Neutron Spectrum Characterisation

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Background

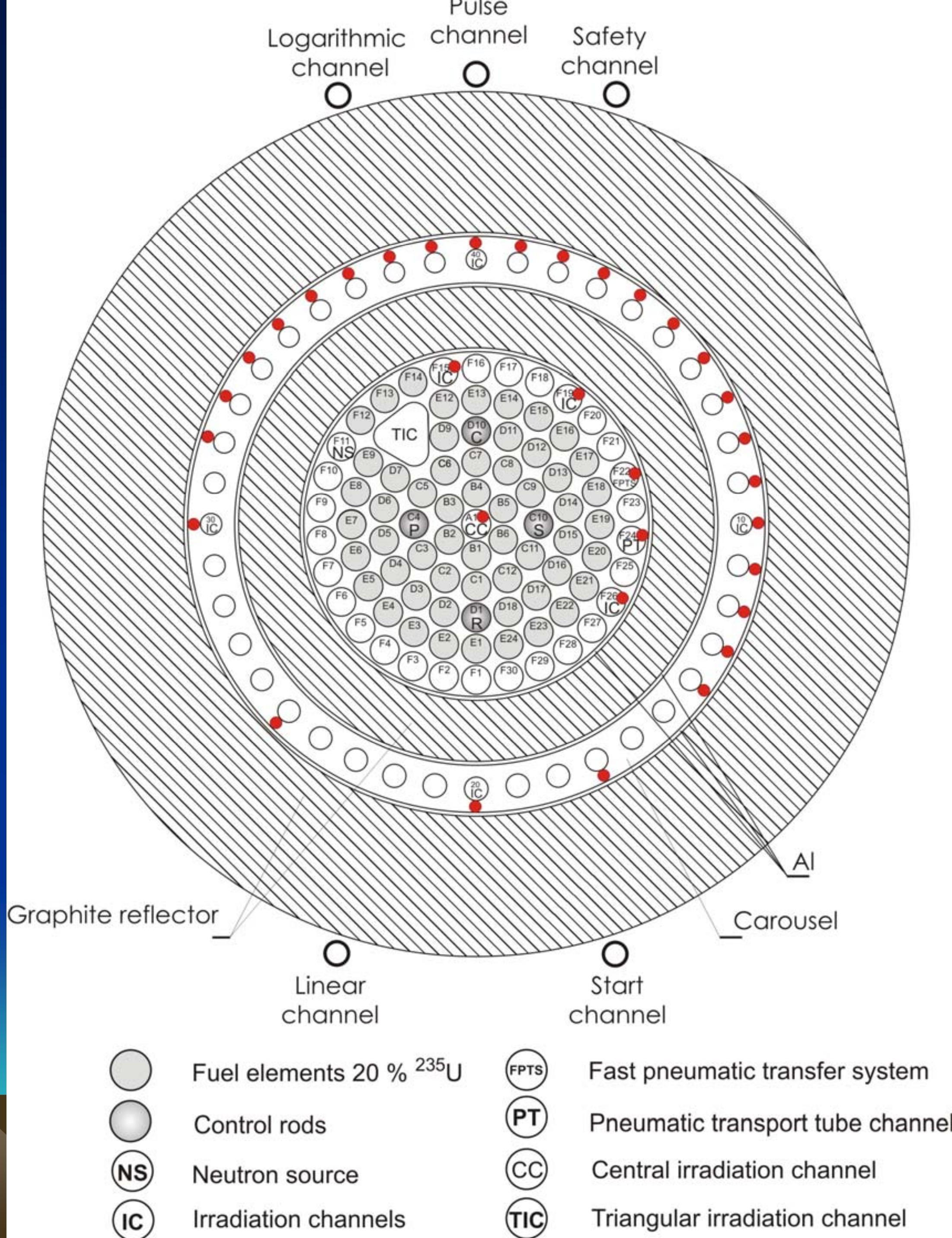
- Spectral effects are dealt with rather crudely in NAA (e.g. fission spectrum).
- Lose definitions of constants in terms of differential cross sections and spectra.
- Conventional spectrum-unfolding techniques often produce unphysical spectrum shapes.

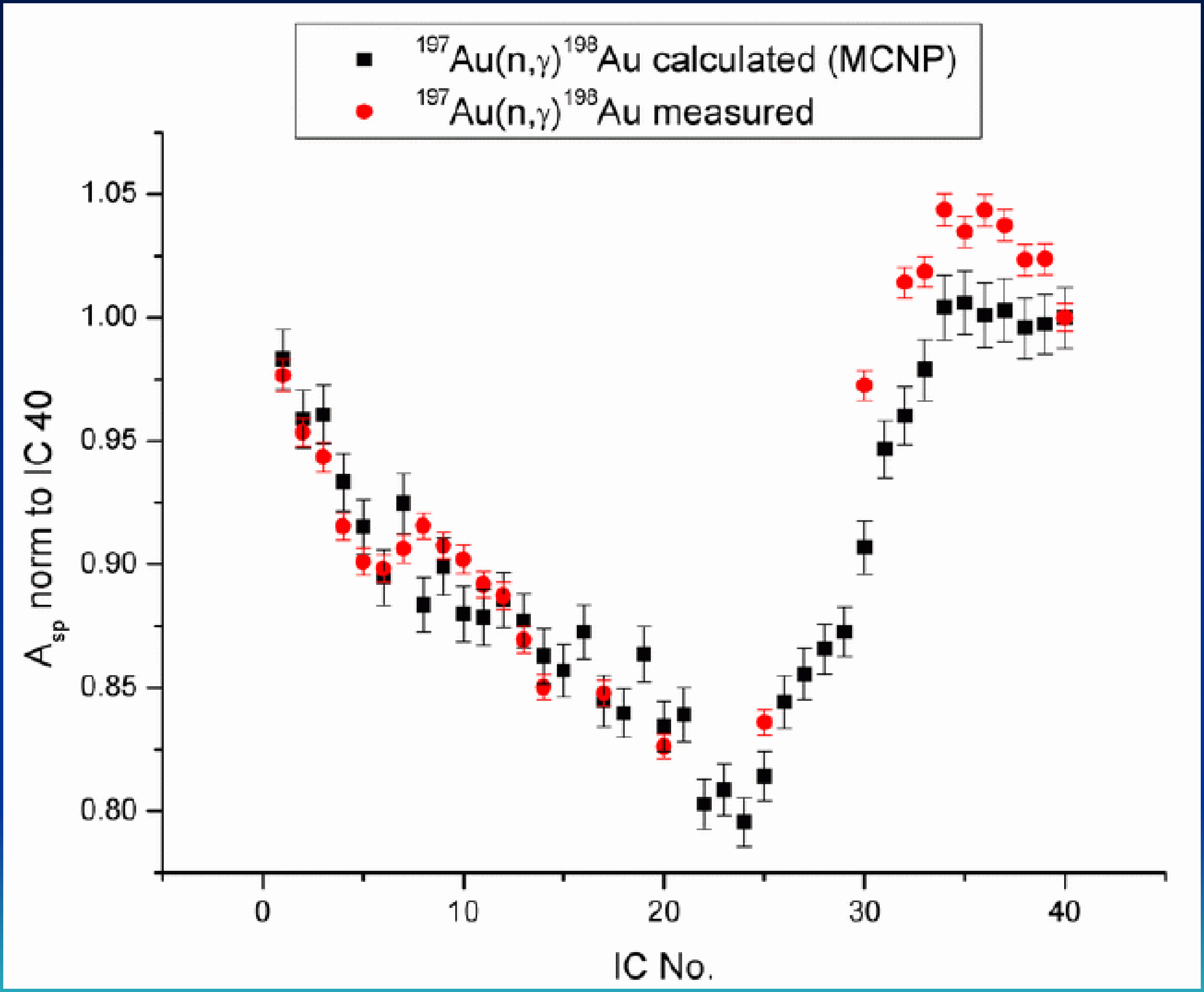
Procedure outline

- Calculate detailed spectrum shape using full-core Monte Carlo transport model.
- Validate the computational model with measurements (flux distribution).
- Parameterise the calculated spectrum with analytic function, keep the shape from the calculation (→ modulating function).
- Perform activation measurement using several monitors (including Cd-ratio measurements).
- Adjust parameters to match measured activities, apply modulating function → final spectrum.

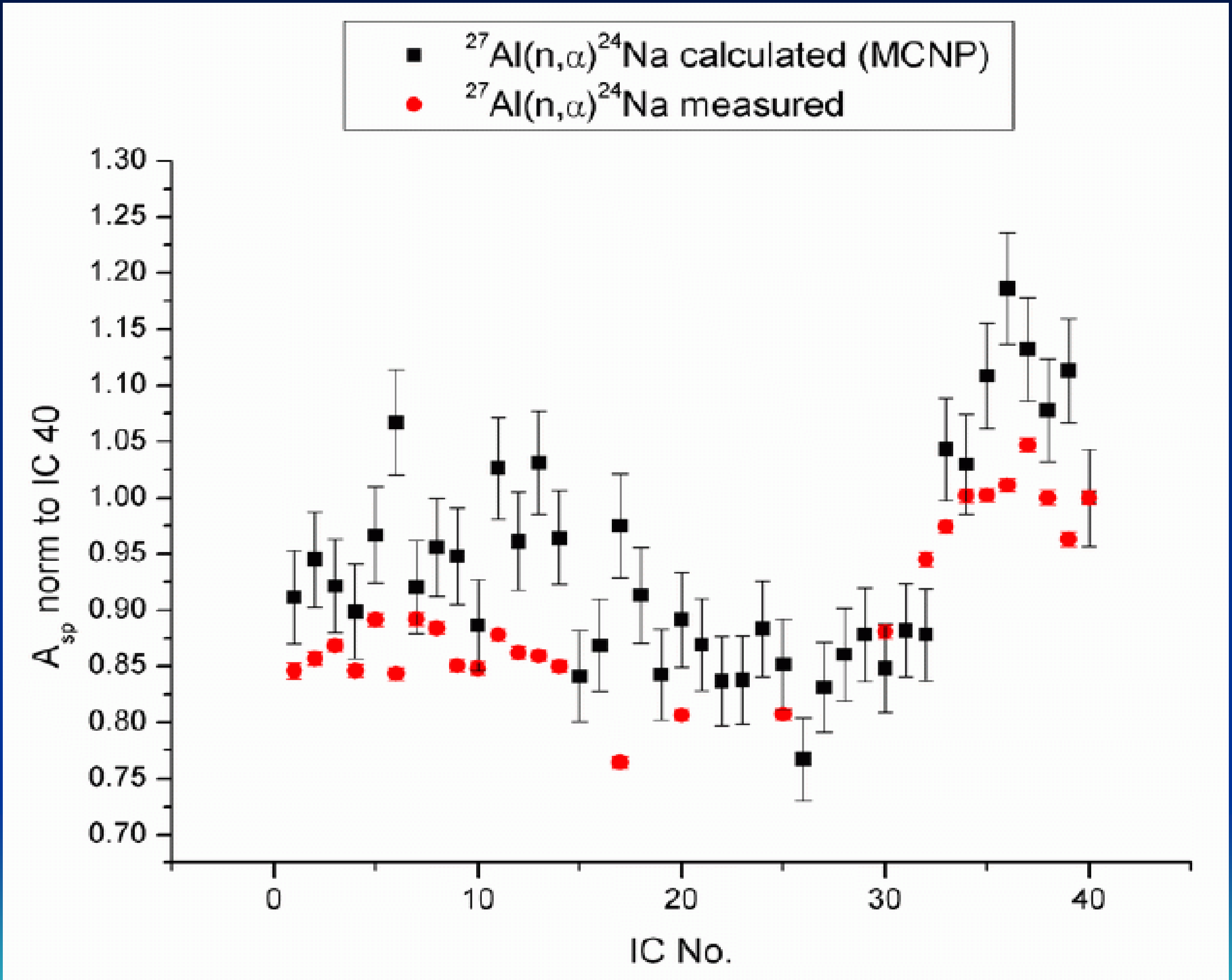
Neutron spectrum

- Detailed Monte Carlo model developed.
- Al-Au(0.1%) foils irradiated in 33 channels (6 in the core, 27 in the reflector)
- $^{197}Au(n,\gamma)^{197}Au$ (thermal flux monitor) and $^{27}Al(n,\alpha)^{23}Na$ (fast flux monitor) activities measured.
- Calculated and measured values compared.


Pulse channel
Logarithmic channel
Safety channel
TIC
NS
CC
P
S
C
R
PT
FPTS
IC
Al
Graphite reflector
Carousel
Linear channel
Start channel
Fuel elements 20 % ^{235}U
Control rods
Neutron source
Irradiation channels
Fast pneumatic transfer system
Pneumatic transport tube channel
Central irradiation channel
Triangular irradiation channel



$^{197}Au(n,\gamma)^{198}Au$ calculated (MCNP)
$^{197}Au(n,\gamma)^{198}Au$ measured
A_{sp} norm to IC 40
1.05
1.00
0.95
0.90
0.85
0.80
0
10
20
30
40
IC No.



27Al(n,α)24Na calculated (MCNP)
27Al(n,α)24Na measured
1.30
1.25
1.20
1.15
1.10
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
Asp norm to IC 40
0
10
20
30
40
IC No.

Neutron spectrum (cont.)

- Computational model validated by flux distribution measurements.
- Spectrum parameterised by analytic function, modulated by the fine structure of the calculated spectrum.
- Multi-monitor irradiation in 4 selected channels.
- Parameters adjusted to match measured activities.

Neutron spectrum (cont.)

$$\psi_t = C_t \, E \left[e^{-E/kT} + C_{t1} e^{-E/kT_1} + C_{t2} e^{-E/kT_2} \right]$$

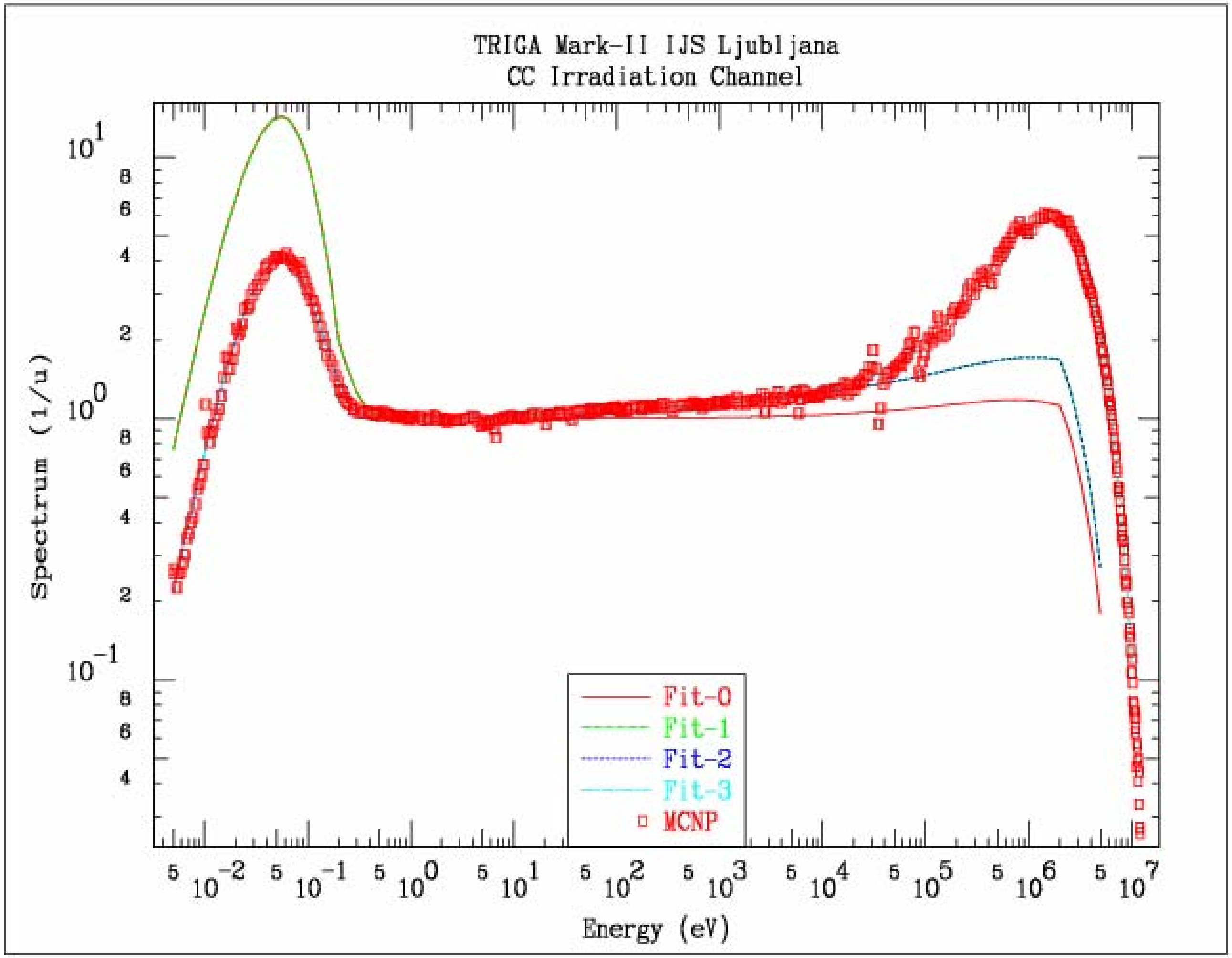
$$\psi_e = E^{-\left[1+\alpha_0+\alpha_1 \log E + \alpha_2 (\log E)^2\right]}$$

$$\psi_f = C_f e^{-E/W} \sinh\left(\sqrt{EW_b}\right) \cdot \frac{1}{E^m} \quad or$$

$$C_f \sqrt{E} \, e^{-E/E_T} \cdot \frac{1}{E^{m_0+m_1 E}}$$

$$\psi = K_t \psi_t + K_e \psi_e + K_f \psi_f$$

Ke = 1 for *Et* < *E* < *Ef*
0 otherwise
Kt = 1 + *Ot* - *Ke*
Kf = 1 + *Of* - *Ke*


TRIGA Mark-II IJS Ljubljana
CC Irradiation Channel
Spectrum (1/u)
Energy (eV)
Fit-0
Fit-1
Fit-2
Fit-3
MCNP

Neutron spectrum (cont.)

Results:

- Selected reaction rate ratios were considered.
- Some reactions excluded – cross sections not reliable enough.

Basis:

- Use computed spectrum on fine group structure.
- Calculate reaction rates by multiplying flux with cross-sections from IRDF-2002.
- Consider epithermal self-shielding.

CC

Target	Product	Ratio	Target	Product	Ratio	Dif.[%]	Unc.[%]
79-Au-197g	79-Au-198	Tot/Tot	13-Al- 27g	13-Al- 28	947.79	-15.5*	(3.4)
13-Al- 27g	12-Mg- 27	Tot/Tot	13-Al- 27g	13-Al- 28	1.629E-2	-13.8*	(2.9)
13-Al- 27g	11-Na- 24	Tot/Tot	13-Al- 27g	13-Al- 28	3.175E-3	-12.5*	(2.9)
13-Al- 27g	12-Mg- 27	Tot/Tot	79-Au-197g	79-Au-198	1.718E-5	1.9	(3.1)
13-Al- 27g	11-Na- 24	Tot/Tot	79-Au-197g	79-Au-198	3.350E-6	3.5	(3.2)
79-Au-197g	79-Au-198	Tot/Tot	40-Zr- 94g	40-Zr- 95	2780	-2.5	(3.2)
40-Zr- 96g	40-Zr- 97	Tot/Tot	40-Zr- 94g	40-Zr- 95	6.3610	-0.3	(2.5)
40-Zr- 90g	40-Zr- 89	Tot/Tot	40-Zr- 94g	40-Zr- 95	1.520E-3	-0.2	(3.2)
79-Au-197g	79-Au-198	Tot/Tot	40-Zr- 96g	40-Zr- 97	437.03	-2.2	(3.2)
40-Zr- 90g	40-Zr- 89	Tot/Tot	40-Zr- 96g	40-Zr- 97	2.390E-4	0.1	(3.0)
30-Zn- 64g	30-Zn- 65	Tot/Tot	30-Zn- 68g	30-Zn- 69m	9.6714	2.2	(2.2)
30-Zn- 70g	30-Zn- 71m	Tot/Tot	30-Zn- 68g	30-Zn- 69m	0.1022	-52.8*	(1.3)
30-Zn- 64g	29-Cu- 64	Tot/Tot	30-Zn- 68g	30-Zn- 69m	0.3832	-16.4*	(1.0)
28-Ni- 64g	28-Ni- 65	Tot/Tot	79-Au-197g	79-Au-198	7.114E-3	16.5*	(1.2)
25-Mn- 55g	25-Mn- 56	Tot/Tot	79-Au-197g	79-Au-198	6.471E-2	22.8*	(0.2)
42-Mo- 98g	42-Mo- 99	Tot/Tot	79-Au-197g	79-Au-198	3.785E-3	2.1*	(2.2)
42-Mo-100g	42-Mo-101	Tot/Tot	79-Au-197g	79-Au-198	2.564E-3	-14.0*	(2.5)
74-W -186g	74-W -187	Tot/Tot	79-Au-197g	79-Au-198	0.3288	-11.1*	(2.3)
28-Ni- 58g	27-Co- 58	Tot/Tot	79-Au-197g	79-Au-198	4.598E-4	-1.1	(2.2)
42-Mo- 92g	41-Nb- 92	Tot/Tot	79-Au-197g	79-Au-198	4.694E-5	-4.9*	(2.5)
28-Ni- 58g	27-Co- 58	Tot/Tot	28-Ni- 64g	28-Ni- 65	6.464E-2	-15.1*	(1.4)
42-Mo- 92g	41-Nb- 92	Tot/Tot	42-Mo- 98g	42-Mo- 99	1.240E-2	-6.8*	(4.3)

FPTS

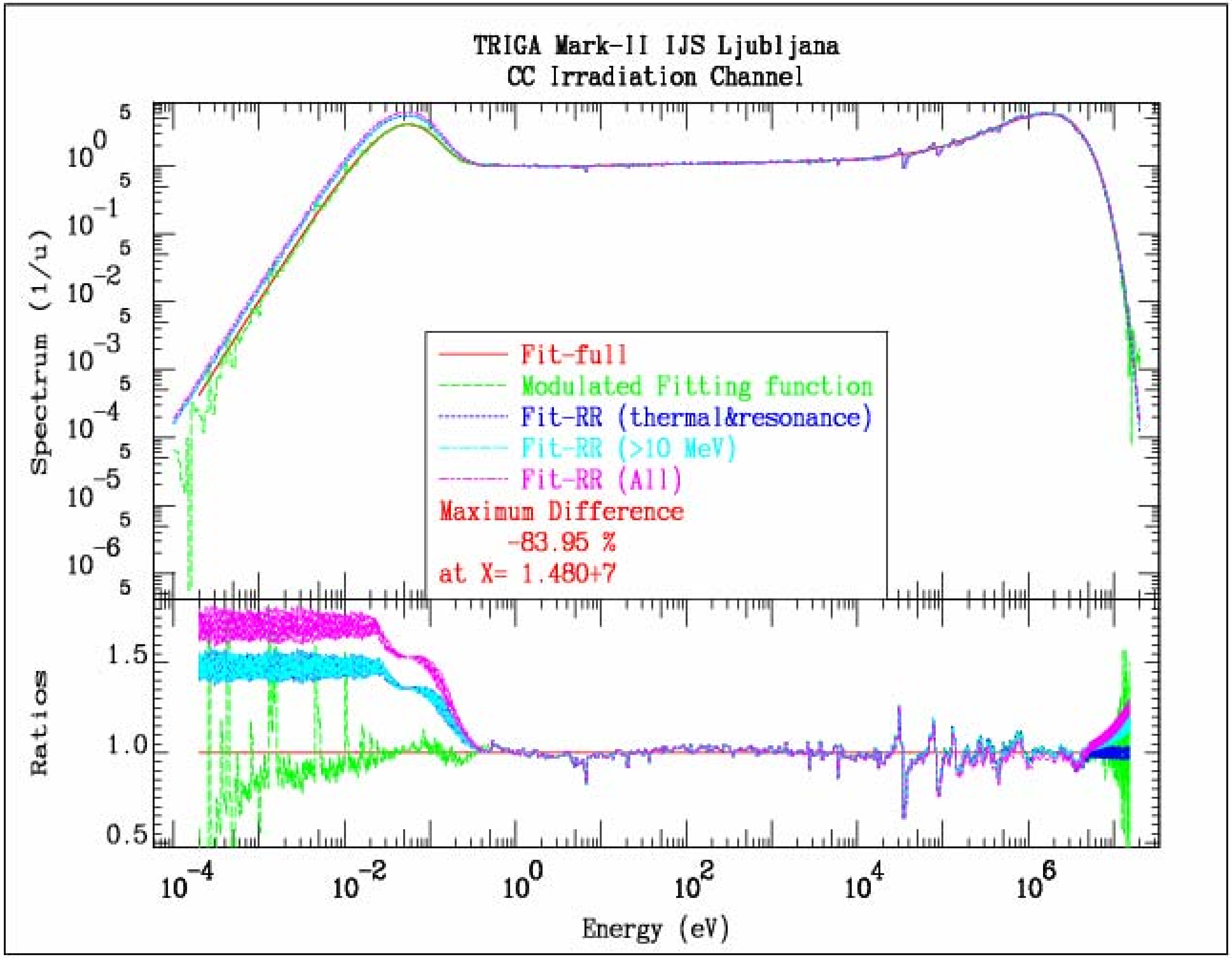
Target	Product	Ratio	Target	Product	Ratio	Dif.[%]	Unc.[%]
79-Au-197g	79-Au-198	Tot/Tot	13-Al- 27g	13-Al- 28	680.89	-8.7*	(3.5)
13-Al- 27g	12-Mg- 27	Tot/Tot	13-Al- 27g	13-Al- 28	5.898E-3	-7.5*	(3.0)
13-Al- 27g	11-Na- 24	Tot/Tot	13-Al- 27g	13-Al- 28	1.188E-3	-9.6*	(3.1)
13-Al- 27g	12-Mg- 27	Tot/Tot	79-Au-197g	79-Au-198	8.662E-6	1.2	(3.3)
13-Al- 27g	11-Na- 24	Tot/Tot	79-Au-197g	79-Au-198	1.745E-6	-1.1	(3.3)
79-Au-197g	79-Au-198	Tot/Tot	40-Zr- 94g	40-Zr- 95	2600	3.1	(3.3)
40-Zr- 96g	40-Zr- 97	Tot/Tot	40-Zr- 94g	40-Zr- 95	3.6928	0.8	(2.6)
40-Zr- 90g	40-Zr- 89	Tot/Tot	40-Zr- 94g	40-Zr- 95	8.125E-4	0.6	(5.7)
79-Au-197g	79-Au-198	Tot/Tot	40-Zr- 96g	40-Zr- 97	704.09	2.3	(3.1)
40-Zr- 90g	40-Zr- 89	Tot/Tot	40-Zr- 96g	40-Zr- 97	2.200E-4	-0.2	(5.6)
30-Zn- 64g	30-Zn- 65	Tot/Tot	30-Zn- 68g	30-Zn- 69m	10.13	2.3	(2.2)
30-Zn- 70g	30-Zn- 71m	Tot/Tot	30-Zn- 68g	30-Zn- 69m	0.1086	-17.8*	(2.3)
30-Zn- 64g	29-Cu- 64	Tot/Tot	30-Zn- 68g	30-Zn- 69m	0.1542	-13.6*	(1.7)
28-Ni- 64g	28-Ni- 65	Tot/Tot	79-Au-197g	79-Au-198	9.856E-3	5.4*	(1.5)
25-Mn- 55g	25-Mn- 56	Tot/Tot	79-Au-197g	79-Au-198	8.818E-2	15.8*	(0.3)
42-Mo- 98g	42-Mo- 99	Tot/Tot	79-Au-197g	79-Au-198	2.710E-3	6.0*	(2.7)
42-Mo-100g	42-Mo-101	Tot/Tot	79-Au-197g	79-Au-198	2.187E-3	5.1*	(5.8)
74-W -186g	74-W -187	Tot/Tot	79-Au-197g	79-Au-198	0.3415	-12.7*	(3.8)
28-Ni- 58g	27-Co- 58	Tot/Tot	79-Au-197g	79-Au-198	2.263E-4	0.2	(2.5)
42-Mo- 92g	41-Nb- 92	Tot/Tot	79-Au-197g	79-Au-198	2.320E-5	49.8*	(9.1)
28-Ni- 58g	27-Co- 58	Tot/Tot	28-Ni- 64g	28-Ni- 65	2.296E-2	-5.0*	(1.4)
42-Mo- 92g	41-Nb- 92	Tot/Tot	42-Mo- 98g	42-Mo- 99	8.561E-3	41.3*	(9.1)

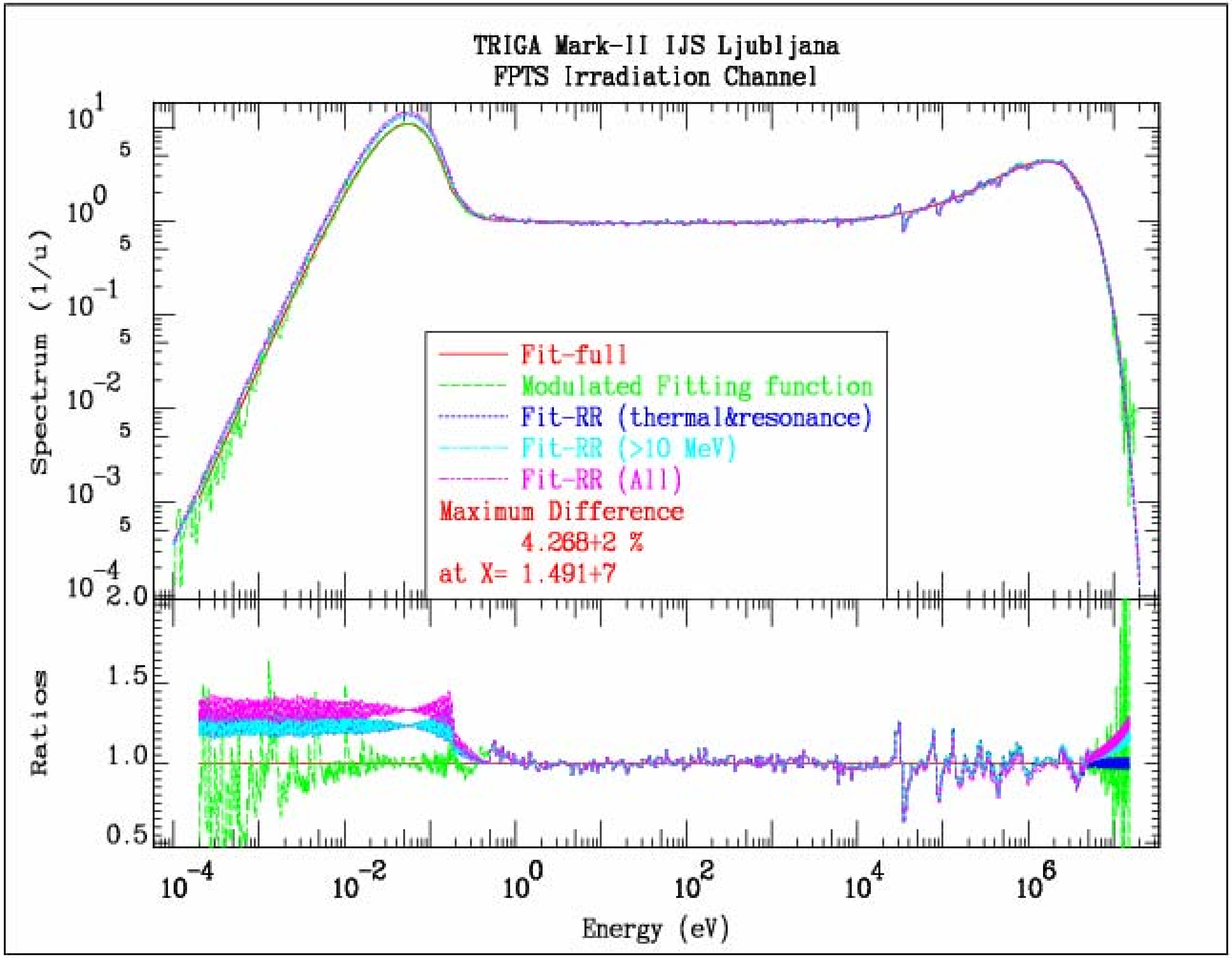
PT

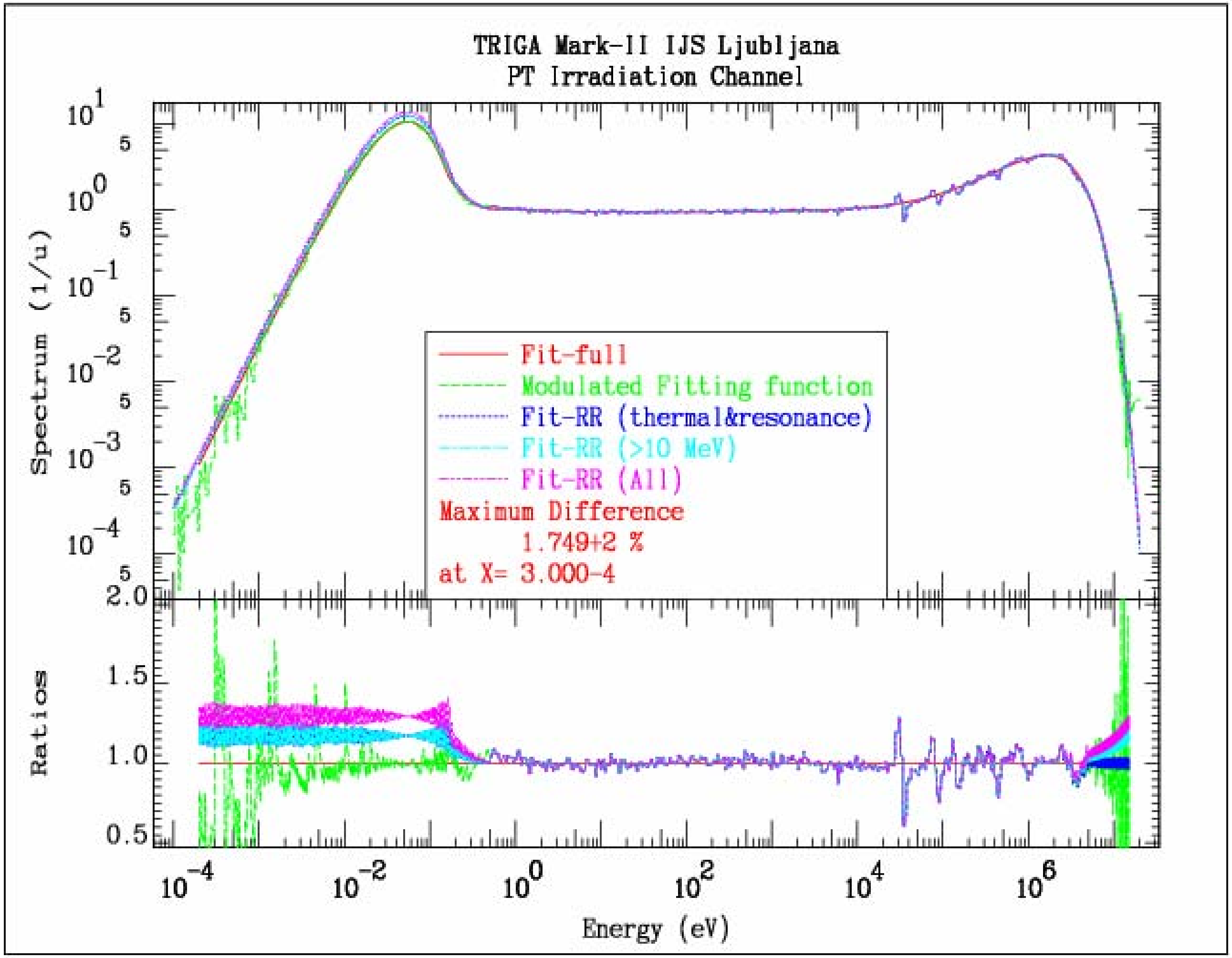
Target	Product	Ratio	Target	Product	Ratio	Dif.[%]	Unc.[%]
79-Au-197g	79-Au-198	Tot/Tot	13-Al- 27g	13-Al- 28	695.88	-6.2*	(3.5)
13-Al- 27g	12-Mg- 27	Tot/Tot	13-Al- 27g	13-Al- 28	6.356E-3	-6.2*	(3.0)
13-Al- 27g	11-Na- 24	Tot/Tot	13-Al- 27g	13-Al- 28	1.280E-3	-4.9*	(3.1)
13-Al- 27g	12-Mg- 27	Tot/Tot	79-Au-197g	79-Au-198	9.133E-6	0.1	(3.3)
13-Al- 27g	11-Na- 24	Tot/Tot	79-Au-197g	79-Au-198	1.840E-6	1.3	(3.3)
79-Au-197g	79-Au-198	Tot/Tot	40-Zr- 94g	40-Zr- 95	2623	4.6	(3.3)
40-Zr- 96g	40-Zr- 97	Tot/Tot	40-Zr- 94g	40-Zr- 95	3.7522	0.8	(2.6)
40-Zr- 90g	40-Zr- 89	Tot/Tot	40-Zr- 94g	40-Zr- 95	8.558E-4	-0.3	(5.7)
79-Au-197g	79-Au-198	Tot/Tot	40-Zr- 96g	40-Zr- 97	699.18	3.8	(3.1)
40-Zr- 90g	40-Zr- 89	Tot/Tot	40-Zr- 96g	40-Zr- 97	2.281E-4	-1.1	(5.6)
30-Zn- 64g	30-Zn- 65	Tot/Tot	30-Zn- 68g	30-Zn- 69m	10.08	0.5	(2.2)
30-Zn- 70g	30-Zn- 71m	Tot/Tot	30-Zn- 68g	30-Zn- 69m	0.1081	-14.5*	(2.3)
30-Zn- 64g	29-Cu- 64	Tot/Tot	30-Zn- 68g	30-Zn- 69m	0.1651	-8.7*	(1.7)
28-Ni- 64g	28-Ni- 65	Tot/Tot	79-Au-197g	79-Au-198	9.650E-3	1.7*	(1.5)
25-Mn- 55g	25-Mn- 56	Tot/Tot	79-Au-197g	79-Au-198	8.636E-2	9.8*	(0.2)
42-Mo- 98g	42-Mo- 99	Tot/Tot	79-Au-197g	79-Au-198	2.718E-3	3.4*	(2.6)
42-Mo-100g	42-Mo-101	Tot/Tot	79-Au-197g	79-Au-198	2.228E-3	3.8*	(3.8)
74-W -186g	74-W -187	Tot/Tot	79-Au-197g	79-Au-198	0.3402	-12.2*	(3.7)
28-Ni- 58g	27-Co- 58	Tot/Tot	79-Au-197g	79-Au-198	2.387E-4	0.0	(2.4)
42-Mo- 92g	41-Nb- 92	Tot/Tot	79-Au-197g	79-Au-198	2.447E-5	51.3*	(7.1)
28-Ni- 58g	27-Co- 58	Tot/Tot	28-Ni- 64g	28-Ni- 65	2.473E-2	-1.7*	(1.4)
42-Mo- 92g	41-Nb- 92	Tot/Tot	42-Mo- 98g	42-Mo- 99	9.003E-3	46.3*	(7.1)

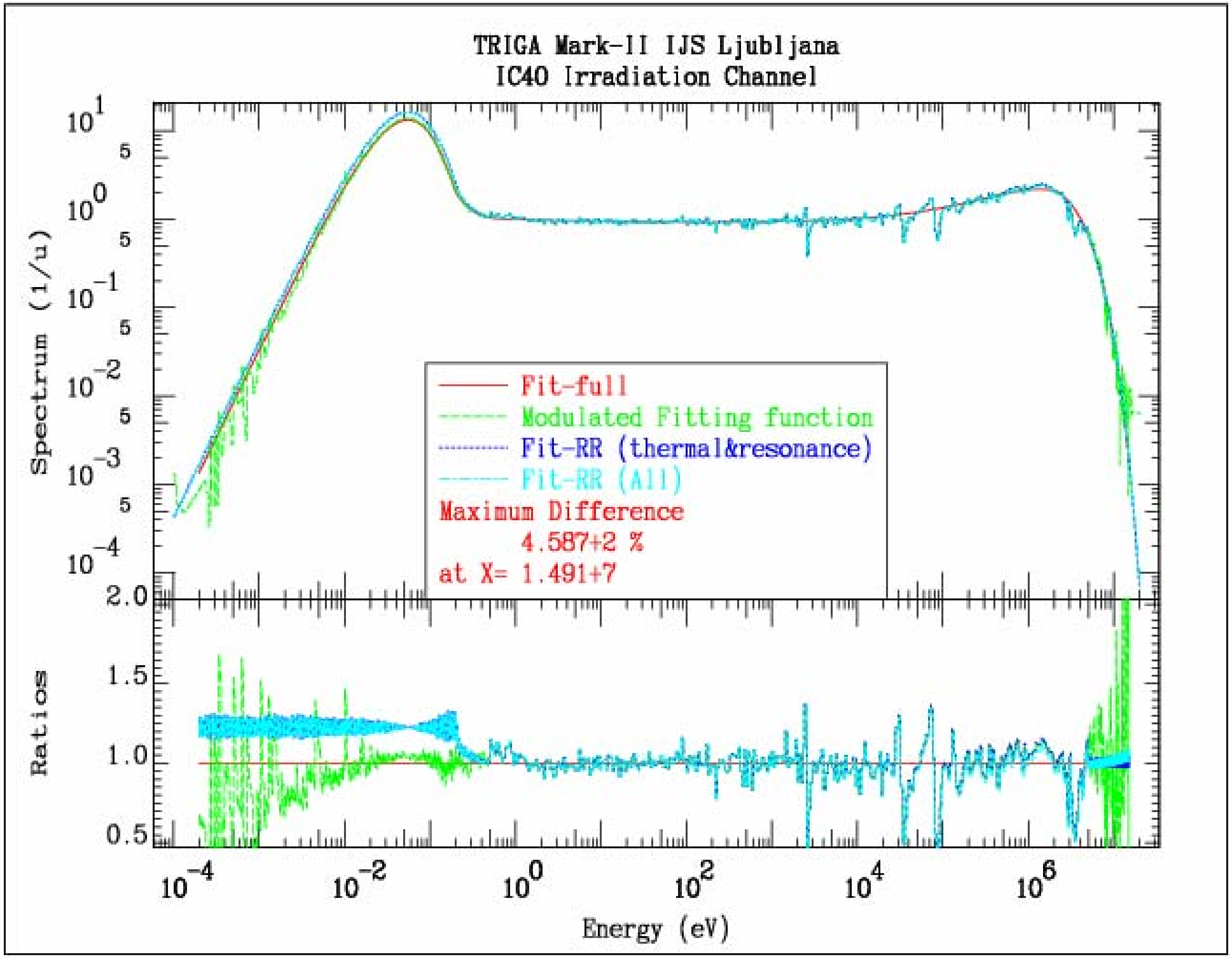
IC40

Target	Product	Ratio	Target	Product	Ratio	Dif.[%]	Unc.[%]
79-Au-197g	79-Au-198	Tot/Tot	13-Al- 27g	13-Al- 28	652.67	-5.3*	(3.5)
13-Al- 27g	12-Mg- 27	Tot/Tot	13-Al- 27g	13-Al- 28	2.110E-3	-9.4*	(3.6)
13-Al- 27g	11-Na- 24	Tot/Tot	13-Al- 27g	13-Al- 28	4.221E-4	0.7*	(4.3)
13-Al- 27g	12-Mg- 27	Tot/Tot	79-Au-197g	79-Au-198	3.233E-6	-4.4	(3.9)
13-Al- 27g	11-Na- 24	Tot/Tot	79-Au-197g	79-Au-198	6.468E-7	6.3	(4.5)
79-Au-197g	79-Au-198	Tot/Tot	40-Zr- 94g	40-Zr- 95	2624	4.0	(3.5)
40-Zr- 96g	40-Zr- 97	Tot/Tot	40-Zr- 94g	40-Zr- 95	3.1672	0.9	(2.9)
40-Zr- 90g	40-Zr- 89	Tot/Tot	40-Zr- 94g	40-Zr- 95	3.090E-4	-2.0	(11.0)
79-Au-197g	79-Au-198	Tot/Tot	40-Zr- 96g	40-Zr- 97	828.50	3.1	(3.2)
40-Zr- 90g	40-Zr- 89	Tot/Tot	40-Zr- 96g	40-Zr- 97	9.757E-5	-2.8	(10.0)
30-Zn- 64g	30-Zn- 65	Tot/Tot	30-Zn- 68g	30-Zn- 69m	10.23	4.3	(2.5)
30-Zn- 70g	30-Zn- 71m	Tot/Tot	30-Zn- 68g	30-Zn- 69m	0.1106	-16.5*	(4.4)
30-Zn- 64g	29-Cu- 64	Tot/Tot	30-Zn- 68g	30-Zn- 69m	5.543E-2	-6.5*	(8.3)
28-Ni- 64g	28-Ni- 65	Tot/Tot	79-Au-197g	79-Au-198	1.027E-2	-0.7*	(1.4)
25-Mn- 55g	25-Mn- 56	Tot/Tot	79-Au-197g	79-Au-198	9.179E-2	11.1*	(0.2)
42-Mo- 98g	42-Mo- 99	Tot/Tot	79-Au-197g	79-Au-198	2.487E-3	9.0*	(3.2)
42-Mo-100g	42-Mo-101	Tot/Tot	79-Au-197g	79-Au-198	2.185E-3	-8.8*	(3.3)
74-W -186g	74-W -187	Tot/Tot	79-Au-197g	79-Au-198	0.3450	-11.1*	(3.8)
28-Ni- 58g	27-Co- 58	Tot/Tot	79-Au-197g	79-Au-198	8.439E-5	0.6	(3.1)
42-Mo- 92g	41-Nb- 92	Tot/Tot	79-Au-197g	79-Au-198	8.665E-6	-12.0*	(100.0)
28-Ni- 58g	27-Co- 58	Tot/Tot	28-Ni- 64g	28-Ni- 65	8.217E-3	-37.5*	(1.7)
42-Mo- 92g	41-Nb- 92	Tot/Tot	42-Mo- 98g	42-Mo- 99	3.484E-3	-19.2*	(100.0)


TRIGA Mark-II IJS Ljubljana
CC Irradiation Channel
Spectrum (1/u)
Ratios
Energy (eV)
Fit-full
Modulated Fitting function
Fit-RR (thermal&resonance)
Fit-RR (>10 MeV)
Fit-RR (All)
Maximum Difference
-83.95 %
at X= 1.480+7


TRIGA Mark-II IJS Ljubljana
FPTS Irradiation Channel
Spectrum (1/u)
Ratios
Energy (eV)
Fit-full
Modulated Fitting function
Fit-RR (thermal&resonance)
Fit-RR (>10 MeV)
Fit-RR (All)
Maximum Difference
4.268+2 %
at X= 1.491+7


TRIGA Mark-II IJS Ljubljana
PT Irradiation Channel
Spectrum (1/u)
Ratios
Energy (eV)
Fit-full
Modulated Fitting function
Fit-RR (thermal&resonance)
Fit-RR (>10 MeV)
Fit-RR (All)
Maximum Difference
1.749+2 %
at X= 3.000-4


TRIGA Mark-II IJS Ljubljana
IC40 Irradiation Channel
Spectrum (1/u)
Fit-full
Modulated Fitting function
Fit-RR (thermal&resonance)
Fit-RR (All)
Maximum Difference
4.587+2 %
at X= 1.491+7
Ratios
Energy (eV)

Conclusions

Results:

– Method seems to work.

– Generally, adjusted spectrum reproduces well the measured reaction rates.

– Calculated thermal spectrum lower than measured by gold activation, particularly in the core centre.

Question:

– Do we trust the results?

Conclusions (cont.)

Weaknesses:

- Threshold cross sections abundant and well-known, resonance cross sections are not.
- Thermal spectrum in present analysis based on Au and Zr.

Further work :

- Include ^{232}Th, ^{238}U and ^{58}Fe
- Add measurements under Cd cover

Summary

- Rigorous definitions of constants for NAA from differential cross sections.
- Spectrum calculation using validated computational model.
- Parameterisation of the calculated spectrum.
- Adjustment of parameters to match measured monitor activities.
- Spectrum can be used to validate/adjust cross sections of other nuclides.