Evaluation of the relative γ-ray intensities emitted from ^{56}Co and ^{66}Ga

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Abstract ^{56}Co and ^{66}Ga with γ-ray energies covering the range of 0.84–3.55 and 0.68–4.81MeV, respectively, are important radionuclides for Ge detector calibration. The newly evaluated relative γ-ray intensities were recommended using the measurements finished after 2000 year by Baglin and Browne in 2004. In 2005 China groups measured the relative γ-ray intensities. The China measurements were about 2% systematically lower than other measurements and these evaluations. In this paper the discrepancies among these measurements and the evaluations are analyzed carefully and the new evaluations are re-recommended.

Key words Evaluation, γ-ray intensities, Ge detector, ^{56}Co, ^{66}Ga

1 Introduction

To calibrate efficiency of a Ge detector in energy range of up to 6 MeV, a reliable standard with known γ-ray emission probabilities is needed. Above 2754 keV, it is relatively hard to find radionuclides suitable for efficiency calibrations. A moderate extension of the calibration to 3548 keV can be achieved using a ^{56}Co source produced by ^{56}Fe(p,n) reaction. Extending the efficiency curve to 4807 keV can be achieved with a ^{66}Ga source produced by ^{66}Zn(p,n) reaction. For precise efficiency calibration in high energies with the two sources, however, it is not reasonable to used the relative γ-ray intensities evaluated and recommended from the measurements before 2000 by Camp D C, *et al*[1] and Phelps M E, *et al*[2]. In 1975, McCallum G J, *et al*[3] found that the relative γ-ray intensities of high-energy γ-rays from ^{56}Co and ^{66}Ga reported in Ref.[1] are systematically lower. The need to correct the intensity for γ-rays of E_γ =2−5 MeV was confirmed in 1996 by Schmid G J, *et al*[4], who found the calibrated detector efficiency, normalized at 6.13 MeV, using the reaction of ^{19}F(p,αγ)^{16}O disagree with the recommended relative intensities of high energy γ-rays.

The efforts since 2000 to obtain more reliable data include several measurements, in which the efficiency of Ge detector were calibrated using ^{14}N(n,γ)^{15}N reaction in high energies, by Raman S, *et al*[5], Molnar G, *et al*[6], and Baglin C M, *et al*[7]. And Baglin C M, *et al*[8] and Browne C M[9] analyzed and evaluated the relative intensities for ^{56}Co and ^{66}Ga γ-rays, respectively. Ref.[8] came up with a correction factor of $F(E_\gamma)= 1.116(11)–0.155(11)E_\gamma+0.0397(22)E_\gamma^2$ to correct the measured detector efficiency in Ref.[1].

In China, the problem of detector calibration efficiency in high energies was noted, too. The experiments in 2005 for precise relative γ-ray intensities for ^{56}Co and ^{66}Ga revealed that the measured values were about 2% systematically lower than other measurements, including the recent evaluations by Baglin C M *et al*[8] and Browne E[9] in 2004. In the present work, we analyzed carefully the discrepancies among the measurements and evaluations. Based on this analysis and comparison, new evaluations of the relative γ-ray intensities for ^{56}Co and ^{66}Ga are re-recommended.

2 Status of the relative γ-ray intensities

The relative intensities for ^{56}Co and ^{66}Ga measured after 2000 are listed in Table 1. It is noted that the measurements of high energy ^{56}Co γ-rays in present work are about 2% lower than other measurements in

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range. And the measurements of in Ref.[5] are also systematically lower than in Refs.[6] and [7]. In low energy range, all the measurements are in good agreement with each other.

Table 1 Measured relative intensities for ^{56}Co and ^{66}Ga γ-rays (in keV)

^{56}Co E_γ	Ref.[5]	Ref.[6]	Present work	^{66}Ga E_γ	Ref.[6]	Ref.[5]	Ref.[7]	Present work
846.8	100.0	100.0(2)	100.0(5)	833.6	15.92(6)	16.02(24)	15.94(14)	15.85(17)
1037.8	14.11(22)	14.07(5)	14.15(8)	1039.4	100.0(3)	100.0(16)	100.0(9)	100.0(5)
1175.1	2.25(4)	2.252(10)	2.26(2)	1333.2	3.171(13)	3.17(5)	3.20(3)	3.15(2)
1238.3	66.6(10)	66.20(17)	66.26(26)	1918.8	5.360(23)	5.33(8)	5.44(6)	5.36(4)
1360.2	4.23(7)	4.22(15)	4.26(3)	2189.9	14.39(6)	14.54(21)	14.50(13)	14.12(12)
1771.4	15.42(25)	15.24(8)	15.36(9)	2422.9	5.072(24)	5.12(8)	5.15(6)	5.17(4)
2015.2	3.03(5)	2.976(15)	3.02(2)	2752.3	61.34(26)	61.2(8)	61.5(6)	60.80(40)
2034.8	7.835(120)	7.69(3)	7.79(5)	3229.2	4.087(22)	4.06(8)	4.07(4)	4.00(6)
2598.5	17.1(3)	16.82(8)	16.62(12)	3381.4	3.950(23)	3.96(8)	3.99(4)	3.83(4)
3202.0	3.16(6)	3.196(18)	3.16(3)	4086.5	3.455(20)	3.38(8)	3.42(4)	3.36(5)
3253.4	7.815(160)	7.85(4)	7.62(6)	4806.6	5.04(3)	4.93(11)	5.00(7)	4.99(8)
3273.0	1.84(4)	1.854(13)	1.82(2)	–	–	–	–	–
3451.2	0.93(3)	0.94(1)	0.919(10)	–	–	–	–	–

After a careful analysis of the experimental data, we think that the systematic discrepancies among the measurements may be due to different detector efficiency curve.

All the data were obtained using Ge detectors. In the energy region of 100–2754 keV, primary standard radioactive sources with well-known activities were used to calibrate absolute efficiencies of the Ge detectors, and all the measurements are in good agreement with each other. Above 2754 keV, there are two methods for calibrating the detector efficiency curve. In present work, the efficiency curve was obtained by the calculated results using the EGS4 M-C code and normalized to the efficiency at 2.754 MeV. Rationality of the calculated efficiency was validated by experimental data at low energy region, and it agreed perfectly with the efficiency at 6.13 MeV was determined by the ^{19}F(p, αγ)^{16}O reaction, while in Refs.[5–7], the ^{14}N(n,γ)^{15}N reaction was used to calibrate the detector efficiency curve. Further analysis found that different authors adopted different γ-ray emission probabilities of ^{14}N(n,γ)^{15}N reaction in calibrating the detector efficiency curve. In Refs.[6,7], γ-ray emission probabilities measured by Kennett T J, *et al*[10] were used, whereas in Ref.[5] γ-ray emission probabilities averaged from measurements of Refs.[10,11] were used.

3 Standard γ-ray emission probabilities for ^{14}N(n,γ)^{15}N reaction

Measurements of γ-ray emission probabilities for ^{14}N(n,γ)^{15}N reaction were done mainly by the groups in Refs.[10–13]. These measurements differ mainly in the level scheme they used. For example, 15, 19, 19 and 17 levels, and 28, 58, 64 and 55 γ-rays, were used in Refs.[10–13], respectively. In Fig. 1, the γ-ray emission probabilities in Refs.[10–13] are compared. Although the measurements of Refs.[12,11] agree well in 1.7–6 MeV (Fig.1a), the ratio of the γ-ray emission probabilities for Ref.[10]/Ref.[11] and Ref.[13]/Ref.[11] are exactly reverse (Fig.1b). From Fig.1c, one sees that the measurements of Ref.[10] are 1.2%–3.7% higher than Ref.[11] in 2.5–4 MeV and 6–8 MeV regions. Therefore, it is not suitable to use the averaged measurements as a standard for detector efficiency calibration.

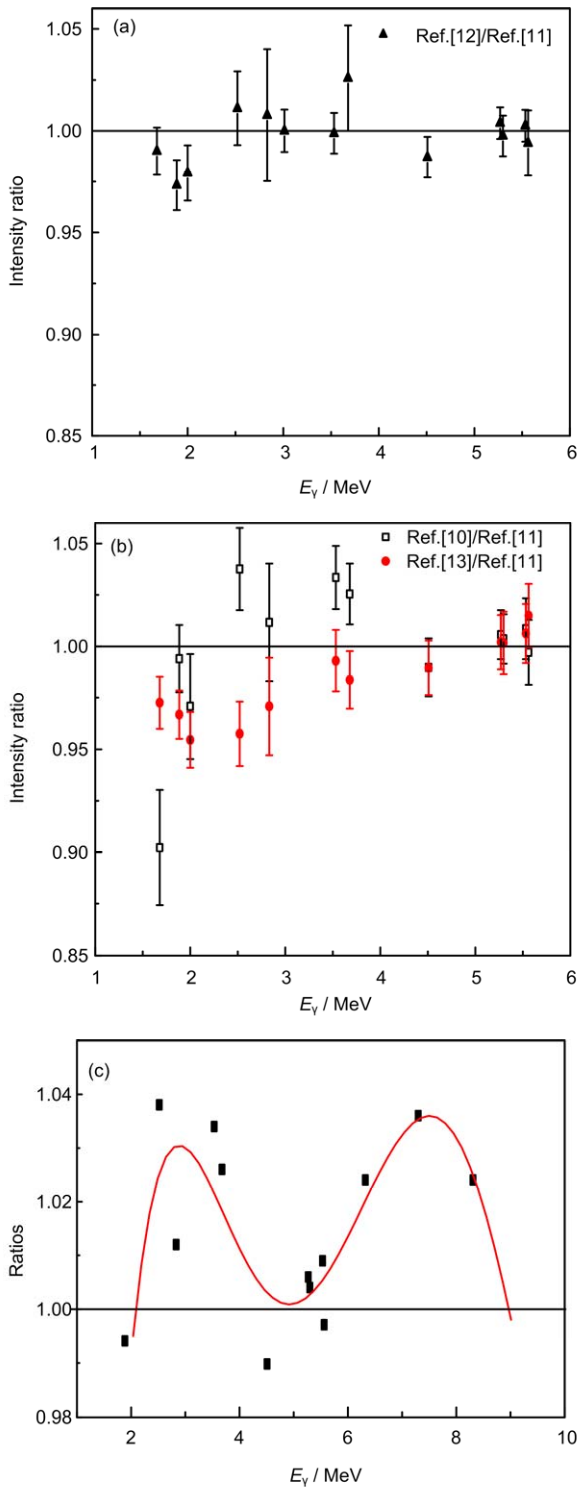

Fig.1 Ratio of measured I_γ as a function of γ-ray energy (a). The ratio of measured I_γ as a function of γ-ray energy (b). The ratio of measured I_γ of Kennett to Jurney as a function of γ-ray energy (c).

About 58 γ-rays were observed in Ref.[11], but only 30 γ-rays in Ref.[10]. For keeping the intensity balance ($\sum I_{\gamma(\text{in-out})}$), the measured γ-ray emission probabilities of Ref.[10] should be higher than Ref.[11], hence the better γ-ray emission probabilities of Ref.[11], in which the level scheme is more reasonable and complete.

Molnar G, *et al*[6] calibrated the detector efficiency curve using ^{14}N(n,γ)^{15}N reaction. Their γ-ray emission probabilities were from the measurements of Ref.[10]. Raman S, *et al*[5] did so with the ^{14}N(n,γ)^{15}N reaction, but averaged γ-ray emission probabilities from measurements of Refs.[10,11] were used. So it is necessary to correct the measurements of Refs.[5,6] above 2.5 MeV.

In the present work the level scheme suggested in Ref.[11] is adopted to correct the γ-rays intensities of ^{56}Co and ^{66}Ga.

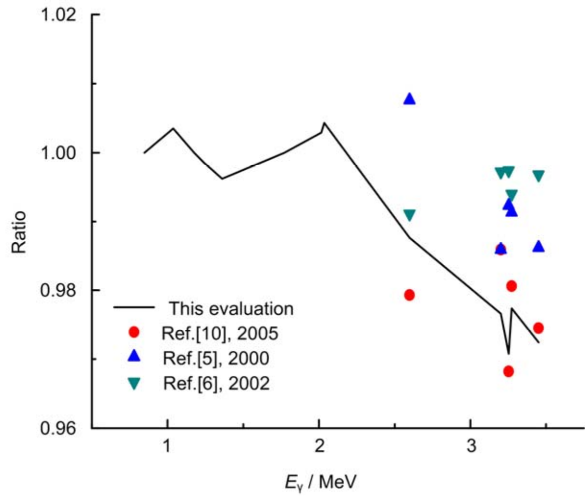

Fig.2 Comparison of the evaluations of Ref.[8] to the newly measured data and the present evaluation for ^{56}Co.

As mentioned above, the measurements above 2.5 MeV in Refs.[5,6] should be corrected using γ-ray emission probabilities in Ref.[11]. This was done, the modified values for ^{56}Co are listed in Table 2, and the systematic deviation among the modified measurements of Refs.[5,6] is not existed. The measurements of present work are in good agreement with the modified values of Refs.[5,6] within 1%.

Above 2.5 MeV, the evaluation was obtained from the unweighted average of the measurements of Refs.[5,6] (the measurements before 2000 are rejected due to the present knowledge of detector efficiency curve). Fig.3 shows the comparison of the present evaluations to the modified measurements of Refs.[5,6,8]. The measurements and evaluated values of relative γ-ray intensities for ^{56}Co are given in Table 2.

Table 2 Comparison of measured and evaluated relative intensities for ^{56}Co γ-rays (in keV)

E_γ	Measurements								Evaluations				
	Ref.[1]	Ref.[16]	Ref.[17]	Ref.[18]	Ref.[19]	Ref.[20]	Ref.[21]	Ref.[22]	Ref.[5]	Ref.[6]	Present work	Present work	Ref.[8]
846.8	100.0(10)	100.0(15)	100.0(11)	100.0(10)	100.0(6)	100.0(3)	100.0(13)	100.0(7)	100.0	100.0(2)	100.0(5)	100.0	100.0
1037.8	14.24(14)	13.7(6)	13.922(116)	14.04(14)	13.5(2)	14.16(5)	14.11(19)	14.0(1)	14.11(22)	14.07(5)	14.15(8)	14.09(3)	14.04(5)
1175.1	2.300(25)	2.3(1)	2.180(24)	2.28(2)	2.11(10)	2.241(12)	2.30(32)	2.28(2)	2.25(4)	2.252(10)	2.26(2)	2.253(6)	2.250(9)
1238.3	67.64(68)	66.2(10)	66.37(74)	66.4(7)	65.1(4)	66.06(21)	68.47(87)	67.6(4)	66.6(10)	66.20(17)	66.26(26)	66.27(18)	66.45(16)
1360.2	4.340(45)	4.4(1)	4.189(52)	4.24(4)	4.24(15)	4.265(21)	4.32(6)	4.33(4)	4.23(7)	4.22(15)	4.26(3)	4.273(3)	4.283(13)
1771.4	15.78(16)	15.9(3)	15.37(24)	15.65(16)	15.26(15)	15.49(5)	15.5(4)	15.70(15)	15.42(25)	15.24(8)	15.36(9)	15.45(3)	15.46(4)
2015.2	3.095(31)	3.1(1)	3.025(72)	3.09(6)	2.97(3)	3.026(17)	3.182(66)	3.08(3)	3.03(5)	2.976(15)	3.02(2)	3.019(8)	3.019(14)
2034.8	7.95(8)	7.8(1)	7.694(146)	7.95(14)	7.64(6)	7.766(32)	8.14(17)	7.89(7)	7.835(120)	7.69(3)	7.79(5)	7.758(17)	7.746(13)
2598.5	–	–	–	–	–	–	–	–	17.1(3)	16.82(8)	16.62(12)	16.77(7)	16.97(4)
3202.0	–	–	–	–	–	–	–	–	3.16(6)	3.196(18)	3.16(3)	3.185(15)	3.205(13)
3253.4	–	–	–	–	–	–	–	–	7.815(160)	7.85(4)	7.62(6)	7.75(4)	7.87(3)
3273.0	–	–	–	–	–	–	–	–	1.84(4)	1.854(13)	1.82(2)	1.844(11)	1.856(9)
	–	–	–	–	–	–	–	–	Modified values				
3451.2	–	–	–	–	–	–	–	–	0.93(3)	0.94(1)	0.919(10)	0.930(7)	0.943(6)
2598.5	–	–	–	–	–	–	–	–	17.0(3)	16.67(12)	–	16.76(12)	–
3202.0	–	–	–	–	–	–	–	–	3.12(8)	3.122(39)	–	3.134(13)	–
3253.4	–	–	–	–	–	–	–	–	7.71(20)	7.66(9)	–	7.66(3)	–
3273.0	–	–	–	–	–	–	–	–	1.817(53)	1.807(26)	–	1.815(4)	–
3451.2	–	–	–	–	–	–	–	–	0.917(37)	0.943(17)	–	0.926(8)	–

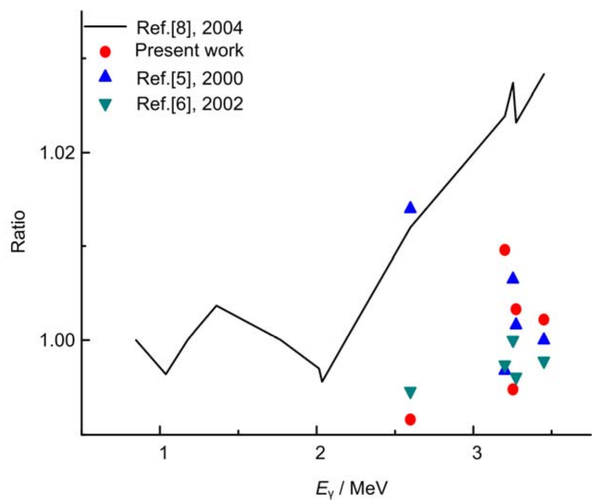

Fig.3 Comparison of the present evaluation with Ref.[8] and the modified measurements for ^{56}Co.

4 Evaluation of relative γ-ray intensities for ^{56}Co

The ^{56}Co decay data recommended previously were evaluated by Baglin[8] based on 33 measurements from 1965 to 2002. We quitted the measured values that are statistical outliers (about 11%) according to the Chauvenet criterion. Also, the measured data relying on linear extrapolations of the efficiency on a log-log plot above 3 MeV were excluded. The remaining data were processed by evaluation methods of weight average (WM), limitation of relative statistical weight average (LWM), normalized residual method (NR)[14] and Rajeval method(RA)[15]. All the measured data, except those exceeding the Chauvenet criterion value, were processed by the evaluation methods. The recommended values were decided from the processed values according to author's judgments. The final recommended data were evaluated based on all the data below 2598 keV and 8 data sets above 2598 keV.

Below 2.5 MeV, 11 measured data sets (Table 2) were adopted based on careful analysis. The present evaluation was obtained from the average of 11 measured data sets using the limitation of relative statistical weight average (LWM), and the present evaluation agrees well (within 0.4%) with Ref.[8], as shown in Fig.2, in which evaluations in Ref.[8] are compared with the new measurements above 2.5 MeV in Refs.[5,6]. One finds that the evaluation data of Ref.[8] are larger than the new measurements.

Table 3 Comparison of recent measured and evaluated relative γ-ray intensities for ^{66}Ga

E_γ / keV	Measurements				Evaluations	
	Ref.[6]	Ref.[5]	Ref.[7]	Present work	Present work	Ref.[9]
833.6	15.92(6)	16.02(24)	15.94(14)	15.85(17)	15.92(5)	15.94
1039.4	100.0(3)	100.0(16)	100.0(9)	100.0(5)	100.0	100.0
1333.2	3.171(13)	3.17(5)	3.20(3)	3.15(2)	3.17(1)	3.16
1918.8	5.360(23)	5.33(8)	5.44(6)	5.36(4)	5.37(2)	5.38
2189.9	14.39(6)	14.54(21)	14.50(13)	14.12(12)	14.37(5)	14.32
2422.9	5.072(24)	5.12(8)	5.15(6)	5.17(4)	5.10(2)	5.08
2752.3	61.34(26)	61.2(8)	61.5(6)	60.80(40)	61.22(20)*	61.35
3229.2	4.087(22)	4.06(8)	4.07(4)	4.00(6)	4.08(2) *	4.08
3381.4	3.950(23)	3.96(8)	3.99(4)	3.83(4)	3.94(2) *	3.94
4086.5	3.455(20)	3.38(8)	3.42(4)	3.36(5)	3.44(2) *	3.43
4806.6	5.04(3)	4.93(11)	5.00(7)	4.99(8)	5.02(3) *	5.03
	Modified values					
2752.3	60.60(48)	60.84(91)	60.6(9)	–	60.71(6)[b]	–
3229.2	3.989(49)	4.01(9)	3.96(7)	–	3.99(1)[b]	–
3381.4	3.847(52)	3.91(9)	3.87(7)	–	3.86(2)[b]	–
4086.5	3.406(34)	3.35(9)	3.37(5)	–	3.37(1)[b]	–
4806.6	5.06(4)	4.94(11)	4.95(7)	–	4.99(3)[b]	–

Note: "*" is evaluated based on measurements of uncorrected for detector efficiency and "b" is unweighted average

5 Conclusion

The newly recommended relative γ-ray intensities for ^{56}Co and ^{66}Ga evaluated in Refs.[8,9] and the present work show that the old standard for detector efficiency calibration has systematic errors (up to 30%) in high energies region. But the present evaluation above 2.5 MeV is lower than the evaluation of Refs.[8] and [9]. The deviation at 3.4 MeV is up to 2.7%. Rationality of the present evaluation and corrected method will be dependent upon new measurements, and more precise standard data are desirable.

The following suggestions can be obtained through the present evaluation: to calibrate the detector efficiency curve using ^{14}N(n,γ)^{15}N reaction above 2.5 MeV, the γ-ray emission probabilities from the measurements of Jurney *et al*[11] in 1997 are still good at present.

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