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Precision Measurement of γ-Ray Energies from the Decay of ^{57}Co, ^{60}Co, ^{137}Cs, ^{152}Eu, ^{153}Sm and ^{198}Au

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Energies of γ-rays from the radioactive decay of ^{57}Co, ^{60}Co, ^{137}Cs, ^{152}Eu, ^{153}Sm and ^{198}Au have been measured relative to the 411.794 keV γ-ray standard from the decay of ^{198}Au. The relative accuracy of the measurement is between 1.7×10^{-5} and 1.0×10^{-5} for $E_\gamma < 900$ keV.

1. Introduction

The present work is the second half of a series of extended measurements which were carried out with the aim to provide a set of very accurately measured γ-rays most of which are frequently used for the calibration of Ge(Li) detectors. As in the previous part of our work [1] the 411.794 keV γ-ray from the decay of ^{198}Au was used as standard.

Sources of ^{57}Co, ^{60}Co and ^{137}Cs are part of the set of standard γ-ray sources. The radioisotope ^{152}Eu is becoming more and more interesting both for energy- and efficiency [2] calibrations of Ge(Li) spectrometers. The lines of ^{153}Sm were measured because they provide a set of close lying calibration lines in the K-X-ray-lines region of the heavy elements. The 675 keV line of ^{198}Au is of interest for a more comprehensive work [3] which is being performed in order to arrive at a rather complete set of very accurately measured γ-rays for calibration purposes.

2. Experimental Method

The measurements were carried out with an interferometric curved crystal spectrometer. The instrument, the measuring procedure and the data reduc-

Table 1. Energies E_r of γ-rays from the radioactive decay of different sources measured relative to the 411.794 ± 0 keV γ-ray from the decay of ^{198}Au. The energy errors dE_r include the measurement errors of both the line E_r and of the standard; 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 schemes by means of the combination principle. The errors dE_c are the corresponding errors. The ratios $|E_r - E_c|/dE_r$ demonstrate the consistency of our results. The energies listed in the last two columns serve for a comparison with previous data.

Radioactive source	E_r keV	dE_r eV	E_c keV	dE_c eV	$\|E_r - E_c\|/dE_r$	E_γ keV	dE eV	Ref.
			14.41266	0.32				
^{57}Co	122.05826	0.12				122.063	4	7
	136.47089	0.30				136.473	4	
^{60}Co	1173.210	6				1173.208	25	7
	1332.470	7				1332.483	46	12
^{137}Cs	661.6492	5.2				661.638	19	7
^{152}Eu	121.7793	0.3	121.7793	0.3	0.00	121.78	30	
	244.6927	0.8	244.6927	0.8	0.00	244.66	30	
	344.2724	1.7				344.31	30	
	367.779	4	367.780	5	0.27			10
	411.107	7	411.111	8	0.57	411.13	50	
	443.979	6	443.979	6	0.00	443.98	50	
	778.905	13	778.890	9	1.15	778.87	50	
	964.007	35	964.014	34	0.20	964.01	50	
			1085.793	34		1085.83	70	
			1407.993	35		1408.02	50	
^{153}Sm	69.67161	0.14	69.67164	0.10	0.21	69.6712	0.5	
	75.42081	0.31	75.42066	0.17	0.49	75.4208	0.7	
	83.36551	0.23	83.36554	0.14	0.13	83.3652	0.5	13
	89.48416	0.27	89.48420	0.15	0.15	89.4824	0.7	
	97.42920	0.26	97.42909	0.16	0.43	97.4283	0.7	
	103.17804	0.21	103.17811	0.13	0.34	103.1774	0.7	
	172.85133	1.63	172.84970	0.14	1.00	172.8550	5.0	
^{198}Au	675.8727	3.8				675.871	4	5

tion and evaluation have been described in detail elsewhere [4, 1]. The ^{57}Co and ^{60}Co sources had activities of 20 mCi and 2 Ci, respectively. The ^{137}Cs source was purchased from Amersham Buchler. Its strength was 100 mCi. The sources of ^{152}Eu, ^{153}Sm and ^{198}Au were produced at the Merlin reactor of the Kernforschungsanlage Jülich. Their activities were of the order of 5 Ci, 4 Ci, and 10 Ci respectively.

3. Results

The results of our measurements are listed in the columns 2 and 3 of Table 1. The γ-ray energies $E_c \pm dE_c$ are based on all of the γ-rays $E_r \pm dE_r$ of one nuclide and the combination principle so that these values $E_c \pm dE_c$ are recommended as calibration line energies. If the combination principle cannot be applied, which is the case for the listed lines of ^{57}Co, ^{60}Co, and ^{137}Cs, the 344 keV line of ^{152}Eu and the 675 keV line of ^{198}Au, the energies $E_r \pm dE_r$ should be used.

A comparison of the measured relative energies E_r with the fitted energies E_c shows that our results are intrinsically consistent (see column 6 of Table 1). Data from other groups and our preliminary result [5] on the 675 keV line are given in the last two columns.

Our relative energies of the lines from the decay of ^{57}Co have an accuracy which has been improved by more than one order of magnitude in comparison with the previous results [6] and the Ge(Li)-data [7]. Because of the strong absorption in the 4 mm thick quartz crystal and the limited angular range of the spectrometer the 14.4 keV γ-line was not accessible to direct measurement. Its energy can, however, be obtained through the application of the combination principle as

$$14.41266 \text{ keV} \pm 0.32 \text{ eV}$$

for $E_r \pm dE_r$. It is in good agreement with the results of Heim and Schult [6]: 14.4147 keV ± 2.5 eV, of Beaden [8]: 14.4125 keV (with a relative error which is probably around $2 \cdot 10^{-5}$), of Konijn and Lingemann [9]: 14.408 keV ± 5 eV, and of Helmer, Greenwood and Gehrke [7]: 14.410 keV ± 6 eV.

Our relative energies of the two γ-rays following the β-decay of ^{60}Co are also much more accurate than the published data. A few comments should be made to explain our quoted errors. 1) These errors correspond to an accuracy in the measurement of the peak position to $\sim 3/1000$ of the FWHM in the fifth order of reflextion. In general, very small asymmetries of the line shapes as are routinely obtained at Ge(Li) measurements imply systematic errors which are larger. At a curved crystal spectrometer, however, the asymmetry of the reflection

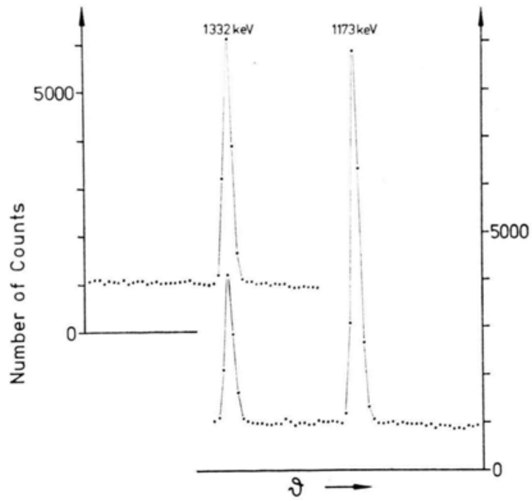

Fig. 1. Second order reflection of the 1.17 and 1.33 MeV lines and background regions recorded with large angular steps in order to determine the slope of the background underneath the peaks. The lower right part was measured with the single channel discriminator set on the 1.17 MeV line and the upper left part was recorded with another single channel discriminator set on the 1.33 MeV transition. Such measurements were also performed for the other orders of reflections and for all other sources.

at the positive Bragg angle is the same as at the negative Bragg angle, and since the angular difference is measured, the asymmetry does not affect the energy determination. 2) Great care must be exercised to correct for background slopes. For this reason, a separate measurement was carried out where the region around the Bragg reflections of the ^{60}Co lines was measured (see Figure 1). This spectrum yields a small slope of the background which causes a line shift of about 4 eV which has been corrected for. 3) Systematic errors of the spectrometer might lead to small displacements of the reflections [4]. Therefore, the lines were measured in the third and fifth order of reflections. The energy error dE of a γ-line measured at a crystal spectrometer is generally proportional to E_γ^2/n, where n is the order of reflection. Lines with smaller energies can, therefore, be measured with much better accuracies dE, in particular, if they are recorded in high order reflection.

The results were corrected for background slope and the relative energies, based on 411.794 are

1173.210 ± 0.009	in third order reflection,
1173.210 ± 0.006	in fifth order reflection,
1332.462 ± 0.007	in third order reflection,
1332.475 ± 0.007	in fifth order reflection.

For the calculation of the mean energies we have used weight 3 for the third order reflection and weight 5 for the fifth order reflection. This is reasonable if one assumes that the systematic error of the spectrometer does not depend on the Bragg angle as long as it is small. One can then calculate the errors either from the quoted errors or from the deviations of the individual values from their weighted mean. Taking the larger error in both cases, we find the relative energies listed in Table 1. Their agreement with the previous results and the old data by Murray, Graham, and Geiger is very good.

Also in the case of the ^{137}Cs line a significant improvement in energy accuracy has been achieved. The previous value is in very good agreement with our result.

Our data on the energies of the γ-rays from the decay of ^{152}Eu have accuracies which are up to a factor of 100 higher than those of the Ge(Li) data by Aubin, Barette, Lamoureux, and Monaro [10]. A more accurate energy than obtained by these authors for the 121 keV line had already been measured [11] ten years ago, namely 121.784 ± 7 eV. With the use of the combination principle we are able to determine rather accurate γ-ray energies also for the 1086 and 1408 keV lines. These energies $E_c \pm dE_c$ are contained in Table 1.

The relative energies of the ^{153}Sm lines had been measured with very high accuracy already by Mühlbauer [13] using the automatized Riso spectrometer [14]. During his measurements the spectrometer [14] had been calibrated with the Kα Röntgen line energies given by Bergvall [15] with an absolute energy accuracy around 1.5×10^{-5} in total.

Apart from Mühlbauer's 89.4 keV line energy which is less by 1.8 eV (i. e. 2×10^{-5}) than our result and his 172 keV line energy which is larger (by 5.3 eV) than ours, very good agreement is observed between both sets of data. This is, in particular, true if his set is reduced in energy by a common scaling factor of about 6×10^{-6}. Therefore, one has to conclude that Bergvall's energies are fully consistent with the present data within his quoted errors [15].

Our new result for the energy of the 675 keV gold line is in full support of our preliminary [5] energy. It is interesting to note that the best figure for the energy distance between this gold line and the ^{137}Cs line is given as 14.229 ± 0.003 keV [7]. Adding this energy to our energy of 675.8727 ± 0.0038 we obtain 661.6437 ± 0.0050 in relative energy units. This figure is in complete agreement with our measured energy of 661.6492 ± 0.0052.

4. Conclusion

The relative energies reported in this work as well as those given previously [5, 1] form a complete set for a very accurate relative energy calibration of Ge(Li)- and other γ-ray-spectrometers. It should be kept in mind that all of these energies are based on the value of 411.794 keV for the gold line. Very recent results show, however, that the absolute energy of the gold line has to be increased somewhat [16–18]. This is important in all cases where absolute energies are required with accuracies better than 2×10^{-5}.

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