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A STUDY OF THE DECAY OF ^{187}W USING A 2 m CURVED-CRYSTAL SPECTROMETER

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Abstract: The gamma rays in the decay of ^{187}W have been studied using the University of Michigan 2 m curved-crystal spectrometer and a lithium-drifted germanium diode spectrometer. One previously unreported transition has been observed and the energies of all observed transitions have been determined with the curved-crystal spectrometer. Upper limits have been determined for the intensities of possible unobserved gamma rays in the 160–1200 keV region. The relative merits and complementarity of the curved crystal spectrometer and the Ge(Li) spectrometer are discussed. In addition, data are presented concerning the reflectivity of the curved crystal using the germanium $(0\bar{2}2)$ planes.

E | RADIOACTIVITY ^{187}W[from $^{186}W(n, \gamma)$]; measured E_γ, I_γ. ^{187}Re deduced levels. Natural target.

1. Introduction

Although the decay of ^{187}W has been studied extensively [1-3]), there are considerable discrepancies in the decay schemes proposed by various authors ††. There is general agreement on the placing of the more intense 72, 134, 479, 686 and 773 keV transitions in the decay scheme, but considerable discrepancy in the number and placing of other transitions. It was felt that improved precision in the determination of the gamma-ray energies and a careful search for weak transitions which in previous works might have been masked by more intense transitions could aid in resolving some of the discrepancies between the various decay schemes which have been proposed. The recent improvements in the technique of gamma-ray energy measurements with a curved-crystal spectrometer which we have made in this laboratoty [4,5]) and the acquisition of a Ge(Li) detector present a useful set of tools for such a study. After this work was completed a study of the decay of ^{187}W using a Ge(Li) spectrometer was published by Sebille *et al.* [3]). Our results verify some of the additions to the decay scheme proposed by these authors and bring out new features of this decay.

† This work supported in part by the United States Atomic Energy Commission.
†† Ref. [1]) contains a fairly complete list of references.

2. Experimental Arrangements

The UM curved crystal spectrometer has been described previously [4,5]) and some results using the Ge($0\bar{2}2$) planes as the diffracting planes were presented. The spectrometer has been calibrated using the 411.800 keV gamma ray in the decay of ^{198}Au. Since the previous work the Ge($0\bar{2}2$) crystal has been recalibrated using the fifth, sixth and seventh order reflection of the 411.800 keV line. For the Ge($0\bar{2}2$) planes in first-order reflection 411.800 keV = 17.72217 ± 0.00006 screw divisions (s.d.) where 1.0 s.d. $\approx$ 90 sec of crystal arc. For the quartz (310) planes 411.800 keV = 30.0387 ± 0.0012 s.d. for first-order reflection.

The sources were tungsten ribbons which had been irradiated in the University of Michigan Ford Nuclear Reactor (thermal flux $\approx 5 \times 10^{12}$ neutrons/sec $\cdot$ cm^2). The sources whose construction is described in ref. [3]) were 0.48 cm thick, 2.54 cm high and 25 to 75 μm wide (i.e., as seen by the curved crystal).

The Ge(Li) detector is an RCA SJGG-1 (area of 0.8 cm^2 and depletion depth of 2 mm) operated at 77°K. The preamp is a Tennelec 100-C and the amplifier-post amplifier is an ORTEC 203 used in the RC mode. The resolution (FWHM) of this system is about 4.5 keV in the energy region of 200–1000 keV.

3. Results

The results of the energy measurements using the curved crystal spectrometer are presented in table 1. The results of other authors are shown for comparison. The relative intensities of close-lying transitions are presented in table 2. These values have been deduced from data obtained with the curved crystal spectrometer using the Ge($0\bar{2}2$) planes in second-order reflection. The peak reflection efficiency for an energy E was taken to be proportional to E^{-k}, where $0.6 \leqq k \leqq 1.2$. This is discussed in the appendix. Limits on the intensities of any gamma rays in various energy regions are presented in table 3. From these data it is apparent that the 732, 760 and 777 keV transitions reported by Michaelis [1]) are not present. This same result was found by Sebille *et al.* [3]). The transitions of 745.29 and 879.56 keV reported by Sebille *et al.* are verified. In addition, a new transition at 588.96 keV has been observed. The decay of each of these transitions has been followed through at least two half-lives and each of them decay with a 23 ± 2 h half-life. On this basis they have been assigned to the ^{187}W decay. Using the relative intensities given by Gallagher *et al.* [6]) and the data in table 2, one obtains an intensity of 0.50 for the 588.96 keV gamma ray compared with a value of 100 for the 479.57 keV transition. Fig. 1 represents the data obtained for the second-order reflection of the 625, 618 and 589 keV gamma rays from one side of the Ge($0\bar{2}2$) planes. Notice that the 618 and 625 keV gamma-ray diffraction profiles are completely separated and the 589 keV gamma ray is obvious at once above the constant background. Figs 2(a) and 2(b) represent the data obtained with the Ge(Li) detector in the region of 450–900 keV. The energies given for the peaks are obtained from table 1. The measurement time was 1000 min with the data being normalized

TABLE 1

Energies of transitions (in keV) in the decay of $^{187}W \rightarrow {}^{187}Re$

	Present investigation	Previous curved-crystal work [a]	Internal conversion work [b]
	72.002±0.004	72.00 ±0.01	71.99±0.04
		72.000±0.007 [c]	
		71.995±0.004 [d]	
	106.596±0.013	106.61 ±0.06	106.58±0.03
	113.746±0.008	113.74 ±0.05	113.74±0.03
	134.247±0.007	134.25 ±0.02	134.24±0.03
		134.25 ±0.02 [c]	
		134.237±0.009 [d]	
	206.247±0.019	206.2 ±0.2	206.18±0.07
	239.196±0.024	239.3 ±0.3	239.16±0.15
	246.276±0.022	246.3 ±0.3	246.3
	479.572±0.028	479.4 ±0.4	478.98±0.13
		479.52 ±0.19 [c]	
		479.56 ±0.13 [d]	
	511.648±0.045	511.3 ±0.7	510.93±0.25
	551.515±0.037	551.7 ±0.7	551.50±0.27
	588.96 ±0.06		
	618.282±0.058	618.2 ±0.6	618.36±0.20
	625.54 ±0.10	625 ±1.6	625.41±0.30
	685.740±0.048	686.1 ±0.4	685.60±0.28
		686.06 ±0.38 [c]	
		685.50 ±0.30 [d]	
	745.29 ±0.10	746 ±1 [e]	
	772.910±0.060	773 ±1	772.76±0.31
	864.71 ±0.18	867 ±3	
	879.56 ±0.19	880 ±1 [e]	
W Kα1	59.3190±0.0025	59.3182 [f]	
Re Kα1	61.1406±0.0029	61.1403±0.0002 [f]	
Re Kα2	59.7167±0.0027	59.7179±0.0001 [f]	

[a] Ref. [6] except as noted.

[b] Ref. [2].

[c] Ref. [7].

[d] Ref. [8].

[e] Ref. [3]. This value obtained with a Ge(Li) spectrometer.

[f] Ref. [9].

to a time of 2000 min. The 589 keV gamma ray is nearly masked by the non-constant Compton background. The spectrum obtained for the 0–450 keV region is nearly useless since the Compton distribution and the backscatterer peaks due to the transitions above 450 keV mask all the low-energy gamma rays except the intense 72 and

TABLE 2

Relative intensities of close-lying gamma-rays in the decay of ^{187}W

Energy (keV)	Relative intensity This work [a])	Gallagher *et al.* [b])
511.65	12.5±1.0	2.6
551.515	100	21.2
588.96	12.3±4.0	
618.28	620±30	26
625.54	100	4.3
745.29	8.2±0.4	
772.91	100	16.2
864.71	385±20	1.54
879.56	100	

[a]) The intensity of the highest energy gamma-ray in each group is assigned a value of 100.
[b]) Ref. [6]); the intensities are normalized to a value of 100 for the 479 keV gamma ray.

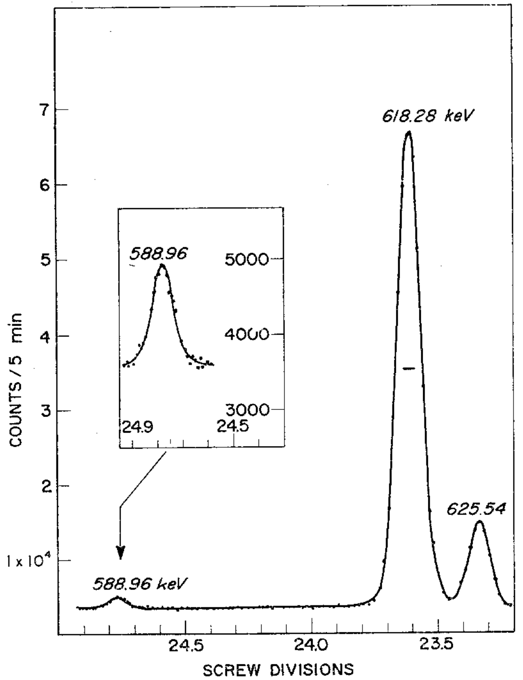

Fig. 1. The diffraction profiles of the gamma-ray lines in the energy region 580–630 keV observed in second-order reflection from the Ge(0$\bar{2}$2) planes. The data have been corrected for source decay. The source width is 0.0076 cm and the resolution (FWHM) is about 2.9 keV.

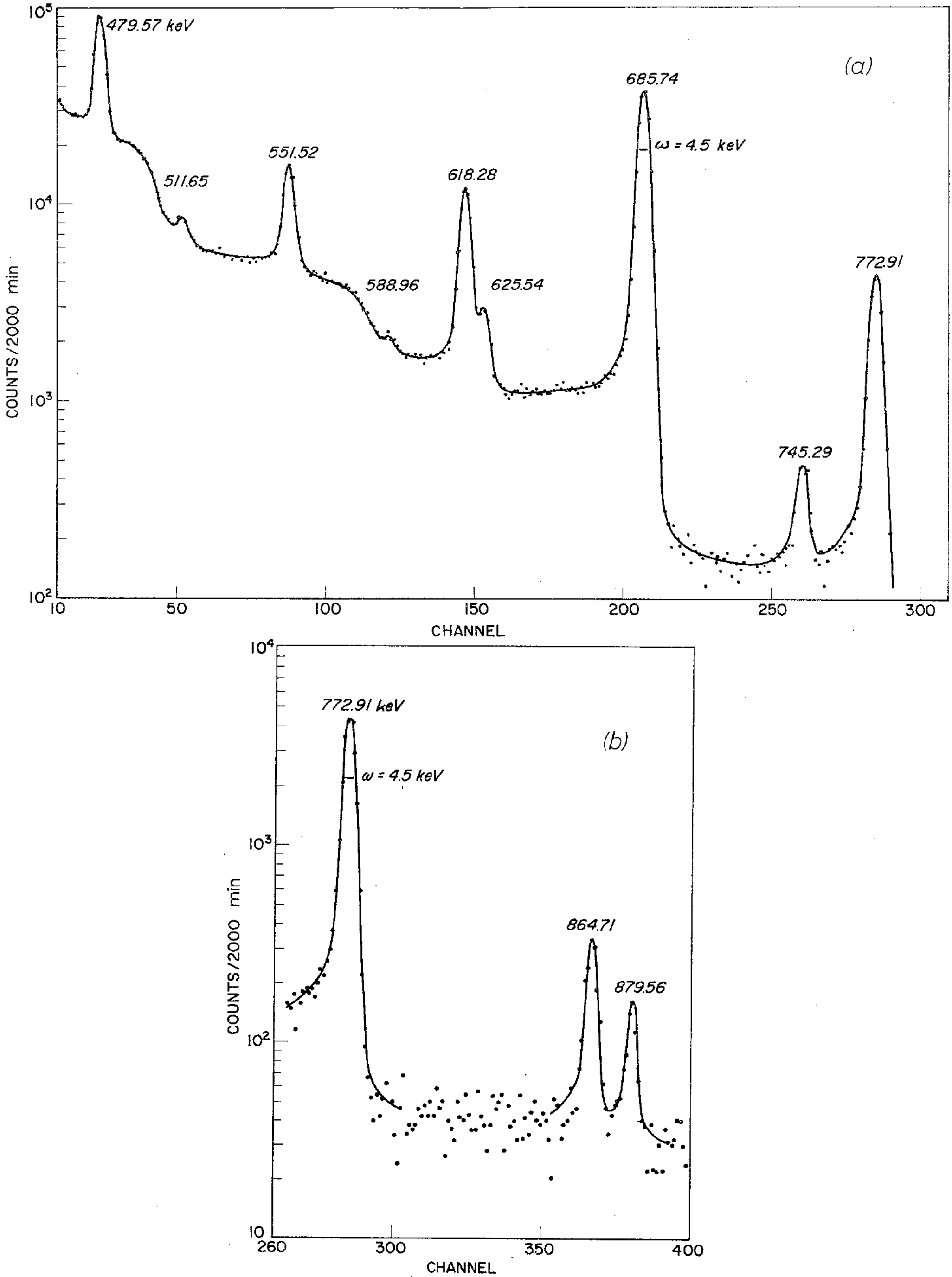

Fig. 2. Gamma-ray singles spectrum of ^{187}W obtained with a 2 mm depletion depth (area of 0.8 cm^2) lithium-drifted germanium diode detector for the energy region (a) 450–775 keV and (b) 755–900 keV.

134 keV lines. Even the 72 keV line is partially masked by the K_β X-ray lines. Fig. 3 represents the data obtained for the third-order reflection of the 511.65 keV gamma ray from the Ge($0\bar{2}2$) planes. The diffraction profile for the fourth-order reflection

TABLE 3

Intensity limits on gamma rays in various energy regions

Energy region (keV)	Maximum intensity [a]
1200–890	$< 0.05\gamma(865)$
840–776, 768–748	$< 0.01\gamma(773)$
743–710	$< 0.005\gamma(773)$
674–632	$< 0.0008\gamma(686)$
610–592, 579–556	$< 0.004\gamma(618)$
550–520	$< 0.002\gamma(552)$
520–512	$< 0.006\gamma(552)$
510–506	$< 0.015\gamma(511)$
504–488, 474–458	$< 0.0005\gamma(479)$
458–389	$< 0.00015\gamma(479)$
385–342, 338–310, 307–305	$< 0.0001\gamma(479)$
306–284	$< 0.0007\gamma(479)$
273–259, 254–247, 245–241, 238–230, 228–207, 205–190	$< 0.0005\gamma(479)$
176–172, 170.5–161	$< 0.007\gamma(134)$
172–170.5	$< 0.014\gamma(134)$

[a]) The quantity $\gamma(E)$ denotes the intensity of the gamma ray of energy E(keV).

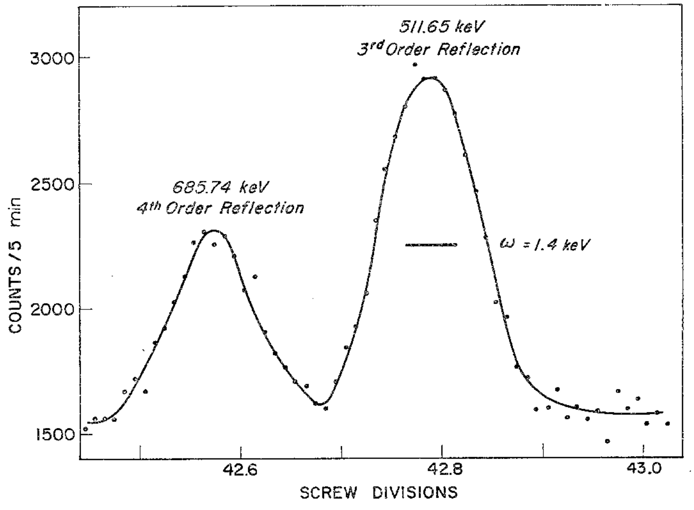

Fig. 3. Diffraction profile of lines observed in the region 42.5–43.0 screw divisions using the Ge($0\bar{2}2$) planes. The discriminator which passed the recorded count pulses was set for the energy interval 400–600 keV. The data have been corrected for source decay. The source width was 76 μm.

of the intense 685.7 keV line is also present. This results from the output of the discriminator corresponding not only to pulses due to the detection of the 511.65 keV gamma ray in the photopeak of the pulse-height distribution from the NaI detector, but corresponding also to the Compton distribution in the 511 keV region which is due to the 685.7 keV gamma ray.

4. Discussion

These energy measurements verify the level scheme for ^{187}Re proposed by Gallagher *et al.* [6]) and extended by Sebille *et al.* [3]) although a slight modification is

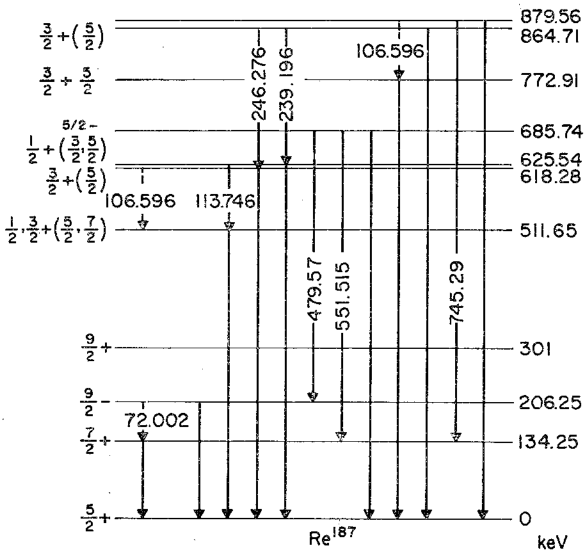

Fig. 4. Proposed decay scheme for the levels in ^{187}Re which are populated by the decay of ^{187}W. The level sequence is taken from the work of Sebille *et al.* [3]) and the spins and parities are those proposed by Gallagher *et al.* [6]).

possible. This level scheme is shown in fig. 4. The spins and parities are those proposed by Gallagher *et al.* The slight modification arises from the fact that there are two possible placings of the weak 106.196 keV transition and these are shown by the dotted lines. The weak transition at 588.96 keV is not placed in this scheme. As in the work of Sebille *et al.*, the placing of the 745.29 keV transition is determined only from the fact that the energy sum 745.29 ± 0.10 keV$+134.25 \pm 0.01$ keV $= 879.54 \pm 0.10$ keV is in agreement with the proposed cross-over transition of measured value 879.56 ± 0.19 keV. Since the uncertainties quoted by Sebille *et al.* for the 745 and 880 keV transitions were 1.0 keV, the present work lends considerably more substantiation to the possibility for the 745–134 keV cascade. It is also interesting that the present energy measurements allow an additional 106.60–772.91 keV cascade to proceed from the 879.56 keV state. This feature has not been noted previously. Usually the 106.60 keV gamma ray is considered to proceed from the 618.28 keV state and this possibility is also consistent with our work. Bisgård *et al.* [11]) have observed possible weak coincidences between the transitions in the 618–686 keV and 107–114 keV regions. This would support the placing of the 106.60 keV transition as proceeding from the 879.56 keV state if transitions from the 772.91 keV to one or more of the states in the 600 keV region are present. With the experimental arrangement used in this work, reliable intensity limits on possible very weak transitions could not be obtained for this 87–155 keV region.

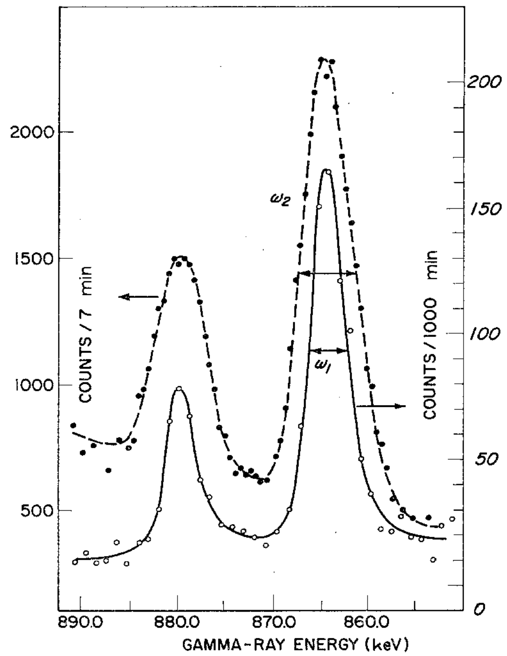

Fig. 5. Comparison of the line shapes for the gamma rays of energy 879.56 keV and 864.71 keV which can be obtained with the Ge(Li) spectrometer (solid curve) and with the curved-crystal spectrometer (dashed curve) using a 0.0076 cm wide source and the Ge(0$\bar{2}$2) planes. The energy resolution of each curve is $\omega_1 = 4.5$ keV and $\omega_2 = 6.2$ keV, respectively. Note the decreasing energy scale. The data represented by the dashed curve have been corrected for decay.

A brief mention should be made of the complementarity of the curved-crystal spectrometer and the Ge(Li) spectrometer. This is best done by a comparison of figs. 1–3. By a tedious scanning [4]) of the entire energy range of 1200–400 keV using the curved-crystal spectrometer diffraction profiles for all the reported transitions are obtained. Then one decides which line is to be measured first, second and so on. However, an easier method is to obtain the spectrum with the Ge(Li) spectrometer, roughly determine the observed gamma-ray energies and intensities, and then plan the sequence of measurements which will be made with the curved-crystal spectrometer. For short-lived sources this procedure can be of considerable help. However, for the precision measurement of a particular gamma-ray energy the Ge(Li) spectrometer is not necessarily faster nor as precise as the curved-crystal spectrometer. From fig. 1 one can see that an energy determination on the 589 keV line took about 6 h (reflection from both sides of the crystal planes); the resultant uncertainty was about 0.15 keV. With the Ge(Li) spectrometer a time of 16 h was not even adequate to obtain an uncertainty of less than 0.5 keV. In fact, if the 589 keV transition had been a little lower in energy it may have been masked by the Compton edge due to the 773 keV line. These rather large Compton edges also limit the usefulness of the Ge(Li) spectrometer in establishing limits on unobserved transitions. The superiority of the curved-crystal spectrometer in this respect is evident from a comparison of figs. 1 and 2(a). The region below 590 keV is flat in the former figure, but is rising due to the 773 keV Compton edge in the latter figure. With fig. 3 one can deduce that it took about 6 h to obtain an energy determination of the 511.68 keV line at a resolution of 1.4 keV. The 511.68 keV line in fig. 2(a) was just barely evident after a 6 h counting time. Increasing the source strength for the Ge(Li) spectrometer merely increased the FWHM of the peaks and almost completely "washed out" the 511.65 and 589 keV lines besides smearing the 618–625 keV doublet. However, in some cases the Ge(Li) detector can give better resolution than that which is easily obtainable with the curved-crystal spectrometer. Such a case is shown in fig. 5 for the doublet in the 870 keV region. The resolution using the curved Ge(0$\bar{2}$2) crystal was $\omega_2 = 6.2$ keV, whereas it was $\omega_1 = 4.5$ keV with the Ge(Li) spectrometer. The total time required to obtain the dashed curve was 7 h. A third-order measurement would have given $\omega_2 = 4.1$ keV and would have taken about 14 h for similar statistical uncertainties for each point (i.e., approx. 3 %).

In the region of 60–480 keV the best method of detecting low intensity transitions in this decay is with the curved-crystal spectrometer since these low-intensity, low-energy lines are not at all observable in the singles spectra obtained with the Ge(Li) spectrometer. With the curved-crystal spectrometer the diffraction profile of even very weak low energy lines are easily discernible above the small non-varying background.

Appendix

A study is in progress concerning the reflecting properties of our Ge(0$\bar{2}$2) crystal. This crystal was obtained by ordering the Ge(422) planes and bending the crystal in this (422) orientation. The crystal was then unclamped, rotated 90° and bent with this new orientation. A new set of planes appeared to be causing reflection and from their apparent spacing (2.000 A^0) and the fact that they must be perpendicular to the 422 planes we assigned the (0$\bar{2}$2) orientation to them. Using the intense 134, 479 and 686 keV lines in the decay of ^{187}W, we have done a rough determination of the variation of peak reflection efficiency as a function of gamma-ray energy for the first- and second-order reflection from the Ge(0$\bar{2}$2) planes. The corrections for source and air absorption, and possible small misalignment of the collimator were avoided by comparing the peak intensity of each diffraction profile using the Ge($0\bar{2}2$) planes for each gamma-ray energy with the gamma-ray intensity determined for each energy using the quartz (310) planes and using the well established [10]) reflectivity energy dependence of E^{-2} for the quartz (310) planes. In this way we have determined that for first-order reflection from the Ge($0\bar{2}2$) planes the reflectivity goes as E^{-k}, where $0.47 \leqq k \leqq 0.65$ in the region 134–686 keV. For second-order reflection we find $0.6 \leqq k \leqq 1.2$. These are remarkable results since until now there has been no evidence for a k value much different from 2 for either curved quartz or germanium crystals. As a tool for measuring gamma-ray energies, this is a very important fact since it means that the reflectivity of the Ge($0\bar{2}2$) does not decrease nearly so rapidly as it does with the Ge(400) where [12]) $k \approx 2$. For $k = 0.5$ an increase of a factor of ten in gamma-ray energy only results in a decrease of a factor of 3.2 in reflection efficiency, whereas the decrease is a factor of 100 for $k = 2$.

Note added in proof: Since the completion of this work Bisgård *et al.* [13]) have presented some work on the decay of ^{187}W. The decay scheme presented by these authors is similar to the one shown in our work with the addition of a level at 582 keV. However, Bisgård *et al.* (private communication) have revised the energy of this level to a value of 589 keV. A 36 keV transition which would now depopulate the 625 keV state is proposed to feed the 589 keV level. A similar interpretation has also been presented by us [14]).

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