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Low Energy Gamma Rays from Thermal Neutron Capture

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The beam tube $P2$ of the 4MW FRM pool reactor was used as the neutron source for this nuclear spectroscopy study. An 8.5 and 13.5 cm lithium drifted germanium detector were used as gamma ray detector to measure the low energy prompt photon emissions from thermal neutron capture in 18 elements (12 rare earth elements) having a σ/A value greater than 0.1. The energy region was from 50–500 keV. Energy and intensity of the gamma ray lines are given.

Introduction

Only a few papers [1, 2] describe the use of the low energy gamma radiation from thermal neutron capture in activation analysis. This may be caused by the short-coming of this energy region in most of the compilations of neutron capture gamma rays. Rasmussen *et al.* [3] using the M.I.T. Ge(Li) spectrometer report only energies above 200 keV, while the other compilations [4–6] are mainly basing on the measurements by NaI(Tl) detectors and thus present only a few lines. But for the application in activation analysis the low energy region is very important because of the high efficiency and good resolution of a germanium detector. In this work two Ge(Li) detectors were used to study the prompt photon emissions from thermal neutron capture in 18 elements of mainly analytical interest having a σ/A (neutron capture cross section/atomic weight) value greater than 0.1.

Experimental Arrangement

The beam tube $P2$ of the research reactor Munich specially constructed for neutron capture experiments, was used as the neutron source for this research. The thermal neutron flux at the target position was $2 \cdot 10^7$ neutrons/cm^2 · sec on an area of 18 mm diameter.

Fig. 1 shows the experimental set-up of the target and of the Ge(Li) detector and its shielding which is described in detail in an earlier paper [2]. A 3 cm diameter lead collimator for the capture gamma rays was

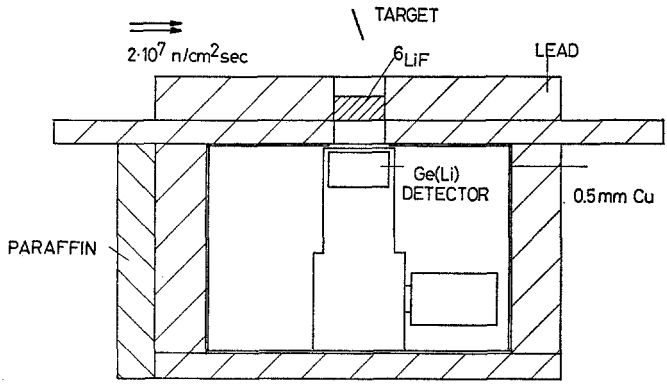

Fig. 1. Experimental arrangement

between the target and the detector. A ^{6}LiF shield was placed in the collimator to reduce neutron scattering into the detector.

The resolution width of the first 13.5 cm^3 Ge(Li) detector was 3.1 keV at 200 keV, while the second 8.5 cm^3 detector had a resolution of 1.6 keV at the same energy. For both detectors an absolute efficiency calibration curve was taken using a gamma standard set of the IAEA. The gamma ray spectra were recorded in 1600 or 4096 channel analyzer.

Results

Because of the high Cd-ratio (>200) of the neutron beam the spectra could be taken in a simple two-spectra mode. From the spectrum of the sample the spectrum of the empty container (aluminium foil) was subtracted. This method reduced background and capture gamma rays from the sample container, sample holder, shielding, etc. To avoid neutron flux depression within the sample, the targets were prepared having area thickness of about 1 to 10 mg/cm^2.

Table 1 lists the observed low-energy capture gamma rays and their intensities in the energy region between 50 and 500 keV of 18 elements which were most interesting using this activation analysis method. Among them there are twelve elements of the rare earths. The neutron capture cross-section σ and the atomic weight A are taken from the chart of the nuclides [7].

The energy E_γ of the peak was determined using lines of known energy of the nuclides Am-241, Co-57, Ba-133, Hg-203 and Na-22 as gamma ray standards. The over-all accuracy of the energy determination including the location of peak centre and the electronic nonlinearity and shift was within ± 0.4 keV for all lines strong enough to be reported. In

Table 1. Low energy neutron capture gamma rays

Element	σ	A	Present work		Rasmussen *et al.* [3]	
			$E\gamma$	$I\gamma$	$E\gamma$	$I\gamma$
Sc	25.0	44.956	51.2	1.5		
			141.8	16		
			147.2	16		
			216.0	8	217.0	6.89
			227.6	29	228.6	39.36
			295.4	13	295.6	15.74
Co	37.2	58.933	57.8	1.2		
			159.0	6.2		
			229.6	21.5	230.5	17.60
			254.6	2.4		
			276.9	12.0	277.7	15.43
			390.3	4.0	391.7	2.27
			446.8	5.2	447.6	5.75
Cu	3.8	63.54	92.4	7.2		
			159.4	12.2		
			186.6	7.2		
			203.3	6.8	203.1	6.64
			278.6	30.6	278.3	30.12
			343.9	5.2	343.9	5.03
			385.7	7.2	385.2	6.98
			465.8	5.0	466.2	5.50
Se	12.2	78.96	89.5	1.8		
			143.8	6.2		
			164.0	8.0		
			200.7	4.7		
			242.6	24.8	239.6	12.78
					286.4	1.45
			292.2	7.8	297.8	1.14
			443.2	5.8	439.9	1.36
In	194	114.82	60.5	9.2		
			86.2	12.5		
			97.4	19.6		
			127.8	3.9		
			163.8	17.8		
			187.5	16.5		
			202.0	2.8		
			234.1	4.9		
			275.8	30.5	273.3	7.07
					298.4	1.9
			336.0	8.2	335.6	2.3
			385.3	12.5	385.3	1.94
			434.0	5.8	434.0	1.03
La	8.9	138.91	162.5	12.5		
			183.6	8.0		

Table 1 (continued)

Element	σ	A	Present work		Rasmussen *et al.* [3]	
			$E\gamma$	$I\gamma$	$E\gamma$	$I\gamma$
			217.8	20.5	219.6	11.77
			238.4	10.4	238.5	9.04
			272.8	8.9	273.2	7.46
			288.2	18.3	289.1	9.99
			423.5	10.6	423.2	6.92
Pr	11.6	140.907	85.6	2.7		
			127.2	3.4		
			141.3	4.4		
			177.1	10.5	178.4	8.23
			182.9	3.9		
			340.8	1.2		
			460.6	1.9	461.3	0.56
Nd	48	144.24	258.9	9.8	256.3	9.20
					428.0	1.37
			452.8	5.4	454.5	5.47
Sm	5820	150.35	333.9	63.2	333.9	83.26
					404.9	1.46
			439.4	34.8	439.4	45.79
Eu	4400	151.96	72.8	6.0		
			89.9	25.4		
			144.5	5.9		
			168.8	3.3		
			208.1	8.9		
					208.0	5.39
					328.9	160.96
					379.4	61.79
Gd	49000	157.25	79.6	10		
			88.9	3.4		
			182.1	20		
			199.2	6.2		
					247.3	22.18
			277.6	1.8	277.9	0.93
Tb	22	158.924	75.0	5.5	no line with	
			95.8	4.6	$I\gamma > 1.0$	
			147.5	4.0		
			182.1	3.4		
			199.3	1.6		
			252.0	2.2		
			350.8	6.5		
Dy	930	162.50	80.6	2.4		
			108.1	1.8		
			184.2	16.2	185.7	19.48
			260.8	1.5	259.5	0.12

Table 1 (continued)

Element	σ	A	Present work		Rasmussen *et al.* [3]	
			$E\gamma$	$I\gamma$	$E\gamma$	$I\gamma$
			282.6	1.0	282.3	0.36
			349.1	3.2	350.7	2.80
			386.6	2.1	386.8	3.94
			411.5	7.4	413.2	6.88
					447.3	1.91
					465.8	2.58
			497.6	4.4	497.6	4.36
Ho	67	164.93	117.2	16.6		
			136.6	28.9		
			149.4	5.4		
			222.0	2.3	222.0	2.14
			240.3	3.1	240.3	4.23
			290.8	2.4	290.4	2.79
					305.7	1.12
					334.3	1.00
			372.1	2.0	372.2	1.67
			426.1	2.8	426.3	3.02
Er	160	167.26	82.0	8.9		
			185.3	52		
			199.6	17		
			284.8	10.4	285.2	9.53
			341.6	7.5	342.9	7.91
Tm	106	168.934	114.2	4.6		
			148.8	12,0		
			179.2	4.8		
			205.8	8.3	205.2	5.35
					220.4	2.42
			235.9	5.0	237.5	7.09
			310.0	2.0	311.5	1.67
			384.2	1.8	384.3	1.58
			411.7	1.4	411.8	1.46
					446.2	1.08
Lu	108	174.97	122.0	13.0		
			138.1	15.2		
			149.6	47.3		
			163.6	11.8		
			187.2	18.0		
			269.0	16.3	169.4	2.39
			320.1	8.2	319.6	3.40
			365.6	7.0	367.5	3.14
			460.3	15.5	458.1	8.90
Hg	375	200.59	71.9	7.5		
			368.5	47.8	367.8	82.56

the case of prominent lines ($I_\gamma > 10$) the reproducibility was easily within ± 0.2 keV. The intensity I_γ of each line is expressed as the number of γ's/100 captures. The intensity was determined by the calculation of the number of counts in the peak, by the determination of the number of γ's emitted by the source using intrinsic and geometry factors, and by the calculation of the total number of captures in the sample using the measured neutron flux and the cross-section value listed in Table 1. A correction for γ ray self-absorption in the sample and for attenuation in the ^{6}LiF shield was also included. The intensity accuracy for lines with I_γ of about 10 is within $\pm 15\%$. For intensities of about 1 the accuracy is between ± 20 and $\pm 40\%$ depending on the peak area and the background.

In view of the application in activation analysis gamma ray lines with $I_\gamma < 1$ were not evaluated. The data given in Table 1 are mean values of at least ten different measurements. No measurement produced data with greater deviations than mentioned above.

For most elements the energy and intensity of the low energy capture gamma rays compiled in Table 1 are in good agreement with the reference values of Rasmussen *et al.* and of the other compilations. Some data below 200 keV could be determined with a higher accuracy in this work. Only for the elements europium, gadolinium, and terbium the data do not agree with the values of Rasmussen *et al.*, while they are in satisfactory agreement with those of the other compilations.

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