Energy Levels of Br^{81} Populated by the Decay of Se^{81m} and Se^{81}†

Soedijono Prawirosoehardjo*
Department of Nuclear Engineering and Department of Physics, The Pennsylvania State University, University Park, Pennsylvania

(Received 3 January 1967)

The γ rays following the decay of Se^{81m} ($T_{1/2}=57$ min) and Se^{81} ($T_{1/2}=18$ min) were investigated using a Ge(Li) detector, a γ-γ coincidence apparatus, and a high-pressure gas proportional counter. Se^{81m} and Se^{81} were produced by neutron bombardment of 94.4% enriched Se^{80} and natural selenium. Nine γ rays have been identified as belonging to the decay of Se^{81m} and Se^{81} by using the Ge(Li) detector. The energies (in keV) and relative intensities (in brackets) of these γ rays are as follows. Se^{81m}: 103.3 ± 0.2 (100) and 1146 ± 2 (3.4 ± 0.6). Se^{81}: 276.3 ± 0.4 (100), 290.2 ± 0.4 (79.6 ± 5.6), 538.7 ± 0.7 (6.2 ± 0.7), 552.7 ± 0.7 (12.8 ± 1.4), 566.1 ± 0.7 (28.9 ± 2.6), 650.4 ± 0.9 (2.6 ± 0.4), and 829.2 ± 0.8 (36.6 ± 2.6). A γ ray of energy 180 ± 2 keV (relative intensity$=0.94\pm0.19$) has also been attributed to Se^{81} through γ-γ coincidence measurements. An energy-level scheme of Br^{81} populated by the decay of Se^{81m} and Se^{81} has been proposed by introducing levels at 276, 566, 650, 815, 829, and 1146 keV. The 1146-keV level is fed by a direct β decay of Se^{81m} with a transition intensity of (0.34 ± 0.13)%. The β-decay transition intensities of Se^{81} to the 0-, 566-, 650-, 815-, and 829-keV levels of Br^{81} were computed to be (98.8 ± 0.33)%, (0.76 ± 0.21)%, (0.014 ± 0.006)%, (0.042 ± 0.013)%, and (0.36 ± 0.10)%, respectively.

I. INTRODUCTION

THE decay of Se^{81m} with a half-life of 57 min to the ground state of Se^{81} is accompanied by the emission of a 103-keV γ ray which is strongly converted.[1–6] The ground state of Se^{81} decays to Br^{81} by $\beta-$ emission with a half-life of 18 min.[1–6] γ rays from Se^{81m} and Se^{81}, as reported by several different investigators,[2–6] are summarized in Table I. These investigations were carried out for the most part using scintillation methods.

In view of the discrepancies in these results, the present work was undertaken to make more accurate measurements of the energy and intensity of each γ ray belonging to Se^{81} or Se^{81m} by using a Ge(Li) detector, and to search for coincidences between these γ rays in order to clarify the energy-level structure of Br^{81}.

II. EXPERIMENTAL METHODS

A lithium-drifted germanium detector with sensitive area $\sim$100 mm² and sensitive depth $\sim$2.2 mm was used for single-spectrum measurements. With the detector operated at -200 V and 77°K, the resolution full width at half-maximum (FWHM), and intrinsic full energy peak efficiency for a 662-keV γ ray were 8.4 keV and 0.44%, respectively. The linearity of the system was found to be better than 0.3% for an energy region from 100 to 1500 keV.

Two 3 in.×3 in. NaI(Tl) crystals placed at a 90° angle to each other, with a lead anti-Compton shield placed between the two detectors, were used for γ-γ coincidence measurements. The system had a resolving time $2\tau\sim70$ nsec and the arrangement was such that the accidental coincidences could be obtained simultaneously with the sum of the true and accidental coincidences.

A gas proportional γ-ray spectrometer was used to search for γ rays in the low-energy region (3–30 keV). The resolution (FWHM) of this system for an 8.0-keV x ray was found to be about 2.3 keV.

Se^{81m} and Se^{81} were produced by irradiating both enriched Se^{80} and natural selenium with neutrons in the Pennsylvania State University Research Reactor. Con-

Table I. Gamma rays from Se^{81m} and Se^{81} as reported by different authors.

Krause *et al.*[a] (keV)	Ythier and Van Lieshout[b] (keV)	Kuroyanagi[c] (keV)	Pratt and Sattler[d] (keV)	Sund and Wiedenbeck[e] (keV)
				30
103	103	103	104	103
		105	110[f]	
	168	170	180	
	200[f]	205		
	269	275		272
282	285	290	282	280
	400[f]	410		
			428	
	450	480		
	545		545	552
565	570	550	565	560
	653	650	647	
820	820	840	827	832

[a] See Ref. 2.
[b] See Ref. 3.
[c] See Ref. 4.
[d] See Ref. 5.
[e] See Ref. 6.
[f] The presence of these γ rays is uncertain.

† This paper is based on a Ph.D. thesis submitted to the Pennsylvania State University, December, 1966.
* Present address: Department of Physics, Bandung Institute of Technology, Bandung, Indonesia.
[1] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.), NRC 59-1-64.
[2] I. Y. Krause, W. D. Schmidt-Ott, K. W. Hoffmann, and A. Flammersfeld, Z. Physik **157**, 106 (1959).
[3] C. Ythier and R. Van Lieshout, J. Phys. Radium **21**, 470 (1960).
[4] T. Kuroyanagi, J. Phys. Soc. Japan **15**, 2179 (1960).
[5] W. W. Pratt and A. R. Sattler, Pennsylvania State University Report (unpublished).
[6] R. E. Sund and M. L. Wiedenbeck, Nucl. Phys. **38**, 478 (1962).

taminant peaks from Se^{75} (120 day), Se^{79m} (3.9 min), Se^{83} (25 min), and Na^{24} (15 h) were sometimes observed, especially in the spectra taken with natural-selenium samples.

III. RESULTS

A. Lithium-Drifted Germanium Detector Measurements

1. *γ-Ray Spectrum*

The energy difference between the Se^{81m} level and the ground state of Br^{81} has been found[3,4] to be about 1660 keV. Therefore, the investigation of γ rays following the decay of Se^{81m} and Se^{81} was carried out for energies up to about 1700 keV.

Figure 1 shows the spectrum of γ rays taken with the Ge(Li) detector in the energy region from about 50 to 315 keV. γ-ray peaks at 103, 276, and 290 keV are clearly visible. The 103-keV γ ray is assigned to the isomeric transition of Se^{81m}, as reported by the previous investigators.[1–6] The 276- and 290-keV γ rays are believed to be attributable to Se^{81} for reasons which will be discussed below. From energy and half-life measurements the peak at 136 keV and the faint hump at 121 keV are identified as belonging to Se^{75}. A broad hump at ~78 keV appears to indicate γ rays (or x rays) of more than one energy. Half-life measurement indicates that these cannot be attributed to Se^{81m} or Se^{81}.

The spectrum in the 310- to 740-keV region is shown in Fig. 2. Peaks at 401, 511, 539, 553, 566, and 650 keV are clearly visible. From energy and half-life measurements the 401-keV γ ray is attributed to Se^{75}, and the peak at 511 keV is due to annihilation radiation from the contaminants. The peaks at 539, 553, 566, and 650 keV are believed to be attributable to Se^{81} for reasons which will be discussed below.

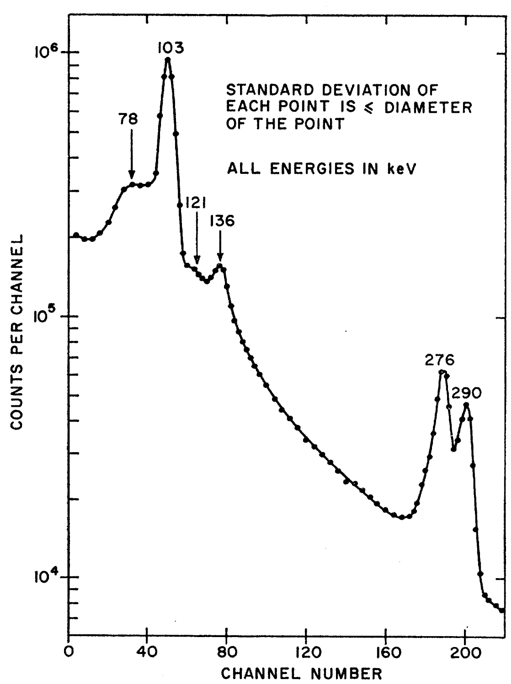

FIG. 1. γ spectrum of Se^{81m} and Se^{81} using a Ge(Li) detector. Energy region 50–315 keV; sample: enriched Se^{80}.

Figure 3 shows the spectrum in the 700- to 1800-keV region. Peaks at 829, 1146, 1368, and 1732 keV are clearly visible. From energy and half-life measurements the 1368- and 1732-keV peaks are attributed to Na^{24}. The latter is a double escape peak from the 2754-keV γ ray of Na^{24}. The 829-keV peak is well known as belonging to Se^{81}. From half-life measurements, described below, the 1146-keV peak appears to belong to direct β decay of Se^{81m}.

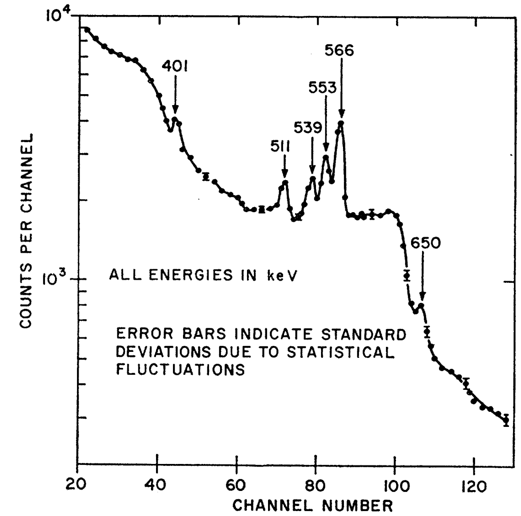

FIG. 2. γ spectrum of Se^{81m} and Se^{81} using a Ge(Li) detector. Energy region 310–740 keV; sample: enriched Se^{80}.

The γ-ray spectrum in the energy region from 60 to 3 keV, taken both with the Ge(Li) and gas proportional detectors, indicates that there are no observable γ rays in this energy region attributable to Se^{81m} or Se^{81}.

2. *Spectrum Comparison Measurements*

Samples of 94.4% enriched Se^{80} and of natural selenium containing the same amount of Se^{80} were used to obtain two γ-ray spectra. Under the same experimental conditions, namely, the same amount of irradiation in the reactor, source to detector distance, waiting time, and counting period, the peaks belonging to Se^{81m} and Se^{81} would appear at about the same strength in both spectra. These spectrum-comparison measurements indicate that the 103-, 276-, 290-, 539-, 553-, 566-, 650-, and 829-keV γ rays can be assigned to the decay of Se^{81m} and Se^{81}.

3. *Half-Life Comparison Measurements*

The ratios of the areas under the 276-, 290-, 539-, 553-, 566-, and 650-keV peaks to that of the 829-keV peak in the same spectrum were measured. The ratio measurements were carried out for spectra taken with several different waiting times. The results for five different waiting times up to about 2 h are shown in Fig. 4. The straight lines are least-square fits to the data. Within an error of about 13% the ratios for each peak are constant with waiting times of up to about 2 h. Since the 829-keV γ ray is well known as belonging to Se^{81}, it is concluded that the 276-, 290-, 539-, 553-, 566-, and 650-keV γ rays may be attributed to Se^{81}.

4. *Investigation of the 1146-keV γ Ray*

The half-life of the 1146-keV γ ray was measured directly. Since the peak due to this γ ray is weak and

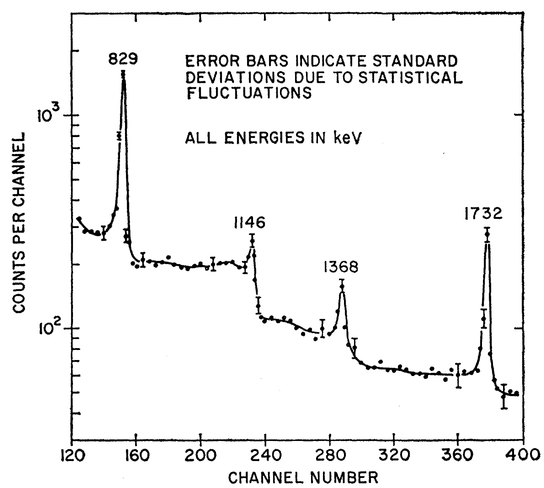

FIG. 3. γ spectrum of Se^{81m} and Se^{81} using a Ge(Li) detector. Energy region 700–1800 keV; sample: enriched Se^{80}.

is superimposed on the Compton edge of the 1368-keV peak of Na^{24}, the measurements could only be carried out with waiting times up to about 100 min. Data with enriched Se^{80} samples irradiated several times were accumulated in the multichannel analyzer to obtain better statistics. A decay curve of this peak is shown in Fig. 5. The half-life of the 1146-keV γ rays was found to be 59±3 min. A decay curve of the 829-keV γ ray of Se^{81} is also shown in Fig. 5 for comparison. Since the half-life of Se^{81m} is about 57 min, the 1146-keV γ ray is presumably due to a direct β decay from Se^{81m} to an excited level of Br^{81}.

5. *Energy and Relative-Intensity Determinations*

Seven γ rays of energies 276, 290, 539, 553, 566, 650, and 829 keV have been identified as belonging to Se^{81} by using the Ge(Li) detector. In addition, γ rays of

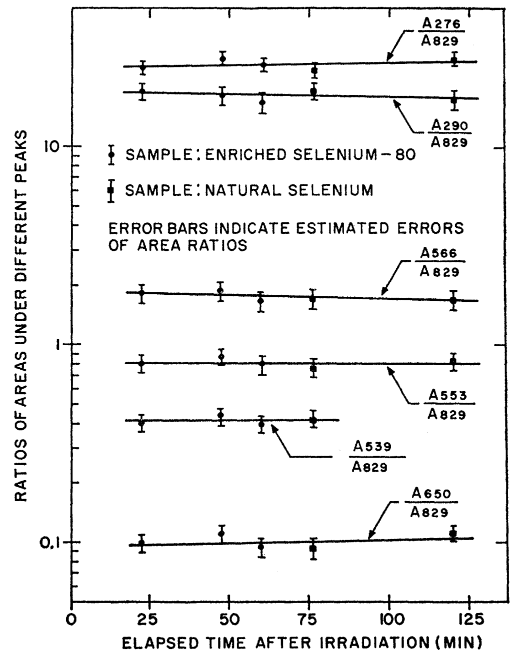

FIG. 4. Half-life comparison measurements of Se^{81} γ rays.

energies 103 and 1146 keV have been attributed to Se^{81m}.

The energies of these γ rays were determined using

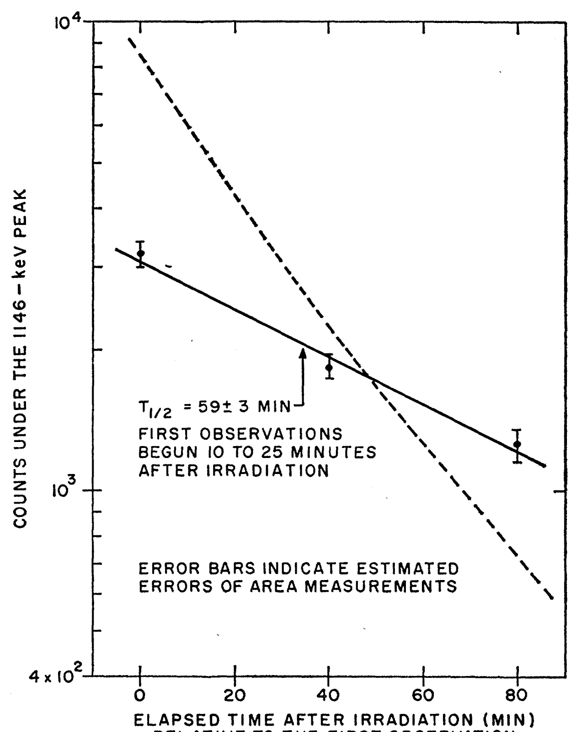

FIG. 5. Half-life measurement of the 1146-keV γ ray. The dashed curve is a decay curve of the 829-keV γ ray of Se^{81}.

TABLE II. Energies and relative intensities of Se^{81m} and Se^{81} γ rays.

Parent	Rao and Fink[a] Energy (keV)	Relative intensity[b]	Present work Energy (keV)	Relative intensity
Se^{81m}	102.7±0.5	100	103.3±0.2	100[c]
Se^{81m}			1146 ±2	3.4 ±0.6[c]
Se^{81}			180 ±2	0.94±0.19[d]
Se^{81}	275.8±0.5	10.2	276.3±0.4	100[d]
Se^{81}	289.9±0.5	8.7	290.2±0.4	79.6 ±5.6[d]
Se^{81}	539.0±0.5	0.8	538.7±0.7	6.2 ±0.7[d]
Se^{81}	553.0±0.5	1.5	552.7±0.7	12.8 ±1.4[d]
Se^{81}	566.1±0.5	2.9	566.1±0.7	28.9 ±2.6[d]
Se^{81}			650.4±0.9	2.6 ±0.4[d]
Se^{81}	829.0±0.5	4.9	829.2±0.8	36.6 ±2.6[d]

[a] See Ref. 7.
[b] Measured when Se^{81m} and Se^{81} have reached equilibrium.
[c] Relative intensities of Se^{81m} γ rays are normalized to that of the 103.3-keV γ rays, which is taken to be 100.
[d] Relative intensities of Se^{81} γ rays are normalized to that of the 276.3-keV γ rays, which is taken to be 100.

standard energy-calibration sources of Se^{75}, Cr^{51}, Au^{198}, Cu^{64}, Bi^{207}, Cs^{137}, Mn^{56}, Sc^{46}, Zn^{65}, and Co^{60}. The relative intensities were measured with the aid of the relative full energy peak efficiency curve of the Ge(Li) detector obtained experimentally using calibration sources of Se^{75}, Bi^{207}, Sc^{46}, and Co^{60}. The results of these measurements are listed in Table II together with the values of Rao and Fink,[7] who have recently reported measurements similar to ours.

The 180-keV γ ray listed in Table II was found to belong to Se^{81} in the γ-γ coincidence measurements to be described below.

B. γ-γ Coincidence Measurements

The spectrum of the γ rays in coincidence with γ rays in the 250- to 320-keV region is shown in Fig. 6. Two peaks at 280 and 550 keV are clearly visible in the spectrum. The 136-keV peak is a backscatter peak of γ rays at energies in the region of 280 keV.

Figure 7 shows the spectrum of γ rays in coincidence with γ rays in the 510- to 590-keV region. The 280-keV peak is clearly visible in the spectrum in addition to the 136-keV backscatter peak.

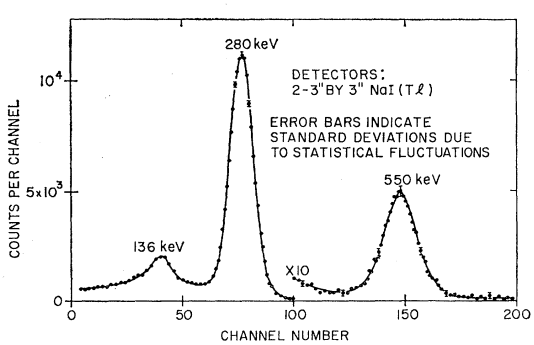

FIG. 6. Spectrum of Br^{81} γ rays in coincidence with γ rays in the 250- to 320-keV region.

When gating in the energy region from 620 to 680 keV (centered at 650 keV) a relatively weak peak at energy 180 keV was present in the spectrum. Figure 8 shows the cumulative spectrum obtained with a number of sources. Precautions were taken to avoid artificial coincidences due to effects of crystal-to-crystal scattering. Therefore, the 180-keV γ ray must also belong to Se^{81}. The energy was measured to be 180±2 keV.

Coincidence measurements with gates centered at 829 and 1146 keV, respectively, indicated that no γ rays are in coincidence, to an observable extent, with these transitions. Coincidence measurements gating in several other energy regions were also performed, but no new information was obtained.

C. Energy Levels of Br^{81}

The presence of the 276-, 290-, and 566-keV γ rays having relative intensities 100, 80, and 29, respectively,

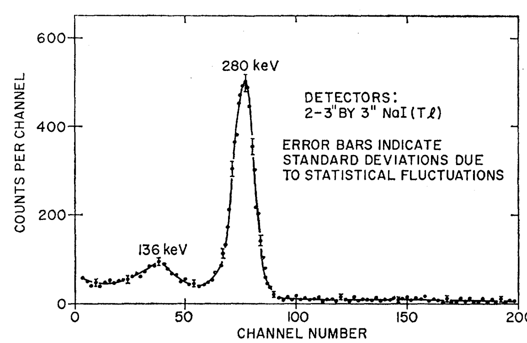

FIG. 7. Spectrum of Br^{81} γ rays in coincidence with γ rays in the 510- to 590-keV region.

and the information from the coincidence spectrum gated at energies from 250 to 320 keV indicate the presence of levels in Br^{81} at 276 and 566 keV. The 566-keV level decays to the ground state directly and by two cascade γ rays of energies 290 and 276 keV. The absence of an appreciable number of γ rays in coincidence with the 829- and 1146-keV γ rays indicates that there are levels at 829 and 1146 keV. The 1146-keV level is fed by a direct β decay of Se^{81m} which has not been reported previously. The 829-keV level decays to the ground state directly and also by the emission of 553-keV γ rays to the 276-keV level. This assumption is supported by the presence of 553-keV γ rays and by the information from the coincidence spectra gating in the 250- to 320-keV and the 510- to 590-keV regions.

Assuming the partial energy-level scheme of Br^{81} which has just been proposed, the relative intensity of transitions in the region of 550 keV which are in coincidence with γ rays in the 250- to 320-keV region can be determined by measuring the ratio of the areas

[7] P. Venugopala Rao and R. W. Fink, Bull. Am. Phys. Soc. 11, 824 (1966); Phys. Rev. (to be published).

under the 280- and 550-keV peaks (see Fig. 6). A value of 18.3±2.7 was obtained for the relative intensity of such a transition. In the energy-level scheme proposed so far only the 553-keV γ ray (relative intensity ~13) is in coincidence with γ rays in the 250- to 320-keV region. Therefore, a level at 815 keV is introduced in Br^{81} which decays by the emission of 539-keV γ rays to the 276-keV level. This assumption is supported by (1) the presence of 539-keV γ rays, (2) the fact that the total relative intensity of the 539- and 553-keV γ rays, equal to 19±2, is in agreement with the value of 18.3±2.7 for the relative intensity of the transition in the region of 550 keV which is in coincidence with γ rays in the 250- to 320-keV region, and (3) the fact that there is no appreciable transition in the region of 550 keV in coincidence with γ rays in the 510- to 590-keV region, as would be expected if a level were to be postulated at 1105 keV (see Fig. 7).

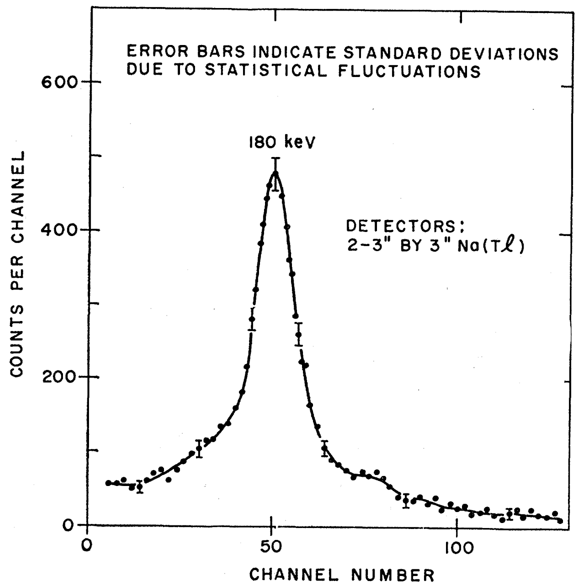

FIG. 8. Spectrum of Br^{81} γ rays in coincidence with γ rays in the 620- to 680-keV region.

The relative intensity of the 180-keV γ rays was determined by taking two coincidence spectra similar to those in Figs. 7 and 8 simultaneously, and then measuring the ratio of the areas under the 180- and 280-keV peaks. A value of 0.94±0.19 was obtained. The fact that the 650- and 180-keV γ rays are in coincidence and the relative intensity of the 650-keV γ rays is larger than that of the 180-keV γ rays suggests the presence of a level at 650 keV in Br^{81}. The 180-keV γ ray is then a transition between the 829- and 650-keV levels.

D. β-Decay Transition-Intensity Determinations

β-decay transition intensities of Se^{81} were determined by measuring the intensity ratio of the transitions in the region of 280 keV to that of 103 keV using a 3 in.×3 in. NaI(Tl) crystal, and then combining the result with the measured relative intensities of all of the γ rays belonging to Se^{81}. γ-ray spectra were obtained 5 to 6 h after the irradiation of the sample. At this time practically all the original Se^{81} had decayed, and the Se^{81m} and Se^{81} had reached equilibrium. Correction factors due to absorption, photopeak to total ratio, total detection efficiency of the crystal, internal conversion coefficient of the 103-keV γ ray, and the different half-lives of Se^{81m} and Se^{81} were used in the transition-intensity determinations. In these measurements the following assumptions are made: (1) No transition occurs between the 829- and 815-keV levels; (2) the internal conversion coefficients of all of the γ transitions in Br^{81} are negligible because the transitions are expected to have low multipole order; (3) no appreciable β decay from Se^{81} to the 276-keV level of Br^{81} is assumed to occur because spins $\frac{1}{2}^-$ of the Se^{81} ground state[8,9] and $\frac{5}{2}^-$ of the 276-keV level[10–12] of Br^{81} indicate that such a transition is second forbidden.

The direct-β-decay transition intensity of Se^{81m} to the 1146-keV level of Br^{81} was determined from the measured value of the relative intensity of the 1146-keV γ ray and the value of the internal conversion coefficient of the 103-keV γ ray.

The values of the transition intensities of the various β groups in the Se^{81} and Se^{81m} decay obtained in the present measurements are listed in Table III together with associated maximum energies, levels of Br^{81}, and logft values computed from the work of Moszkowski.[13]

TABLE III. Beta decay of Se^{81m} and Se^{81}.

Parent	Maximum β energy (MeV)	Br^{81} level (keV)	Percent of total decay	log ft
Se^{81m}	0.517	1146	0.34 ±0.13	6.1
Se^{81}	1.560[a]	ground	98.8 ±0.33	5.0
Se^{81}	0.994	566	0.76 ±0.21	6.2
Se^{81}	0.910	650	0.014±0.006	7.9
Se^{81}	0.745	815	0.042±0.013	7.1
Se^{81}	0.731	829	0.36 ±0.10	6.1

[a] Adopted from Refs. 3 and 4.

IV. CONCLUSIONS

Levels in Br^{81} at 276, 566, 650, 815, 829, and 1146 keV have been found to be populated by the decay of Se^{81m} and Se^{81}. The 1146-keV level, which is fed by a direct β decay from Se^{81m}, decays directly to the ground state. The presence of an 1146-keV level in Br^{81} has

[8] M. Mayer, S. Moszkowski, and L. Nordheim, Rev. Mod. Phys. **23**, 315 (1951).
[9] E. K. Lin, Phys. Rev. **139**, B340 (1965).
[10] A. Goodman and A. W. Schardt, Bull. Am. Phys. Soc. **4**, 56 (1959).
[11] R. L. Robinson, F. K. McGowan, and P. H. Stelson, Oak Ridge National Laboratory Report No. ORNL-3582, 1964 (unpublished).
[12] A. P. Arya and H. C. Long, Bull. Am. Phys. Soc. **8**, 86 (1963).
[13] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).

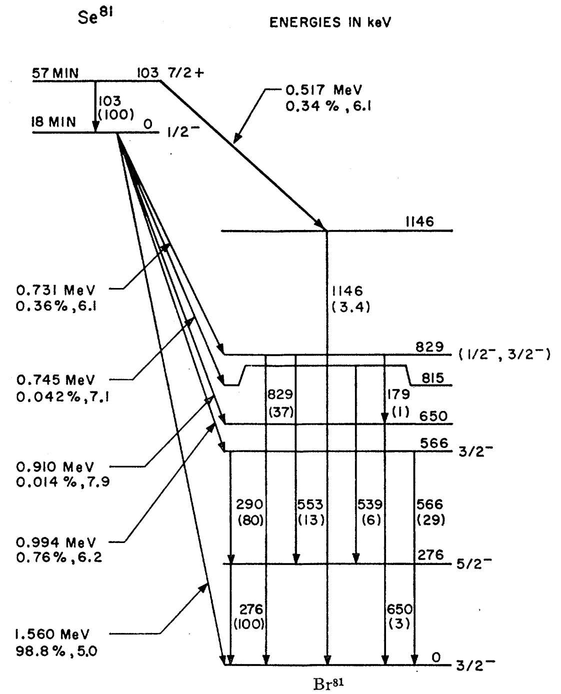

FIG. 9. Proposed energy-level scheme of Br^{81} populated by the decay of Se^{81m} and Se^{81}. Numbers in parentheses ( ) correspond to relative intensities. Relative intensities of Se^{81m} γ rays are normalized to that of the 103-keV γ rays, which is taken to be 100 and those of Se^{81} γ rays are normalized to that of the 276-keV γ rays, which is also taken to be 100.

not been reported previously. The 829-keV level decays to the ground state directly, to the 276-keV level by the emission of 553-keV γ rays, and to the 650-keV level by the emission of 179-keV γ rays. The 815-keV level, which also has not been reported previously, decays by the emission of 539-keV γ rays to the 276-keV level. (Instead of a level at 815 keV, Rao and Fink[7] propose a level at 539.0 keV with possible spin parity of $\frac{5}{2}^-$ or $\frac{7}{2}^-$.) The 566-keV level decays to the ground state directly and by cascade γ rays of energies 290 and 276 keV, respectively. The 650-keV level decays only to the ground state. The decay scheme of Se^{81} and Se^{81m} obtained as a result of the present work is shown in Fig. 9.

The ground-state spin of Br^{81} has been measured[14] to be $\frac{3}{2}^-$. The Se^{81} ground state is known as a $\frac{1}{2}^-$ state.[8,9] These assignments are consistent with the present result that the β-decay transition of Se^{81} to the ground state of Br^{81} has an intensity which has been measured to be 98.8% ($\log ft = 5.0$) which indicates an allowed transition. Spins and parities $\frac{5}{2}^-$ and $\frac{3}{2}^-$ of the 276- and 566-keV levels, respectively, have been deduced from Coulomb excitation in Br^{81}, angular-distribution measurements of the 276-keV γ rays, and angular-correlation measurements of the 276- and 290-keV γ rays.[10–12] The β transition from Se^{81} to the 566-keV level will consequently be an allowed transition. Allowed transitions with $\log ft$ value 6.2 or larger have frequently been observed for nuclei in this mass range.[15] The β decay from Se^{81} to the 829-keV level ($\log ft = 6.1$) is probably either an allowed or a nonunique first-forbidden transition.[15] However, the 829-keV level has been produced by $E2$ Coulomb excitation.[11] Therefore, spin and parity $\frac{1}{2}^-$ or $\frac{3}{2}^-$ may be assigned to the 829-keV level. The β decay from Se^{81} to the 650- and 815-keV levels of Br^{81} having $\log ft$ values 7.9 and 7.1, respectively, are probably nonunique first-forbidden transitions.[15] Therefore, the spins and parities of the 650- and 815-keV levels are probably either $\frac{1}{2}^+$ or $\frac{3}{2}^+$. Based on its $\log ft$ value ($=6.1$), the direct β decay from Se^{81m} to the 1146-keV level is probably either allowed or nonunique first forbidden.[15] Since the spin and parity of Se^{81m} are known[9,16] to be $\frac{7}{2}^+$, this corresponds to the spin and parity assignment of $\frac{5}{2}^\pm$, $\frac{7}{2}^\pm$, or $\frac{9}{2}^\pm$ for the 1146-keV level of Br^{81}. Spin and parity assignments for the 650-, 815-, 829-, and 1146-keV levels cannot be made unambiguously.

ACKNOWLEDGMENTS

The author wishes to thank Dr. William W. Pratt, who suggested this problem, for his continued guidance and patience while this work was in progress. Appreciation is also expressed to Dr. Thomas T. Thwaites for allowing the author to utilize the Ge(Li) detector, to the staff of The Pennsylvania State University Research Reactor for their assistance in preparing the radioactive sources, and to Dr. Anthony H. Foderaro for his advice during the author's study program in the United States.

[14] J. E. Mack, Rev. Mod. Phys. **22**, 64 (1950).

[15] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington 25, D. C.), NRC 5-5-146 (Nov. 1963).

[16] G. M. Drabkin, V. I. Orlov, and L. I. Rusinov, Izv. Akad. Nauk SSSR, Ser. Fiz. **19**, 324 (1955), Columbia Tech. transl., p. 294; Dokl. Akad. Nauk SSSR **97**, 417 (1954).