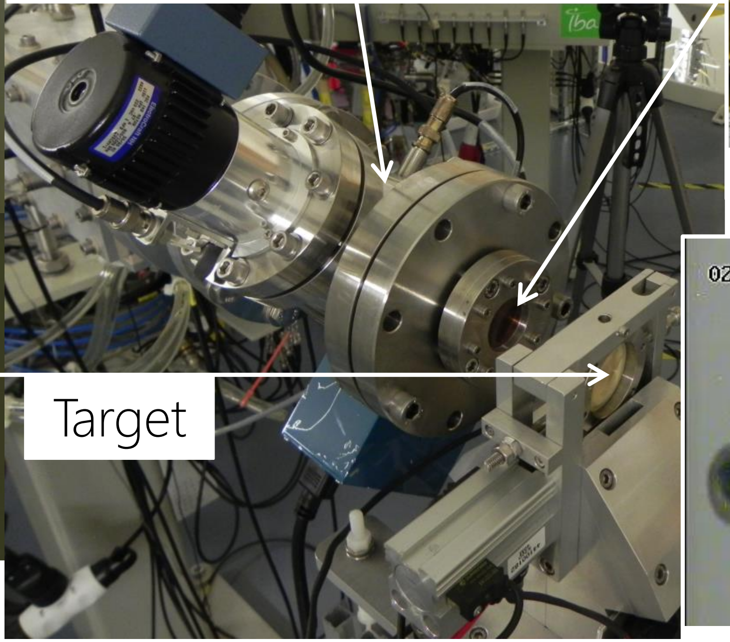
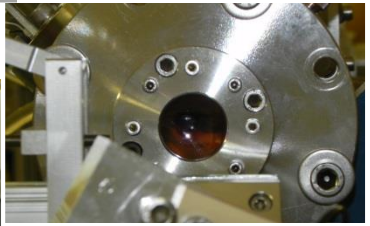
Beam line under vaccum



Target



Kapton© foil

Alumina target under irradiation

Thin foil after irradiation

HPGe

Gamma-spectrometry

5. Radionuclides of interest for nuclear medicine

Production cross section study

Functional imaging/Diagnosis	Therapy

Functional imaging/Diagnosis	Therapy
positron emitters e^+ Sc-44 $T_{1/2} = 3.97\ h$ → Of interest for PET + γ (1.157 MeV) → Of interest for the 3 γ imaging technique developed at the SUBATECH lab (Xenon group) Ca-44(d,2n)	

Functional imaging/Diagnosis	Therapy

positron emitters e^+

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Ca-44(d,2n)

photon emitters γ

Tc-99m → Widely used in functional imaging (SPECT)

$T_{1/2} = 6.01\ h$

→ Tc-99m "crisis"

Th-232(d,f) and Th-232(p,f)

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Therapy

electrons emitters e^-

Re-186g → β-, used in clinical trials

$T_{1/2} = 3.72\ d$ *palliative therapy for painful metastases*

W-nat(d,xn)

Tb-155 → Auger e- / γ for imaging

$T_{1/2} = 5.32\ d$

Gd-nat(d,xn)

Sn-117m → Conversion e-, used in clinical trials

$T_{1/2} = 13.60\ d$ *cardiovascular diseases*

Cd-116(α,3n)

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Cd-116(α,3n)

α particles emitters

Th-226 → High cell destruction power (4 part. α)

$T_{1/2}$ = 30.57 m

Ac-225 → High cell destruction power (3 part. α)

$T_{1/2}$ = 10.0 d

Ra-223 → Xofigo© radiopharmaceutical

$T_{1/2}$ = 11.44 d

Th-232(d,x) and Th-232(p,x)

6. The TALYS code

Code for the simulation of nuclear reactions

TALYS

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

Code for the simulation of nuclear reactions

TALYS

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

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

Energy: 1 keV to 1 GeV

Targets: Z = 3 to 110

Code for the simulation of nuclear reactions

. Includes several nuclear models to cover the main reaction mechanisms

. Provides a description of all the reactions channels and observables

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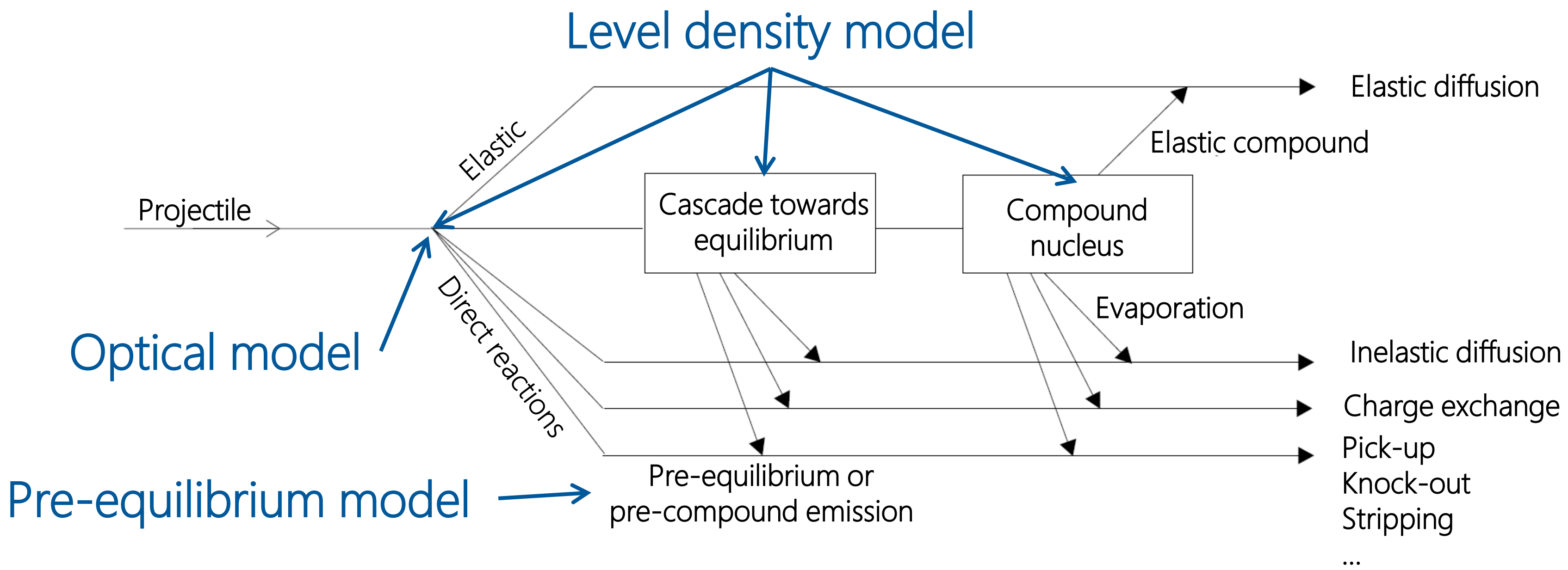

Adapted from S. Benck, PhD thesis, 1999

Code for the simulation of nuclear reactions

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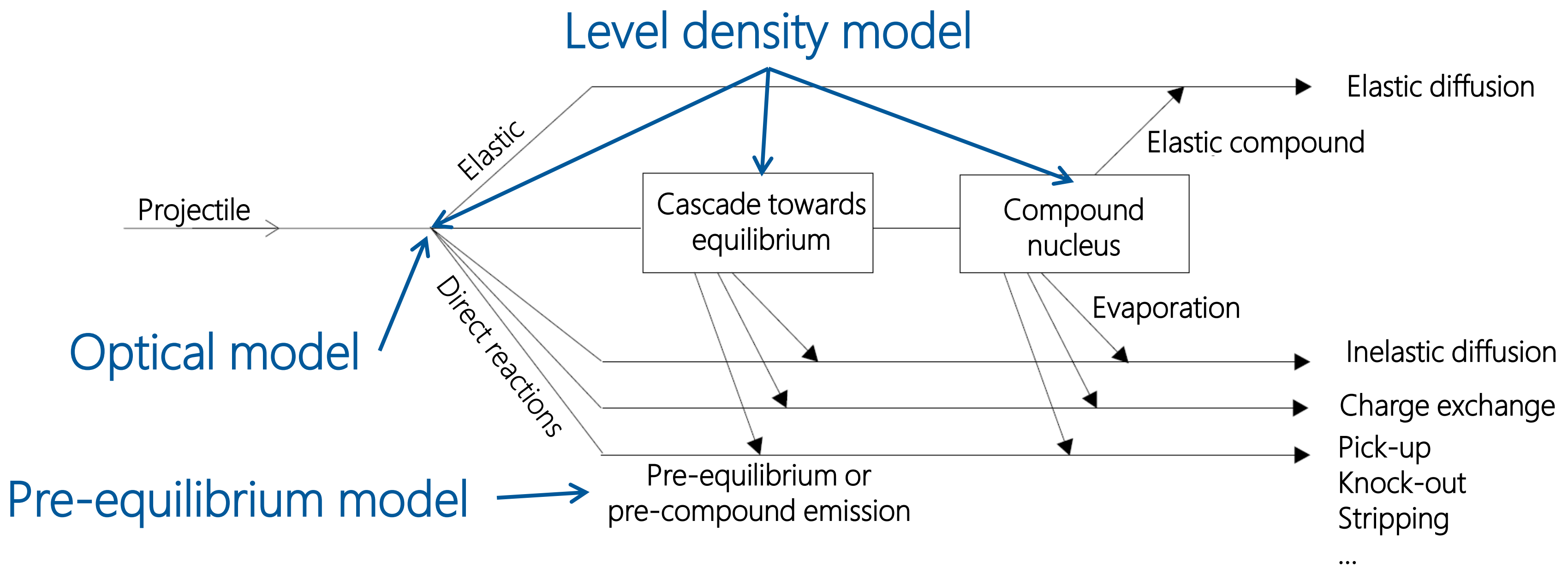

Adapted from S. Benck, PhD thesis, 1999

→ Influence on the calculated production cross section values

Study with the TALYS code version 1.6

. 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 1.6 Default

Study with the TALYS code version 1.6

. 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 1.6 Default

. One combination of models that best describes our whole set of data for proton, deuteron, alpha particles as projectile (and literature data) has been defined during this study.

⇨TALYS 1.6 Adj.

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⇨TALYS 1.6 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) …
	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) …

7. Comparison between the experimental results and the TALYS code

→ α particles as projectiles

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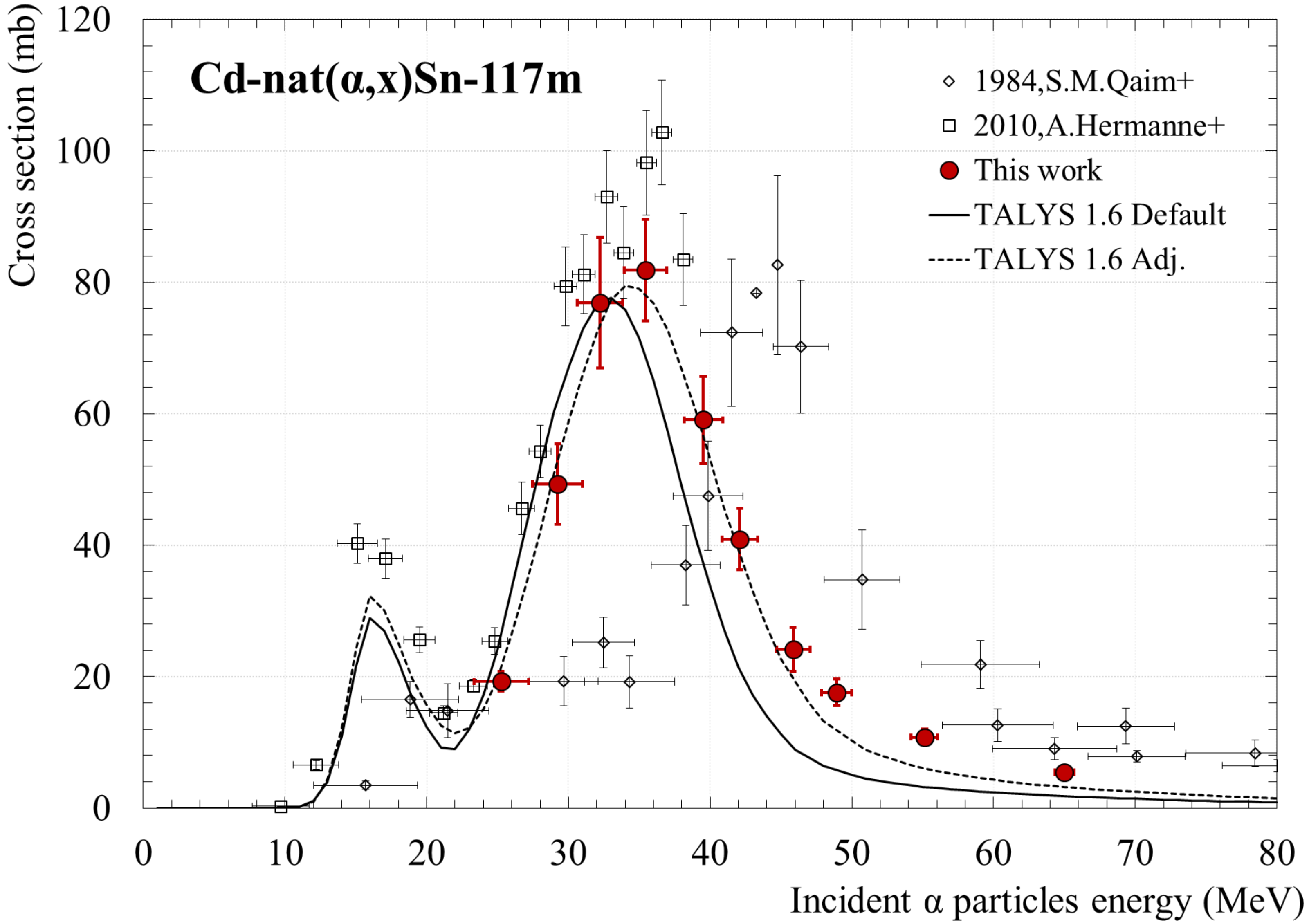
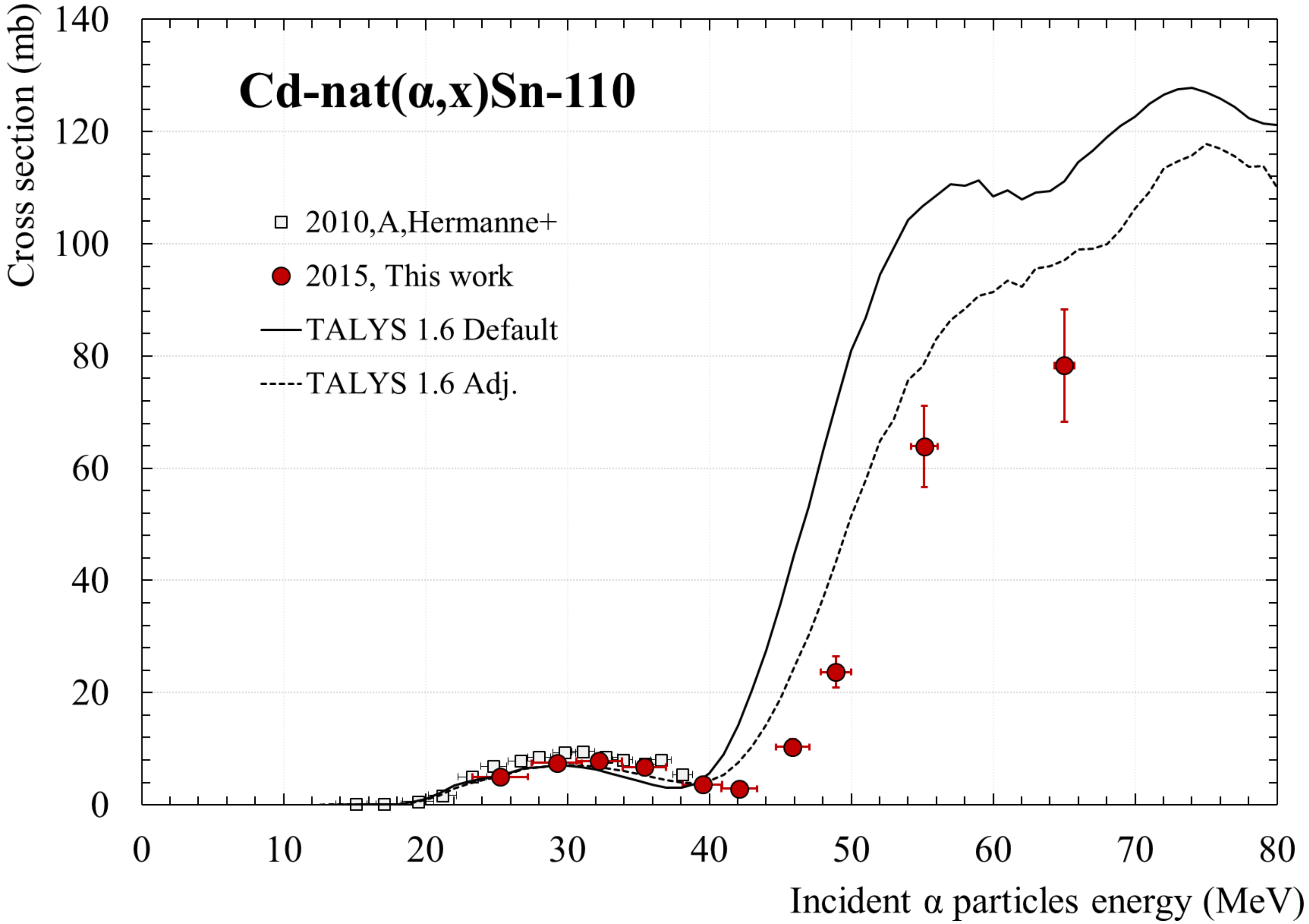
Used in clinical trials

cardiovascular diseases

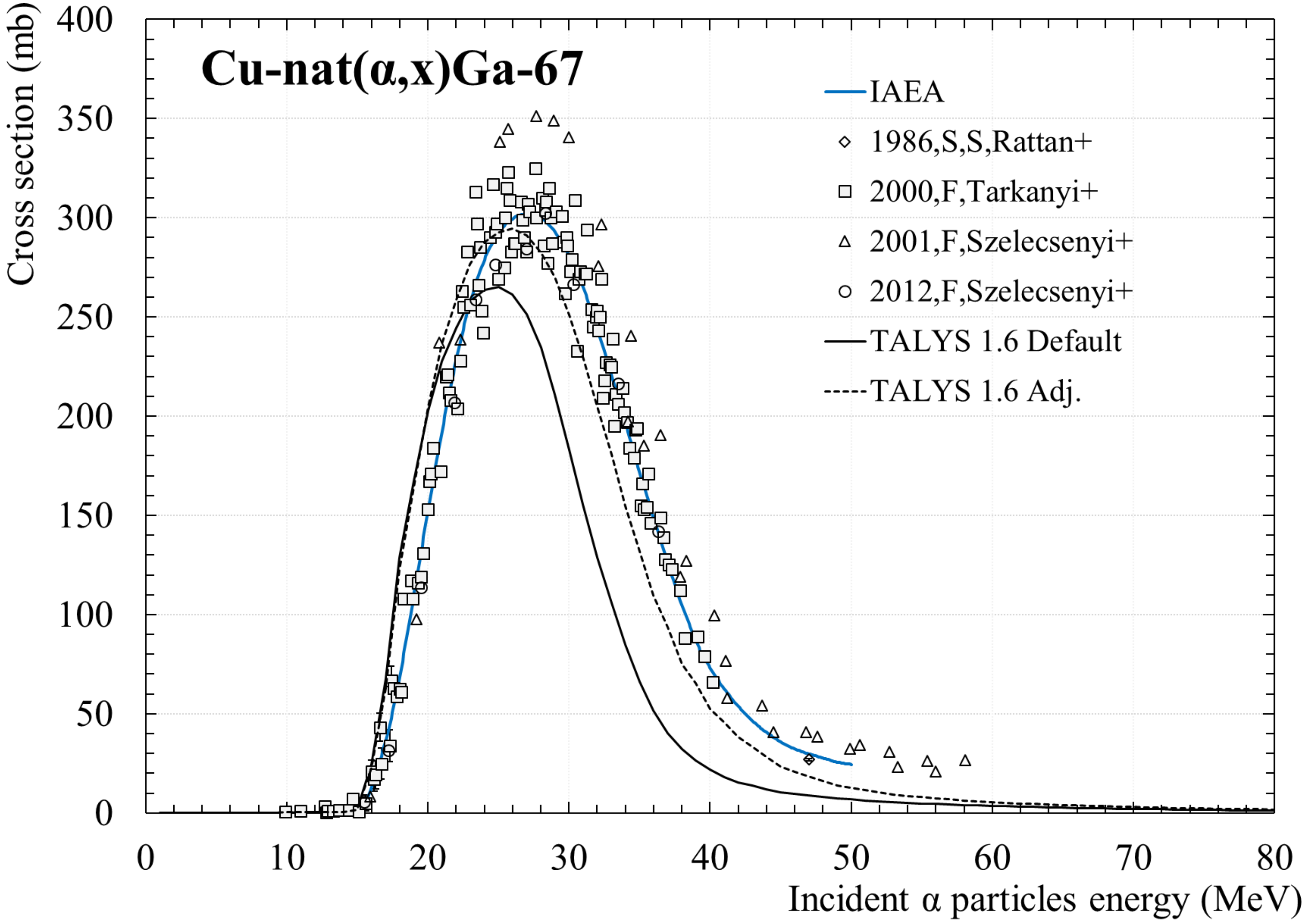


→ α particles as projectiles



→ α particles as projectiles

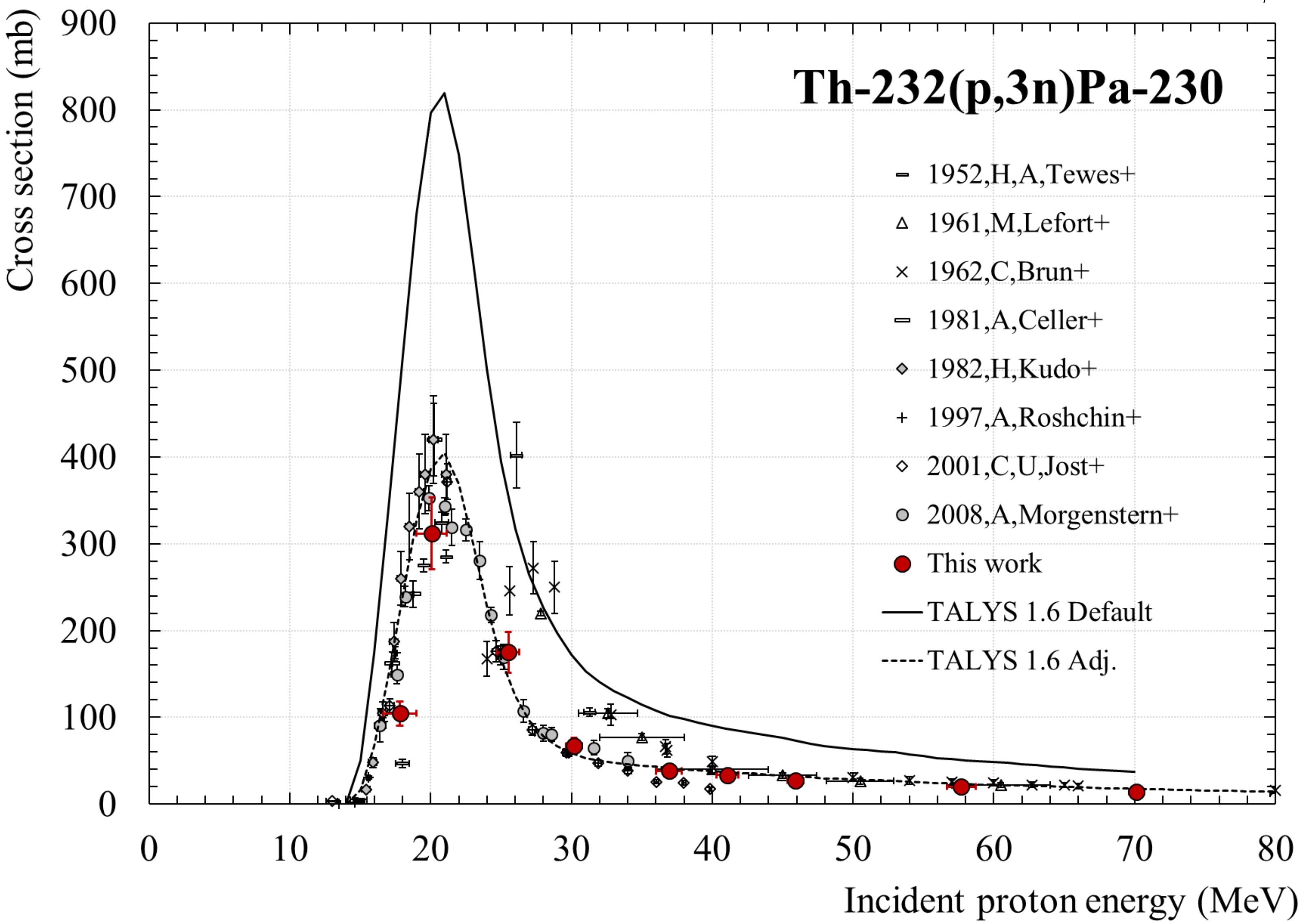
Of interest for PET imaging



→ protons as projectiles

→ protons as projectiles

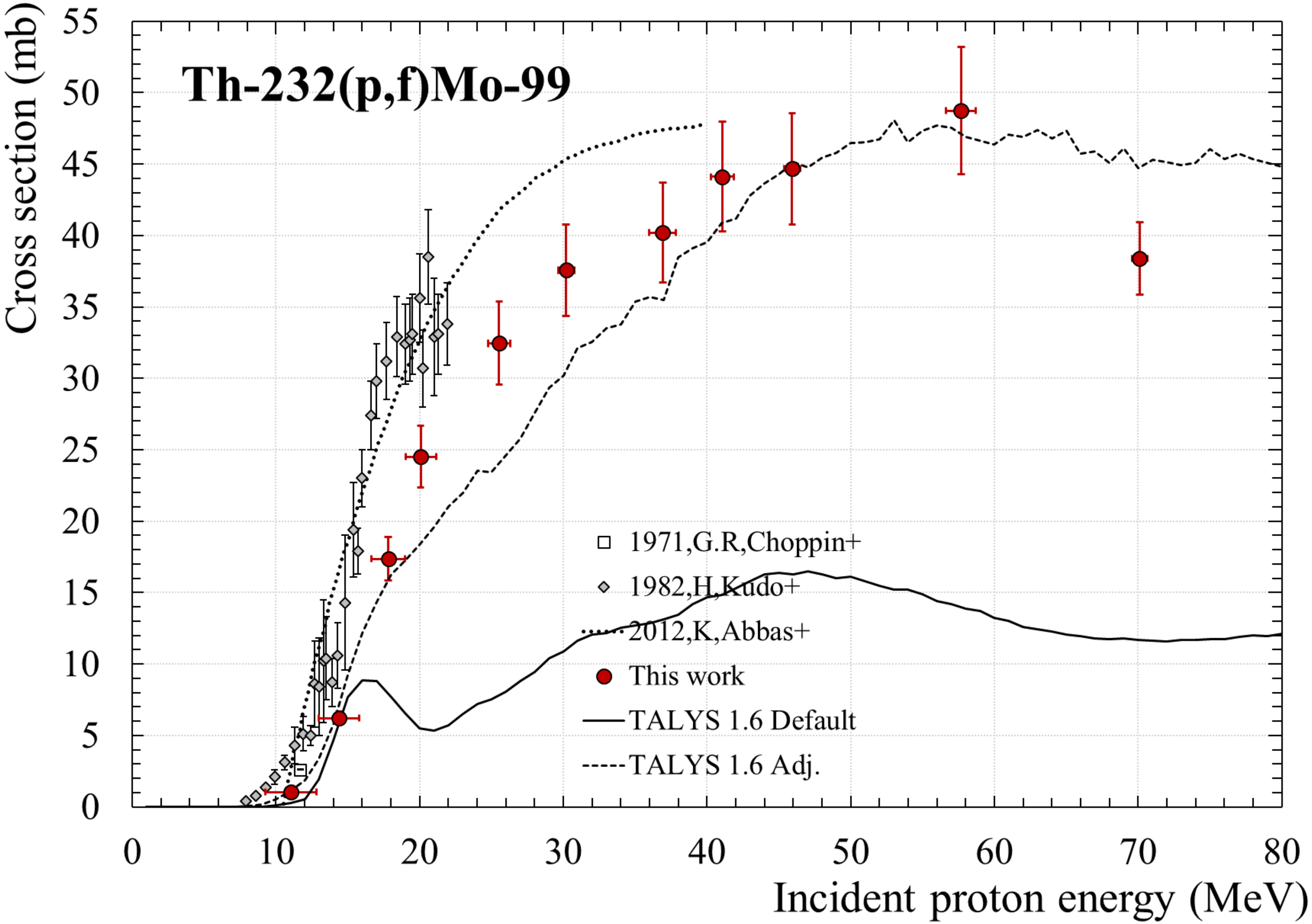
Produces Th-226
Candidate for alpha immunotherapy



→ protons as projectiles

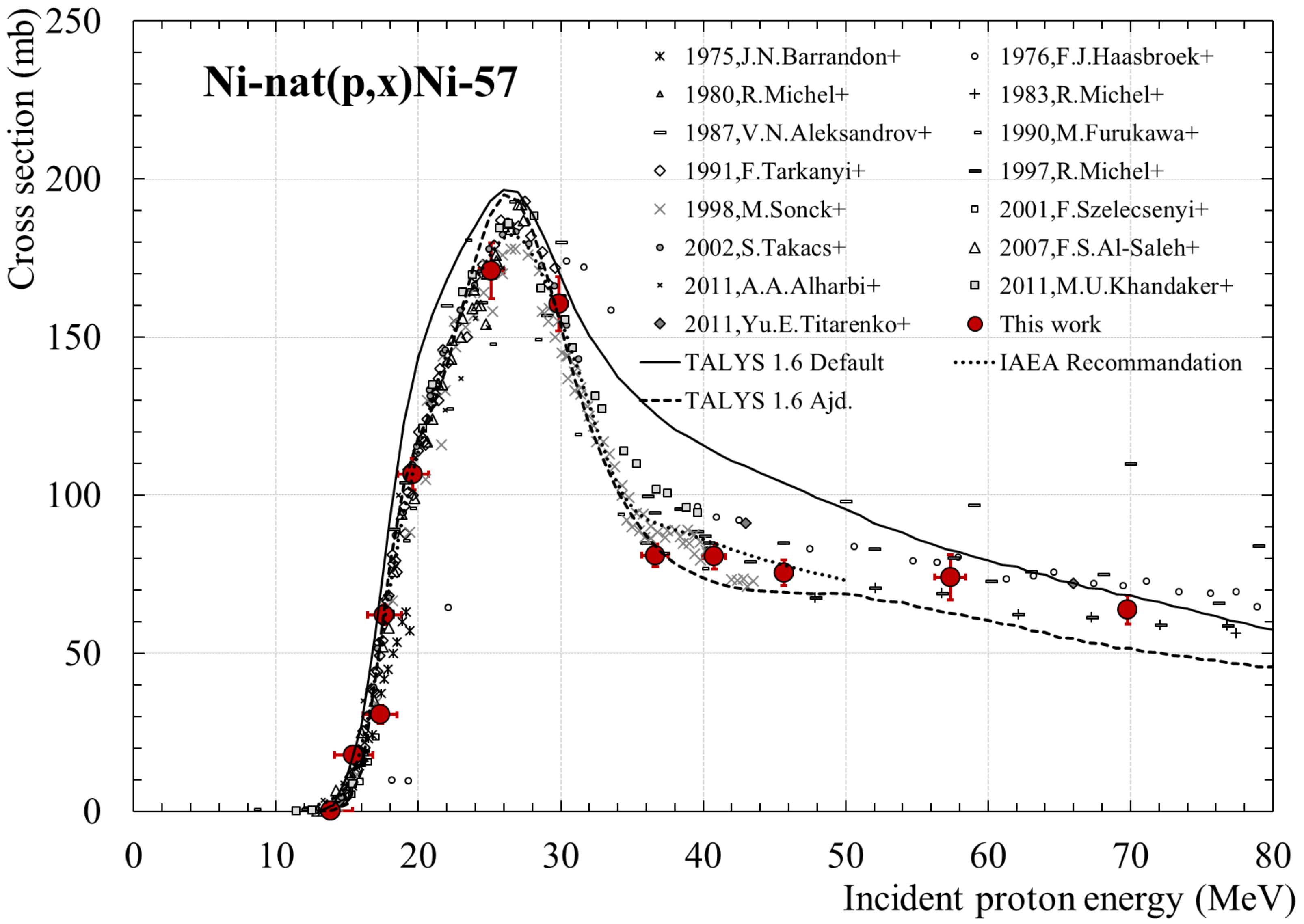
Produces Tc-99m

For SPECT



→ protons as projectiles

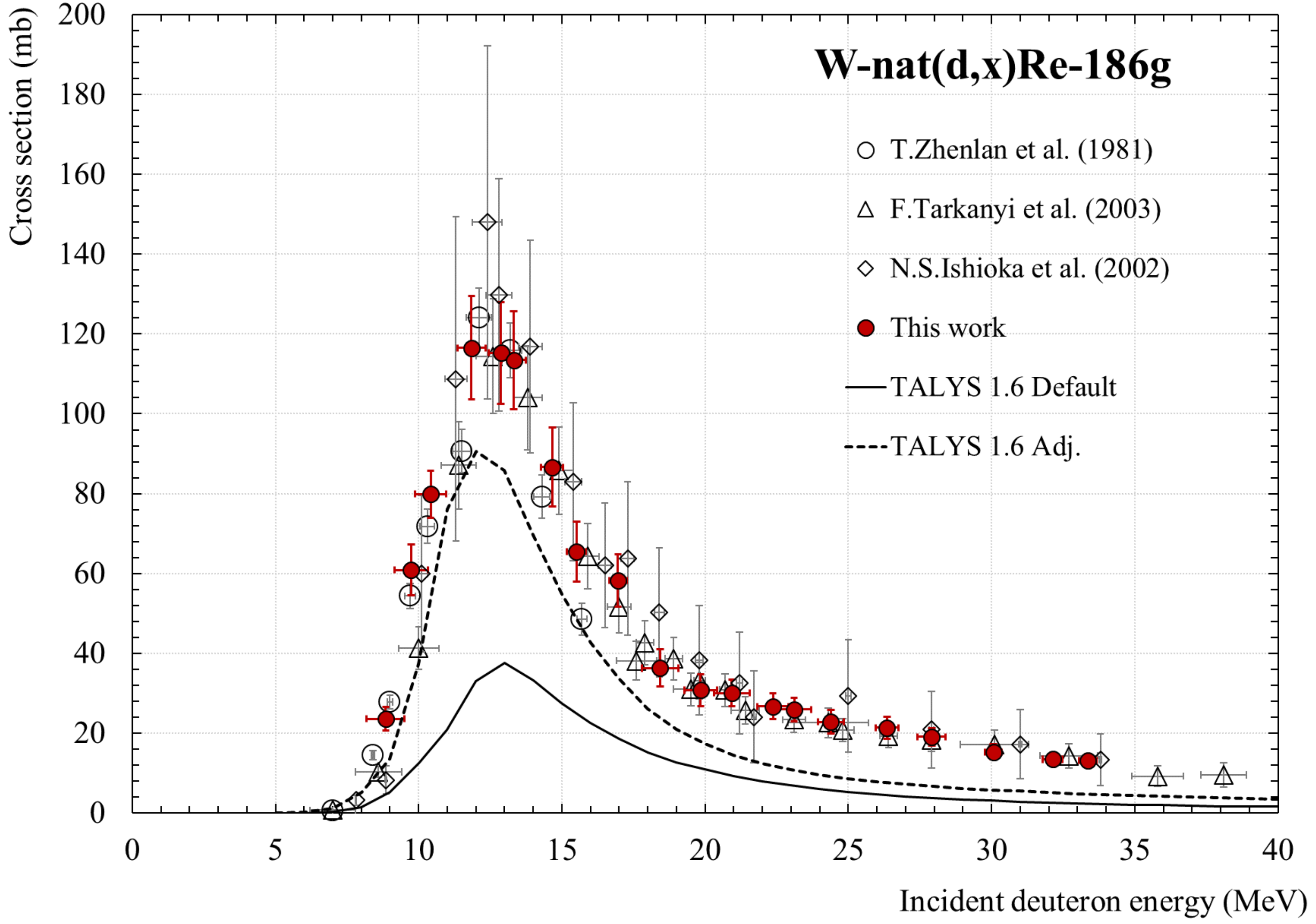
Monitor reaction



→ deuterons as projectiles

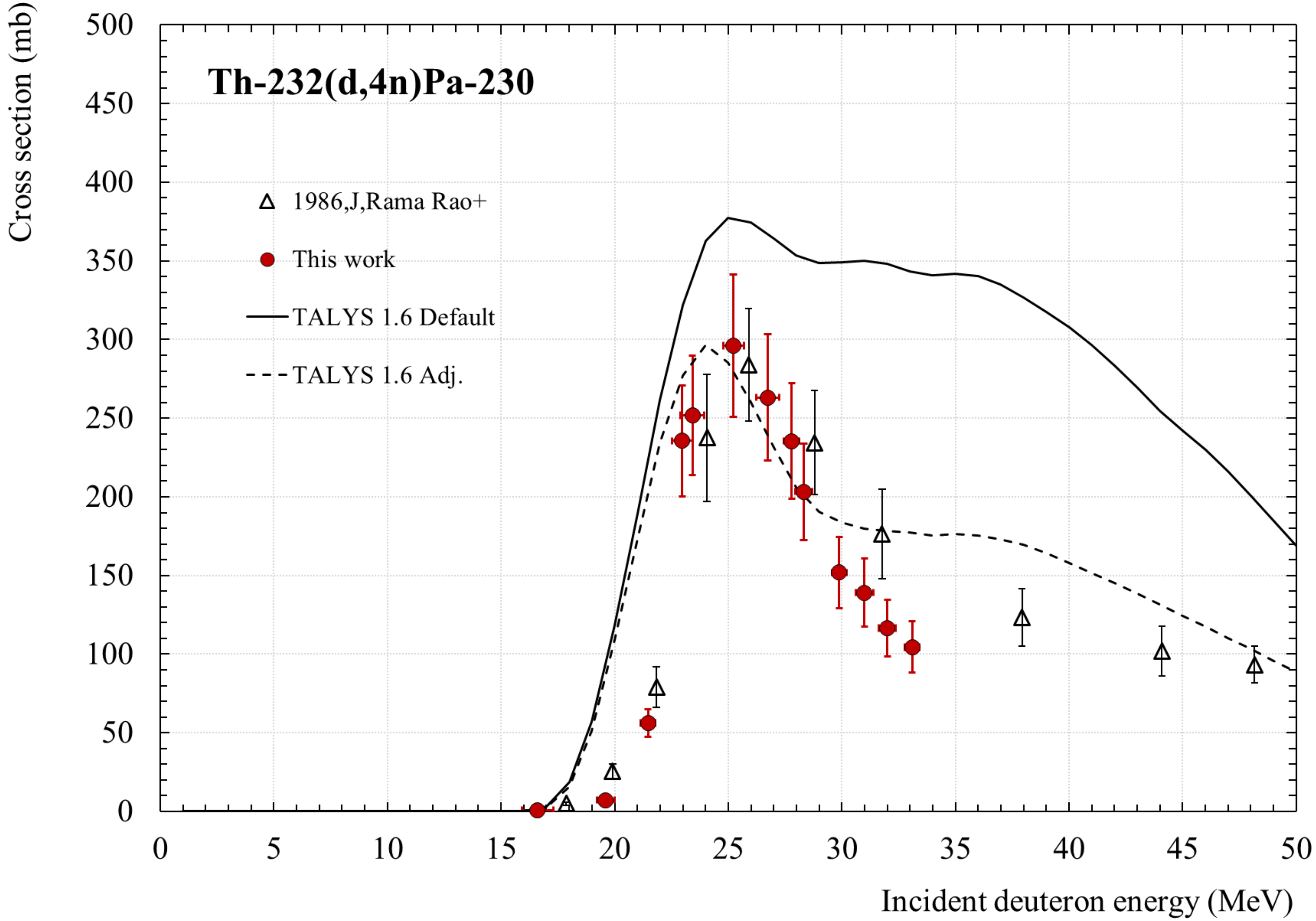
→ deuterons as projectiles

Used in clinical trials
palliative therapy for painful metastases



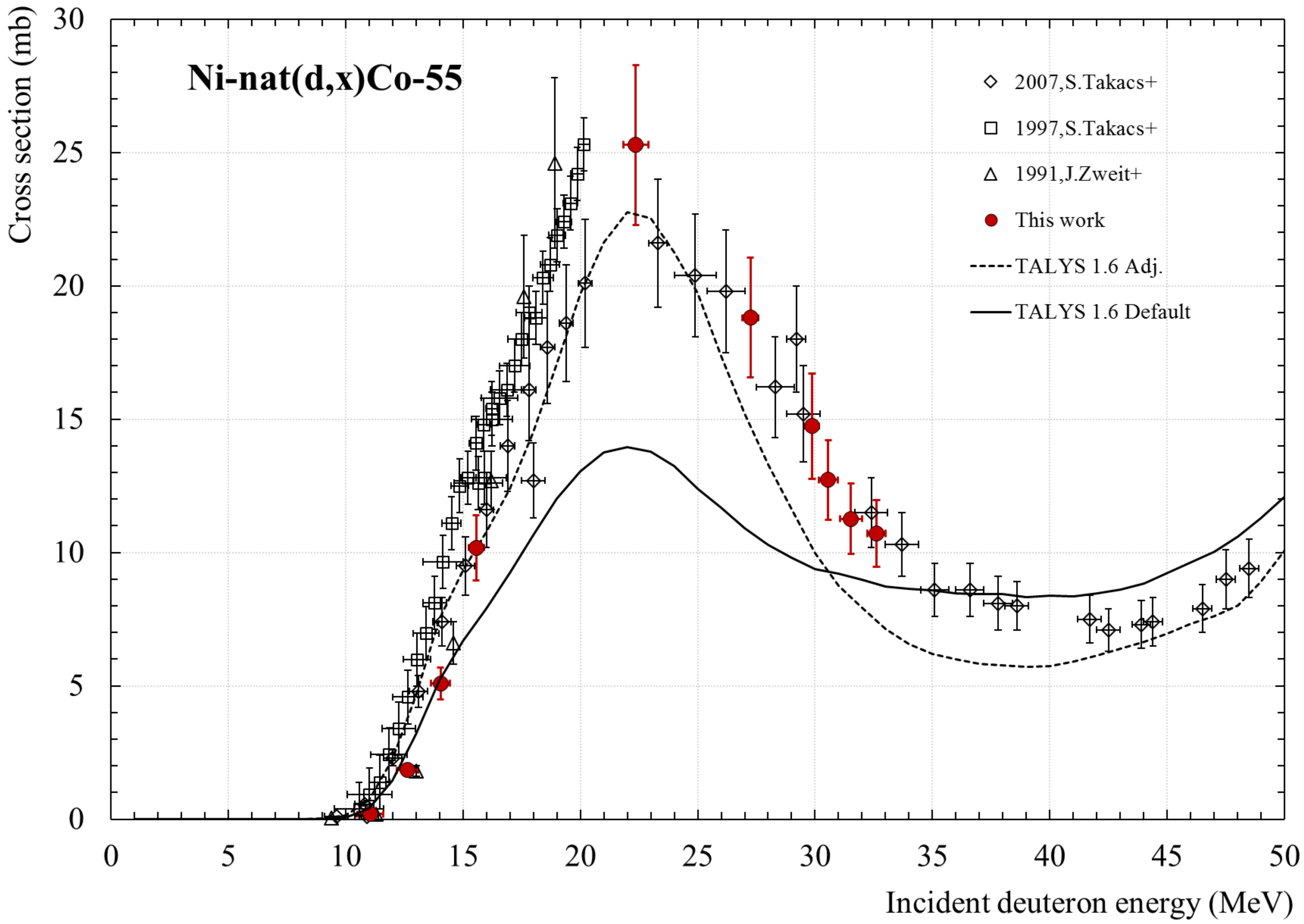
→ deuterons as projectiles

Produces Th-226
Candidate for alpha immunotherapy



→ deuterons as projectiles

Of interest for PET imaging



8. Conclusions

. 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 on a wide mass range
- On radionuclides for diagnosis and therapy purposes in nuclear medicine

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- optical potential
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- preequilibrium model

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. Further investigations are ongoing on other mechanisms that can affect the computation of the production cross sections.

UNIVERSITÉ DE NANTES · CNRS IN2P3 Les deux infinis · MINES Nantes · Subatech · ARRONAX · Arronax Plus · iron labex · Région PAYS DE LA LOIRE

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List of publications related to the topic

Nucl. Med. and Biol. **49** (2017) **30-37**

Appl. Rad. And Isot. **118** (2016) **281-89**

Appl. Rad. And Isot. **115** (2016) **113-24**

NIMB **383** (2016) **191-212**

Phys. Med. Biol. **60** (2015) **6847-6864**

Appl. Rad. And Isot. **97** (2015) **52–58**

Frontiers in Medicine **2** (2015) **31**

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

Press article Medical Physics Web Feb 16, 2015

Nucl. Med. and Biol. **41** (2014) **e16–e18**

Nuclear Data Sheets **119** (2014) **267–269**

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