NATIONAL TECHNICAL UNIVERSITY OF ATHENS and
NATIONAL CENTER for SCIENTIFIC RESEARCH
"DEMOKRITOS"

Study of (n,2n) reaction on ^{191,193}Ir isotopes and isomeric cross section ratios

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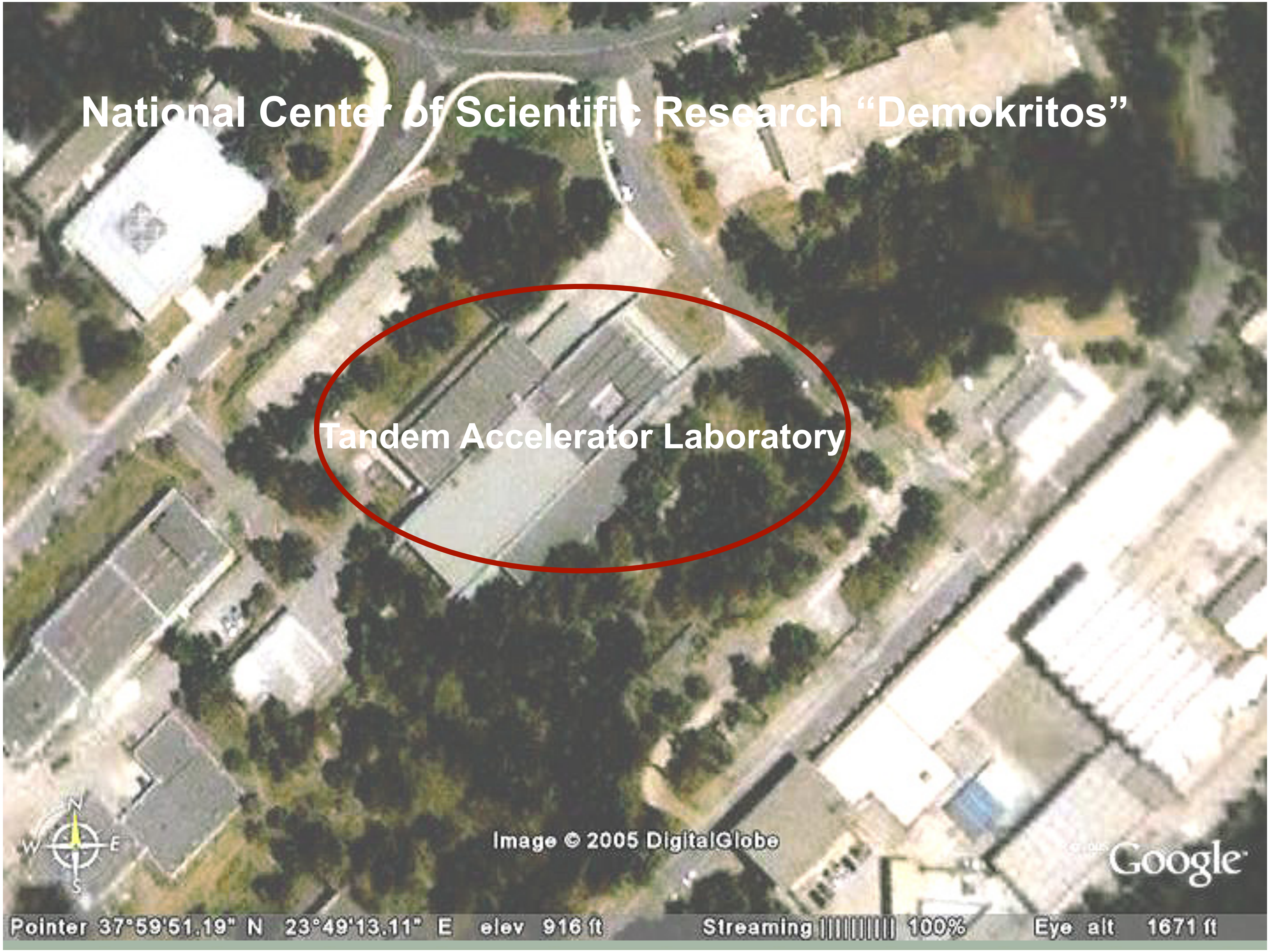
National Center of Scientific Research "Demokritos"
Tandem Accelerator Laboratory
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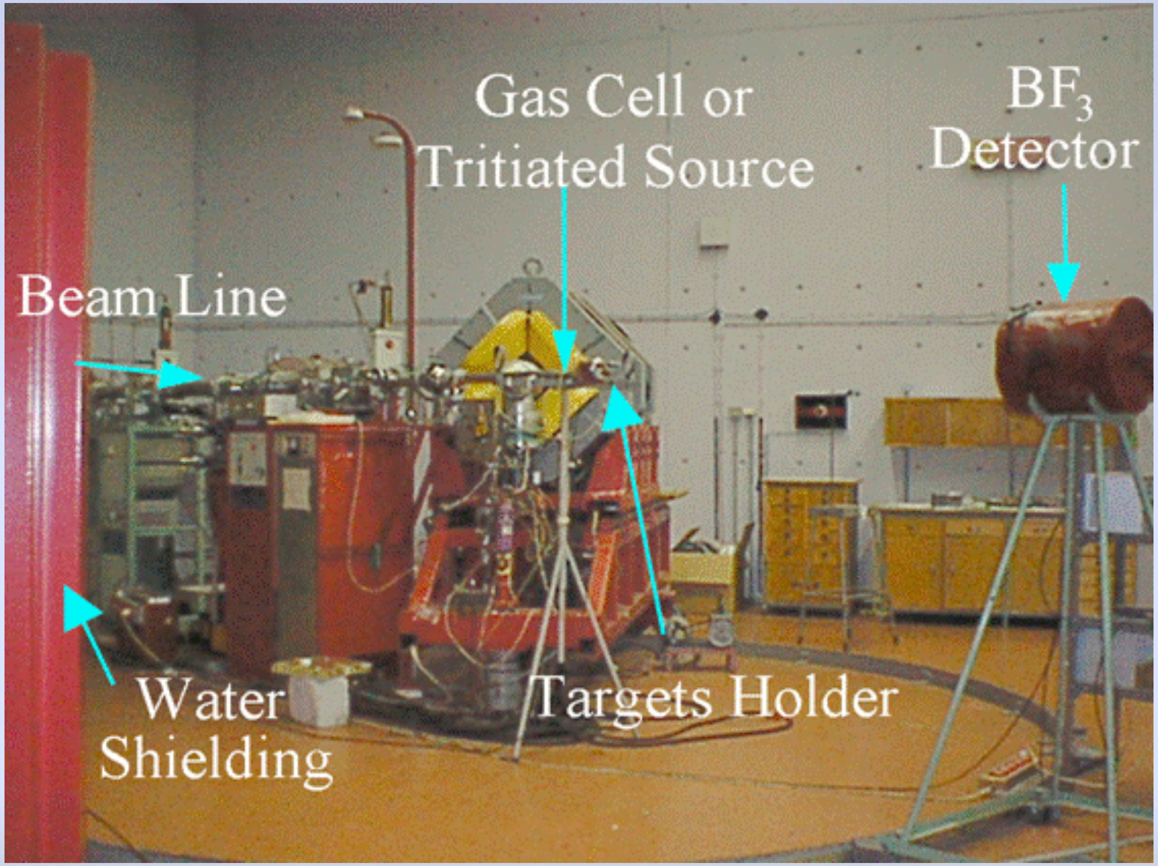
Neutron Facility at NCSR "Demokritos"

The neutron facility at the 5.5 MV tandem T11/25 Accelerator can deliver quasi-monoenergetic neutron beams at energies 4.0-11.5 MeV via the $^{2}H(d,n)^{3}He$ reaction by using deuteron beams in the energy range 0.8-9.6 MeV



Gas cell with 5μm Mo foil as entrance window and Pt foil as beam stop, filled with deuterium : P ≈ 1.2 bar

Neutron flux ≈ 10^6 n/(cm^2 s) To monitor the neutron flux a BF_3 detector is used, while the absolute flux of the beam is determined via the $^{27}Al(n,\alpha)$ reference reaction

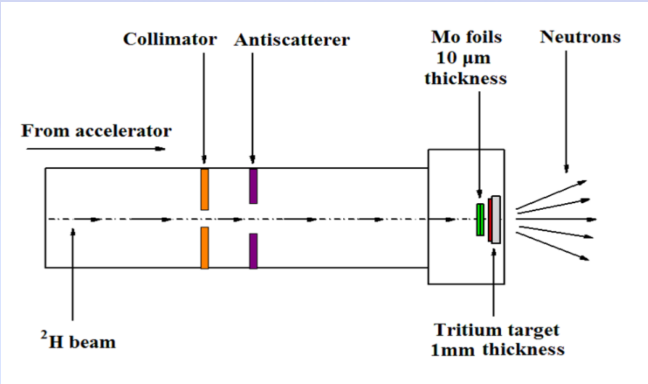
Cross section measurements via the activation technique

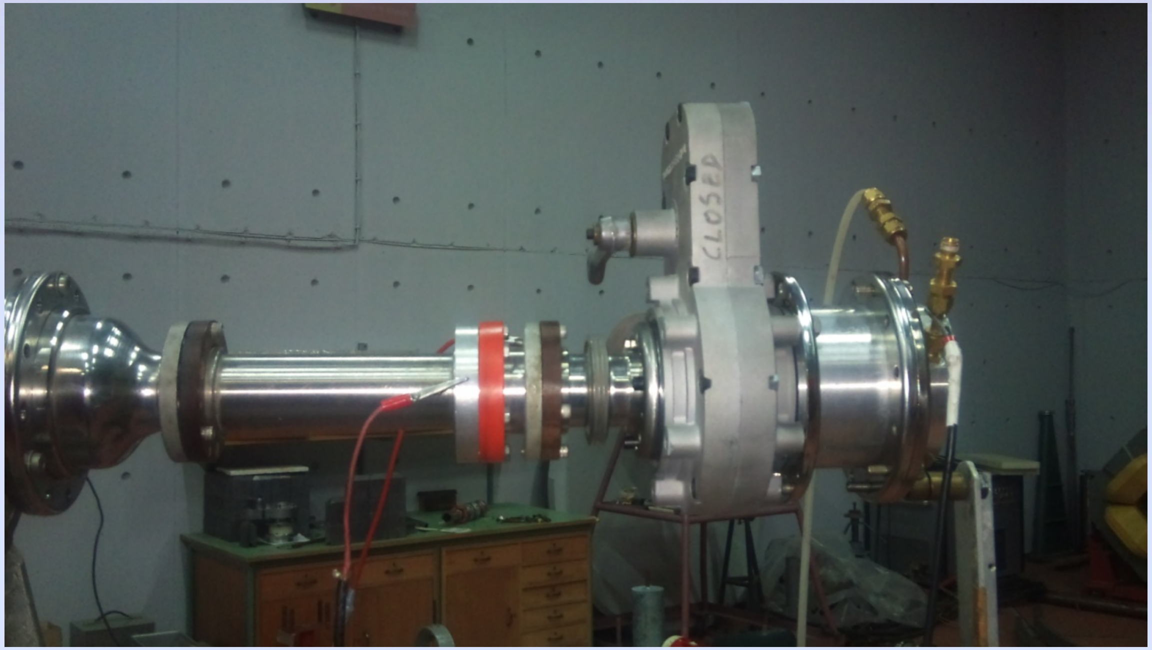
Samples: disks of 1.3 cm diameter, high purity natural foils

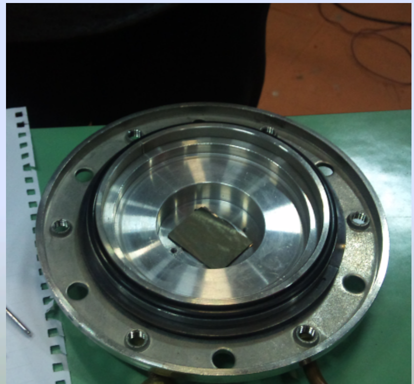
After the neutron irradiation : Off-line measurements of γ-ray transitions from the residual nuclei by using **HPGe detectors** ε_r ≈ 80% and 56%

The new High Energy Neutron Facility

The neutron beam can be produced at energies **~ 15-21 MeV** by means of the **$^3H(d,n)^4He$** reaction. A **new Ti-tritiated target of** 373 GBq activity, consists of 2.1 mg/cm^2 Ti-T layer on a 1mm thick Cu backing for good heat conduction.
The flange with the tritium target assembly was air cooled during the deuteron irradiation.
The neutron flux was 10^5-10^6 n/(cm^2 s), depending on the energy







Neutrons at 17.1 and 20.9 MeV have been used for cross section measurements via the activation technique

The neutron beam is not purely monoenergetic due to parasitic neutrons mainly coming from deuteron break up reactions : $^{3}H(d,pn)^{3}H$, $^{2}H(d,n)^{3}He$ and reactions with Ti(d,n) and C(d,n) etc

In the absence of time-of-flight capabilities, the investigation of neutron fluence energy dependence has been carried out using the Monte Carlo simulation codes **NeuSDesc** and **MCNP**

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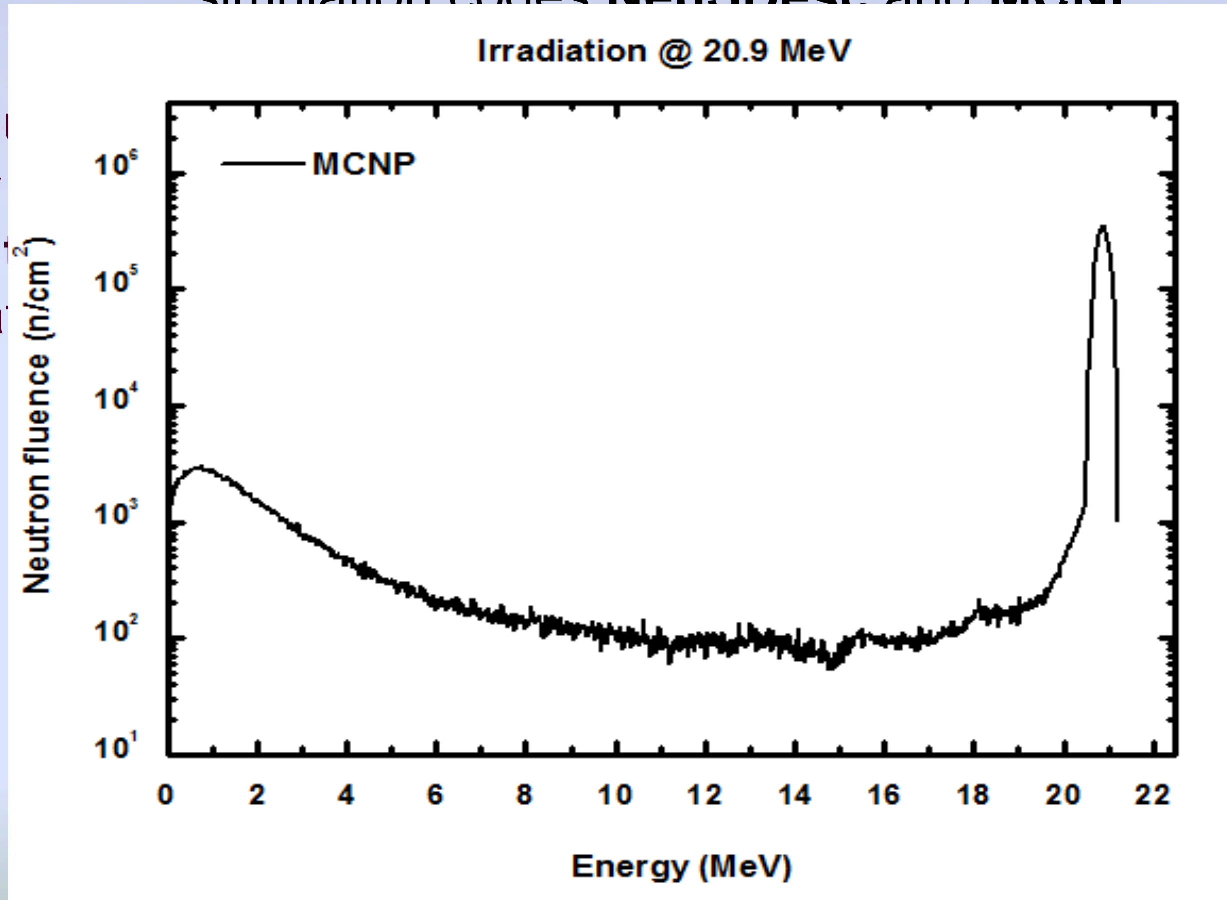
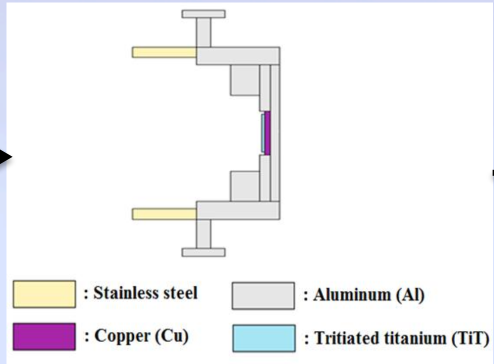


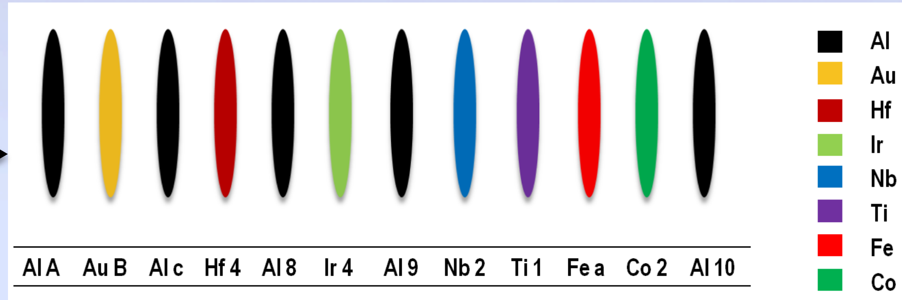
In addition to the simulations, the energy spectrum of the neutron beam has been investigated by means of the **Multiple Foil Activation Analysis technique** using reactions with different energy thresholds

High purity foils of natural Au, In, Ni, Ti, Zn, Fe, Al, Nb and Co were placed in close contact at a distance of ~2 cm from the tritium target for the irradiation. The induced activities of product radionuclides were measured off-line by a 100% and a 16% efficiency HPGe detector systems

d beam



n beam



The experimental reaction rates of all high and low threshold reactions have been deduced :

$$R.R = \frac{\lambda \cdot N_p}{N_\tau \cdot \left(1 - e^{-\lambda t_B}\right)}$$

The experimental results have been compared with the simulated ones in order to validate the simulations

In order to verify the simulated neutron energy distribution, the reaction rate *R.R* has been deduced for all the reactions from :

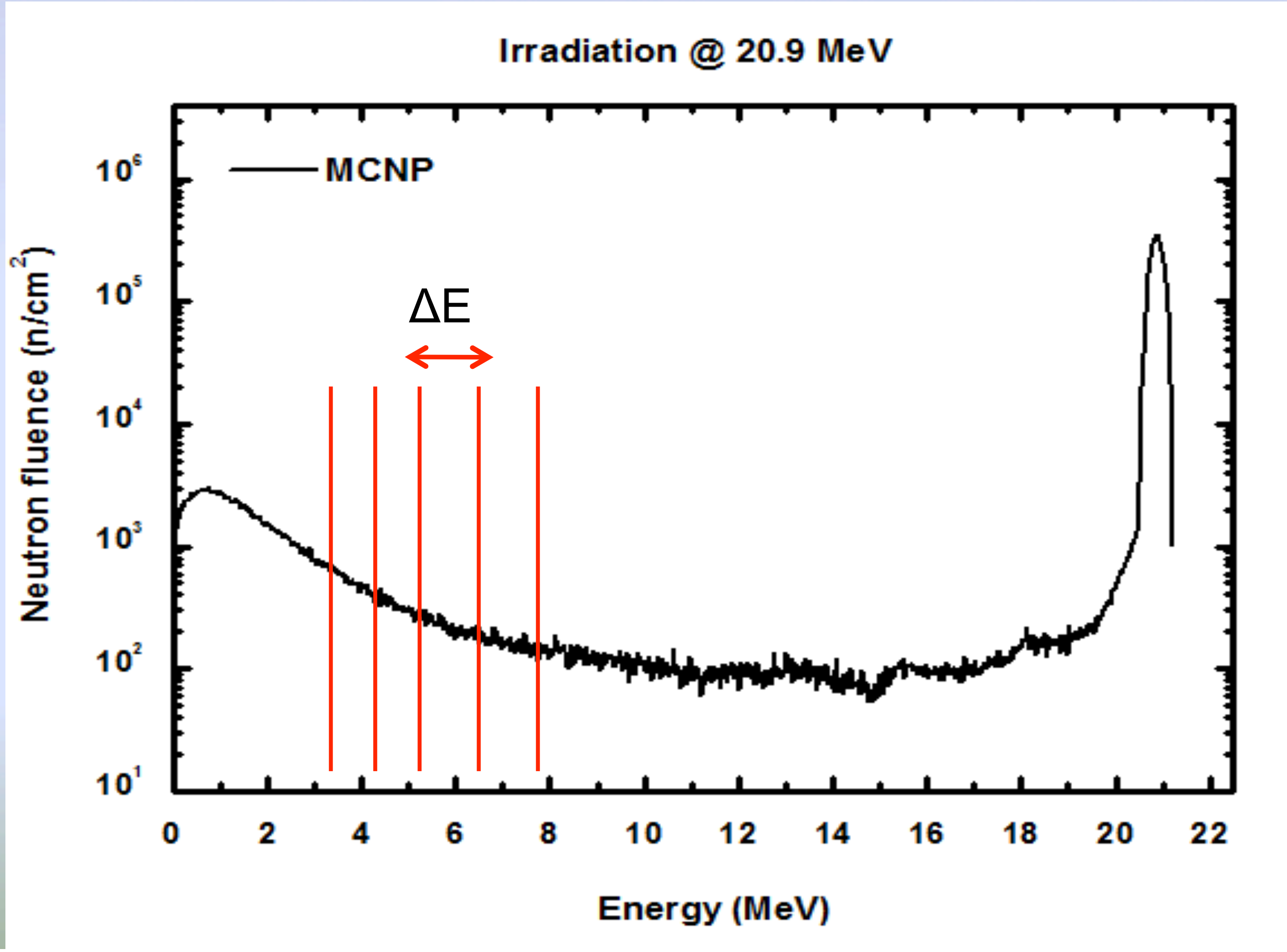
$$R.R = \int_{Eth,i}^{\infty} \sigma_i(E) \cdot \Phi_i(E) \, dE$$

$\sigma(E)$ from ENDF-VII

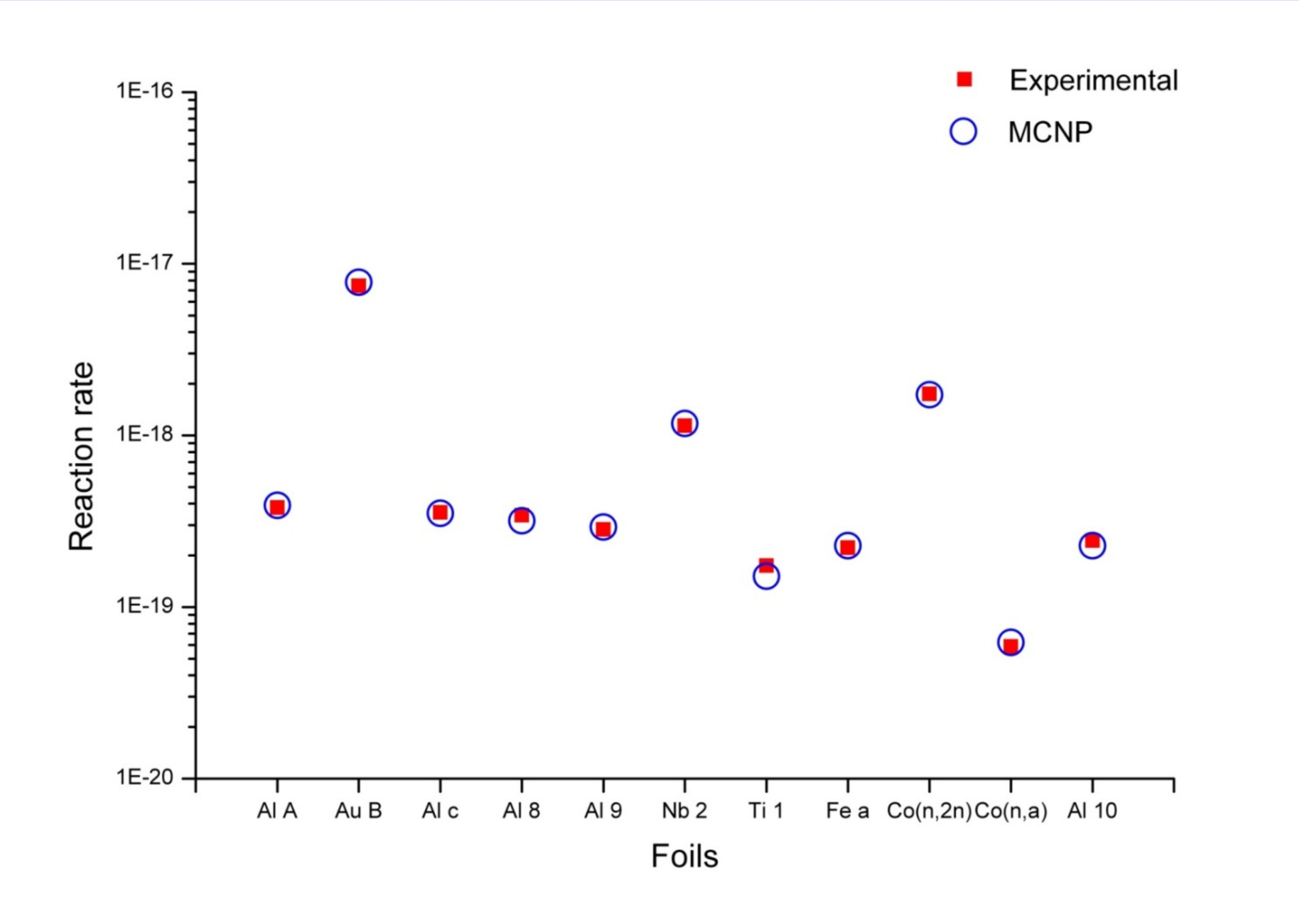
$\Phi(E)$ from the simulations

$$R.R = \sum_{\Delta E} \sigma(E) \cdot \Phi(E)$$

from energy threshold

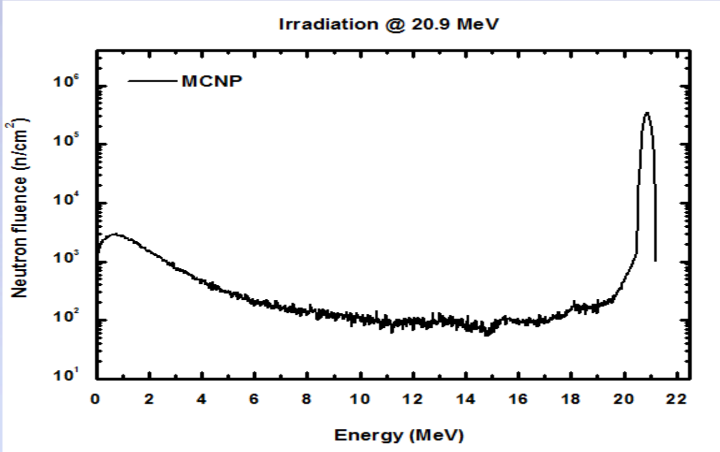


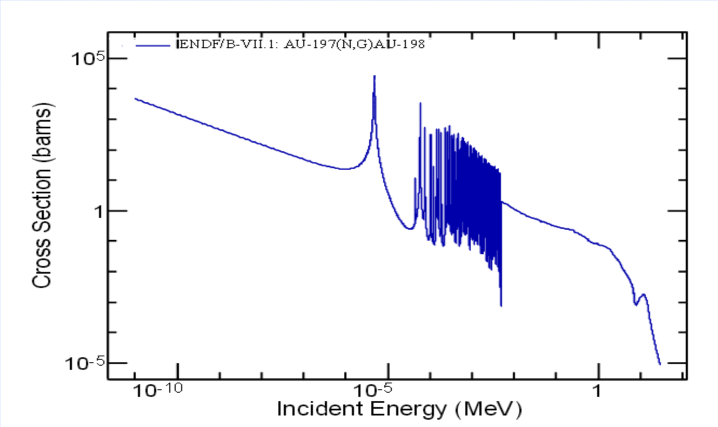
Comparison of the simulated and experimental Reaction Rates

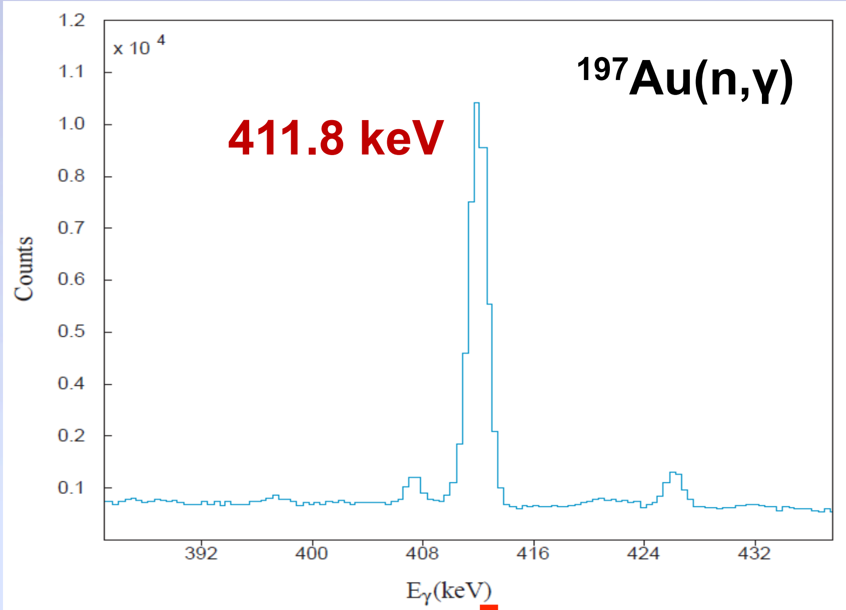


Validation of the simulated neutron energy distribution above 1MeV (threshold)

The only non-threshold reaction is the **^{197}Au(n,γ)** : suitable to validate the neutron fluence in the low energy region







$$R.R = \sum_{\Delta E} \sigma(E) \cdot \Phi(E)$$

$$N_\gamma = \frac{N_\tau \cdot \left(1 - e^{-\lambda t_B}\right) \cdot \varepsilon \cdot I \cdot D \cdot f_c \cdot F}{\lambda} \cdot R.R$$

$N_\gamma^{exp} = 3180$ counts

$N_\gamma^{simul} = 3070$ counts

Validity of the simulations has been demonstrated, thus the simulated neutron fluence can be used to solve problems arising in cross section measurements

Cross Section Measurements

of reactions already investigated with the low energy neutron facility in the past using the activation technique - reference reactions from Al and Au foils placed before and after the target foils

(n,2n) reactions on ^{191}Ir, ^{193}Ir, ^{174}Hf, ^{176}Hf measured at 17.1 and 20.9 MeV

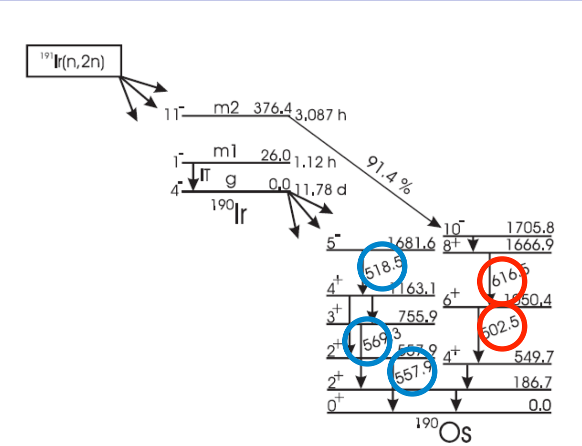
^{193}Ir(n,2n)^{192}Ir contaminated by ^{191}Ir(n,γ)^{192}Ir

^{176}Hf(n,2n)^{175}Hf contaminated by ^{174}Hf(n,γ)^{175}Hf

and (n,γ) reactions are affected by the parasitic low energy neutrons can be corrected using the simulation technique

(n,2n) reactions on Ir isotopes

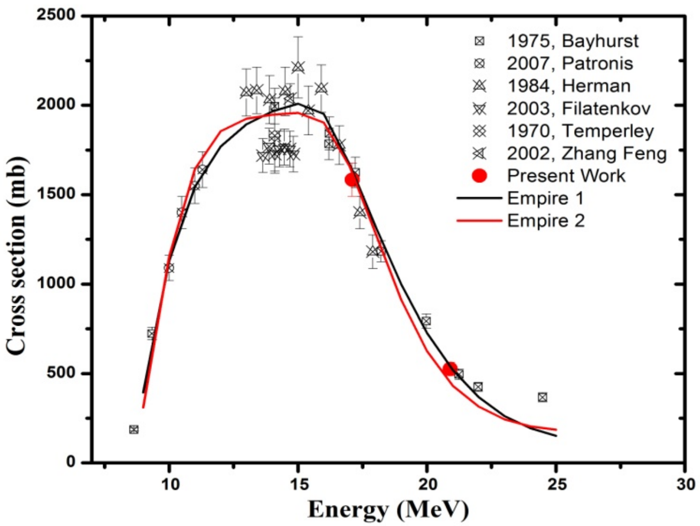
a) The $^{191}Ir(n,2n)^{190}Ir^{g+m1}$ and $^{191}Ir(n,2n)^{190}Ir^{m2}$ reactions



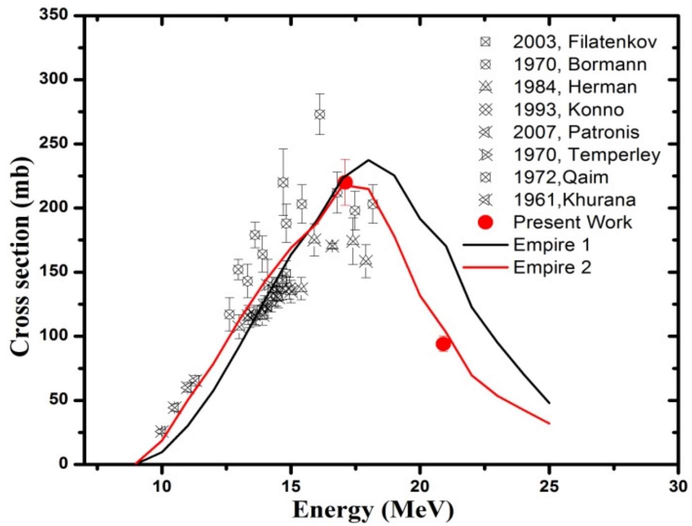
Natural Ir consists of two isotopes ^{191}Ir and ^{193}Ir with 37.3% and 62.7% abundances, respectively.

The $^{191}Ir(n,2n)$ reaction leads to the formation of ^{190}Ir in its ground 4^- state g ($T_{1/2}$=11.78d) as well as its metastable m 11^- state ($T_{1/2}$=1.12h) and m2 11^- state ($T_{1/2}$=3.087h), which decay to ^{190}Os. Due to the short half life of m1, the sum of **m1+g** cross sections was determined via the most intensive **518.5 keV** transition of ^{190}Os, while the population of the **m2** state can be determined independently via the **616.5 keV** γ-ray .

$^{191}Ir(n,2n)^{190}Ir^{g+m1}$



$^{191}Ir(n,2n)^{190}Ir^{m2}$



Further measurements are planned at ~15 and ~19 MeV to resolve discrepancies in experimental points and theoretical predictions

(n,2n) reactions on Ir isotopes

b) The $^{193}Ir(n,2n)^{192}Ir$

Natural Ir consists of two isotopes ^{191}Ir and ^{193}Ir with 37.3% and 62.7% abundances, respectively.

Thus, the $^{193}Ir(n,2n)^{192}Ir$ threshold reaction is **contaminated by the $^{191}Ir(n,\gamma)^{192}Ir$**.

The residual nucleus ^{192}Ir decays to ^{192}Pt with a half life of 74.2 d and its population can be determined via the 316.5 keV transition

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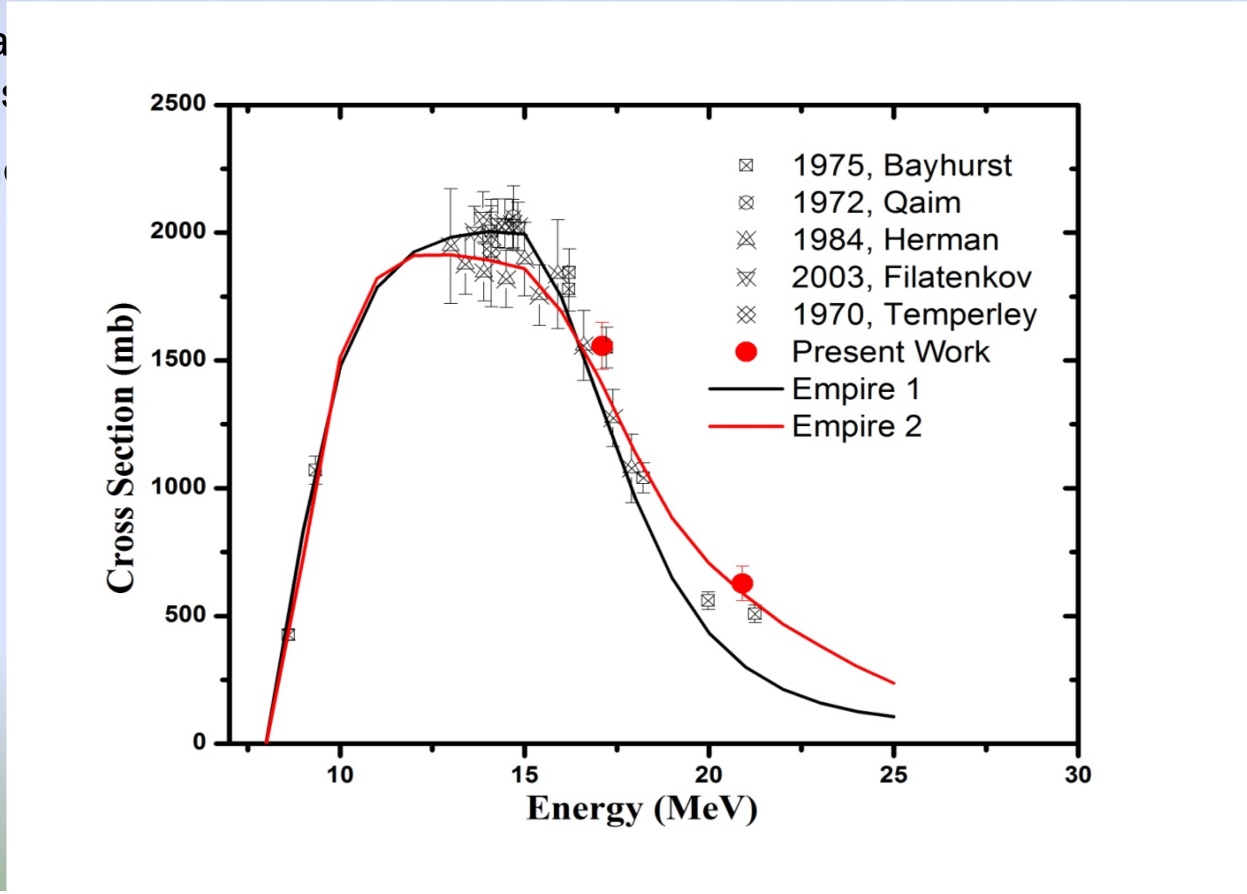
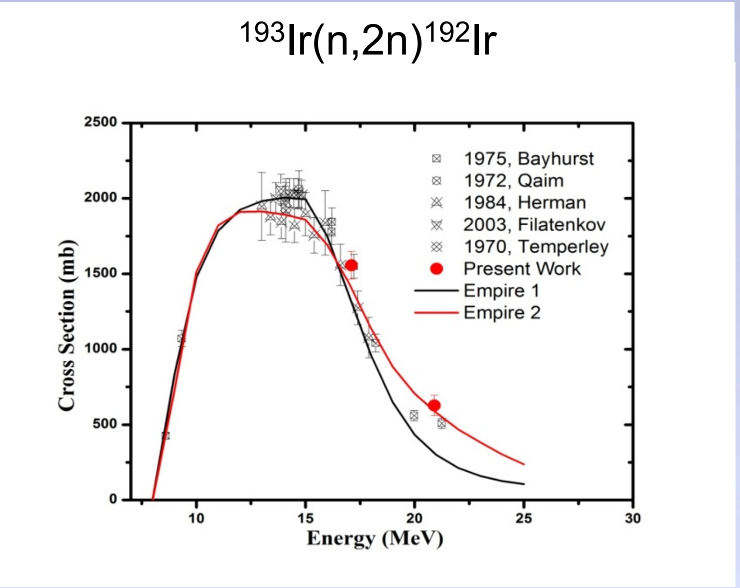
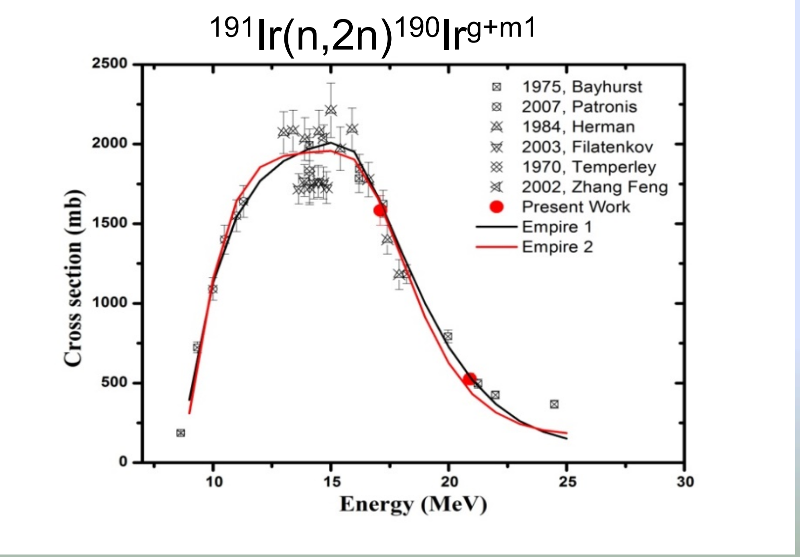
At 17.1 MeV th … 0% and affects

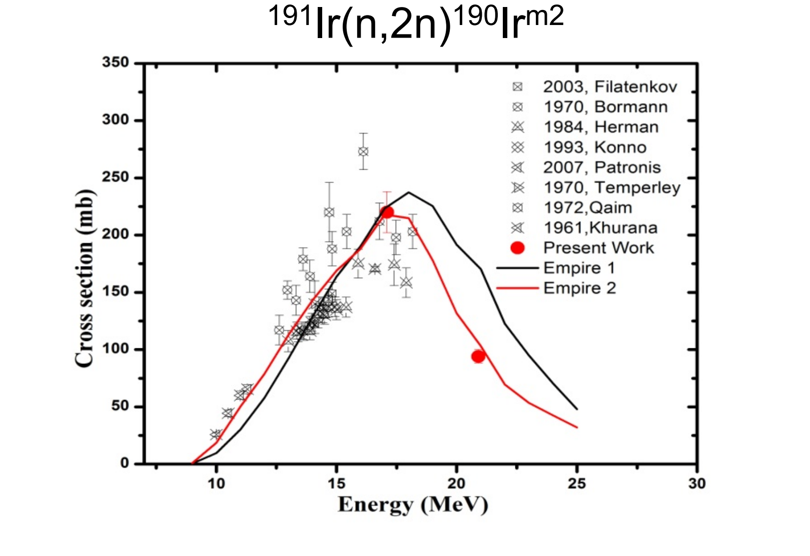


EMPIRE calculations



Pre-equilibrium effects were taken into account via the multi-step direct (MSD) and multi-step compound (MSC) formulations as implemented in the code. The sensitivity of the calculations for the reproduction of the cross section for both isotopes and mainly for the isomeric state m2, was tested using several combinations of optical model potentials (OMP) for outgoing neutrons and nuclear level densities (NLD). **The best results were achieved with the local OMP of M.B Chadwick and Gilbert & Cameron NLD (Empire1) as well as with the spherical OMP of R.L.Varner and the Generalized Superfluid Model (GSM, Ignatyuk et al) NLD (Empire 2).** As for the outgoing protons, the EMPIRE specific OMP by Koning-Delaroche was used. Also**, the existing data on (n,p), (n, 3n) and (n,n') reactions on Ir, are also reproduced fairly well** with the aforementioned parametrization.

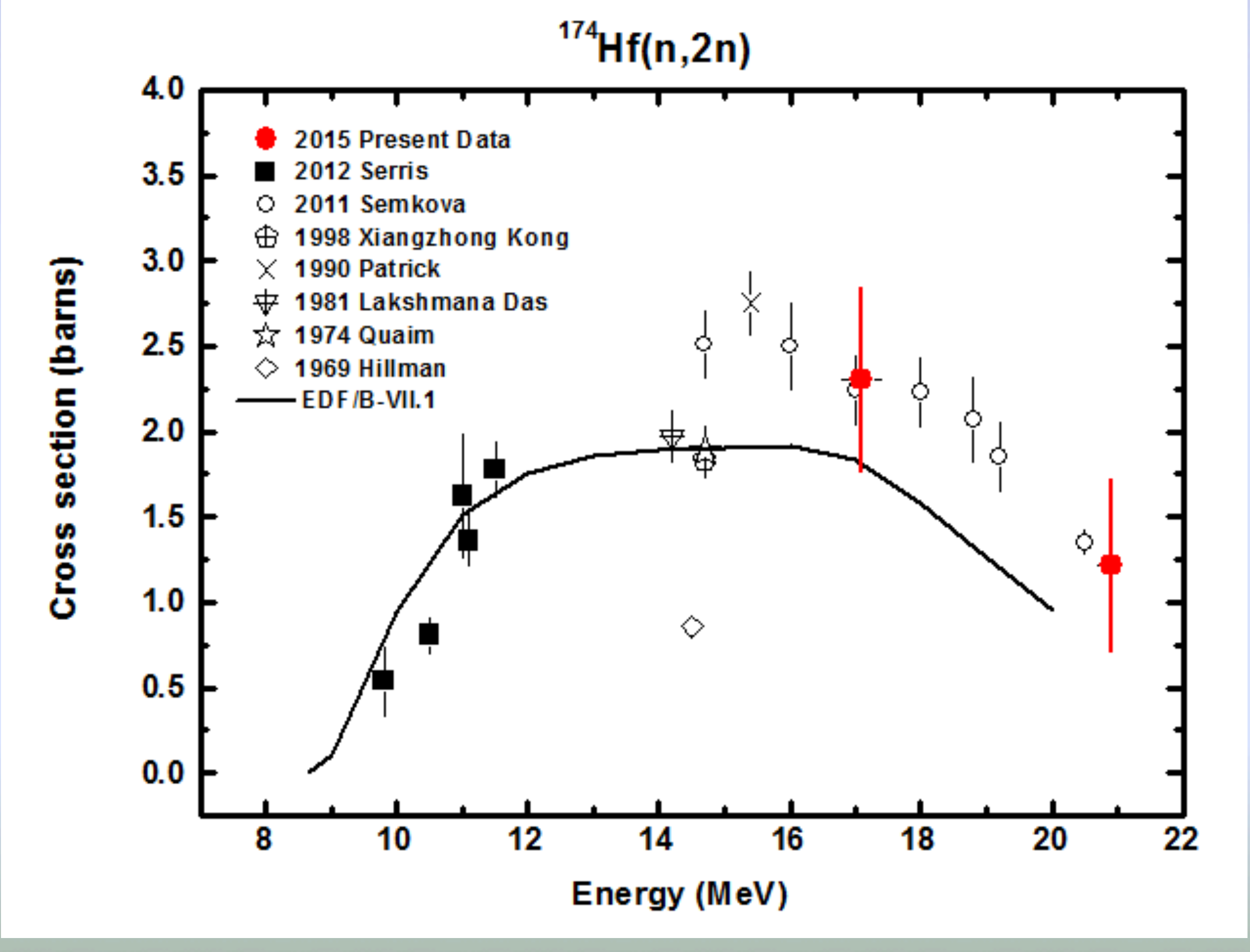




$^{174}Hf(n,2n)^{173}Hf$ reaction

From the 5 isotopes in natural Hf, only the ^{174}Hf (0.16%) and ^{176}Hf (5.2%) can be used for (n,2n) cross section measurements via the activation method

The residual nucleus ^{173}Hf ($T_{1/2}$=23.6 h) decays to ^{173}Lu and the characteristic transition **123.7 keV** from its de-excitation is used for the determination of (n,2n) cross section



Further measurements are planned at ~15 and ~19 MeV

$^{176}Hf(n,2n)^{175}Hf$ reaction

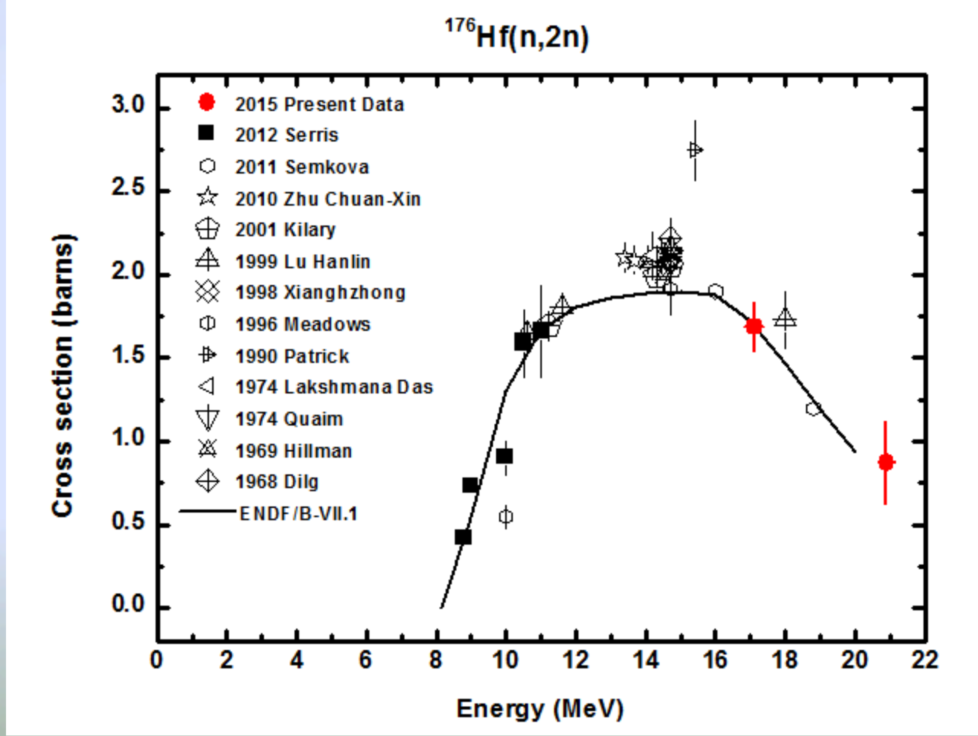
From the 5 isotopes in natural Hf, only the ^{174}Hf (0.16%) and ^{176}Hf (5.2%) can be used for (n,2n) cross section measurements via the activation method

The residual nucleus ^{175}Hf ($T_{1/2}$=70 d) decays to ^{175}Lu and the characteristic transition 343.4 keV from its de-excitation is used for the determination of (n,2n) cross section, however, $^{176}Hf(n,2n)^{175}Hf$ threshold reaction is **contaminated by the $^{174}Hf(n,\gamma)^{175}Hf$**

The contamination from the **$^{174}Hf(n,\gamma)^{175}Hf$** reaction has been deduced using *σ(E)* from ENDF-VII and the simulated *Φ(E)*, normalized to the experimental fluence on the front Al foil. The **correction was 0.1-0.5%**

But correction is needed for the $^{177}Hf(n,3n)^{175}Hf$ reaction
At 17.1 MeV the correction was 46% and at 20.9 MeV 86%

Further measurements are planned at ~15 and ~19 MeV



Collaborators

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Thank you

For your attention

The neutron beam is not purely monoenergetic due to parasitic neutrons mainly coming from deuteron break up reactions : $^{3}H(d,pn)^{3}H$, $^{2}H(d,n)^{3}He$ and reactions with Ti(d,n) and C(d,n)

In absence of time-of-flight capabilities, the energy spectrum of the neutron beam has been investigated by means of the Multiple Foil Activation Analysis technique using reactions with different energy thresholds

Reaction	$T_{1/2}$	E_γ(keV)	I_γ	E_{thr}(MeV)	E'_{thr}(MeV)
$^{27}Al(n,\alpha)^{24}Na$	14.96 h	1369	100%	3.25	6.8
$^{58}Ni(n,p)^{58}Co$	70.82 d	810.78	99.45%	0	1.4
$^{93}Nb(n,2n)^{92m}Nb$	10.1 d	934.44	99.07%	8.93	9
$^{197}Au(n,2n)^{196}Au$	6.18 d	356	87%	8.11	8.2
$^{197}Au(n,\gamma)^{198}Au$	2.69 d	411	98.6%		
$^{56}Fe(n,p)^{56}Mn$	2.58 h	846.75	98.9%	2.97	6.0
$^{59}Co(n,\alpha)^{56}Mn$	2.58 h	846.75	98.9%	0	9.1
$^{115}In(n,n')^{115m}In$	4.49 h	336.24	45.8%	0.5	1
$^{46}Ti(n,p)^{46m+g}Sc$	83.83 d	889,3 1120.5	99.98% 99.99%	1.8	3.5
$^{47}Ti(n,p)^{47}Sc$	3.34 d	159.4	68%	0	2.3
$^{48}Ti(n,p)^{48}Sc$	1.82 d	983.5	100%	3.2	7.0
$^{64}Zn(n,p)^{64}Cu$	12.7 h	511	35.7	1	2.5