Precise Determination of
Gamma-ray Emission Probabilities and Beta-ray Intensities
for Nuclides with Relatively Short Half-lives

Nada Marnada, Hiroshi Miyahara*, Gatot Wurdiyanto
Keiichi Ikeda, Nobuo Hayashi, and Yoshichika Katoh
Department of Nuclear Engineering, Graduate School of Engineering
Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464-8603
e-mail: nada@avocet.nucl.nagoya-u.ac.jp
*Department of Radiological Technology, School of Health Sciences
Nagoya University, 1-1-20 Daiko-Minami, Higashi-ku, Nagoya 461-8673

The ability of a 4πβ-γ coincidence apparatus to measure shortly and precisely disintegration rates has resulted in precise emission probabilities of principal γ-rays for nuclides of ^{76}As, ^{139}Ba, ^{159}Gd, ^{183}W and ^{193}Os of which the half-lives are relatively short. The precise emission probabilities gave β-ray intensities for transitions to excited states and the ground states of the daughter nuclides with precise values.

1. Introduction

Gamma-ray emission probability is an important factor in some research fields of nuclear radiation products and radioisotope applications such as fission product decay-heat, isotopic monitoring, neutron activation analysis, and nuclear medicine. Precise data of emission probabilities are therefore desired in order to get precise results. Many nuclides have been investigated or evaluated by previous authors to provide the data of γ-ray emission probabilities. However, the results are still incorrect due to inappropriate method used.

Emission probabilities can be determined directly using disintegration rate, and disintegration rate can be precisely measured by the 4πβ-γ coincidence apparatus [1]. To satisfy the need for precise γ-ray emission probabilities of nuclides with relatively short half-lives, i.e. ^{76}As, ^{138}Ba, ^{159}Gd, ^{183}W and ^{193}Os, the apparatus was used in the present work. The nuclides were selected, as their evaluated emission probabilities show large uncertainties.

2. Experimental Details and Data Analysis

Sample sources with activities between 15 and 40 kBq were produced at KURRI by thermal neutron activation and measurements were carried out at KURRI and Nagoya University. The coincidence apparatus [1] consisted of 4πβ-counter, γ-detector, electronics for coincidence, and two-dimensional data-acquisition system. One atmospheric 4πβ proportional counter and vertical-type coaxial HPGe γ-detector were used at KURRI, and high-pressure 4πβ proportional counter and horizontal-type HPGe γ-detector were used at Nagoya University. Absolute disintegration rates and absolute γ-ray intensities were obtained from the coincidence apparatus. Measurements were also carried out by γ-ray spectrometer for obtaining relative γ-ray intensities. Sample sources with stronger activities than those used in the coincidence apparatus were prepared for the spectrometry. The results were used to establish β-ray intensities of the nuclides under study. Six standard sources of ^{46}Sc, ^{56}Co, ^{57}Co, ^{60}Co, ^{133}Ba and ^{152}Eu were also measured in every series with the same manner for determination of γ-ray detection efficiency curve.

Data obtained from the coincidence apparatus were analyzed by computer discrimination method [2] to deduce coincidence efficiency function [3]. Extrapolation of the function to β-ray detection efficiency of 100% resulted in absolute disintegration rate. The γ-ray detection efficiencies of the standard sources were fitted using a method described by Brandt [4] to obtain detection efficiency curves. Detection efficiencies of designated energies for the sample sources were derived from the efficiency curves.

3. Results and Discussions

Emission probabilities (P_γ) are calculated from $P_\gamma = N_\gamma / (N_0 \cdot \varepsilon_\gamma)$, where N_γ is absolute γ-ray intensity, N_0 is absolute disintegration rate and ε_γ is detection efficiency. The uncertainty of emission probability consists of statistical uncertainty coming from those three parameters and systematical uncertainty of about 0.7%. The results are shown in Tables 1 to 5 for emission probabilities of principal γ-rays and strong β-ray intensities. The means of the present results are also given for comparison with the evaluated values or the previously reported ones. Uncertainties are indicated by numbers in respective parentheses.

The present emission probabilities of principal γ-rays for ^{76}As shown in Table 1 agree with each other within standard deviations for respective energies. The uncertainties of about 1% are obtained for the means of emission probabilities of 559.1, 657.1 and 1228.5 keV γ-rays, and those are much smaller than the uncertainties of emission probabilities evaluated in the Nuclear Data Sheets [5]. The uncertainties for the other energies are more than 1% due to peak pileup. Present γ-ray emission probabilities which are smaller by about 10% brought to smaller β-ray intensities of the excited states and larger β-ray intensity of the ground state by about 10% than the evaluated values.

Table 2 shows the present and previous emission probabilities of 165.9 and 1420.5 keV γ-rays for ^{139}Ba. The present emission probability of 165.9 keV γ-rays is smaller by about 3% than those of refs. [6] and [7] and the uncertainty is much smaller. Burrows [6] evaluated the emission probability using relative γ-ray intensity and a normalizing factor. He adopted the emission probability for 1420.5 keV reported in ref. [7] for deducing the normalizing factor. Gehrke [7] used nickel foils to obtain various β-ray efficiencies for determination of disintegration rate. The method resulted in relatively not precise disintegration rate and the emission probabilities with large uncertainties. The emission probabilities of 1420.5 keV γ-rays were deduced using relative intensities of 1420.5 keV γ-rays and emission probabilities of 165.9 keV γ-rays by us and Gehrke. However, the present result is more precise because it was calculated using more precise emission probability. The present precise emission probabilities provided precise β-ray intensities for excited states and the ground state of ^{139}La. The results are also shown in Table 2.

Agreeable γ-ray emission probabilities within standard deviations for ^{159}Gd are exhibited in Table 3 for the present results. Uncertainty of the mean of the present strongest γ-rays is less than 0.5%, whereas that of evaluated one [8] is more than 25%. The evaluated value was derived using the relative γ-ray intensity and a normalizing factor, and the uncertainties of those two parameters were 5 and 23.7%, respectively. As the precise γ-ray emission probabilities were used in the calculation, the present β-ray intensities shown in Table 3 for excited states and the ground state are more precise than those reported by Helmer [8].

The present emission probabilities of principal γ-rays for ^{187}W shown in Table 4 are the mean values of twelve measurement results. Therefore, much small uncertainties are provided for the γ-ray emission probabilities. Uncertainty of the strongest emission probability of 685.8 keV γ-rays is less than 0.3% which is much smaller than the uncertainty of that evaluated in ref. [9] or reported by Herman et al. [10]. Larger absolute values of the means by about 20% than those in both references brought to larger β-ray intensities of excited states by about 20% and smaller β-ray intensities of the ground state of ^{187}Re by about 40%.

Table 1 γ-ray emission probabilities and β-ray intensities for ^{76}As

γ-ray emission probabilities (%)								β-ray intensities (%)		
Energy (keV)	Present work						Singh and Viggars [5]	Energy (keV)	Present work	Singh and Viggars [5]
	a	*b*	*c*	*d*	*e*	Mean				
559.1	40.70 (66)	41.37 (75)	40.29 (68)	40.55 (56)	40.45 (59)	40.67 (29)	45 (2)	306.7	0.96 (1)	1.03 (6)
563.2	1.106 (97)	1.125 (114)	1.105 (103)	1.103 (78)	1.100 (81)	1.108 (43)	1.20 (8)	532.9	1.52 (7)	1.69 (12)
657.1	5.454 (72)	5.590 (86)	5.520 (50)	5.601 (60)	5.583 (72)	5.550 (31)	6.17 (42)	1174.4	1.58 (1)	1.77 (13)
1212.9	1.310 (165)	1.301 (181)	1.324 (163)	1.264 (97)	1.280 (101)	1.296 (65)	1.44 (11)	1745.9	6.72 (11)	7.5 (5)
1216.1	3.055 (227)	3.032 (247)	3.040 (218)	2.947 (133)	2.984 (139)	3.012 (88)	3.42 (24)	2402.9	31.9 (3)	35.2 (16)
1228.5	1.037 (32)	1.029 (41)	1.035 (15)	1.034 (24)	1.037 (31)	1.034 (13)	1.22 (10)	*2962.0*	*56.0 (3)*	*51 (2)*

Table 2 γ-ray emission probabilities and β-ray intensities for ^{139}Ba

γ-ray emission probabilities (%)								
Energy (keV)	Present work						Burrows [6]	Gehrke [7]
	a	*b*	*c*	*d*	*e*	Mean		
165.9	23.06 (18)	22.95 (15)	23.12 (15)	22.91 (15)	22.93 (15)	22.99 (7)	23.7 (34)	23.76 (25)
1420.5						*0.259 (2)*	0.261 (37)	*0.261 (5)*

β-ray intensities (%)			
Energy (keV)	Present work	Burrows [6]	Gehrke [7]
833.6	0.0175 (10)	0.0175 (20)	
889.5	0.292 (2)	0.287 (7)	
2144.1	28.70 (7)	29.68 (31)	29.65 (32)
2310.0	*70.95 (7)*	*69.98 (31)*	

Table 3 γ-ray emission probabilities and β-ray intensities for ^{159}Gd

γ-ray emission probabilities (%)								β-ray intensities (%)		
Energy (keV)	Present work						Helmer [8]	Energy (keV)	Present work	Helmer [8]
	a	*b*	*c*	*d*	*e*	Mean				
58.0	2.350 (94)	2.371 (97)	2.550 (89)	2.539 (82)	2.410 (55)	2.44 (4)	2.3 (6)	607.1	12.19 (5)	12 (3)
226.0	0.215 (8)	0.215 (11)	0.221 (9)	0.218 (5)	0.216 (6)	0.217 (4)	0.21 (5)	622.4	0.310 (3)	0.31
348.2	0.254 (8)	0.255 (11)	0.241 (7)	0.237 (5)	0.258 (5)	0.249 (3)	0.22 (6)	912.6	29.01 (44)	26 (7)
363.5	11.61 (11)	11.65 (11)	11.98 (13)	11.85 (10)	11.83 (10)	11.78 (5)	10.8 (28)	*970.6*	*58.38 (45)*	*62 (9)*

Table 4 γ-ray emission probabilities and β-ray intensities for ^{187}W

γ-ray emission probabilities (%)				**β-ray intensities (%)**			
Energy (keV)	**Present work**	**Firestone [9]**	**Herman *et al.* [10]**	**Energy (keV)**	**Present work**	**Firestone [9]**	**Herman *et al.* [10]**
134.2	10.219 (28)	8.85 (28)	8.77	538.3	5.09 (2)	4.23 (9)	4.2 (4)
551.5	6.134 (21)	5.08 (17)	5.0 (5)	625.4	66.09 (79)	54.9 (8)	53.1 (16)
618.4	7.613 (25)	6.28 (21)	8.0 (8)	685.7	4.09 (53)	3.3 (4)	5.2 (5)
625.5	1.333 (10)	1.09 (4)	1.58 (15)	692.8	5.82 (53)	4.7 (5)	5.2 (5)
685.8	32.868 (85)	27.3 (9)	26.9 (11)	1177.0	1.27 (62)	0.7 (3)	0.7 (3)
772.9	4.953 (19)	4.12 (13)	4.1 (4)	*1311.2*	*16.1 (13)*	*29.8 (10)*	*25.1 (24)*

Table 5 γ-ray emission probabilities and β-ray intensities for ^{193}Os

γ-ray emission probabilities (%)							**β-ray intensities (%)**		
Energy (keV)	**Present work**					**A-Cohen [11]**	**Energy (keV)**	**Present work**	**A-Cohen [11]**
	a	*b*	*c*	*d*	Mean				
138.9	3.66 (12)	3.63 (17)	3.80 (18)	3.70 (17)	3.69 (8)	4.27 (26)	583.3	2.33 (13)	2.4 (2)
280.4	1.21 (1)	1.19 (1)	1.27 (1)	1.26 (1)	1.22 (1)	1.24 (8)	680.1	7.69 (6)	7.9 (4)
321.6	1.21 (1)	1.21 (1)	1.29 (1)	1.27 (1)	1.24 (1)	1.28 (8)	1001.7	10.2 (2)	12.4 (9)
387.5	1.21 (1)	1.20 (1)	1.26 (1)	1.27 (1)	1.23 (1)	1.26 (8)	1067. 6	17.6 (29)	18 (4)
460.5	3.81 (4)	3.78 (3)	3.97 (4)	3.95 (4)	3.86 (2)	3.95 (25)	*1140.6*	*58.0 (29)*	*55 (4)*

The emission probabilities of principal γ-rays for ^{193}Os obtained from present measurements are shown in Table 5. The uncertainties of less than 1% are obtained for the means of respective energies except for that of 138.9 keV. The 138.9 keV γ-rays make peak-pileup on 142.1 keV γ-rays; therefore, the uncertainty of emission probability is about 2.2%. But this uncertainty is still smaller than 6% given for the evaluated value [11]. Excluding the emission probability of 138.9 keV γ-rays, the present results are smaller on the average by about 2.5% than those evaluated in ref. [11]. Table 5 also shows the β-ray intensities obtained from the present work and the evaluation [11]. The present β-ray intensities of excited state calculated using present γ-ray emission probabilities and relative γ-ray intensities are smaller than the evaluated values.

The smaller values resulted in larger present β-ray intensities of the ground state of ^{193}Ir by about 5%. The uncertainty is large because the relative intensity of 73 keV γ-rays reported in ref. [11] was used for calculation of β-ray intensities of first excited state with energy level of 73 keV.

4. Conclusions

Emission probabilities of principal γ-rays for short half-life nuclides of ^{76}As, ^{139}Ba, ^{159}Gd, ^{187}W and ^{193}Os have been established in the present work. The results are more precise than the previously evaluated or reported ones. The precise results are obtained due to the ability of the 4πβ-γ coincidence apparatus to provide precise parameters of disintegration rate, absolute γ-ray intensities, and detection efficiency. Present precise γ-ray emission probabilities and measured relative γ-ray intensities brought to more precise β-ray intensities than those previously evaluated or reported.

Acknowledgments

Most of the experiments were carried out at Kyoto University Research Reactor Institute (KURRI). The authors would like to appreciate Drs. S. Yamada and A. Taniguchi of KURRI for supporting the experiments.

References

[1] Miyahara, H., Matumoto, H., Wurdiyanto, G., Yanagida, K., Takenaka, Y., Yoshida, A. and Mori, C.: Nucl. Instr. Meth., A353, 229 (1994).
[2] Smith, D.: Metrologia 11, 73 (1975).
[3] Baerg, A. P.: Nucl. Instr. Meth., 112, 143 (1973).
[4] Brandt, S.: "Statistical and Computation Methods in Data Analysis," North-Holland, Amsterdam (1976).
[5] Singh, B. and Viggars, D. A.: Nucl. Data Sheets, 42, 233 (1984).
[6] Burrows, T. W.: Nucl. Data Sheets, 57, 337 (1989).
[7] Gehrke, R. J.: Int. J. Appl. Radiat. Isot., 31, 37 (1980).
[8] Helmer, R. G.: Nucl. Data Sheets, 72, 83 (1994).
[9] Firestone, R. B.: Nucl. Data Sheets, 62, 159 (1991).
[10] Herman, A. W., Heighway, E. A. and MacArthur, J. D.: Can. J. Phys., 48, 1040 (1970).
[11] Agda Artna-Cohen: Nucl. Data Sheets, 83, 921 (1998).