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THE γ-SPECTRUM OF ^{74}Se ACCOMPANYING THE β-DECAY OF ^{74}Br

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Abstract: The spectrum of ^{74}Se following the β-decay of ^{74}Br has been analysed with a Ge(Li) γ-spectrometer and a high resolution Ge(Li)$\gamma\gamma$ coincidence spectrometer. A partial decay scheme is proposed containing 15 excited states placed at 634.61, 1269.13, 1362.9, 1884.1, 2108.0, 2563.6, 2918.7, 3077.5, 3675.2, 4442.4, 4496.6, 4517.5, 4592.0, 4662.0 and 4700 keV. The ^{74}Br sources are produced by the Se(d, xn)^{74}Br process and subsequent mass separation.

E | RADIOACTIVITY ^{74}Br[from Se(d, xn)]; measured E_γ, I_γ, $\gamma\gamma$-coin. ^{74}Se deduced levels. Natural target.

1. Introduction

In a study of the β-decay of ^{74}As populating levels of the two stable isotopes ^{74}Ge and ^{74}Se Siegbahn *et al.* [1]) in 1951 found a γ-decay energy of 635.2 keV, which they assigned to a transition in ^{74}Se. In the following time it could be shown from Coulomb excitation experiments performed by several authors [2-4]) that this transition corresponds to the decay of the first excited state of ^{74}Se to the ground state. A considerable number of γ-transitions have been observed from the decay of states in ^{74}Se which are excited by β-disintegration of the 40 min isotope ^{74}Br [refs. [5,6])]. However, the arrangement of these transitions into a decay scheme has been insufficiently worked out. In particular, the identification of a two-phonon 2^+ state expected for ^{74}Se from the collective model has not yet lead to consistent results [5-7]).

To investigate the level scheme of ^{74}Se, the γ-spectrum following the β-decay of ^{74}Br has been remeasured with increased accuracy using a Ge(Li) spectrometer. In addition high resolution $\gamma\gamma$ coincidence measurements have been performed with two Ge(Li) detectors counting into a 4096 × 4096 matrix. The transition energies and the information extracted from the coincidence spectra serve to propose a partial decay scheme into which a large part of the observed transitions may be arranged.

2. Source preparation and spectrometers

The production of the 40 min isotope ^{74}Br proceeded by the Se(d, xn)^{74}Br reactions. Tablets weighing approximately 80 mg were pressed from natural Se powder and bombarded in a watercooled target assembly [8]) by the internal beam of the Karlsruhe Isochronous Cyclotron. The irradiation with a deuteron current of 12 μA at an energy of 50 MeV lasted over a period of 20 min. Then the ^{74}Br activity is mass separated [9]) from the other bromine isotopes and collected on Cu foils 0.1 mm thick.

The singles spectra were taken with a detector of active volume $\approx$ 12 cm^3. The pulses from the detector were amplified by a preamplifier (Ortec 118A) and a main amplifier (Nuclear Enterprise 4603) and analysed by a 4096-channel ADC (Nuclear Data 161).

The coincidence spectrometer consisted of two Ge(Li) detectors with a large active volume of 33 cm^3 to attain a high detection efficiency as well as a high energy resolution. The detectors were mounted in a 180° geometry, 2 cm apart. Using a timing signal for the fast coincidence circuit produced by a unit accounting especially for the varying pulse rise times of the Ge(Li) detectors (Ortec 453), a coincidence resolving time of $2\tau = 12$ ns was obtained. When measuring the coincidence spectra of ^{74}Se the coincidence resolving time of the fast coincidence was adjusted to 20 ns. The amplitudes of the coincident signals were measured with two 4096-channel pulse-height analysers and pairs of such energy values representing the coincidence events were stored on magnetic tape.

3. Transition energies and $\gamma\gamma$ coincidence spectra

The calibration of the γ-ray spectrometer was based on the energy standards [10]) ^{56}Co, ^{57}Co, ^{60}Co, ^{203}Hg, ^{137}Cs, ^{65}Zn, ^{88}Y, ^{66}Ga and ^{182}Ta [ref. [11])]. In order to avoid overlapping of the calibration peaks with the peaks of the spectrum in question, the calibration spectra were recorded separately. The calibration spectra and the unknown ^{74}Se spectrum are related to each other by means of five standard energies of ^{203}Hg, ^{57}Co and ^{60}Co contained in all spectra.

When evaluating the spectra with a computer program [12]) it was observed that in the different calibration spectra the calibration factor ε(keV/channel) and the zero point k_0 [channels] determined from the ^{203}Hg, ^{57}Co and ^{60}Co standard energies was not constant within the accuracy required for a direct comparison of these spectra. The variations, of the order of $\Delta k_0 \approx \pm 1$ channel and $\Delta\varepsilon/\varepsilon \approx 3 \cdot 10^{-4}$, were probably generated from starting and stopping the ADC. However, for different records the deviation of the calibration points of ^{203}Hg, ^{57}Co and ^{60}Co from a calibration line as obtained with these reference energies by a least-squares fit is reproduced within less than 0.05 channels. This indicates that the nonlinearity of the spectrometer is reproducible and an experimental correction curve for the deviation from linearity obtained from the standard sources quoted above allows an accurate determination of the unknown transition energies of ^{74}Se.

Because of the reduced accuracy of the calibration energies for higher energies the accuracy of the transition energies listed in table 1 decreases as the energy increases. For the energy determination of the weak ^{74}Se transitions the spectra were taken containing no calibration lines in order to reduce the Compton background. The strong transitions of ^{74}Se measured previously were used as reference energies.

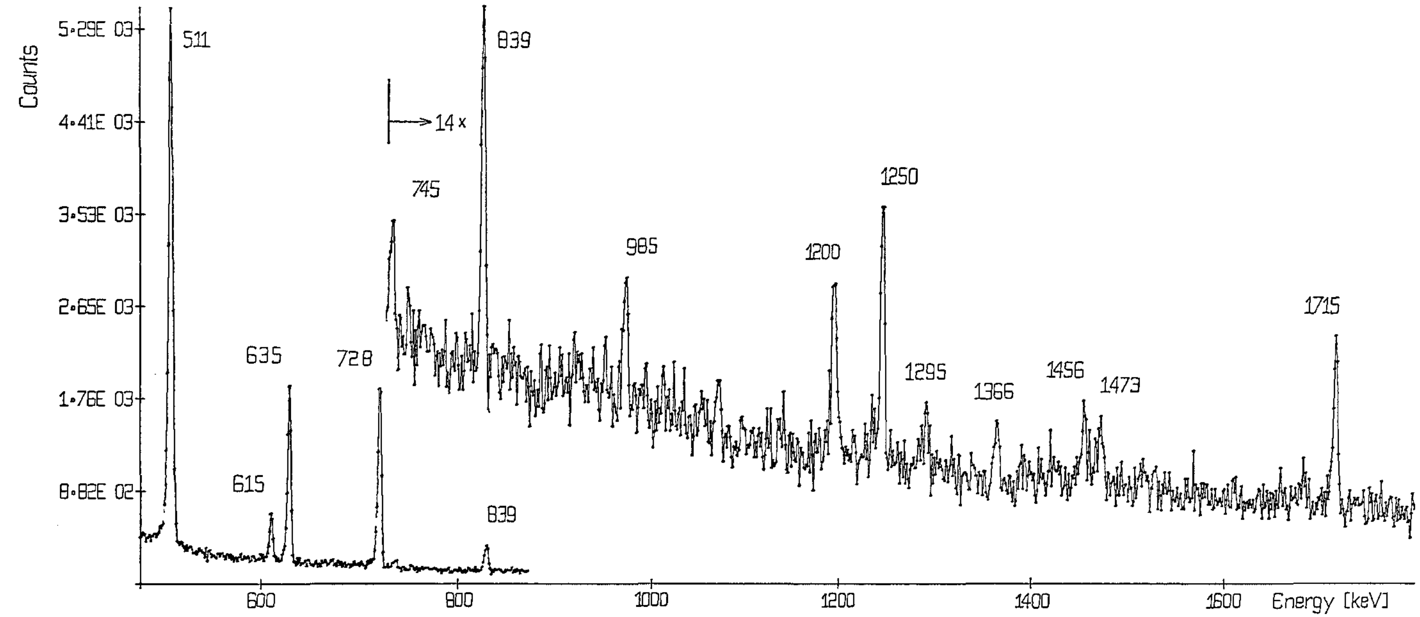

Fig. 1. Part of the coincidence spectrum of the peak at 635 keV.

TABLE 1

Transition energies in the spectrum of ^{74}Se

Energy (keV)	Error (keV)	Relative intensity	Error	Coincidences measured with the following transitions (keV)
219.02	0.1	6.0	1.0	511, 635, 985, 1456, 1930, 2184
368.2	0.6	$\leqq$0.6		
511				219, 511, 615, 635, 728, 839, 985, 1201, 1250, 1269, 1367, 1456, 1474, 1680, 1715, 1844, 2184, 2284, 2313
521.0	1.0	$\leqq$0.9		
615.09	0.15	6.5	0.7	511, 635, 778, 1269, 1367, 2701
634.61	0.15	100.0		511, 635, 728, 745, 839, 985, 1081, 1201, 1250, 1295, 1367, 1456, 1474, 1680, 1715, 1844, 2284, 2313, 3040, 3337, 3808, 3862, 3883, 3957, 4028
634.61		16.7	3.0	
679.02	0.15	0.8	0.2	
728.30	0.15	40.5	3.0	511, 635, 745, 869, 1201, 1367, 1456, 1715, 2313, 2409, 3154, 3228, 3298, 3337, 3431
744.80	0.15	2.1	0.4	511, 635, 728
777.6	0.4	0.7	0.2	
839.0	0.15	5.1	0.6	511, 635, 1269
850.7	0.3	0.7	0.2	
868.6	0.35	0.6	0.2	
935.6	0.9	0.4	0.2	
985.1	0.35	4.2	0.5	219, 511, 635
1045.5	0.5	0.5	0.2	
1080.8	0.4	1.0	0.2	
1200.62	0.25	5.6	0.7	511, 635, 728
1249.56	0.20	6.8	0.9	511, 635
1269.13	0.15	9.5	1.1	511, 615, 839
1295.0	0.4	2.9	1.0	511, 635, 1269
1366.57	0.25	2.5	0.5	511, 615, 635, 728
1421.8	0.6	0.9	0.2	
1456.3	1.0	2.1	0.7	511, 635, 728
1473.6	1.0	1.9	0.6	511, 635
1649.5	0.8	$\leqq$ 0.4		
1679.9	0.6	1.0	0.2	511, 635
1714.6	0.35	6.8	0.7	511, 635, 728
1837.7	1.5	0.7	0.2	
1843.6	1.5	1.0	0.3	511, 635
1889.6	1.5	$\leqq$ 0.6		
1930.0	1.5	0.9	0.2	219, 635
1953.0	1.5	$\leqq$ 0.4		
2018.3	1.5	(d.e. of 3040.3) [a]		
2028.8	1.5	$\leqq$ 0.5		
2183.5	1.5	1.5	0.3	219, 615, 635
2284.2	1.5	2.3	0.5	511, 635
2312.5	0.5	3.8	0.8	511, 635, 728
2333.5	1.5	1.0	0.4	511, 635, 839
2388.0	1.5	1.6	0.4	511, 635, 839
2408.8	1.5	(d.e. of 3431?)		511, 635, 728
2660.9	2.0	$\leqq$0.9		
2700.8	2.0	$\leqq$2.0		511, 635, 615
2785.1	1.5	(d.e. of 3808)		

TABLE 1 (continued)

Energy (keV)	Error (keV)	Relative intensity	Error	Coincidences measured with the following transitions (keV)
2840.4	1.5	(d.e. of 3862)		
2860.0	1.5	(d.e. of 3883)		
2935.4	1.5	(d.e. of 3957)		
3005.7	1.5	(d.e. of 4028)		
3040.3	1.5	1.3	0.3	
3136.8	1.5	$\leqq 0.8$		
3154.0	1.5	$\leqq 0.9$		
3173.6	1.5	1.2	0.3	
3227.5	1.5	0.7	0.2	
3250.3	2.0	$\leqq 0.6$		
3298.2	1.5	2.3	0.5	635, 728
3323.9	1.5	$\leqq 0.3$		
3336.9	1.5	$\leqq 0.8$		
3393.0	1.5	$\leqq 0.8$		
3431.2	1.5	1.2	0.3	
3446.6	1.5	(s.e. of 3957) [b]		
3516.0	1.5	$\leqq 0.6$		
3627.0	1.5	$\leqq 0.5$		
3808.3	2.0	1.1	0.3	635
3862.4	1.0	2.3	0.5	
3882.5	1.5	1.1	0.3	
3957.3	1.5	4.8	1.0	635
4028.3	2.0	1.3	0.3	
4065	5.0	$\leqq 0.2$		
4345	5.0	$\leqq 0.2$		
4384	5.0	$\leqq 0.4$		

[a]) d.e. means double escape peak.
[b]) s.e. means single escape peak.

The determination of the relative intensities given in table 1 is based on a calibration of the detector efficiency using a set of calibration sources distributed by the IAEA. The assignments to the 635 keV transition are discussed in the next section.

The electron spectrum accompanying the decay of ^{74}Br was recorded with a silicon detector appropriate for electron spectroscopy up to 1 MeV (2.7 keV resolution for ^{207}Bi conversion electrons at 975 keV). On a strong β^+ background three peaks were found at the following energies: 206.5 keV, 622.0 keV and 841.4 keV. Adding the 12.66 keV K-shell binding energy for Se to these values the transition energies at 219 keV and 635 keV are obtained, which are also found in the γ-spectra. However the last peak corresponds to a transition at 854 keV not found in the γ-spectra. The intensity ratio of the two corresponding conversion electron and γ-ray transitions have been measured.

The coincidence spectrum containing $6 \cdot 10^6$ events was taken in a measurement lasting 12 h. Using three single-channel analysers an energy range from 0.5 MeV to 4.5 MeV in one branch and two intervals from 210 keV to 230 keV and from 0.6 MeV to 2.7 MeV in the other branch of the spectrometer were selected out. As a result, counts which do not carry any useful information were neglected because they are triggered by Compton events. The intensity of the source at the spectrometer was adjusted for coincidence counting rates of about 150 counts/sec the rate of random coincidences being less than 1 %. The energy resolution was approximately 4 keV FWHM at 1270 keV in both branches of the spectrometer.

The coincidences delivered from the spectrometer in the course of the measurement were stored on tape. Simultaneously all counts falling into definite rows or columns of the 4096×4096 energy matrix are summed up by an on-line computer. By this projection of the two-dimensional coincidence spectrum on the axes of the matrix, two linear summed coincidence spectra were generated. For the determination of the coincidence spectrum of a special peak the data stored on tape were scanned by a computer analysis. The program used allows the composition of a linear spectrum of such events which are marked with a definite channel number of one of the ADC's of the spectrometer. From the summed coincidence spectrum of one of the detectors then all channels under the peak in question may be selected out. The coincidence spectra of these channels are traced out according to the above procedure and added together resulting in the coincidence spectrum of the peak as seen from the other detector.

Part of the events picked out in this manner must be considered as background events. To correct for this a background coincidence spectrum was constructed from a few channels on both sides of the peak and subtracted from the coincidence spectrum. An example of a corrected coincidence spectrum is given in fig. 1. In the last column of table 1 those transitions are listed which by the described analysis are found to be coincident with the transition given in the first column.

4. Proposal of a level scheme

Because of the accuracy of the measured transition energies the determination of levels rests mainly on Ritz' principle. For a meaningful selection of levels constructed according to this method by systematic combinations, reference is taken to intensities and coincidence spectra. So a level at 635 keV found by Coulomb excitation is reconfirmed as the first excited state.

In the singles spectra a peak is observed at 1269 keV the energy of which is equal within the limits of error to just twice the energy of the 635 keV transition. This hint for a state at 1269 keV is clearly confirmed by the coincidence measurements. Here in the coincidence spectrum of the 635 keV transition a peak appears with the same energy of 635 keV. Therefore a cascade decay may be concluded to start from the state at 1269 keV and consisting of two subsequent transitions of almost the same energy.

The energies of 1250 keV and 1474 keV of the singles spectrum can be obtained from addition of the transition energies 635 keV + 615 keV and 635 keV + 839 keV, respectively. Therefore these two transitions may be considered as crossover decays. It can be decided from the coincidence spectra of these two transitions both containing a peak at 635 keV that they do not decay directly to the ground state. Rather they connect the first excited state with two higher levels at 1884 keV and 2108 keV, respectively. With the exception of the 3078 keV level only those levels which are supported by at least two transitions are shown in the decay scheme of fig. 2. The 3078 keV state is assumed as the 1715 keV transition is strong and coincident only with the 635 keV and 728 keV transitions.

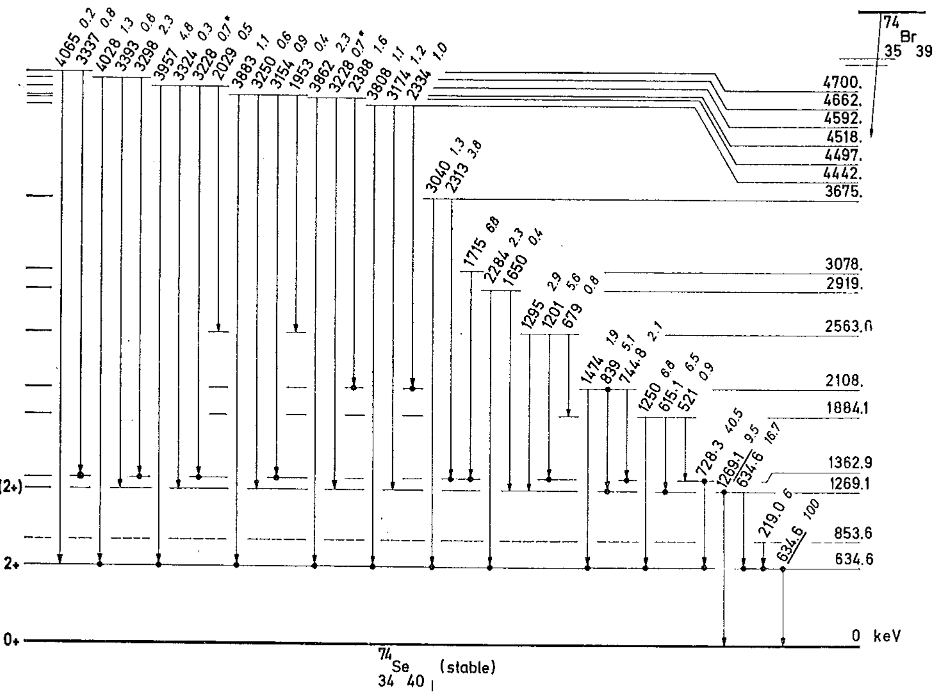

Fig. 2. Nuclear level scheme of ^{74}Se. All energies in keV. Cascading transitions, which are marked with dots are confirmed by coincidences. A transition energy used twice in the spectrum is asterisked. The relative intensities are related to the intensity of the lower 635 keV transition. Proposed energy levels for ^{74}Se are: 634.61±0.15, 1269.13±0.15, 1362.9±0.3, 1884.1±0.3, 2108.0±0.3, 2563.6±0.6 2918.7±2.0, 3077.5±1.0, 3675.2±1.0, 4442.4±2.0, 4496.6±1.5, 4517.5±2.0, 4592.0±2.0, 4662.0±2.0 and 4699.7±2.0 keV.

Two lines of considerable intensity with energies at 985 keV and 1456 keV which are in coincidence with a transition at 219 keV, and the 219 keV transition itself are difficult to arrange into the decay scheme. Nevertheless there is no doubt about the fact that these two lines belong to the spectrum of ^{74}Se due to their coincidence with the 635 keV line. Although no γ-transition with an energy of 854 keV (= 635 keV+ 219 keV) is found in the spectrum of ^{74}Se the assumption of such a level is confirmed by the conversion electron spectrum. Here a peak at 854 keV appears besides the peaks at 219 keV and 635 keV. The intensity and the coincidence spectrum of the 219 keV transition is in agreement with this assumption.

Since the ground state of ^{74}As lies only 1.35 MeV above the ground state of ^{74}Se only the low-lying levels of ^{74}Se can be populated by the β-decay of ^{74}As. To confirm the state at 854 keV with another experiment we tried to find the 219 keV transition in the γ-spectrum following the decay of ^{74}As. A peak found at this energy lies on a high Compton background and is too weak to be considered as certain. To conclude, the existence of the 854 keV level was not regarded as fully certain especially as a reasonable fit of the two transitions coincident with the 219 keV decay into the level scheme was not achieved.

From the coincidence spectrum of the 635 keV peak and from the singles spectrum the intensity ratio $I(\underline{635}):I(\overline{635})$ of the lower transition $(\underline{635})$ connecting the first excited state to the ground state and the upper one $(\overline{635})$ from the 1269 keV level to the first excited state can be determined. Denoting by $N(X, Y)$ the number of events in which the first detector measures an energy X and the second one an energy Y the quantity $2K$ can be found experimentally from the coincidence spectrum of the 635 keV peak:

$$2K = [N(\underline{635}, \overline{635})+N(\overline{635}, \underline{635})]/N(\underline{635}, 728) = 0.94.$$

Since $N(\underline{635}, \overline{635}) = N(\overline{635}, \underline{635})$ and $N(\underline{635}, 635)/N(\underline{635}, 728) = N(\overline{635})/N(728)$ where $N(X)$ is the number of γ-transitions of energy X, the equation $N(\overline{635})/N(728) = K = 0.47$ holds. On the other hand, from the singles spectrum the ratio S is given by $S = [N(\underline{635})+N(\overline{635})]/N(728) = 3.29$. Hence the relative intensity of the two transitions of energy 635 keV amounts to

$$I(\underline{635})/I(\overline{635}) = (S-K)/K = 6.0.$$

The accuracy of this result depends only on statistical errors and on pile up effects, while the efficiency of the detectors cancels. With respect to this the complete result for the intensity ratio is

$$I(635)/I(\overline{635}) = 6.0 \pm 1.1.$$

5. Discussion

The low-lying levels deduced from the present measurements may be discussed in the light of the unified model for a spherical nucleus [13]). This model is expected to be appropriate for an even nucleus as ^{74}Se with a neutron configuration $(2p_{\frac{1}{2}})^2$, corresponding to a closed subshell [14]). The qualitative features of the model can be obtained considering small oscillations of the nuclear surface [15,16]). Different modes of shape oscillations are possible, but here only those of the quadrupole type will be considered: Thus a spectrum of nearly equidistant surface oscillation states is expected. Those states which are excited by two or more oscillator quanta (phonons) split up into multiplets, especially the two-phonon state into a $0^+, 2^+, 4^+$ triplet and the three-phonon state into a $0^+, 2^+, 3^+, 4^+, 6^+$ quintet. The γ-transition probabilities between the phonon states are essentially characterized by the approximate validity of selection rules for E2 transitions between harmonic oscillator levels.

The states at 1269 keV and 1363 keV are found in the energy range typical for two-phonon excitations (fig. 2). Regarding the decay properties of these states the I^{π} value 2^+ is tentatively assigned to the 1269 keV level, since from the 1363 keV level no crossover to the ground state was observed. A γ-transition energy found at 1367 keV possibly corresponding to the ground state decay of the 1363 keV level deviates from the sum of 635 keV+728 keV by more than 10 standard deviations. In addition, two peaks at 635 keV and 728 keV appear in the coincidence spectrum of this line.

This identification of the 1269 keV level disagrees from an assignment obtained in an earlier experiment by Coulomb excitation [7]). In the Coulomb excitation work the coincidences of the cascade decay 1269 keV $\rightarrow$ 635 keV $\rightarrow$ 0 keV have been missed. This may be explained by the strong background of random coincidences and the resemblance of the energies of the real and random coincidence events. On the other hand, the cascade 1373 keV $\rightarrow$ 635 keV $\rightarrow$ 0 keV has been observed in this work and it has been interpreted as the $2^+ \rightarrow 2^+ \rightarrow 0^+$ decay. Here the argument has been used that in view of the weak dependence of the excitation cross section from the charge of the exciting projectiles the excitation must be considered as a direct process. In this way from the ground state only the 2^+ level of the two-phonon triplet can be populated with an appreciable efficiency. However, the dependence of the cross section from the charge of the projectiles seems to be insufficient to distinguish between direct and multiple Coulomb excitation processes under the conditions of this experiment.

Neglecting the contributions of the $(\overline{635})$ transition the conversion coefficient of the $(\underline{635})$ decay can be estimated from the intensity ratio of the 635 keV conversion electrons to the corresponding γ-rays. The obtained value $\alpha(635) \approx 0.001$ is consistent with an E2 transition as predicted for a vibrational nucleus. This conversion coefficient and the experimental fact that the 854 keV transition is only found in the electron spectrum can be used to estimate $\alpha \approx 0.1$ as a lower limit for the conversion coefficient of the 854 keV transition. Hence a multipole order of at least five must be ascribed to this transition, which in a single-particle estimate corresponds to a lifetime against γ-decay of about 10^6 s. The observed lifetime, however, is of the order of 10^4 s, so it must be concluded that this electron line corresponds to a $0 \rightarrow 0$ transition. Then, according to the collective model the 854 keV state might be considered as the 0^+ state belonging to the two-phonon triplet.

Besides the fact that the 854 keV level is not connected to one of the otherwise ascertained states by the observed γ-transitions it is also remarkable that only one crossover decay has been found leading directly to the ground state. Furthermore, the $\log ft$ values for the β-transitions into the excited states of ^{74}Se as estimated from the γ-intensities correspond to allowed β-decays for the higher-lying levels and to forbidden decays to the low-lying levels. Therefore the assumption is supported that a large spin value $I \geqq 3$ must be assigned to the high excited states of ^{74}Se, and that the state of ^{74}Br feeding these levels with a half-life of about 40 min also has a high spin value.

On the other hand, a spin $I = 0$ or 1 has been concluded for the ground state of ^{74}Br because ^{74}Kr decays with an allowed β-decay into this nucleide. This process is not accompanied by γ-radiations [17]). Therefore the existence of an isomeric state in ^{74}Br may be suggested.

As already noted the transitions from the higher levels of ^{74}Se do not end on the ground state but mainly populate the 1363, 1269 and 635 keV levels. Regarding the integral γ-intensities leading to these states from the higher levels, the 1363 keV state seems to be favoured with a feeding intensity of 24 compared to the one- and two-phonon 2^+ states which are fed by intensities of 23 and 18.5 respectively. It therefore seems probable that the 1363 keV state has a high spin and that this state is the two-phonon 4^+ state expected in this energy range.

Finally the striking branching ratios for the γ-decay of the two levels at 1884 and 2108 keV into the one-phonon state 2 and the two-phonon state 2′ should be noticed. In view of the strong energy dependence of γ-transition probabilities the measured intensities show that the decay probabilities from both states to the 2′ state are clearly enhanced as compared to the corresponding probabilities to the 2 state. Assuming a pure E2 character for the emitted radiation the following ratios for the reduced transition probabilities can be estimated: $B(\mathrm{E2};\, 1884 \rightarrow 2')/B(\mathrm{E2};\, 1884 \rightarrow 2) = 33 \pm 8$ and $B(\mathrm{E2};\, 2108 \rightarrow 2')/B(\mathrm{E2},\, 2108 \rightarrow 2) = 45 \pm 19$. These decay properties and the position of the levels at 1884 and 2108 keV indicate that they may be interpreted as members of a three-phonon quintet in analogy to previously discussed similar cases [18,19]).

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