Decays of ^{95}Zr and ^{95}Nb

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(Received 15 May 1969)

The ^{95}Zr→^{95}Nb→^{95}Mo decay chain has been investigated with a high-resolution 30-cm^3 Ge(Li) detector and a Si(Li) detector and 4096-channel analyzer. The following γ rays were observed for a ^{95}Zr-^{95}Nb equilibrium source (energies in keV and intensities in parentheses): 234.70±0.14 (0.34±0.03), 724.23±0.04 (81.0±1.0), 756.74±0.04 (100), and 765.83±0.04 (218.0±3.0). β feedings of (1.0±0.1)%, (44.2±0.5)%, and (54.6±0.5)% were calculated for the 234.7-, 724.2-, and 756.7-keV levels in ^{95}Nb. The K-conversion coefficients for the 724.2-, 756.7-, and 765.8-keV γ rays were measured by the NPG method to be (1.56 ±0.14)×10^{-3}, (1.45±0.15)×10^{-3}, and (1.32±0.13)×10^{-3}, respectively.

INTRODUCTION

THE long-lived isotopes ^{95}Zr (65d) and ^{95}Nb (35d) are produced as fission products and are useful in nondestructive analysis of burn-up in fuel elements. It is possible to determine the burn-up by measuring relative γ-ray intensities from different fission products. At the time our work was undertaken, even recent measurements[1,2] in the decay chain of ^{95}Zr→^{95}Nb→^{95}Mo exhibited wide discrepancies in the relative γ-ray intensities of the transitions observed. These γ-ray intensity measurements included external conversion studies at relatively poor resolution and Ge(Li) detector studies where the 756.7- and 765.8-keV transitions were not completely resolved. As the intensity ratio of the 724.2- and 756.7-keV transitions in the decay of ^{95}Zr is important in the calculation of burn-up in fuel elements, we have reinvestigated this decay chain with a high resolution, 30 cm^3 lithium-drifted Ge(Li) detector and 4096-channel analyzer to obtain accurate γ-ray intensities.

With the large volume detector, we also have looked for a weak γ ray at 840 keV reported by Zarubin[3] and a 763-keV transition reported by Eissa, Meligy, Farrash, and Girgis.[2] This later transition was seen rather prominantly in internal conversion spectra shown in Ref. 2. Conversion electron spectra were measured with a Si(Li) detector and K-conversion coefficients measured to clarify this report.[2] Since our work was completed,[4] a new determination of the γ-ray intensities has been reported and these results[5] are in agreement with our measurements.

EXPERIMENTAL PROCEDURE AND ANALYSIS

A fission-produced ^{95}Zr-^{95}Nb equilibrium source was obtained from Oak Ridge National Laboratory. Because of the high affinity of zirconium for impurities, a careful search for possible source impurities as well as room background was made. A large volume 30-cm^3 Ge(Li) detector and a 4096-channel analyzer were used in this investigation. The spectrometer was calibrated with the following calibration lines from sources of ^{57}Co, ^{203}Hg. ^{22}Na, ^{137}Cs, ^{54}Mn, ^{88}Y, and ^{60}Co: 121.97 ±0.05, 136.33±0.04, 279±0.02, 511.006±0.002, 661.604 ±0.047, 834.84±0.05, 897.98±0.05, 1173.22±0.03, 1274.54±0.05, and 1332.52±0.03 keV.

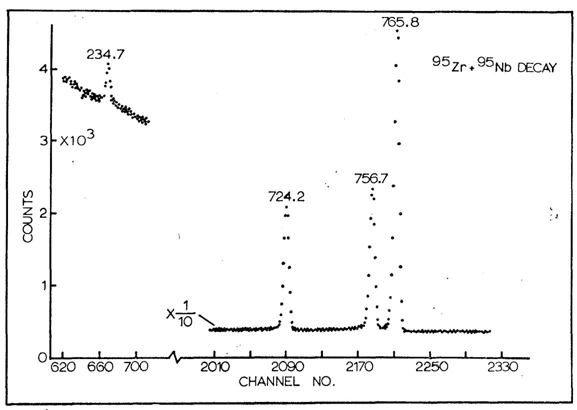

FIG. 1. Typical γ-ray singles spectrum of a ^{95}Zr-^{95}Nb source taken with a 30-cm^3 Ge(Li) detector.

For the energy and intensity measurements, several singles runs were taken for periods ranging 11–24 h separately as well as mixed with standard sources. The peak channel positions of the standard lines obtained from hand calculations as well as from a computer program[6] agreed very well within 0.2 of a channel or better (≲0.05 keV). A computer least-squares fit to a third-order polynomial was performed for each of the runs. The constants thus obtained were used to obtain the energies of the γ-rays in the ^{95}Zr→^{95}Nb→^{95}Mo decay chain. The sets of data used in this analysis were collected under different experimental conditions to in-

* Work supported in part by the National Science Foundation.
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[3] P. P. Zarubin, Izv. Akad. Nauk. SSSR, Ser. Fiz. **18**, 563 (1954).
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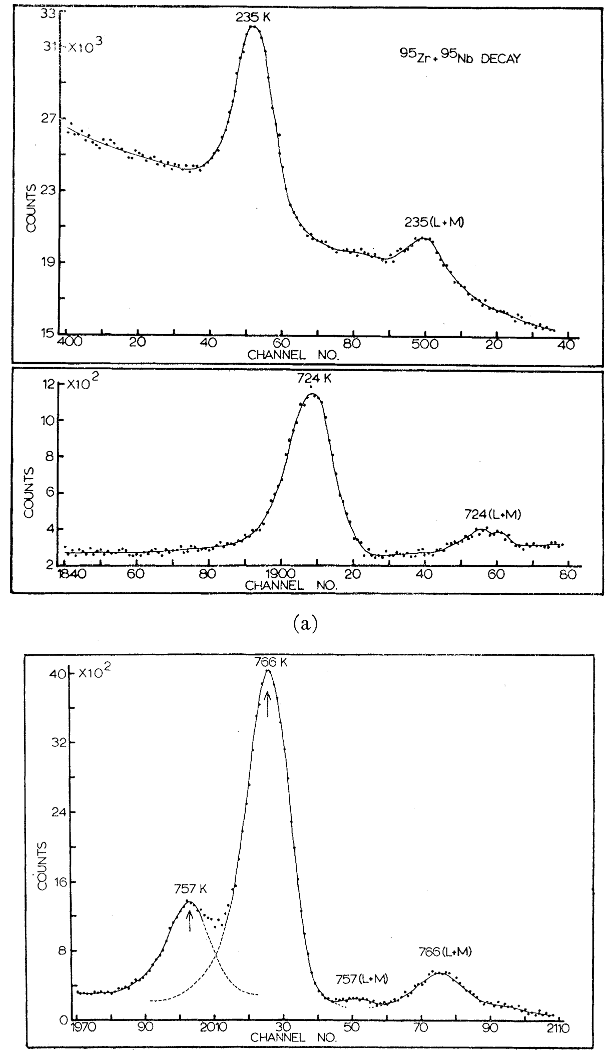
TABLE I. γ-ray energies and intensities in the decay of a ^{95}Zr-^{95}Nb equilibrium source. The first three transitions in column 1 are in ^{95}Nb, the 765.83 in ^{95}Mo, and Ref. 2 assigned the 762.5 to ^{95}Mo.

Energies (keV)						Intensities[a]			
Ref. 2	Ref. 1	Ref. 5	Ref. 8	Ref. 9	Present work	Ref. 2	Ref. 1	Ref. 5	Present work
237.23±0.41	≈235	235.6±0.5			234.70±0.14	8.56±0.52	<0.4	0.6±0.2	0.34±0.03
726.38±1.30	723±1	724±2		724.24±0.06	724.23±0.04	96.6±5.8	77.6±1.3	82.5±1.6	81.0±1.0
757.1±1.30	756±1	758±2		756.87±0.09	756.74±0.04	100±17	100	100	100
762.5±2.0						7.7±1.7			
765.6±1.8	765±1		765.83±0.07	765.84±0.05	765.83±0.04	1000±270[b]			218±3

[a] In the course of publication, our attention was directed to another new measurement [see J. E. Hiscott, Nucl. Sci. Abstracts **22**, 10 (1968)] of the intensities per decay of the 724.2- and 756.7-keV transitions of 43.5 and 54.5%, respectively. In that work, the 765.8-keV transition from the decay of ^{95}Nb was not completely resolved.

[b] It is difficult to understand this large value given by Eissa *et al.* (Ref. 2). From the data in Fig. 2, a value more like 1:3 is obtained for the 722- and 766-keV transitions. This could be explained if there were a different normalization in Ref. 2 for the 757- and 766-keV transitions.



(a)

(b)

FIG. 2. Electron-conversion spectrum for a ^{95}Zr-^{95}Nb source with a Si(Li) detector. These data are corrected for γ background.

TABLE II. β branchings and logft values for the levels in ^{95}Nb in the decay of ^{95}Zr.

β energy (keV)	β-branching intensity (%)[a] Ref. 10	Ref. 1	Ref. 5	Present work	logft values Present work
364.3	49	55.5	54.1	54.6±0.5	6.7
396.8	49	43.1	44.7	44.2±0.5	6.9
886.3	2	0.5–1.0	1.2	1.0±0.1	9.8
1121.0		0.4[b]			10.6[b]

[a] In the course of publication, our attention was directed to another new measurement [see J. E. Hiscott, Nucl. Sci. Abstracts **22**, 10 (1968)] of the intensities of the two lowest-energy β groups in the decay of ^{95}Zr as 54.5 and 43.5%, for the 364.3- and 396.8-keV groups, respectively.

[b] Taken from Ref. 3.

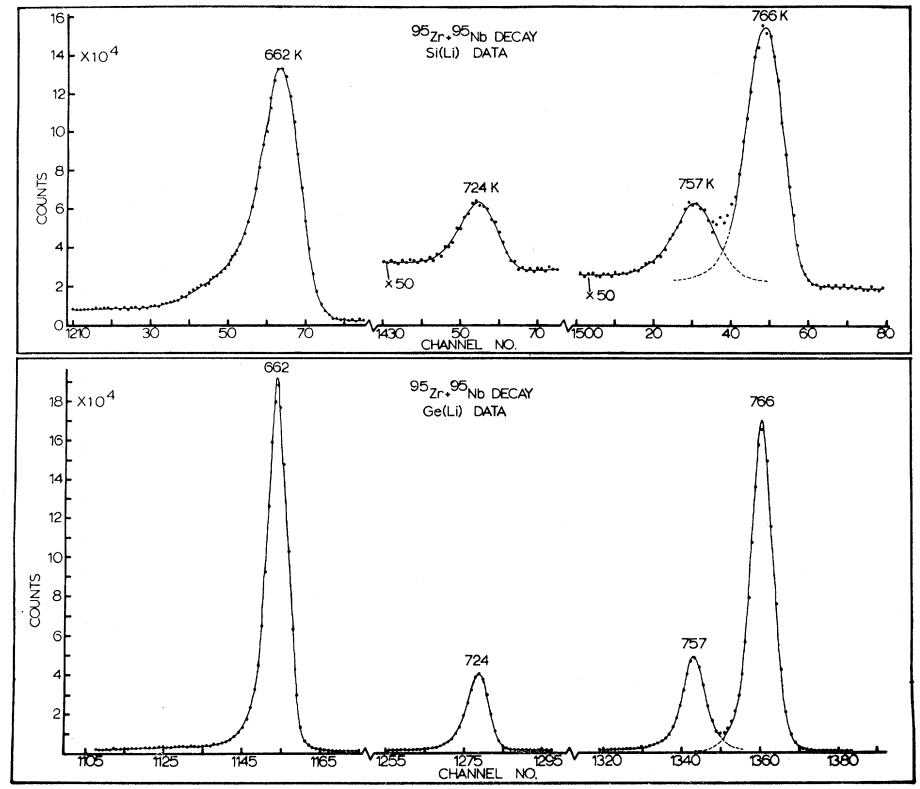


FIG. 3. Electron and γ-ray spectra taken with Si(Li) and Ge(Li) detectors for K-conversion coefficient measurements. The source was an equilibrium ^{95}Zr-^{95}Nb source with ^{137}Cs mixed into the source.

sure no systematic errors entered into the measurements.

For intensity measurements, the area under each peak was obtained first from an analysis by hand of the total number of counts by subtracting an appropriate average background which was nearly flat (see Fig. 1). The total number of counts in each of the peaks was also obtained by using a least-squares routine which fits each of the γ rays to a standard Gaussian shape and fits the background to an nth-order polynomial as demanded by the background variations for that particular peak. As a cross check on these two methods, the total number of counts in each peak were also obtained by computer-fitting the γ rays to the standard Gaussian shape and using the average background obtained in the first method by hand calculations. In three separate runs, the deviation from the average of the total number of counts obtained for each of the three strong peaks in all three methods was less than 1% for each individual peak, with two exceptions where it was $\lesssim$2.3% out of the 27 areas determined. A careful calibration of the detector efficiency had been carried out in other work[7] in this time and the results were used in the present work. A search was made for a highly converted 763-keV transition reported by Eissa *et al.*[2] A Si(Li) detector and a 4096-channel analyzer were used in these studies. In the absence of sufficient resolution to resolve the reported[2] close-lying K lines of transitions of 763 and 766 keV, accurate measurement of the peak positions relative to that of the accurately known K line of the 757-keV transition was carried out. The Si(Li) detector and the 4096-analyzer system were operated with a spread of 0.36 keV per channel and a 24-h run of a ^{95}Zr+^{95}Nb was taken. A similar run for a period of 24-h under the same conditions was taken with a 3-mm-thick Al absorber to correct for the γ background. This system also was used to obtain the K-conversion coefficients of 724-, 757-, and 765-keV transitions by using the 662-keV line of ^{137}Ba as an internal conversion standard. The method used to measure the α_K is the normalized electron peak to γ-peak method. A mixed source of ^{95}Zr+^{95}Nb and ^{137}Cs was used to obtain the relative conversion electron intensities from a 24-h run with the Si(Li) detector and 4096-channel analyzer. This run was followed up by a Al absorber run to correct for the γ background. Then this source was counted on a 30-cm^3 Ge(Li) detector and 4096 analyzer system for 8 h to obtain the relative γ intensities.

RESULTS AND DISCUSSION

Accurate Energy and Intensity Measurements

A typical γ-ray spectrum in one of our singles runs is given in Fig. 1. The high resolution of our 30-cm^3

[7] D. J. McMillen, Ph.D. thesis, Vanderbilt University, 1969 (to be published).

TABLE III. The K-conversion coefficient measurements for the 235-, 724-, 757-, and 766-keV γ rays. The first three are in ^{95}Nb, and the last transition is in ^{95}Mo.

Energy (keV)	$\alpha_K \times 10^3$ (expt) Ref. 2	Present work[b]	$\alpha_K \times 10^3$ (theor) Sliv and Band[a] $M1$	$E2$	$M4$	Multipolarity assignment
235	2350±200[5]	2210±270			2280	
724	1.28±0.13	1.56±0.14	1.32	1.42		$E2(M1)$
757	1.42±0.26	1.45±0.15	1.19	1.29		$E2(M1)$
766	1.26±0.25	1.32±0.13	1.29	1.30		$M1$–$E2$

[a] S. H. Vegors, R. L. Heath, and W. Hammer (unpublished) cite the graph is of the K-conversion coefficients calculated by Sliv and Band.

[b] Normalized to a value of 0.0894±0.0010 for the 662-keV transition in ^{137}Ba.

Ge(Li) enabled us to resolve completely the 756.7- and 765.8-keV γ rays in contrast to the earlier work of Broman and Boreving[1] with a small Ge(Li) detector and that of Eissa *et al.*,[2] where photoelectron lines were only partially resolved. The completely resolved lines make it possible to obtain more reliable and accurate values for the intensities as compared to results from partially resolved lines where one has to go through the process of stripping the two γ rays. The primary γ rays of interest in this work occur between 724 and 766 keV and hence, the uncertainty in the relative efficiency correction used to obtain relative intensities is reduced considerably. The average values of the energies and intensities obtained from all our sets of data are given in Table I. Table I also includes the results of other recent measurements[1,2,5] on energies and intensities. Our energy measurements are in excellent agreement with those of Black and Heath[8] and Legrand *et al.*[9] The intensity ratio of the 724.2- and 756.7-keV transitions falls between the recently measured values of Broman and Boreving[1] and Eissa *et al.*[2] There is good agreement between our results and that of Foin *et al.*[5] Our intensity on the 234.7-keV γ ray is within the upper limit set by Broman and Boreving[1] but is much smaller than that of Eissa *et al.*[2] The results of Foin *et al.*[5] are somewhat higher than our results but their error limit is large.

Figure 2 shows the electron-intensity data corrected for γ background. The arrows indicate the peak locations which are separated by 8.10±0.18 keV. This energy is in fact the difference in the K-conversion lines of the 756.74-keV transition in ^{95}Nb and the 765.83-keV transition in ^{95}Mo (binding energy difference of 1.01 keV). Hence, no evidence was found for the existence of a 763-keV transition. It is difficult to understand the reported data on a 763-keV transition. The transition observed may be an impurity but in any case the conversion coefficient reported does not seem to agree with the figure shown. No evidence was found for a reported[3] 840-keV transition. Our upper limit for this transition is $I_\gamma < 0.02$.

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[9] J. Legrand, J. P. Boulanger, and J. P. Brethon, Nucl. Phys. **A107**, 177 (1968).

From our accurate intensity values, the β feedings and logft values to the levels of ^{95}Nb in the decay of ^{95}Zr were obtained. These are given in Table II along with the results of the other studies.[1,2,5,10] Our principal β branchings are in near agreement with the values of Broman and Boreving[1] and in excellent agreement with Foin *et al.*[5] The intensity of the 886.3-keV β group to the 235.7-keV level in ^{95}Nb was obtained from our γ-ray intensity and an electron intensity calculated from the γ intensity and a theorectical total conversion coefficient $(\alpha_K+\alpha_L+1.3\alpha_M=2.9)$. There is good agreement on the β feeding of this level as reported here and by Foin *et al.*[5]

K-Conversion Coefficient Measurements

The data taken in these measurements are shown in Fig. 3. The areas under the peaks were measured with a planimeter and were used in the calculations of α_K with proper efficiency corrections. The value[11] of 0.0894±0.0010 was used for the α_K standard of the 662-keV γ-ray in ^{137}Ba. The calculated α_K values for

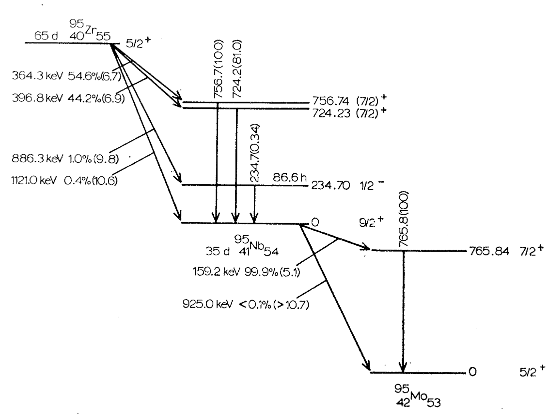

FIG. 4. Decay schemes of ^{95}Zr+^{95}Nb based on the present work. Intensities of the β groups to the ground state were taken from Refs. 3 and 12. Other information on the decay of ^{95}Nb is found in Ref. 13.

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[11] J. S. Merritt and J. G. V. Taylor, Anal. Chem. **37**, 351 (1965).

the 235-, 724-, 757-, and 766-keV transitions are given in Table III together with internal-external conversion measurements of Eissa *et al.*[2] The theoretical values of α_K given in Table III help us to make the multipolarity assignments for the three transitions.

Decay Schemes

Figure 4 shows the ^{95}Zr→^{95}Nb→^{95}Mo decay chain based on the present investigation. The intensities of β groups to the ground states were taken from Refs. 3 and 12, and other information on the decay of ^{95}Nb was taken from Ref. 13. The precise value of energies obtained in this work could serve as additional calibration standards for routine calibration of solid state spectrometers and the accurate value of the intensity ratio of the 724.2- and 756.7-keV transitions is useful in the calculation of burn-up in fuel elements.

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PHYSICAL REVIEW VOLUME 187, NUMBER 4 20 NOVEMBER 1969

^{208}Pb(^{3}He, α)^{207}Pb Reaction at 47.5 MeV*

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(Received 1 April 1969)

The absolute differential cross sections for the six lowest-lying levels of ^{207}Pb excited by the ^{208}Pb(^{3}He, α)^{207}Pb reaction have been measured for 47.5-MeV incident energy. A distorted-wave analysis yields relative spectroscopic factors which are apparently not in good agreement with those obtained from the (d, t) reaction. Transitions with large l transfer are strongly favored over those with small l. Further, the theoretical predictions for small l are sensitive to the treatment of the contributions from the nuclear interior. The precise value of l is not easily determined from angular-distribution measurements at this bombarding energy.

I. INTRODUCTION

BECAUSE of shell closure for both neutrons and protons, ^{208}Pb is a good nucleus for investigation of shell-model states via a single-nucleon-transfer reaction. Results from the ^{208}Pb(d, t)^{207}Pb reaction[1,2] indicate the usefulness of the shell-model description despite the evidence for core-excitation contributions which was obtained from recent measurements[3] on the ^{207}Pb(p, p') reaction. Although the (^{3}He, α) reaction has also been used for single-nucleon pickup, it is relatively unexplored for heavier nuclei and at higher bombarding energies. It is, therefore, of some interest to directly compare the results of the two reactions in the lead region. The ^{208}Pb(^{3}He, α) reaction has also been measured recently[4] at the lower energy of 28 MeV, and we shall compare the results from the two energies.

The (^{3}He, α) data were collected simultaneously with the ^{3}He elastic and inelastic scattering data described in Ref. 2, minimizing the systematic errors to be expected in comparing the two experiments. Since the experimental details were fully described in that paper, only a brief summary is presented here. An energy-analyzed 47.5-MeV ^{3}He beam from the Berkeley 88-in. cyclotron was directed through a thin self-supporting ^{208}Pb metallic foil and collected in a Faraday cup. Outgoing particles were detected in two cooled Si(Li) counter telescopes. ^{3}He and α particles were separated by a Goulding-Landis particle identifier[5] and stored in separate groups of a 4096-channel analyzer. Although the statistical uncertainties are rather large, the lack of background counts and large separation between peaks made the data analysis quite unambiguous.

* Research sponsored in part by the U.S. Atomic Energy Commission under contract with the Union Carbide Corporation.
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