Decay Properties of Zr^{86}†

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A restudy of the radiations of 16.5-h Zr^{86} was carried out with lithium-drifted germanium and silicon detectors and with a NaI crystal spectrometer. Besides x rays, there are gamma rays of 28, 243, and 612 keV in relative intensity 21, 100, and 5.4. No other gamma rays were detected. No annihilation radiation was present. There is no evidence for formation of 48-min Y^{86m} in the decay of Zr^{86}. The K-conversion coefficient of the 243-keV transition was found to be 0.035 ± 0.003. The lifetime was measured as 29 ± 3 nsec. These properties agree well with an $E2$ multipolarity. The lifetime and conversion coefficient of the 28-keV transition are <10 nsec and 3.8 ± 0.5, respectively, which corresponds to an $E1$ multipolarity. A decay scheme is constructed and reasonable shell-model assignments are made to all levels except the 2− level of Y^{86}, whose character is uncertain.

I. INTRODUCTION

THE decay scheme of Zr^{86} is of interest principally for the information it provides on the level scheme of Y^{86}, a member of a group of nuclei near Zr^{90} upon which many shell-model calculations have been made in recent years.

The first measurements on Zr^{86} were made by Hyde and O'Kelley,[1] who produced a mixture of light zirconium isotopes by the bombardment of niobium targets with high-energy protons. These authors reported a half-life of (17 ± 2) h for electron-capture decay. Hyde, Florence, and Stephens[2] detected a prominent γ ray of 241-keV energy. The possibility was considered that this was a delayed $E3$ transition analogous to the prominent 395-keV $E3$ transition in the decay of Zr^{88}, but its half-life was found to be <5 μsec. This half-life and the conversion electron K/L ratio of 9.3 determined a multipolarity assignment of $E2$.

Schooley and Rasmussen[3] remeasured values of (243 ± 2) keV for the transition energy and 8.47 for the K/L ratio.

A recent study of Zr^{86} was made by Awaya and Tendow[4] with samples prepared by the bombardment of yttrium oxide with 55-MeV protons. Their samples contained other zirconium isotopes, principally 1.8-h Zr^{87}, 85-day Zr^{88}, and 79-h Zr^{89}. With the aid of a NaI gamma-ray spectrometer, Awaya and Tendow found γ rays of (247 ± 2), (615 ± 5), and (32 ± 3) keV in relative abundance 100, 7 ± 2, and ~25, respectively. The first two were found to be in coincidence with each other, within a resolving time of 0.1 μsec, but neither was in coincidence with positrons. They redetermined a half-life value of (16.5 ± 0.1) h.

In the present work we have re-examined the radiations of Zr^{86} with gamma-ray detectors of lithium-drifted germanium and silicon and with NaI detectors. In addition to measurement of singles spectra we have measured pairs of radiations by coincidence techniques including prompt and delayed coincidence. The results serve to characterize the radiations and to establish a decay scheme. In a final section of our report we discuss possible shell-model assignments to the observed levels.

II. EXPERIMENTAL PART

A. Preparation of Samples

It proved convenient for us to prepare Zr^{86} by bombardment of thin foils of pure niobium metal with 300-MeV protons in the 184-in. cyclotron for periods of about 1 h. The isotope is produced in a yield of about 20 mb but is somewhat contaminated with Zr^{87}, Zr^{88}, and Zr^{89}. We also made samples by bombardment of pure yttrium oxide with 50-MeV protons in the 88-in. cyclotron. In this case the ratio of Zr^{86} to Zr^{88} and Zr^{89} was greater.

The zirconium fraction was separated from the bombarded targets by standard radiochemical techniques.[1,5] The principal steps in the purification were the absorption of zirconium on a Dowex 1 anion-exchange resin from 10M HCl and desorption with dilute hydrochloric acid. This was usually followed by extraction of zirconium into benzene as the thenoyl trifluoroacetone complex. The benzene solution of the zirconium complex was washed repeatedly with 2M perchloric acid. Zirconium was then back extracted into concentrated hydrochloric acid from the benzene.

B. Gamma Radiation—Singles Spectra

The gamma radiation was studied with a lithium-drifted germanium gamma detector. This crystal had dimensions 2×3 cm and a sensitive layer 8 mm deep.

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[1] E. K. Hyde and G. D. O'Kelley, Phys. Rev. **82**, 944 (1951).
[2] E. K. Hyde, M. G. Florence, and F. S. Stephens, University of California Lawrence Radiation Laboratory Report No. UCRL-2813, 1954 (unpublished).
[3] J. F. Schooley and J. O. Rasmussen, University of California Lawrence Radiation Laboratory Report No. UCRL-2932, 1954 (unpublished).
[4] Y. Awaya and Y. Tendow, J. Phys. Soc. Japan **19**, 606 (1964).
[5] E. P. Steinberg, Natl. Acad. Sci.–Natl. Res. Council Publ. No. NAS-NS-3011.

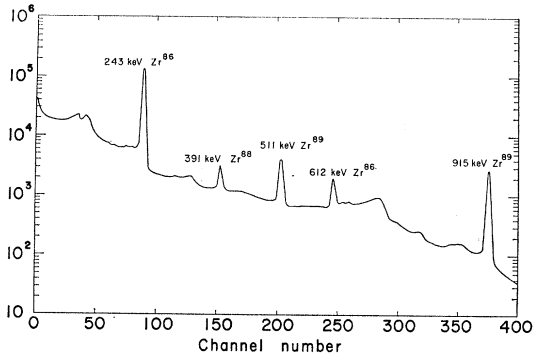

FIG. 1. Gamma spectrum of Zr^{86} taken with lithium-drifted germanium crystal.

It was prepared by the semiconductor counter group at our laboratory.[6] Low-energy gamma radiation and x rays were measured with a lithium-drifted silicon detector 0.785 $cm^2 \times 3$ mm deep and with a NaI(Tl) scintillator (1 in.$\times$2 in.) covered with a thin beryllium window. The associated electronic circuitry in all cases consisted of the Goulding-Landis[7] system. Pulse-height analysis was performed with 400-channel analyzers of commercial manufacture. The energy calibration and the photopeak efficiency were determined with a series of standard sources.

A typical spectrum taken with the germanium detector is shown in Fig. 1. Zirconium-86 γ rays of (243 ± 1) and (612 ± 2) keV are clearly seen. The intensity of the latter with respect to the former (after correction for photopeak efficiency) is 0.054. Examination of the energy region above 1.0 MeV revealed no other gamma rays which could be assigned to Zr^{86}. In this spectrum we would not have expected to see radiation of 32-keV energy[4] because of absorption in the crystal housing and in the sample covering. The annihilation radiation and 915-keV radiation in the spectrum are contributed by 79-h Zr^{89}.

Low-energy radiations measured with the silicon detector and the thin sodium iodide crystals are shown in Fig. 2. The energy scale in these spectra was standardized with an Am^{241} source. The neptunium x rays and the 59.6-keV γ ray present in Am^{241} decay serve as a convenient calibration of the energy region of interest. Barium x rays from a Cs^{137} source were also used.

In the Zr^{86} spectra there are 15-keV x rays resulting from electron-capture decay and from conversion of gamma rays. There is also some contribution of x rays from other zirconium activities. A (28 ± 0.5) keV γ ray is present; this confirms the report of Awaya and Tendow[4] of the occurrence of a (32 ± 3) keV γ ray.

[6] F. S. Goulding and D. A. Landis, Natl. Acad. Sci.–Natl. Res. Council, Publ. 1184, 1963. F. S. Goulding, Lawrence Radiation Laboratory Report No. UCRL-11302, 1964 (unpublished).

[7] W. L. Hansen and B. V. Jarrett, Lawrence Radiation Laboratory Report No. UCRL-11589, 1964 (unpublished).

C. Measurement of Lifetime of 243-keV Transition

Previous measurements of an upper limit to the lifetime of the 243-keV transition and of the K/L ratio of the conversion electrons had established a multipolarity of electric quadrupole. The predicted lifetime[8] for a single-particle transition is 30 nsec. We decided it would be of interest to measure this lifetime. The predicted lifetime values for other multipolarities are: $E1$ (3×10^{-14} sec), $M1$ (3×10^{-13} sec), $M2$ (3×10^{-6} sec), and $E3$ (10^{-1} sec).

We proceeded on the assumption that the 28- and 243-keV radiations were in cascade and performed a delayed coincidence experiment with a time–to–pulse-height converter,[9] operating on a capacitive discharge principle over a 1.0-μsec range.

The 243-keV radiation was measured in a lithium-drifted germanium detector and the 28-keV photons in

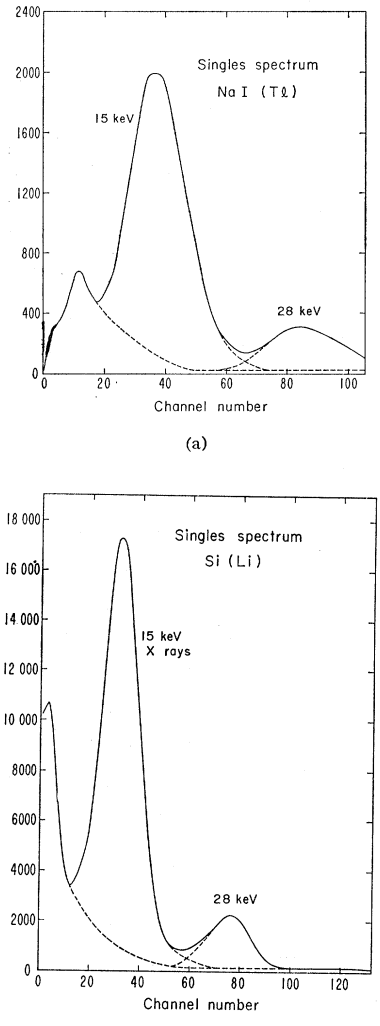

FIG. 2. Low-energy gamma spectrum of Zr^{86} taken (a) with NaI(Tl) crystal covered with Be window and (b) with Si(Li) semiconductor detector.

[8] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).

[9] D. Wieber, Nucl. Instr. Methods **24**, 269 (1963).

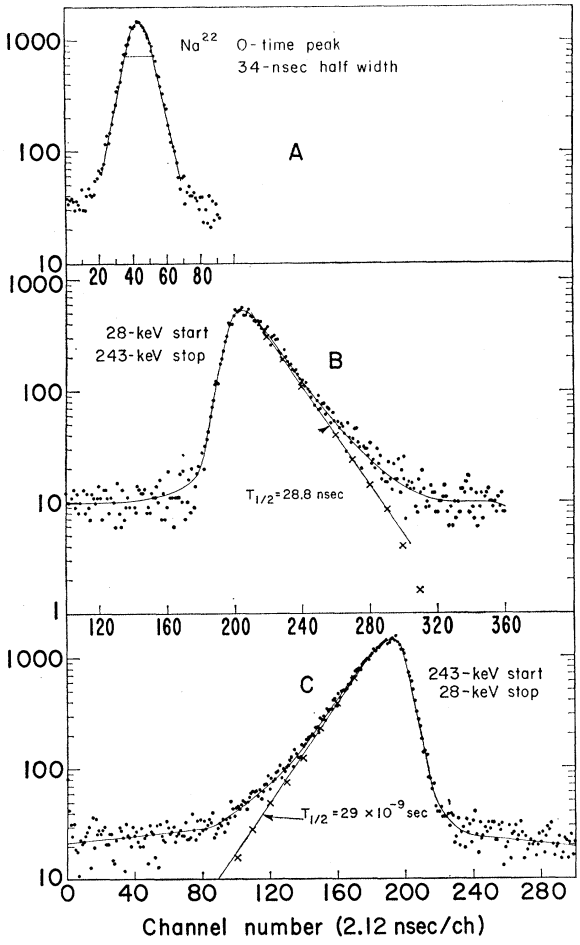

FIG. 3 (a). Time–to–pulse-height spectrum taken with Na^{22} "prompt" standard. This curve shows shape for a fast transition and determines the time resolution of the system. (b). Time–to–pulse-height spectrum for the case 28-keV γ start, 243-keV γ stop. The 28-keV photons were detected with a NaI(Tl) crystal. (c). Time–to–pulse-height spectrum for the case 243-keV γ start, 28-keV γ stop. The 28-keV photons were detected with a NaI(Tl) crystal.

a 2 in.×1 in. NaI(Tl) detector covered with a beryllium window.

The system was calibrated by use of the delayed trigger of a Tektronix type 555 oscilloscope which had in turn been calibrated with a 10-megacycle crystal oscillator. Preliminary runs with a Na^{22} source (carried out with the coincident 511- and 1276-keV radiations) served to determine the zero position and the time resolution of the system. The zero position could be adjusted to a convenient point in the scale by introducing an arbitrary delay in one signal. The Na^{22} calibration spectrum is shown in Fig. 3(a). The time resolution was found to be 34 nsec.

The time–to–pulse-height spectrum obtained from the system operating with start pulses generated by 28-keV photons and stop pulses generated by 243-keV photons is shown in Fig. 3(b). The reverse choice of start and stop pulses is shown in Fig. 3(c).

Inspection of these figures clearly indicates that a delay is being observed. The shift of the delay from the right-hand to the left-hand side of the peaks from Fig. 3(b) to Fig. 3(c) proves that the 28-keV transition precedes the 243-keV transition in the decay of Zr^{86}. From the slope of the delay curve a half-life of the 243-keV transition was determined as (29±3) nsec which is close to the predicted 30-nsec value for a "single-particle" $E2$ transition.

D. Conversion Coefficient of 243-keV Transition

We made use of a conversion coefficient spectrometer constructed in this laboratory by Easterday, Haverfield, and Hollander[10] to measure the conversion coefficient of the 243-keV transition. This spectrometer consisted of a germanium semiconductor detector and a silicon semiconductor detector mounted in a fixed geometrical position with respect to a radioactive sample. The over-all efficiencies of both crystals were carefully measured by use of a series of standards.

The procedure for measurement of the K-conversion coefficient consisted of the following: A sample of Zr^{86}, mounted on a 0.001-in. thick aluminum disc, was placed in the spectrometer. The electron and γ spectra were measured simultaneously and the areas under the γ photopeak and the K-electron peak were determined. Efficiency factors were applied for both radiations. The photon and electron spectra are shown in Figs. 4, 5, and 6.

The conversion coefficient was computed to be $(3.5\pm0.3)\times10^{-2}$. This characterized the radiation unambiguously as $E2$. Theoretical values from the tables of Sliv and Band[11] are $E2(3.8\times10^{-2})$, $E1(7.5\times10^{-3})$, $M1(1.6\times10^{-2})$, and $M2(8\times10^{-2})$.

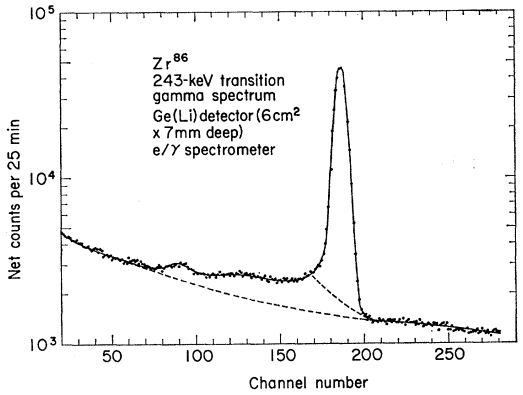

FIG. 4. 243-keV gamma photon spectrum taken on germanium semiconductor detector in conversion coefficient spectrometer. Active volume of detector 6 cm^2×7 mm deep. The slanting dotted line indicates the mode of resolution from the background.

[10] H. T. Easterday, A. J. Haverfield, and J. M. Hollander, Nucl. Instr. Methods **32**, 333 (1965).

[11] L. A. Sliv and I. M. Band, in *Alpha, Beta, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, 1965), Appendix 5.

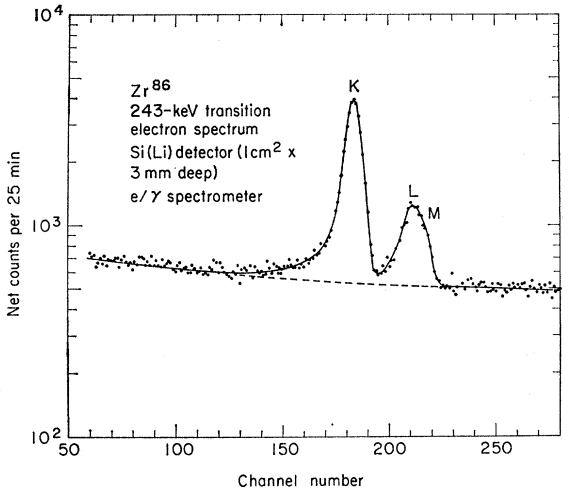

FIG. 5. Conversion lines of 243-keV transition in decay of Zr^{86} as taken with silicon semiconductor detector (1 $cm^2 \times 3$ mm deep sensitive layer) in conversion coefficient spectrometer. Dotted line shows choice of background subtraction.

The K/L ratio according to the resolution of our curve is 6.7. The K/L ratio for an $E2$ transition from the tables of Sliv and Band is 7.7. Previously measured values of the K/L ratio are 9.3,[1] 8.47,[3] and 6.1.[4]

E. Determination of Upper Limit on Half-Life of 28-keV Transition

According to the Weisskopf single-particle transition-rate formula,[8] the following are the approximate expected half-lives for a 28-keV transition occurring in a nucleus of mass 86: $E1$ (5×10^{-11} sec), $M1$ (5×10^{-10} sec), $E2$ (5×10^{-3} sec), $M2$ (0.2 sec), $E3$ (5×10^{6} sec), $M3$ (5×10^{7} sec).

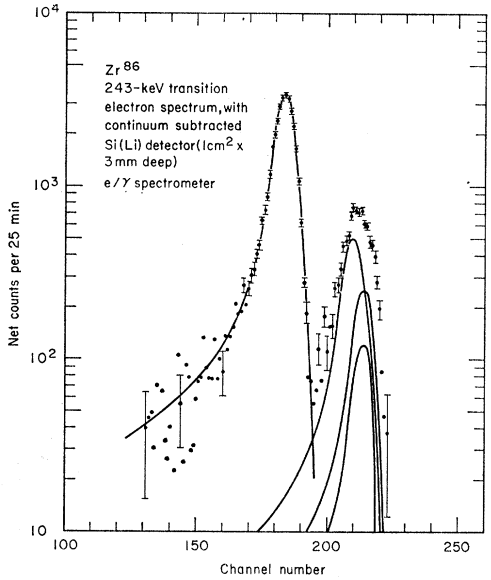

FIG. 6. Resolution of conversion electron spectrum of 243-keV transition. Raw data shown in previous figure.

It is clear that any multipolarity greater than dipole would lead to isomerism which could easily be detected. Before coincidence experiments were attempted, the possibility of a long half-life was investigated. Zirconium-86 was extracted into benzene as the thenoyltrifluoroacetone complex (TTA-complex) and daughter Y^{86} was stripped from the benzene into a 2 M perchloric acid solution. A small amount of lanthanum was precipitated as LaF_3 and examined with a sodium iodide crystal covered with a beryllium window. No evidence was found for 28-keV radiations in a series of experiments in which the chemical steps were so timed that a half-life of a few seconds to a few hours would have been readily detected.

An attempt was made to measure the half-life of the 28-keV transition by a delayed coincidence between signals from the 15-keV x rays and 28-keV photons. The time–to–pulse-height converter system described in Sec. IIC was used in this experiment. A sample of Zr^{86} was placed between two thin NaI(Tl) counters, both covered with thin beryllium windows. Pulse-height analysis was used to select 15-keV radiation from one counter (whose output was used as the start signal) and 28-keV radiation from the second crystal (whose output was used as the stop signal). The pulse-height–versus–time curve obtained in this case showed no detectable difference in shape from a standard curve taken with the prompt radiations of a Na^{22} source. It was concluded that if electron capture precedes the 28-keV transition, then the half-life of the transition is less than 10 nsec.

This limit on the half-life restricts the choice of multipolarity to $E1$ or $M1$. The conversion coefficient measurement, discussed in the next section, indicates an $E1$ assignment.

F. Conversion Coefficient of 28-keV Transition

From the tables of Sliv and Band[11] one can estimate the following values for the conversion coefficient for different multipolarity assignments: $E1$ (4.47), $M1$ (8.33), $E2$ (60.4), $M2$ (83), and $E3$ (496).

An estimate of the conversion coefficient can be made from a calculation based on the ratio of the intensity of the K x rays to the 28-keV photons in the singles spectrum. This calculation depends on the nearly certain assumption that one 28-keV transition occurs in every decay of Zr^{86}. The calculation may be outlined as follows.

In every 100 decay events 89.4 K vacancies are produced by K-electron capture, for an estimated decay energy of 1.14 MeV.[12] L and M capture account for the remaining events.

In every 100 events, 3.5 K vacancies are produced by conversion of the 243-keV transition. K vacancies are

[12] A. H. Wapstra, G. J. Nijgh, and R. van Lieshout, *Nuclear Spectroscopy Tables* (North-Holland Publishing Company, Amsterdam, 1959), p. 59.

also contributed by conversion of the 28-keV gamma ray. Let us set $\alpha_K=N_{e_K}/N_\gamma$, $\alpha_T=N_e/N_\gamma$, and $N_e+N_\gamma=100$, where α_K is the K-conversion coefficient, α_T is the total conversion coefficient, N_{e_K} is the number of K-conversion electrons, N_e is the number of conversion electrons of all types, and N_γ is the number of 28-keV photons. Straightforward algebra leads to

$$N_\gamma=100/1+\alpha_T \quad \text{and} \quad N_{e_K}=100\alpha_K/1+\alpha_T. \quad (1)$$

The total number of K vacancies in 100 decay events is then $89.4+3.5+100\alpha_K/(1+\alpha_T)$; this number must be multiplied by the K-fluorescent yield (0.675) to get the number of K x rays. The experimentally observed ratio of 28-keV photons to K x rays (N_{K-x}) can now be expressed as

$$\frac{N_\gamma}{N_{K-x}}=\frac{100/(1+\alpha_T)}{(0.675)[89.4+3.5+100\alpha_K/(1+\alpha_T)]}$$

$$=\frac{100}{62.7(1+\alpha_T)+67.5\alpha_K}. \quad (2)$$

We estimate that $\alpha_T=1.13\alpha_K$ from an interpolation of tables of Sliv and Band for K and L conversion of a 28-keV $E1$ or $M1$ transition in element 40. Conversion in higher electron shells can be neglected within the error of our experimental result.

Making the substitution, we obtain

$$N_\gamma/N_{e_K}=100/(62.7+138\alpha_K). \quad (3)$$

The experimental value of this ratio in the singles spectrum shown in Fig. 2(b) is 0.18 after correction for an estimated efficiency factor in silicon of 80% for the 28-keV radiation. This leads to a value of 3.6 for α_K.

Our experimental ratio of x rays to 28-keV photons could be too high if an appreciable part of the x rays are contributed by other isotopes in our sample. Two coincidence experiments were performed to check this possibility.

In the first a standard $\gamma\gamma$ coincidence experiment was done to determine the low-energy spectrum in coincidence with 612-keV photons. The 612-keV photons were detected with a germanium semiconductor counter coupled to a single-channel analyzer. The coincident low-energy gamma rays and x rays were detected with a NaI crystal. The ratio N_γ/N_{K-x} in this spectrum was the same within statistical error of ±0.02 units. The above-cited expression [Eq. (3)] is also applicable in this case.

This experiment also establishes the cascade relationship of the 28- and 612-keV γ transitions. The relative abundance of the photons proves that the 612-keV gamma ray lies higher in the decay scheme.

A second coincidence experiment was done in which the low-energy γ spectrum was measured in a silicon detector for those pulses which were time coincident with the x-ray pulses detected in a sodium iodide gate crystal. This spectrum is shown in Fig. 7. With the assumption that $\alpha_T=1.13\alpha_K$, it can be shown that the following relationship holds in this case:

$$N_\gamma/N_{K-x}=100/(140\alpha_K+4.5). \quad (4)$$

The experimental ratio $N_\gamma/N_{K-x}=0.183$, from which we calculate a value of 3.9 for the conversion coefficient. From all of the determinations of the K-conversion coefficient we estimate a value of 3.7 ± 0.5, which is in better agreement with the theoretical value for $E1$ (4.2) than for $M1$ (8.3).

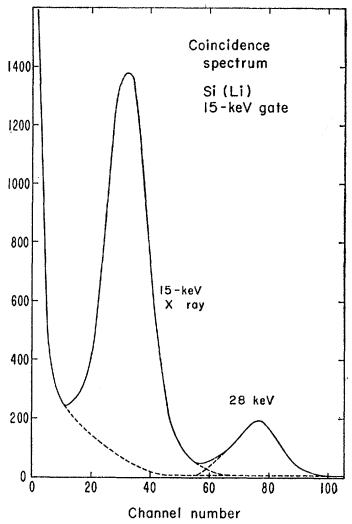

FIG. 7. Low-energy γ spectrum recorded by a lithium-drifted silicon crystal operated in coincidence with pulses corresponding to 15-keV x rays detected in a NaI(Tl) detector.

G. Absence of β^+ Decay in Zr^{86}

The annihilation radiation present in our samples was contributed by Zr^{89}. In order to set a limit on the amount of annihilation radiation accompanying the decay of Zr^{86} we performed a triple $\gamma\gamma$ coincidence experiment in which 511-keV photons served as the gate pulses. The source was placed between two 3 in.$\times$3 in. sodium iodide crystals positioned 180° from each other. A third, lithium-drifted germanium detector was placed at 90°. Gamma rays were recorded in this third detector only if they were coincident with 511-keV photons recorded in both sodium iodide counters. The resolution time was adjusted to a value long compared to the 28-nsec half-life of the 243-keV transition. No 243-keV photons were observed in the coincidence spectrum. An analysis of the data resulted in the conservative upper limit of 0.1% for any positron decay of Zr^{86} to Y^{86} levels feeding the 243-keV level.

III. CONSTRUCTION OF THE DECAY SCHEME

The experimental information summarized in the previous section is compatible with the decay scheme shown in Fig. 8.

The coincidence results prove that the three observed

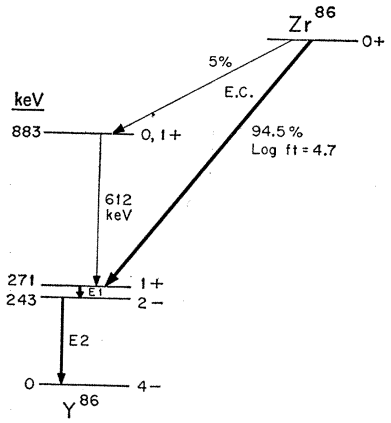

FIG. 8. Decay scheme of Zr^{86}.

γ rays form a cascade. The low abundance of the 612-keV gamma ray places it highest. The delayed coincidence experiments [Figs. 3(b) and 3(c)] establish the order of the 28- and 243-keV transitions. The logft value for the electron-capture decay to the 271-keV level can be computed from estimated decay energy of Zr^{86}. The mass tables of Cameron[13] give 2.52 MeV. Yamada and Matumoto[14] estimate 1.14 MeV. We believe that the estimate of Yamada and Matumoto is the better. The absence of any annihilation radiation supports this choice. If the total decay energy is 1.14 MeV, the decay energy to the 271-keV level is 871 keV and the logft value is 4.7. This low logft value indicates $\Delta I=0$ or 1 and no parity change in the beta decay. This limits the assignment of the 271-keV level to 0, 1+.

The $E1$ character of the 28-keV transition and the $E2$ character of the 243-keV transition determine a 1+ assignment for the 271-keV level and a 2− assignment for the 243-keV level. The 4− assignment of the Y^{86} ground state is clearly established[15,16] by the decay scheme of Y^{86}.

About 5.5% of the electron-capture events populate the level at 883 keV. The logft value is about 5.4 which suggests (0,1)+ for the assignment of this level. No further comment can be made since the multipolarity of the 612-keV transition is unknown.

Our scheme differs from that favored by Awaya and Tendow,[4] who placed the 28-keV transition below the 243-keV transition. Our delayed coincidence experiments rule out their scheme. However, Awaya and Tendow considered the scheme favored here to be an alternative possibility.

[13] A. G. W. Cameron, Can. J. Phys. **35**, 102 (1957); and tables in Chalk River Project Report, CRP-690, 1957 (unpublished).
[14] T. Yamada and Z. Matumoto, J. Phys. Soc. Japan **16**, 1497 (1961).
[15] T. Yamazaki, H. Ikegami, and M. Sakai, Nucl. Phys. **30**, 68 (1962).
[16] B. Van Nooijen *et al.*, Nucl. Phys. **63**, 241 (1965).

IV. DISCUSSION

According to the shell model[17] the odd proton in $_{39}Y^{86}$ should occupy the $2p_{1/2}$ orbital and one of the low-lying orbitals should be $1g_{9/2}$. In agreement with this, the neighboring yttrium nuclei, Y^{87} and Y^{89} have ground-state spins $\frac{1}{2}$ and their first excited states have spin $\frac{9}{2}$. In Y^{85} there is a reversal and the $g_{9/2}$ state is lower by 40 keV. Above these states one would expect to see $3p_{3/2}$ and $1f_{5/2}$; in Y^{91}, states of spin $\frac{3}{2}-$ and $\frac{5}{2}-$ are observed.

From the shell model one may safely predict that the odd neutron in Y^{86} occupies the $1g_{9/2}$ orbital. This agrees with the $\frac{9}{2}$ spin assignments to the ground state in nuclei with 1 hole in the 50-neutron shell (Zr^{89}, Sr^{87}, and Kr^{85}) as well as in nuclei with 3 holes in the 50-neutron shell (Zr^{87}, Sr^{85}, and Kr^{83}). The shell model predicts $2p_{1/2}$ for the next excited state for nuclei with 49 neutrons and this is in agreement with observation for Zr^{89}, Sr^{87}, and Kr^{85}. In the case of nuclei with 47 neutrons, a $\frac{7}{2}+$ state is observed just above the ground state in Kr^{83} and Sr^{85}. This state is believed to be a composite state of the $(g_{9/2})^{-3}$ configuration.[18,19] It is to be expected that such a state might contribute to the spectrum of Y^{86} levels. Besides the $g_{9/2}$, $p_{1/2}$, and $\frac{7}{2}+$ neutron states the available states in the $N=28-50$ shell are $p_{3/2}$ and $f_{5/2}$.

The possible combinations of most of these proton and neutron states are listed in Table I.

We now turn to Fig. 9 which displays the levels of Y^{86} observed in the decay of Zr^{86} and in the decay of

TABLE I. Configurations contributing to level structure of Y^{86}.

Proton configuration	Neutron configuration	Resultant spin state	Parity
$p_{1/2}$	$g_{9/2}$	4, 5	−
$p_{1/2}$	7/2+	3, 4	−
$p_{1/2}$	$p_{1/2}$	0, 1	+
$g_{9/2}$	$g_{9/2}$	0, 1, 2, ⋯, 9	+
$g_{9/2}$	7/2+	1, 2, 3, 4, ⋯, 8	+
$g_{9/2}$	$p_{1/2}$	4, 5	−
$p_{3/2}$	$g_{9/2}$	3, 4, 5, 6	−
$p_{3/2}$	7/2+	2, 3, 4, 5	−
$p_{3/2}$	$p_{1/2}$	1, 2	+
$f_{5/2}$	$g_{9/2}$	2, 3, 4, 5, 6, 7	−
$f_{5/2}$	7/2+	1, 2, ⋯, 6	−
$f_{5/2}$	$p_{1/2}$	2, 3	+
$p_{1/2}$	$p_{3/2}$	1, 2	+
$g_{9/2}$	$p_{3/2}$	3, 4, 5, 6	−
$p_{1/2}$	$d_{5/2}$	2, 3	−
$g_{9/2}$	$d_{5/2}$	2, ⋯, 7	+

[17] M. G. Mayer and J. H. D. Jensen, *Elementary Theory of Nuclear Shell Structure* (John Wiley & Sons, Inc., New York, 1955), Chap. IV.
[18] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).
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the isomeric state Y^{86m}.[20] We remark in passing that our experimental evidence clearly rules out any formation of Y^{86m} in the decay of 16.5-h Zr^{86}; this is quite understandable from the high spin of the isomer. The ground state of Y^{86} is 4— as determined from the decay scheme of 14-h Y^{86}. The probable structure of this state is $(p_{1/2})_p(g_{9/2})_n$. Kim, Hollander, and Horen[15] assign the 5— member of this doublet to the 208-keV level in the decay of Y^{86m}. The 1+ level at 271 keV is probably analogous to the 1+ level observed at 395 keV in Y^{88} in the decay scheme of Zr^{88}. The assignment $(p_{1/2})_p$ $(p_{1/2})_n$ seems logical, but we argue below for a $(p_{1/2})_p(p_{3/2})_n$ assignment. Kim *et al.*[20] discuss the 8+ isomeric level at 218 keV and assign the structure $[(g_{9/2})_p(\frac{7}{2}+)_n]_{8+}$ to it.

It is difficult to suggest a configuration for the 2— level which is consistent both with the shell model and the requirements of the decay scheme. In particular the low logft value for the electron-capture step and the $E1$ and $E2$ multipolarity of the 28- and 243-keV transitions put severe restrictions on the choice of configuration of the level at 243 keV. If we restrict ourselves to the simple shell model, the only choice is the configuration $(p_{1/2},d_{5/2})_{2-}$ involving a $d_{5/2}$ neutron from the next shell. The sequence of steps in the decay scheme is then

$$\underset{\text{proton}}{p_{1/2}} \xrightarrow{\log ft=4.7} \underset{\text{neutron}}{p_{3/2}} \xrightarrow{E1} \underset{\text{neutron}}{d_{5/2}} \xrightarrow{E2} \underset{\text{neutron}}{g_{9/2}} .$$

Strong objection can be raised to the postulated participation of a $d_{5/2}$ neutron in a state as low as 243 keV in Y^{86}. Some clear evidence for the participation of $d_{5/2}$ neutrons in nuclei with fewer than 50 neutrons is reported in a study[21] of selenium isotopes by (d,p) and (d,t) reactions. In this work low-lying $\frac{5}{2}+$ states with some $d_{5/2}$ character were excited in Se^{77}, Se^{79}, and Se^{81} (containing 43, 45, and 47 neutrons, respectively), indicating a small mixture of $d_{5/2}$ neutrons in the ground states of Se^{78}, Se^{80}, and Se^{82}. It is certain that the ground state of Zr^{86} consists of a mixture of configurations and it is probable that the levels of Y^{86} are not as simple in composition as we suggest in our preliminary analysis. Unfortunately at present there exists no theoretical calculation of the level scheme of odd nuclei near Y^{86} in which the effects of residual interactions between the odd particles is explicitly calculated. Our result may suggest that the $d_{5/2}$ neutron state should be considered in any such calculation.

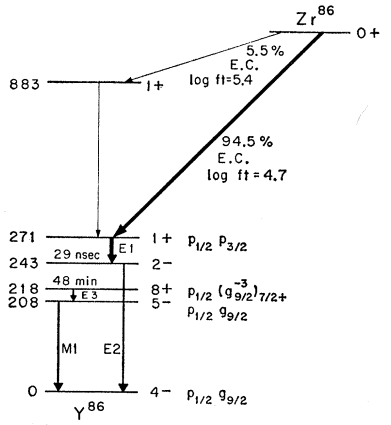

FIG. 9. Interpretation of decay scheme of Zr^{86}. Level energies are given in keV.

It is possible that the 2— state has a collective character, but the close agreement of the 243-keV photon decay rate with the single-particle estimate argues against this.

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