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# PRECISION MEASUREMENTS OF GAMMA-RAY ENERGIES UP TO 2 MeV USING A 2 m CURVED-CRYSTAL MONOCHROMATOR

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**Abstract:** Precision measurements of gamma-ray energies up to 2 MeV were performed using a 2m curved-crystal monochromator. Effective source activities of less than 40 mCur were used for the measurements of the transitions in the 2 MeV region. In the 150 keV region, effective source activities of less than 200 $\mu$Cur may be used. Measurements have been performed on the transitions of energies less than 2150 keV which follow the decay of $In^{116}$(54 min), $Mn^{56}$ (2.6 h) and $Sc^{46}$ (85 d). In addition, results are presented which indicate that the reflection coefficient is approximately linear with respect to wavelength for the second order reflection from the germanium ($0\bar{2}2$) planes in the region of 6–90 mÅ (2000–135 keV).

E RADIOACTIVITY $^{46}$Sc, $^{56}$Mn, $^{116}$In [from $^{45}$Sc, $^{55}$Mn, $^{115}$In(n, $\gamma$)], measured $E_\gamma$, $I_\gamma$ Natural targets.

## 1. Introduction

During the past four decades large amounts of data concerning the decay of nuclei have been accumulated and level schemes for great many nuclei have been proposed. In the study of nuclear decay via gamma-ray emission a large part of these data has resulted from the use of the NaI(Tl) spectrometer. Even though this type of spectrometer can be quite efficient, it is well known that the study of complicated decay schemes is often hindered by the resolution obtainable with NaI(Tl) and by the pulse-height distribution one obtains for a given gamma-ray energy. These two factors often limit the certainty with which one can establish a decay scheme even when coincidence techniques are employed. High accuracy in the measurement of gamma-ray energies is not possible and the determination of the relative intensities of close-lying gamma-ray transitions becomes difficult. The fine points of many decay schemes are thereby often not obtainable. Formerly, these fine points were of little concern; but, with the increasing sophistication of nuclear models, they assume much greater importance. The transition energy corresponding to a given gamma-ray can often be determined with greater accuracy by studying the internal conversion electrons and, indeed, this has been a fruitful field of study particularly in the energy region of 40–1000 keV. The limitations and problems of this method are well-known. Gamma-ray

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intensities cannot be directly determined, although conversion-electron intensities can be measured. This often results in the possible deduction of multipolarities of the transitions. Energy determinations of high accuracy (approximately 0.01 %) require (i) the use of spectrometers and elaborate arrangements such as iron-free buildings and de-gaussing arrangements, (ii) calculations of electron binding energies and determinations of work functions and (iii) high specific source activity and sometimes complex source preparation techniques. This latter requirement is often the most difficult to meet and is often avoided by using the method of external conversion. If the internal conversion spectrum is further complicated by the presence of electrons from nuclear beta-decay, this latter method is often the better for studying a decay involving many gamma-rays. Generally, the resolution is not as good and energy determinations are less accurate using this method rather than measuring the internal conversion electrons but one does obtain the relative intensities of the gamma-rays. The useful upper limit using this method is generally 1000–1200 keV. In this energy region the Compton spectrometer becomes a useful tool, and until recently, above 2 MeV it has proven to be the most feasible method for obtaining gamma-ray energies with some precision. However, sources of high activity are needed since the efficiency of this method is inherently quite small.

Precision energy measurements and determinations of relative intensities of gamma-rays have also been performed using crystal diffraction techniques. Quartz curved-crystal spectrometers have enabled workers to extend the useful energy range of this technique; but, as a rule, this range has only encompassed the region of 10–600 keV. A notable exception is the useful range of 40–2000 keV which has been obtained with the Argonne 7.7 quartz-curved-crystal spectrometer [1]). In addition, the range of the double flat-crystal spectrometer at Chalk River [2]) appears to extend at least to 3 MeV.

These latter spectrometers have required very high source activities (with a general requirement of large source volume) and appeared to be limited to the study of neutron capture gamma-rays from target materials which are obtainable in gram quantities.

The recent development [3]) of the lithium-drifted germanium diode detector has greatly improved the resolution with which one can measure gamma-rays compared with that obtainable using NaI(Tl). In some cases the resolution of the Li-drifted germanium detector also surpasses that which can be obtained using a curved-crystal spectrometer. However, precision energy measurements on high energy gamma-rays with these diode detectors are still less precise than those determined with the curved-crystal spectrometer. This is due, in part, to the relatively poor determination of high-energy gamma-ray energies even of the so-called "calibration energies" or "standards". Due to improvements in experimental techniques, it has also become necessary to obtain better energy measurements on high-energy gamma rays which can be used in the study of the non-proportional response of NaI(Tl) and other crystals. In addition, although the lithium drifted germanium diode detector can have better

resolution than the curved-crystal spectrometer a distinct advantage is offered by the latter instrument. With the diode detector a weak gamma-ray may be masked by the Compton distribution or "escape peaks" due to higher energy gamma-rays. With the curved-crystal spectrometer these interferences are generally unimportant. In particular, in the region of 200 keV the detection of real gamma-rays is often quite easy even though these same gamma-rays may be unobserved using scintillation or diode detectors due to the backscatter radiation which may mask weak gamma-rays in this energy region.

Recent technological advances indicated that a 2 m curved-crystal spectrometer could be built with a modest financial investment which would enable high accuracy measurements of gamma-ray energies to be made. The availability of large single crystals of germanium and the evident superiority of these crystals compared with quartz in resolution and reflectivity [4]) suggested the possibility of extending the useful range of the 2 m curved-crystal spectrometer to 2 MeV or greater. It appeared that measurements could be performed in this energy region on gamma-rays from sources obtained from milligram amounts of target material and the activities of these sources would not prohibit their being removed from the reactor and transported to the instrument. Also, calculations indicated that the partial cross-section could possibly be in the millibarn region so gamma-rays from cyclotron-produced reactions would be of sufficient intensity to allow measurements to be made on them. The work presented in this paper demonstrates the results that can be obtained using a 2 m curved-crystal spectrometer with a germanium crystal in the region of 130–2100 keV. Two of the isotopes which were investigated ($Sc^{46}$ and $Mn^{56}$) are suitable for "standards" since they can be produced from naturally occurring mono-isotopic elements and have fairly long half-lives. The third isotope $In^{116}$ has a much shorter half-life and, if produced from natural In, a small amount of $In^{114}$ is present. However, the gamma-ray spectrum contains transitions extending over the region of 130–2100 keV and the gamma-ray intensities extend from 80% to 2% of the total decay. This latter fact enabled one to investigate the possibility of measuring a weak high energy gamma-ray which is below two very intense higher energy gamma-rays and all occurring in the decay of a short-lived (54 min) isotope. It was felt that this would certainly demonstrate the feasibility of measuring weak gamma-rays with the spectrometer.

## 2. Experimental Procedure

The University of Michigan curved-crystal spectrometer and experimental procedures have been described previously [5]). In the present work the germanium $(0\bar{2}2)$ and (400) planes were used for the measurements. Each crystal had an effective area of about 4 $cm^2$. The measurements with the $(0\bar{2}2)$ planes were obtained in second or third order. With the (400) planes measurements were taken in second or third order except for energies above 1300 keV when only the first order reflection was used.

The source preparation has been described previously [5]). The $Sc^{46}$ source was ob-

tained by irradiation of $Sc_2O_3$ powder in the ORNL High Flux Reactor. The powder had been sealed in a 2.4 cm × 0.0254 cm inside diameter quartz tube. The activity was about 0.2 Cur. The $In^{116}$ (54 min) was obtained by irradiation of natural indium foil in the University of Michigan Ford Nuclear Reactor (approx. $5 \times 10^{12}$ neutrons · $sec^{-1}$ · $cm^{-2}$). The foil was 2.4 cm × 0.159 cm × 0.0102 cm and the maximum activity was roughly 3 Cur. The $Mn^{56}$ was obtained by irradiation in the University of Michigan reactor of a flat source made from a powdered manganese-epoxy mixture. The source was 2.4 cm × 0.159 cm × 0.0127 cm and the maximum activity was about 0.4 Cur.

## 3. Results

The results of the measurements are presented in table 1. It is interesting to note the excellent agreement between corresponding measurements with the two crystals (columns 2 and 3). The more precise values obtained with the (0$\bar{2}$2) crystal results

TABLE 1

Comparison of the determinations of the transition energies (in keV) following the decay of the indicated isotope

| Isotope | Present investigation | | Previous investigations [a]) | | Ref. |
|---|---|---|---|---|---|
| | (0$\bar{2}$2)Ge | (400)Ge | | | |
| $In^{116m}$ | | 138.326±0.008 | 138.32±0.01 | c | [10]) |
| | 416 990±0 044 | 416 960±0.061 | 417.2 ±0 1 | c | [10]) |
| | 818.65 ±0.17 | 818.66 ±0.26 | 819.4 ±0.2 | c | [10]) |
| | 1097.21 ±0.18 | 1096.88 ±0 46 | 1096.7 ±0 7 | c | [10]) |
| | 1293.29 ±0.41 | 1293.63 ±0.98 | 1293.4 ±0 6 | c | [10]) |
| | 1507.54 ±0.59 | 1507.60 ±1 32 | 1504 ±2 | EC | [19]) |
| | 1753 38 ±2.23 | | | | |
| | 2111.21 ±1.35 | 2108.6 ±9.9 | | | |
| $Mn^{56}$ | 846.79 ±0 10 | 846.79 ±0.15 | 845± 6 Scin, 851±5 Cp | | [20,22]) |
| | 1810.98 ±0.63 | 1811.2 ±2.3 | 1809± 9 Scin, 1814±8 Cp | | [20,21]) |
| | 2110.0 ±1.6 | 2112.1 ±6.2 | 2134±11 Scin, 2117±8 Cp | | [20,21]) |
| $Sc^{46}$ | | 889.15 ±0.13 | 885± 2 EC, 892±3 Scin | | [23,24]) |
| | | 1120.30 ±0.22 | 1119± 2 EC, 1118±3 Scin | | [23,24]) |

[a]) The following designations are used c = curved crystal, EC = external conversion, Scin = scintillation spectrometer, Cp = Compton spectrometer.

from the better resolution and greater reflectivity [5]) of this crystal compared with the (400) crystal. In ref. [5]) it was shown that the reflectivity of the (400) planes in first order is about 40 % greater than for the (0$\bar{2}$2) planes in second order for 412 keV gamma-rays. However, it appears that the dependence of the reflectivity on wavelength is nearly linear for the second order reflection from the germanium (0$\bar{2}$2) planes (see appendix), whereas the wavelength dependence is approximately quadratic for the first order reflection from the (400) planes[4]). Therefore, above 600 keV great-

er reflectivity is obtained using the second order reflection from the $(0\bar{2}2)$ planes. Since the dispersion of the $(0\bar{2}2)$ planes in second order (411.800 keV = 35.4466 screw divisions (s.d.), 1 s.d. $\approx$ 1.46 min of arc) is greater than that of the (400) planes in first order (411.800 keV = 25.0647 s.d.) and the FWHM of the reflected line profile for the $(0\bar{2}2)$ planes is about 0.8 times the FWHM of the line profile for the (400) planes, it is obvious that greater precision should be obtained with the $(0\bar{2}2)$ planes. If measurements are made using the higher order reflections from the (400) planes, then the accuracy which one obtains with either crystal is roughly the same and is mainly determined by the monochromator error [5]). The fourth and fifth columns of table 1 present the previous best measurements which have been made for the corresponding transitions.

### 3.1. THE DECAY $Sc^{46} \xrightarrow[85\,d]{} Ti^{46}$

The measurements on the two intense lines in the decay of $Sc^{46}$ were made in first, second and third order. A total of five measurements were made on the 889.15 keV gamma-ray and three measurements on the 1120.30 keV gamma-ray. This source was received about a year before the Ge$(0\bar{2}2)$ crystal was obtained so no measurements were made with this crystal. With our present flat source technique, the uncertainties on these measurements could be decreased at least a factor of two since by our present standards this source was quite wide (0.025 cm). Note the factor of ten or more decrease in the uncertainties as compared with previous best measurements †. A search was made for other transitions, but none were found. In particular, the intensity of any gamma-ray with energy 80–200 keV $I_\gamma$ (80–200) is less than 0.0005 $I_\gamma$ (889) whereas $I_\gamma$ (200–400) $< 0.003\ I_\gamma$ (889) and $I_\gamma$(400–600) $< 0.01\ I_\gamma$ (889).

### 3.2. THE DECAY $Mn^{56} \xrightarrow[2.54\,h]{} Fe^{56}$

Only the three strong transitions below 2150 keV were measured in this decay. The values in column 2 of table 1 represent the best energy determinations of these gamma-rays. The 1811 keV determination was obtained from two separate second order measurements and the 847 keV determination was obtained from one second order measurement and two third order measurements. Fig. 1 represents the data for the second order reflection of the 1811 keV gamma-ray from one side of the Ge$(0\bar{2}2)$ planes. The effective source strength is roughly 35 mCur. The peak reflection efficiency at this energy for this order reflection is approximately $5.5 \times 10^{-8}$. The peak reflection efficiency for second order reflection $R(\gamma, 2)$ is defined as the ratio of the maximum possible number of quanta of a given energy $\gamma$ which can be diffracted into the peak of the second order diffraction profile compared with the number of quanta of this energy which are emitted by the nuclei of the source. The maximum possible number of diffracted quanta is calculated from the observed peak counting rate by applying corrections for source and air absorption, attenuation in the crystal, and the efficiency for detection of the scattered quanta in the photopeak of the NaI(Tl) de-

† See note added in proof.

tector. There is no correction for the transmission of the collimator. The transmission of the collimator is essentially constant and equal to about 0.5. Due to these corrections, the value of the effective peak reflection efficiency $R_{\text{eff}}(\gamma, 2)$ is smaller than the peak reflection efficiency. For the higher energies the dominant correction is for the efficiency of the 7.8 cm × 7.8 cm sodium iodide detector and is of the order of 0.18 so $R_{\text{eff}}(\gamma, 2)$ is approximately 0.18 $R(\gamma, 2)$ for $1500 \leqq \gamma \leqq 2500$ keV. Notice in fig. 1

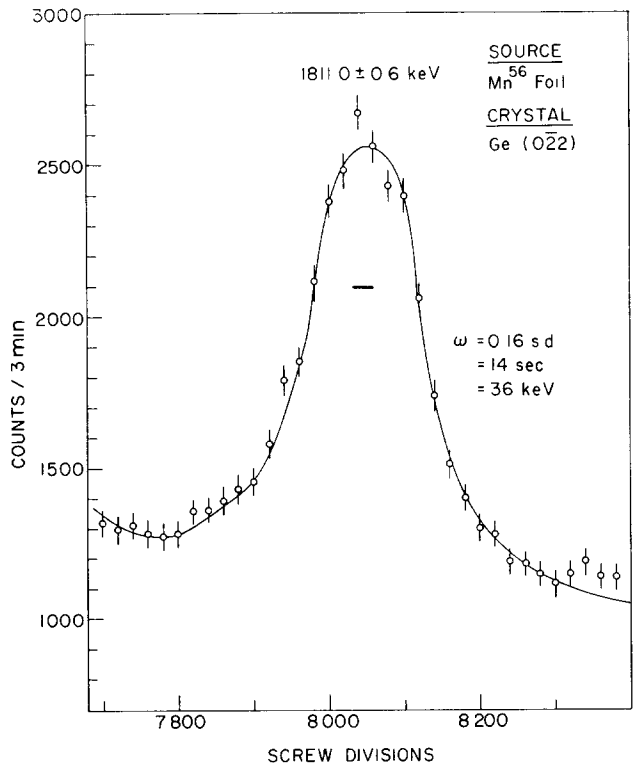


Fig. 1. The 1811 0 keV gamma-ray line in the decay of $Mn^{56}$ observed in second order reflection from the germanium (0$\bar{2}$2) planes. The full width at half-maximum intensity (FWHM) is designated $\omega$. The data have been corrected for source decay. The partial source activity is 35 mCur. The solid line merely shows the general trend of the data points.

that the (peak less background)/background ratio is about 1.1 with the change in background rate being about 20 % as one goes across the peak, and the resolution is 2 %. With the first order reflection from the Ge(400) planes this ratio is 0.45 with the background rate on the high energy side of the diffraction profile being 2.3 times the rate on the low energy side of the profile and the resolution is about 6 %. However, by displacing the collimator 1.0 s.d. the (peak less background)/background ratio was increased to 0.7 with the background rate on the high energy side of the diffraction profile being only 1.5 times the rate on the low energy side of the profile. Since

the resolution of the collimator is about a factor of twenty times coarser than the resolution of the crystal, this displacement cannot affect the position of the diffracted peak. The result of displacing the collimator will be discussed later. At this point it is of interest to note that the energy determinations with the (400) planes of the two high energy transitions were obtained by displacing the collimator. When the collimator was not displaced, the uncertainties in these determinations were a factor of

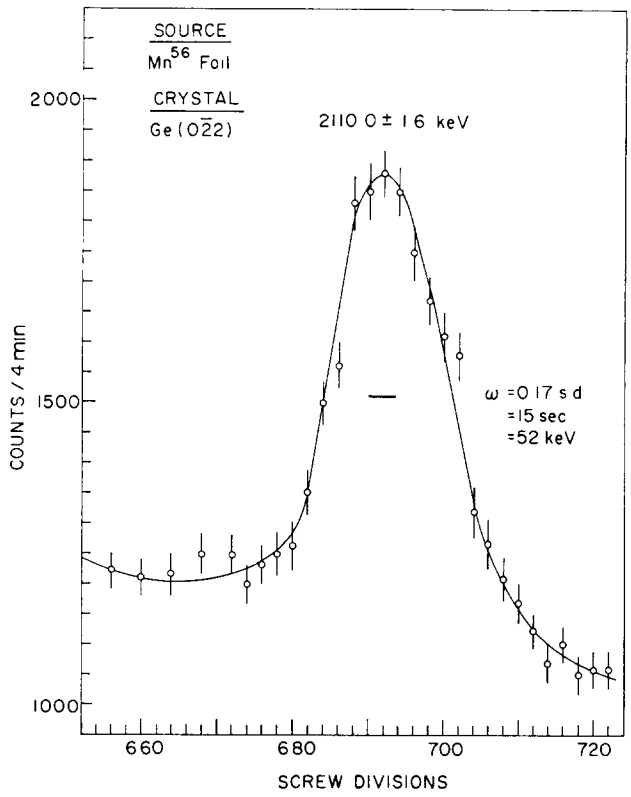


Fig. 2. The 2110.0 keV gamma-ray observed in second order reflection. The data have been corrected for source decay. The partial source activity is about 13 mCur. The solid line merely shows the general trend of the data points.

2 or 3 larger. Such is not the case for the second order reflection from the (0$\bar{2}$2) planes. As of the present time we have had no reason to displace the collimator when using this latter configuration.

Fig. 2 represents the data for the second order reflection of the 2110 keV gamma-ray from the (0$\bar{2}$2) planes. The effective source strength is roughly 13 mCur and $R(2110,2) \approx 4 \times 10^{-8}$. Notice that the (peak less background)/background ratio is 0.65 with the change in the background rate being 20 % as one goes across the peak.

The resolution is 2.5 %. The decay scheme for $Mn^{56}$ which is given in the Nuclear Data Sheets [6]) is presented in fig. 3. The transitions measured in this work are denoted by heavy lines and the energies of the levels are obtained from the present measurements (except for the highest state and the level at 2085 keV). A search was made for other possible gamma-rays with energies below 1500 keV. An upper limit of 0.0004 times the 846.8 keV gamma-ray intensity can be placed on the intensity

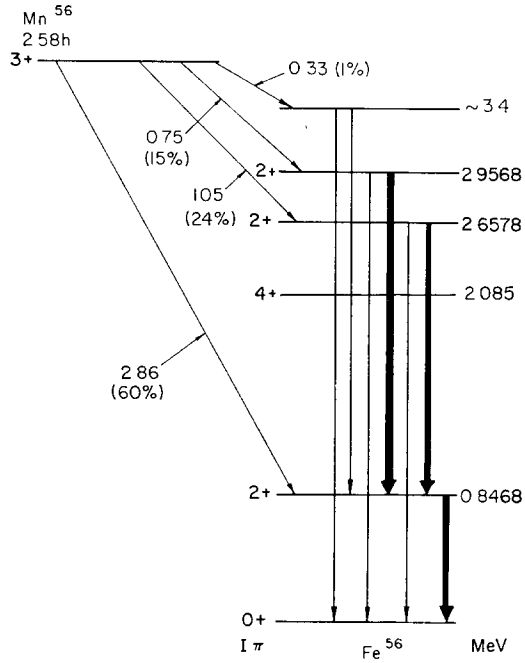


Fig. 3. Decay scheme of $Mn^{56}$ taken from ref. [6]). The heavy lines represent the transitions measured in this work. The five place energy values are those obtained from this work.

value for the 299 keV gamma-ray which might proceed from the fourth to the third excited state. The 2085 keV state is populated by the electron capture decay in $Co^{56}$ but attempts by other authors to detect transitions which could populate or depopulate this level in the decay of $Mn^{56}$ have proven fruitless. Possible gamma-rays would have approximate energies of 1238, 872 and 573 keV. A careful search was made for these gamma-rays but none was observed. An upper limit of 0.0015 $I_\gamma$ (847) is placed on the intensity of any of these transitions.

### 3.3. THE DECAY $In^{116m} \xrightarrow[54\,min]{} Sn^{116}$

Most authors are now in agreement on the main features of the $In^{116m}$ decay [7–10]). The decay scheme taken from ref. [8]) is shown in fig. 4 with the energies obtained from the present work. The energies of all the gamma-rays shown in the decay scheme

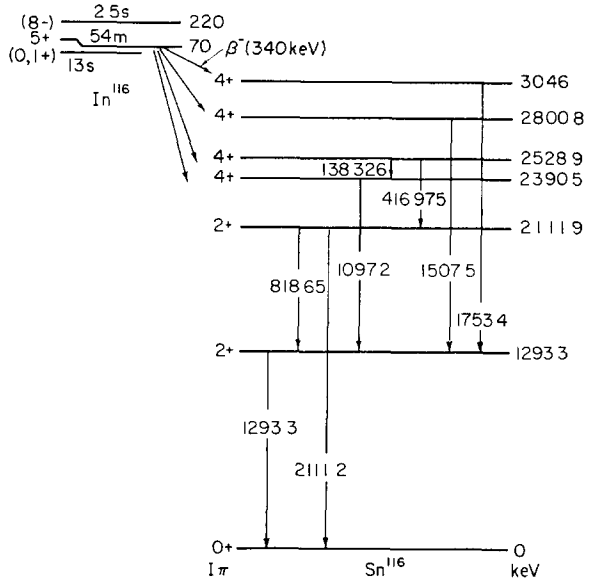


Fig. 4. Decay scheme of 54 min $In^{116m}$ taken from ref. [8]). The energy values are obtained from this work.

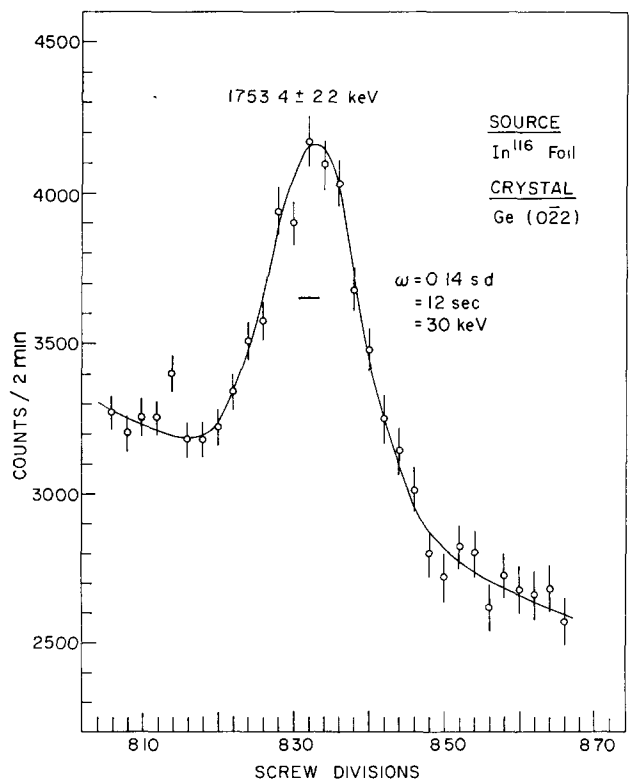


Fig. 5. The 1753.4 keV gamma-ray in the decay of 54 min $In^{116m}$ observed in second order reflection. The data have been corrected for source decay. The partial source activity is 16 mCur. The solid line shows the general trend of the data points only.

were measured with the curved-crystal monochromator. Of particular interest is the 1753 keV transition which depopulates the highest state in $Sn^{116}$ excited in the beta decay. The 1753 keV transition intensity is $\approx 2\,\%$ of the total decay. In the singles spectrum obtained with NaI(Tl) the 1753 keV peak is superimposed on the shoulder of the Compton distribution of the 2111 keV transition. Girgis and Lieshout [7]) were first definitely to establish the presence of the 1753 keV transition. It was felt that the measurement on this weak high energy transition would be a good test of the performance of the curved-crystal monochromator. The data representing the second order reflection from one side of the $(0\bar{2}2)$ planes are shown in fig. 5. The partial activity leading to this transition is roughly 16 mCur. Notice that the peak/background ratio is only 1/2.5 for this weak transition with the background rate changing fairly slowly as one goes across the diffraction profile. The measurements on the other gamma-rays are presented in table 1.

TABLE 2

Results of energy measurements using the 2 m curved-crystal monochromator

| Decay | Gamma-ray energy (keV) | Gamma-ray designation |
|---|---|---|
| $Mn^{56} \rightarrow Fe^{56}$ | 846 79 ±0 09 | |
| | 1810.98 ±0.63 | |
| | 2110.0 ±1.6 | |
| $In^{116m} \rightarrow Sn^{116}$ | 138.326±0.008 | $\gamma_1$ |
| | 416.975±0 037 | $\gamma_2$ |
| | 818.65 ±0 17 | $\gamma_3$ |
| | 1097 21 ±0.18 | $\gamma_4$ |
| | 1293.29 ±0 41 | $\gamma_5$ |
| | 1507.54 ±0 59 | $\gamma_6$ |
| | 1753.4 ±2 2 | $\gamma_7$ |
| | 2111.2 ±1.4 | $\gamma_8$ |
| $Sc^{46} \rightarrow Ti^{46}$ | 889.15 ±0.13 | |
| | 1120 30 ±0 22 | |

The first five values in column 4 of table 1 were obtained by John and Jewell [10]) using a 2 m curved-quartz-crystal spectrometer in the Cauchois geometry. These measurements were a byproduct of their study on the capture gamma-rays in indium. The agreement between the values obtained in the present work and those of John and Jewell is good except for the 417 and 819 keV transitions. However, it should be noted that in this present work the agreement between the energy determinations for these two transitions obtained with both germanium crystals is excellent. The final results for the energy values of the gamma-ray transitions in the 54 min $In^{116}$ decay are presented in table 2. From the decay scheme we have an internal check on some of these energies from cross-over sums. Using the gamma-ray designation of table 2, these sums must be consistent with $\gamma_3+\gamma_5 = \gamma_8$ and $\gamma_1+\gamma_4 = \gamma_2+\gamma_3$. In the first

sum one has $\gamma_3+\gamma_5 = 2111.94\pm0.44$ keV compared with the measured value of $2111.2\pm1.4$ keV for $\gamma_8$. In the second sum one has $\gamma_1+\gamma_4 = 1235.54\pm0.19$ keV and $\gamma_2+\gamma_3 = 1235.63\pm0.18$ keV. The agreement is excellent in both cases. John and Jewell could not obtain agreement between the values obtained in the sum $\gamma_1+\gamma_4 = \gamma_2+\gamma_3$. They attributed this to an underestimate of their uncertainty in $\gamma_4$. However, their lack of agreement could also have resulted from their seemingly high values for $\gamma_2$ and $\gamma_3$.

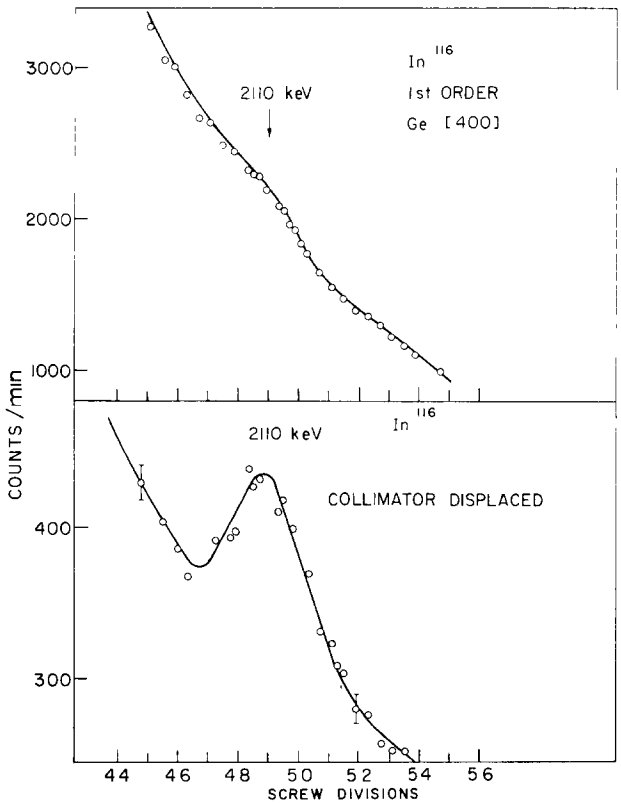


Fig. 6. The 2111 keV gamma-ray in the decay of 54 min $In^{116m}$ observed in first order reflection from the germanium (400) planes. The data have been corrected for source decay. The solid line denotes the general trend of the data points only. The upper section represents the data obtained in the usual manner. The lower section represents the data one would obtain with the same source activity with the collimator displaced 1 s.d. (about 1.5 min of crystal arc.).

A search was also made for other possible transitions. In particular, Bolotin [9]) has reported a 385 keV gamma-ray with $I_\gamma(385) = 0.028\, I_\gamma(417)$ and a 435 keV gamma-ray with $I_\gamma(435) = 0.017\, I_\gamma(417)$. In this assignment the 385 keV transitions proceed from the 2111.9 keV state to a state at 1720 keV and the 435 keV transition proceeds from the 1720 keV to the 1293.3 keV state. In the present work, however, these

transitions were not observed. Upper limits of $I_\gamma(456\text{–}422) < 0.001\ I_\gamma(417)$ and $I_\gamma(402\text{–}360) < 0.0015\ I_\gamma(417)$ are placed on any gamma-ray occurring in these regions. Other transitions which could occur between the various levels and might be observed in the present work are 245.2, 271.9, 410.3, 517.1 and 1235.6 keV. None of these possible transitions were observed and upper limits on their intensity are as follows: $I_\gamma(270\text{–}276) < 0.001\ I_\gamma(417)$, $I_\gamma(\approx 410) < 0.02\ I_\gamma(417)$, $I_\gamma(\approx 245) < 0.01\ I_\gamma(417)$, $I_\gamma(517) < 0.01\ I_\gamma(417)$ and $I_\gamma(\approx 1236) < 0.005\ I_\gamma(1293)$.

Mention was made earlier that the technique of displacing the collimator was studied in conjunction with these measurements. The measurement on the 2111 keV line using the (400) planes was performed with the collimator displaced 1.0 s.d. The results are presented in fig. 6. The upper curve represents the data obtained from the first order reflection from the (400) planes in the usual manner while the lower curve represents data obtained with the collimator displaced 1.0 s.d. All data have been corrected for source decay and the two sets of data have been corrected for the time lapse between the two runs. From measurements using the 1120 keV transition in the decay of $Sc^{46}$ it was determined that displacing the collimator 1.0 s.d. decreased the counting rate of the diffracted peak by 20 % and a 2.0 s.d. displacement decreased the counting rate of the diffracted peak to half the value when the collimator was in the usual undisplaced position. Returning to fig. 6, notice that the background rate has been decreased a factor of 7 by displacing the collimator. Since this results in only a 20 % decrease in the diffracted peak intensity we obtain a factor of 5.6 increase in the (peak less background)/background ratio at this dispersion (4.9 s.d.). From the results presented in the $Mn^{56}$ decay it is evident that the increase in this ratio is only about a factor of 1.6 at 5.7 s.d. (1811 keV). This smaller increase results from the fact that the background which is mostly due to the undiffracted beam is not changing as rapidly for the greater dispersion. Therefore, it appears that this technique is most useful in the region below 5.5 s.d. Using the second order reflection from the $(0\bar{2}2)$ planes this corresponds to the region above 2600 keV. At 3.0 MeV the dispersion is 4.9 s.d., which corresponds to the dispersion represented in fig. 6. From these considerations and the fact that the reflectivity of the $(0\bar{2}2)$ planes seem to be nearly linear for second order reflection, it appears that measurements on gamma-rays in the 3 MeV region are feasible with the present arrangement.

## 4. Conclusions

From the results it has been shown that gamma-ray energy measurements can be performed up to at least 2110 keV. The accuracy of an energy determination of a gamma-ray in the 2 MeV region is approximately 0.08 %. At 1500 and 800 keV the accuracy is about 0.04 % and 0.02 %, respectively. The partial source activity can be in the mCur region. With our present source techniques and a thermal neutron flux of $5 \times 10^{12}$ neutrons $\cdot$ cm$^{-2}$ $\cdot$ sec$^{-1}$ maximum source activities are $\approx 25\sigma$ mCur, where $\sigma$ denotes the thermal neutron capture cross-section in barns. A partial acitvity of 10

mCur corresponds to a peak less background counting rate of 3 cps for the second order diffraction profile of a 2100 keV line using the germanium $(0\bar{2}2)$ planes. Thus, partial cross-sections of the order of 400 mb are certainly sufficient to allow energy measurements of gamma-rays in the 2100 keV region. For a similar source activity and using the displaced collimator technique, the peak counting rate for a 3 MeV line could be 1.5 counts/sec. Using a larger NaI detector would increase this rate, of course, with little or no increase in the (peak less background)-to-background ratio. This latter ratio would be about $\frac{1}{10}$. With a decay of sufficient half-life ($T_{\frac{1}{2}} > \approx 10$ h) it appears that a partial source activity of 1 mCur would be sufficient to allow measurements on gamma-rays in the 2 MeV region. This activity would correspond to a partial cross-section of about 40 mb. In the 150 keV region measurements could be performed on sources with partial activities of 100 $\mu$Cur which corresponds to a partial cross-section of 4 mb.

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## Appendix

During the course of this work it became evident that the reflectivity of the germanium $(0\bar{2}2)$ planes for second order reflection did not change as rapidly as one would expect for an $E^{-2}$ dependence, where $E$ is the energy of the gamma-ray. This is of considerable interest in view of the fact that up until now the reflectivity of curved-crystal planes seemed to follow an approximate $E^{-2}$ dependence for planes in both quartz [11-16]) and germanium [4,17]) crystals.

The following work presents the preliminary results in the study of the reflectivity of the germanium $(0\bar{2}2)$ planes for second order reflection. A more complete study is in progress. Fig. 7 represents the data which were obtained with a $W^{187}$ source. This was a 0.0075 cm $\times$ 0.47 cm flat source and there was appreciable attenuation of the 134 keV gamma-ray in this high $Z$ material. Since it is practically impossible to determine accurately the orientation of the source (see ref. [5])), this correction for source attenuation was obtained in the following manner. The peak counting rate (less background) was determined for the three gamma-rays at 134, 480 and 686 keV using the quartz (310) planes. The data were corrected for the known $E^{-2}$ dependence of the reflectivity for these planes, attenuation in the quartz crystal, and the efficiency for detection of these gamma-rays in the photopeak of the NaI detector. The source attenuation factor was then obtained by comparing the resulting intensities with the intensities reported by Gallagher *et al.* [18]) and assuming the 686 keV gamma-ray was not attenuated by the source. The deduced source attenuation factor for the 134 keV gamma-ray was roughly 8.0 and for the 480 keV gamma-ray it was about 0.2. From the FWHM of the diffraction profile using the germanium $(0\bar{2}2)$

planes an approximate source orientation was deduced. The attenuation factors which were obtained from the (310) quartz data are in quantitative agreement with the factors which were calculated from the deduced source orientation. The peak counting rate (less background) was then determined for the same three gamma-rays

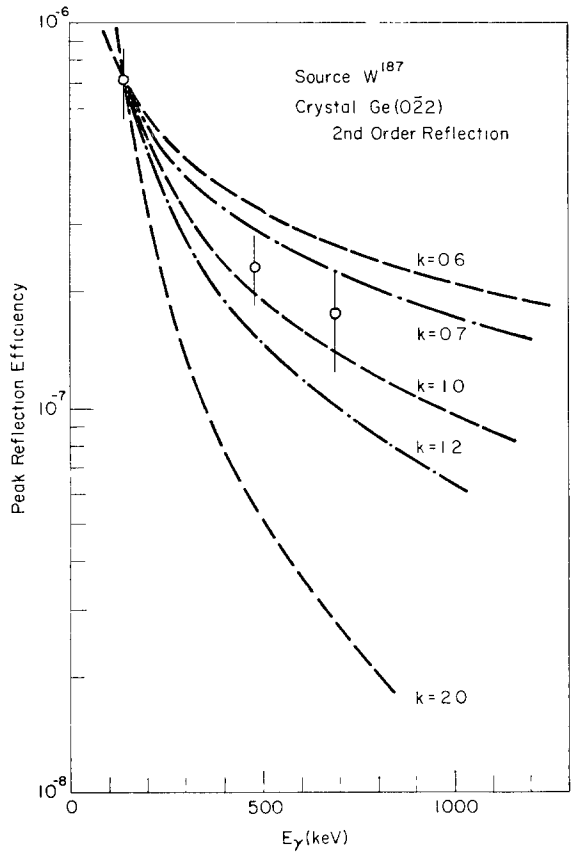


Fig. 7. Peak reflection efficiency $R$ for the second order reflection of 134, 480 and 686 keV gamma-rays from the germanium (0$\bar{2}$2) planes. The peak reflection efficiency is defined as the ratio of the maximum possible number of quanta of a given energy $E$ which can be diffracted into the peak of the diffraction profile compared with the number of quanta of energy $E$ which are emitted by the nuclei in the source. The maximum possible number of diffracted quanta which is source and detector independent is obtained from the observed peak counting rate as described in the text. The dashed lines show the shape of the function $R = R_0 E^{-k}$ for various values of $k$. The constant $R_0$ has been determined by setting the value of the function $R$ at 134 keV equal to the experimental value at this energy.

using the second order reflection from the germanium (0$\bar{2}$2) planes. The data were corrected for source attenuation using the results from the (310) quartz data, attenuation in the germanium crystal and the efficiency of the NaI detector. If one assumes that the reflectivity of the second order germanium (0$\bar{2}$2) planes is a function $f(E)$

of the gamma-ray energy $E$, then the above analysis gives

$$\frac{I_{exp}(E, 0\bar{2}2)}{I_{exp}(E, 310)E^2} \frac{\varepsilon_1}{\varepsilon_2} \frac{\omega(0\bar{2}2)}{\omega(310)} = f(E), \tag{1}$$

where $I_{exp}(E, x)$ is the diffracted peak counting rate less background for a gamma-ray of energy $E$ and using the $x$ crystal; $\varepsilon_1$ and $\varepsilon_2$ denote the fraction of the diffracted

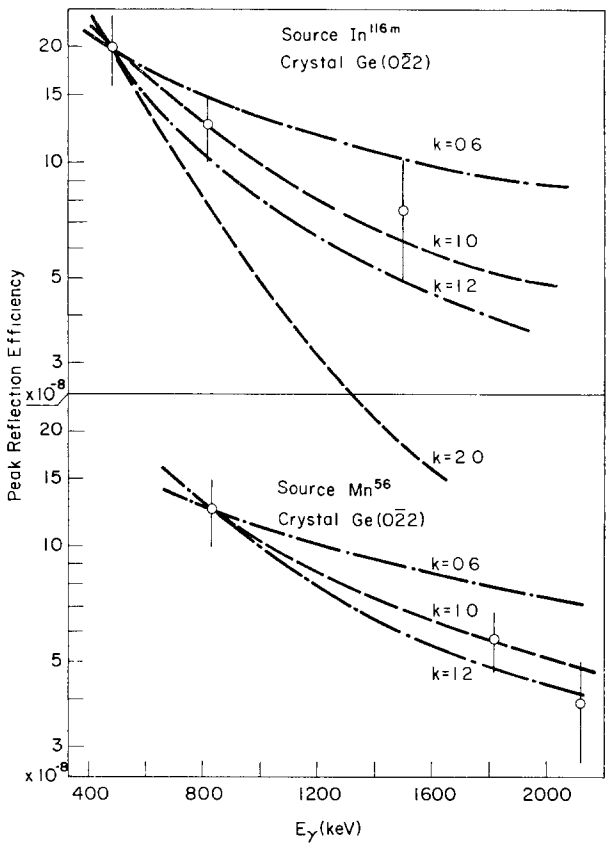


Fig. 8. Peak reflection efficiency $R$ for the second order reflection from germanium (0$\bar{2}$2) planes of gamma-rays in the region 400–2100 keV. The dashed lines show the shape of the function $R = R_0E^{-k}$ where $R$ is normalized to the experimental value for the lowest energy point.

gamma rays of energy $E$ which do not undergo attenuation in the 310 or 0$\bar{2}$2 crystals, respectively, and $\omega(x)$ denotes the FWHM of the diffraction profile for reflection from the $x$ planes ($\omega(0\bar{2}2)/\omega(310)$ is a constant for all gamma-rays considered here). One should also note that since the dispersion from the quartz (310) planes (411.800 keV = 30.0387 s.d.) is only about 15 % smaller than the second order dispersion from the germanium (0$\bar{2}$2) planes (411.800 keV = 35.4466 s.d.) a first order correc-

tion for any slight misalignment of the collimator is "built into" the analysis. Thus, plotting the left-hand side of eq. (1) versus $E$ for a suitable range of $E$, one might obtain a graphical determination of $f(E)$. If, in addition, the absolute peak reflection efficiency can be determined for one gamma-ray energy, then from the plot one can obtain this efficiency for any other energy $E$. The absolute peak reflection efficiency was determined for the reflection of the 480 keV gamma-ray from the quartz (310) and second order germanium ($0\bar{2}2$) planes. This determination involved a calculation of the source strength which depends on the neutron flux ($\approx 5 \times 10^{12}$ neutrons · $\sec^{-1} \cdot \mathrm{cm}^{-2}$ in our case). Due to the uncertainty (about a factor of two) in this number, the peak reflection efficiency may be in error by a factor of two. However, it is interesting to note that using the calculated source strength, the peak reflection efficiency for the 480 keV gamma-ray corrected for the solid angle subtended by the crystal was determined to be 0.006 for the 2 mm thick quartz (310) crystal. Lind *et al.* [11]) found a value of 0.003 for their 1 mm thick quartz (310) crystal and a gamma-ray energy of 411.8 keV. The results represented in fig. 7 were obtained by using eq. (1) and the data for the 134, 480, and 686 keV gamma-rays in the decay of $W^{187}$. The points have been normalized to the calculated peak reflection efficiency for the 480 keV transition. Although this latter value may be in error by a factor of two, the relative values for the points will remain unchanged. The uncertainties are estimated by assigning maximum reasonable errors to the quantities in eq. (1). The dashed curves denote the shape of the function $R = R_0 f(E)$ where $f(E) = E^{-k}$ for various values of $k$. Fig. 8 represents the data for gamma-rays in the decay of $Mn^{56}$ and $In^{116}$. The error flags represent estimates of the uncertainties. Due to the relatively high energy of these gamma-rays, no correction for source attenuation or attenuation in the crystal was necessary. Although these corrections are non-zero, they are all small and nearly the same value for all gamma-rays in this energy region. The results represented in the top section of the figure were obtained without disturbing the source at any time. The peak counting rates less background were determined for the three energies 417, 819 and 1508 keV. After corrections for decay and NaI efficiency, the resulting intensities were compared with previous determinations of these intensities [7-10]). The values used for these three gamma-ray intensities were 35 %, 17 % and 82 % of the total decay, respectively. The source activity was calculated and from this the peak reflection efficiency for each gamma-ray was determined. The bottom section of fig. 8 represents the results derived in the same manner for the 847, 1811 and 2110 keV transitions in $Mn^{56}$. The intensities of these gamma-rays are taken [6]) as 100 %, 24 % and 15 %, respectively. The dashed lines in both sections denote the shape of the function $E^{-k}$. It is evident from figs. 7 and 8 that the reflection coefficient for second order reflection from the germanium ($0\bar{2}2$) planes cannot be a quadratic function of the gamma-ray energy. Instead, it appears that the relation between the reflectivity $R$ and gamma-ray energy $E$ can be given by $R \propto E^{-k}$, where $1.2 \leqq k \leqq 0.6$ for the second order reflection from the germanium ($0\bar{2}2$) planes and $130 \leqq E$ (keV) $\leqq 2110$.

From the results presented in figs. 7 and 8 one can calculate the fraction $\Gamma(E)$ of the gamma-rays of energy $E$ which strike the diffracting crystal and are diffracted into the peak of the diffraction profile. For the $(0\bar{2}2)$ crystal arrangement used in this work, the solid angle subtended by the crystal is $10^{-4}$ sr and the transmission of the collimator is about 50 %. One can easily find that $\Gamma(2110) = 0.010$. Also, using fig. 7, one can calculate that for a 134 keV line a recorded peak less background counting rate of 100 counts per minute corresponds to a partial source activity of only about 100 $\mu$Cur. This activity corresponds to a partial cross section of 4 mb.

*Note added in proof*: Measurements on the transition following the decay of $Sc^{46}$ have also been reported by Bartlett *et al.* [25]). The method of superposition of external conversion spectra was used, with $Co^{60}$ as the reference standard. These authors obtained the values of $888.3 \pm 0.4$ and $1119.2 \pm 0.6$ keV for the two transitions. There appears to be no explanation for the discrepancy between these values and the values presented in this work.

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