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GAMMA-RAY ENERGIES FOR CALIBRATION OF Ge(Li) SPECTROMETERS*

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INTRODUCTION

At the last Conference in this series, we reported (1) on our work in the comparison and measurement of γ -ray energies with multi-channel spectrometer systems using Ge(Li) detectors. Since that time two things have occurred that are pertinent to the definition of precise calibration energies. First, the 1973 adjustment of the values of the fundamental constants by Cohen and Taylor (2) can be used in place of the values of Taylor *et al.* (3) of 1969. Second, a number of new precise energy measurements have been made with bent crystal spectrometers. In this paper, we review the existing measurements and our work in this area.

ENERGY SCALES

In γ -ray spectrometry, energies have been measured commonly on two different scales. The first group of γ -ray energies has been measured with respect to the energies, or wavelengths, of the atomic x rays. These data have been (or can be) referred to the x-ray energies compiled and correlated by Bearden (4) where the energy scale is referenced to the $W\text{K}\alpha_1$ x ray. As shown in Table I the newest value of $E(W\text{K}\alpha_1)$ is down only 2.9 ppm from the 1969 value and up 13 ppm from the Bearden value (4). The reference error in this energy scale is taken to be the 5.6 ppm quoted in ref. 2 for the $W\text{K}\alpha_1$ energy.

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TABLE I
REFERENCE ENERGIES

Quantity	Value (keV)			Change (ppm)	
	1967 Bearden	1969 Taylor et al.	1973 Cohen & Taylor	67-73	69-73
$W_{K\alpha_1}$	59.31824	59.31918(35)	59.31901(33)	+ 16	- 2.9
m_0c^2		511.0041(16)	511.0034(14)		- 1.4
$^{198}\text{Au}-411$		411.794(8)	511.794(7)		

The second group of γ -ray energies have been measured with respect to a scale based on the energy equivalent of the mass of the electron, m_0c^2 . As indicated in Table I, the latest value of m_0c^2 is reduced by only 1.4 ppm from the previous value. The basic measurement on this energy scale is the single determination (5,6) of the energy of the 411-keV line from the decay of ^{198}Au relative to the m_0c^2 value as observed in positronium annihilation. For this line, the current error is 7 eV or 17 ppm which is taken to be the reference error in this scale.

Several measurements have been made to determine the consistency of the two energy scales, with varying results. This question will be discussed in another paper at this Conference (7). We have chosen not to make any adjustments between the energies measured on the two scales.

In all cases a distinction has been made between two components of the energy uncertainty: (1) the contribution from the reference energy defining the energy scale, σ_r , and (2) that from the specific measurements σ_m , and $\sigma_t^2 = \sigma_r^2 + \sigma_m^2$.

GAMMA-RAY ENERGIES

Comparison of Recent Bent Crystal Measurements

For primary calibration for our γ -ray energy measurements on Ge(Li) spectrometers, a set of precisely known γ -ray energies, measured by other techniques, was compiled. Besides having the necessary precision, only those data were included which were available with sufficient detail to allow reevaluation to correspond to the current set of fundamental constants.

Of special interest are two groups of recent precise measurements (8-11) relative to the Au-411 line made with bent-crystal (diffraction) spectrometers. Some of these new values are quoted

with very high precision; for example, $c_m = 0.06$ and 0.4 eV at 100 and 200 keV. For the energies of ^{182}Ta and ^{192}Ir a comparison is given in Table II. Of the 20 entries, the agreement is not quite within the quoted errors since 12 differences are over 1σ , five are over 2σ and three are over 4σ . At this level of precision, this agreement may be quite reasonable. However, it should be noted that for many lines the uncertainty in the discrepancy comes primarily from the work of Kern et al. (8-9) and as a result, does not indicate whether the Borchert et al. (10,11) errors are realistic.

These data also indicate that for ^{182}Ta any systematic difference is quite small while for ^{192}Ir the Borchert et al. values are larger by 5-10 ppm.

TABLE II
COMPARISON OF RECENT BENT-CRYSTAL MEASUREMENTS

Parent Isotope	Energy (keV)	Uncertainty		Difference (eV)
		Piller (8)	Borchert (10)	
^{182}Ta	65	0.2	0.15	1.1 ± 0.3
	67	0.2	0.13	1.3 ± 0.2
	100	0.3	0.06	2.7 ± 0.3
	113	1.2	0.26	-2.3 ± 1.2
	152	1.4	0.27	1.7 ± 1.4
	156	1.2	0.35	-1.6 ± 1.3
	179	1.8	0.53	0.5 ± 1.9
	198	2.2	0.44	0.6 ± 2.2
	222	2.4	0.45	-2.6 ± 2.4
	229	3.0	0.63	0.0 ± 3.1
	264	5.2	0.61	2.0 ± 5.2
^{192}Ir		Beer (9)	Borchert (11)	
	136	0.7	0.7	-0.5 ± 1.0
	295	1.5	0.5	-2.4 ± 1.6
	308	1.7	2.2	-0.6 ± 2.8
	316	1.6	0.3	-2.3 ± 1.6
	416	5.	3.0	-8.1 ± 5.8
	468	4.	0.6	-8.2 ± 4.0
	588	8.	4.0	-22.0 ± 8.9
	604	8.	2.2	-2.1 ± 8.3
	612	9.	2.6	-5.3 ± 9.4

Energy from Other Authors

Our treatment of data in the literature is illustrated for the case of ^{192}Ir . The data used here for these γ -ray energies are indicated at the bottom of Table III along with the type of instrument used and the reference line. The various energies for one line were averaged (1/ σ weighting). These average values were then used as input to a least-squares fitting program which determines the "best" level energies for the decay scheme. The "best" γ -ray energies and uncertainties were then computed from these level energies.

In addition to these γ -ray energy values, the input to this particular least-squares determination of the level energies included two γ -ray energy differences. These were our measured 588-604 and 588-612 differences. The inclusion of these differences is significant in that it increases directly the energy of the 588-keV line by 3 eV and indirectly the 416- and 884-keV energies. The average energies are quite consistent since the reduced- χ^2 of the least-squares fit is 0.60. This is in contrast to the various experiments which are somewhat inconsistent as indicated by the reduced- χ^2 values for the averages.

TABLE III
 ^{192}Ir GAMMA ENERGIES

Error (eV)	Average		Least-Squares Value (keV)	Uncertainty (eV)	
	Reduced- χ^2			Measurement	Total (Au)
0.5	0.3		136.3398	0.5	2.4
0.8	1.8		205.7903	0.8	3.6
1.3	4.4		295.9496	1.0	5.1
2.4	3.4		308.4491	1.1	5.3
1.0	4.9		316.4994	0.9	5.5
3.7	1.9		416.4602	1.4	7.2
1.3	2.2		468.0588	1.0	8.1
6.6	3.2		588.5692	1.1	10.1
2.6	0.4		604.3982	1.0	10.3
3.0	0.7		612.4485	1.0	10.5
24.0	---		884.5179	1.8	15.1

Author	Date	Ref. Line	Spectrometer	No. Energies
Murray et al. (6)	1965	Au-411	Electron	7
Daniel et al. (12)	1966	Au-411	Electron	1
Reidy (13)	1970	Au-411	Bent-crystal	5
Helmer et al. (14)	1971	--	Ge(Li)	2
Inoue et al. (15)	1973	--	Ge(Li)	1
Beer & Kern (9)	1974	Au-411	Bent-crystal	10
Borchert et al. (11)	1975	Au-411	Bent-crystal	10

In this manner we have evaluated the γ -ray energies for a number of isotopes including only bent-crystal and electron spectrometer measurements. The recent measurements (8-11) for ^{192}Ir and ^{183}Ta and the low-energy ^{182}Ta lines have been combined with earlier data and evaluated by the above methods including a least-squares fit to the level scheme. In addition to these three isotopes, we have included energies from 12 other isotopes and a total of 21 lines.

Our Measurements

The goal of our measurements of γ -ray energies has been to extend the above set of calibration energies, especially above 400 keV. All of our measurements have been made on Ge(Li) spectrometers. In a few cases, our energies have been determined simply by determining the energy of a peak from spectra calibrated with several known lines. More generally our measurements have been of the difference in energy between closely spaced lines, one of which has a "known" energy. This method is used for two reasons. First, highly accurate differences can be obtained on Ge(Li) spectrometers in spite of their inherent nonlinearity and ill-defined "zero". Second, the values of the energy differences are independent of small changes in the calibration energies and, therefore, can be updated as the primary calibration energies change.

In many cases, cascade-crossover relationships have been used to compute the energy of one of the transitions involved. In particular, two chains of energy combinations have been developed separately up to above 1 MeV as shown in Fig. 1. One chain consists of the lines from ^{192}Ir and ^{160}Tb and the other consists of ^{198}Au , ^{59}Fe and ^{182}Ta . As indicated in the figure, precise comparisons between the two chains can be made to indicate the magnitude of potential systematic errors. In computing the uncertainties in the discrepancy, the 884-keV(^{192}Ir) and 1087-keV(^{198}Au) energies have first been assumed to be exact. Thus, the first error includes only the measurement uncertainties above these points in the chains. The average discrepancy for two comparisons is (11 ± 4) eV. On the basis of this result, we might conclude that there is a small, real discrepancy between the energies of the two chains at above 1 MeV. However, if one includes the measurement errors in the 884-keV(^{192}Ir) and 1087-keV(^{198}Au) energies, the average discrepancy becomes (11 ± 12) eV. This result indicates that this discrepancy is not unreasonable compared to the magnitude of the measurement errors. The major contribution to this 12 eV measurement error is the 11 eV term from the 675-keV line of ^{198}Au .

At 1 MeV typical errors are $\sigma_m = 4$, $\sigma_r = 17$ and $\sigma_t = 17$ eV for γ rays based on the ^{192}Ir -884 line and $\sigma_m = 11$, $\sigma_r = 17$ and $\sigma_t = 20$ eV for those based on the ^{198}Au -1087 line.

Fig. 1. Gamma-ray energy differences and sums involved in going from ^{192}Ir -884 to ^{160}Tb -1177 and from ^{198}Au -411 to ^{182}Ta -1189; and the results of comparing the ^{160}Tb -1177 and ^{182}Ta -1189 energies.

COMMENTS

In summary, based on the primary calibration energies from other types of spectrometers, our energy differences and energy combinations have been used to determine the energies of 150 γ rays below 3450 keV from 35 isotopes. The energies of 79 lines below 1300 keV have been published (14,16), but these have recently been reevaluated based on the new fundamental constants and the new bent-crystal measurements.

For the above treatment of γ -ray energies, the single measurement that would be the most effective in improving the existing energies would be a more precise comparison of the energy of the 675-keV line from ^{198}Au to that of the 411-keV line of ^{198}Au .

Another significant improvement would result from a more accurate measurement of the 411-keV energy from ^{198}Au . For example, in Table III the 884-keV line from ^{198}Ir has a total uncertainty of

15 eV, but a measurement error of only 2 eV. So a very precise (error of ~ 1 eV) 411-keV energy would make a vast improvement. If this were combined with a comparable measurement of the 675-keV line of ^{198}Au , one would have both energy chains with errors at 1 MeV of a few eV.

In contrast to the last Conference, we have not discussed the techniques used in Ge(Li) spectrometry. It should only be noted that on Ge(Li) detectors the apparent energy does depend on the source position. We have reported (17) measurements on the shift of peak positions with the source-detector distance, with observed shifts as large as 100 eV for a 2000 keV γ ray.

REFERENCES

1. HELMER, R. G., GREENWOOD, R. C., and GEHRKE, R. J., Atomic Masses and Fundamental Constants 4, eds. J. H. Sanders and A. H. Wapstra, Plenum Press (London) 1972.
2. COHEN, E. R. and TAYLOR, B. N., J. Phys. Chem. Ref. Data 2 (1973) 663.
3. TAYLOR, B. N., PARKER, W. H., and LANGENBERG, D. N., Rev. Mod. Phys. 41 (1969) 375.
4. BEARDEN, J. A., Rev. Mod. Phys. 39 (1967) 78.
5. MURRAY, G., GRAHAM, R. L. and GEIGER, J. S., Nucl. Phys. 45 (1963) 177.
6. MURRAY, G., GRAHAM, R. L. and GEIGER, J. S., Nucl. Phys. 63 (1965) 353.
7. VAN ASSCHE, P. H. M., BORNER, H., DAVIDSON, W., KOCH, H. R., and PINSTON, J. A., a paper presented at this Conference.
8. PILLER, O., BEER, W. and KERN, J., Nucl. Instr. and Meth. 107 (1973) 61.
9. BEER, W. and KERN, J., Nucl. Instr. and Meth. 117 (1974) 183.
10. BORCHERT, G. L., SCHECK, W. and SCHULT, O. W. B., Nucl. Instr. and Meth. 124 (1975) 107.
11. BORCHERT G. L., SCHECK, W. and WIEDER, K. P., Zeits. für Naturforsch. 30a (1975) 274.
12. DANIEL, H., JÄHN, P. and TODT, W., Bull. Akad. Sci. USSR, Phys. Ser. 30 (1966) 2107.
13. REIDY, J. J., private communication.
14. HELMER, R. G., GREENWOOD, R. C., and GEHRKE, R. J., Nucl. Instr. and Meth. 96 (1971) 1973.
15. INOUE, H. and YOSHIZAWA, Y., Nucl. Instr. and Meth. 108 (1973) 385.
16. GREENWOOD, R. C., HELMER, R. G., and GEHRKE, R. J., Nucl. Instr. and Meth. 77 (1970) 141.
17. HELMER, R. G., GEHRKE, R. J., and GREENWOOD, R. C., Nucl. Instr. and Meth. 123 (1975) 51.