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DECAY OF Se^{81m} AND Se^{81}

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Abstract: The gamma rays in Se^{81} and Br^{81} following the decay of Se^{81m} and Se^{81} were studied with a magnetic spectrograph. Three internal conversion lines were observed in these measurements. Gamma-ray spectra taken with a NaI(Tl) detector indicated a transition at 30 keV in addition to previously reported gamma rays. Measurements were made of spectra of gamma rays in coincidence with gamma rays in five energy regions. The results indicate levels at 280 keV, 560 keV and 832 keV in Br^{81} and agree with the main features of the decay scheme proposed by Krause *et al.* Beta-gamma coincidence measurements showed that the 560 keV level in Br^{81} is a different level than the 550 keV level which is excited in (p, γ) and (γ, γ') reactions. Intensities of the transitions were computed.

1. Introduction

The ground state of Se^{81} decays to Br^{81} via beta emission with a half-life of 18.6 min. [1-3]). A metastable level at 103 keV in Se^{81} has a half-life of 57 min and decays to the Se^{81} ground state [1-5]). The 103-keV transition has been observed in internal conversion measurements [2,4,5]).

Krause *et al.* [1]) observed transitions at 103, 282, 565 and 820 keV in gamma-ray spectra of Se^{81m} and Se^{81}. A well-crystal spectrum indicated two coincident gamma rays at 282 keV [1]). The half-lives of the transitions at 282, 565 and 820 keV showed that they followed the decay of the Se^{81} ground state [1]). Krause *et al.* [1]) proposed a decay scheme with levels at 282, 565 and 820 keV in Br^{81}, and with gamma rays from each level to the ground state, from the 565-keV level to the 282-keV level, and possibly from the 820-keV level to the 282-keV level and/or to the 565-keV level.

The level at 282 keV in Br^{81} has been observed in Coulomb excitation [6,7]). A level at 550 ± 20 keV in Br^{81} which was produced by (p, γ) and (γ, γ') reactions has been observed to decay by two coincident gamma rays of 275 keV and with a half-life of 36.7 μsec [8,9]). Krause *et al.* [1]) did a beta-gamma coincidence measurement with beta rays of all energies in the decay of Se^{81}. The relative gamma-ray intensities observed in this measurement compared to those in the "singles" spectrum suggested that the 565-keV level has a half-life of less than 3×10^{-7} sec, and is therefore a different level than the one at 550 keV.

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Ythier and Van Lieshout [10]) have studied the decay of Se^{81m} and Se^{81} produced through a (10 MeV-d, p) reaction with Se enriched to 98 % in Se^{80}. By analysing the scintillation spectrum with a method using successive subtractions, gamma rays of 103, 168, 269, 285, 450, 545, 570, 653 and 820 keV and possibly at 200 and 400 keV were observed. Spectra taken by Ythier and Van Lieshout [10]) with the source inside and outside a well crystal suggest levels in Br^{81} at 285, 570 and 820 keV, and probably at 450, 545 and 653 keV.

Kuroyanagi [11]) has produced Se^{81m} and Se^{81} through irradiation of natural Se with various energy bremsstrahlung beams. Gamma rays at 103, 170, 275, 410, 480 550, 650 and 840 keV were observed in a scintillation spectrum. Additional gamma rays at 105, 205, 275 and 290 keV appeared in coincidence measurements. On the basis of these measurements he proposed levels at 170, 275, 410, 480, 650, 690, 840 and two levels near 550 keV. Kuroyanagi [11]) states that the intensities of the 170, 410 and 480-keV transitions are all larger than the intensity of the 550-keV gamma ray which occurs in the Se^{81} decay.

The present research was undertaken in order to resolve some of the previous uncertainties and to study the decay more completely.

2. Experimental Method

Samples of Se enriched to 96.9 % and 94.4 % in Se^{80} were irradiated in a flux of 2×10^{12} neutrons per $cm^2 \cdot sec$ in the Ford Nuclear Reactor.

The magnetic spectrograph sources were made by oxidizing the enriched Se with nitric acid, forming SeO_2. The nitric acid was evaporated, and the SeO_2 was dissolved in water and then ruled on aluminized Mylar. The elapsed time between the end of an irradiation and the start of an exposure on the photographic plate was about 2 min. While one source was in the camera, another sample was irradiated. The irradiation time averaged about 19 min and the exposure time was about 18 min. Two spectrograms of 37 and 177 exposures were taken. After each spectrogram a photographic plate was exposed for a long time with one of the samples to check for any long-lived impurities. A source of Dy^{165} was used to calibrate the plates.

The sources used in the gamma-ray measurements consisted of enriched SeO_2 dissolved in water. The samples were irradiated for periods of 10 sec to 15 min in the Ford Nuclear Reactor, and the measurements were taken between 4 min and 20 min after irradiation.

The gamma-ray detectors consisted of 5.1 cm diameter by 5.1 cm thick NaI(Tl) crystals mounted on RCA 6342A phototubes. Beta-ray shields of 6.5 mm Teflon were used in front of the gamma-ray detectors. A plastic scintillator covered with aluminized Mylar was used to detect beta rays in the coincidence measurements.

A conventional fast-slow coincidence circuit with a resolving time of 30 nsec was used in the coincidence measurements. Pulses coincident with gamma rays or beta rays in a selected energy range were fed through a linear gate and recorded on a

256-channel analyser. A Compton shield was used in both the gamma-gamma and beta-gamma coincidence measurements to prevent radiation from scattering from one detector to the second one. In all the coincidence measurements the accidental spectra were small and were subtracted to obtain the curves shown. The gamma rays in Na^{22}, Mn^{54}, Co^{57}, Ba^{133}, Cs^{137}, Au^{198} and Hg^{203} were used in energy calibrations of the spectra.

3. Results

3.1. MAGNETIC SPECTROGRAPH MEASUREMENTS

Three conversion electron lines corresponding to two gamma transitions were observed in the spectrograph measurements. The conversion electron energies and their assignments are given in table 1. In these measurements the magnetic field was adjusted so that the film would detect electrons with an energy between 8 and 130 keV. A number of possible lines were observed below an electron energy of 83 keV. In this region the high beta-ray background makes it difficult to make a positive identification of a weak electron line.

TABLE 1
Magnetic spectrograph measurements

Electron energy (keV)	Assignment (keV)			Strength [a]
83.1	K	Se^{79}	95.8	M
90.8	K	Se^{81}	103.4	S
102.5	L+M	Se^{81}	103	M

[a] S = strong, M = medium.

3.2. SCINTILLATION SPECTRA

Fig. 1 shows the gamma-ray spectrum of Se^{81m} and Se^{81} as recorded on a 256-channel analyser 6 min after the source was irradiated. In order to study the low-energy gamma rays better, the spectrum shown in fig. 2 was taken about 7 min after irradiation with an increased amplifier gain. Both spectra were taken with a source-to-crystal distance of 3 cm. Gamma rays are indictaed in the regions of 30, 103, 280, 560 and 832 keV in these spectra. A spectrum taken with a 0.04 cm Cd absorber shows a large decrease in the 30-keV to 280-keV intensity ratio, indicating that the 30-keV peak is not caused by any scattering from high energy transitions. Spectra taken over a period of 5 h after the irradiation show that the 103- keV transition decays with a half-life of 57 min. The remaining parts of the spectrum decay with a half-life of approximately 19 min immediately after irradiation and gradually change to a half-life of 57 min, indicating that the remaining gamma rays follow the decay of the ground state of Se^{81}.

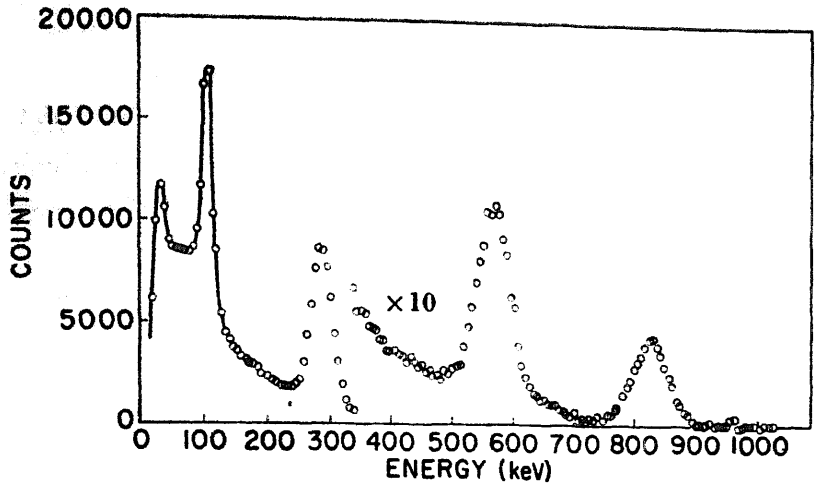

Fig. 1. Scintillation spectrum of gamma rays in the decay of Se^{81m} and Se^{81}. Above 340 keV the scale is increased by a factor 10.

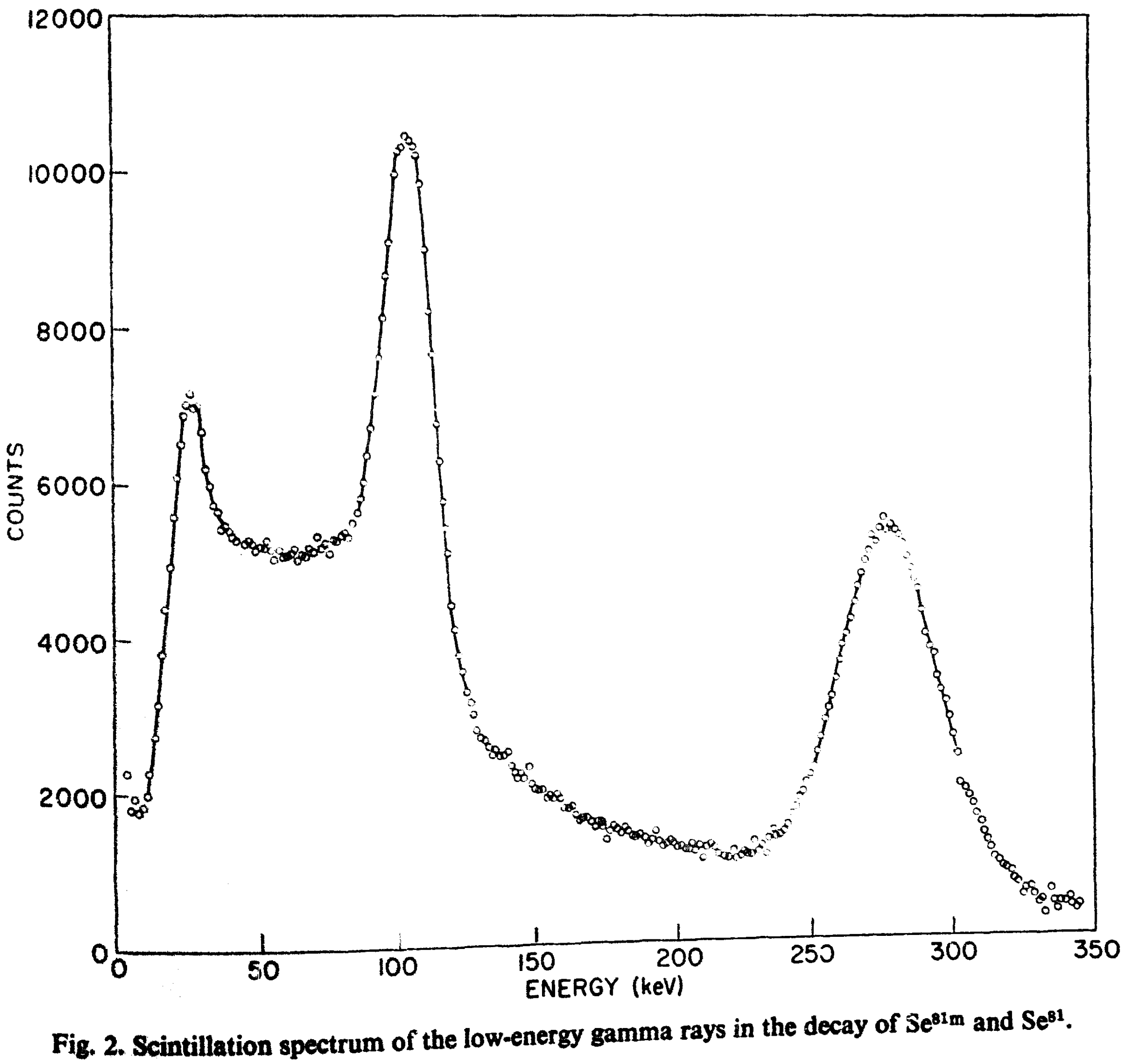

Fig. 2. Scintillation spectrum of the low-energy gamma rays in the decay of Se^{81m} and Se^{81}.

3.3 GAMMA-GAMMA COINCIDENCE MEASUREMENTS

Fig. 3 illustrates the spectrum of gamma rays in coincidence with the gamma ray in the 250- to 320-keV region. Gamma transitions are indicated at approximatel 280 and 560 keV.

The spectrum of gamma rays in coincidence with gamma rays in the 515- to 63(

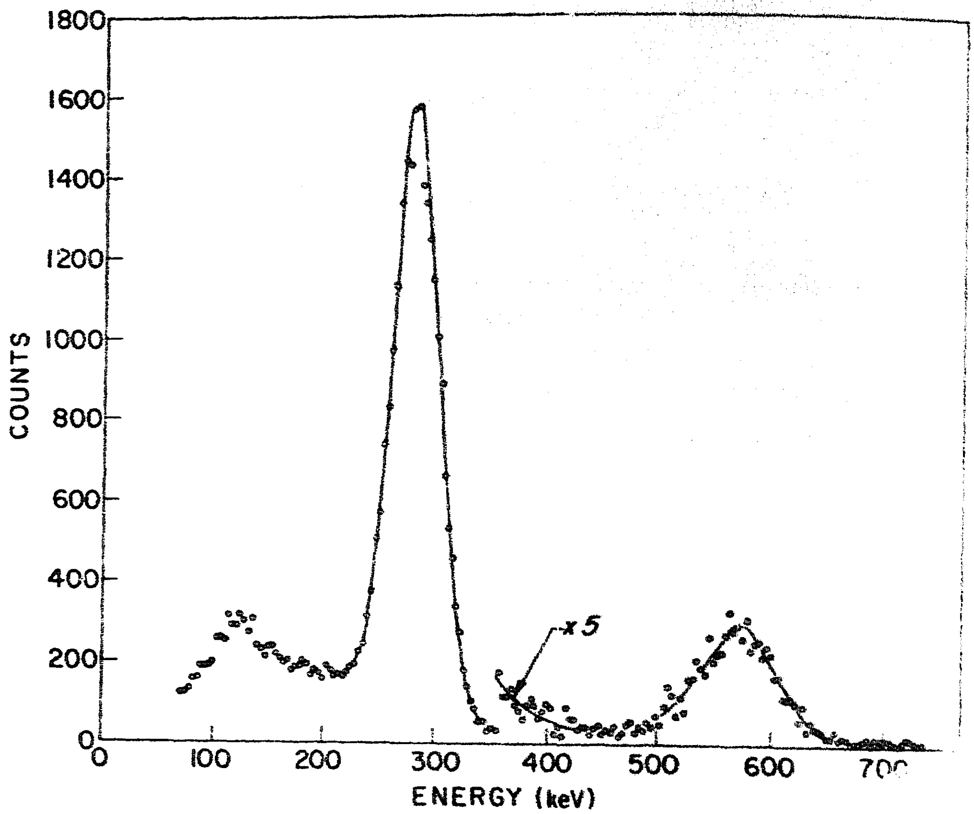

Fig. 3. Spectrum of gamma rays in coincidence with the gamma rays in the 250- to 320-keV regi(

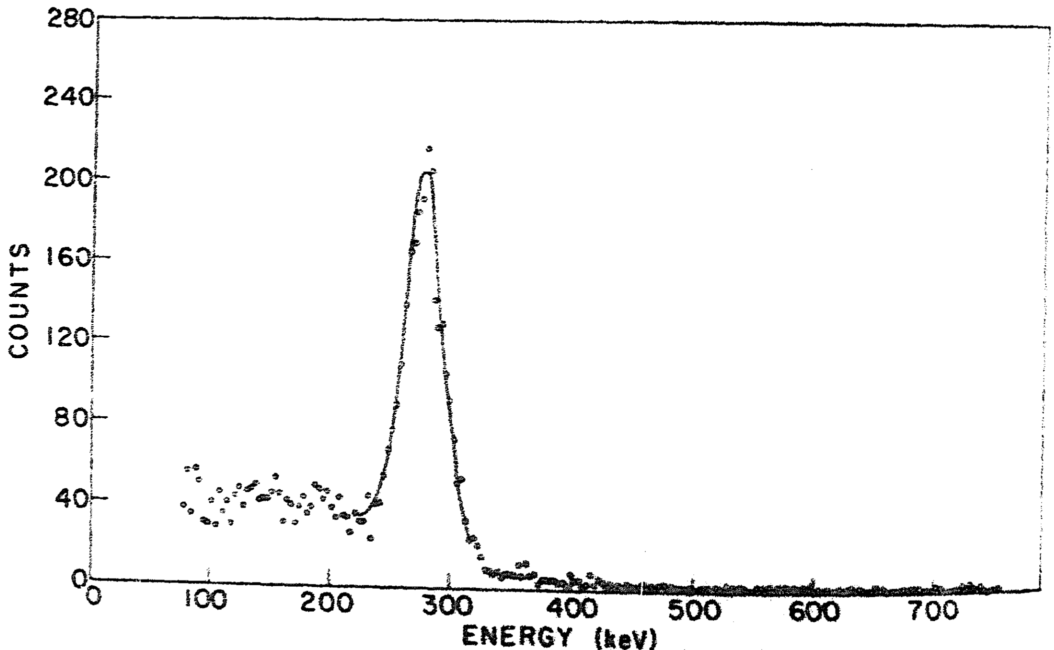

Fig. 4. Spectrum of gamma rays in coincidence with the 515- to 630-keV region.

keV region is shown in fig. 4. A coincidence is indicated at about 280 keV.

In order to study the low-energy transitions more completely, coincidence measurements with the 250- to 320-keV region and the 515- to 630- keV region were repeated so that the region from 10 to 200 keV was displayed on the analyser in both cases. No low-energy gamma rays were observed in these measurements.

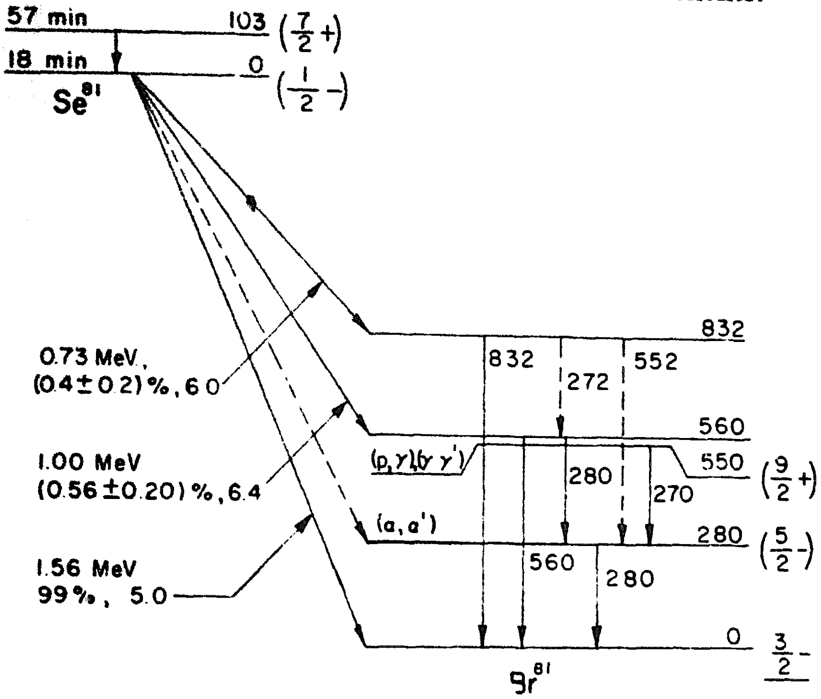

Fig. 5. Decay scheme of Se^{81m} and Se^{81}. The energies are in keV except where noted. The numbers after the beta-ray intensities are the log *ft* values.

Coincidence measurements with the 832-keV transition indicated that no gamma-rays are in coincidence with this transition.

Coincidence measurements with the 16- to 51-keV interval and also with the 45- to 68-keV interval show no coincidences in the spectra covering the 10- to 200-keV region. In the spectra covering the region up to 1 MeV, coincidence measurements with the 16- to 51-keV interval and with the 45- to 68-keV interval both indicate gamma rays at about 280 and 560 keV. These are probably due to the Compton gamma rays of higher energy transitions being detected in the 16- to 51-keV region and in the 45- to 68-keV region.

The scintillation spectra and the coincidence measurements support the decay scheme shown in fig. 5. The principal features are in agreement with the decay scheme proposed by Krause *et al.* [1]). The 560-keV level is supported by the 560-keV transition and by the two coincident gamma rays at 280 keV. Coincidence measurements with the 250- to 320-keV region and with the 515- to 630-keV region indicate the existence of the 272- and/or the 552-keV gamma ray. The approximate equal spacing of the levels makes the interpretation of the data difficult. The beta-ray energy from the Se^{81} ground state to the Br^{81} ground state shown in fig. 5 is taken from the results of Rutledge *et al.* [2]), Kuroyanagi [11]) and Ythier and Van Lieshout [10]).

3.4 BETA-GAMMA COINCIDENCE MEASUREMENTS

Several beta-gamma coincidence measurements were done in order to study more completely than in previous research the possible difference between the 560-keV

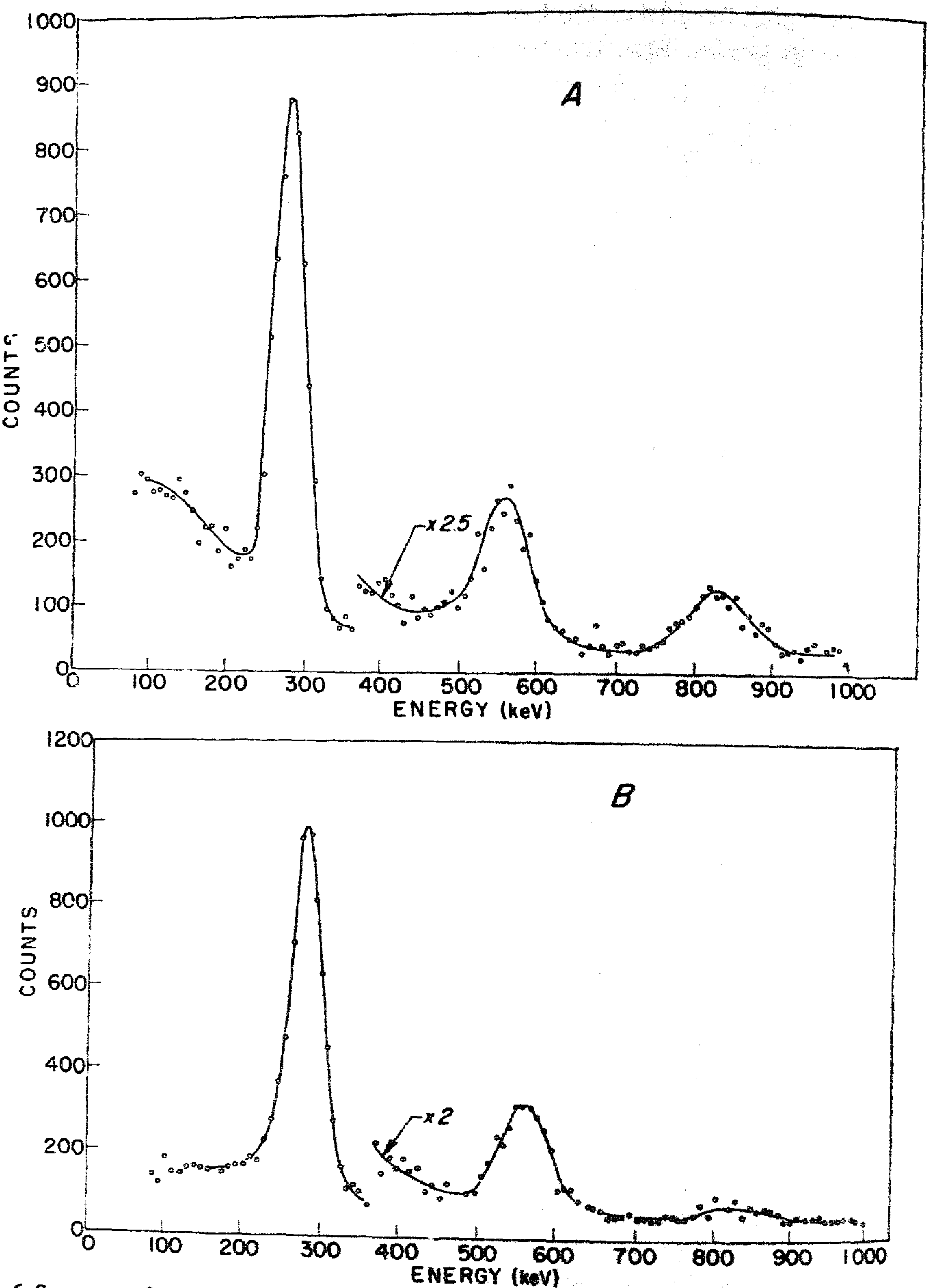

Fig. 6. Spectrum of gamma rays in coincidence with beta rays in selected energy regions in the dec of Se^{81m} and Se^{81}. Curve A is the spectrum of gamma rays in coincidence with beta rays of all energi Curve B is the spectrum of gamma rays in coincidence with beta rays above an energy of 570 ke

level occurring in the Se^{81} decay and the 550-keV level observed in (p, γ) and (γ, γ') reactions. Gamma rays in coincidence with beta rays in selected energy regions were recorded with a 256-channel analyser. Fig. 6A is the spectrum of gamma rays in coincidence with beta rays of all energies, and fig. 6B is the spectrum of gamma rays in coincidence with beta rays above an energy of 570 keV in the decay of Se^{81} and Se^{81m}. The latter discriminator setting eliminates most of the beta rays feeding the 832-keV level in preference to the beta rays feeding the lower levels in Br^{81}. The enhancement of the 560- to 832-keV intensity ratio on spectrum 6B as compared to the same ratio on spectrum 6A indicates that the 560-keV transition observed in spectrum 6B follows the 560-keV level and cannot be the 552-keV gamma ray from the 832-keV level. Therefore the 560-keV level has a half-life of less than 30 nsec and hence is definitely a different level than the 550-keV level excited in (p, γ) and (γ, γ') reactions. This conclusion is supported by the fact that the relative intensities of the gamma rays in the regions of 280, 560 and 832 keV in fig. 6A are the same, within error limits, as observed in a gamma ray "singles" spectrum. The latter result agrees with the data taken by Krause *et al.* [1]) with a fact coincidence resolving time of 3×10^{-7} sec.

4. Discussion

The 30-keV gamma ray is not indicated on the decay scheme since it did not occur in the coincidence measurements and its location in the decay scheme is uncertain. It could possibly feed the ground state of Br^{81} or a state with a longer half-life than the coincidence circuit resolving time. The lack of positive observance of the 30-keV transition in the magnetic spectrograph measurements can be attributed to the decreasing photographic plate efficiency for electrons below 100 keV and to the high beta-ray background.

TABLE 2

Relative intensities of the gamma-rays near 30, 280, 560 and 832 keV from the decay of Se^{81}

Gamma-ray energy (keV)	Relative gamma-ray intensities (normalized to gamma-rays in 280-keV region)
30	0.24 ± 0.08
272 280 280	1.00
552 and 560	0.37 ± 0.08
832	0.25 ± 0.06

The large number of counts between 30 and 103 keV are probable due to the iodine x-ray escape peak for the 103-keV gamma-ray, the Compton gamma-rays from higher-energy transitions, and the bremsstrahlung background. The latter contribution is large because of the high intensity of the beta ray between the ground states of Se^{81} and Br^{81}. The bremsstrahlung observed in the gamma-ray spectra has a broad peak at approximately 40 keV, since the low-energy gamma rays are attenuated by the absorbers. The bremsstrahlung also accounts for approximately one-half of the count between the photopeaks at 103-keV and in the 280-keV region.

Table 2 shows the relative intensities of the gamma-rays near 30, 280, 560 and 83 keV occurring in the decay of Se^{81} as computed from a "singles" spectrum. The dat were corrected for absorption, crystal efficiency, peak-to-total ratio, and the iodin x-ray escape.

Krause *et al.* [1]) state that the beta decay to the 280-keV state is about 7% as stron as the beta decay to the 560-keV state. Kuroyanagi [11]) concludes that there is n beta decay to the 280-keV level.

From the spectrum of gamma rays in coincidence with the gamma rays in the 25 to 320-keV region, an upper limit may be put on the intensity of the 272-keV gamm ray and on the intensity of the 552-keV gamma ray. In the calculations the intensi of the beta ray feeding the 280-keV state was assumed to be negligible compared the intensity of the beta ray feeding the 560-keV state. Also, the internal conversio coefficients for the gamma rays with energies of 272 keV or greater were assum to be negligible in these calculations. The upper limit for the 552-keV gamma r occurs if there is no 272-keV transition; in this case the intensity ratio of the 552-ke transition to the 560-keV transition computed from the data shown in fig. 3 is 0.4 If there is no 552-keV gamma ray, then the intensity ratio of the 272-keV transiti to either of the 280-keV transitions is 0.88. The narrow width of the photopeak ne 280 keV in the "singles" spectrum indicates that this ratio is probably lower. If t 272-keV intensity is assumed equal to the 552-keV intensity, then the resulti gamma-ray intensities are as shown in table 3. The error limits are large due to t assumption.

TABLE 3

Relative intensities of the gamma-rays from Se^{81} decay

Gamma-ray energy (keV)	Relative gamma-ray intensity
30	0.12
272	0.18
280 (upper)	0.82
280 (lower)	1.00
552	0.18
560	0.57
832	0.51

The beta-ray feeding the 280-keV state is assumed to have a negligible intensity, and the intensi of the 272- and 552-keV gamma rays are assumed to be equal. The error limits are large due to assumptions.

Apparently the additional gamma-rays observed by Kuroyanagi [11]) and by Yth and Van Lieshout [10]) are due to impurities.

A gamma-ray spectrum taken $5\frac{1}{2}$ h after irradiating the source was used in determining the beta-ray branching for the beta rays from Se^{81}. After this amount of time, the original Se^{81} has practically all decayed, and the Se^{81m} and Se^{81} have reached equilibrium. This spectrum showed that the intensity ratio of the transitions in the region of 280 keV compared to the 103-keV transition is 0.0136 ± 0.0035. Corrections were made for absorption, photopeak-to-total area, iodine x-ray escape peak, crystal efficiency, and the 103-keV internal conversion coefficient in obtaining this ratio. A K-shell internal conversion coefficient of 8.6 ± 2.4 and a $K/(L+M)$ ratio of 4.0 ± 0.2 were used for the 103-keV gamma ray [5]; the internal conversion coefficients for any of the gamma-rays near 280 keV were assumed to be negligible. In order to determine the branching of the beta rays from Se^{81} feeding the excited states in Br^{81} compared to the beta ray feeding the ground state, an additional factor was used to account for the different half-lives of Se^{81m} and Se^{81}. Combining these data with the gamma-ray intensities shown in table 3, the beta-ray intensities and resulting log *ft* values shown in fig. 5 were obtained.

The ground state of Br^{81} has been measured [12]) to have a spin and pairty of $\frac{3}{2}-$, which corresponds to the $p_{\frac{3}{2}}$ state in the shell model theory. The allowed character of the beta transition between the ground states of Se^{81} and Br^{81} indicates that Se^{81} has a spin of $\frac{1}{2}-$, $\frac{3}{2}-$ or $\frac{5}{2}-$. The 280-keV level in Br^{81} has been reached by Coulomb excitation [6, 7]); therefore, its spin and parity is limited to half integers between $\frac{1}{2}-$ and $\frac{7}{2}-$. The negligible intensity [1, 11]) of the beta ray from Se^{81} to the 280-keV level in Br^{81} indicates that the spin change between the two levels should be at least two, since a smaller spin would indicate an allowed beta-ray transition.

Spins of $\frac{5}{2}-$ for the 280-keV level and $\frac{1}{2}-$ for the Se^{81} ground state fit the above requirements. A spin of $\frac{1}{2}-$ for Se^{81} corresponds to a $p_{\frac{1}{2}}$ level in the shell model. In this case the 103-keV level in Se^{81} would have a spin of $\frac{7}{2}+$, since the half-life and $K/(L+M)$ ratio indicate that the 103-keV transition is E3 [1-5, 13]). The lack of a strong beta-ray from the ground state of Se^{81} to the 550-keV level [1, 11]), the lack of an observed 550-keV gamma ray [8, 9]) and the M2 nature of the 270-keV gamma ray, as indicated by the 37 μsec half-life for the 550-keV level [8, 9, 13]), suggest $\frac{9}{2}+$ as a possible spin for this level. This is analogous to the $\frac{9}{2}+$ level at 208 keV in Br^{79} with a half-life of 4.8 sec. [9, 14]). The log *ft* values and gamma-ray intensities suggest a spin of $\frac{3}{2}+$ for the 560-keV level and a spin of $\frac{1}{2}+$ or $\frac{3}{2}+$ for the 832-keV level. Krause *et al.* [1]) observed that the beta decay from Se^{81m} to the excited levels in Br^{81} must have an intensity smaller than 0.4% of the Se^{81m} decay, and Kuroyanagi [11]) states that an upper limit for the intensity of the beta ray from Se^{81m} to the 550-keV level is 0.005% of the total decay intensity for Se^{81m}. These data indicate that this beta ray has a log *ft* value of 7 of higher, and that it is somewhat hindered from the allowed transition probability suggested by the spins of the associated levels.

Other spin assignments are possible, but are less likely due to the observed beta-ray and gamma-ray intensities and the gamma-ray multipolarities.

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