Neutron-induced activation cross sections on Hf isotopes from the threshold to 20 MeV

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Outline

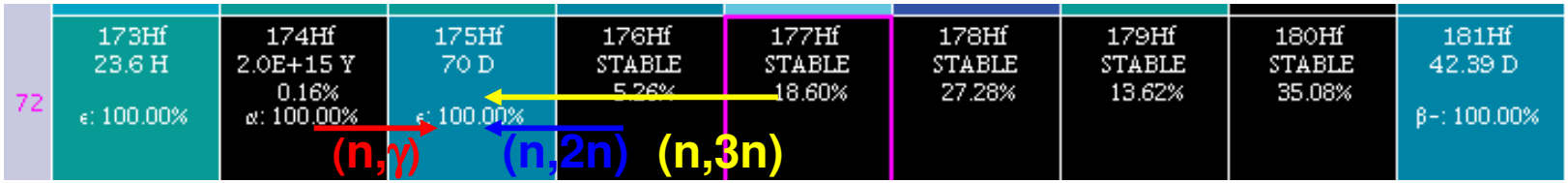
- Motivation
- Ground and isomeric states information for the hafnium isotopes and studied reaction products
- Experimental procedure
- Results for the following reaction cross sections:
  - $^{174}Hf(n,2n)^{173}Hf$
  - $^{176}Hf(n,2n)^{175}Hf$ and $^{177}Hf(n,3n)^{175}Hf$
  - $^{177}Hf(n,p)^{177g}Lu$ and $^{178}Hf(n,x)^{177g}Lu$
- Conclusions

Motivation

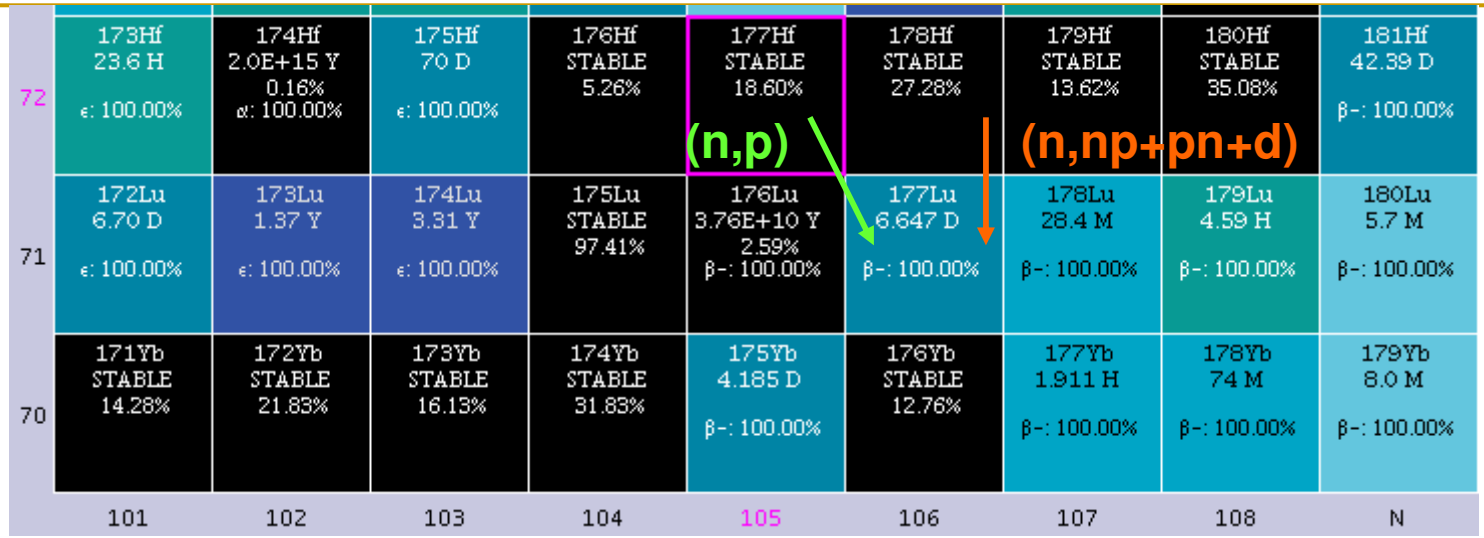
- Nuclear data for applications
  - Nuclear reactors. Hafnium has long been used as a burnable-poison in fission-energy systems.
  - Fusion technology. Hafnium is alloying element of the low activation materials that are under development for use in ITER and DEMO reactors.
- Data for nuclear models development. The elemental hafnium is a mixture of add and even isotopes. All are highly deformed collective rotors with complex exited structure.
- There are very little experimental data for the fast-neutron interaction with any of the hafnium isotopes.

Experimental procedure

- Neutron source: 7 MV Van de Graaff accelerator at IRMM, Geel, producing quasi-monoenergetic neutrons in 13.3 - 20 MeV energy range via $^{3}H(d,n)^{4}He$ reaction at E_d = 1, 2, 3, 4 MeV, solid-state 2 mg/cm^2 Ti/T target
- Neutron spectrum unfolding: Mean neutron energy and energy distribution for the irradiation geometry were determined by EnergySet program, spectrum unfolding by time-of-flight measurements in combination with threshold activation unfolding procedure were used in order to determine contribution of the low energy neutrons
- Measuring technique: Standard γ-ray spectrometry. The Monte Carlo simulation of the detector response allowed to increase the accuracy and the geometry flexibility of the measurement
- The neutron fluence rate was determined by the $^{27}Al(n,\alpha)^{24}Na$ standard cross section
- Corrections were applied for the neutron source intensity variation during irradiation, neutron flux attenuation in the sample stack, low energy neutrons, coincidence summing effects.



Ground and isomeric information						
Isotope	E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Abundance	Decay Modes
^{177}Hf	**0.0**	**7/2-**	**-52.889**	**STABLE**	**18.60% *9***	
	1.3155	**23/2+**	**-51.574**	**1.09 s *5***		**IT : 100 %**
	2.74	**37/2-**	**-50.149**	**51.4 m *5***		**IT : 100 %**
^{178}Hf	**0.0**	**0+**	**-52.4443**	**STABLE**	**27.28% *7***	
	1.1474	**8-**	**-51.2968**	**4.0 s *2***		**IT : 100 %**
	2.4461	**16+**	**-49.9982**	**31 y *1***		**IT : 100 %**
^{179}Hf	**0.0**	**9/2+**	**-50.4710**	**STABLE**	**13.62% *2***	
	0.3750	**1/2-**	**-50.0960**	**18.67 s *4***		**IT : 100 %**
	1.1058	**25/2-**	**-49.3652**	**25.05 d**		**IT : 100 %**
^{180}Hf	**0.0**	**0+**	**-49.7884**	**STABLE**	**35.08% *16***	
	1.1415	**8-**	**-48.6469**	**5.47 h *4***		**IT: 99.70%, β⁻: 0.30%**

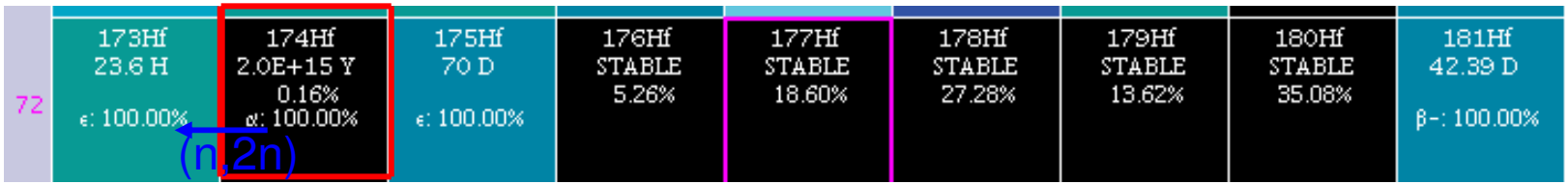


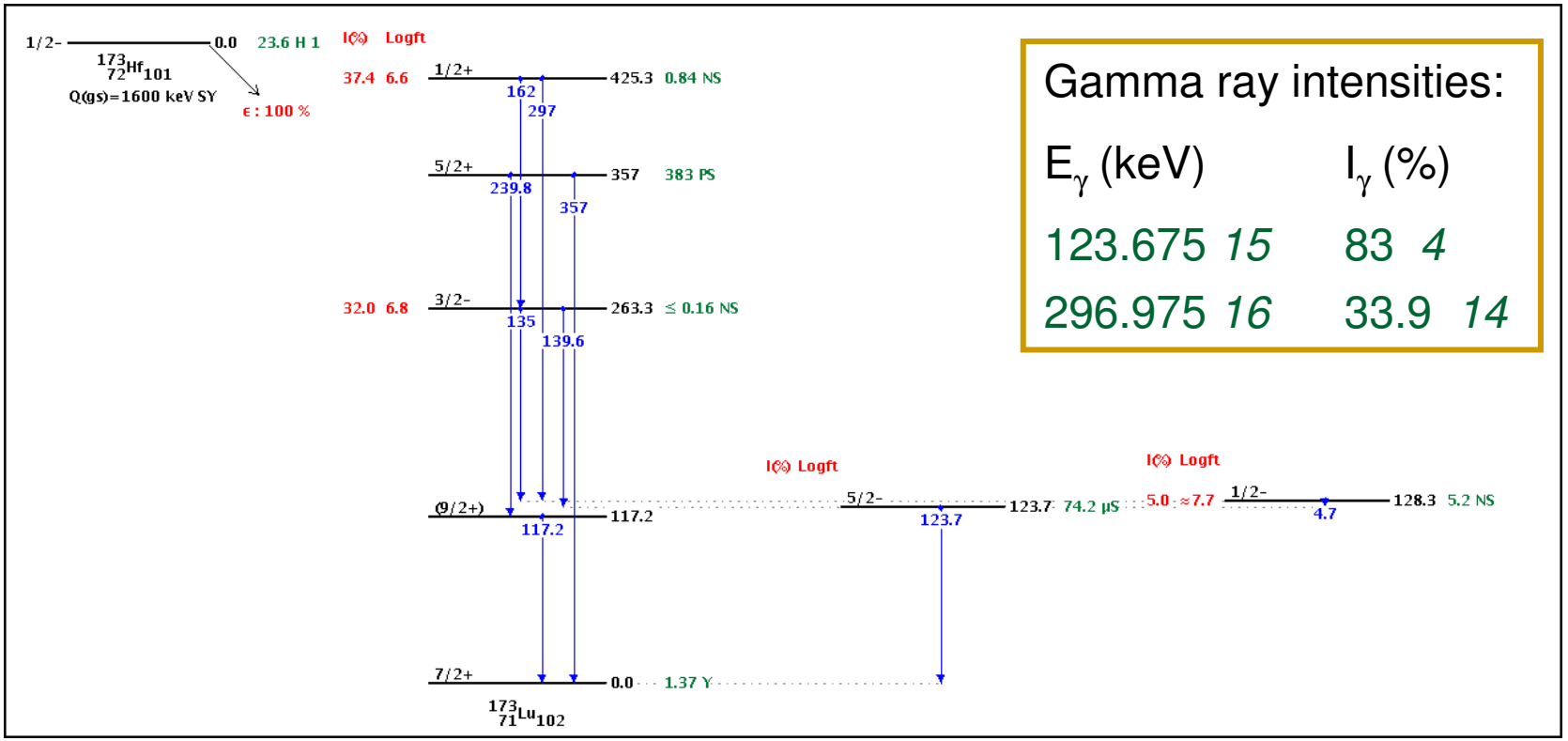
Ground and isomeric information					
Isotope	E(level) (MeV)	Jπ	Δ(MeV)	$T_{1/2}$	Decay Modes
^{178}Lu	**0.0**	**1(-)**	**-50.3430**	**28.4 m 2**	**β⁻: 100 %**
	0.1200	**(9-)**	**-50.2230**	**23.1 m 3**	**β⁻: 100 %**
^{177}Lu	**0.0**	**7/2+**	**-52.3890**	**6.647 d 4**	**β⁻: 100 %**
	0.9702	**23/2-**	**-51.4188**	**160.44 d 6**	**β-: 78.60% IT: 21.40%**
^{177}Yb	**0.0**	**(9/2+)**	**-50.9892**	**1.911 h 3**	**β⁻: 100 %**
	0.3750	**(1/2-)**	**-50.6577**	**6.41 s *2***	**IT : 100 %**
^{175}Yb	**0.0**	**(7/2-)**	**-54.7000**	**4.185 d 1**	**β⁻: 100 %**
	0.5149	**1/2-**	**-54.1851**	**68.2 ms 3**	**IT: 100 %**

Samples

Sample	Abundance (%)					
	^{174}Hf	^{176}Hf	^{177}Hf	^{178}Hf	^{179}Hf	^{180}Hf
Natural	0.16	5.26	18.6	27.3	13.6	35.1
^{176}Hf	<0.05	**65.0**	22.9	6.3	1.8	4.0
^{177}Hf	<0.05	1.0	**85.4**	11.3	0.9	1.4
^{178}Hf	<0.05	0.8	1.9	**92.4**	3.3	1.6
^{179}Hf	<0.05	0.2	1.3	4.1	**72.1**	22.3

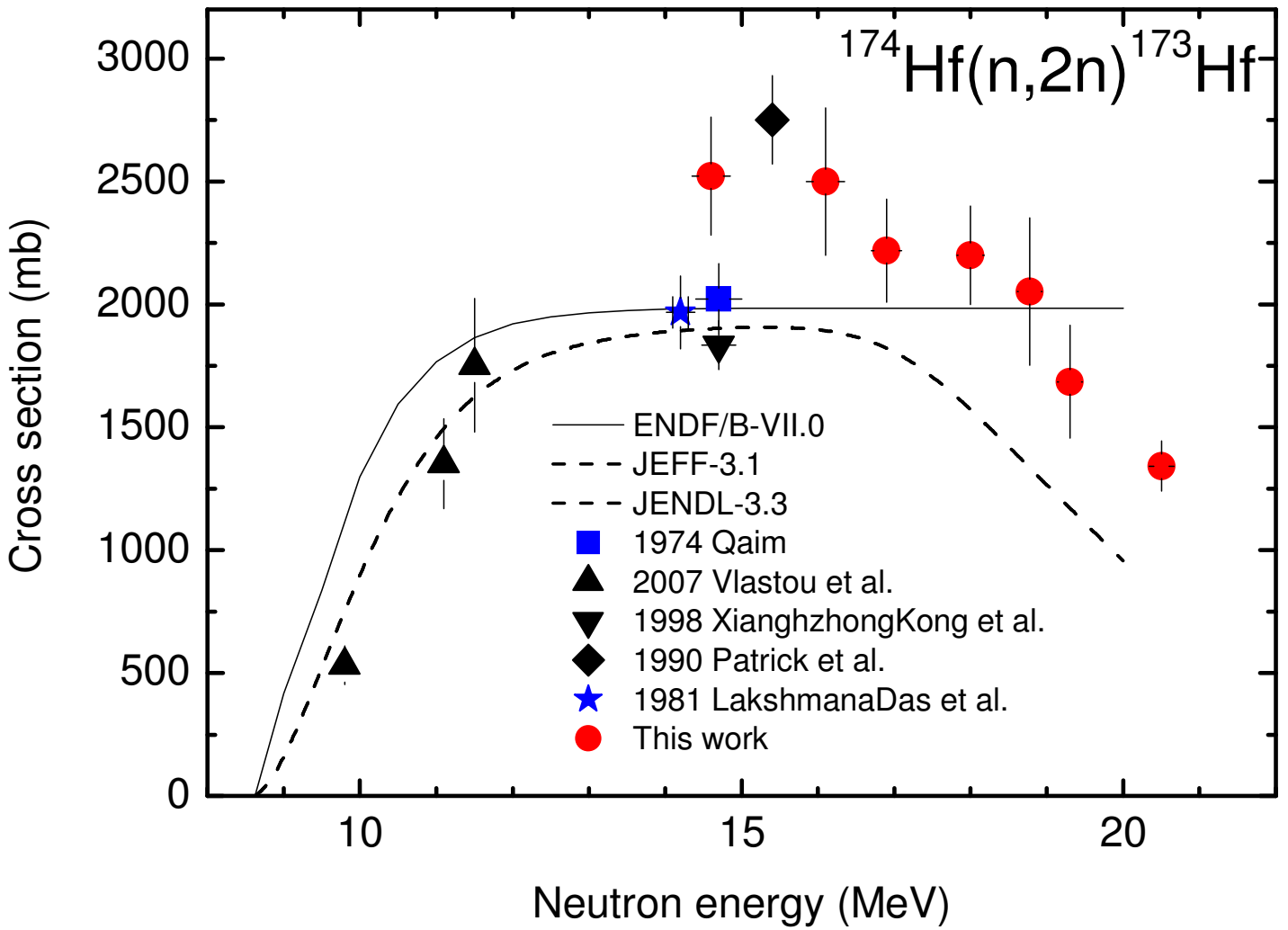
$^{174}Hf(n,2n)^{173}Hf$





Gamma ray intensities:

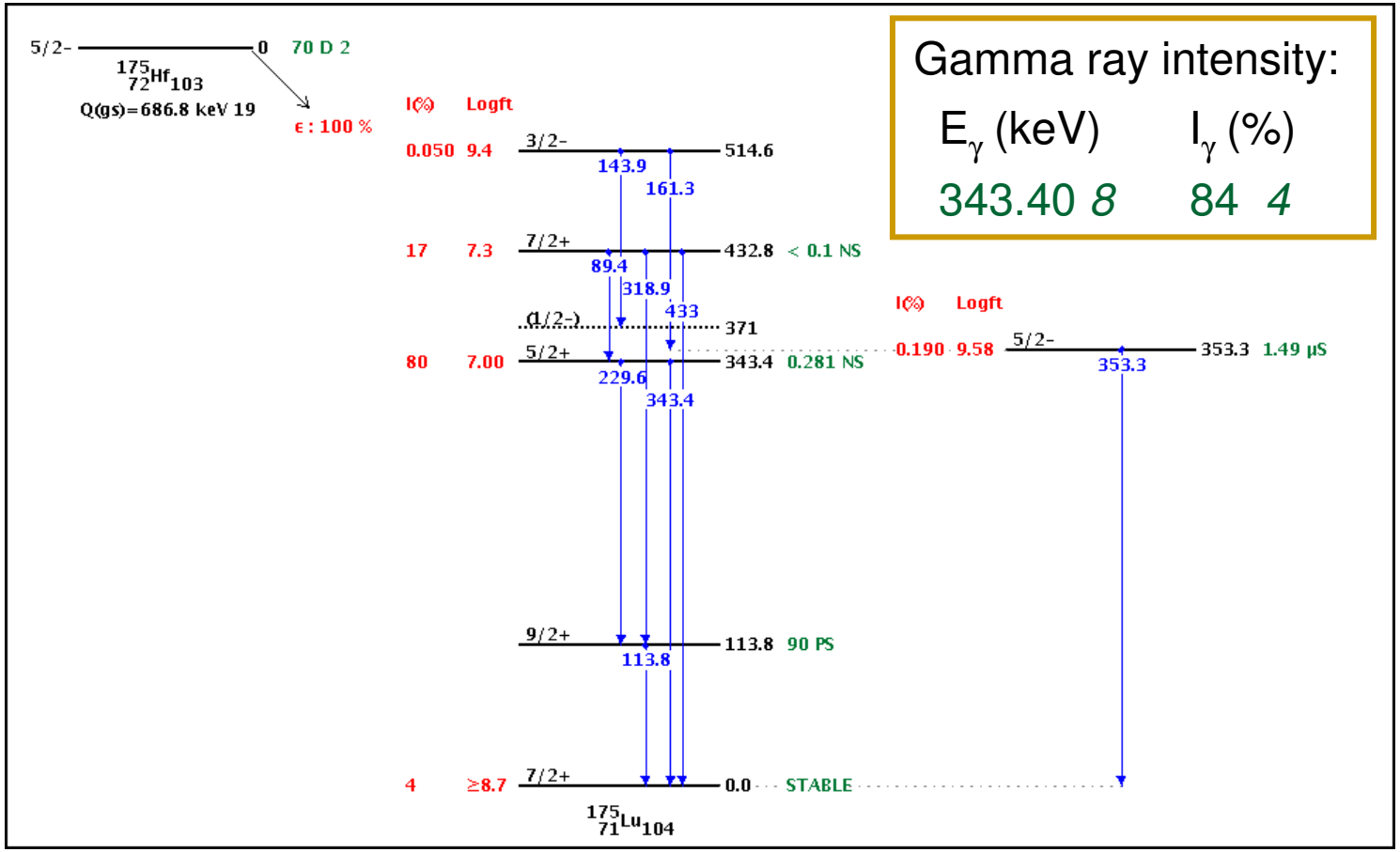
E_γ (keV)	I_γ (%)
123.675 *15*	83 *4*
296.975 *16*	33.9 *14*


^{174}Hf(n,2n)^{173}Hf
Cross section (mb)
Neutron energy (MeV)
3000
2500
2000
1500
1000
500
0
10
15
20
ENDF/B-VII.0
JEFF-3.1
JENDL-3.3
1974 Qaim
2007 Vlastou et al.
1998 XianghzhongKong et al.
1990 Patrick et al.
1981 LakshmanaDas et al.
This work

$^{176}Hf(n,2n)^{175}Hf$ and $^{177}Hf(n,3n)^{175}Hf$

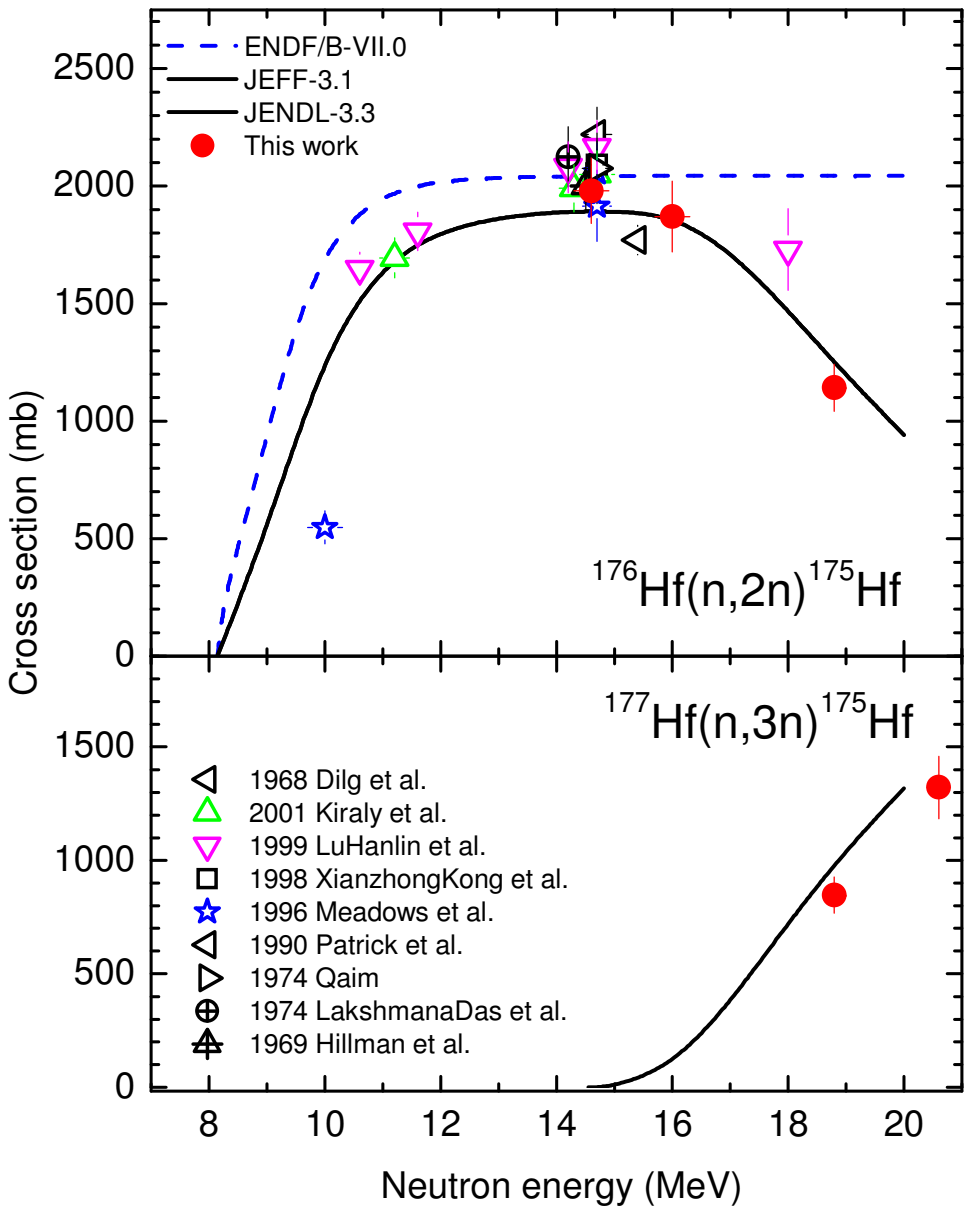
	173Hf	174Hf	175Hf	176Hf	177Hf	178Hf	179Hf	180Hf	181Hf
72	23.6 H ε: 100.00%	2.0E+15 Y 0.16% α: 100.00%	70 D ε: 100.00%	STABLE 5.26%	STABLE 18.60%	STABLE 27.28%	STABLE 13.62%	STABLE 35.08%	42.39 D β-: 100.00%

(n,2n) (n,3n)



Gamma ray intensity:

E_γ (keV)	I_γ (%)
343.40 *8*	84 *4*


ENDF/B-VII.0
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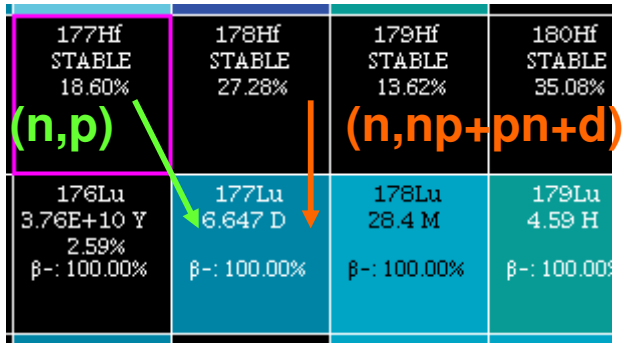
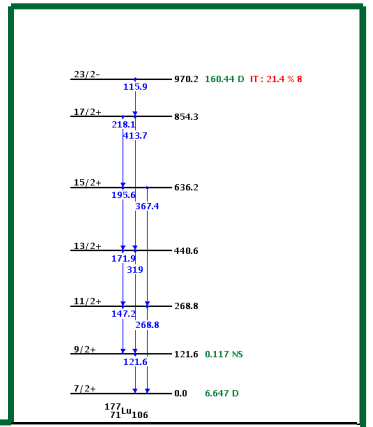
This work
^{176}Hf(n,2n)^{175}Hf
^{177}Hf(n,3n)^{175}Hf
1968 Dilg et al.
2001 Kiraly et al.
1999 LuHanlin et al.
1998 XianzhongKong et al.
1996 Meadows et al.
1990 Patrick et al.
1974 Qaim
1974 LakshmanaDas et al.
1969 Hillman et al.
Cross section (mb)
Neutron energy (MeV)
0
500
1000
1500
2000
2500
8
10
12
14
16
18
20

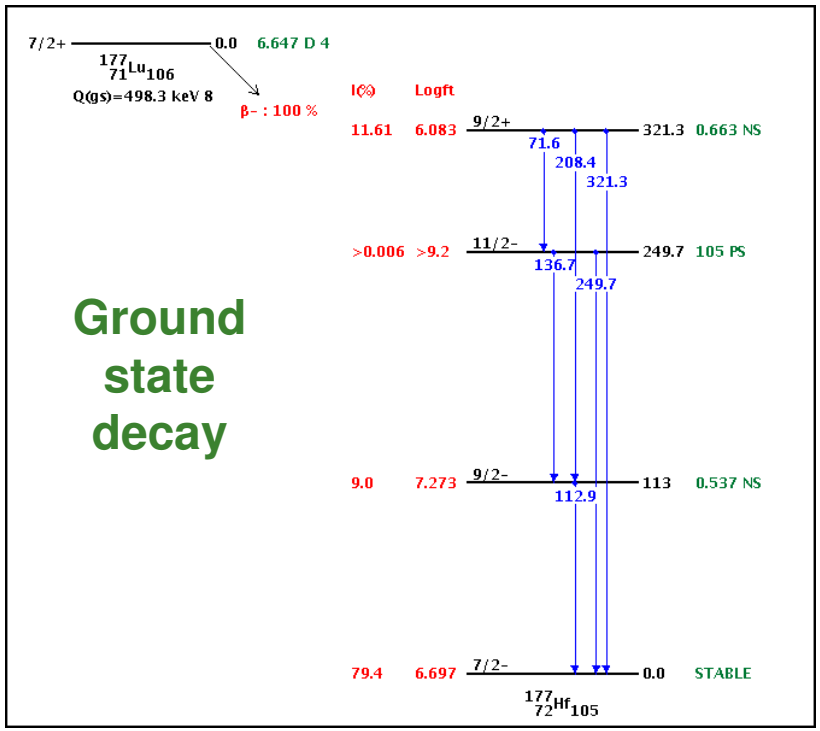
^{177}Hf(n,p)^{177g}Lu and ^{178}Hf(n,x)^{177g}Lu



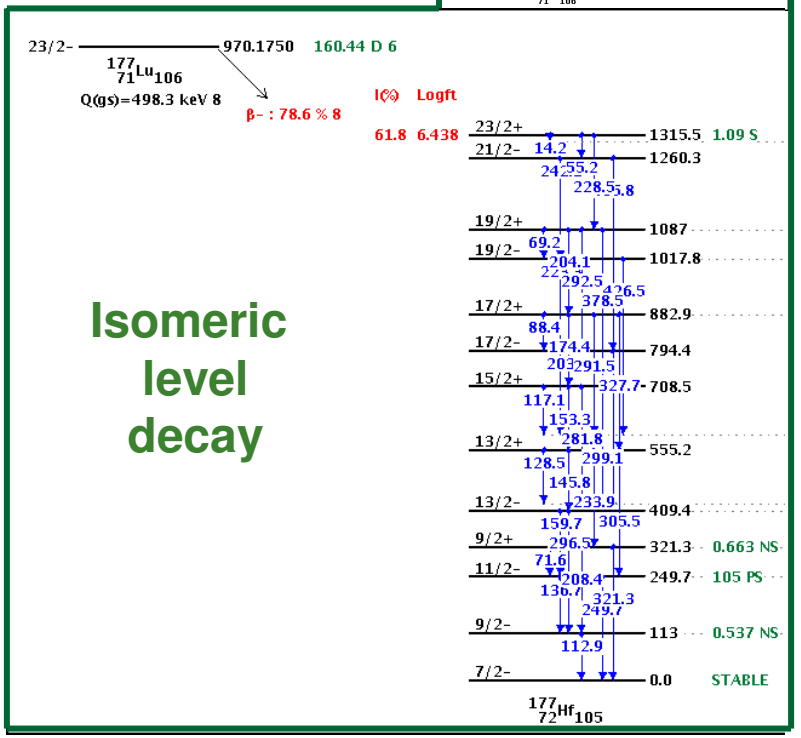
Gamma ray intensities:

E_γ (keV)	I_γ (%)
208.3662 *4*	10.36 *4*
112.9498 *4*	6.17 *7*

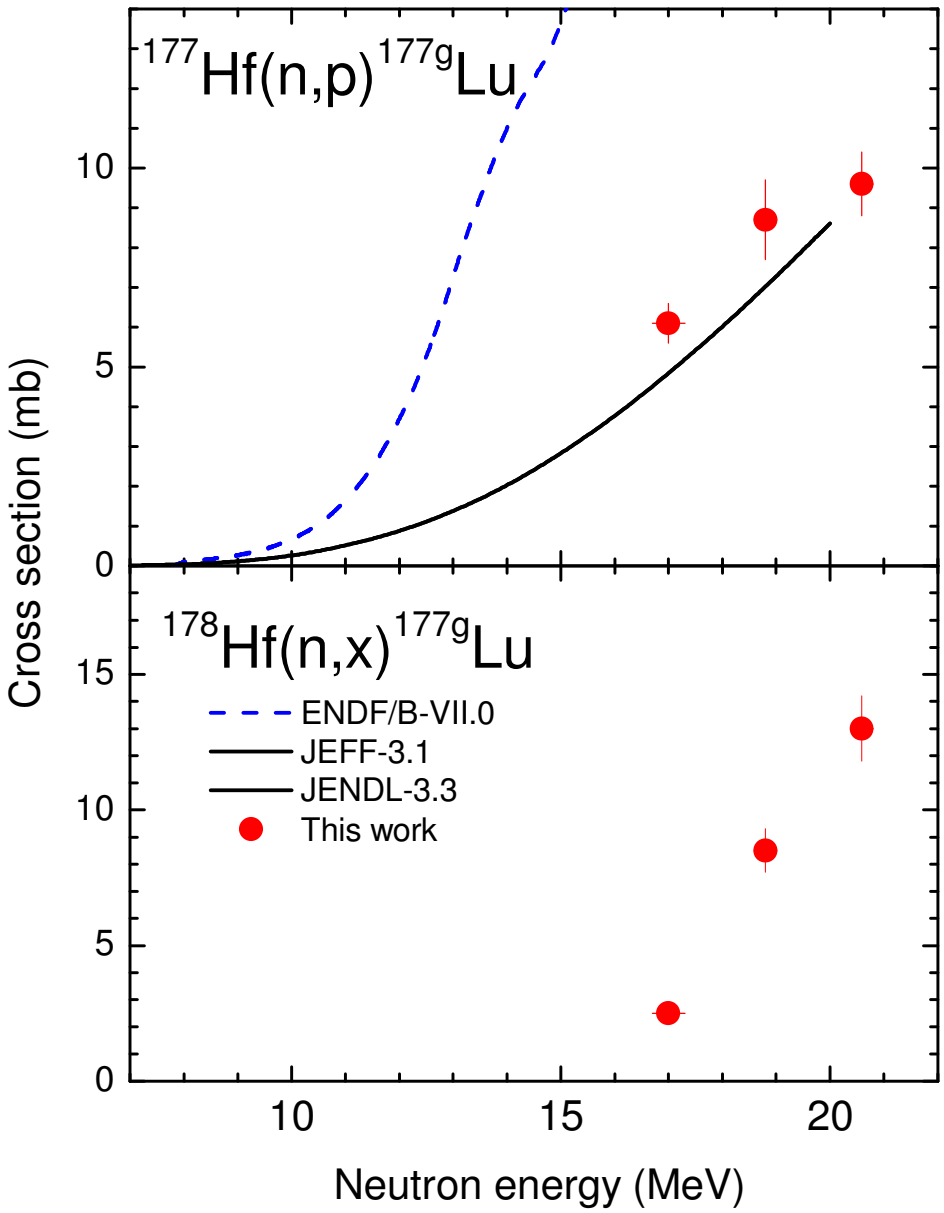




Ground state decay



Isomeric level decay


^{177}Hf(n,p)^{177g}Lu
^{178}Hf(n,x)^{177g}Lu
ENDF/B-VII.0
JEFF-3.1
JENDL-3.3
This work
Cross section (mb)
Neutron energy (MeV)
0
5
10
15
20