k_0-factor determination for ^{95}Zr and ^{97}Zr-^{97m}Nb

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k_0-value determination

when f = 50

$$\frac{f + Q_{0,Au}}{f + Q_{0,Zr}} = 0.22$$

^{198}Au, Q_0=15.71

^{97}Zr, Q_0 =

248 (1986), 251.6 (2000), 233 (2003)

83% activity of ^{97}Zr from Φ_{epi}

(n, γ) reactions with high Q_0-values

(n, γ) product	$Q_0 = I_0/\sigma_0$	(n, γ) product	$Q_0 = I_0/\sigma_0$
^{110m}Ag	16.7	^{131}Ba	24.8
^{115}Cd-^{115m}In	32.4	^{134m}Cs	11.8
^{134}Cs	12.7	^{159}Gd	29.9
^{116m}In	16.8	^{109m}Pd-^{109}Pd-^{109m}Ag	26.6
^{186}Re	15.4	^{153}Sm	14.4
^{75}Se	10.8	^{170}Tm, 84 keV	13.7
^{239}U-^{239}Np	103.4	^{97}Zr	251.6

k_0-factor

$$k_0 = \left(\frac{\theta \cdot e_\gamma \cdot \sigma_0}{M} \right) \Big/ \left(\frac{\theta \cdot e_\gamma \cdot \sigma_0}{M} \right)_{Au}$$

θ – isotopic abundance

M – atomic weight

e_γ – γ-ray emission intensity

σ_0 – 2200 $m \cdot s^{-1}$ (n, γ) cross-section

k_0-value determination

$$k_0 = \frac{A_{sp}}{A_{sp,\,Au}} \cdot \frac{f + Q_{0,\,Au}(\alpha)}{f + Q_0(\alpha)} \cdot \frac{\varepsilon_{p,\,Au}}{\varepsilon_p}$$

A_{sp} – specific activity
f = Φ_{th}/Φ_{epi}
Q_0 (α) – the ratio I_0/σ_0 corrected for the α-factor
α – correction for epithermal flux deviation from 1/E shape
ε_p – γ-ray counting efficiency
Au – stands for the reference reaction ^{197}Au (n, γ) ^{198}Au, 412 keV

k_0-value determination

^{198}Au, Q_0=15.71

^{97}Zr, Q_0 =

248 (1986), 251.6 (2000), 233 (2003)

when f = 50

$$\frac{f + Q_{0,Au}}{f + Q_{0,Zr}} = 0.22$$

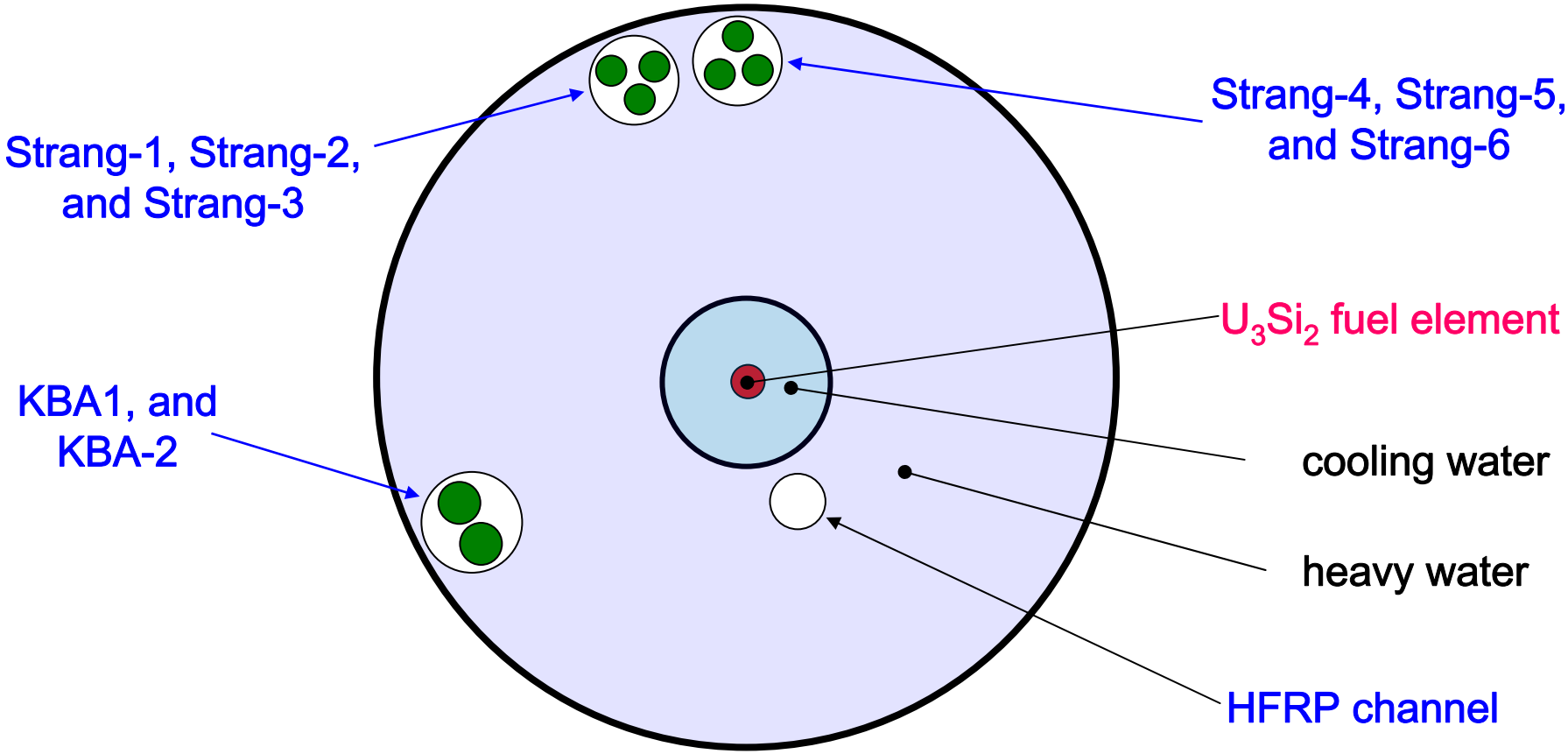
83% activity from Φ_{epi}

if f = 25000

$$\frac{f + Q_{0,Au}}{f + Q_{0,Zr}} = 0.9907$$

1% activity from Φ_{epi}

Irradiation positions in the reactor FRM-II



Neutron flux parameters from bare-monitors

Irradiation position, date, and reactor power	f	f_{fast}
Strang-4, 10-05-05, 20MW	3000	1300
Strang-5, 10-05-05, 20MW	3400	6600
Strang-1, 09-05-04, 20MW	5300	17700
Strang-2, 09-05-04, 20MW	4800	37000
Strang-6, 09-05-04, 20MW	5800	47000
Strang-3, 09-05-05, 20MW	6400	68000

Cd-covered Irradiation: Experimental

- **used flux monitors:**
  Au-Al (0.2 % Au) wire and Zr-foil

- **Cd-container:**
  Φ 10 mm x 12 mm, 1 mm wall-thickness

- **Irradiations with and without Cd-container performed at 300 kW**

- **after irradiation, monitors measured at detectors**

Determined Cd-ratio

irradiation position	experiment date	Cd-ratio value from ^{198}Au	uncertainty (1s)	from ^{97}Zr	uncertainty (1s)
Strang-4	24-Aug-2006	83.3	2.1	11.34	0.57
Strang-5	24-Aug-2006	397	12	48.7	2.4
Strang-1	23-May-2006	750	23	84.7	4.5
Strang-2	23-May-2006	1027	31	103.3	6.2
Strang-6	23-May-2006	1434	52	116.0	9.5
Strang-6	24-Jan-2007	1418	42	127.0	8.9
Strang-3	23-May-2006	1794	75	135.4	13
Strang-3	24-Jan-2007	1835	50	134.0	5.9

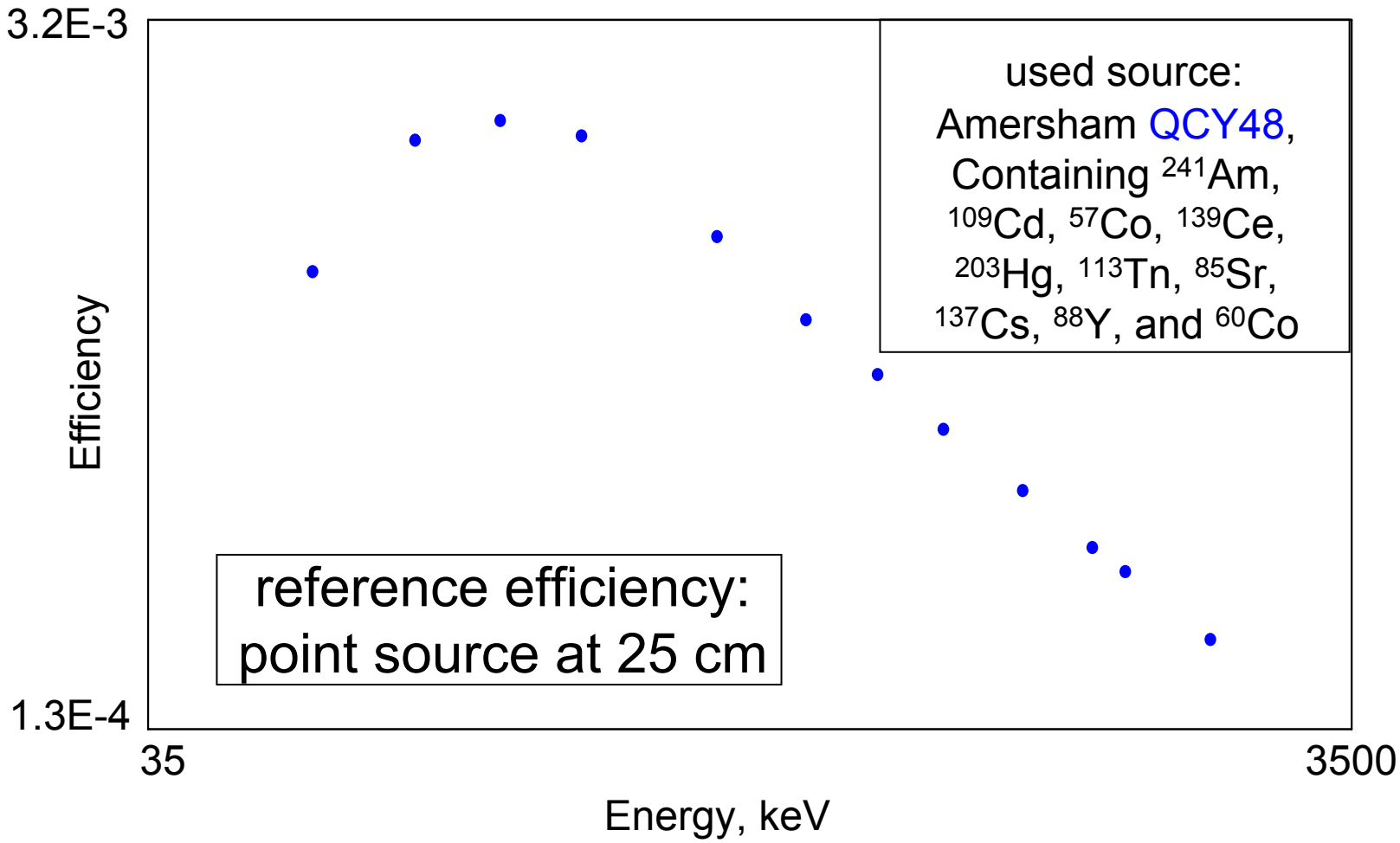
Uncertainty on Cd-ratio (Strang-3)

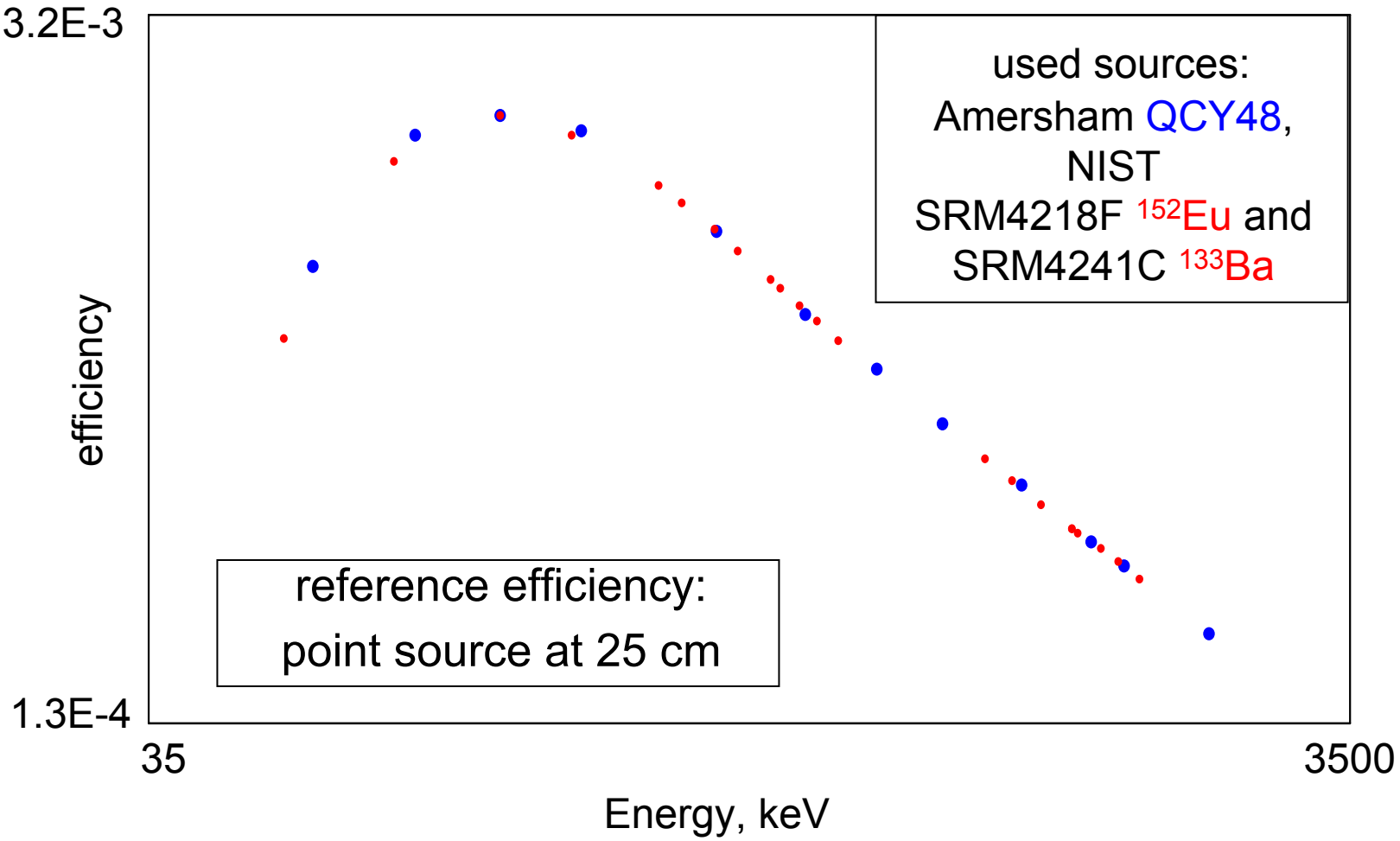
Uncertainty source	Relative uncertainty (1s), %			
	bare ^{198}Au	^{198}Au in Cd-box	bare ^{97}Zr	^{97}Zr in Cd-box
monitor mass (Au-Al-35mg, Zr-45mg)	0.029	0.029	0.022	0.022
monitor positioning in irradiation container	0.1	0.1	0.1	0.1
irradiation duration	0.17	0.11	0.17	0.11
irradiation saturation factor (due to half-life uncertainty)	0.1	0.1	0.1	0.1
neutron flux stability during the dual irradiation (with and without Cd-box), evaluated from reactor operation record	0.1	0.1	0.1	0.1
monitor positioning in gamma-ray counting (causing different efficiency)	1.5	1.5	1.5	1.5
gamma-ray counting statistics	0.1	1.5	0.3	3.8
live-time correction	0.5	0.5	0.5	0.5
decay correction (due to half-life uncertainty)	0.02	0.01	0.02	0.02
combined uncertainty on Cd-ratio		**2.71%**		**4.43%**

f-value from determined Cd-ratio

irradiation position	experiment date	f-value from ^{198}Au Cd-ratio	uncertainty[a] (1s)
Strang-4	24-Aug-2006	1283	40
Strang-5	24-Aug-2006	6180	220
Strang-1	23-May-2006	11670	420
Strang-2	23-May-2006	15990	560
Strang-6	23-May-2006	22330	910
Strang-6	24-Jan-2007	22080	770
Strang-3	23-May-2006	28000	1300
Strang-3	24-Jan-2007	28580	930

a - evaluated from uncertainties on Cd-ratio and ^{198}Au Q_0-value


3.2E-3
1.3E-4
Efficiency
35
3500
Energy, keV
used source:
Amersham QCY48,
Containing ^{241}Am,
^{109}Cd, ^{57}Co, ^{139}Ce,
^{203}Hg, ^{113}Tn, ^{85}Sr,
^{137}Cs, ^{88}Y, and ^{60}Co
reference efficiency:
point source at 25 cm


3.2E-3
1.3E-4
efficiency
35
3500
Energy, keV
used sources:
Amersham QCY48,
NIST
SRM4218F 152Eu and
SRM4241C 133Ba
reference efficiency:
point source at 25 cm

Reference efficiencies and uncertainties

Gamma-ray, keV	Peak efficiency	Relative uncertainty, % (1s)
344.28	9.45E-04	0.58
356.0	9.10E-04	0.38
383.84	8.45E-04	0.45
391.7	8.12E-04	1.6
411.13	7.89E-04	0.77
443.96	7.21E-04	0.71
514.0	6.31E-04	1.3
661.6	4.944E-04	1.1
778.9	4.183E-04	0.64
867.39	3.803E-04	0.87
898.1	3.715E-04	0.95
964.08	3.419E-04	0.60
1085.84	3.066E-04	0.70

Determination of k_0-values for Zr-isotopes: experimental

- **Au-Al foil, 37mg, 12mm x 12mm:**
  IRMM-530 (1.00 ± 0.02 g Au/kg, k=2; 0.1mm of thickness)

- **Zr-foil, 27mg, 12mm x 12mm:**
  AlfaAesar (99.9+ % of purity; 0.025mm of thickness)

- **a piece of Au-Al foil and a piece of Zr-foil co-irradiated at Strang-3 or Strang-6 for 30 – 60 minutes at reactor full power of 20 MW**

- **after irradiation, monitors measured individually at 25cm position from detector**

Determined k_0-values for Zr-isotopes

Irradiation position	Exp. No.	k_0, (uncertainty, %, 1s)			
		^{94}Zr (n, γ) ^{95}Zr			^{96}Zr (n, γ) $^{97}Zr^{/97m}Nb$
		724.2 + 756.7 keV	724.2 keV	756.7 keV	743.4 keV
Strang-3	1	2.025E-4 (3.1)	9.037E-5 (3.1)	1.120E-4 (3.1)	1.265E-5 (3.1)
	2	2.022E-4 (3.1)	9.046E-5 (3.1)	1.116E-4 (3.1)	1.258E-5 (3.1)
	3	2.007E-4 (2.5)	8.967E-5 (2.5)	1.109E-4 (2.5)	1.269E-5 (2.5)
	4	2.014E-4 (2.5)	9.018E-5 (2.5)	1.112E-4 (2.5)	1.275E-5 (2.5)
	5	2.022E-5 (2.5)	9.048E-5 (2.5)	1.117E-4 (2.5)	1.281E-5 (2.5)
	6	2.027E-4 (2.5)	9.067E-5 (2.5)	1.119E-4 (2.5)	1.280E-5 (2.5)
	7	2.014E-4 (2.5)	9.008E-5 (2.5)	1.112E-4 (2.5)	1.274E-5 (2.5)
Strang-6	1	2.018E-4 (3.1)	9.028E-5 (3.1)	1.115E-4 (3.1)	1.293E-5 (3.1)
	2	2.007E-4 (3.1)	8.974E-5 (3.1)	1.109E-4 (3.1)	1.283E-5 (3.1)
Mean value		**2.017E-4**	**9.022E-5**	**1.114E-4**	**1.275E-05**
% standard deviation		**0.36**	**0.37**	**0.36**	**0.84**

Uncertainty evaluation on the determined k_0-values

Source of uncertainty	Relative uncertainty on k_0-value (1s), %		
	^{198}Au	^{95}Zr (724.2 + 756.7keV)	^{97}Zr
monitor mass	0.027	0.037	0.037
monitor concentration	1	0.01	0.01
irradiation duration	0.06	0.06	0.06
irradiation situation factor	0.1	0.01	0.1
neutron flux stability during irradiation period	0.1	0.1	0.1
from $(f+Q_0^{Au})/(f+Q_0)$ item, the maximum	-	0	0.33
monitor positioning at 25cm or 15cm gamma-ray counting position	0.2 at 25cm, 0.5 at 15cm	0.2 at 25cm, 0.5 at 15cm	0.2 at 25cm, 0.5 at 15cm
gamma-ray counting efficiency at 25cm or 15cm position	1.3 at 25cm, 2 at 15cm	1.3 at 25cm, 2 at 15cm	1.3 at 25cm, 2 at 15cm
live-time correction	0.5	0.5	0.5
decay correction	0.13	0.001	0.002
gamma-ray counting statistics	0.1 - 0.2	0.1 - 0.5	0.1 - 0.4
combined uncertainty on k_0-value		**2.24 - 3.22 %**	**2.27 - 3.22 %**

$^{97}Zr/^{97m}Nb$ k_0-values determined at different reactor powers: ^{95}Zr used as an internal comparator

Irradiation position	Reactor thermal power	k_0-value[a]
Strang-3	200kW	1.269E-05
Strang-3	300kW	1.278E-05
Strang-3	2MW	1.284E-05
Strang-3	19MW	1.283E-05
Strang-3/6 (^{198}Au as comparator)	**20MW**	**1.276E-5 (2.5)**

a - the k_0-values calculated against the internal comparator of ^{95}Zr 724.2+756.7keV with k_0 = 2.018E-4

Summary

- **Irradiation positions in reactor FRM-II with very high thermal-to-epithermal neutron flux ratio up to 28163 were characterized, which are very suitable for k_0-factor determination particularly for nuclides with high Q_0-values.**

- **HPGe detectors were re-calibrated using standard sources with low uncertainty of less than 0.4 %, which are suitable for k_0-factor determination in the energy range of 50 keV – 2000 keV**

Summary: k_0-values for Zr-isotopes

Nuclide	gamma-ray, keV	k_0-value (uncertainty, %)				
		from this work	KFKI-AEKI[a]	IRMM/SCK[a]	INW[a]	Grand mean[b]/ Recommended[c]
^{95}Zr	724.2 + 756.7	**2.018E-4 (2.3)**	2.039E-4 (0.34)	1.959E-4 (0.88)	2.001E-4 (0.38)	**2.000E-4 (1.2)**
	724.2	**9.02E-5 (2.3)**	n.r.[d]	n.r.[d]	n.r.[d]	**8.90E-5 (1.3)**
	756.7	**1.114E-4 (2.3)**	n.r.[d]	n.r.[d]	n.r.[d]	**1.10E-4 (1.3)**
^{97}Zr/^{97m}Nb	743.4	**1.276E-5 (2.3)**	1.238E-5 (0.22)	1.174E-5 (3.2)	1.235E-5 (0.69)	**1.237E-5 (0.3)**

a - KFKI-AEKI, IRMM/SCK, and INW - three institutions where the k_0-determinations were carried out: A Simonits, et.al., The k_0 and Q_0 values for the Zr-isotopes: A re-investigation, J. Radioanal. Nucl. Chem., 245 (2000) 199

b - the recommemded k_0-values were the Grand means of the values shown in this table from KFKI-AEKI, IRMM/SCK.

c - F. De Corte and A. Simonits, Recommended nuclear data for use in the k_0 standardization of neutron activation analysis, Atom. Data and

d - not reported

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IAEA – International Atomic Energy Agency, Vienna, Austria

k_0- and other relevant values for reaction ^{129}I (n, γ) ^{130}I

Target	θ, %	σ_0, b	I_0, b	Q_0	$\bar{E}_r$ eV	Nuclide formed	Half-life	γ-line, keV	e_γ, %	$k_{0,Au}$ calc.	$k_{0,Au}$ deter.
^{129}I	(100)	17.8	18.2			^{130m}I	8.84 m				
					F = 0.84 ↓						
		12.5	15.6	1.13	212	^{130}I	12.36 h	417.9	34.2	0.152	0.158
								536.1	99	0.441	0.455
								668.6	96	0.427	0.446
								739.5	82	0.345	0.383
								1157.4	11.3	0.0503	0.0530

Coincidence counting-loss of nuclide ^{130}I

Detector	Counting distance	Nuclide	γ-line, keV	COI
D19, Canberra p-Type, Al-window, 34% rel. efficiency	0cm	^{130}I	417.9	0.578
			536.1	0.653
			668.5	0.650
			739.5	0.639
			1157.4	0.879