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# $^{56}$Co AS A CALIBRATION SOURCE UP TO 3.5 MeV FOR GAMMA RAY DETECTORS

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Energies and relative intensities of the transitions in $^{56}$Fe which follow the decay of $^{56}$Co were determined with Ge(Li) detectors and are presented. These results are combined with other, recent high resolution studies to give the relative intensities of the principal $^{56}$Co gamma rays with an accuracy of about 3%. This provides a means of obtaining the relative efficiency of a gamma ray detector in the energy range 800 to 3500 keV.

## 1. Introduction

The study of the decay of $^{56}$Co to the levels of $^{56}$Fe is instructive both to provide information on the transitions themselves and on their attendant de-excitation gamma rays and also to provide a convenient source for relative efficiency and energy calibrations of the high resolution gamma ray detectors which are now almost universally available. It was towards this latter end that the work described here was principally directed.

$^{56}$Co is easily produced via the $^{56}$Fe(p,n)$^{56}$Co reaction, $Q = 5.5$ MeV, using natural iron, and has a half-life against decay by positron emission and electron capture of 77.3 days[1]. The levels in $^{56}$Fe which are populated in this decay de-excite by emission of gamma rays whose energies extend up to 3.5 MeV and whose intensities relative to the most prominent line at about 845 keV are amply sufficient to be used in calibrations.

Thus it may be seen that precise values for the energies and relative intensities of the gamma rays following the decay of $^{56}$Co would enable gamma ray spectrometers to be calibrated quickly and easily in an energy region in which there has been an absence of data.

## 2. Present measurements

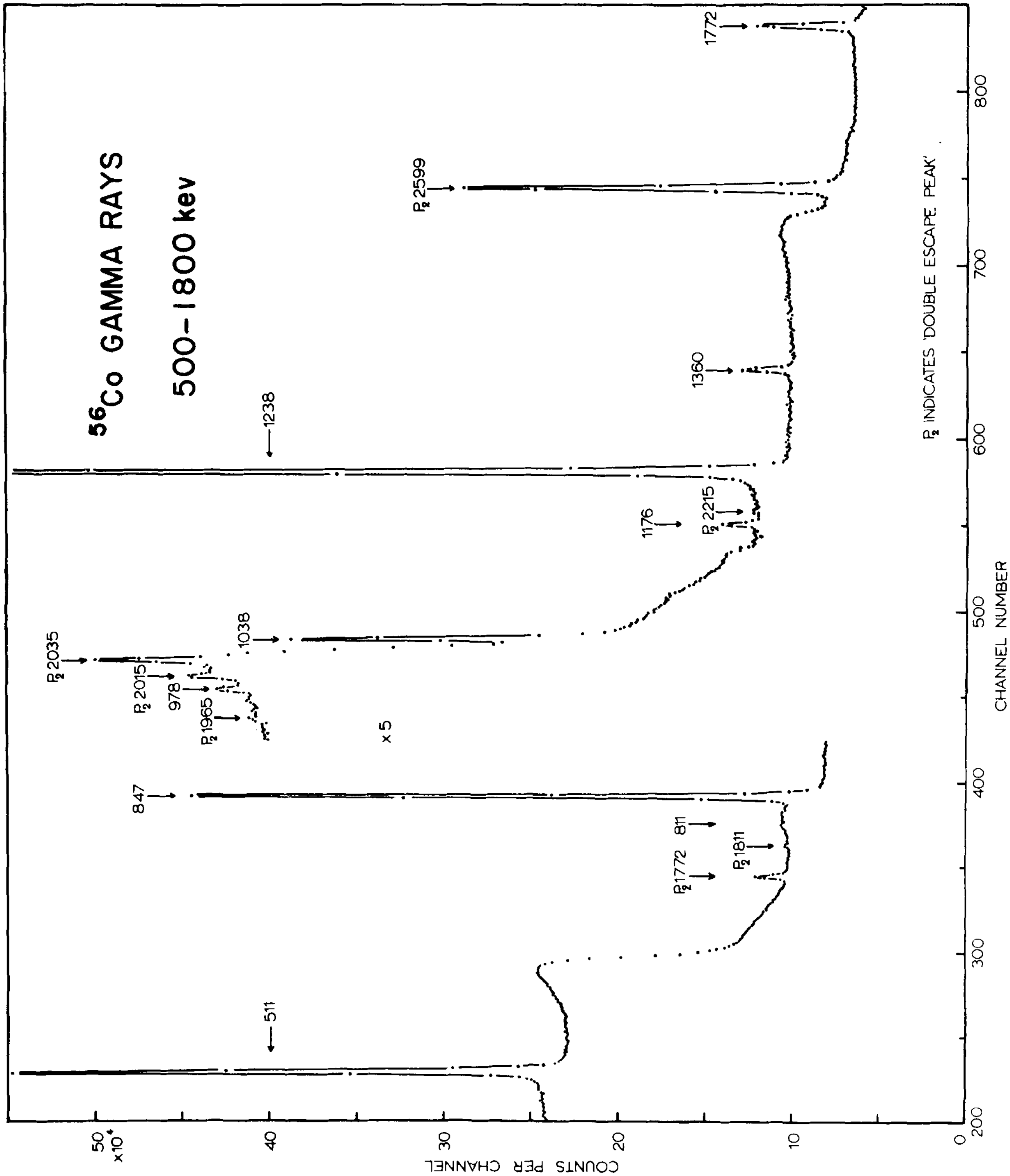
$^{56}$Co was prepared via the $^{56}$Fe(p,n)$^{56}$Co reaction using protons of 10–15 MeV from the external, degraded beam of the University of Manitoba cyclotron. The target material was either pure $^{56}$Fe in the form of ferric oxide powder for spectrum identification, or was 99.95% pure iron wire for precision determinations. After standing for several weeks, the source was then examined with germanium lithium drifted solid state detectors of active volumes 3.6 cm$^3$ and 0.5 cm$^3$, both of which displayed a full width at half maximum of about 6 keV at 1.2 MeV.

The standards used for gamma ray energy calibrations were: annihilation radiation, $511.006 \pm 0.002$ keV[2]), $^{137}$Cs $661.595 \pm 0.076$ keV[3]), $^{54}$Mn $834.84 \pm 0.07$ keV[4]) and $^{60}$Co $1173.226 \pm 0.04$ and $1332.483 \pm 0.046$ keV[5]). At the beginning of each run a "mixed sources" calibration was performed from 500–1300 keV with these standards and the $^{56}$Co source to establish the energies of the most intense gamma rays in this region. These were then used as internal calibrations for subsequent measurements lasting several days. Using the difference in energy between a "full energy" and a "second escape" peak, (1022.01 keV), the calibration was extended in a series of steps which enabled energies of over 4 MeV to be determined by the positions of their corresponding "second escape" peaks.

Measurement of the intensities of the transitions required a determination of the relative efficiency response of the Ge(Li) detector. In the region 100–1600 keV, precise relative intensities of the gamma rays following the decay of $^{140}$La have been given by Fairweather et al.[6]). These data provided a suitable means of measuring the relative efficiency curve of the detector with 5% quoted accuracy, but in which there was a gap between the values at 950 and 1600 keV.

To establish a point within this region, the relative efficiency of the detector for the 511 and 1274 keV gamma rays, emitted following the decay of $^{22}$Na, was examined. Taking into account the possibility of positronium formation and also of annihilation in flight of the positron, the calculations of Emery et al.[7]) give the ratio of the numbers of 511 keV and 1274 keV quanta emitted as $1.795 \pm 0.01$. This value is obtained by adopting the positron branching ratio to the ground and first excited states of $^{22}$Ne, $\beta_0/\beta_1$, of $0.062 \pm 0.015\%$ [8]) and the electron capture ratio, E.C./$(\beta_0 + \beta_1)$, of $10.41 \pm 0.07\%$ [9]). Freeman et al.[10]) give $1.812 \pm 0.001$ for $N(511)/N(1274)$, but did not take into account the possibility of positron annihilation in flight.

$^{24}$Na decays almost entirely to the second excited state of $^{24}$Mg at 4.122 MeV, with the largest other branch being $4 \times 10^{-2}\%$ to the state at 5.23 MeV[11]). The former de-excites through a cascade of spin sequence $4^+ \rightarrow 2^+ \rightarrow 0^+$ giving gamma rays of 2754



$^{56}$Co GAMMA RAYS
500–1800 kev
511
847
$P_2$1772
$P_2$1811
811
$P_2$1965
978
$P_2$2015
$P_2$2035
1038
× 5
1176
$P_2$2215
1238
1360
$P_2$2599
1772
$P_2$ INDICATES 'DOUBLE ESCAPE PEAK'
CHANNEL NUMBER
200
300
400
500
600
700
800
COUNTS PER CHANNEL
0
10
20
30
40
50 ×10$^4$

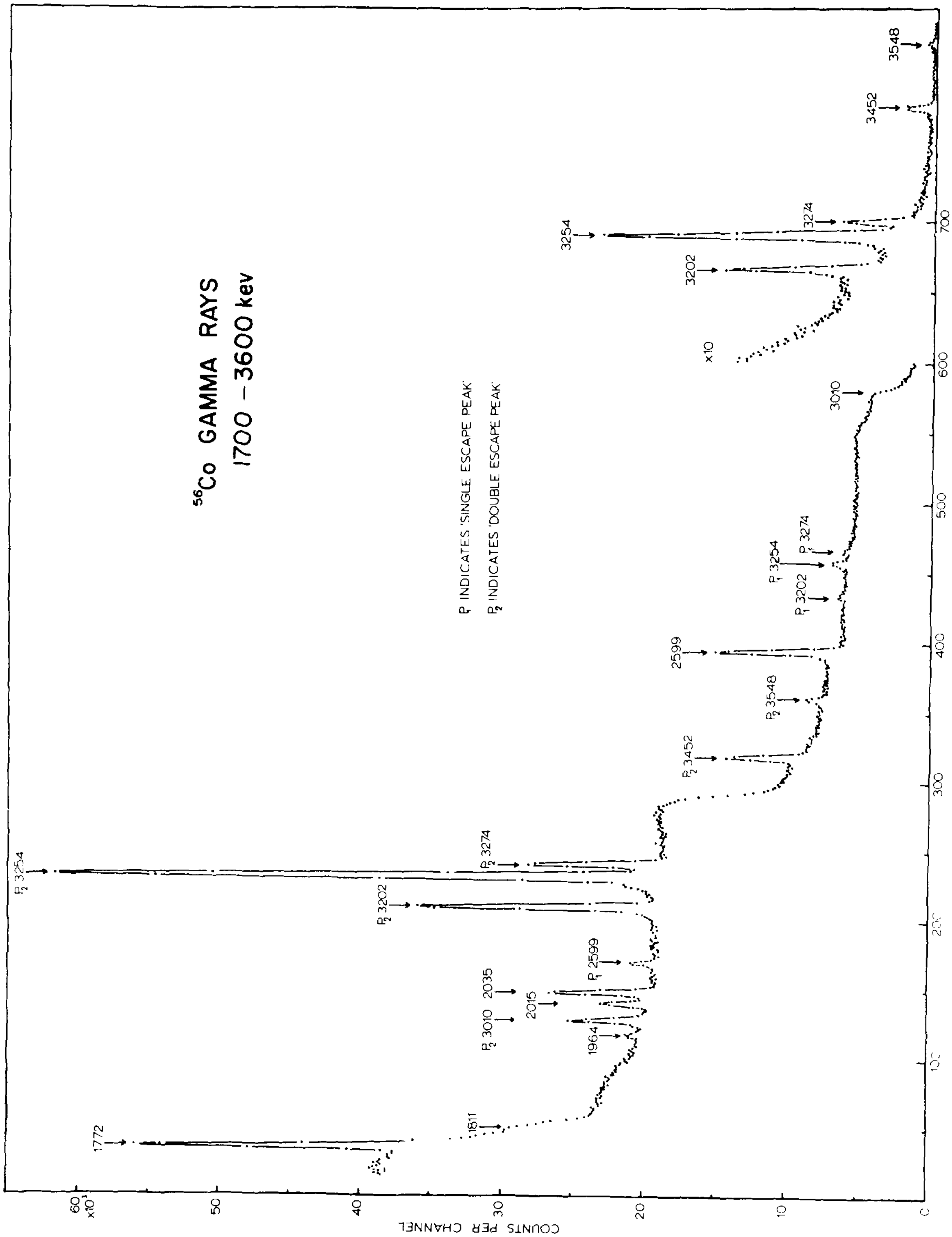



Fig. 1. $^{56}Co$ gamma ray spectrum. Energies in keV.

and 1369 keV. Because of the absence of other beta branches and the small conversion coefficients, ($< 10^{-5}$), the two gamma rays should have the same intensity within one part in a thousand. Dzhelepov[12]) has measured the ratio as $1.02 \pm 0.04$. They were used therefore to establish a higher point, at 2.75 MeV, on the relative efficiency curve.

A graph of log (relative efficiency) vs log (energy) for the smaller detector at energies above 150 keV was close to a straight line. A least-squares fit of the form $\log(\text{eff}) = a + b(\log E) + c(\log E)^2$ to the points gave $c/b = -0.06$. A quadratic function of this type was used for the evaluation of the $^{56}Co$ gamma ray relative intensities.

Fig. 1 shows a $^{56}Co$ gamma ray spectrum, taken with the smaller detector, which confirms the recent work of Auble et al.[13]) and Huguet et al.[14]). Of the small peaks at about 800 keV, that at 811 keV is almost certainly due to $^{58}Co$, and although a transition of 788 keV has been reported[13,15]), it would be unresolvable from the 1811 keV "second escape" peak in the present work.

Table 1 gives the energies and intensities of the transitions. In general, energy crossover sums agree to well within the quoted errors, and in the case of the 847 keV level, the total relative numbers of gamma rays forming and de-exciting the state were 101:100.

TABLE 1
Gamma rays from the decay of $^{56}Co$.

| Energy (keV) | Intensity |
|---|---|
| 846.80 ± 0.10 | ≡ 100 |
| 977.54 ± 0.25 | 1.62 ± 0.10 |
| 1037.88 ± 0.10 | 13.7 ± 0.8 |
| 1175.50 ± 0.20 | 2.03 ± 0.14 |
| 1238.20 ± 0.10 | 72.1 ± 5.0 |
| 1360.08 ± 0.30 | 4.80 ± 0.3 |
| 1771.70 ± 0.15 | 16.9 ± 1.0 |
| 1810.8 ± 0.7 | 1.3 ± 0.6 |
| 1963.9 ± 0.40 | 1.1 ± 0.2 |
| 2015.18 ± 0.35 | 2.93 ± 0.3 |
| 2034.81 ± 0.25 | 7.37 ± 0.5 |
| 2113.0 ± 1.0 | 0.4 ± 0.1 |
| 2214.5 ± 0.7 | 0.4 ± 0.1 |
| 2598.68 ± 0.20 | 15.0 ± 1.3 |
| 3010.11 ± 0.35 | 0.8 ± 0.3 |
| 3202.25 ± 0.30 | 2.9 ± 0.3 |
| 3253.84 ± 0.25 | 6.6 ± 0.6 |
| 3273.56 ± 0.30 | 1.35 ± 0.2 |
| 3451.97 ± 0.40 | 0.63 ± 0.15 |
| 3547.57 ± 0.70 | 0.11 ± 0.05 |

## 3. Discussion

Recently there have been several high resolution studies of the gamma ray transitions in $^{56}Fe$ which follow the decay of $^{56}Co$. These have involved Ge(Li) detectors[13,16,17]), a double focusing spectrometer for internal conversion electrons[15]) and a three crystal pair spectrometer[14]). It seemed therefore that by combining these with the present measurements more precise results could be quoted, particularly for the relative intensities.

Table 2 shows the individual intensities and also the weighted means of the energies and intensities of the principal transitions given in earlier publications [13-17]) and in the present work. The mean value, $\alpha_m \pm \sigma_m$, of a series of $k$ measurements of $\alpha$ has been taken to be

$$\alpha_m = \sum_k \alpha_i \sigma_i^{-2} / \sum_k \sigma_i^{-2},$$

whilst $\sigma_m$ has been taken to be the larger of the two quantities

TABLE 2
$^{56}Co$ Gamma rays: Combined results.
(Relative intensity)

| Energy (keV) | Barker | Petterson | Auble | Dolan | Schoneberg | Huguet | mean |
|---|---|---|---|---|---|---|---|
| 846.76 ± 0.09 | 100 | 100 | 100 | 100 | 100 | 100 | 100 |
| 1037.99 ± 0.09 | 13.7 ± 0.8 | 14.1 ± 1.5 | 12.8 ± 0.9 | 12.5 ± 0.5 | 14.0 ± 2.0 | 14.5 ± 1.5 | 13.02 ± 0.35 |
| 1238.38 ± 0.10 | 72.1 ± 5.0 | 66.8 ± 4.0 | 69.9 ± 3.5 | 71.2 ± 2.6 | 66.3 ± 6.0 | 70.5 ± 7.0 | 69.9 ± 1.6 |
| 1360.42 ± 0.12 | 4.80 ± 0.3 | 4.0 ± 0.8 | 4.5 ± 0.3 | 3.8 ± 0.3 | 3.8 ± 0.4 | 4.5 ± 0.7 | 4.3 ± 0.3 |
| 1771.74 ± 0.12 | 16.9 ± 1.0 | 16.2 ± 1.4 | 16.1 ± 0.8 | 15.0 ± 1.3 | 13.5 ± 1.4 | 12.5 ± 1.3 | 15.6 ± 0.7 |
| 2015.45 ± 0.20 | 2.93 ± 0.3 | 4.1 ± 1.2 | 2.7 ± 0.2 | 3.8 ± 0.7 | 3.5 ± 0.4 | 3.7 ± 0.6 | 2.98 ± 0.2 |
| 2034.98 ± 0.15 | 7.37 ± 0.5 | 9.2 ± 1.7 | 7.4 ± 0.6 | 7.8 ± 1.0 | 6.5 ± 0.8 | 8.3 ± 1.5 | 7.4 ± 0.3 |
| 2598.88 ± 0.15 | 15.0 ± 1.3 | 17.4 ± 1.5 | 17.3 ± 0.9 | 16.0 ± 2.7 | 17.4 ± 1.7 | 20.0 ± 2.0 | 17.1 ± 0.6 |
| 3202.42 ± 0.25 | 2.9 ± 0.3 | 3.2 ± 0.5 | 3.4 ± 0.2 | 2.9 ± 1.1 | 3.4 ± 0.4 | 3.8 ± 0.45 | 3.31 ± 0.14 |
| 3253.99 ± 0.25 | 6.6 ± 0.6 | 8.5 ± 0.6 | 7.8 ± 0.4 | 5.8 ± 2.2 | 8.3 ± 0.8 | 9.2 ± 0.9 | 7.86 ± 0.36 |
| 3452.25 ± 0.30 | 0.63 ± 0.15 | 0.95 ± 0.15 | 0.87 ± 0.09 | 0.7 ± 0.3 | 0.7 ± 0.1 | 1.1 ± 0.2 | 0.81 ± 0.06 |
| 3547.98 ± 0.40 | 0.11 ± 0.05 | – | 0.15 ± 0.03 | 0.2 ± 0.1 | 0.21 ± 0.03 | 0.16 ± 0.03 | 0.165 ± 0.02 |

$$\sigma_{mi} = (\sum_k \sigma_i^{-2})^{-\frac{1}{2}}$$

and

$$\sigma_{me} = [\sum_k \{(\alpha_i - \alpha_m)/\sigma_i\}^2 / \{(k-1)\sum_k \sigma_i^{-2}\}]^{\frac{1}{2}}.$$

This latter expression may be thought of as a test of the external consistency of the measurements; for a "good" set, the ratio of $\sigma_{me}$ to $\sigma_{mi}$ should be close to unity. In the present case, the largest value of $\sigma_{me}/\sigma_{mi}$ was 1.67 for the 1360 keV transition and for the others the ratio was generally between 1.2 and 0.8. In all cases except the 3548 keV transition, $\sigma_m$ was $\pm 7\%$ of $\alpha_m$ or better, whilst for most, $\sigma_m$ was $\pm 4\%$ of $\alpha_m$ or better.

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