Precision Measurement of the γ-Ray Energies from the Radioactive Decay of ^{51}Cr, ^{169}Yb, ^{170}Tm, ^{192}Ir and ^{203}Hg

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The energies of the γ-rays from radioactive decay of ^{51}Cr, ^{169}Yb, ^{170}Tm, ^{192}Ir and ^{203}Hg have been measured relative to the 411.794 keV standard from the decay of ^{198}Au with relative accuracies between 4×10^{-7} and 4×10^{-6}.

1. Introduction

Modern X- and γ-ray spectroscopy with germanium or silicon detectors has been developed to such a level of performance [1, 2] that the energy uncertainty of the calibration lines becomes comparable with the accuracy of the measurement itself. Therefore it is desirable to have a consistent set of γ-rays whose energies have been measured with an accuracy such that the uncertainties can be neglected during spectroscopic studies with solid state counters. For most of the cases very precise relative energies are sufficient.

For the precision measurement of relative X- and γ-ray energies a curved crystal spectrometer with an interferometric angle measuring system has been built [3] and successfully used for very accurate measurements [3] of the energies of γ-rays from the radioactive decay of ^{199}Au, ^{182}Ta and ^{183}Ta. For these measurements the γ-line from the decay of ^{198}Au was used as standard: $E\gamma = 411.794 \pm 0$ keV. This line was also used as standard in the present work.

2. Experimental Method

The measurements were carried out with our diffractometer. A brief description of the instrument and the measuring procedure as well as the reduction of the data has been given elsewhere [3]. The sources were produced at the reactor FRJ-2 and had activities ranging from 0.5 – 10 Ci which was sufficient to produce intense reflections even in higher orders and for weak γ-lines.

As outlined in detail earlier [3], each source consisted of the probe to be measured and of a ^{198}Au-foil providing the standard. For several runs ^{169}Yb was used as secondary standard because of the convenience of its longer half life. Up to eight reflections including at least two of the standard were measured under positive and negative Bragg angles consecutively about 10 – 20 times in one run. Several runs including in general different γ-rays of the probe were taken for each source. The data obtained in this way were split in sub-sets each of which was completely analyzed. Because of the sufficiently large number of sub-sets and the measurements in different orders of reflection, a statistical analysis of the data was possible and the errors were calculated from the scattering of the individual results.

Table 1. Energies E_r of the γ-rays from the radioactive decay of ^{169}Yb measured relative to the 411.794 ± 0 keV γ-ray from the decay of ^{198}Au. The energy errors dE_r include the measurement error of the line E_r and the error of the measurement of the gold line; they do not include the absolute energy error of ±7 eV of the 411.794 keV γ-ray. The energies E_c were obtained as the best values resulting from a fit of the E_r-values into the level scheme by means of the combination principle. The errors dE_c are the corresponding errors of these best values. They have not been multiplied by the quality of fit value χ (≈0.78). The last column demonstrates the over all consistency of our data.

E_r / keV	dE_r / eV	E_c / keV	dE_c / eV	$\lvert E_r - E_c\rvert$ / dE_r
63.11921	0.03	63.11921	0.03	0.10
93.61260	0.06			
109.77709	0.05	109.77710	0.05	0.20
118.18697	0.20			
130.52034	0.07	130.52035	0.06	0.14
177.20968	0.08	177.20969	0.06	0.12
197.95287	0.08	197.95292	0.06	0.63
261.07228	0.26	261.07205	0.07	0.89
307.72999	0.14	307.72988	0.06	0.79

3. Results

The resulting energies of the γ-rays emitted after the capture decay of ^{169}Yb are listed in Table 1. Note that these energies E_r are based on the 411.794 ± 0 keV gold standard. Their relative energy errors dE_r are between $4\cdot10^{-7}\,E_r$ and $2\cdot10^{-6}\,E_r$. Since the measured relative energies E_r have to obey the energy combination principle, a best value set E_c can be computed. These relative energies E_c and their errors dE_c together with E_r (93.6 keV) and E_r (118.1 keV) and the respective errors dE_r of the latter two γ-rays form the set of ^{169}Yb γ-ray energies based on the gold standard and recommended as calibration lines for solid state counter work.

The relative energy of the 84 keV line from the decay of ^{170}Tm is given in Table 2 where our result is also compared with previous values which were adjusted to the gold standard and which are in good agreement with our result except for the energy given in Reference [5].

Table 2. Energy of the γ-ray from the decay of ^{170}Tm measured relative to the 411.794 ± 0 keV gold standard.

Reference	Energy (keV)	Rel. Error (eV)	Absol. Error (eV)
4	84.253		3.0
1	84.254		3.0
5	84.25168	0.38	1.5
Present data	84.25265	0.13	1.4

Table 3. Energy of the γ-ray from the decay of ^{51}Cr relative to the gold standard.

Reference	Energy (keV)	Rel. Error (eV)	Absol. Error (eV)
6	320.077		8.0
Present data	320.0761	0.4	5.5

Table 3 includes our result on the relative energy of the 320 keV γ-line from the decay of ^{51}Cr. The other value taken from Ref. [6] is in excellent agreement with our very precise result.

Our result of the measurement of the relative energy of the 279 keV γ-line from the decay of ^{203}Hg is shown in Table 4. The other data, in particular the result from Ref. [6], are in very good agreement with our value.

Table 4. Energy of the γ-ray from the decay of ^{203}Hg relative to the gold standard.

Reference	Energy (keV)	Rel. Error (eV)	Absol. Error (eV)
7	279.185		10
1	279.188		6
6	279.189		6
Present data	279.1897	1.0	4.9

Table 5 is a summary of the results of the present measurement of the strongest γ-line energies from the decay of ^{192}Ir and of the corresponding results of six other groups. The agreement with the old data given in Ref. [8] is good, that with other recent results is very good. A more detailed comparison with the energies determined by other authors [9, 5, 2] is given in Table 6 which also contains our best values E_c and their uncertainties dE_c, which again have not been multiplied by χ (≈ 0.72). The agreement between the different sets is clearly better than expected on the basis of statistical errors.

Table 5. Energies E_r of the γ-rays from the decay of ^{192}Ir relative to the gold standard. The first set of data is the result of the present measurement. The other six sets have been obtained by other authors in previous measurements. The set obtained by Bergvall and given relative to the energy of the Kα_1-line of tungsten was normalized against 411.794 ± 0 keV with the use of Bergvall's data given in Ref. 8 and our ratio of the energies of the Kα_1-line of tungsten [10] and of the gold line: 59.31785/411.79400. The other data were normalized on the 411.795 keV value for the gold line and have been adjusted to the presently accepted value 411.794 keV. Note that the energies from Ref. 9 are based on internal conversion data only.

Present measurement		Ref. 8		Ref. 9		Ref. 1		Ref. 6		Ref. 2		Ref. 5	
E_r/keV	dE/eV	E_r/keV	dE/eV	E_r/keV	dE/eV	E_r/keV	dE/eV	E_r/keV	dE/eV	E_r/keV	dE/eV	E_r/keV	dE/eV
136.3403	0.7					136.339	5					136.3398	0.5
295.9510	0.5	295.955	21	295.939	9	295.949	6	295.951	5	295.949	4	295.9484	1.0
308.4473	2.2	308.439	22	308.434	10	308.445	7	308.450	6	308.444	5	308.4464	1.1
316.5005	0.3	316.503	20	316.490	10	316.497	7	316.500	5	316.496	5	316.4979	1.0
416.4601	3.0											416.4515	5.0
468.0602	0.6	468.073	50	468.054	14	468.062	10					468.0514	3.0
588.5730	4.0	589.148	230	588.567	17	588.572	12			588.566	8	588.550	7.6
604.3981	2.2	604.520	240	604.389	17	604.401	12			604.393	8	604.395	8.0
612.4513	2.6	612.753	250	612.442	17	612.450	13			612.445	8	612.445	9.0
201.3061	0.7	201.284	20										
205.7909	0.6	205.797	21										
374.4757	0.8												
484.5646	1.8					484.570	11						

Table 6. Comparison of the most accurate energies of the decay γ-lines of ^{192}Ir. The first three sets E_r' are obtained from the data E_r given in Ref. 9, 2 and 5 by a weighted fit to our experimental data, the fourth set. The degree of agreement between these three adjusted sets and our set is expressed for each energy by $q_{min} = (E_r - E_r')/(dE_r^2 + dE^2)^{1/2}$, where dE_r is the error of the present measurement and dE is the error of the previous measurements [9, 2, 5]. The very good agreement is remarkable and demonstrates the consistency of the different sets. The best values $E_c \pm dE_c$ were computed in the same way as outlined in the caption of Table 1. The last column shows the consistency of our set.

Ref. 9 E_r' keV	q_{min}	Ref. 2 E_r' keV	q_{min}	Ref. 5 E_r' keV	q_{min}	Present data E_r keV	dE_r eV	E_c keV	dE_c eV	$\lvert E_r - E_c \rvert / dE_r$
				136.34107	−0.90	136.3403	0.7	136.3400	0.65	0.47
295.9456	0.59	295.9520	−0.25	295.95115	−0.16	295.9510	0.5	295.9510	0.48	0.13
308.4409	0.62	308.4471	0.04	308.44927	−0.80	308.4473	2.2	308.4491	0.89	0.81
316.4971	0.33	316.4992	0.25	316.50084	−0.37	316.5005	0.3	316.5005	0.30	0.02
				416.45537	0.81	416.4601	3.0	416.4616	2.41	0.49
468.0645	−0.31			468.05575	1.44	468.0602	0.6	468.0600	0.56	0.30
588.5802	−0.41	588.5719	0.12	588.55547	2.04	588.5730	4.0	588.5704	2.45	0.65
604.4026	−0.26	604.3991	0.12	604.40062	−0.30	604.3981	2.2	604.3996	0.79	0.66
612.4558	−0.26	612.4512	0.02	612.45070	0.06	612.4513	2.6	612.4510	0.56	0.13

4. Conclusion

Through the results of the present experiment and the data reported elsewhere [3] the standards recommended by Lederer, Hollander and Perlman in their Tables of Isotopes [11] have been improved in relative accuracy by factors between 7 and 120.

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