values at 14–15 MeV. Salisbury and Chalmers[39] reported values for neutrons between 2 and 17 MeV, and they included a theoretical curve obtained by Büttner, Lindner, and Meldner[40] from a statistical-model calculation. Liskien and Paulsen[41] discussed the relative merits of all existing measurements. Most of these were made by the emulsion technique and thus are actually values for the sum of the $(n,p)+(n,pn)$ reactions, which would be larger. The values obtained by direct detection of emitted protons with a scintillator are also expected to yield the sum. Thus, only two previous activation measurements exist for the (n,p) cross section of Fe^{54}, by Pollehn and Neuert (254 mb at 14.1 MeV)[42] and by Cross *et al.*[43] (310 mb at 14.5 MeV), which are in fair agreement with the present value.

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TABLE III. Summary of available 14–15-MeV cross-section values for $Fe^{54}(n,\alpha)Mn^{54}$.

Neutron energy (MeV)	σ (mb)	Reference
14.1	131 ±25	Ref. 42
14.7	270 ±135	Ref. 11
14.5	109 ±10	Ref. 43
14.05	91.6±37.1	Ref. 39
14.4	90 ±10	Present work

The values of (n,α) cross sections of Fe^{54} available are summarized in Table III. The present value stands lower than many previous measurements, but somewhat higher than the calculated value by Büttner *et al.*[40]

ACKNOWLEDGMENTS

We thank Mrs. Ann Galli and Dorsey Smith for operation of the 200-kV accelerator and S. J. Amir for assistance in data processing. One of us (P.V.R.) thanks the National Aeronautics and Space Administration for financial support under NASA Grant No. NsG-657.

PHYSICAL REVIEW VOLUME 154, NUMBER 4 20 FEBRUARY 1967

Gamma Decay of $Se^{73m,g}$ and $Se^{81m,g}$ Isomeric Pairs*

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(Received 21 September 1966)

The gamma decay of the isomeric pairs (42-min Se^{73m}, 7-h Se^{73g}), and (57-min Se^{81m}, 18.6-min Se^{81g}) was investigated with Ge(Li) and NaI(Tl) detectors by means of singles, coincidence, and sum-peak coincidence spectrometry. The half-lives of Se^{73g} and Se^{81m} were determined to be 7.0±0.1 h and 56.6±0.6 min, respectively. The gamma energies from 7-h Se^{73g} were determined to be 66.9±0.5 and 360.4±0.5 keV. A new gamma of 75.7±0.5 keV was found in 42-min Se^{73m} decay and is placed as the ground-state transition from a 76-keV level ($\frac{1}{2}$-, $\frac{3}{2}$-) in As^{73}. The absence of a 42-min component in the intensity of the 67-keV gamma indicates that the 67-keV ($\frac{5}{2}$-) first excited state of As^{73} is not fed from 42-min Se^{73m} either directly or through the 76-keV state. The energies and relative intensities of seven gammas in $Se^{81m,g}$ equilibrium decay have been measured: 102.7±0.5 (100) (isomeric transition), 275.8±0.5 (10.2), 289.9±0.5 (8.7), 539.0±0.5 (0.8), 553.0±0.5 (1.5), 566.1±0.5 (2.9), and 829.0±0.5 (4.9) keV. A new level at 539.0 keV is proposed tentatively in Br^{81} with a possible spin parity of $\frac{5}{2}$- or $\frac{7}{2}$-. Decay schemes are proposed for $Se^{73m,g}$ and $Se^{81m,g}$ which are consistent with all available data.

INTRODUCTION

EXCITED levels in odd-A nuclei contain, in addition to single-particle states, both quasi-particle and phonon states, resulting from pairing interactions and vibrational modes, respectively. Nathan and Nilsson[1] have pointed out that if nuclear oscillations are small-amplitude harmonic oscillations, the level scheme will consist of pure quasi-particle states and a band of vibrational states. The energy of the degenerate multiplet, resulting from the combination of a particle state and a vibrational state, is nearly equal to that of the corresponding first phonon state in neighboring even-even nuclei. In most cases, however, the coupling between particle motion and the oscillating field is strong, and the low-lying levels in odd-A nuclei are strongly mixed.

The situation concerning odd-A bromine isotopes has been summarized by Bonacalza[2], who points out that the first excited states lie lower than the corresponding first phonon state in neighboring even-even nuclei. In

* Supported in part by the U. S. Atomic Energy Commission.
† Postdoctoral Research Associate, supported by National Aeronautics and Space Administration, under Grant No. NsG-657.
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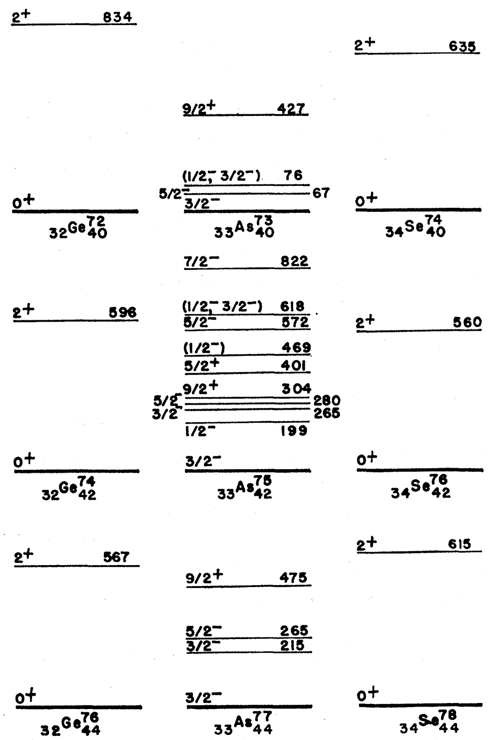

FIG. 1. Levels in odd-A arsenic isotopes, and the first excited states in neighboring even-even nuclei.

Br^{79} there are many more levels than would be expected from a band of vibrational states coupled with single-particle states, indicating the presence of several possible quasi-particle states. The systematics concerning odd-A arsenic isotopes is summarized in Fig. 1, where again similar features are observed. The data on the level structure of arsenic isotopes are taken from the recent literature,[3–5] and the rest from *Nuclear Data Sheets*.[6]

42-MIN AND 7-H $Se^{73m,g}$ ISOMERS

The ground-state decay of Se^{73} (7.0 h) has been investigated by several authors.[7] Hooge and Aten[8] found a 44-min, 1.7-MeV β^+ activity of selenium by irradiating GeO_2 with alpha particles, and assigned it as an isomer of Se^{73}. Hayward and Hoppes[9] suggested that this activity might arise from a $p_{1/2}$ level in Se^{73}. Ricci, Van Lieshout, and Van den Bold[10] determined the half-life to be 42±3 min, and reported 251-, 580-, and 88-keV gammas by analyzing the sum spectrum in a NaI(Tl) detector. They determined the maximum energy of the β^+ spectrum to be 1.72±0.10 MeV. Kuroyanagi[11] also found the 44-min activity while studying the photoreaction products of selenium; however, no gammas were detected.

The single-particle shell model[12] predicts a close-lying pair of $p_{1/2}$, $g_{9/2}$ levels for a nucleus with 39 neutrons. The 7.0-h ground state[9] is assigned a spin-parity of $\frac{9}{2}+$. An assignment of $p_{1/2}$ to the isomeric state would be predicted. This would require an $M4$ transition between the isomeric and ground states, the partial half-life of which would be of the order of 10^4 to 10^5 days, according to the Weisskopf estimate. In such a case, the $p_{1/2}$ isomeric state would decay independently to low-spin levels in As^{73}, and the $M4$ isomeric transition probably would be undetectable.

Natural-selenium samples (of 99.999+% purity) were irradiated with 14.4±0.3-MeV neutrons from the Geogia Tech 200-kV accelerator. These produce $Se^{73m,g}$ by the $Se^{74}(n,2n)$ reaction. The gamma spectrum was observed with a 2 mm deep×1 cm^2 area Ge(Li) detector having a resolution of 4 keV full width at half maximum (FWHM). The photopeak efficiency of the detector was calibrated with standard gammas relative to a 3×3-in. NaI(Tl) crystal. The energies were calibrated with gammas from Ta^{182}, Se^{75}, Cs^{137}, Mn^{54}, Na^{22}, and Co^{60}. A typical gamma spectrum taken 10 min after irradiation is shown in Fig. 2. The annihilation radiation exhibited half-lives of 42 min and 7.0 h, indicating

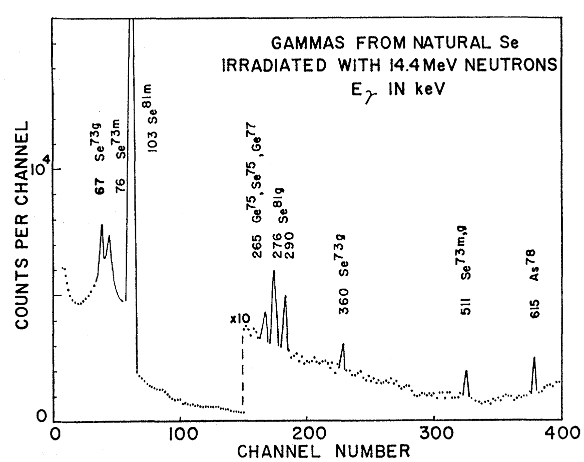

FIG. 2. Ge(Li) singles gamma spectrum from natural selenium approximately 10 min after irradiation with 14.4-MeV neutrons. The decay of individual peaks was followed, and the indicated assignments of parent activities made from the energies and half-lives.

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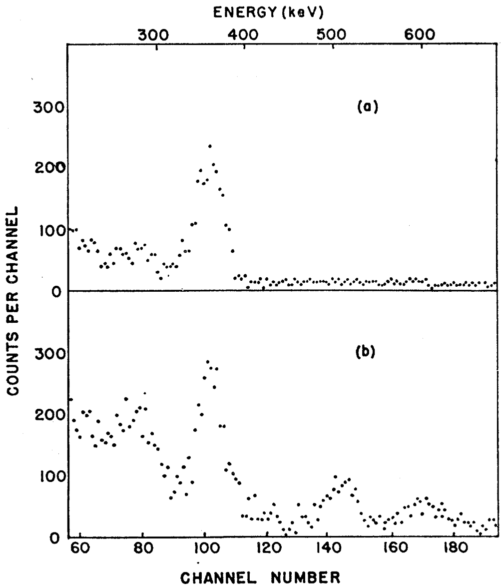

FIG. 3. (a) Gamma spectrum from $Se^{73m,g}$, taken with a 3×3-in. NaI(Tl) detector, in prompt coincidence with the 67+76-keV gammas gated by a Ge(Li) detector placed at 90°. This spectrum was taken approximately 10 min after irradiation with 14.4-MeV neutrons. The peaks at ≈280 and ≈600 keV are due to coincidences with the Compton tail present in the window. (b) Same spectrum taken approximately 3 h after irradiation, when the 76-keV activity had essentially decayed completely. The 67-keV gamma is not in coincidence with annihilation radiation, but is in prompt coincidence with the 360-keV gamma. A comparison of (a) and (b) shows the presence of prompt coincidences between the 76-keV gamma and annihilation radiation.

production of both Se^{73m} and Se^{73g}. There was also a long-lived component of the annihilation radiation from the $Se^{74}(n,p)As^{74}$(18.7 days) reaction, but of very low intensity.[13] A 75.7±0.5-keV gamma, which decays with a half-life of 42 min, also was observed, but no higher energy gammas were detected with this half-life. A careful search revealed no 67-keV gamma component decaying with a 42-min half-life. The energies of the gammas from Se^{73g} decay were calibrated to be 66.9±0.5 and 360.4±0.5 keV, and, by following the decay of these two gammas, the half-life of Se^{73g} was determined to be 7.0±0.1 h.

The relative intensities of 67- and 360-keV gammas from Se^{73g} were $I_{67}/I_{360}=0.76\pm0.08$, in fair agreement with the value (0.77) obtained by Hayward *et al.*[9] This yields a total internal-conversion coefficient $\alpha_T=0.30 \pm0.04$ for the 67-keV transition, assuming little or no direct feeding of the 67-keV level in Se^{73g} decay, and an $\alpha_T=0.013$ for the 369-keV transition. This is consistent with the $M1$ nature[7] of the 67-keV transition.

Figure 3(b) shows the region between 200 and 700 keV in a 3×3-in. NaI(Tl) spectrometer, observed in coincidence with 67+76-keV peaks in the Ge(Li) detector. It is evident that the annihilation radiation is in prompt coincidence with the 76-keV gamma, since the coincidence-resolving time of the Ge(Li)-NaI(Tl) system was 150 nsec. Figure 3(a) shows the same spectrum taken several hours after all of the 76-keV gamma had decayed, and shows no 511-keV peak but only a 360-keV peak known to be in prompt coincidence with the 67-keV transition.[7]

Figure 4 shows the proposed decay scheme for $Se^{73m,g}$. The separation between isomeric state and the ground state is not determined accurately. From the available information on the maximum β^+ energy, an upper limit of 110 keV can be placed on it. This is consistent with the decreasing trend in the $p_{1/2}$-$g_{9/2}$ splitting of odd-neutron levels below $N=50$.[12] The 76-keV gamma is placed as a ground-state transition from the first excited state in As^{73} fed by positron decay of the 42-min $p_{1/2}$ level in Se^{73}. The absence of a 42-min component in the intensity of the 67-keV gamma indicates that the 67-keV level ($\frac{5}{2}-$) is not excited in 42-min Se^{73m} decay, and the 76-keV level completely de-excites to the ground state. From the systematics of the low-lying levels of odd-proton nuclei As^{73}, As^{75}, and As^{77} (Fig. 1), the 76-keV level can be assigned a spin-parity of either $\frac{1}{2}-$ or $\frac{3}{2}-$. In either case, the beta branching to both the ground and the 76-keV levels should be approximately equal. Assuming a K/β^+ ratio of ≈0.18,[14] the ratio of 76-keV gammas to annihilation radiation in Se^{73m} decay ($I_{76}/I_{511}\approx0.24$) gives a total internal-conversion coefficient for the 76-keV transition of $\alpha_T\approx0.22$. A theoretical estimate of α_T for a 76-keV $M1$ transition, based on Rose's tables,[15] is 0.18, indicating that most of the transition is of the $M1$ type. The log ft values calculated for the β^+ transition to the 76-keV and ground states are ≈4.9, consistent with the allowed nature of tne transitions. The relative branching of β^+, and electron-capture feeding of the ground and the 76-keV excited states could not be estimated, because of the very low activity of Se^{73m} produced in the fast-neutron irradiations. An (α,Xn) reaction on germanium could

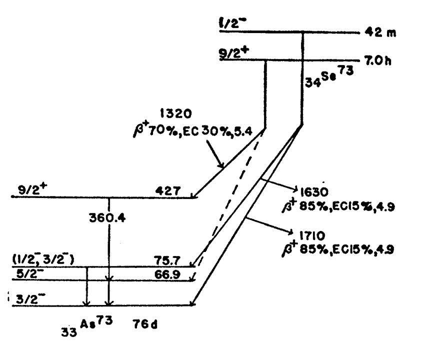

FIG. 4. Proposed decay scheme of $Se^{73m,g}$.

[13] P. V. Rao and R. W. Fink, preceding paper, Phys. Rev. **154**, 1023 (1967).

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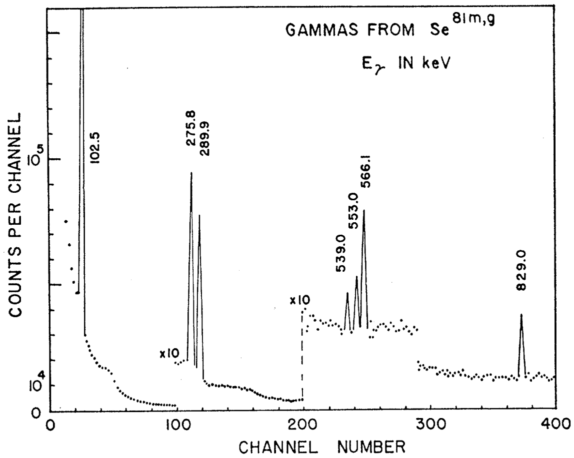

FIG. 5. Ge(Li) singles gamma spectrum from $Se^{81m,g}$ decay approximately 15 min after irradiation of enriched Se^{80} with thermal neutrons in the reactor.

produce stronger, purer sources of $Se^{73m,g}$ which would be useful with conversion-electron spectroscopy to determine the multipolarity of the 76-keV transition.

18-MIN AND 57-MIN $Se^{81m,g}$ ISOMERS

The decay of Se^{81g} (18 min) and Se^{81m} (57 min) has been reported by several authors. Krause *et al.*[16] proposed a decay scheme with levels at 282, 565, and 820 keV in Br^{81}, all being fed only by the 18-min decay of Se^{81g}. Ythier and Van Lieshout[17] reported several gammas with energies between 100 and 900 keV by studying the NaI(Tl) spectrum using "peeling-off" methods, and suggested additional levels at 450, 545, and 653 keV. Kuroyanagi[11] also observed several gammas, and proposed levels at 170, 275, 410, 480, 650, 690, and 840 keV, and two levels at 550 keV. Sund and Wiedenbeck[18] made conversion-electron and -gamma spectra studies, and substantially agreed with Krause *et al.*[16] in placing the levels at 280, 560, and 832 keV. They also decided that the level at 560 keV is different from the 550±20-keV level, which is produced by (p,γ) and (γ,γ') reactions,[19,20] and which decays by emitting two coincident gammas with a half-life of 37 μsec.

Enriched (93.65%)Se^{80} samples were irradiated with thermal neutrons in the Georgia Tech reactor. The gamma spectrum was studied with a Ge(Li) detector, described above. The low-energy region (<100 keV) was examined with a Harshaw integral-line assembly,

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TABLE I. Relative intensities of gammas from $Se^{81(m+g)}$ equilibrium decay.

Energy (keV)	Relative intensity
102.7±0.5 (isomeric transition)	100
275.8±0.5	10.2±0.5
289.9±0.5	8.7±0.4
539.0±0.5	0.8±0.2
553.0±0.5	1.5±0.3
566.1±0.5	2.9±0.3
829.0±0.5	4.9±0.5

consisting of an Amperex XP-1010 photomultiplier and a thin (0.8 mm) NaI(Tl) detector fitted with a 0.127-mm beryllium window. This detector exhibited a resolution of 50% for the Mn *K* x-ray (5.9 keV). No evidence was found for 30-keV gammas reported by Sund and Wiedenbeck.[18] The half-life of Se^{81m} was found to be 56.6±0.6 min by following the decay of the 103-keV gamma peak. Figure 5 shows the gamma spectrum from $Se^{81m,g}$ taken with the Ge(Li) detector.

Table I summarizes the intensities and energies of the gammas observed. All, except for the 103-keV line, decayed with the 18-min half-life of the Se^{81} ground state, indicating that no direct β^- decay of the isomeric state occurs to any excited levels in Br^{81}. The relative proportion of the high-energy gammas to the 103-keV line was obtained several hours after bombardment, in order to allow the initially-produced 18-min Se^{81g} to decay completely. The ratio also was checked in a separate experiment,[13] using the $Se^{82}(n,2n)$ reaction with 14.4-MeV neutrons. A separate exhaustive search

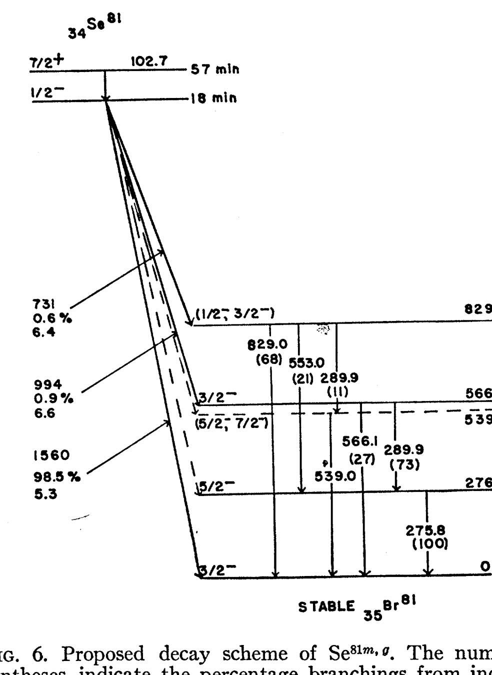

FIG. 6. Proposed decay scheme of $Se^{81m,g}$. The numbers in parentheses indicate the percentage branchings from individual levels. All energies are in keV. The numbers after beta branches are log *ft* values.

TABLE II. Beta-decay branching and log ft values in 18-min Se^{81g} decay.

Level in Br^{81} (keV)	$J\pi$	Branching[a] (percent)	Log ft
829.0	($\frac{1}{2}$-, $\frac{3}{2}$-)	0.61±0.05	6.4
566.1	$\frac{3}{2}$-	0.92±0.05	6.6
0	$\frac{3}{2}$-	98.5 ±0.1	5.3

[a] In estimating the beta-branching percentages from data in Table I, the total number of 18-min Se^{81g} distintegrations was obtained by using a total conversion coefficient of $\alpha_T = 7.07$ for the 102.7-keV isomeric transition, and a value of 0.68 for the ratio of Se^{81m}/Se^{81g} activities at equilibrium. In addition, total conversion coefficients for transitions between levels in Br^{81} were assumed to be negligible.

for gammas above 829 keV with the Ge(Li) detector revealed none.

An integral-bias sum-peak coincidence spectrometer,[21] consisting of two 3×3-in. NaI(Tl) detectors, with a coincidence-resolving time of 30 nsec, was used to examine the sum peaks due to cascade transitions. Two sum peaks corresponding to 562- and 829-keV levels were observed. The two sum peaks disappeared when the detectors were biased to eliminate the composite peak of 276- and 290-keV gammas.

Figure 6 shows the proposed-decay scheme consistent with the intensities and coincidences observed. Table II lists the decay branchings and log ft values. The theoretical value of the total conversion coefficient, $\alpha_T = 7.07$, was used[15] for the 103 keV transition, in order to estimate the total number of transitions feeding the ground state of Se^{81}. The transition is $E3\,(\frac{7}{2}+ - \frac{1}{2}-)$, which should be pure, because multipolarity admixtures are not normally encountered in gamma transitions of high-multipole order.[22] A recent comparison by Geiger[22] of the most accurately known experimental $E3$ K- and L-shell conversion coefficients with theotetical values listed by Rose,[15] and by Sliv and Band, shows that there is very good agreement between theory and experiment.

The spins of the first and second excited states have been established to be $\frac{5}{2}$- and $\frac{3}{2}$-, respectively, by Coulomb excitation,[23,24] and by angular correlation experiments.[25] The log ft value indicates that the spin of the 829-keV level can be either $\frac{1}{2}$- or $\frac{3}{2}$-.

A level at 539 keV is tentatively proposed to account for the observed 539-keV gamma. It is not in coincidence with 553-, 556-, or 829-keV gammas, since no corresponding sum peaks were observed in the sum-peak coincidence spectrum, and no gammas with energies higher than 829 keV were found to indicate levels at higher energies. The proposed 539-keV level can not be identical with the 550±20-keV level of spin-parity $\frac{9}{2}+$ and half-life 37 μsec, which was observed in (p,γ) and (γ,γ') reactions,[19,20] and which decays by emitting two coincident gammas to the ground state. No evidence was found in the present work for a stopover 263-keV gamma corresponding to a transition between the 276- and 539-keV levels. If the 539-keV level was directly fed from $Se^{81g}(\frac{1}{2}$-) ground state, the estimated log ft value would be 7.8±0.2, indicating that the beta transition is either allowed or nonunique first-forbidden.[26] A non-unique first-forbidden beta transition requires a low-spin, *positive* parity assignment for this level. No such low-spin, positive parity level has been found, however, in the neighboring odd-proton nucleus Br^{79}. An allowed beta transition would require a low-spin, *negative* parity state, in which case the 539-keV level would be expected to be fed more strongly than the 829-keV level. The observed gamma intensities contradict this. Alternatively, the 539-keV level might possibly be an intermediate step for a cascade of 290- and 539-keV gammas de-exciting the 829-keV level. The spin-parity of the 539-keV level can be $\frac{5}{2}$- or $\frac{7}{2}$-. This is in line with the observed predominantly direct de-excitation of this level to the ground state with little or no stopover transition. A coincidence experiment between the 290- and 539-keV gammas, preferably using two Ge(Li) detectors of larger efficiency, or with a Ge(Li) detector and NaI(Tl) crystal, could establish this firmly. The intensities encountered in the present work are very low, since most of the beta decay from Se^{81g} is to the ground state of Br^{81}, and the Ge(Li) detector used is not large enough for performing such coincidence studies with reasonable efficiency. It would also be of interest to determine accurately the position of the $\frac{9}{2}+$ level seen in the (p,γ) and (γ,γ') reactions. If the $\frac{9}{2}+$ level at 550±20 keV lies above the 539-keV ($\frac{5}{2}$-, $\frac{7}{2}$-) level, it should de-excite preferentially through the latter. To account for the observation that the $\frac{9}{2}+$(550±20-keV) and the 539-keV ($\frac{5}{2}$-, $\frac{7}{2}$-) levels apparently decay independently, the former by a cascade of two coincident gammas and the latter by a single ground-state transition, it is necessary to place the $\frac{9}{2}+$ level below the 539-keV level in the decay scheme.

ACKNOWLEDGMENTS

The authors wish to thank Milton McLain for his help with reactor irradiations, and S. J. Amir for his help in processing the data. We also thank Mrs. Ann Galli for assistance with the 200-kV accelerator.

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