Anomalous $\frac{5}{2}^+$ States in ^{77}Se from the Decay of 56-h ^{77}Br†

D. G. SARANTITES AND B. R. ERDAL*
Department of Chemistry, Washington University, St. Louis, Missouri 63130
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The levels in ^{77}Se from the decay of 56-h ^{77}Br were investigated. From singles measurements of the γ-ray energies and intensities employing a high-resolution Ge(Li) detector, and from coincidence relationships determined in γ-γ coincidence measurements using two Ge(Li) detectors, it was established that levels at 161.9, 238.9, 249.7, 301.1, 439.5, 520.7, 581.2, 682.3, 752.2, 818.2, 824.8, 911.9, 1005.6, and 1187.5 keV are populated in the decay of 56-h ^{77}Br. From present logft values and K-shell conversion coefficients, and from previously reported (d, p) and (d, t) reaction data, many J^π values were assigned. The level structure of the anomalous $\frac{5}{2}^+$ and $\frac{7}{2}^+$ states is compared with recent calculations on the pairing-plus-quadrupole model extended to include higher shell-model orbits, with satisfactory qualitative agreement between experiment and theory.

I. INTRODUCTION

THE level structure of ^{77}Se has been the subject of a number of recent investigations, the most definitive of which will be mentioned here. Ythier and co-workers[1] have studied the levels of ^{77}Se from β^- decay of ^{77}As using Ge(Li) γ-ray detectors and found levels at 162.0, 238.8, 249.5, and 520.7 keV.

The first thorough study of the decay of ^{77}Br to ^{77}Se was that of Monaro,[2] by means of NaI(Tl) scintillation spectrometry using γ-γ coincidence, and γ-γ directional correlation techniques. Monaro assigned levels at 161, 242, 248, 440, 515, 820, and 1000 keV.

More recently, Ardisson and Ythier[3] have reinvestigated the decay of ^{77}Br using Ge(Li) detectors and they observed γ rays from 23 transitions in ^{77}Se. With the addition of a level at 824.5 keV, based on energy sums, the work of Ardisson and Ythier[3] is in good agreement with the findings of Monaro.

Levels in ^{77}Se have been also investigated by means of Coulomb excitation by Temmer and Heydenburg[4]; and recently by Robinson and co-workers,[5] who, using Ge(Li) detectors, observed γ rays at 200.6, 239.3, 250.1, and 439.8 keV from $(\alpha, \alpha'\gamma)$ Coulomb excitation.

The levels in ^{77}Se have been studied by the ^{76}Se(d, p) reaction by Macefield and co-workers[6] and by Lin.[7] From that work, levels at 170, 245, 306, 440, 522, 682, 826, 956, 1013, 1134, 1191, and 1258 keV have been assigned to ^{77}Se and some spin and parity assignments have been made from the l_n values of the transferred neutron. Spectroscopic factors[7] have been calculated from the analysis of the (d, p) data and comparisons with the predictions of the pairing theory have been made.[7]

The levels in ^{77}Se have been interpreted[2] in terms of the core-particle model[8] and the pairing-plus-quadrupole model of Kisslinger and Sorensen[9] by Lin.[7] The pairing theory does not predict[9] a low-lying $\frac{9}{2}^+$ state in ^{77}Se although a $\frac{7}{2}^+$ may arise from a more complex neutron configuration. Many low-lying positive parity $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{9}{2}$ states have been identified in the odd Se isotopes.[10] In particular, low-lying $\frac{5}{2}^+$ and $\frac{7}{2}^+$ states in ^{79}Se and ^{81}Se have been identified and characterized as "anomalous" states, together with similar states for nuclei with Z or N equal to 43, 45, and 47. Recently, Ikegami and Sano (IS)[11] have presented preliminary results of calculations attempting to explain the nature of these anomalous states on the basis of an extended pairing-plus-quadrupole model.

The detailed study of the decay of ^{77}Br to ^{77}Se was undertaken because it was thought that a significant contribution to the knowledge of the states in ^{77}Se could be made by using the high sensitivity of high-resolution Ge(Li) for detection of weak γ rays combined with the ability to perform γ-γ coincidence experiments using two such detectors. In particular, it was thought that some of the low-lying anomalous $\frac{5}{2}^+$ and $\frac{7}{2}^+$ states should be observable by γ decay from $\frac{3}{2}^-$ and $\frac{5}{2}^-$ states in ^{77}Se. Thus we were able to identify 27 new γ-ray transitions in ^{77}Se and establish five new levels populated from ^{77}Br decay. Two of these have not been observed before either from decay of ^{77}Br, or from (d, p) reaction studies.

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* Present address: Department of Chemistry, Brookhaven National Laboratory, Upton, New York 11973.

[1] C. Ythier, G. Rennuci, M. Huguet, G. Ardisson, H. Grassi, H. Maria, and J. Dalmasso, Physica **32**, 1350 (1966).
[2] S. Monaro, Nuovo Cimento **30**, 1379 (1963).
[3] G. Ardisson and C. Ythier, Physica **34**, 53 (1967).
[4] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).
[5] R. L. Robinson, F. K. McGowan, and P. H. Stelson, Phys. Rev. **125**, 1373 (1962); R. L. Robinson, P. H. Stelson, F. K. McGowan, J. L. C. Ford, Jr., and W. T. Milner, Nucl. Phys. **74**, 281 (1965).
[6] B. E. F. Macefield, R. Middleton, and D. J. Pullen, Nucl. Phys. **74**, 281 (1965).
[7] E. K. Lin, Phys. Rev. **139**, B340 (1965).
[8] A. DeShalit, Phys. Rev. **122**, 1530 (1961).
[9] L. S. Kisslinger and R. A. Sorensen, Rev. Mod. Phys. **35**, 853 (1963).
[10] A. Artna, Nucl. Data **B1**-4-1 through **B1**-4-31 (1966).
[11] H. Ikegami and M. Sano, Phys. Letters **21**, 323 (1966).

From measurements of α_K values, log*ft* values, and relative γ-ray intensities of crossover transitions, many spins and parities could be assigned.

Our work is in good agreement with the previously reported studies of Ardisson and Ythier[3] and of Monaro.[2] Our results are also in good agreement with the spin and parity assignments of Macefield *et al.*,[6] and of Lin[7] (with the possible exception of the spin of the 162-keV level).

II. EXPERIMENTAL PROCEDURES

A. Preparation of the ^{77}Br Samples

The ^{77}Br samples were produced by the ^{75}As(^{4}He, 2*n*)^{77}Br reaction, using 22-MeV ^{4}He ions from the Washington University cyclotron on As_2O_3 targets. At this energy ^{76}Br could not be detected in the samples. In a number of cases (for the singles measurements) a radiochemical purification procedure was introduced to ensure that all the observed weak transitions were associated with the 58-h ^{77}Br decay. The following purification procedure was employed. The solid As_2O_3 was leached with 10 ml of 1*M* HNO_3, 1 ml of 1*M* $NaBrO_3$ solution was added, the solution was mixed and then 2 ml of 1*M* $NaHSO_3$ solution were added. The solution was transferred to an extraction vessel. Ten ml of carbon tetrachloride were added followed by a small excess of 1*M* $KMnO_4$ solution, and the Br_2 produced was extracted by stirring. The bromine was back extracted by shaking with 1 ml of 1*M* $NaHSO_3$ and 10 ml of distilled H_2O. Finally, AgBr was precipitated and mounted for counting by addition of a small excess of Ag^+.

Essentially carrier-free samples for the measurement of conversion electrons were prepared by leaching the As_2O_3 with a few ml of dilute HNO_3, 1 ml of 1*M* $NaHSO_3$ was added, and the $^{77}Br^-$ activity was transferred by heterogeneous exchange to a Ag foil which had been previously treated with a dilute solution of Br^- and HNO_3 for a short time. Samples thus prepared were followed for decay and no contaminating activities could be detected.

B. Detection Equipment and Methods of Counting

Only Ge(Li) detectors were used for γ-ray measurements. The two coaxial detectors in these measurements had active volumes of 20 and 30 cm^3, with full widths at half-maximum of 2.4 and 3.0 keV, respectively, for the 662-keV γ ray from ^{137}Cs. These same detectors were also employed in γ-γ coincidence measurements. They were positioned at approximately 90° with a $\frac{3}{8}$ in. Pb absorber between them to minimize the cross-talk from Compton scattering. The resolving times employed were 50–100 nsec. Under these conditions the random events were less than 1% of the total coincidence events. In view of this fact, the random events were not subtracted from

TABLE I. Relative intensities of γ rays following ^{77}Br decay from γ-ray singles and conversion-electron data.

γ-ray energies (keV)	Relative γ-ray intensities	$10^3\alpha_K$	Suggested multipolarity
20.6±0.2	0.19±0.10		
77±2.0	0.1±0.05[a]		
87.8±0.1	5.36±0.20	61±11	(*E*1)
139.2±0.1	0.49±0.05		
161.9±0.1	5.2±0.2	680±100	(*E*3)
176.2±1.6	0.21±0.08[b]		
180.6±0.1	1.31±0.08		
187.0±0.1	0.33±0.04		
200.4±0.1	5.3±0.4		
231.5±0.5	0.43±0.05[b]		
238.9±0.1	100	9.6±1.3	*M*1
243.8±0.5	0.19±0.03[b]		
249.7±0.1	12.4±0.5		
270.6±0.1	1.30±0.04		
277.4±0.6	0.16±0.06[b]		
281.6±0.1	9.3±0.4	4.3±1.0	*M*1
292.8±0.6	0.12±0.06		
297.2±0.1	16.0±0.3	4.6±1.0	*M*1
303.8±0.1	4.76±0.09		
325.2±1.0	0.10±0.02[c]		
331.4±0.1	0.31±0.06		
378.5±0.1	0.23±0.07		
385.1±0.1	3.04±0.09	2.5±1.0	*M*1
419.4±0.2	0.069±0.010[c]		
439.7±0.1	6.2±0.2	3.1±0.7	*E*2(*M*1)
472.5±1.1	0.073±0.018		
484.8±0.1	3.65±0.07	1.6±0.5	*M*1(*E*2)
511.3±0.3	6.35±0.20		
521.0±0.1	90.6±0.2	1.4±0.2	*M*1(*E*2)
566.5±0.4	1.65±0.10		
568.6±0.3	3.23±0.16		
575.1±0.2	4.25±0.09		
579.4±0.1	10.8±0.2		
585.9±0.1	4.87±0.10		
610.7±0.7	0.10±0.1		
656.3±0.6	0.082±0.016[c]		
663.0±0.1	0.44±0.03		
682.3±0.6	0.064±0.030[b]		
704.6±0.2	0.10±0.01		
750.6±0.6	0.19±0.03[c]		
756.0±0.1	5.5±0.1		
767.0±0.1	0.18±0.01		
791.9±0.3	0.49±0.007[c]		
811.7±0.3	0.066±0.019[c]		
818.5±0.1	7.8±0.2		
825.1±0.1	0.55±0.08		
843.8±0.1	0.18±0.03		
886.4±0.2	0.034±0.005		
911.8±0.2	0.023±0.003		
992.3±0.2	0.077±0.005		
1005.7±0.2	3.15±0.06		

[a] Intensity estimated from the coincidence spectrum.
[b] Average value from three different spectra.
[c] Average value from five different spectra.

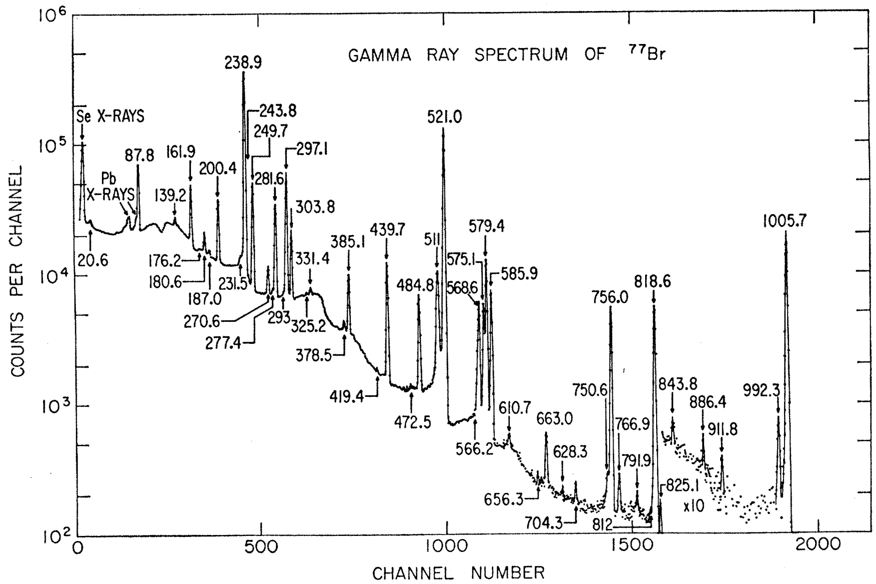

FIG. 1. Singles γ-ray spectrum from 56-h ^{77}Br decay obtained with a 20-cm^3 Ge(Li) detector.

the spectra used in the illustrations. However, in the analysis of the data the intensities of all the coincidence events were evaluated and when the contribution from random events was subtracted they showed no significant change in the coincidence spectra.

Two different Si(Li) detectors were employed for conversion electron measurements. These detectors had active areas of 1.0 and 2.0 cm^2 and depletion depths of 0.5 and 3.0 mm, respectively. The thin detector was used for conversion electrons up to 520 keV in order to minimize the amount of Compton shoulders from the γ rays interacting in the sensitive volume of the detector. The electron detectors were calibrated for full energy peak efficiency using a mixed source of ^{203}Hg, ^{113}Sn (^{113}In), and ^{207}Bi of known internal conversion coefficients and relative γ-ray intensities.

A 4096-channel pulse-height analyzer with two 4096-channel analog-to-digital converters was used for pulse-height analysis. The analyzer was equipped with a buffer-tape and a read-search control unit, coupled with an IBM computer compatible magnetic tape drive. With this system, two parameter coincidence spectra were recorded in a 256×1024-channel Ge(Li) configuration.

The fast-coincidence requirement could be switched in or out by means of a programming unit coupled with a time-base generator. Thus, singles events could be recorded separately on the first plane of each axis for a small fraction (usually 1 or 2%) of the time. This allowed one to check for any drift or change of the conditions during the 20 h of coincidence counting required for good statistics. Data were accumulated at a rate of $\sim$100 coincidence events per second, without significant loss in resolution other than that of a limited number of channels per energy axis. The 30-cm^3 Ge(Li) detector was used as the gating axis and 800 keV were recorded in 256 channels. The peaks had a width of three channels in most of the cases. The coincidence spectra were obtained with the 20-cm^3 Ge(Li) detector with a gain of 0.90 keV per channel and are displayed at this gain in some of the illustrations; in some others the spectra were integrated every two channels for graphical simplicity.

III. RESULTS

A typical singles spectrum of the γ rays from the 56-h ^{77}Br is shown in Fig. 1. The assignment of the weakest γ rays at 176.2, 277.4, 419.4, 472.5, 656.3, and 811.7 keV is based on the observation of these γ rays in approximately the same relative intensity in the spectra with the best statistics taken at different times from the same source. Accurate half-period measurements for these γ rays were not possible because of the very low intensity. For the stronger γ rays it was possible to take spectra with good statistics over time periods covering approximately two half-lives. From these spectra the half-period for each γ ray could be unambiguously determined to be close to 56 ± 3 h. The energies and relative intensities of the γ rays determined from nine different spectra are shown in Table I.

Figure 2 shows a typical conversion electron spectrum of ^{77}Br obtained with the 3.0-mm-deep Si(Li) detector. This spectrum is shown here because the conversion electrons from the 756- and 819-keV transitions can be seen. The Compton shoulders from the prominent γ rays recorded in the Si(Li) counter can be clearly seen. In the spectra obtained with the 0.5-mm Si(Li) detector, the Compton events were substantially reduced. These spectra were used for

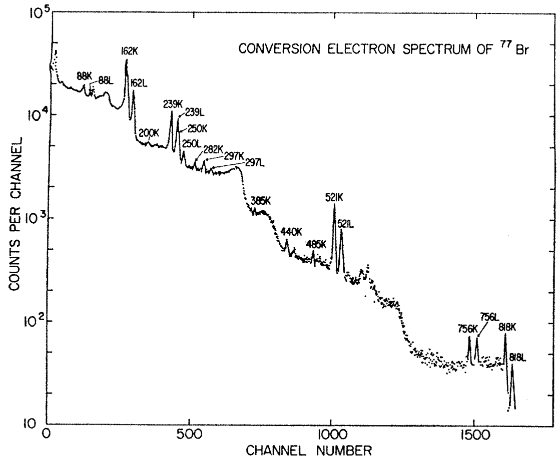

FIG. 2. Typical spectrum of the conversion electrons from 56-h ^{77}Br decay, obtained with a 3.0-mm Si(Li) detector. The Compton shoulders from the stronger γ rays can be seen.

the determination of the conversion coefficients for the transitions below 521 keV. The measured values for the K-shell conversion coefficients for nine of the strongest transitions in the decay of ^{77}Br are listed in Table I. The K-shell conversion coefficients were measured by preparing mixed sources of ^{77}Br and ^{113}Sn (^{113}In) with measured relative γ-ray intensities. The values are based on the α_K value[12] of 0.438 ± 0.008 for the 391.7-keV transition in ^{113}In.

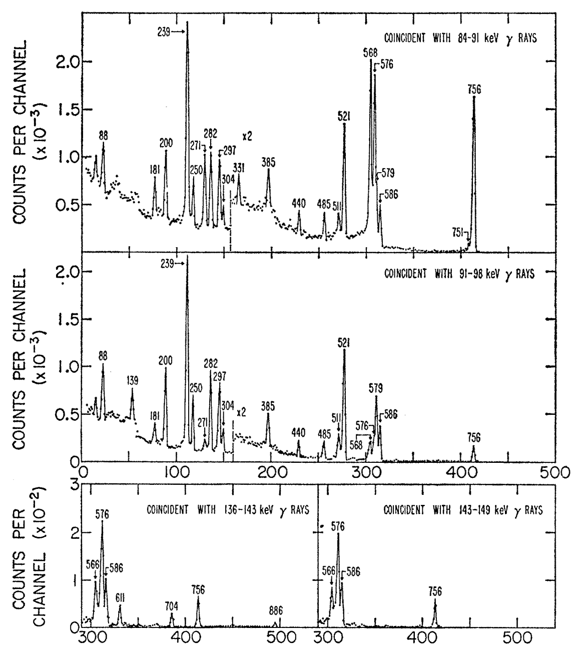

FIG. 3. Spectra of the γ rays from ^{77}Br recorded with the 20-cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30-cm^3 Ge(Li) detector. Adjacent energy regions of the gating axis are displayed to indicate the γ rays coincident with the underlying Compton-scattered γ rays from higher energy transitions.

[12] J. H. Hamilton *et al.*, Nucl. Data **A1**, 521 (1966).

The coincidence data were analyzed by adding every two planes of the 30-cm^3 gating detector to obtain consecutive spectra, each covering an energy range of $\sim$6.5 keV on the gating axis. Only the spectra falling in the planes containing the important peaks are shown in Figs. 3–8. Together with these, we show the spectra coincident with the energy region immediately above each peak, so that by inspection it is quite clear which γ rays are in strong coincidence

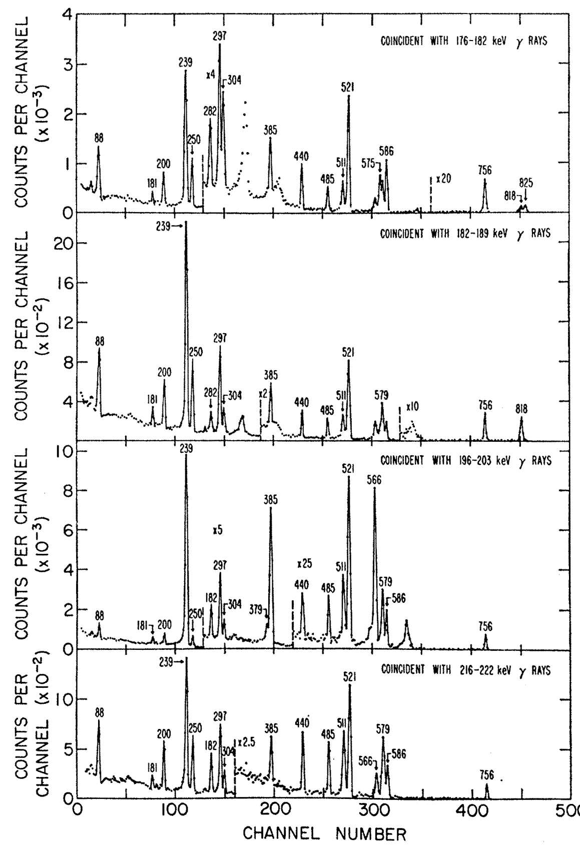

FIG. 4. Spectra of the γ rays from ^{77}Br recorded with the 20-cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30-cm^3 Ge(Li) detector. Adjacent or neighboring energy regions of the gating axis are displayed to indicate the γ rays coincident with the underlying Compton-scattered γ rays from higher-energy transitions.

with the selected peaks. In the upper part of Fig. 7 one can see that the intensity of random events can be estimated from the intensity of the 521 keV relative to the 485-keV γ ray in this spectrum and the singles spectrum. This is found to be $\sim$1/120.

IV. CONSTRUCTION OF DECAY SCHEME

In Fig. 9 we show the proposed decay scheme for the decay of ^{77}Br and below we summarize the arguments for this.

The 161.9-keV transition is well known to correspond to the isomeric transition from a 17.5-sec level in ^{77}Se.[10] This is confirmed by the fact that the 161.9-keV γ ray was not seen in any of the coincidence spectra and that the energy sum of this and the 87.8-keV transition gives 249.7 keV. Both the 88- and 250-keV γ rays are in strong coincidence with the 271-, 331-, 568-, 576-, and 756-keV γ rays (see Fig. 3, coincident with 84–91 keV and 91–98 keV and Fig. 5, coincident with 246–253 keV and 253–260 keV). These two γ rays are not in coincidence with any other γ ray. The 250-keV γ ray must feed

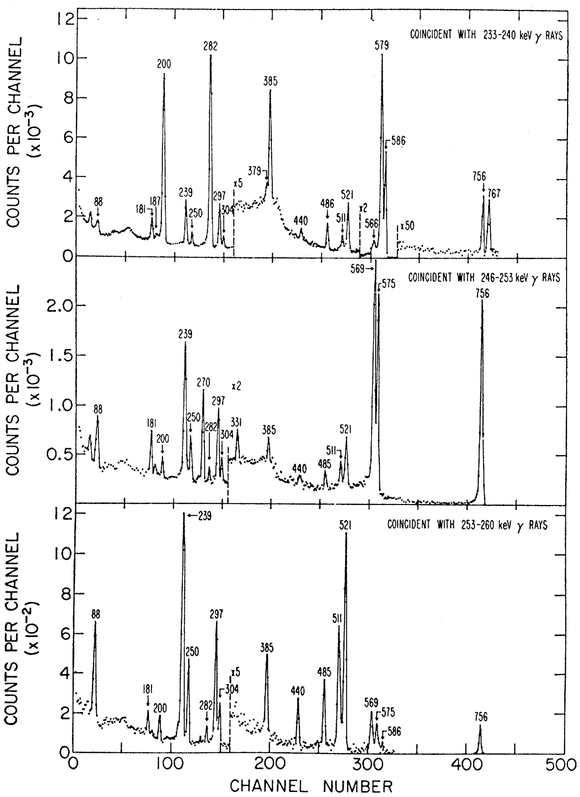

FIG. 5. Spectra of the γ rays from ^{77}Br recorded with the 20-cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30-cm^3 Ge(Li) detector. Here, 7-keV gates are placed on the 239- and 250-keV γ rays. The spectrum in coincidence with the 253–260-keV region indicates the γ rays coincident with the underlying Compton-scattered γ rays from higher-energy transitions.

the ground state, because of its high intensity compared with the γ rays coincident with it. This establishes a level at 249.7 keV with the 88-keV transition also de-exciting this level. Furthermore, the observed strong coincidences with the 88- and 250-keV γ rays suggest levels at 520.7, 581.2, 818.2, 824.8, and 1005.6 keV. A number of weak coincidences are also seen in the above mentioned spectra, and since they are consistent with the proposed scheme, they will not be discussed in detail here.

The 239-keV γ ray is in strong coincidence only with the 200-, 282-, 297-, 304-, 385-, 579-, 586-, and 767-keV γ rays (see Fig. 5, coincident with 233–

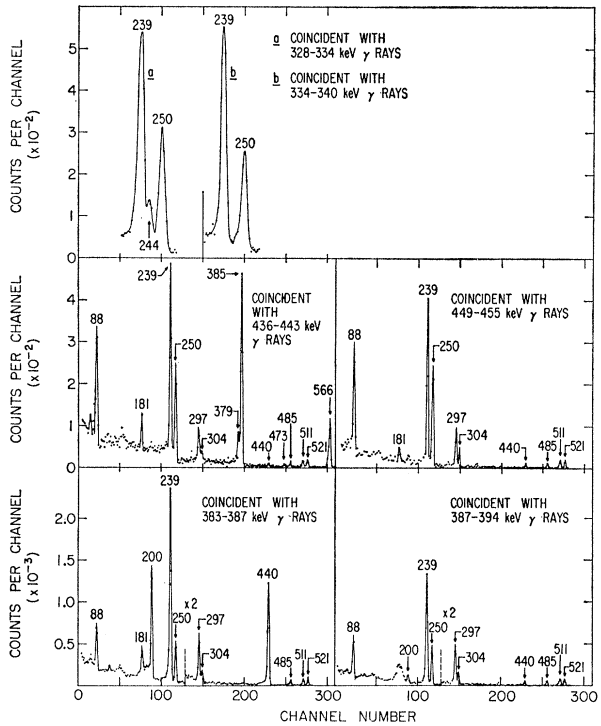

FIG. 6. Spectra of the γ rays from ^{77}Br recorded with the 20-cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30-cm^3 Ge(Li) detector. Here, 7-keV gates are placed on the 3.31-, 440-, and 385-keV γ rays and on the regions above them for Compton background.

240 keV and 253–260 keV). Because of the very high intensity of the 239-keV γ ray, it must feed the ground state. This coincidence information suggests a level at 439.5 keV, and confirms the presence of levels at 520.7, 818.2, 824.8, and 1005.6 keV. The

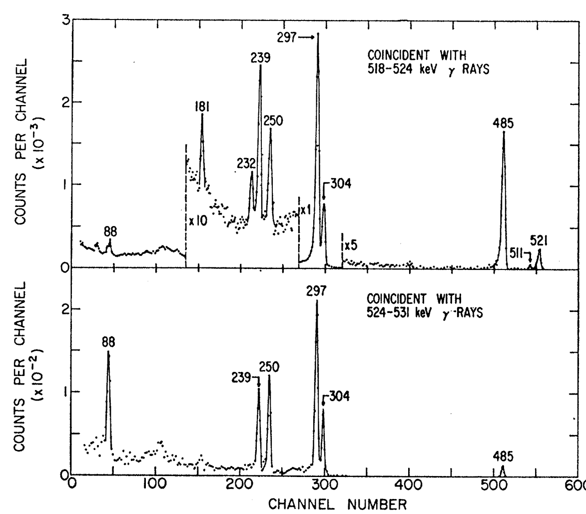

FIG. 7. Spectra of the γ rays from ^{77}Br recorded with the 20-cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30-cm^3 Ge(Li) detector. The γ rays coincident with the 521-keV γ ray can be clearly seen.

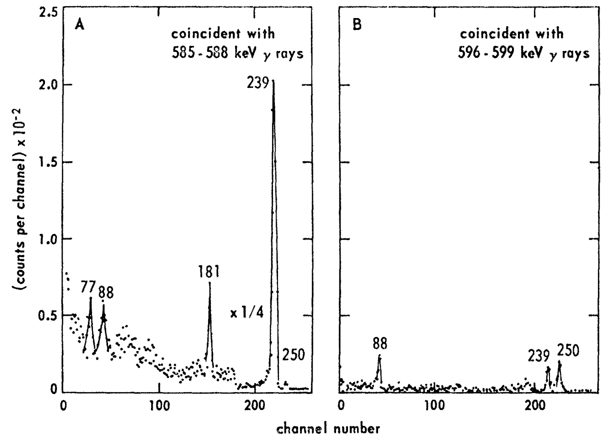

FIG. 8. Spectra of the γ rays from ^{77}Br recorded with the 20-cm^3 Ge(Li) detector in coincidence with the indicated energy regions in the 30-cm^3 Ge(Li) detector. The intensity of the 77-keV γ ray was estimated from this spectrum by comparison with the intensity of the 181-keV γ ray.

level at 439.5 keV is firmly established by the fact that the 440-keV γ ray, the crossover to the ground state, and the 200-keV γ ray are in strong coincidence with the 379-, 385-, and 566-keV γ rays (Figs. 4 and 6). This information further confirms the levels at 818.2, 824.8, and 1005.6 keV.

The 473-keV γ ray was seen in coincidence with the 440-keV γ ray, but not with the 200-keV γ ray. This is due to the interference from the larger number of scattered γ rays in the 200-keV window compared with the 440-keV window. This suggests a level at 911.8 keV.

The very weak γ rays at 611, 704, and 886 keV are seen in coincidence with the weak γ ray at 139 keV (see Fig. 3, coincident with 136–143 keV and 143–149 keV). The energy sum 161.9+139.2+704.3 is 1005.4 while the sum 161.9+139.2+610.7 is 911.8 in excellent agreement with the energies of the levels at 911.9 and 1005.6 keV. Furthermore, a level at 306 keV in ^{77}Se has been observed in ^{76}Se(d, p) reaction studies.[6,7] This information strongly supports the assignment of levels at 301.1 and 911.9 keV. From the latter level, the transitions to the ground and first excited states have been associated with the observed γ rays at 750.6 and 911.8 keV on the basis of energy sums. The 886-keV γ ray seen in coincidence with the 139-keV γ ray suggests a level at 1187.5 keV. A level at this energy has also been observed in (d, p) reaction studies.[6] The presence of a level at 581.2 keV suggested earlier is further supported by the observed strong coincidence of the weak 244-keV γ ray with the weak 331-keV γ ray (see Fig. 6, coincident with 328–334 keV and 334–340 keV). The 244-keV γ ray de-excites the established level at 824.8 keV. The 419.4-keV γ ray is placed to de-excite this 581.2-keV level and populate the 161.9-keV level on the basis of the energy sum.

Five γ rays at 181, 232, 297, 304, and 485 keV are seen in strong coincidence with the 521-keV γ ray (see Fig. 7, coincident with 518–524 keV and 524–531 keV). All of these γ rays, with the exception of the 181-keV γ ray, are not seen in coincidence with any γ-ray de-exciting levels lying higher than the 521-keV level. This establishes a level at 752.2 keV and further confirms the levels at 818.2, 824.8, and 1005.6 keV. The 181-keV γ ray is seen to be in strong coincidence with the 304-, 385-, 575-, 586-, and 825-keV γ rays (see Fig. 4, coincident with 176–182 keV and 216–222 keV; also see Fig. 6, coincident with 383–387 keV and 389–394 keV). This evidence firmly places the 181-keV γ ray to feed the 824.8-keV level and de-excite the 1005.6-keV level. The 187-keV γ ray is in strong coincidence with the 297- and 818-keV γ rays (see Fig. 4, coincident with the 182–189 keV and 216–222 keV). Therefore, this γ ray populates the 818.2-keV level and de-excites the 1005.6-keV level.

A level at 682.3 keV is placed on the basis of the sum 682.3+325.3 keV and the fact that a level at this energy was observed in (d, p) reaction studies.[6,7] A transition to the 162-keV level should have an energy of 520.4 keV. However, such a γ ray cannot be distinguished from the observed 520.7-keV γ ray populating the ground state.

Finally, the 77-keV γ ray is seen in coincidence with the 586-keV γ ray (see Fig. 8) and with the 282-keV γ ray. Therefore, it is assigned to de-excite the 239-keV level, and its intensity is estimated to be $\sim$0.1. The sensitivity of our coincidence experiments was high enough to have detected coincidences with the unassigned γ rays at 992.3, 811.7, and 791.9 keV. Since we do not observe these γ rays in the coincidence spectra, we suggest that they populate either the ground or the first excited isomeric state. In any case, the total intensity of the unassigned γ rays is only 0.2%.

V. ASSIGNMENT OF J VALUES AND PARITIES

We have measured the percentage of the total positron emission and found it to be 0.82±0.05%, in good agreement with the previously reported value of 0.83%.[3] This result is based on the relative intensities of the 511-keV radiation and the other γ rays as given in Table I, and on the calculated ratio EC/β^+ of 49 for the transition to the ground state of ^{77}Se. The Q_{EC} value of 1365 keV was used in this work, based on the (p, n) threshold measurement.[10] Positron decay to the excited states is expected to be very small and was neglected here. The logft values given in Fig. 9 were calculated using Moszkowski's nomogram.[13] The discussion of the character of the electron-capture (EC) decays is given below, together with the assignment of the spins from the internal-

[13] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (John Wiley & Sons, Inc., New York, 1967), 6th ed., Appendix IV.

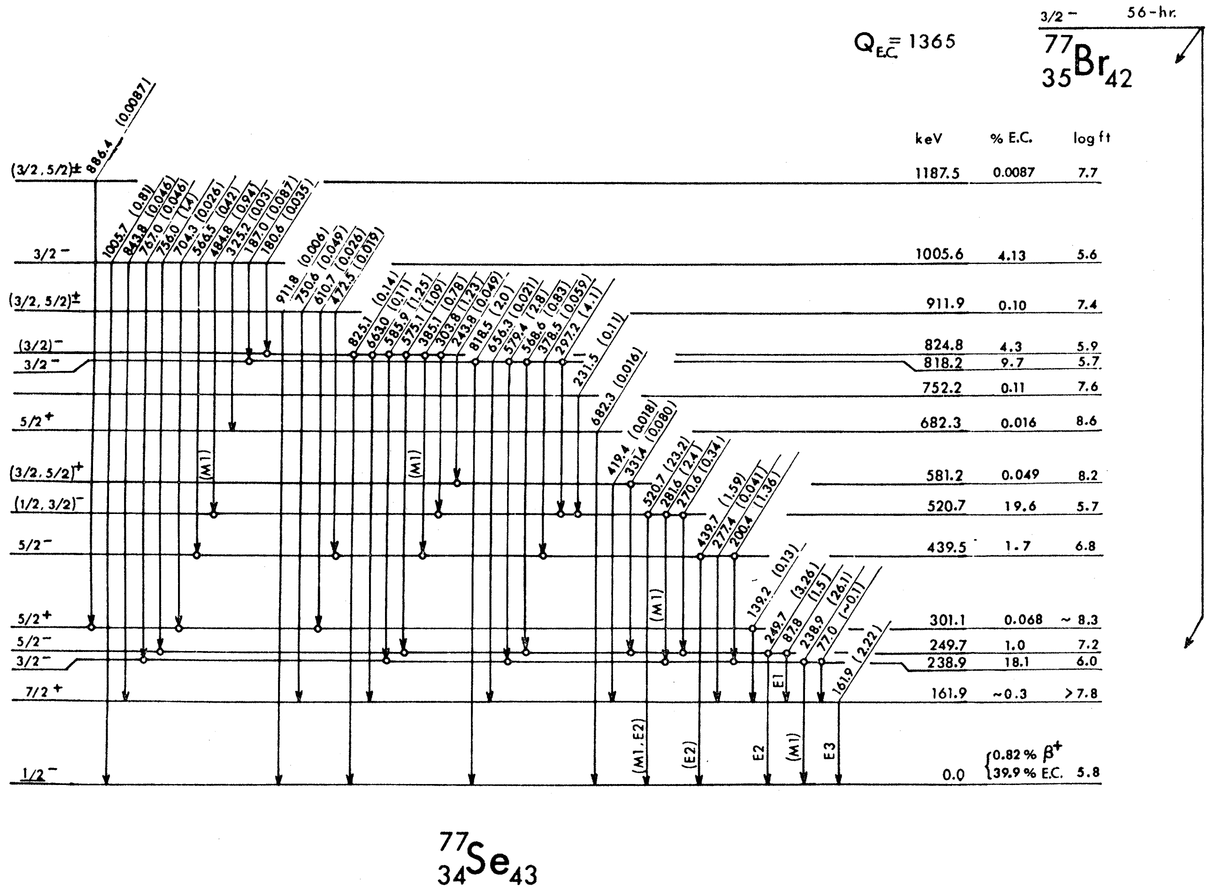

FIG. 9. Proposed decay scheme for the 56-h ^{77}Br. The conventions used are those of *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Offices, National Academy of Sciences–National Research Council, Washington, D.C.), except that the energies are given in keV. The γ-ray intensities given in parentheses refer to 100 decays of ^{77}Br.

conversion data. The K-shell conversion coefficients presented in Table I, when compared to the values of Sliv and Band,[14] suggest the most probable multipolarities for some of the transitions involved, as shown in the last column in Table I.

The total angular momentum J and the parity of the ground state ^{77}Se are known to be $\frac{1}{2}^-$.[10] The J^π value of the 162-keV level has been assigned as $\frac{7}{2}^+$ on the basis of K/L ratio of 4.6 of Rutledge *et al.*[15] Our measurement of 0.68 ± 0.10 for α_K for this transition is in agreement with the value of 0.79 ± 0.06 of Weigmann[16] and supports the assignment of $E3$ for the 162-keV transition. From the (d,p) data of Macefield *et al.*[6] a value of 3 or 4 for l_n, the orbital angular momentum of the transferred neutron, is consistent with the observed angular distributions; Lin,[7] however, prefers an l_n value of 4, although a value of 3 cannot be excluded. On the basis of this evidence, we favor the assignment of $\frac{7}{2}^+$. The 239-keV level de-excites to the ground state by a transition with an α_K of 0.0096 ± 0.0010, consistent with a $M1$ assignment. The 77-keV transition to the $\frac{7}{2}^+$ level at 162 keV is very weak and this is consistent with the assignment of $\frac{3}{2}^-$ to the 239-keV level. The (d,p) data for this state cannot be used for spin assignments here because of the unresolved doublet at 239 and 250 keV. The angular correlation data of Robinson and co-workers[5] support also the $\frac{3}{2}^-$ assignment for the 239-keV level. The 250-keV level is only weakly populated by electron capture. Monaro's angular-correlation[2] measurements support the assignment of $(\frac{3}{2}^-, \frac{5}{2}^-)$, while the correlation data of Robinson and co-workers[5] support the assignment $\frac{5}{2}^-$. The angular-distribution data from the (d,p) work[6,7] for the 245 doublet indicate a mixed l_n of 1+3 and this is consistent with the $\frac{5}{2}^-$ assignment for the 250-keV state since the 240-keV state was assigned as $\frac{3}{2}^-$.

The level at 301 keV is only very weakly populated by electron capture, and the estimated logft value suggests a first-forbidden transition. A level at 0.31

[14] L. A. Sliv and I. M. Band in *Alpha-, Beta-, and Gamma-ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), p. 1640.

[15] W. R. Rutledge, J. M. Cork, and S. B. Burson, Phys. Rev. **86**, 775 (1952).

[16] H. Weigmann, Z. Physik **167**, 547 (1962).

MeV was assigned an l_n value of 2 from the (d, p) work by Lin.[7] This level is seen to de-excite by populating the $\frac{7}{2}^+$ level below. A ground-state transition from the 301-keV level was not observed, thus indicating that the spin of the 301-keV state should be higher than $\frac{3}{2}$. From the (d, p) work[6,7] it is apparent that the $d_{5/2}$ states were observed lower than the $d_{3/2}$. This evidence supports a $\frac{5}{2}^+$ assignment for the 301 state.

The 440-keV level is only weakly populated by electron capture. The l_n value assigned for this state from the (d, p) data[7] is 3. Furthermore, our α_K value for the 440-keV transition supports an $E2$ assignment for the multipolarity, although $M1$ cannot be excluded. The correlation data of Robinson *et al.* support a $\frac{5}{2}^-$ assignment. This evidence strongly suggests an assignment of $\frac{5}{2}^-$ to the 440-keV level.

The 521-keV level is strongly populated by electron capture. The α_K values for the transitions to the ground and the 239-keV state agree with and $M1$ character for both of these, and the l_n value from the (d, p) work[6,7] is 1. This information excludes the $\frac{5}{2}^-$ assignment. Lin[7] prefers an assignment of $\frac{1}{2}^-$ over $\frac{3}{2}^-$ for the 521-keV level. By examining the $\frac{3}{2}^-$ states we see that at least they weakly populate the $\frac{7}{2}^+$ state at 162 keV. An upper limit of 0.02% for a transition from the 521-keV level to the 162-keV level can be placed here. The 521-keV level is further weakly populated from the decay of the $\frac{5}{2}^-$ level at 825 keV (see discussion below). This supports a $\frac{3}{2}^-$ assignment for the 521-keV level although the $\frac{1}{2}^-$ cannot be excluded.

The level at 581 keV is very weakly populated by electron capture and the estimated log*ft* suggests a first-forbidden transition. This level populates only the $\frac{5}{2}^-$ and $\frac{7}{2}^+$ levels at 260 and 162 keV, and is populated from the decay of the $\frac{5}{2}^-$ level at 825 keV above. An upper limit for the transition from the 581-keV level to the ground state of 0.3% can be placed here, despite the presence of the strong 579-keV γ ray which interferes with a better estimate. Gating on the 578–582 keV region did not show a 244-keV γ ray in coincidence, which is in agreement with this upper limit for the 581-keV γ ray. This information limits the assignment to $(\frac{3}{2}, \frac{5}{2})^+$ for the 581-keV level. A level at 682 has been observed in (d, p) studies[6,7] and an l_n of 2 was determined.[7] If the 682-keV γ ray de-excites this level, then the log*ft* value is 8.6, in agreement with a $\frac{5}{2}^+$ assignment. The level at 752 keV is rather weakly populated by electron capture and it was not observed in the (d, p) or (d, t) reaction studies.[6,7] The available information is insufficient to limit the possible spin assignment from $(\frac{1}{2}, \frac{3}{2}, \frac{5}{2})^\pm$. The levels at 818 and 825 keV are strongly populated by electron capture and feed a wealth of levels below. In the (d, p) work the 818-, 824-keV doublet was not resolved, but the determined l_n value[6,7] was equal to 1. This limits the spins to $\frac{1}{2}^-$ or $\frac{3}{2}^-$. The choice of $\frac{1}{2}^-$ can be excluded on the basis of strong feeding to the $\frac{5}{2}^-$ lower-lying levels (see Fig. 9) and the observed feeding to the $\frac{7}{2}^+$ state at 162 keV. This leaves the choice of $\frac{3}{2}^-$ for both 818- and 825-keV levels. The level at 912 keV is weakly populated by electron capture and rather strongly feeds the $\frac{7}{2}^+$ level at 162 keV. This eliminates a $\frac{1}{2}$ assignment. From the present evidence we can only limit the spin assignment for this level to $(\frac{3}{2}, \frac{5}{2})^\pm$. The level at 1006 keV is strongly populated by electron capture and has been assigned an l_n value of 1 from (d, p) reaction studies.[6,7] This level substantially feeds the $\frac{7}{2}^+$ level at 162 keV as well as the $\frac{5}{2}^+$ levels at 301 keV and perhaps at 682 keV. On this basis, we eliminate the $\frac{1}{2}^-$ as a possibility leaving the value of $\frac{3}{2}^-$ for the 1006-keV level. Finally, the level at 1188 is only weakly populated by electron capture and is identified with the level at 1191 observed by Macefield.[6] Decay only to the $\frac{5}{2}^+$ level at 301 keV was observed. By analogy with the 912-keV level we limit the spin assignment to $(\frac{3}{2}, \frac{5}{2})^\pm$ for this level.

VI. INTERPRETATION OF LEVELS

In discussing the nature of the states in nuclei with Z or N between 40 and 50, it is important to distinguish the positive from the negative parity states. The $\frac{3}{2}^-$, $\frac{5}{2}^-$, $\frac{5}{2}^-$, and $\frac{3}{2}^-$ states at 238.9, 249.7, 439.5, and 521 keV, respectively, have been observed by Coulomb excitation. In particular, the 239- and 440-keV levels have been interpreted[8] earlier as arising from the coupling of the odd neutron in its lowest state $(p_{1/2})$ with the first 2^+ state of the ^{76}Se core. The pairing-plus-quadrupole model as formulated by Kisslinger and Sorensen[9] is not expected to be very successful in this region because the short-range proton-neutron correlation has been neglected; here, the protons and neutrons are essentially filling the same subshells. Of particular interest, however, are the so-called anomalous $\frac{7}{2}^+$ and $\frac{5}{2}^+$ states in nuclei with Z or N equal to 43, 45, and 47, which have been explained by a multiparticle configuration $[(g_{9/2})^{3,5,7}]$ $\frac{5}{2}$, $\frac{7}{2}$.[17,18] The energies of the $\frac{5}{2}^+$ and $\frac{7}{2}^+$ states arising from this configuration do not agree with experiment,[18] since the calculated $\frac{7}{2}^+$ states are not found below the $\frac{9}{2}^+$ state. In a recent paper, Ikegami and Sano[11] have attempted to expand their calculations to include admixtures from the next major shell (e.g., $d_{5/2}$, $g_{7/2}$, $s_{1/2}$, and $d_{3/2}$ from the Z, N 50–82 major shells). Their model is essentially the pairing-plus-quadrupole model extended to include 40 shell model orbits (nine major shells).[11] In Fig. 10 we show a comparison of the experimentally determined levels of ^{77}Se, ^{79}Se, and ^{81}Se with the results of Ikegami and Sano.[11] Before discussing the comparison with the theory, we note some interesting features of the anomalous

[17] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).
[18] B. H. Flowers, Proc. Roy. Soc. (London) **215**, 398 (1952).

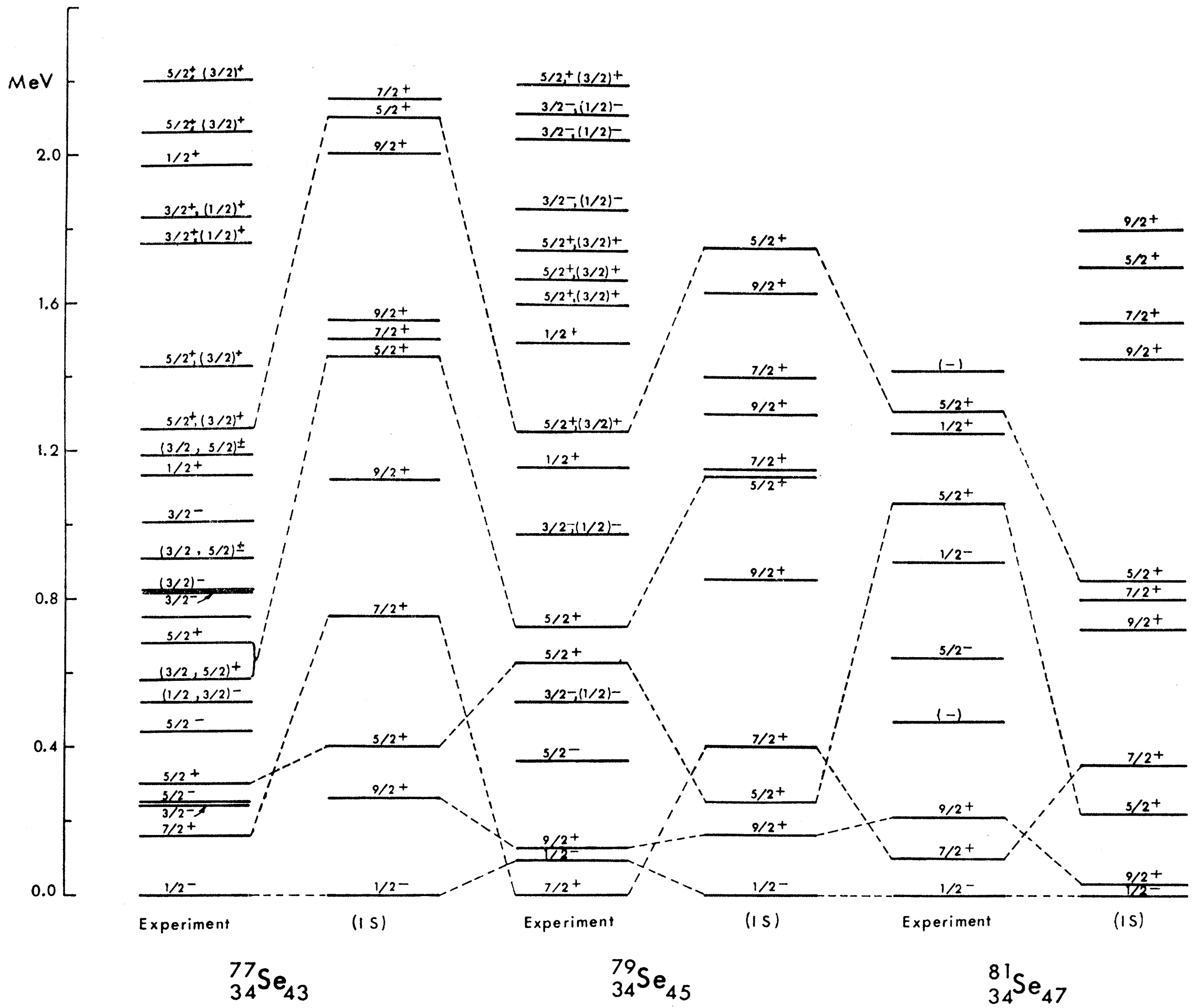

FIG. 10. Comparison of the experimental anomalous $\frac{5}{2}^+$ and $\frac{7}{2}^+$ states in the odd selenium isotopes with the theory of Ikegami and Sano (denoted by IS). See text for the discussion.

states in the Se isotopes. The lowest $\frac{5}{2}^+$ state appears to move to lower energies as the neutron number decreases and at ^{75}Se becomes the ground state.[10] The first $\frac{7}{2}^+$ state appears near the ground state and it is not moving rapidly with N. The first $\frac{9}{2}^+$ state lies below 210 keV in ^{81}Se and ^{79}Se and has not been observed in ^{77}Se. The results of the (d, p) work give a l_n of 3 or 4 for a level at 177 keV and this may well be an unresolved doublet (see also comment F in Ref. 10, p. B1-4-6) consisting of the $\frac{7}{2}^+$ level at 161.9 keV and the $\frac{9}{2}^+$ at ~180 keV Higher $\frac{7}{2}^+$ and $\frac{9}{2}^+$ states in ^{77}Se have not been observed from decay of ^{77}Br (^{77}Br is only $\frac{3}{2}^-$) or from (d, p) studies on ^{76}Se (low spectroscopic factors). The Ikegami-Sano calculations are successful in predicting the first $\frac{9}{2}^+$ state in $^{77-81}$Se. The behavior of the anomalous $\frac{5}{2}^+$ and $\frac{7}{2}^+$ states is correctly predicted in that their energy drops more rapidly than the other states with increasing $S_2'^{-1/2}$, the strength of the phonon-quasiparticle interaction. However, the first $\frac{7}{2}^+$ state does not cross the first $\frac{9}{2}^+$ state in all the Se isotopes. For ^{77}Se the predicted higher $\frac{5}{2}^+$ states are too high, while for the heavier Se isotopes the predicted $\frac{5}{2}^+$ levels are too low. It is possible, although unlikely, that this is due to incomplete experimental evidence in ^{79}Se and ^{81}Se for these $\frac{5}{2}^+$ states. It is worthwhile pointing out that the $\frac{9}{2}^+$ states are mostly one quasiparticle in the $g_{9/2}$ orbit, in contrast to the $\frac{5}{2}^+$ and $\frac{7}{2}^+$ states in which the one-quasiparticle components are small.[11]

In conclusion, we see that anomalous states in the Se isotopes can be, at least qualitatively, interpreted correctly by including configurations in the wave function from the next major shell. We note that this was also concluded by Lin[7] in order to interpret the spectroscopic factors observed in the (d, p) reaction studies on the Se isotopes. The agreement with experiment may further improve if the p-n residual interaction is included in the pairing-plus-quadrupole model calculations.

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Decay Schemes of ^{60}Zn and ^{62}Zn†

E. J. HOFFMAN AND D. G. SARANTITES
Department of Chemistry, Washington University, St. Louis, Missouri 63130
(Received 12 August 1968)

The decays of 2.4-min ^{60}Zn and 9.3-h ^{62}Zn have been investigated with the use of Ge(Li) and NaI(Tl) γ-ray detectors. Coincidence relationships among the γ rays were determined in γ-γ coincidence experiments. It was established that the decay of 2.4-min ^{60}Zn populates levels at 61.4, 334.4, 364.6, 572.4, and 669.7 keV in ^{60}Cu, and the decay of 9.3-h ^{62}Zn populates levels at 40.84, 243.43, 287.86, 548.25, and 637.20 keV in ^{62}Cu. Many spin assignments have been made from present logft values, previously reported conversion-electron data, and spectroscopic studies from nuclear reactions. The half-life of ^{60}Zn was measured to be 2.42±0.02 min. The fraction of β decay (positron plus electron capture) of ^{62}Zn to the ground state of ^{62}Cu was measured to be 0.43±0.05; the ratio of positron to K capture for the same decay was measured to be 0.22±0.01.

I. INTRODUCTION

THE discovery of ^{60}Zn was reported in 1955 by Lindner and Brinkman[1] who reported a half-life of 2.1±0.1 min. No work could be found on the decay scheme of the 2.4-min ^{60}Zn up to the present time. However, levels in ^{60}Cu have been reported by Miller and Kavanagh[2] and by Young and Rapaport[3] from studies of the ^{58}Ni(^{3}He, p)^{60}Cu reaction. Finally, Birstein and co-workers[4] have reported levels in ^{60}Cu from studies of the ^{60}Ni(p, $n\gamma$)^{60}Cu reaction.

The decay scheme of the 9.3-h ^{62}Zn has been the subject of several recent works,[5–7] the most definitive being the Ge(Li) γ-ray work of Roulston *et al.*[6] and the conversion-electron and Ge(Li) γ-ray work of Antman *et al.*[7] The last named authors assigned levels at 40.88, 243.40, 287.89, 548.37, and 637.45 keV populated in the decay of the 9.3-h ^{62}Zn. The only coincidence work is that of Brun and co-workers[5] and involved NaI(Tl) scintillation spectroscopy. The definite coincidences seen were the 590-, 510-, and one of the 250-keV complex coincident with the 41-keV line and one of the 250-keV complex coincident with one of the 390-keV complex.

The investigation of the decay schemes of the 2.4-min ^{60}Zn and the 9.3-h ^{62}Zn was undertaken in order to obtain the levels, the γ-ray transitions, and their coincidence relationships. This information is essential to studies of γ rays from nuclear reactions induced on ^{58}Ni and ^{60}Ni that we are presently investigating. The scheme for the decay of the 2.4-min ^{60}Zn that we are proposing has not been previously reported. The scheme for the decay of the 9.3-h ^{62}Zn determined in this work is in good agreement with the previously reported one.[6,7]

II. EXPERIMENTAL PROCEDURES

A. Production of ^{60}Zn Samples

The ^{60}Zn samples were produced by the (^{3}He, n) reaction at the Washington University cyclotron on 10.5-mg/cm^2 natural nickel foils. The maximum ^{3}He-ion energy was kept below 10 MeV to minimize the ^{60}Ni(^{3}He, $2n$) reaction, which produces the 86-sec ^{61}Zn. The bombardment times were about 60 sec. The most prominent 476-keV γ ray from ^{61}Zn was not observed in any of the samples. The targets were mounted on carriers in a pneumatic tube which returned the sources to the counting area in less than 5 sec after the end of bombardment. In all cases, the following procedure was

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[1] L. Lindner and G. A. Brinkman, Physica **21**, 747 (1955).
[2] R. G. Miller and R. W. Kavanagh, Nucl. Phys. **A94**, 261 (1967).
[3] Helen J. Young and J. Rapaport, Phys. Letters **26B**, 143 (1968).
[4] L. Birstein, Ch. Drory, A. A. Yaffe, and Y. Zioni, Nucl. Phys. **A97**, 203 (1967).
[5] E. Brun, W. E. Meyerhof, J. J. Kraushaar, and D. J. Horen, Phys. Rev. **107**, 1324 (1957).
[6] K. I. Roulston, E. H. Becker, and R. A. Brown, Phys. Letters **24B**, 93 (1967).
[7] S. Antman, H. Petterson, and A. Suarez, Nucl. Phys. **A94**, 289 (1967).