# Decay Scheme of $^{79}$As

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The $\gamma$-transitions in $^{79}$Se following the decay of $^{79}$As were investigated with a Ge(Li) detector. Six previously unreported $\gamma$-transitions were observed and energy and intensity measurements on eleven $\gamma$-rays are reported. A new decay scheme is proposed which incorporates all the observed $\gamma$-rays. Results concerning the decay schemes of some isotopes of selenium (81 and 73) are also presented.

## 1. Introduction and Experimental Techniques

Some information about the levels of $^{79}$ Se has been obtained by (d, p) and (d, t) reactions[1]. The decay of 9 min $^{79}$As has been studied by Kuroyanagi[2] and his proposed decay scheme as well a more complete level scheme including reaction data are presented and discussed in Nuclear Data[3]. Many inconsistencies are very obvious and it was thought worth-while to reinvestigate the decay of $^{79}$As.

The $^{79}$As was prepared by irradiating metalic Se (enriched to 97.8% in $^{80}$Se) in the linear accelerator of the C.B.P.F. The maximum energy of the bremsstrahlung beam was 22 MeV and irradiations were performed using up to 600 mg samples with irradiation times up to 30 min.

The gamma-ray spectra were detected by a 2 cm³ Ge(Li) diode. The pulses were fed via an ORTEC 109 preamplifier into an ORTEC 410 amplifier and displayed on a 4096 channel Intertechnique analyser. The overall resolution (FWHM) of the system was of 4 keV for the photopeak of the 662 keV line of $^{137}$Cs.

## 2. Results

The gamma transitions observed by Kuroyanagi[2] were identified with the following energies: 95.5 keV, 364.5 keV, 432.0 keV, 723.6 keV and 878.5 keV. A gamma-ray of 540 keV given in Ref.[2] was not observed in the present work. The following transitions were observed for the first time: 402.3 keV, 446.8 keV, 476.0 keV, 552.0 keV, 715.0 keV and 993.4 keV. The relative photon intensities are given in Table 1, Fig. 1 gives a typical pulse-height spectrum taken for 5 min starting 4 min after the end of the irradiation.

| Energy (keV) | $\gamma$-Intensity |
|---|---|
| 95.5 ± 0.5 | 1099 ± 100 |
| 364.5 ± 0.5 | 125 ± 4 |
| 402.3 ± 0.7 | 6.5 ± 1.5 |
| 432.0 ± 0.5 | 100 ± 2 |
| 446.8 ± 0.5 | 17.5 ± 2.0 |
| 476.0 ± 0.5 | 24.0 ± 2.5 |
| 552.0 ± 0.7 | 9.0 ± 1.6 |
| 715.1 ± 0.5 | 20.0 ± 2.0 |
| 723.6 ± 1.0 | 7.6 ± 0.8 |
| 878.5 ± 0.5 | 94 ± 4 |
| 993.4 ± 0.9 | 8.8 ± 2.5 |

Table 1. Energies and intensities of the gamma-rays found in the decay of $^{79}$As. Intensities are arbitrarilynormalized to $I_\gamma$ (432 keV) = 100.

Some peaks from the decay of $^{81}$Se are present in the spectrum shown in Fig. 1. Indeed, ($\gamma$, $n$) reactions on the even mass isotopes of Se are by far the most important source of contamination since the maximum energy available in our accelerator is not big enough to give a favorable $\sigma(\gamma, p)/\sigma(\gamma, n)$ ratio. In particular, the direct formation of $^{79}$Se and the fact that the halflives of this isomer and that of $^{79}$As are of the same order of magnitude is a major difficulty when we try to compare relative intensities of the 96 keV transition with the other transi-

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1 E. K. Lin, Phys. Rev. **139**, B 340 (1965).

2 T. Kuroyanagi, J. Phys. Soc. Japan **16**, 2369 (1961).

3 Nuclear Data, Section B, Vol. 1, no. 4, Ed. by K. Way, Academic Press (1966).

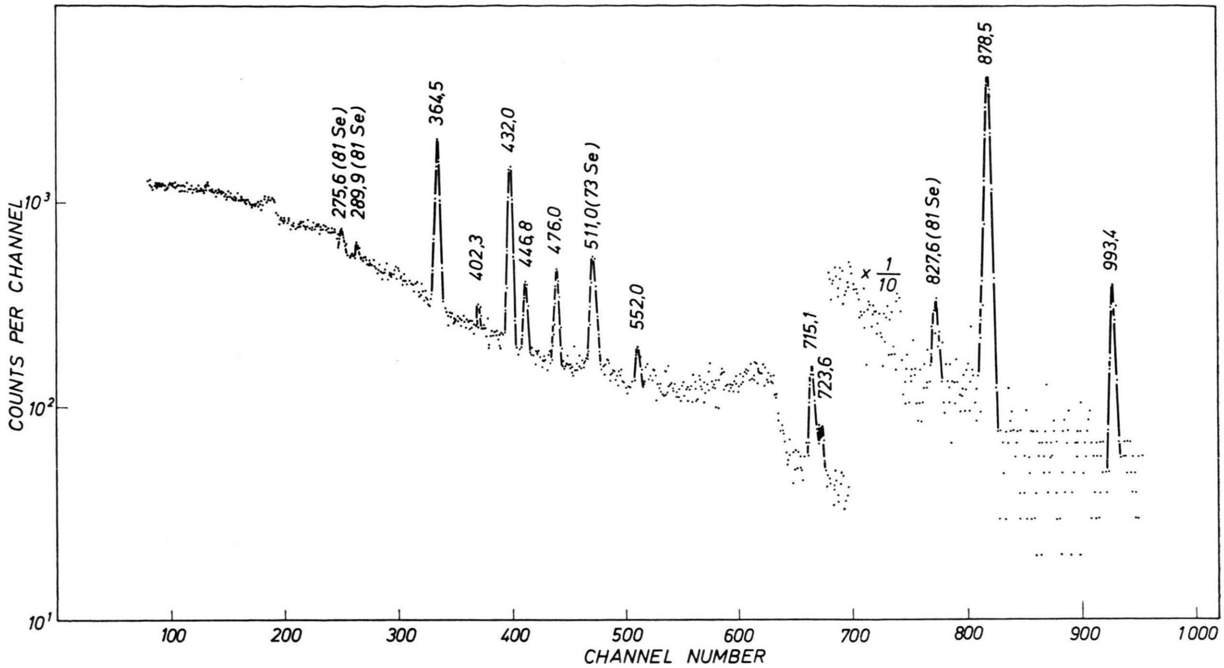


Fig. 1. Typical pulse — height spectrum taken for 5 min starting 4 min after the end of the irradiation. A Pb-Cu absorber was used in order to absorb partially the very intense gamma-ray of 95.5 keV.

tions we find in the decay of $^{79}$As. A series of spectra obtained at least 50 min after irradiation was used for this purpose. The decay curve starting at this point shows a negligible contribution of the 4 min activity. Another source of error in the determination of the relative intensity of the 95.5 keV transition is the absence of a direct measurement of the total internal conversion coefficient of this transition. Since the measured[4] ratio $e_K/\gamma$ for the isomeric transition agrees very well with the calculated values[5,6] of $\alpha_K$, the theoretical value of $\alpha_{tot} = 10.0$ was used to determine the relative transition intensity. An overestimated relative error of about 10% is given for this intensity.

The revised decay scheme deduced from our data is given in Fig. 2. Levels given in Ref.[2] at 0.46 MeV and 0.83 MeV were suppressed and new levels at 571.5 keV, 1079.5 keV and 1088.5 keV are suggested. These new levels are indicated by broken lines and shall be discussed in the next section. They are included in order to incorporate all the observed transitions in the decay scheme.

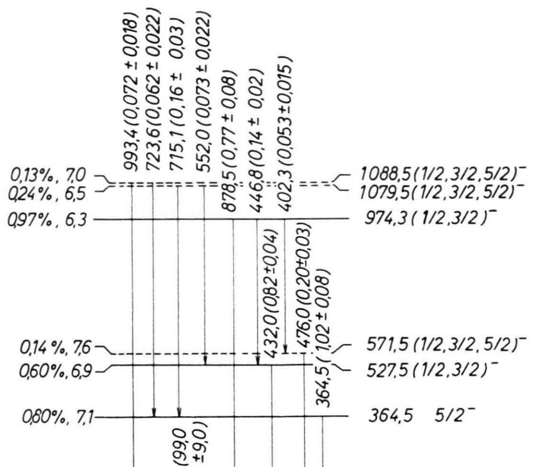


Fig. 2. Proposed decay scheme of $^{79}$As. Transition energies are given in keV and the intensities are transitions for 100 decays. The small arrows at left indicate the beta branches. The numbers are relative intensities and log ft, in this order. The maximum energy of the most intense branch is 2.14 MeV[2]. The ground state of $^{79}$As is supposed to be 3/2⁻.

[4] H. WEIGMANN, Z. Physik **167**, 549 (1962).
[5] M. E. ROSE, Internal Conversion Coefficients, North Holland Publishing Company (1958).
[6] L. A. SLIV and I. M. BAND, in Alpha-, Beta- and Gamma-Ray Spectroscopy, Ed. by K. SIEGBAHN, North Holland Publishing Company (1965).

Partial half-lives of the beta branches indicate odd parity and spin ranging from 1/2 to 5/2 for all the levels directly populated by the beta decay. Introducing further some restrictions on the $l$ value indicated by the reaction data[1] we obtain the quantum numbers given in Fig. 2.

## 3. Discussion of the Results

From simple shell model considerations we expect the neutrons in the region $28 < N < 50$ to be filling the p 3/2, f 5/2, p 1/2 and g 9/2 orbitals. For the 45 neutrons of $^{79}$Se the $1/2^-$ and $9/2^+$ states must appear as the ground and/or the first excited state. Surprisingly, the measured[7] ground state of $^{79}$Se is 7/2 and its parity is unambigously given as positive. Such $7/2^+$ states are low-lying isomeric states of $^{77}$Se and $^{81}$Se. More generally, this state is a common feature in almost all $41 \leqq N, Z \leqq 47$ nuclei. A possible coupling scheme which would result in a low-lying $7/2^+$ level in these nuclei is discussed by IKEGAMI and SANO[8]. The more natural $9/2^+$ state appears as an excited state at 135 keV in $^{79}$Se and at 294 keV in $^{81}$Se. The 135 keV level can not be fed by the beta decay of $^{79}$As as otherwise we should observe a possible 135 keV transition.

It is perhaps worth comparing the level scheme of $^{77}$Se as given in Ref.[3] with our proposed level scheme of $^{79}$Se with some additional levels given by nuclear reactions[1]. The number of levels up to 1.2 MeV in both level schemes is essentially the same and we tried an one — by — one identification. So, the lines connecting levels in Fig. 3 must be regarded as a mere tentative to correlate both spectra. The letter D on the 162 keV level of $^{77}$Se and on the 135 keV level of $^{79}$Se indicates possible doublets with the presence of a $l = 1$ level in addition to the indicated $l = 4$ levels. Concerning the isomeric pair there is no possible doubt, but the situation remains questionable for the other levels. Thus, for instance, the $l = 3$ levels that appear at 249 keV in $^{77}$Se and at 364.5 keV in $^{79}$Se decay predominantly to the $7/2^+$ states and, on the other hand, the $l = 3$ level that appears at 440 keV in $^{77}$Se and an assigned $5/2^-$ state at 571.5 keV in $^{79}$Se are identified one with the other since both are negligibly populated by the beta decay of As and both de-excite predominantly to $l = 1$ states. We identify also the $l = 1$ levels at 239 keV in $^{77}$Se and at 527.5 keV in $^{79}$Se since both are fed by beta branches with essentially the same $ft$ values. The 521 keV $l = 1$ level in $^{77}$Se populated by a beta branch with log $ft = 5.2$ is identified with the 974.3 keV $l = 1$ level in $^{79}$Se populated by a beta branch with log $ft = 6.3$. The most intense transitions de-exciting these levels are to the first $1/2^-$ level and to the first $3/2^-$ level, in this order. Identification of the two higher $l = 1$ levels of $^{77}$Se with proposed levels at 1079.5 keV and at 1088.5 keV in $^{79}$Se is much more arbitrary. In both nuclei we find below 1 MeV two $l = 2$ levels (not fed by the beta decay), and some $l = 0$ states are present around 1 MeV.

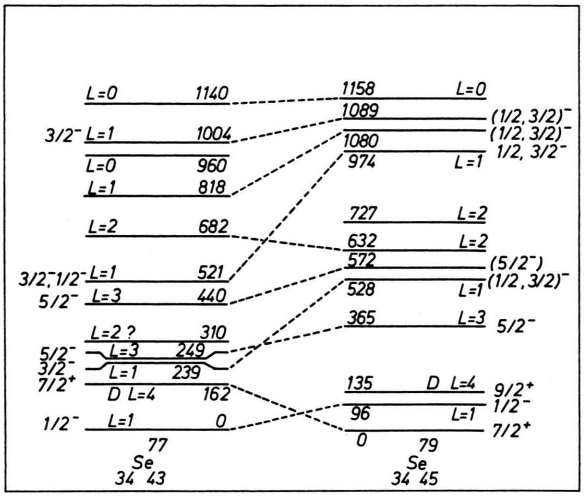

Fig. 3. Comparison between the level schemes of $^{77}$Se and $^{79}$Se. The lines connecting levels are to be regarded as a tentative one-by-one correlation and are merely indicative.

The great density of odd parity levels at low energy may be correlated to the minimum reached by the energy of the $2^+$ state in $^{76}$Se and $^{78}$Se. In fact the core of the odd mass nuclei in the region from $Z = 50$ upwards seems to become softer and softer as we go from Ni to Se, through Zn and Ge. Such a situation is discussed by KISSLINGER and KUMAR for the odd — $Z$ nuclei[9]. If it is correct to describe some low-lying levels in $^{77,79}$Se in terms of

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quasi-particle-phonon coupling we can understand this multiplicity of levels of equal parity as well as the relatively strong hindrances observed in some allowed $\beta$ transitions. The situation is very similar to that observed in some odd-A isotopes in the region ranging from Sb to Pm[10,11].

## 4. Miscellaneous Results Concerning the Decay Schemes of Some Isotopes of Selenium

The existence of a line of 552 keV in the decay scheme of $^{79}As$, the same energy as that of a transition observed in the decay of $^{81}Se$, was the main reason to re-examine this last decay scheme. For this purpose we irradiated natural selenium (1 g samples of 99.999% purity) with the bremsstrahlung beam. We observed gamma-rays with energies in keV (and intensities) of $275.6 \pm 0.3$ ($10.2 \pm 0.3$), $289.9 \pm 0.3$ ($8.4 \pm 0.3$), $538.0 \pm 0.4$ ($0.64 \pm 0.16$), $552.1 \pm 0.4$ ($1.35 \pm 0.20$), $566.0 \pm 0.4$ ($3.05 \pm 0.30$) and $827.7 \pm 0.3$ ($4.1 \pm 0.5$). The energy of the isomeric transition $^{81m}Se \rightarrow {}^{81g}Se$ was found to be $103.7 \pm 0.5$ keV. These results are in agreement with those obtained by RAO and FINK[12]. It was not possible to prove that the 290 keV line is double, as suggested by Rao and Fink. These authors proposed a level in $^{81}Br$ at 538 keV populated by a 290 keV transition from the 828 keV level and being de-excited by a 538 keV transition to the ground state. The following levels of $^{81}Br$ were confirmed: $275.6 \pm 0.3$ keV ($5/2^-$), $566.0 \pm 0.5$ keV ($3/2^-$) and $827.7 \pm 0.4$ keV ($1/2^-$, $3/2^-$). In addition there are below 1 MeV at least three levels not fed by the beta decay of $^{81}Se$: an isomeric state at about 0.55 MeV ($9/2^+$) and levels at 767.3 keV ($5/2^-$, $7/2^-$) and at 836.4 keV observed by Coulomb excitation[13]. We believe that this last level, identified by ROBINSON[13] is not the same level as observed in the beta decay at 827.7 keV since a difference of 8.7 keV is far beyond the experimental error in both experiments.

In Fig. 4 we present a portion of the gamma spectrum obtained seven minutes after irradiating the natural selenium at a maximum energy of about 20 MeV. The three gamma rays of 538 keV, 552 keV and 566 keV pertaining to the decay of $^{81m,81g}Se$ exhibit a complex half life (18 min + 57 min). The annihilation peak decays also with a complex half-life but the components are now 38 min and 7 h, indicating that it is due to the decay of $^{73m,73g}Se$. The transition of 558.7 keV pertains to the decay of $^{76}As$. We observe also in the figure a line of 577.5 keV attributed to the decay of $^{73}Se$ (38 min).

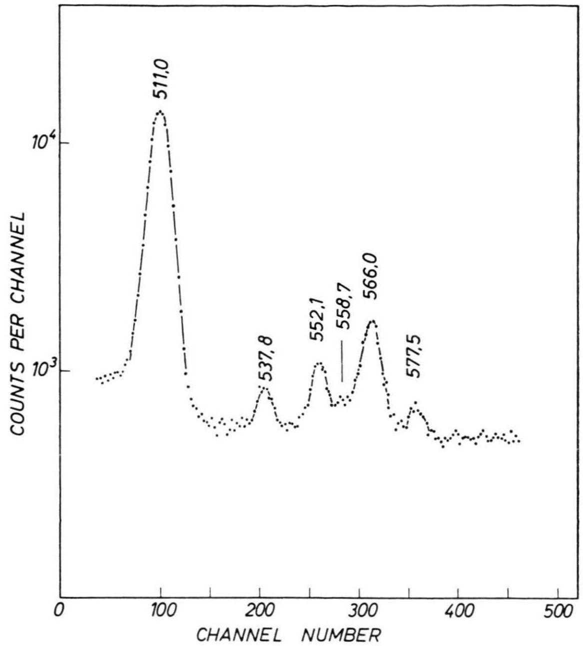


Fig. 4. Portion of the gamma spectrum resulting from the irradiation of natural selenium.

The sources obtained by irradiating natural selenium exhibit a number of unknown lines with half lifes in the range 30—45 min. Poor statistics did not permit to determine with precision these periods and even to distinguish between simple and complex half-lifes. Many of them could be associated with the decay of the 38 min $^{73}Se$, namely: 253.8 keV, 320.1 keV, 392.3 keV, 401.1 keV, 577.5 keV, 649.5 keV, 976.2 keV, 986.2 keV, 1003 keV, 1076.6 keV, 1104.6 keV, 1171 keV and

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[11] I. V. GOLDSTEIN, J. M. F. JERONYMO and A. G. DE PINHO (to be published).
[12] P. V. RAO and R. W. FINK, Phys. Rev. **154**, 1028 (1967).
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1176.3 keV. The energy of the isomeric transition in $^{73}As$ was measured to be 360.4 ± 0.4 keV. The isomeric level at 427.3 ± 0.4 keV is fed by the 7 h $^{73}Se$.*

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* *Note added in proof:* Very recently MURRAY et al. (Nucl. Phys. A **130**, 563, june 1969) published the energies and relative intensities of the gamma-rays following the decays of 7.1 h $^{73}Se$ and 42 min $^{73m}Se$ produced by $^{70}Ge(\alpha,n)$ reaction. The gamma-rays of 253.8 keV, 320.1 keV, 392.3 keV, 401.1 keV, 577.5 keV, 1002.6 keV and 1076.6 keV observed by us were confirmed. The lines of 84.3 keV, 848.8 keV and 992.1 keV were also present in our spectra. They are associated to the decay of $^{73m}Se$ by MURRAY et al. — The absence of some conspicous peaks observed in our spectra obtained by irradiating natural selenium among the transitions reported by MURRAY et al. forced us on a revision of some conclusions concerning the origin of those peaks. Thus, the 649.5 keV transition is now attributed to the decay of $^{81}Se$ in agreement with previously reported results of PRAWIROSOEHARDJO (Phys. Rev. **157**, 995 [1967]). Another transition to be attributed to the same decay is that of 260.2 keV, as suggested by YTHIER et al. (Physica **34**, 559 [1967]). The relative intensities of these lines are 0.40 ± 0.07 and 1.05 ± 0.13, respectively. However, five gamma-ray, namely those with 976.2 keV, 986.2 keV, 1104.6 keV, 1171 keV and 1176.3 keV, remain without definite assignement.

# The Functional Method in the Theory of Real Gases

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The relations of the theory of real gases which have first been derived by Mayer and his coworkers can be obtained in a simple way by the functional method. In this case the assumption of the pairwise additivity of the intermolecular potential can be dropped. Apart from some new relations for distributions functions the expansion of the direct correlation functions is obtained as a power series in density with coefficients consisting of integrals over Husimi functions.

In a series of papers[1] the functional method has been analysed to derive integral equations for molecular distribution functions. In (I) we have shown that successive applications of functional operations lead to hierarchies of functions and their interrelations. In particular we have found that the Ursell and the Husimi expansions can be expressed in terms of appropriate functional derivatives which in turn generate relations between different hierarchies of integral equations. As these expansions are also used in the theory of real gases developed by MAYER and his coworkers[2–5] one may suspect that the functional method yields a simple derivation of the MAYER theory.

In the following sections we want to present this derivation showing that it is by far less complicated than that given by Mayer himself. Furthermore, the intermolecular potential is restricted only by the properties required for the existence of the relevant integrals. Moreover, this method leads to some new relations for distribution functions and the density expansions of the direct correlation functions. The coefficients in this power series are cluster integrals over Husimi functions.

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