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# Decay of Mass-Separated $^{93}$Y

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The levels of $^{93}$Zr populated in the $\beta$ decay of $^{93}$Y have been deduced from Ge(Li)-Ge(Li) coincidence and Ge(Li) singles $\gamma$-ray spectra. 22 of the 23 observed $\gamma$-ray transitions have been placed in a level scheme for $^{93}$Zr with 11 excited states. These results are compared with those of previous investigations. A number of corrections, clarifications, and expansions of decay schemes previously reported resulted from the use of high-resolution detectors and a mass-separated source strong enough to permit coincidence studies of the weak as well as the intense transitions. Spin-parity assignments of the $^{93}$Zr levels have been deduced using relative $\gamma$-ray transition rates, $\beta$-decay log$ft$ values, and results of nuclear-reaction studies. Possible interpretations of some of the levels are presented, based on shell-model descriptions.

[RADIOACTIVITY $^{93}$Y (from $^{93}$Kr decay); measured $E_\gamma$, $I_\gamma$, $\gamma$-$\gamma$ coin, calculated log$ft$. $^{93}$Zr deduced levels, $J$, $\pi$. Mass-separated $^{93}$Kr activity.]

## I. INTRODUCTION

The decay scheme of $^{93}$Y has been the subject of a number of investigations.[1-5] Some of the interest in this decay[3-5] has centered on the prediction by Talmi[6] of the existence of a $\frac{9}{2}^+$ level in $^{93}$Zr at an energy of about 1.1 MeV and arising from the $(d_{5/2})^3$ neutron configuration (which is also assumed to describe the $\frac{5}{2}^+$ ground state and $\frac{3}{2}^+$ first excited state at 0.267 MeV). In the more recent studies,[2-5] a substantial number of discrepancies exist among the reported energies, intensities, and placements of the $\gamma$-ray transitions observed in the decay of $^{93}$Y, with corresponding differences in decay-scheme details.

The purpose of the present work has been to clarify many of these discrepancies by using mass-separated sources and high-resolution (2.5 keV at 1.33 MeV), large-volume (60-cm$^3$) Ge(Li) $\gamma$-ray detectors for coincidence and singles measurements. Coincidence measurements made with the large-volume detectors in a two-parameter manner provided needed cascade information for the weak as well as the intense transitions.

From the results obtained in the present work, most of the ambiguities and discrepancies have been resolved and a decay scheme is presented in which all but one of the observed transitions have been placed on the basis of coincidence data and precise energy relationships. A preliminary version of the results presented here has been reported in the latest revision of the *Nuclear Data Sheets* for $A = 93$ and was used as the basis for the adopted decay scheme of $^{93}$Y.[7]

The $\beta$ spectrum of $^{93}$Y decay has been measured by Knight *et al.*[1] with two important results. The ground-state $\beta$ group was shown to have a unique spectrum shape, and the ratio of the 267-keV $K$-electron conversion intensity to the total $\beta$-decay intensity was measured to be 0.0015. The $K$-shell internal-conversion coefficient for the 267-keV transition was subsequently measured by Ohya and Matumoto[5] to be $0.022 \pm 0.004$. We have made use of these data to determine absolute transition intensities.

There have been several reaction studies of the levels of $^{93}$Zr, using the $^{92}$Zr$(d,p)$ and $^{92}$Zr$(\alpha,{}^3\text{He})$ stripping reactions,[8-12] as well as the $^{94}$Zr$(d,t)$, $^{94}$Zr$(p,d)$, and $^{94}$Zr$({}^3\text{He},\alpha)$ pickup reactions.[12-14] These studies have yielded information useful in corroborating spin-parity assignments deduced from decay studies. A presentation of the individual results, as well as a summary of the level properties, is contained in the $A = 93$ compilation by Kocher.[7]

## II. EXPERIMENTAL PROCEDURE

### A. Source Preparation

The $^{93}$Y sources studied in this work were obtained as decay products of mass-separated $^{93}$Kr which is available at the TRISTAN on-line isotope-separator facility at the Ames Laboratory research reactor.[15] The half-lives for the $^{93}\text{Kr} \rightarrow {}^{93}\text{Rb} \rightarrow {}^{93}\text{Sr} \rightarrow {}^{93}\text{Y} \rightarrow {}^{93}\text{Zr}$ decay chain are 1.29 sec, 5.8 sec, 7.6 min, and 10.1 h, respectively.[7] After a time interval following collection which is long compared to 7.6 min, the activity of the collected sample should be largely $^{93}$Y, since $^{93}$Zr is essentially stable ($T_{1/2} = 1.53\times10^6$ yr[7]).

In the samples obtained, some $A = 92$ contaminant was expected due to the presence of $^{92}$KrH$^+$ ions in the mass-93 ion beam, and to delayed neutron emission[16] during the decays of $^{93}$Kr and $^{93}$Rb. For this reason, a chemical separation of Y from Sr was made to eliminate the 2.71-h $^{92}$Sr activity which, together with the 3.53-h $^{92}$Y daughter activity, could produce significant contamination in the $\gamma$-ray spectrum. Although the chemical separation effectively removed the Sr activities, there was present a significant $^{92}$Y contamination which was produced during the collection of the mass-93 sample (collection times ranged from 7 to 12 h). Since the decay of $^{92}$Y had been studied earlier at this laboratory,[17] the spectrum contribution from this activity was easily determined and interfered with the $^{93}$Y $\gamma$-ray spectrum only in the 972-keV region.

The chemical-separation procedure, suggested by Nazin, Levin, and Golutvina,[18] consisted of dissolving the thin copper collection foil in 12 $N$ HNO$_3$, extracting the yttrium with tri-butyl phosphate, and precipitating it with NH$_4$OH as Y(OH)$_3$. The hydroxide precipitate was centrifuged to the bottom of a plastic centrifuge tube, the supernate poured off, and the tube with precipitate carried to the detector system. The sources thus prepared were concentrated in the form of a hydroxide at the bottom of a thin plastic centrifuge tube, making a rather small source with negligible self-absorption of the $\gamma$ rays emitted.

### B. Data Accumulation and Analysis

Two main experimental periods comprise the present work. Initially, singles $\gamma$-ray spectra were obtained using a 30-cm$^3$ Ge(Li) detector having a resolution of 3.5 keV at 1.33 MeV. Later, both coincidence and singles spectra were measured with 60-cm$^3$ Ge(Li) detectors having resolutions of about 2.5 keV at 1.33 MeV. The investigations for the two experimental periods can be considered as independent studies, since the instrumentation and calibrations were different, as were the computer programs used to analyze the data. Despite these differences, the results were remarkably reproducible (the energies agreed to within 0.1 keV for the intense $\gamma$ rays, and to within 0.3 keV for most of the weak transitions).

To follow the half-lives of the spectral peaks, several spectra were obtained for each sample. At first an 18-h counting period was used, in which two 3-h accumulations were followed by a 6-h delay interval and a final 6-h accumulalation. Later 12 separate spectra were accumulated over a 25-h period. The individual spectra were analyzed to verify half-lives of the transitions, and the summed composite spectra were analyzed to give energy and intensity information.

For the coincidence measurements, the two 60-cm$^3$ Ge(Li) detectors were placed in a 180° geometry, with a source-to-detector distance of about 3 cm. Standard constant-fraction timing was used, with a full-width time window of 40 nsec. About $3\times10^6$ coincidence events were recorded using a buffer memory tape system in which all coincidence events are stored in a $4096\times4096$ format on magnetic tape as they occur. Coincidence and coincidence-background gates were digitally selected using the buffered tape control system, and the recorded events were searched to obtain coincidence and coincidence-background gated spectra. Coincidence relationships were determined at first by visual inspection of the coincidence spectra. For a few cases, quantitative analysis of the coincidence data was required to verify the proposed decay scheme.

Spectrum-peak centroids and areas were determined for the singles data by applying a nonlinear least-squares fit of a skewed-Gaussian-fit function to the data using the IBM 360/Model 65 computer at the Iowa State University Computation Center. Together with other utility routines, this analysis transformed centroid and area information into transition energies and intensities. The construction of the level scheme was assisted by use of energy crossover and sum relationships, as well as by coincidence information.

## III. EXPERIMENTAL RESULTS AND DECAY SCHEME

### A. Singles $\gamma$-Ray Results

The $\gamma$-ray energies and intensities obtained in this work are presented in Table I, together with those reported in the other recent Ge(Li) studies.[2-5] Because of the diversity of results represented in Table I for this relatively simple decay, the results of this work (referred to subsequently as TH) are compared in the following discussion with those of the other investigators. Selected portions of the singles $\gamma$-ray spectrum from the later study are presented in Fig. 1 to aid in the discussion.

*Ohya and Matumoto (OM).*[5] All transition energies between 267 and 2184 keV (except for 1159.3 keV) are lower than those of TH by 0.5 to 1 keV. OM do not report the transitions at 714, 962, 971, 988, and 2457 keV. The 1169-keV peak was observed by OM but was interpreted to be entirely the 2191-keV double-escape (DE) peak. Intensities agree within the quoted errors except for the 1237-, 1470-, and 1643-keV transitions, for which

TABLE I. Energies and intensities of $\gamma$ rays emitted in the decay of $^{93}$Y.

| Present work | | Ohya and Matumoto (Ref. 5) | | Hontzeas and Marsden (Ref. 4) | | Arad *et al.* (Ref. 3) | | Polak (Ref. 2) | |
|---|---|---|---|---|---|---|---|---|---|
| Energies (keV) | Intensities [a,b] | Energies (keV) | Intensities | Energies (keV) | Intensities | Energies (keV) | Intensities | Energies (keV) [c] | Intensities |
| 266.9 ± 0.1 | 1000 ± 53 | 267.0 ± 0.2 | 1000 | 267.0 ± 0.5 | 1000 | 267.0 ± 0.5 | 1000 | 267 | 1000 |
| | | | | 273.0 ± 1.0 | 9.5 ± 2.0 | | | | |
| | | | | 287.0 ± 1.0 | 10.3 ± 1.5 | | | | |
| | | | | 341.5 ± 0.5 | 6.0 ± 2.0 | 343 ± 1.5 | 6 ± 3 | | |
| | | | | | | | | 490 | <0.5 |
| 680.2 ± 0.1 | 87.0 ± 4.4 | 679.1 ± 0.2 | 79 ± 8 | 687.0 ± 0.5 | 88.5 ± 3.2 | 679.4 ± 0.3 | 75 ± 8 | 681 | 90 ± 2 |
| 714.4 ± 0.2 | 2.3 ± 0.3 | | | | | | | | |
| 947.1 ± 0.1 | 279 ± 14 | 946.1 ± 0.2 | 242 ± 24 | 947.1 ± 0.5 | 274 ± 12 | 946.5 ± 0.3 | 229 ± 24 | 947 | 293 ± 8 |
| 962.3 ± 0.2 | 1.6 ± 0.2 | | | | | | | | |
| 971.0 ± 0.8 | 0.9 ± 0.3 | | | | | | | | |
| 987.7 ± 0.3 | 1.4 ± 0.3 | | | | | | | | |
| 1158.5 ± 0.2 | 4.0 ± 0.4 | 1159.3 ± 1.5 | 5 ± 3 | 1158.0 ± 1.0 | 3.8 ± 0.7 | | | | |
| 1168.6 ± 0.2 | 1.4 ± 0.5 | | | 1168.0 ± 1.0 | 2.6 ± 0.5 | 1167.7 ± 1.0 | 14 ± 8 | | |
| 1183.5 ± 0.1 | 6.0 ± 0.5 | 1182.9 ± 0.6 | 5 ± 2 | 1182.7 ± 0.6 | 2.6 ± 0.5 | 1186.2 ± 1 | 8 ± 5 | 1184 | 8 ± 1 |
| | | | | 1184.7 ± 0.6 | 2.7 ± 0.5 | | | | |
| 1203.3 ± 0.1 | 14.7 ± 0.9 | 1202.4 ± 0.5 | 14 ± 2 | Longer half-life | | 1202.9 ± 1 | 10 ± 5 | 1204 | 14 ± 1 |
| 1237.4 ± 0.1 | 3.9 ± 0.9 | 1236.4 ± 0.8 | 2 ± 1 | 1237.0 ± 2 | 3.5 ± 0.7 | 1236.5 ± 1.5 | 5 ± 3 | | |
| 1425.4 ± 0.1 | 34.0 ± 1.8 | 1424.7 ± 0.3 | 32 ± 3 | 1425.4 ± 0.5 | 35.6 ± 1.6 | 1425.5 ± 0.3 | 5 ± 3 | 1426 | 33 ± 1 |
| 1450.5 ± 0.1 | 48.0 ± 2.5 | 1449.6 ± 0.3 | 46 ± 5 | 1450.8 ± 0.3 | 43.6 ± 1.2 | 1450.8 ± 0.3 | 32 ± 3 | 1451 | 44 ± 1 |
| 1470.1 ± 0.1 | 9.7 ± 0.6 | 1469.6 ± 0.5 | 6 ± 1 | Shorter half-life | | 1471.1 ± 1.5 | 5 ± 3 | 1471 | 6 ± 1 |
| 1642.7 ± 0.1 | 6.7 ± 0.5 | 1641.8 ± 0.8 | 10 ± 2 | 1642.8 ± 0.7 | 8.2 ± 0.9 | 1643 ± 0.3 | 3 ± 2 | 1643 | 8 ± 1 |
| 1651.7 ± 0.2 | 3.1 ± 0.4 | 1650.4 ± 1.0 | 4 ± 3 | 1651.7 ± 0.7 | 5.4 ± 1.1 | | | 1653 | 3 ± 1 |
| 1827.8 ± 0.2 | 3.1 ± 0.4 | 1827.1 ± 0.8 | 3 ± 1 | 1826.0 ± 1.5 | 5.2 ± 1.1 | | | 1828 | 3 ± 1 |
| 1917.8 ± 0.1 | 201 ± 10 | 1917.2 ± 0.3 | 206 ± 21 | 1914.2 ± 0.6 | 238 ± 13 | 1917.9 ± 0.3 | 159 ± 16 | 1918 | 212 ± 4 |
| 2184.6 ± 0.1 | 22.2 ± 1.7 | 2184.4 ± 0.5 | 20 ± 3 | 2180.7 ± 1.5 | 25 ± 2 | 2184.3 ± 0.3 | 17 ± 2 | 2184 | 21 ± 1 |
| 2190.8 ± 0.1 | 24.5 ± 1.4 | 2190.7 ± 0.5 | 26 ± 3 | 2186.5 ± 1.5 | 25 ± 2 | 2190.7 ± 0.3 | 19 ± 2 | 2190 | 22 ± 1 |
| 2457.3 ± 0.3 | 0.9 ± 0.2 | | | | | | | | |
| 2473.8 ± 0.2 | 1.6 ± 0.2 | 2474.7 ± 1.0 | 2 ± 1 | 2468.5 ± 3.0 | 1.5 ± 0.4 | | | 2472 | 1.4 ± 0.2 |
| | | | | 2605.0 ± 3.0 | 1.5 ± 0.6 | | | | |

[a] $I_\gamma$ in transitions per 100 decays of $^{93}$Y is obtained by using the factor 0.006 99.

[b] $I_\gamma$ for 266.9-keV $\gamma$ ray is a relative *transition* intensity, including correction of 0.025 for internal conversion.

[c] Energy uncertainty is reported to be <1 keV.

there are discrepancies of about 50%.

*Hontzeas and Marsden (HM)*.[4] The results of HM are most notably characterized by the large discrepancies in transition energies compared with other studies, especially for the high-energy region. While the energy reported for the 687-keV $\gamma$ ray is nearly 7 keV above that of TH, the energies of the 1914-, 2181-, 2187-, and 2468-keV $\gamma$ rays are 3 to 5 keV below those of TH. In the decay scheme presented by HM, some of the energy sum relationships are in disagreement with crossover transition energies by as much as 9 keV. HM do not assign the 1203- and 1470-keV transitions to $^{93}$Y on the basis that these transitions exhibit half-lives different from the others. These lines have a decay time consistent with $^{93}$Y according to all the other studies included in Table I. While HM do not report the low-intensity transitions found by TH at 714, 962, 971, 988, and 2457 keV, they do include $\gamma$ rays at 273, 287, 342, and 2605 keV and one member of the 1183-1185-keV doublet, which are not reported in any of the other studies except for the 343-keV transition of Arad *et al.*[3] (It could be speculated that the 2605-keV $\gamma$ ray may be the $^{228}$Th 2614-keV transition present in most background spectra.) The assignment of these extraneous transitions by HM to the decay of $^{93}$Y is in disagreement with the data displayed in Fig. 1. (A comparison of the spectrum in Fig. 1 with that shown in Fig. 2 of HM clarifies this point.) In general, the transition intensities reported by HM are in good agreement with those of TH. Minor intensity discrepancies exist for the 1169-, 1184-, 1652-, 1828-, and 1918-keV transitions.

*Arad, Boulter, Prestwich, and Fritze (ABPF)*.[3] The transition energies reported by ABPF are in agreement within quoted errors with those of TH except for the $\gamma$ rays at 679, 946, and 1186 keV. The low-intensity $\gamma$ rays at 962, 971, 988, 1158, 1652, 1828, 2457, and 2474 keV with $I_\gamma < 4$ reported by TH were not observed by ABPF. A transition at 343 keV was reported by ABPF but not observed by TH. Transition intensities reported by ABPF tend to be about 20% lower than those of TH. There is a more substantial discrepancy for the 1450-keV transition, and the discrepancies for the 1168- and 1426-keV $\gamma$ rays are essentially order of magnitude.

*Polak*.[2] The transition energies reported by Polak to an uncertainty of <1 keV are in agreement with those of TH, except for the 2472-keV $\gamma$ ray.

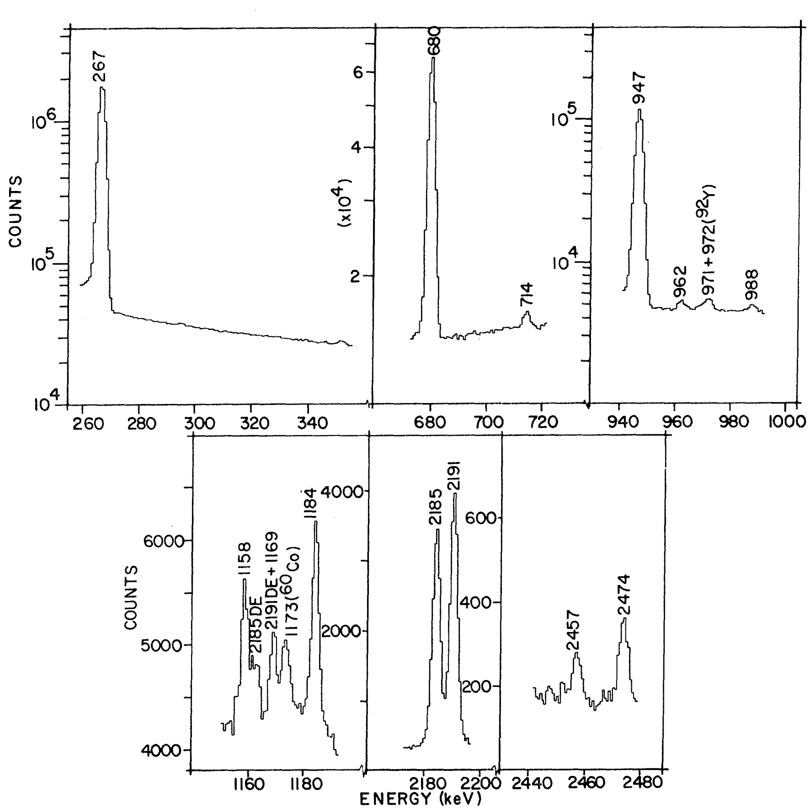

FIG. 1. Regions of the $\gamma$-ray spectrum from the decay of $^{93}$Y using a 60-cm$^3$ Ge(Li) detector, selected to illustrate points made in the text.

The intensities are also in good agreement with TH. Eight low-intensity transitions reported by TH were not observed by Polak.

It can be noticed that the most consistent variances of the present work with the other studies center about three energy regions, at 975, 1170, and 2460 keV. The portions of the singles spectrum at these energies are included in Fig. 1, to illustrate the extent to which the transitions reported in this work were observed. The doublet at 2185-2191 keV is also included for comparison with the 1163-1169 peaks to illustrate that the 1169-keV peak is not due entirely to the double-escape peak of the 2191-keV $\gamma$ ray.

### B. Coincidence Results

The results of the Ge(Li)-Ge(Li) coincidence measurements are presented in Table II. Examples of the spectra yielding these results are shown in Figs. 2–4. Coincidence spectra were obtained using as gating transitions all of the transitions evident in the "coincidence profile" (i.e., the spectrum of all events in the gating detector that are coincident with any events in the other detector). The 1425-, 1450-, 1470-, 2185-, 2457-, and 2474-keV transitions were not observed in the coincidence profile, indicating that they are ground-state transitions depopulating levels that are populated mainly by direct $\beta$ feeding.

The coincidence results reported in earlier studies[3-5] are very limited, since these studies were confined to the more intense transitions and generally employed NaI(Tl) as one of the coincidence detectors. In a comparison with the results reported here, there is general consistency for the limited number of cases, but two important discrepancies arise in the comparison with the results of ABPF.[3] The determination in the present work of the 267-2191 cascade and the observation that the 2185-keV $\gamma$ ray is a ground-state transition is contrary to the results reported by ABPF for the 2185- and 2191-keV transitions. The 267-1440 cascade reported by ABPF is also contrary to the observation in this work that the 1425-, 1450-, and 1470-keV $\gamma$ rays are all ground-state transitions. The 2371.8-keV level proposed by ABPF is inconsistent with the ground-state placement of the 1425-keV $\gamma$ ray in this work.

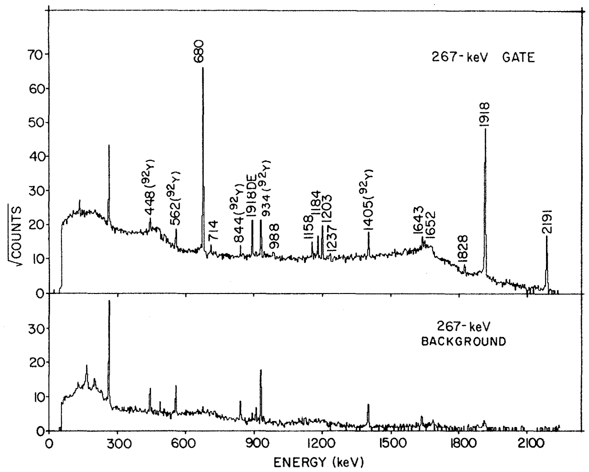

FIG. 2. $\gamma$-ray spectra gated by the 267-keV transition and adjacent background.

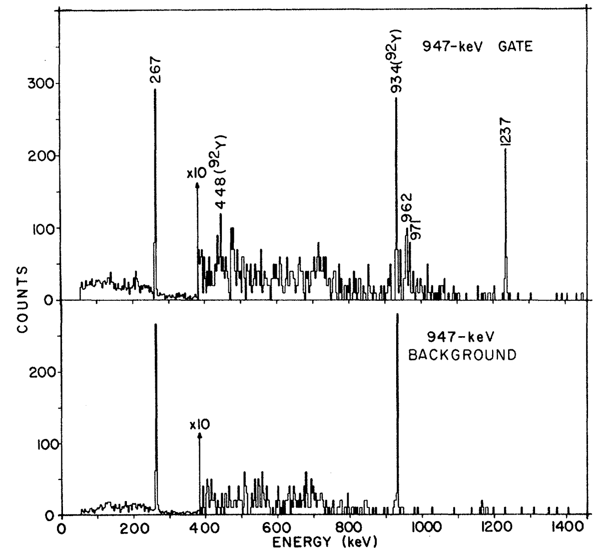

FIG. 3. $\gamma$-ray spectra gated by the 947-keV transition and adjacent background.

TABLE II. $\gamma$-ray coincidences in the decay of $^{93}$Y.

| Gating transition (keV) | Coincident transition (keV) |
|---|---|
| 267 | 680, 714, 962(?), 988(?), 1158, 1184, 1203, 1237, 1643, 1652, 1828, 1918, 2191, 1169 (may all be 2191 DE) |
| 680 | 267, 972(?), 1237 |
| 947 | 962, 971, 1237 |
| 962 | 267(?), 947 |
| 971 | 267, 947 |
| 1158 | 267 |
| 1169 | 267 (may all be from 2191 DE) |
| 1184 | 267 |
| 1203 | 267, 714, 988 |
| 1237 | 680, 947 |
| 1643 | 267 |
| 1652 | 267 |
| 1828 | 267 |
| 1918 | 267 |
| 2191 | 267 |

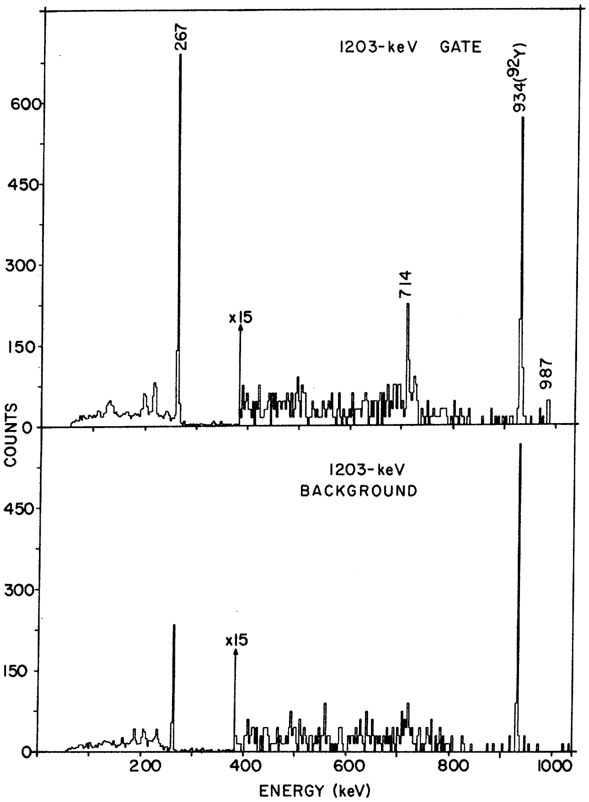

FIG. 4. $\gamma$-ray spectra gated by the 1203-keV transition and adjacent background.

### C. Decay Scheme

The decay scheme for $^{93}$Y based on the results of this work is shown in Fig. 5. The coincidence relationships are illustrated by the use of closed circles placed at the heads or tails of the transitions. All $\gamma$-ray cascades indicated in the decay scheme have been verified by coincidences, and all level energies are established by energy sums which agree with crossover energies to within the quoted energy uncertainties. The absolute transition intensities per 100 $\beta$ decays are indicated in parentheses after the energies.

The level energies, determined from a weighted average of all transition energies into or out of the respective levels, along with the resulting statistical uncertainties, are presented in Table III. Calculated log$ft$ values and $\beta$-branching information deduced from $\gamma$-ray intensity imbalances are also included. For the log$ft$-value calculations, a $Q_\beta$ of 2.89 MeV was used.[1] The ground-state $\beta$-branch intensity was deduced from the ratio of the 267-keV $K$-conversion electron intensity to total $\beta$-decay intensity reported by Knight *et al.*[1] and the total internal-conversion coefficient of the 267-keV transition.

The total conversion coefficient was obtained from the tables of Hager and Seltzer[19] using a multipolarity for the 267-keV transition of 60 ± 27% $E2$ (40% $M1$). This multipolarity was deduced from the $K$-conversion coefficient of 0.022 ± 0.004 reported by Ohya and Matumoto.[5]

There are several features of the proposed decay scheme which should be emphasized. The only transition not placed in the level scheme for $^{93}$Zr is that at 1169 keV. The placement of this transition, and the evidence for its existence, is complicated by the presence of the double-escape peak of the 2191-keV $\gamma$ ray at essentially the same energy. The existence of the 1169-keV $\gamma$ ray is based upon a comparison of its intensity to that of the 1163-keV peak intensity, which is asserted to be the double-escape peak of the 2185-keV $\gamma$ ray.

TABLE III. Level energies for excited states in $^{93}$Zr and the corresponding $\beta$ branching and log$ft$ values for $^{93}$Y decay.

| Level energy (keV) | Percent | $\beta$ branching log$ft$ | Log$f_1t$ |
|---|---|---|---|
| 0.0 | 90.25 ±2.15 | | 9.10 ± 0.09 |
| 266.87 ± 0.05 | 4.54 ±1.09 | 8.85 ± 0.14 | |
| 947.13 ± 0.07 | 2.51 ±0.57 | 8.57 ± 0.13 | |
| 1425.39 ± 0.09 | 0.27 ±0.06 | 9.05 ± 0.13 | |
| 1450.44 ± 0.07 | 0.38 ±0.09 | 8.87 ± 0.13 | |
| 1470.13 ± 0.07 | 0.15 ±0.03 | 9.26 ± 0.13 | |
| 1909.54 ± 0.10 | 0.058 ± 0.014 | 9.05 ± 0.13 | |
| 1918.55 ± 0.20 | 0.028 ± 0.007 | 9.35 ± 0.14 | |
| 2094.67 ± 0.21 | 0.022 ± 0.006 | 9.13 ± 0.14 | |
| 2184.60 ± 0.06 | 1.60 ±0.37 | 7.08 ± 0.13 | |
| 2457.65 ± 0.13 | 0.19 ±0.04 | 7.28 ± 0.14 | |
| 2473.80 ± 0.20 | 0.011 ± 0.003 | 8.45 ± 0.15 | |

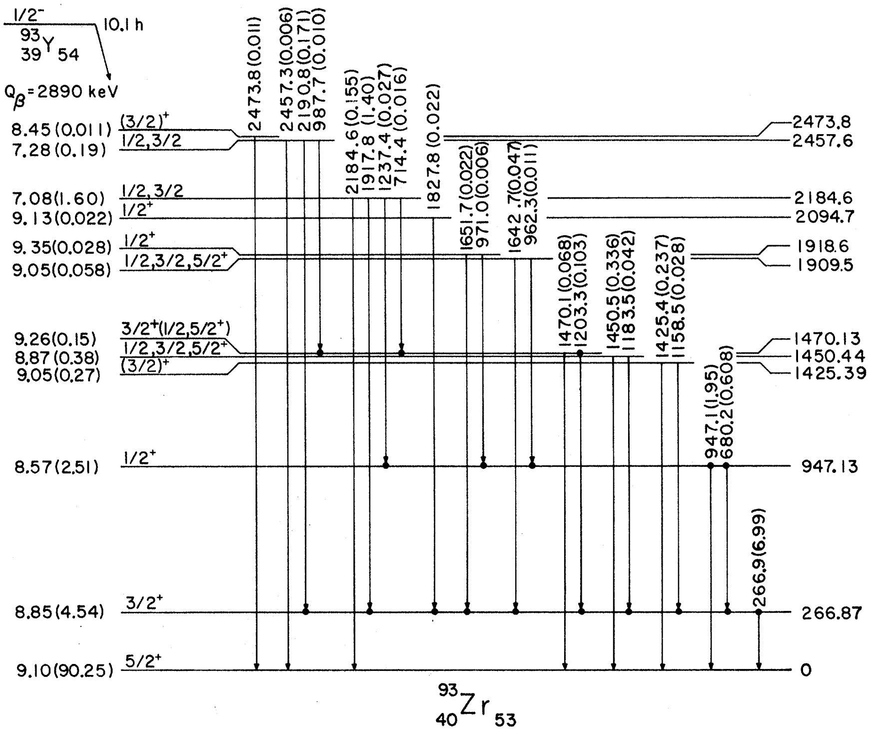

FIG. 5. The decay scheme of $^{93}$Y. The transition intensities indicated in parentheses are per 100 $\beta$ decays. Log*ft* values and $\beta$ branching intensities are to the left of each level.

Figure 1 includes the portions of the $\gamma$-ray spectrum which illustrate the conclusion of this work that the 1169-keV peak is not composed entirely of the 2191-keV double-escape peak. Coincidence measurements with the 1169-keV transitions were inconclusive. A definite coincidence with the 267-keV transition was observed, and although the coincidence intensity appeared to be greater than that expected for the 2191-keV double-escape-peak contribution, the counting statistics were not good enough to give an unambigous interpretation. The data do not rule out the possibility of a level at 1168.6 keV which could possibly confirm the prediction by Talmi[6] of a $\frac{9}{2}^+$ state at 1.1 MeV. If this level were to exist, it would have to be fed by $\gamma$ rays from higher-lying states, as direct $\beta$ feeding would be highly forbidden. No evidence for any (even weak) cascade transitions from higher-lying levels was found in the 1169-keV gated coincidence spectrum. The only difference between the proposed decay scheme and the preliminary one communicated to Kocher[7] is in the placement of the 1169-keV $\gamma$ ray.

The 2457-keV transition was determined not to be a sum peak by the simple fact that its intensity was consistent for both experimental periods, in which different detectors and geometries were used.

The 971.0-keV $\gamma$-ray peak exhibited interference from the $^{92}$Y 972.3-keV transition. To check the effectiveness in resolving the contributions of each transition to the peak from the singles analysis, the 947-keV gated coincidence spectrum was analyzed for the relative intensities of the 971- and 962-keV $\gamma$ rays. The analysis confirmed the intensities reported from the singles data results.

Because of the close energy agreement of the 1918.55-keV level with the strong 1917.8-keV transition, the 267-keV coincidence spectrum was analyzed to determine the relative intensities of the 680-, 1203-, 1918-, and 2191-keV transitions. The analysis resulted in a confirmation of the placement of the 1918-keV transition entirely in cascade with the 267-keV transition. While the analysis doesn't rule out a weak component of the 1918-keV peak which could be assigned as a 1918.55-keV ground-state transition, it does limit the relative intensity of such a transition to 11 ± 12, on the scale used in Table I. However, the computer fit obtained for the 1918-keV peak in the singles data does not indicate that a 5% component is present in the peak at a location 0.7 keV higher than the main centroid. Thus, it is assumed that all of the 1918-keV $\gamma$ ray is in cascade with the 267-keV transition.

The proposed decay scheme differs substantially from those of HM[4] and ABPF.[3] It is most similar to that proposed by OM[5] and differs by suggesting levels at 2094.7 and 1918.6 keV, but not at 1827.1 and 1650.4 keV. The observation in this work of several low-intensity $\gamma$ rays in both the singles and coincidence measurements provides the evidence for these differences. The evidence for the 1470-, 1910-, 2185-, and 2458-keV levels proposed by OM is strengthened by the observation in this work of other low-intensity transitions, in both coincidence and singles spectra.

Spin-parity assingments shown for the levels of $^{93}$Zr have been made utilizing the momentum transfers reported in reaction studies as compiled by Kocher,[7] the log$ft$ values calculated for the $\beta$ branching (according to the rules proposed by Raman and Gove[20]), and the assumption that the observed $\gamma$ rays have multipolarities of $E1$, $E2$, $M1$, or $E2/M1$.

## IV. DISCUSSION

The level structure of $^{93}$Zr has been studied rather extensively using nuclear reactions. For several of the levels populated in the decay of $^{93}$Y, spin-parity assingments have been made on the basis of the angular momentum transfer in neutron pickup reactions. Such results make it possible to describe at least a portion of the configurations of some levels in terms of single-particle neutron states. There remain, however, some levels which elude description in terms of simple configurations.

Talmi[6] and Vervier[21] have made calculations of the levels of $^{93}$Zr taking as a basis the $\nu(d_{5/2})^3$, $\pi(g_{9/2})^2$, and $\pi(p_{1/2})^2$ configurations. Paradellis, Hontzeas, and Blok[22] have made complementary calculations by consideration of the coupling of the neutron $d_{5/2}$, $s_{1/2}$, $d_{3/2}$, and $g_{7/2}$ single-particle states to the $^{92}$Zr core. Each scheme of calculation is limited by an incomplete basis set, but both schemes are useful in the interpretation of a few of the levels observed in this work. It is worthwhile to note that the levels observed in this work cannot have spin higher than $\frac{5}{2}$, owing to the presence of $\beta$ branches to all levels. Hence, the question of the presence of the $\nu(d_{5/2})^3{}_{9/2}$ state predicted by Talmi[6] is outside the scope of this work. Some interesting observations are nevertheless detailed below.

It is well accepted that the ground state of $^{93}$Zr consists of the $\nu(d_{5/2})^3{}_{5/2}$, seniority-1 configuration. This description is consistent not only with the reaction studies, but with the measured spin and $\beta$-decay branching properties.[7]

The 267-keV state has a structure which must be predominantly the $\nu(d_{5/2})^3{}_{3/2}$, seniority-3 configuration. The evidence for this assignment includes the very weak strength for this level in neutron pickup reactions as well as the systematic occurrence of such $j$-1 couplings at low excitations in other odd-$n$ nuclei in this region. The calculations by Talmi[6] and Vervier[21] have also been very successful in describing this level. However, the configuration is not completely pure $\nu(d_{5/2})^3{}_{3/2}$, since this level has a small observable strength in pickup reactions and since an $M1$ component to the 267-keV transition is deduced from the conversion coefficient[5,7] (such a component cannot occur in the recoupling scheme[6]). The $M1$ component, though highly hindered,[7] could be allowed through a small admixture of the $\nu(d_{3/2})$ state which would also explain the observation of the 267-keV level in pickup reactions and $\beta$-decay branching to this level.

The 947-keV level is assigned a spin-parity of $\frac{1}{2}^+$ on the basis of pickup reactions, which indicate that this is the $\nu(s_{1/2})$ single-particle state. The relative $\gamma$-ray branches to the ground state and 267-keV level are consistent with $E2$ multipolarity assignments for both the 947- and 680-keV transitions although, for the latter, some $M1$ mixing is indicated from angular-correlation measurements.[5] The presence of any $M1$ component is difficult to explain in terms of the state vector components proposed for the 947-keV level by the single-particle plus core calculations,[22] which consist mainly of the $\nu(s_{1/2})\otimes 0_0^+(70\%)$ and $\nu(d_{5/2})\otimes 2_1^+$ (27%) configurations.

A detailed discussion of the levels above 947 keV in terms of the available calculations becomes complicated and laced with contradictions. In particular, it is striking to note the $\gamma$- and $\beta$-ray branching similarities between the members of level pairs at 1425 and 1450 keV, 1910 and 1919 keV, and 2185 and 2485 keV.

The levels at 1425 and 1450 keV have dominant ground-state deexcitations and secondary branching to the first excited state, with remarkable intensity-ratio similarities. These levels may be responsible for the difficulties associated with the analysis of the pickup reactions to a level at 1440 keV, in that they may be unresolved in such studies. Paradellis, Hontzeas, and Blok[22] consider the level reported in reaction studies to be composed dominantly of the $\nu(d_{3/2})\otimes 0_0^+$ (52%) and $\nu(d_{5/2})\otimes 2_1^+$ (39%) configurations which, if applied to the level at 1425 keV, would explain in a reasonable fashion the deexcitations observed. The level at 1450 keV, apparently not seen in reaction studies, could be an $s_{1/2}$ neutron coupled to a core excitation, and must be of spin value different from that of the 1425-keV level for them to be nearly degenerate in energy. A minor admixture of single-particle character would be necessary to explain the $\beta$ branching to the level at 1450 keV.

The levels at 1910 and 1919 keV appear to have very similar properties. Paradellis, Hontzeas, and Blok[22] describe a reaction level at 1900 keV as consisting mainly of the $\nu(s_{1/2})\otimes 0_0^+$ (27%) and $\nu(d_{5/2})\otimes 2_1^+$ (67%) configurations, which may apply to the level at 1919 keV considered here and which is apparently seen in reaction studies, though perhaps unresolved from the 1910-keV level. The relative $\gamma$-ray branching intensities of this pair of levels to the 267- and 947-keV levels are consistent with $M1$ multipolarities for both transitions deexciting each level which, however, would not be expected with the main state vector components mentioned for the 1919-keV level. The 1910-keV level may consist of a $d_{3/2}$ neutron coupled to a core excitation, with different angular momentum than the 1919-keV level. Again, the $\beta$ branching to this core-coupled level must arise from some single-particle admixture.

The levels at 2185 and 2458 keV are characterized by relatively low log$ft$ values and very similar deexcitation patterns. Most noteworthy is the common large transition branching to the 267-keV level. This suggests strongly that these levels (which are not seen in reaction studies) have a component of the $\nu(d_{5/2})^3{}_{3/2}\otimes 2_1^+$ configuration (the $2_1^+$ state in $^{90}$Zr is at 2186 keV). The ground-state transitions and relatively low log$ft$ values suggest the presence of some $\nu(d_{3/2})\otimes 0_0^+$ configuration. The energy splitting of these levels is again difficult to account for, although Paradellis, Hontzeas, and Blok[22] suggest that the $\nu(d_{5/2})^3{}_{3/2}\otimes 2_1^+$ configuration may apply to levels at 2180 and 2320 keV seen in reaction studies.

In view of the speculated nature of the levels at 2185 and 2458 keV, transitions from these levels to the level at 1470 keV, and subsequent deexcitation of this level to the 267-keV level and ground state, suggest that the $\nu(d_{5/2})^3{}_{3/2}$ configuration may also apply to the level at 1470 keV (as coupled to the $0_1^+$ $^{90}$Zr core state at 1761 keV).

The levels at 2094 and 2473 keV can possibly be associated with excitations at 2090 and 2481 keV reported in pickup reactions[7] with neutron angular momentum transfers of 0 and 2, respectively. Since each level is deexcited by only one $\gamma$ ray, no further attempt will be made to describe these levels from the available information.

In conclusion, the properties of the levels of $^{93}$Zr are far from understood, but the details of the level scheme determined from the decay of $^{93}$Y add new information to consider in further calculations. An extended combination of the single-particle plus core and $\nu(d_{5/2})^3$ models, using as complete a basis set as possible, would be most interesting to compare to the experimental picture.

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