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Measurements and calculations of the neutron spectrum in different irradiation channels of the TRIGA Mark II reactor, Slovenia

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Abstract

In order to develop a methodology for characterisation the neutron spectrum in the irradiation channels and to define and analyze integral experiments for the validation of the computational models for the analysis of the nuclear research TRIGA Mark II reactor experimental determinations of the neutron spectrum in different irradiation channels are needed. The TRIGA Mark II reactor at the Jožef Stefan Institute (JSI) contains 7 irradiation channels in the reactor core and 40 irradiation channels in the carousel facility (CF). In our experiment 33 irradiation channels were investigated using Al-Au(0.1%) discs, 6 were irradiated in the core and 27 in the CF. Determination of thermal and fast neutron spectra in the mentioned channels were done by measurements of induced activities of ^{198}Au and ^{24}Na produced by (n,γ) and (n,α) reactions, respectively. Results show that the thermal neutron flux on the core periphery drops by a factor of three compared to the flux in the central channel, while the fast neutron flux drops by a factor of ten. Measurement data sets done on two independent HPGe systems agree to within about 2% after normalization. Variations of the thermal neutron flux around the core in the carousel facility relative to the position IC40 is about 20%, while for the fast neutron flux it is about 30%.

1. Introduction

The aim of the IAEA Co-ordinated Research Project (CRP) on the Reference Database for Neutron Activation Analysis is to improve the status of the database of nuclear constants for k_0-NAA, to contribute to the nuclear structure and decay data and to remove or reduce some of the discrepancies that exist between the integral constants and values derived from differential data.

To reach some of the goals of the IAEA project we conducted an experiment for the determination of the neutron flux distribution in different irradiation channels of the TRIGA Mark II reactor. The primary purpose of the exercise was to validate the computation model.

In this work, 33 sample foils (Al-Au(0.1%) discs) were irradiated in 33 irradiation channels in the reactor core and the carrousel facility. Sample activation was measured twice with two different HPGe detectors and results obtained in both measurements were compared.

2. Method

For calculation of the specific activity for investigated radionuclides we applied the following equation:

$$A_{sp} = \frac{N_p}{P_\gamma \, \varepsilon_p \, t_m \, m} \frac{1}{S\,D\,C} \frac{1}{COI} \tag{1}$$

where:

N_p – number of counts in the full energy peak,

P_γ – absolute gamma-intensity (%),
ε_p – full-energy peak detector efficiency, including correction for gamma-attenuation,
t_m – measuring time (s),
m – mass of irradiated element (g),
S – saturation factor = $1-e^{-\lambda t_{irr}}$, λ – decay constant = (ln2)/$T_{1/2}$, with $T_{1/2}$ = half-life (s), t_{irr} = irradiation time (s),
D – decay factor = $e^{-\lambda t_d}$, t_d = decay time (s),
C – "measurement" factor = $\frac{1-e^{-\lambda t_m}}{\lambda t_m}$
COI – correction factor for true-coincidence effects.

3. Experimental

3.1. Experimental equipment

The samples were irradiated at the Reactor Infrastructure Centre (RIC) of the Jožef Stefan Institute (JSI), Ljubljana. The first measurement of induced activity of the samples was done at the Department of Environmental Sciences (O-2) and the second measurement, for the same samples, at the Reactor Physic Department (F-8).

Equipment used for the experiment is as follows:

- 250 kW light-water moderated nuclear research reactor TRIGA Mark II with graphite reflector [1, 2].
- Semiconductor coaxial HPGe detector (Canberra, 45% relative efficiency) at the O-2.
- Semiconductor coaxial HPGe detector type NIGC 26 (PGT, serial No. DN 124) at the F-8.
- Analytic weight METTLER AE 163 (accuracy ± 0.00001 g)
- Al-Au discs (Al(99.9%)-Au(0.1%)) 5 mm in diameter and 0.2 mm high.
- Polyethylene containers
- Al and polyethylene rabbits.

3.2. Sample preparation

Al-Au discs 5 mm in diameter and 0.2 mm high were prepared from Al-Au wire (Al(99.9%)-Au(0.1%)) 1.0 mm in diameter using a hydraulic press (SPECAC, UK). After weighing the samples on an electronic balance, the samples were packed in thin polyethylene foil and fixed at the bottom in the centre of a polyethylene container 8 mm in diameter. In this way we prepared 33 samples, 6 for irradiation in reactor core and 27 in the carousel facility of the TRIGA reactor core No. 189, set-up on 12 June 2006 (see Fig. 1).

3.3. Irradiation

All 33 samples were inserted into the TRIGA rector and irradiation on maximum power (250 kW) was started on 13 June 2006 at 10:47:17 and finished at 12:00:17. Therefore, the samples were irradiated for 73 minutes. During irradiation the reactor operator recoded at 15 minutes interval the power on the linear channel (P_1) and the safety channel (P_2), position of regulation rod (R), fuel temperature at two points T_{f1} and T_{f2} and water temperature at two points T_{v1} and T_{v2} (Table 1). Positions of other control rods were not changed.

Table 1. Time and some parameters recorded during irradiation on 13.6.2006, where R is regulation rod. Positions of other rods are: compensation rod is at 350 steps of 900, safety and shim rods are withdrawn (step 0 of 900).

Time	P_1/P_2 [% P_{max}]	Position R	T_{f1}/T_{f2} [°C]	T_{v1}/T_{v2} [°C]
11:00:00	97/104	384	215/210	16/26
11:15:00	98/105	383	215/210	15/26
11:30:00	98/106	383	215/210	15/26
11:45:00	98/106	382	215/210	15/26

3.4. Measurement(s)

After the irradiation we measured the radionuclides produced by the following reactions:

- ^{197}Au(n,γ) ^{198}Au, $T_{1/2}$ = 3880.8 min; E_γ = 411.8 keV.
- ^{27}Al(n,α) ^{24}Na, $T_{1/2}$ = 897.6 min; E_γ = 1368.6 keV.

The first reaction is important in order to follow the distribution of mostly thermal part of the neutron spectrum, while the second is important for the fast part of the neutron spectrum. Effective threshold energy (σ > 1 mb) for ^{27}Al(n,α) ^{24}Na is E_{thr} = 2.1 MeV.

3.4.1. First measurement

The first measurement of activated samples were done at the Department of Environmental Sciences (O-2). It started 21 hours after the end of irradiation and finished within 12 hours time. Measuring time (real time) for all samples was 20 min. In this way, both of the important nuclear reactions were detected with reasonable counting statistics. For the measurement absolutely calibrated coaxial type of an HPGe detector (Canberra, 45% relative efficiency), connected to an ORTEC® DSPEC^{PLUS} high-rate multichannel analyzer, was used. To keep the dead time for all samples approximately equal, different distances between sample-detector were used. For the net peak area evaluation, the HyperLab program [3, 4] was used. For effective solid angle, true-coincidence and specific activity calculations the KayWin program [5] was applied.

3.4.2. Second measurement

The second measurement of activated samples were done at the Reactor Physic Department (F-8). The measurements started after three days of cooling time, so the measurement of threshold reaction (n,α) was not suitable for all samples and results obtained are not reported. Measuring time (real time) for samples varied from 5 to 80 min. All the measurements were completed within 17 days of cooling time. For the measurements a PGT (Princeton Gamma Tech) type NIGC 26 coaxial HPGe detector, connected to a NUCLEUS multichannel analyzer, was used.

4. Results and discussion

The results obtained for specific activity of ^{198}Au and ^{24}Na of the first (A_{sp1}) and the second measurement (A_{sp2}) together with their associated total uncertainty are presented in Table 2. As can be seen, the total uncertainty of A_{sp} for ^{198}Au varies from 1.5 to 1.8% in the first measurement and around 3.7% in the second measurement. Contribution to the total uncertainty coming from the net peak area determination of ^{198}Au (411.8 keV) in the first measurement was negligible due to very low standard deviation of the peak (0.06-0.22%) evaluated by the HyperLab program. This contribution in the second measurement varied from 0.24 to 0.77%. The total uncertainty of A_{sp} for ^{24}Na (1368.6 keV) varies from 0.9 to 1.9% (only the first measurement). In the last column the difference (in %) between the first and second measurements for specific activity of ^{198}Au is given. A systematic discrepancy is observed, varying from -3.2 to -7.2%. It was traced to the “point source” assumption in the second measurement. Graphical presentations of numerical data obtained in Table 2 are shown in Figs. 2-3.

For the estimation of the total uncertainty for A_{sp} in both measurements some input parameters shown in Table 3 were used. In addition, standard deviation of net peak area of investigated radionuclides is added. The mean contributions to the total uncertainty are coming from uncertainty in mass measurement (measurement of about 10 mg of an Al-Au disc), inhomogeneity of the Al-Au wire and full-energy peak efficiency (ε_p). More details of other contributions to the total uncertainty are reported by Rogan et al. [7].

To eliminate the systematic error observed in Table 2, the normalization of each data set (I. and II. measurements) on channel IC40 was done. Results of this normalization are presented in Table 4. Now, the differences (in %) for specific activity of ^{198}Au for the first (N_1) and the second measurement (N_2) vary from -1.89 to +2.31%. Graphical presentations of numerical data obtained in Table 4 are shown in Figs. 4-5. From Fig. 5 it can be observed that the normalized average specific activity of ^{198}Au (N_{AVG}) varied in the carousel facility from 83 to 105% (about 20%). The maximum variation in the F-ring of the reactor core is two times lower (around 8%). This was expected due to non-symmetrical distribution of the fuel elements in the core. The normalized average specific activity of ^{24}Na (N_1) varied in the carousel facility from 88 to 120% (about 30%). The maximum variation in the F-ring for N_1 was two times lower (around 18%), the similar behaviour as we get for N_{AVG}.

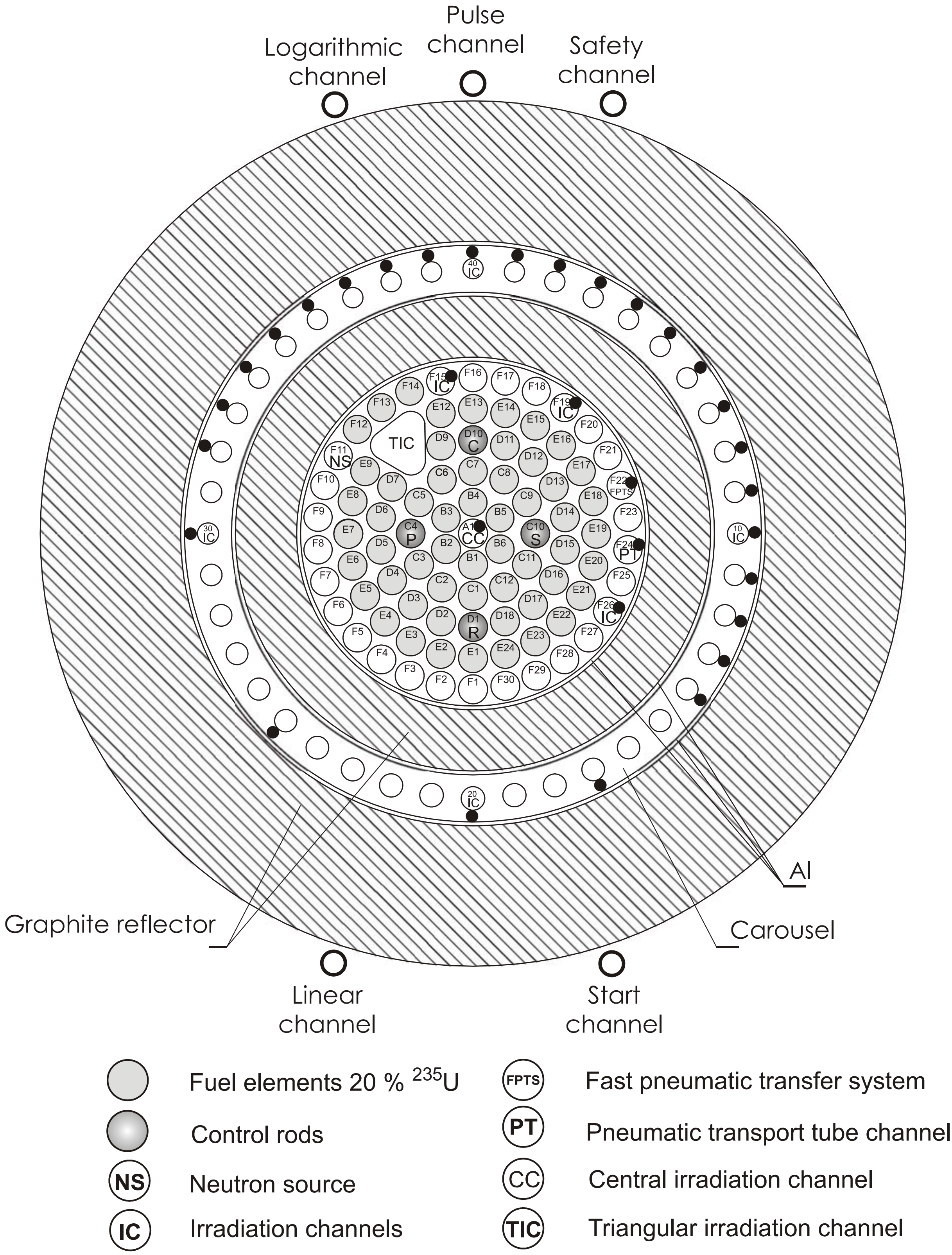


Fig. 1. Horizontal cross section of the TRIGA Mark II reactor core (core No. 189 set-up at 12.6.2006). Investigated irradiation channels are marked by small balls [1].

Table 2. Specific activities of ^{198}Au (411.8 keV) and ^{24}Na (1368.6 keV) in the first (A_{sp1}) and in the second measurement (A_{sp2}). In the last column the differences (in %) between specific activities of ^{198}Au in both measurements are given.

No.	Irr. ch.	I. measurement				II. measurement		Diff. ^{198}Au [%]
		^{198}Au		^{24}Na		^{198}Au		
		A_{sp1} [g^{-1} min^{-1}]	ΔA_{sp1} [%]	A_{sp1} [g^{-1} min^{-1}]	ΔA_{sp1} [%]	A_{sp2} [g^{-1} min^{-1}]	ΔA_{sp2} [%]	
1	CC#	2.04E+14	1.55	4.79E+09	0,91	2.14E+14	3.65	-4.34
2	F15	9.39E+13	1.52	1.37E+09	1,13	9.84E+13	3.65	-4.64
3	F19	9.67E+13	1.56	1.20E+09	1,18	1.02E+14	3.67	-4.88
4	F22##	8.93E+13	1.53	1.18E+09	1,14	9.37E+13	3.66	-4.67
5	F24###	9.30E+13	1.58	1.16E+09	1,24	9.67E+13	3.69	-3.84
6	F26	9.16E+13	1.62	1.29E+09	1,25	9.46E+13	3.76	-3.17
7	IC1	2.72E+13	1.80	1.31E+08	1,90	2.83E+13	3.69	-3.98
8	IC2	2.66E+13	1.81	1.33E+08	1,68	2.77E+13	3.69	-3.82
9	IC3	2.62E+13	1.77	1.35E+08	1,64	2.77E+13	3.67	-5.23
10	IC4	2.55E+13	1.80	1.31E+08	1,71	2.68E+13	3.69	-4.82
11	IC5	2.50E+13	1.79	1.38E+08	1,60	2.64E+13	3.68	-5.20
12	IC6	2.49E+13	1.81	1.31E+08	1,68	2.64E+13	3.69	-5.69
13	IC7	2.52E+13	1.81	1.38E+08	1,73	2.66E+13	3.69	-5.23
14	IC8	2.54E+13	1.78	1.37E+08	1,68	2.68E+13	3.71	-5.31
15	IC9	2.53E+13	1.81	1.32E+08	1,76	2.63E+13	3.69	-3.90
16	IC10	2.51E+13	1.78	1.31E+08	1,65	2.62E+13	3.68	-4.20
17	IC11	2.48E+13	1.84	1.36E+08	1,86	2.60E+13	3.71	-4.58
18	IC12	2.47E+13	1.84	1.34E+08	1,70	2.59E+13	3.73	-4.59
19	IC13	2.42E+13	1.77	1.33E+08	1,74	2.55E+13	3.67	-5.28
20	IC14	2.35E+13	1.77	1.32E+08	1,65	2.52E+13	3.67	-6.86
21	IC17	2.35E+13	1.77	1.18E+08	1,71	2.51E+13	3.67	-6.47
22	IC20	2.29E+13	1.82	1.25E+08	1,81	2.43E+13	3.69	-5.69
23	IC25	2.32E+13	1.77	1.25E+08	1,73	2.46E+13	3.67	-6.00
24	IC30	2.69E+13	1.76	1.36E+08	1,66	2.89E+13	3.66	-7.15
25	IC32	2.81E+13	1.76	1.46E+08	1,68	2.99E+13	3.66	-6.00
26	IC33	2.83E+13	1.79	1.51E+08	1,77	2.99E+13	3.68	-5.30
27	IC34	2.89E+13	1.81	1.55E+08	1,90	3.09E+13	3.69	-6.65
28	IC35	2.87E+13	1.76	1.55E+08	1,91	3.06E+13	3.66	-6.19
29	IC36	2.89E+13	1.78	1.57E+08	1,68	3.09E+13	3.67	-6.50
30	IC37	2.88E+13	1.75	1.62E+08	1,78	3.06E+13	3.66	-5.88
31	IC38	2.84E+13	1.79	1.55E+08	1,78	3.00E+13	3.67	-5.25
32	IC39	2.83E+13	1.81	1.49E+08	1,77	3.04E+13	3.69	-6.72
33	IC40	2.77E+13	1.79	1.35E+08	1,79	2.93E+13	3.71	-5.35

Central Channel; ## Fast Pneumatic Transfer System (FPTS); ### Pneumatic Tube (PT)

Table 3. Parameters and their associated uncertainties used to estimate the total uncertainty of the measurement.

Parameter	Uncertainty	Reference/Comment
m (g)	0.00005	estimate
P_γ (^{198}Au), %	0.07	JEFF- 3.1 [6]
P_γ (^{24}Na), %	0.0005	JEFF- 3.1 [6]
t_d (min)	1.0	estimate
t_m (min)	0.003	estimate
t_{irr} (min)	0.2	estimate
λ (^{198}Au), s^{-1}	5.3E-08	JEFF-3.1 (JANIS 2.2.1) [6]
λ (^{24}Na), s^{-1}	0.0000001	JEFF-3.1 [6]
Inhomogeneity of Al-Au(0,1%) wire, %	1.0	IRMM-530
ε_p (I. measurement), %	0.5 -1.0*	[1]
ε_p (II. measurement), %	3.0	estimate [2]

* different distance between sample and an HPGe detector

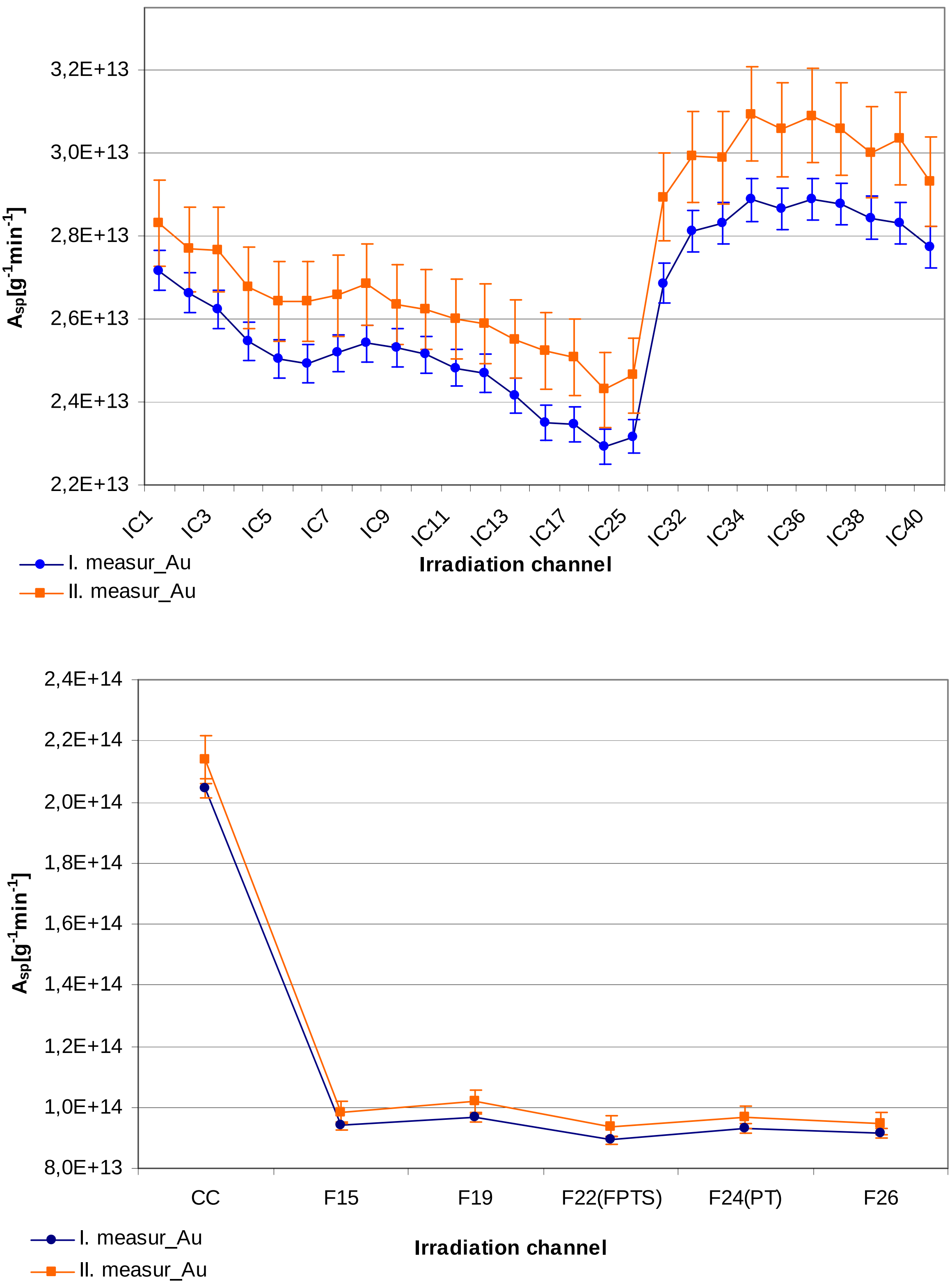
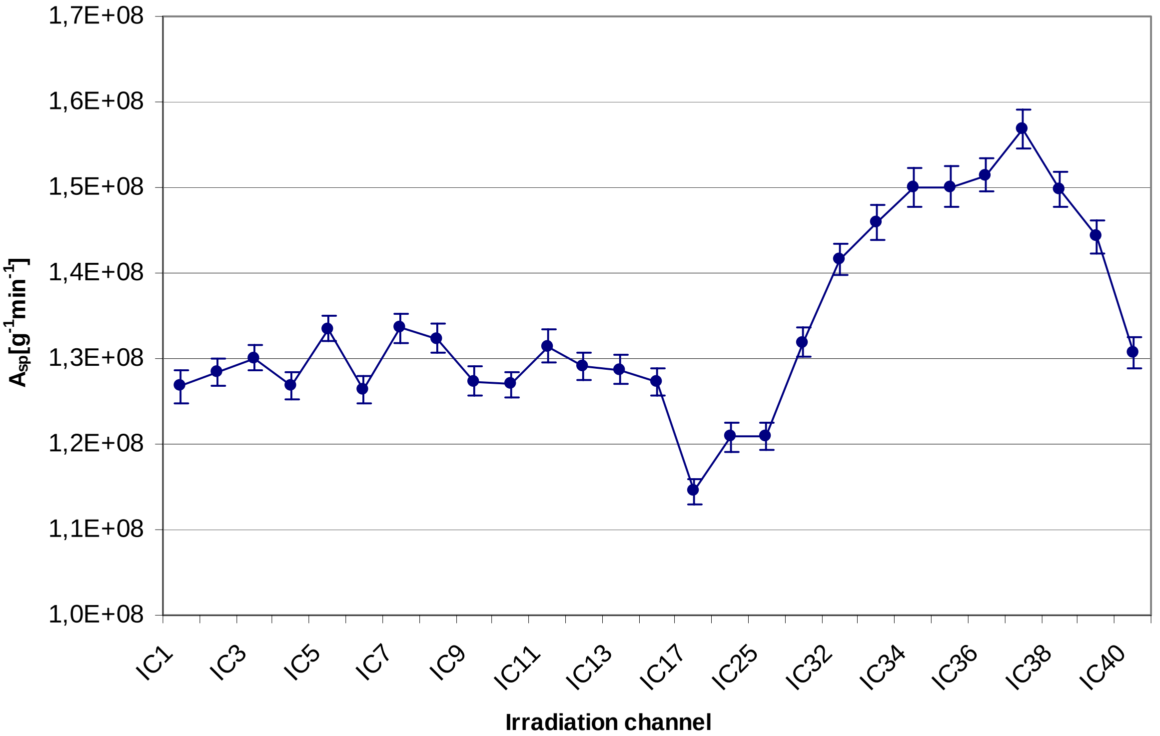


Fig. 2. Specific activity of ^{198}Au in investigated irradiation channels.



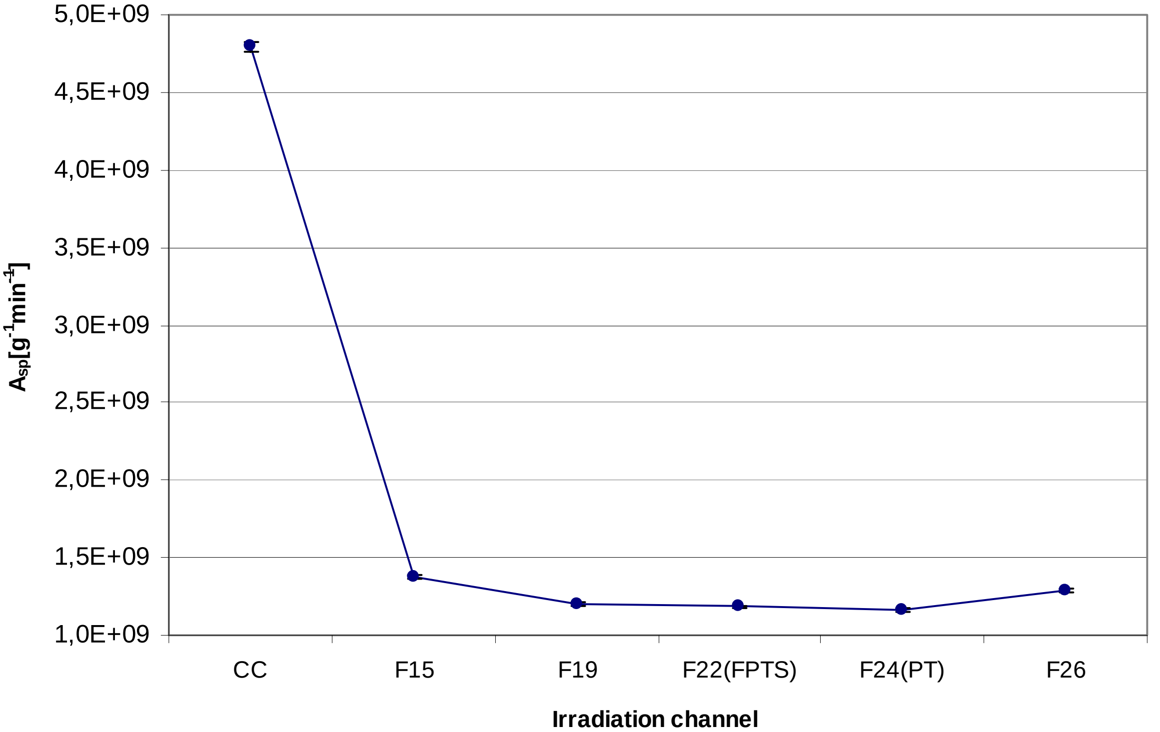


Fig. 3. Specific activity of ^{24}Na in investigated irradiation channels only for the first measurement.

Table 4. Comparison of normalized specific activity of ^{198}Au for the first (N_1) and the second measurement (N_2). The average of normalized specific activity of ^{198}Au and uncertainty are marked as N_{AVG} and ΔN_{AVG}, respectively. In the last two columns the normalized specific activity and uncertainty of ^{24}Na only for the first measurement are given.

No.	Irr. ch.	^{198}Au							^{24}Na	
		N_1	ΔN_1 [%]	N_2	ΔN_2 [%]	Diff. [%]	N_{AVG}	ΔN_{AVG} [%]	N_1	ΔN_1 [%]
1	CC#	7.37	2.05	7.29	2.12	1.07	7.33	1.47	36.70	2.44
2	F15	3.38	2.04	3.36	2.16	0.76	3.37	1.48	10.49	2.57
3	F19	3.49	2.07	3.47	2.18	0.50	3.48	1.50	9.17	2.63
4	F22##	3.22	2.05	3.20	2.17	0.72	3.21	1.49	9.05	2.58
5	F24###	3.35	2.10	3.30	2.27	1.60	3.33	1.54	8.88	2.69
6	F26	3.30	2.15	3.23	2.52	2.31	3.27	1.64	9.90	2.73
7	IC1	0.98	1.59	0.97	2.26	1.46	0.97	1.30	0.97	2.54
8	IC2	0.96	1.59	0.94	2.28	1.62	0.95	1.30	0.98	2.36
9	IC3	0.95	1.54	0.94	2.21	0.13	0.94	1.26	1.00	2.28
10	IC4	0.92	1.58	0.91	2.26	0.57	0.92	1.29	0.97	2.37
11	IC5	0.90	1.58	0.90	2.24	0.16	0.90	1.29	1.02	2.26
12	IC6	0.90	1.59	0.90	2.27	-0.35	0.90	1.30	0.97	2.35
13	IC7	0.91	1.59	0.91	2.28	0.13	0.91	1.30	1.02	2.40
14	IC8	0.92	1.56	0.92	2.36	0.05	0.92	1.30	1.01	2.33
15	IC9	0.91	1.61	0.90	2.27	1.54	0.91	1.32	0.98	2.42
16	IC10	0.91	1.56	0.90	2.23	1.22	0.90	1.28	0.97	2.30
17	IC11	0.89	1.63	0.89	2.33	0.82	0.89	1.34	1.01	2.55
18	IC12	0.89	1.86	0.88	2.45	0.80	0.89	1.48	0.99	2.37
19	IC13	0.87	1.56	0.87	2.23	0.07	0.87	1.28	0.99	2.37
20	IC14	0.85	1.54	0.86	2.22	-1.59	0.85	1.26	0.97	2.29
21	IC17	0.85	1.57	0.86	2.22	-1.18	0.85	1.28	0.88	2.34
22	IC20	0.83	1.71	0.83	2.28	-0.35	0.83	1.37	0.93	2.47
23	IC25	0.84	1.54	0.84	2.23	-0.68	0.84	1.27	0.93	2.36
24	IC30	0.97	1.54	0.99	2.20	-1.89	0.97	1.26	1.01	2.30
25	IC32	1.01	1.52	1.02	2.18	-0.68	1.02	1.25	1.08	2.30
26	IC33	1.02	1.58	1.02	2.24	0.06	1.02	1.29	1.12	2.42
27	IC34	1.04	1.59	1.06	2.26	-1.37	1.05	1.30	1.15	2.55
28	IC35	1.03	1.54	1.04	2.19	-0.88	1.04	1.26	1.15	2.52
29	IC36	1.04	1.56	1.05	2.21	-1.21	1.05	1.28	1.16	2.32
30	IC37	1.04	1.51	1.04	2.18	-0.55	1.04	1.24	1.20	2.39
31	IC38	1.03	1.63	1.02	2.23	0.11	1.02	1.31	1.15	2.41
32	IC39	1.02	1.61	1.04	2.27	-1.44	1.03	1.32	1.10	2.44
33	IC40	1.00	1.57	1.00	2.37	0.00	1.00	1.31	1.00	2.44

Central Channel; ## Fast Pneumatic Transfer System (FPTS); ### Pneumatic Tube (PT)

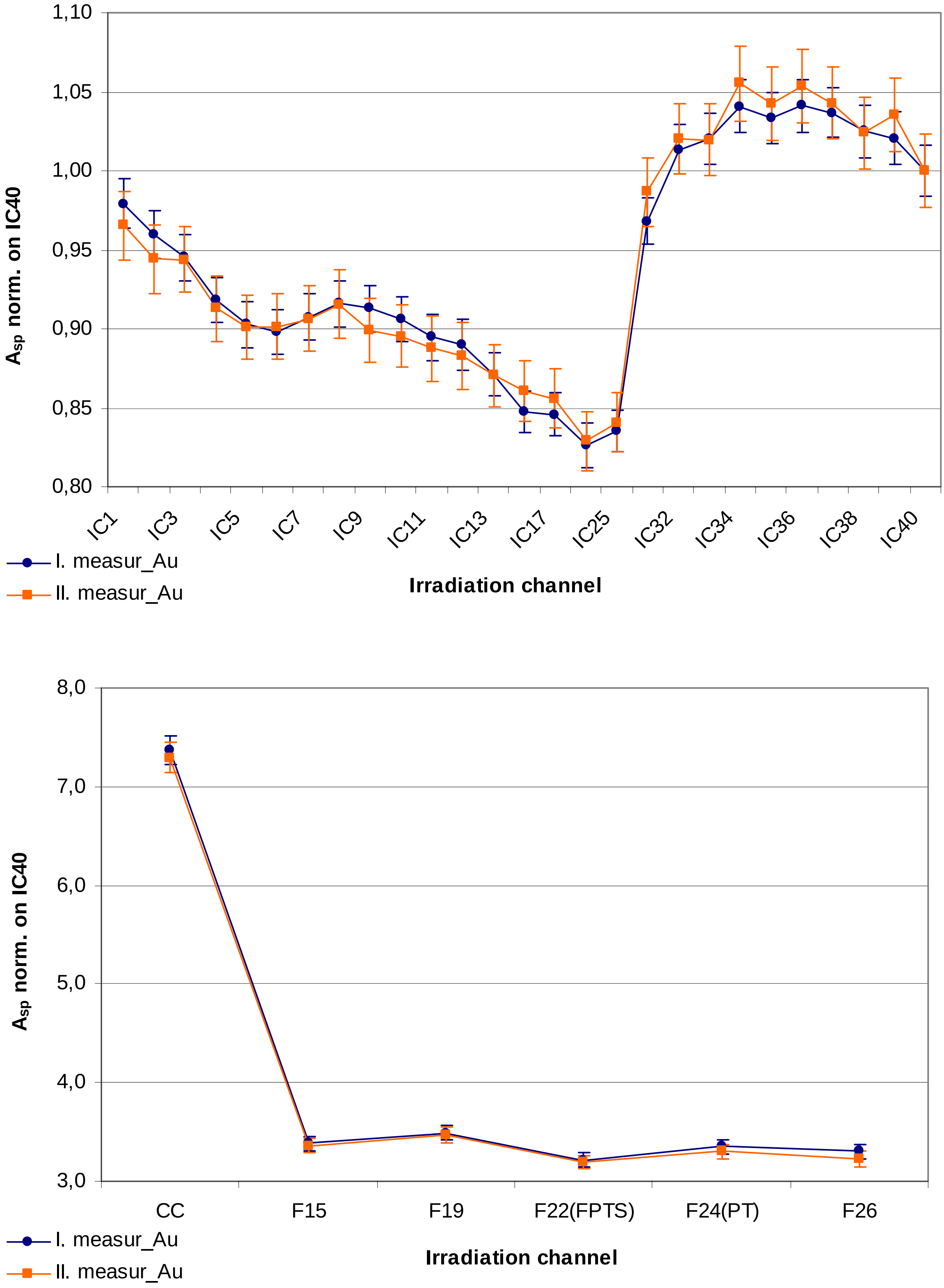
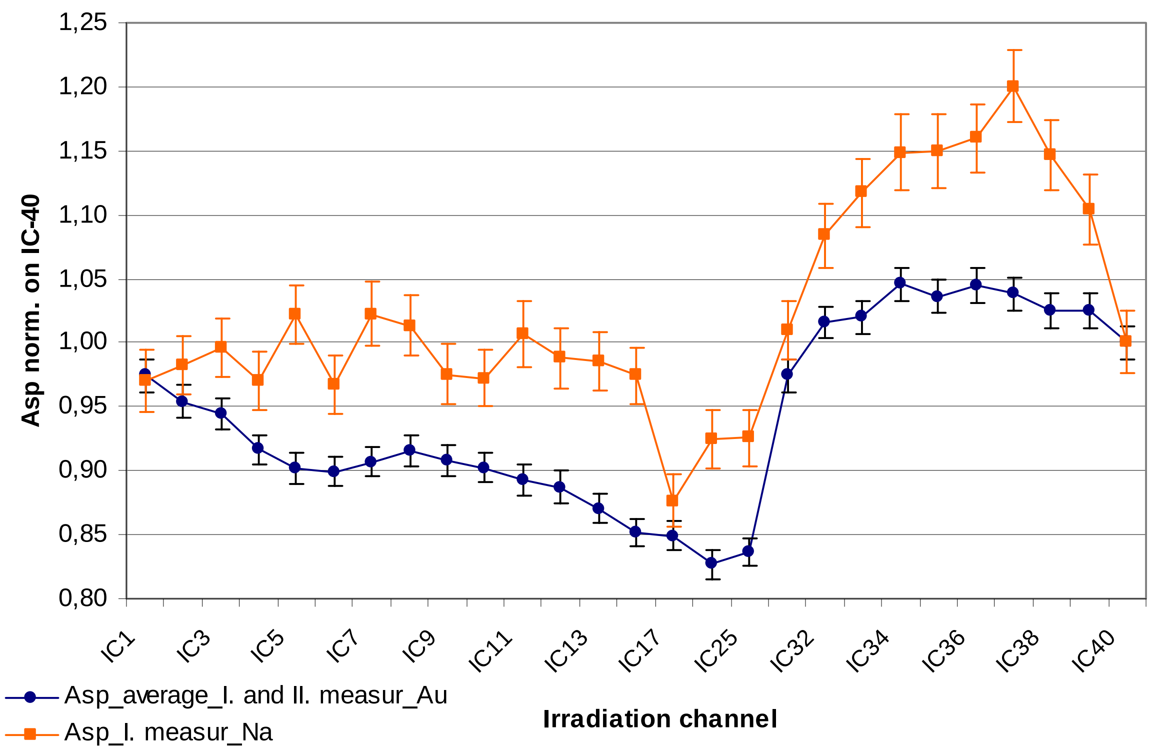


Fig. 4. Normalized specific activities of ^{198}Au in investigated irradiation channels.



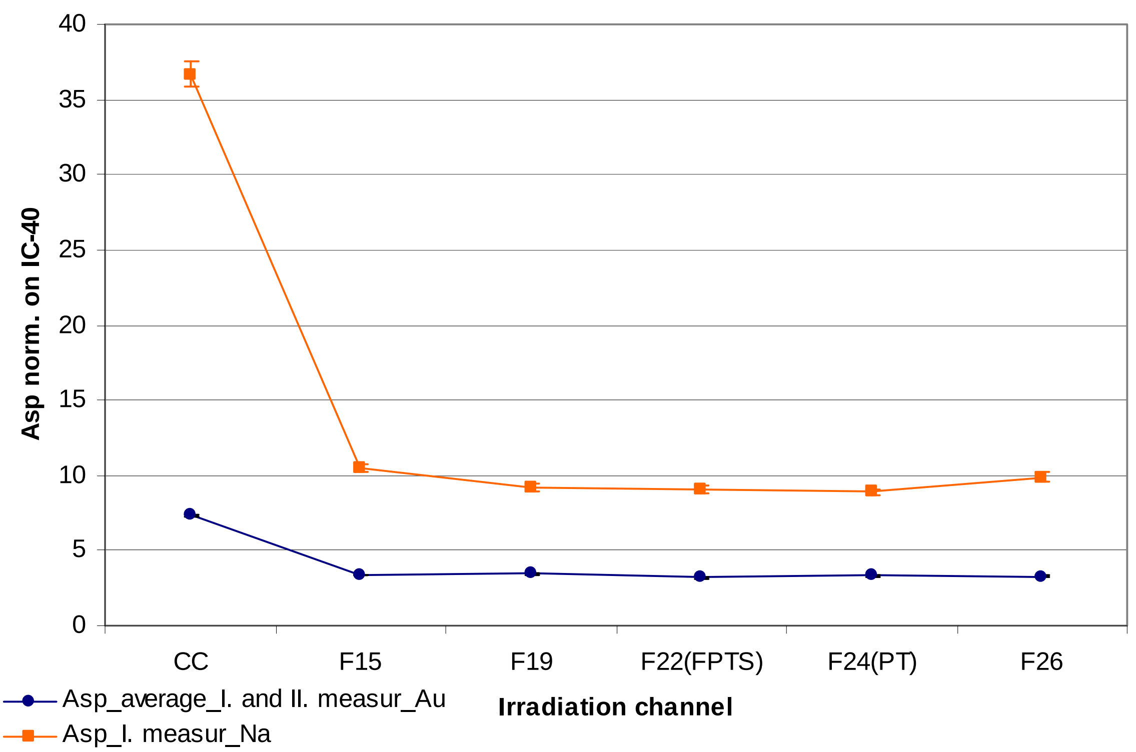


Fig. 5. Normalized specific activity of ^{198}Au and ^{24}Na in both measurements.

5. Conclusions

Detailed experimental data of the neutron spectrum in 33 irradiation channels of the TRIGA reactor (core No. 189) were presented. The results show that the thermal neutron flux on the core periphery drops by a factor of three compared to the flux in the central channel, while the fast neutron flux drops by a factor of ten. Measurement data sets agree to within about 2% after the normalization. Variations of the thermal neutron flux around the core in the carousel facility relative to the position IC40 range from 0.83 to 1.05 (relative values) and for fast neutron flux from 0.88 to 1.20 (relative values). Further measurements to validate the neutron spectra in selected irradiation channels are in progress.

6. References

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