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PRECISION GAMMA RAY ENERGIES IN THE ENERGY INTERVAL BETWEEN 45 AND 1275 keV*

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Curved-crystal spectrometers have been utilized to obtain measurements of more than forty gamma ray energies in the energy interval between 45 and 1275 keV for nuclei with $109 \leq A \leq 193$. Many of these energy measurements have sufficiently small uncertainties associated with them to make them useful for the calibration of Ge(Li) spectra.

1. Experimental arrangements

Two curved-crystal spectrometers and three curved-crystals were utilized in obtaining the gamma ray energy measurements reported in this paper. A description of the design of the spectrometers and the various experimental techniques associated with their use has been given elsewhere[1,2]. All three crystals were bent to a 2 m radius and the characterizations of the crystals were as follows: Ge(0$\bar{2}$2), Ge(400) and Q(310). The energy resolutions of the three crystals were about equal for a given source width. For the most frequently used source width the best crystal had an energy resolution given by $\Delta E(\text{fwhm}) = 2.2 \times 10^{-5} (E^2/n)$, where n is the order of reflection and E is the gamma ray energy in keV while the poorest crystal had an energy resolution which was about 20% greater. The Ge(0$\bar{2}$2) and Ge(400) crystals were calibrated using the 411.794 ± 0.008 keV gamma ray occurring in the decay of ^{198}Au [3–5], while the Q(310) crystal was calibrated using the 59.31918 ± 0.00035 keV Kα_1 X-ray of tungsten accompanying the decay of ^{182}Ta [4–6].

All samples were produced in the University of Michigan Ford nuclear reactor (thermal neutron flux $\sim 10^{13}$ neutrons/sec·cm^2). Several of the samples were fabricated using enriched isotopes obtained from Oak Ridge National Laboratory. These enriched isotopes and their enrichments were as follows: ^{151}Eu(96.8%), ^{152}Sm(99.2%), ^{153}Eu(98.8%), ^{190}Os(95.5%) and ^{192}Os(98.7%).

Measurements were taken in the highest order permitted by gamma ray intensity and counting time. All final energy values are the average of the values obtained in several runs.

2. Results and discussion

The results of the present investigation are given in table 1. A discussion of these results and the results of previous investigators is given below.

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^{109}Cd: No measurement of the energy of the 88 keV gamma ray occurring in the decay of ^{109}Cd utilizing a curved-crystal spectrometer has been reported as yet. The measurement given in table 1 was performed in this laboratory by Diethrich[7]. His value of 88.035 $\pm$0.006 keV is in agreement with five of the seven recent values given in table 2 and has an uncertainty associated with it which is smaller than any of the uncertainties assigned to these previous measurements.

^{152}Eu: The energies of several of the gamma rays associated with the decay of ^{152}Eu have been measured previously with curved-crystal spectrometers[14–18]. These measurements are summarized in table 3. Precision measurements of the energies of the ^{152}Eu gamma rays have also been made using other spectrometers and table 4 shows a comparison between the values obtained by two groups and those of the present work.

^{153}Sm: All of the ^{153}Sm gamma rays which we investigated have been investigated previously with curved-crystal spectrometers[18,22–27]. A summary of the results obtained in previous investigations is given in table 5. In addition, a precision measurement of the energy of the gamma ray de-exciting the 97 keV level of ^{153}Eu has been made using a Ge(Li) spectrometer by Greenwood et al.[5]. Their result is 97.432 ± 0.005 keV.

^{154}Eu: Two of the gamma rays associated with the decay of ^{154}Eu have been studied previously with curved-crystal spectrometers[15,18]. Table 6 lists previously obtained results. The most complete sets of precision measurements of ^{154}Eu gamma ray energies previously reported are given by Aubin et al.[19] and Meyer[28]. Both of these investigations utilized Ge(Li) spectrometers. In table 7 we show a comparison between the results of these studies and those of the present study. As a part of the present investigation we have made an effort to measure the energies of several weak low energy gamma rays reported by Meyer[28].

TABLE 1

Precision gamma ray energies in the energy interval between 45 and 1275 keV for nuclei with $109 \leqslant A \leqslant 193$.

Parent nucleus	Gamma ray energy (keV)
^{109}Cd	88.035 ±0.006
^{152}Eu	121.780 ±0.004
	244.693 ±0.010
	295.934 ±0.038
	344.267 ±0.010
	411.071 ±0.032
	443.924 ±0.085
^{153}Sm	54.1988±0.0022
	69.6715±0.0020
	75.4212±0.0023
	83.3666±0.0024
	89.4853±0.0033
	97.4292±0.0033
	103.179 ±0.004
^{154}Eu	123.070 ±0.004
	131.570 ±0.035
	146.035 ±0.025
	156.31 ±0.10
	188.246 ±0.013
	247.939 ±0.008
	444.443 ±0.073
	581.91 ±0.11
	591.814 ±0.038
	692.48 ±0.15
	723.430 ±0.075
	756.919 ±0.062
	873.236 ±0.076
	996.00 ±0.22
	1004.57 ±0.18
	1274.69 ±0.06
^{155}Eu	45.2972±0.0013
	57.9805±0.0020
	60.0100±0.0018
	86.0621±0.0051
	86.5452±0.0033
	105.308 ±0.003
^{156}Eu	88.9637±0.0024
	199.214 ±0.012
^{170}Tm	84.2572±0.0026
^{191}Os	82.4272±0.0099
	129.431 ±0.005
^{193}Os	138.947 ±0.008

TABLE 2

Recent precision measurements of the energy of the 88 keV gamma ray occurring in the decay of ^{109}Cd.

Reference	Gamma ray energy (keV)
5	88.036±0.008
8	88.041±0.087
9	88.05 ±0.05
10	88.033±0.042
11	88.09 ±0.03
12*	88.008±0.042
13	88.21 ±0.03

* The value quoted can be found in footnote 14 of ref. 12.

TABLE 3

Previous measurements of the energies of gamma rays occurring in the decay of ^{152}Eu using curved-crystal spectrometers.

Reference	Gamma ray energy (keV)
14	121.779±0.006
	344.24 ±0.05
15	121.79 ±0.03
	244.84 ±0.20
	344.37 ±0.60
16	121.78 ±0.05
18	122.31 ±0.04*
	244.64 ±0.08
	344.34 ±0.23

* A revised value for the 122 keV gamma ray is given in ref. 15; it is quoted as 121.87±0.06 keV.

TABLE 4

A comparison of measurements of the energies of ^{152}Eu gamma rays (units: keV).

This work	Ref. 19	Ref. 20
121.780±0.004	121.78±0.03	121.77±0.01
244.693±0.010	244.66±0.03	244.68±0.02
295.934±0.038	295.97±0.07	295.95±0.14
344.267±0.010	344.31±0.03	344.27±0.03
411.071±0.032	411.13±0.05	411.12±0.06
443.924±0.085	443.98±0.05	443.96±0.10

We were able to make energy measurements on three of these gamma rays and were able to detect the presence of a forth one, but we were not able to find any evidence for three of these weak gamma rays (table 8).

^{155}Eu: All of the ^{155}Eu gamma rays which we have studied have been studied previously with curved-crystal spectrometers[15,29]). A summary of the results obtained in these previous investigations is given in table 9. The two measurements reported by Alexander[29]) were reported without any estimation of the uncertainties associated with them.

TABLE 5

Previous measurements of the energies of gamma rays occurring in the decay of ^{153}Sm using curved-crystal and beta spectrometers.

Reference	Gamma ray energy (keV)
18	103.27 ±0.02
21	69.672±0.006
22	69.66 ±0.02
	103.18 ±0.04
23	69.66 ±0.02
	97.42 ±0.04
	103.17 ±0.04
24	103.175±0.004
25	69.675±0.002
	103.181±0.003
26	69.676±0.007
	103.180±0.010
27	54.19 ±0.02
	69.68 ±0.01
	75.43 ±0.01
	83.37 ±0.02
	89.49 ±0.02
	97.45 ±0.02
	103.19 ±0.02

TABLE 6

Previous measurements of the energies of gamma rays occurring in the decay of ^{154}Eu using curved-crystal and beta spectrometers.

Reference	Gamma ray energy (keV)
15	123.07±0.04
	248.08±0.15
17	123.06±0.03
18	123.54±0.09*

* A revised value is given in ref. 15; it is quoted as 123.21± ±0.04 keV.

TABLE 7

A comparison of measurements of the energies of ^{154}Eu gamma rays (units: keV).

This work	Ref. 19	Ref. 28
123.070±0.004	123.10±0.03	123.14±0.04
247.939±0.008	247.92±0.03	248.04±0.04
444.443±0.073	444.34±0.07	444.40±0.05
591.814±0.038	591.71±0.04	591.74±0.05
692.48 ±0.15	692.42±0.06	692.41±0.05
723.430±0.075	723.27±0.04	723.30±0.04
756.919±0.062	756.82±0.05	756.87±0.05
873.236±0.076	873.21±0.05	873.19±0.05
996.00 ±0.22	996.30±0.05	996.32±0.04
1004.57 ±0.18	1004.78±0.05	1004.76±0.04
1274.69 ±0.06	1274.42±0.05	1274.45±0.09

TABLE 8

Results of investigation of some weak low energy ^{154}Eu gamma rays reported by Meyer[28]).

Energy (relative intensity) Ref. 28	Energy This work
125.39 keV (70)	not observed
128.4 keV (≤ 100)	not observed
129.5 keV (140)	not observed
131.58 keV (110)	131.570±0.035 keV
134.84 keV (72)	observed; too weak to measure
146.05 keV (260)	146.035±0.025 keV
156.19 keV (100)	156.31 ±0.10 keV

TABLE 9

Previous measurements of the energies of gamma rays occurring in the decay of ^{155}Eu using a curved-crystal spectrometer.

15	45.29±0.01
	60.00±0.02
	86.54±0.01
	105.32±0.03
29	58.00
	86.05

TABLE 10

Previous measurements of the energies of gamma rays occurring in the decay of ^{156}Eu using curved-crystal spectrometers.

Reference	Gamma ray energy (keV)
15	88.97 ±0.01
	199.19 ±0.06
25	88.967±0.002
	199.216+0.005
30	88.974+0.011
	199.24 ±0.05

TABLE 11

Previously reported measurements of the energy of the 139 keV gamma ray occurring in the decay of ^{193}Os.

Reference	Gamma ray energy (keV)
32	138.96 ±0.02
33	138.887±0.007
34	138.95 ±0.05
35	138.92 ±0.05

^{156}Eu: Both of the ^{156}Eu gamma rays which we have studied have been previously studied with curved-crystal spectrometers and the previous results are presented in table 10 [15,25,30]).

^{170}Tm: Measurements of the energy of the 84 keV gamma ray occurring in the decay of ^{170}Tm using curved-crystal spectrometers have been made by other groups. Day[31]) reported a value of 84.229±0.041 keV. Hatch and Boehm[15]) obtained a value of 84.26± ±0.01 keV, and Marklund and Lindström[14]) give a value of 84.262±0.004 keV.

^{191}Os: There have been no reported curved-crystal spectrometer studies of the gamma rays accompanying the decay of ^{191}Os. Mazets and Sergeenkov[32]) have measured the energies of the same two gamma rays that we have studied. They utilized a prism-type beta spectrometer and obtained the following results: 82.52±0.03 keV and 129.41±0.01 keV.

^{193}Os: No curved-crystal spectrometer measurement of the energy of the 139 keV gamma ray occurring in the decay of ^{193}Os has been reported previously. Several energy measurements using beta spectrometers have been obtained, however, and these results are given in table 11 [32–33]).

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Note added in proof

A study of the gamma rays associated with the decay of ^{165}Dy has recently been undertaken in this laboratory by Ludington[36]). His curved-crystal spectrometer measurements for five of the strong transitions are as follows: 94.692±0.003 keV, 279.759±0.015 keV, 361.670±0.018 keV, 633.432±0.060 keV and 715.345±0.076 keV.

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