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THE DECAY PROPERTIES OF Zr^{86}

Berkeley, California

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August 1965

THE DECAY PROPERTIES OF Zr^{86} *

E. K. Hyde, W. J. Treytl, A. Siivola†, D. H. Sisson and D. J. Horen‡

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ABSTRACT

A restudy of the radiations of 16.5 hour 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-minute 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 nanoseconds. These properties agree well with an E2 multipolarity. The lifetime and conversion coefficient of the 28 keV transition are < 10 nanoseconds 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 hours 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 microseconds. 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 hour Zr^{87}, 85 day Zr^{88}, and 79 hour 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 microsecond, but neither was in coincidence with positrons. They redetermined a half life value of 16.5 ± 0.1 hours.

In the present work we have reexamined 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" cyclotron for periods of about 1 hour. The isotope is produced in a yield of about 20 millibarns 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" 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 10 M 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 2 M 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. 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 ×3 mm deep and with a NaI(Tl) scintillator (1" × 2") 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 hour Zr^{89}.

Low energy radiations measured with the silicon detector and the thin sodium iodide crystal 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.

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 nanoseconds. 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 keV 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 microsecond range.

The 243 keV radiation was measured in a lithium-drifted germanium detector and the 28 keV photons in a 2" × 1" 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 nanoseconds.

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 nanoseconds which is close to the predicted 30 nanosecond 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 overall efficiency of both crystals was 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 inch 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 $(3.5 \pm 0.3) \times 10^{-2}$. This characterized the radiation unambiguously as E2. Theoretical values from the tables of Sliv and Band[11] are E2(3.8×10^{-2}), E1(7.5×10^{-3}), M1(1.6×10^{-2}) and M2(8×10^{-2}).

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).

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 thenoyltrifluoro acetone 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 section C 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 nanoseconds.

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, three K-vacancies are produced by conversion of the 243 keV transition. K-vacancies are also contributed by conversion of the

28 keV gamma ray. Let us set $\alpha_K = \frac{Ne_K}{N_\gamma}$ and $Ne_K + N_\gamma = 100$ where α_K is the conversion coefficient, Ne_K is the number of conversion electrons, and N_γ is the number of 28 keV photons. Straightforward algebra leads to

$$N_\gamma = \frac{100}{1+\alpha_K} \quad \text{and} \quad Ne_K = \frac{100\alpha_K}{1+\alpha_K} \tag{1}$$

The total number of K-vacancies in 100 decay events is then $89.4 + 3 + \frac{100\alpha}{1+\alpha}$; 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 can now be expressed as

$$\frac{N_\gamma}{N_{K-x}} = \frac{100/1+\alpha_K}{(0.675)(89.4+3 + (100\alpha_K/1+\alpha_K))} = \frac{148}{192.4\alpha_K + 92.4} \tag{2}$$

The experimental value of this ratio in the singles spectra 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 3.7 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 gate pulses were measured with a germanium semiconductor detector coupled to a pulse height analyzer. The coincident low energy gamma rays and x-rays were measured with a NaI crystal. The ratio N_γ/N_{K-x} in this spectrum was the same within statistical error of $\pm$ 0.02 units. The above-cited expression (Eq. (2)) 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. It can be shown that the following relationship holds in this case:

$$\frac{N_\gamma}{N_{K-x}} = \frac{100}{139\alpha_K + 4.7} \qquad (2)$$

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 3.8 ± 0.5, which is in better agreement with the theoretical value for E1 (4.5) than for M1 (8.3).

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 $\gamma\gamma$ coincidence experiment in which 511 keV photons served as the gate pulses. Lithium-drifted germanium crystals were used on both sides of the coincidence system. The resolution time was adjusted to a value long compared to the 28 nanosecond 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 1 percent 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 3 observed 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 log ft value for the electron capture decay to the 269 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 log ft value is 4.7. This low log ft 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 log ft 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 alternate possibility.

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 1/2 and their first excited states have spin 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 3/2- and 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 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 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 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 the isomeric state Y^{86m}.[20] We remark in passing that our experimental evidence clearly rules our any formation of Y^{86m} in the decay of 16.5 hour 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 hour 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 $[(g_{9/2})_p(7/2+)_n]_{8+}$ 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 log ft 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 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.

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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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	+

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†Permanent address: Department of Physics, University of Helsinki, Finland.

‡Present address: Naval Radiological Defense Laboratory, San Francisco.

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, UCRL-2813 (1954) unpublished.
3. J. F. Schooley and J. O. Rasmussen, University of California Lawrence Radiation Laboratory Report, UCRL-2932 (1954) unpublished.
4. Y. Awaya and Y. Tendow, J. Phys. Soc. Japan 19, 606 (1964).
5. E. P. Steinberg, "The Radiochemistry of Zirconium and Hafnium," National Research Council, National Academy of Sciences Report, NAS-NS-3011.
6. F. S. Goulding and D. A. Landis, "Techniques in Nuclear Pulse Analysis," National Academy of Sciences, National Research Council, Washington, 1963, Publication 1184. F. S. Goulding, Lawrence Radiation Laboratory Report, UCRL-11302 (February 1964) unpublished.
7. W. L. Hansen and B. V. Jarrett, Lawrence Radiation Laboratory Report, UCRL-11589 (August 1964) unpublished.
8. V. F. Weisskopf, Phys. Rev. 83, 1073 (1951).
9. D. Wieber, Nucl. Instr. Methods 24, 269 (1963).
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 "Tables of Internal Conversion Coefficients" Appendix 5 in "Alpha, Beta, and Gamma-Ray Spectroscopy," K. Siegbahn ed., (North-Holland Publishing Co., Amsterdam, 1965).
12. A. H. Wapstra, G. J. Nijgh, and R. van Lieshout, "Nuclear Spectroscopy Tables," (North-Holland Publishing Co., Amsterdam, 1959) p. 59.

13. A. G. W. Cameron, Can. J. Phys. 35, 102 (1957) and unpublished tables in Chalk River Project Report, CRP-690, March 1957.

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 Nookjen et al., Nucl, Phys. 63, 241 (1965).

17. M. G. Mayer and J. H. D. Jensen, "Elementary Theory of Nuclear Shell Structure," (John Wiley and Sons, Inc., New York, 1955).

18. M. Goldhaber and A. W. Sunyar, Phys. Rev. 83, 906 (1951).

19. I. Talmi, I. Unna, Nucl. Phys. 19, 225 (1960).

20. Y. E. Kim, D. J. Horen, and J. M. Hollander, Nucl. Phys. 31, 447 (1962).

21. E. K. Lin, Phys. Rev. 139, B340 (1965).

FIGURE CAPTIONS

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

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.

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.

Fig. 3(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.

Fig. 3(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.

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

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.

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

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.

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

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

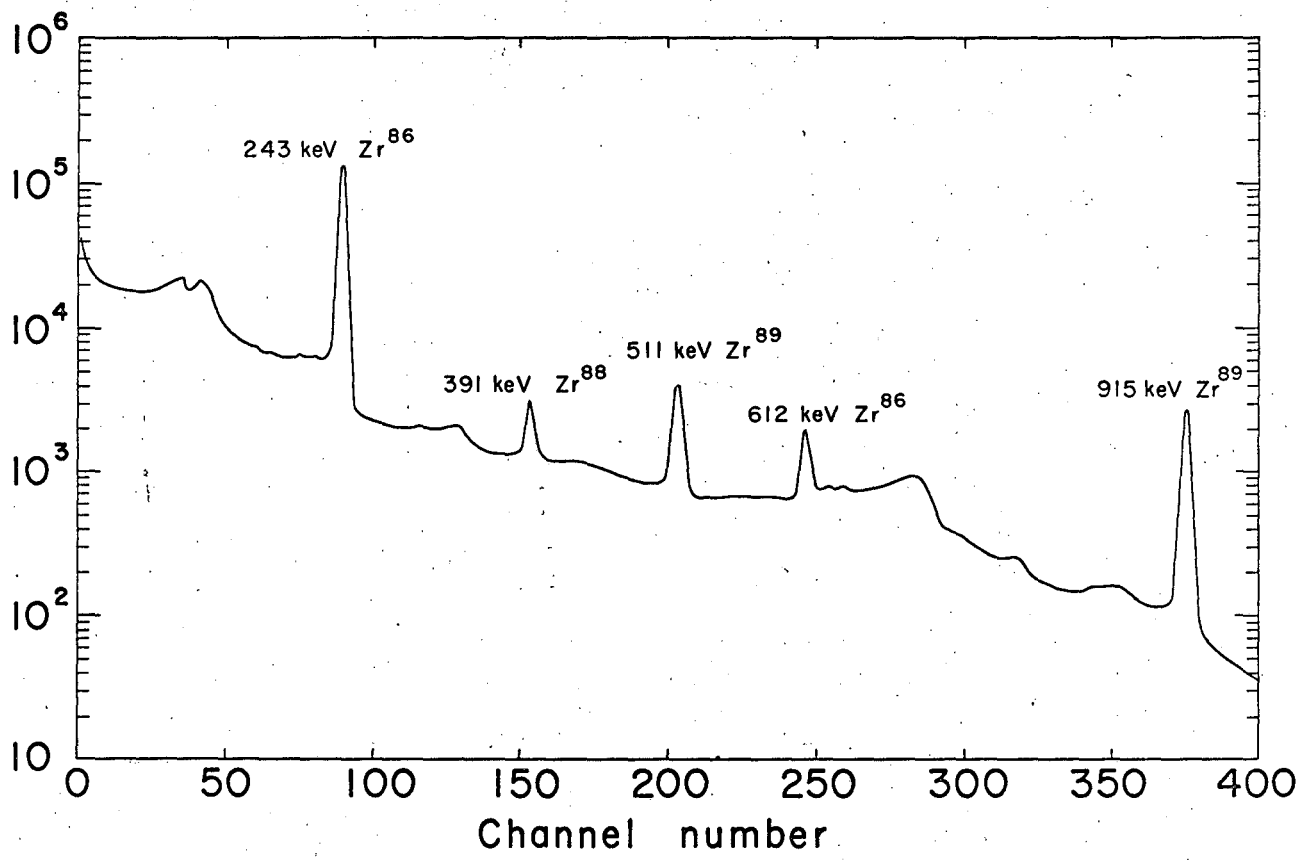
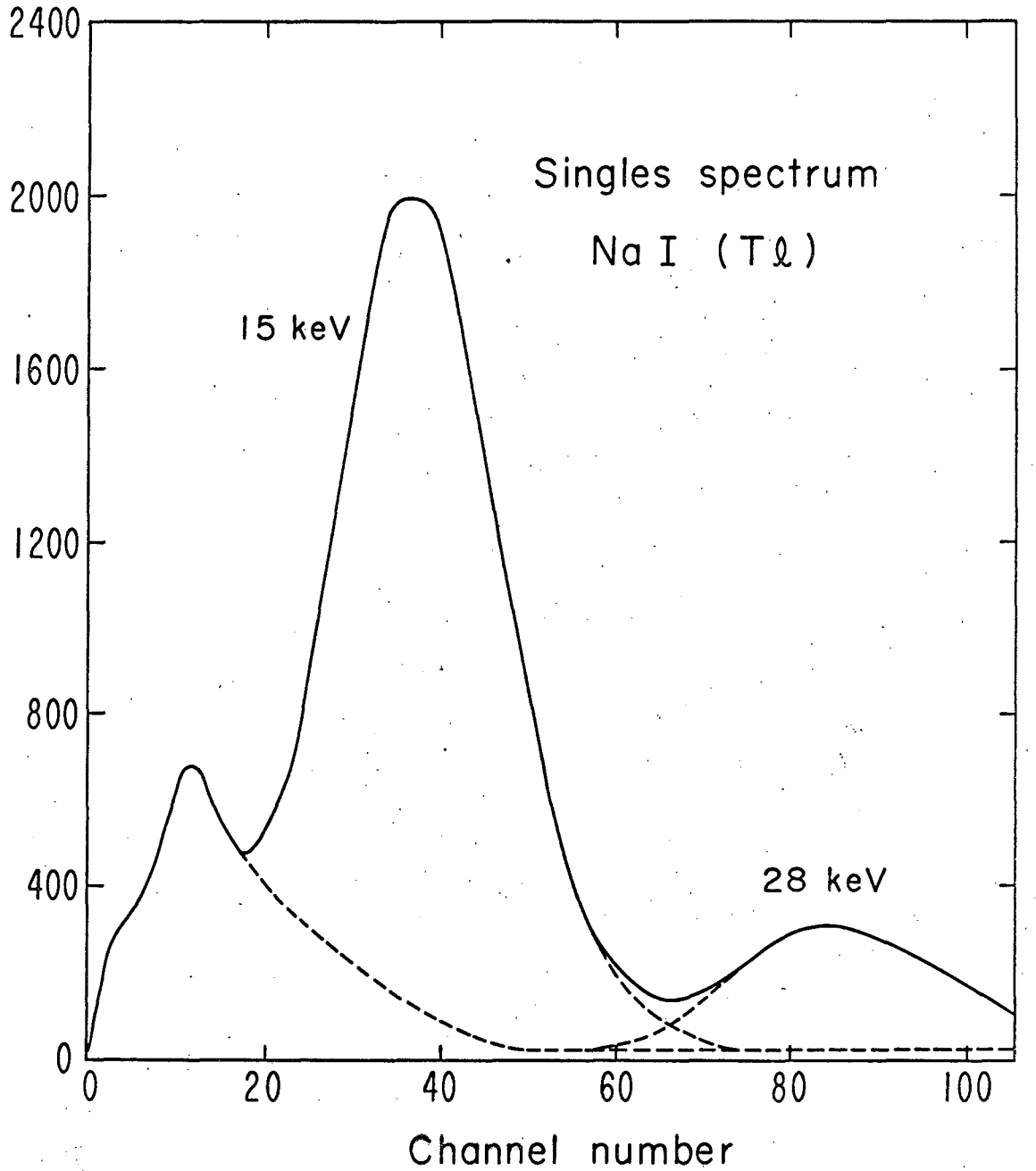

243 keV Zr86
391 keV Zr88
511 keV Zr89
612 keV Zr86
915 keV Zr89
10^6
10^5
10^4
10^3
10^2
10
0
50
100
150
200
250
300
350
400
Channel number
MUB-7885

Fig. 1



MUB-7882

Fig. 2 (a)

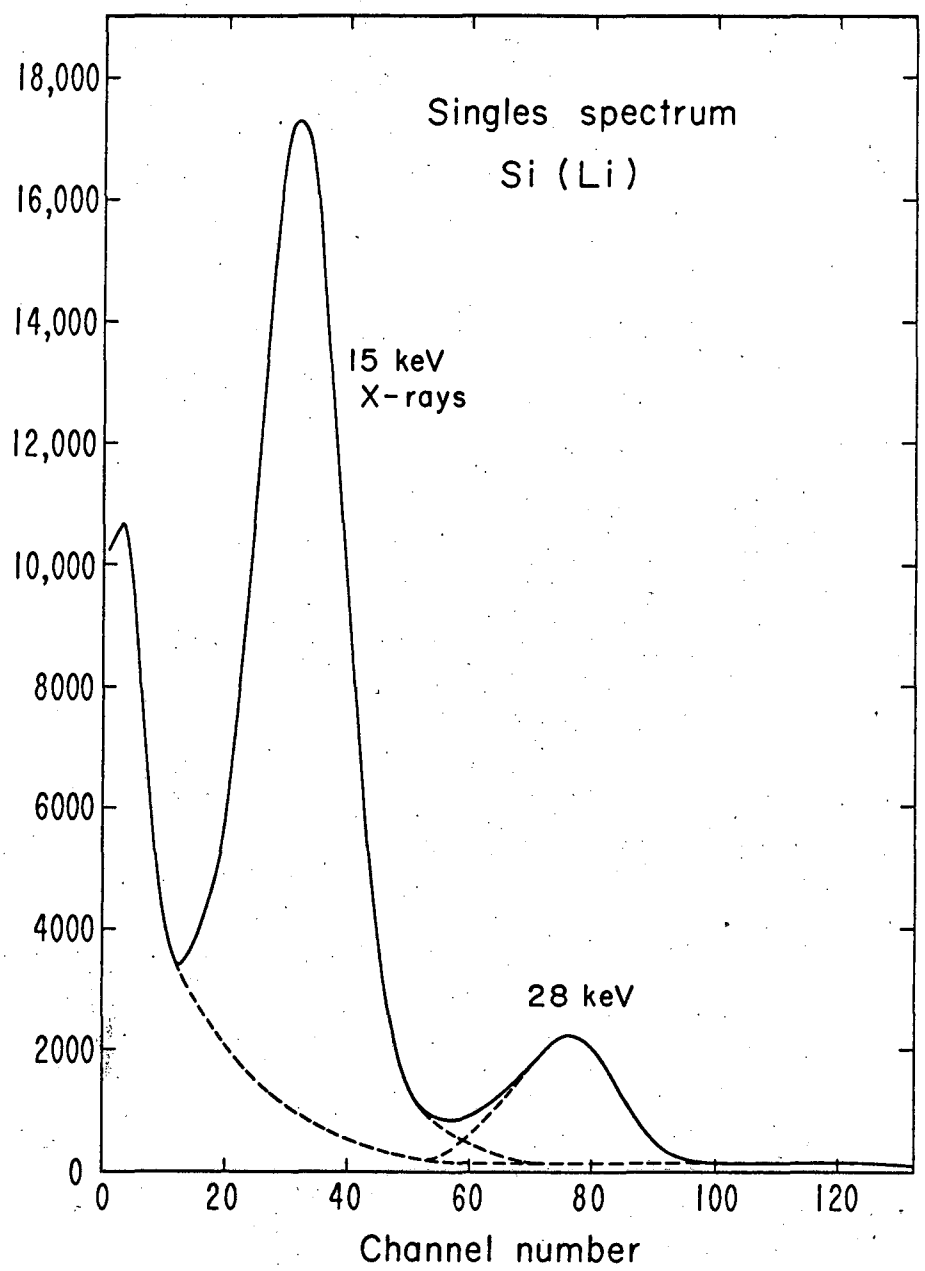


Fig. 2(b)

MUB-7883

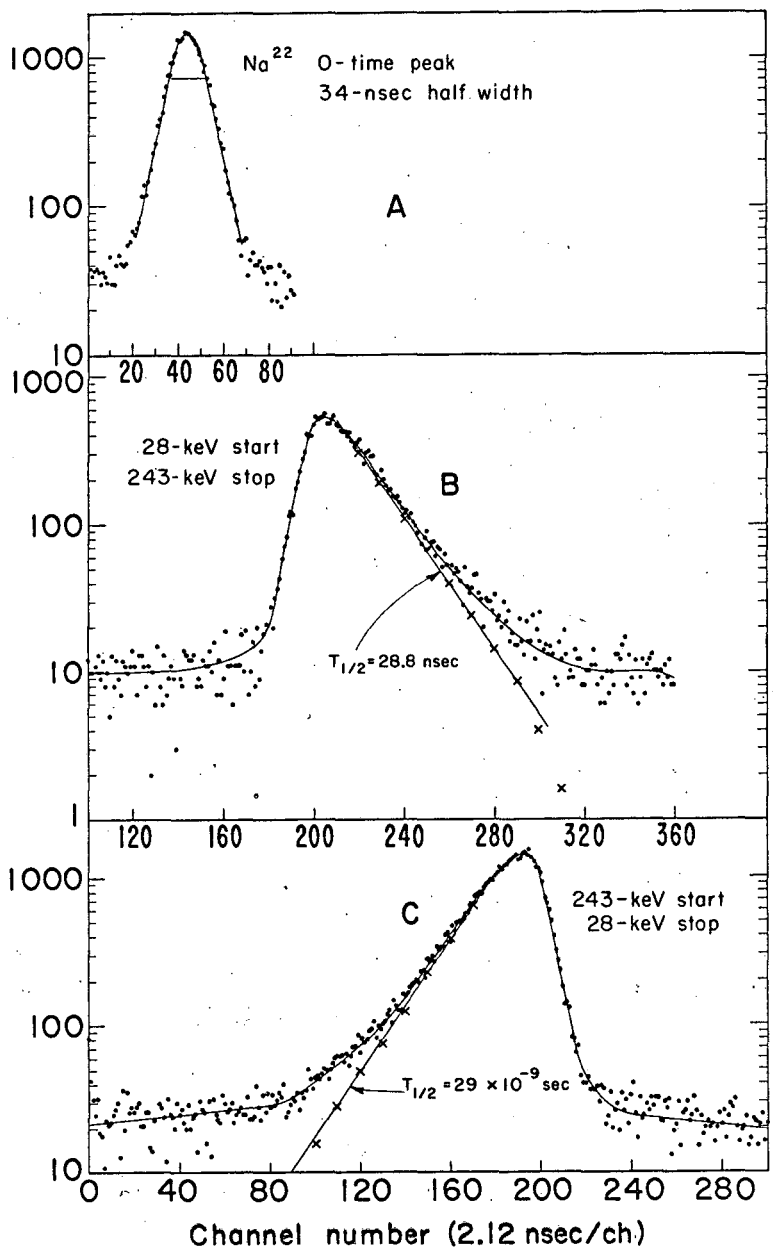
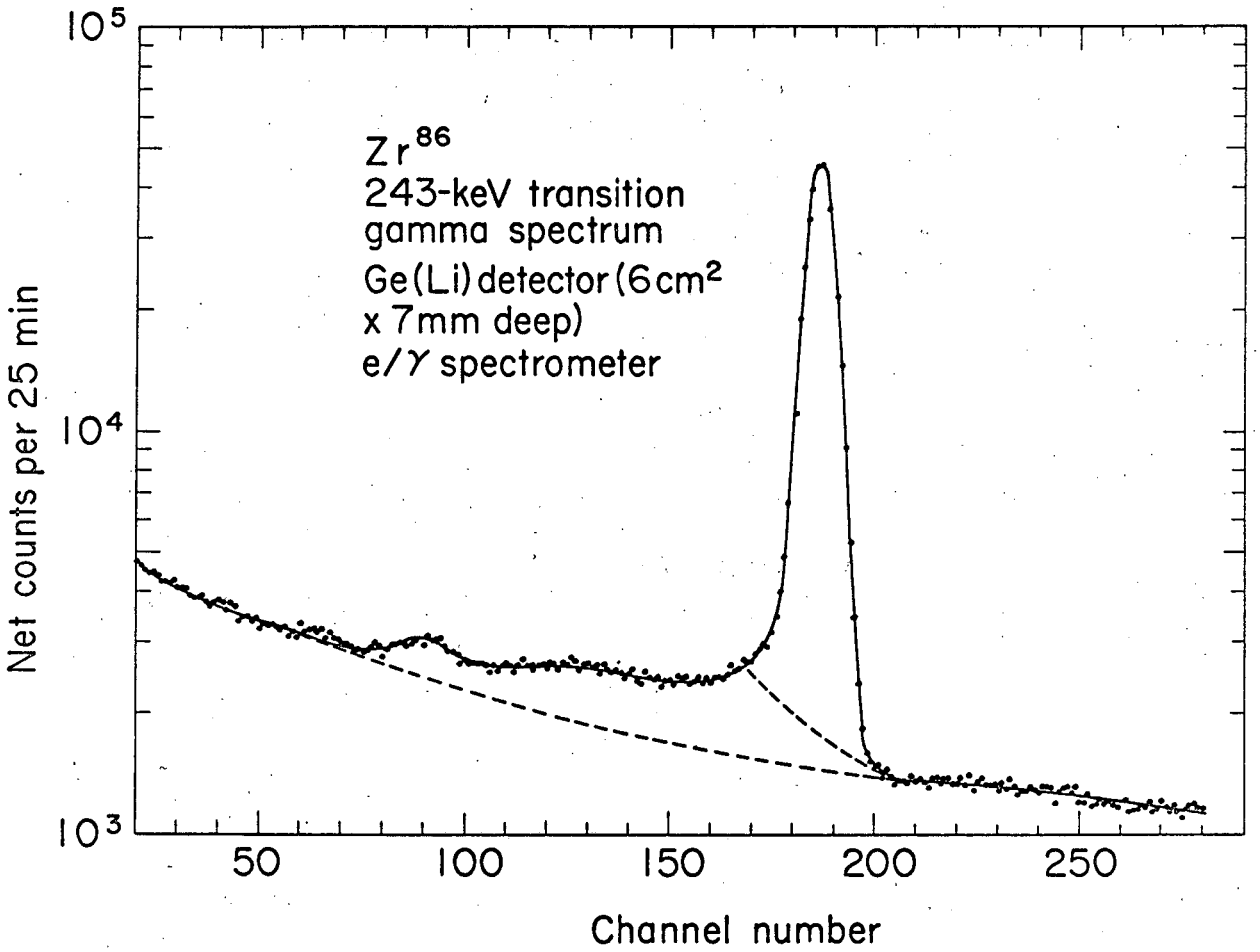
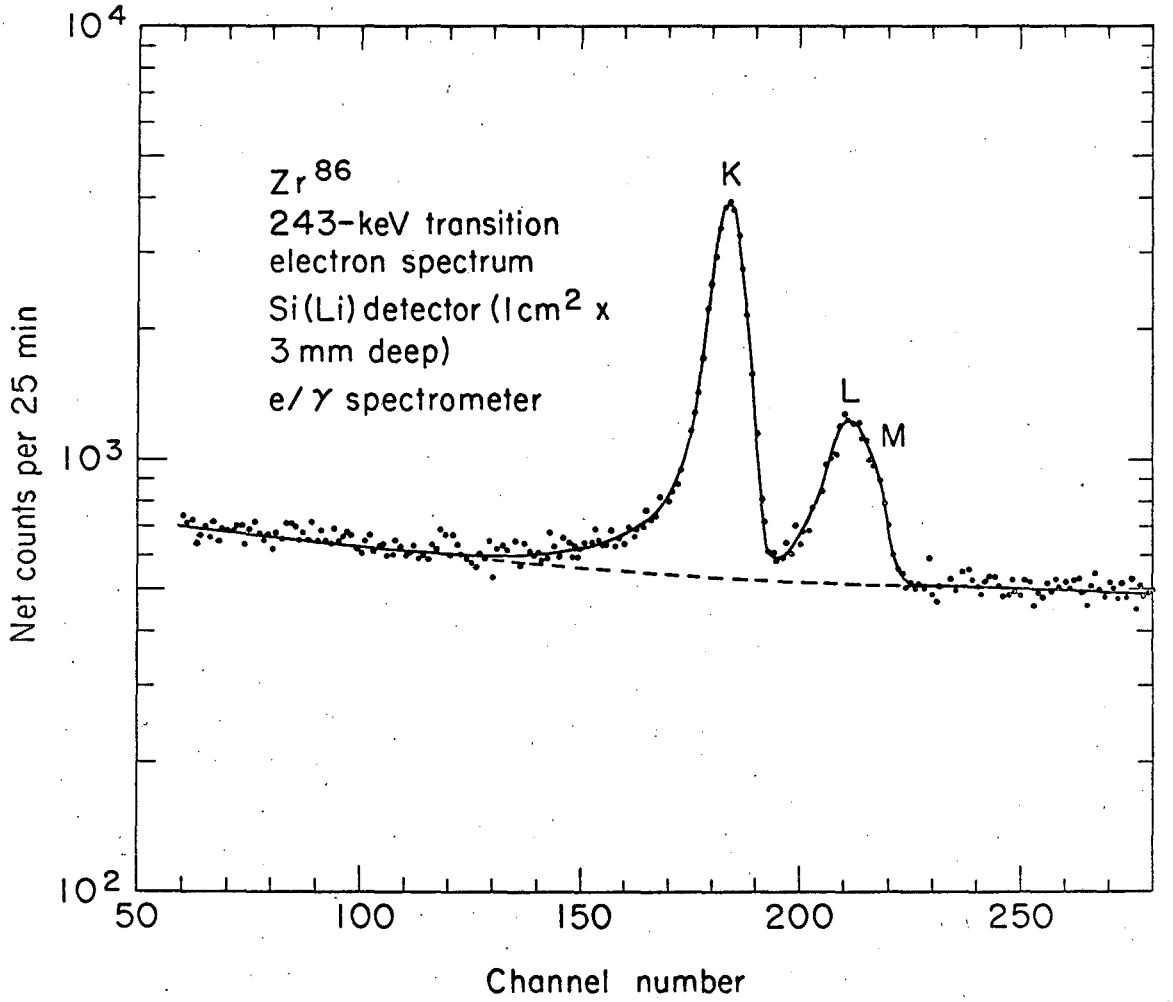

Na22 0-time peak
34-nsec half width
A
28-keV start
243-keV stop
B
T1/2=28.8 nsec
243-keV start
28-keV stop
C
T1/2 =29 ×10-9 sec
Channel number (2.12 nsec/ch)

Fig. 3



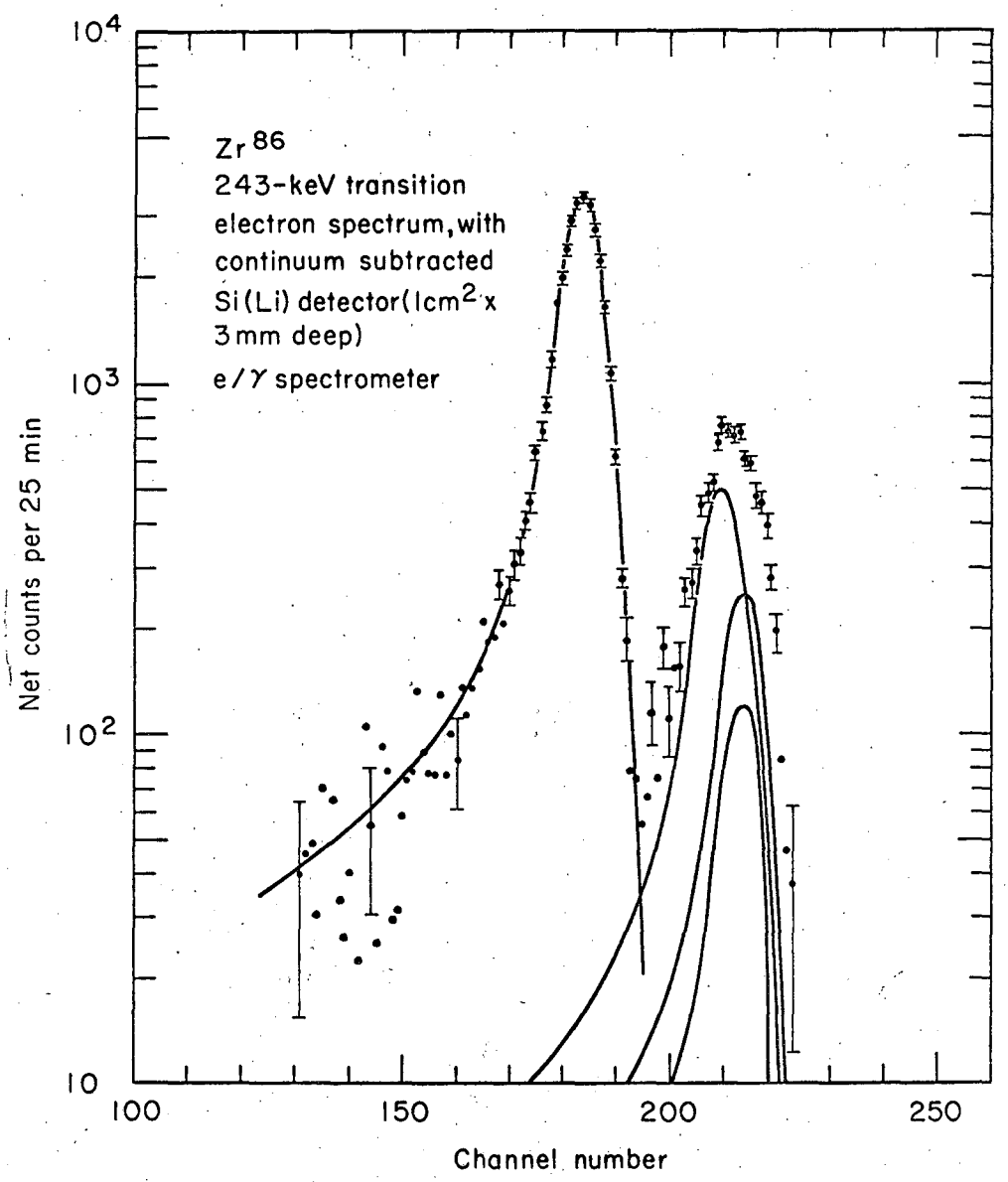
MUB-6686

Fig. 4



MUB-6687

Fig. 5



MUB-6688

Fig. 6

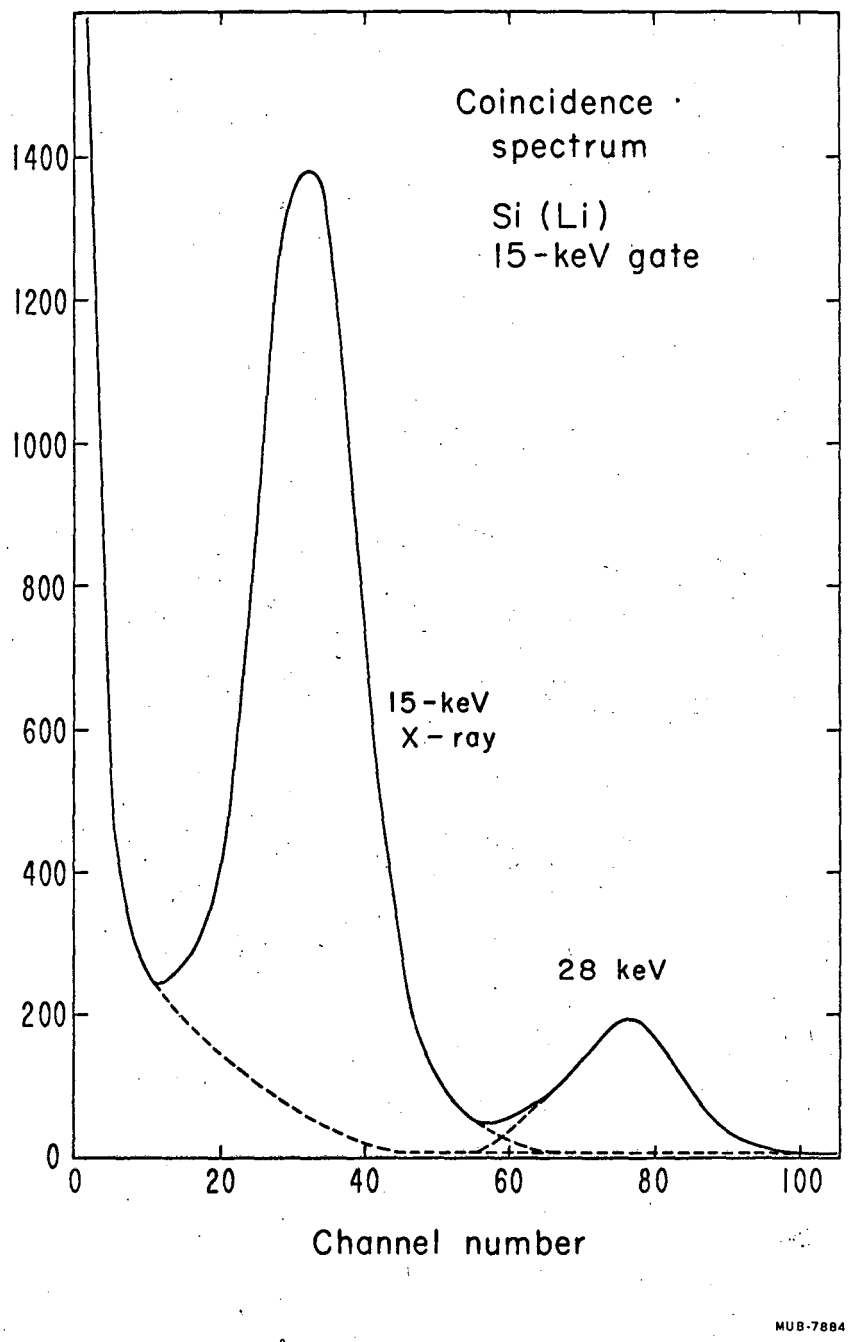
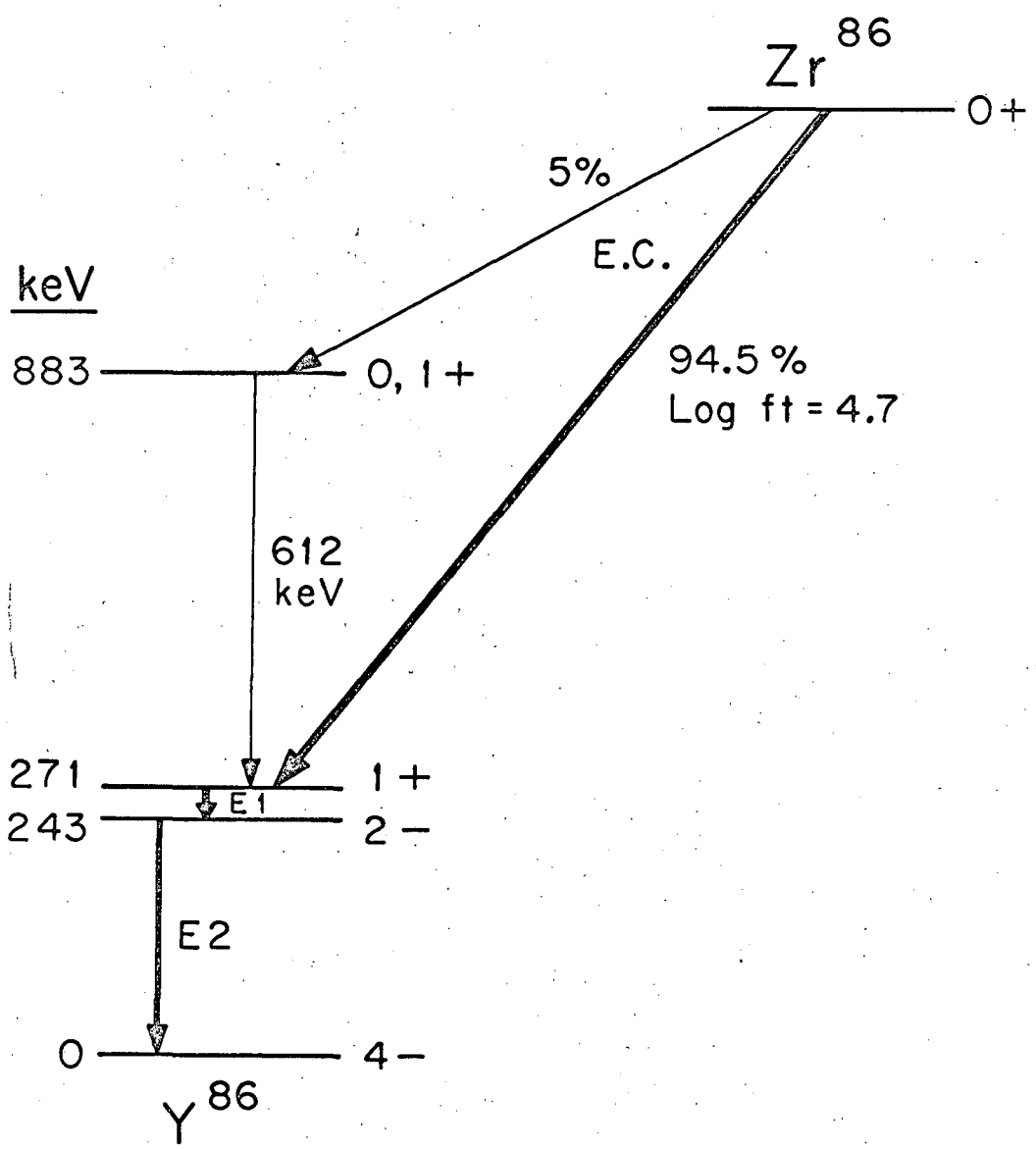
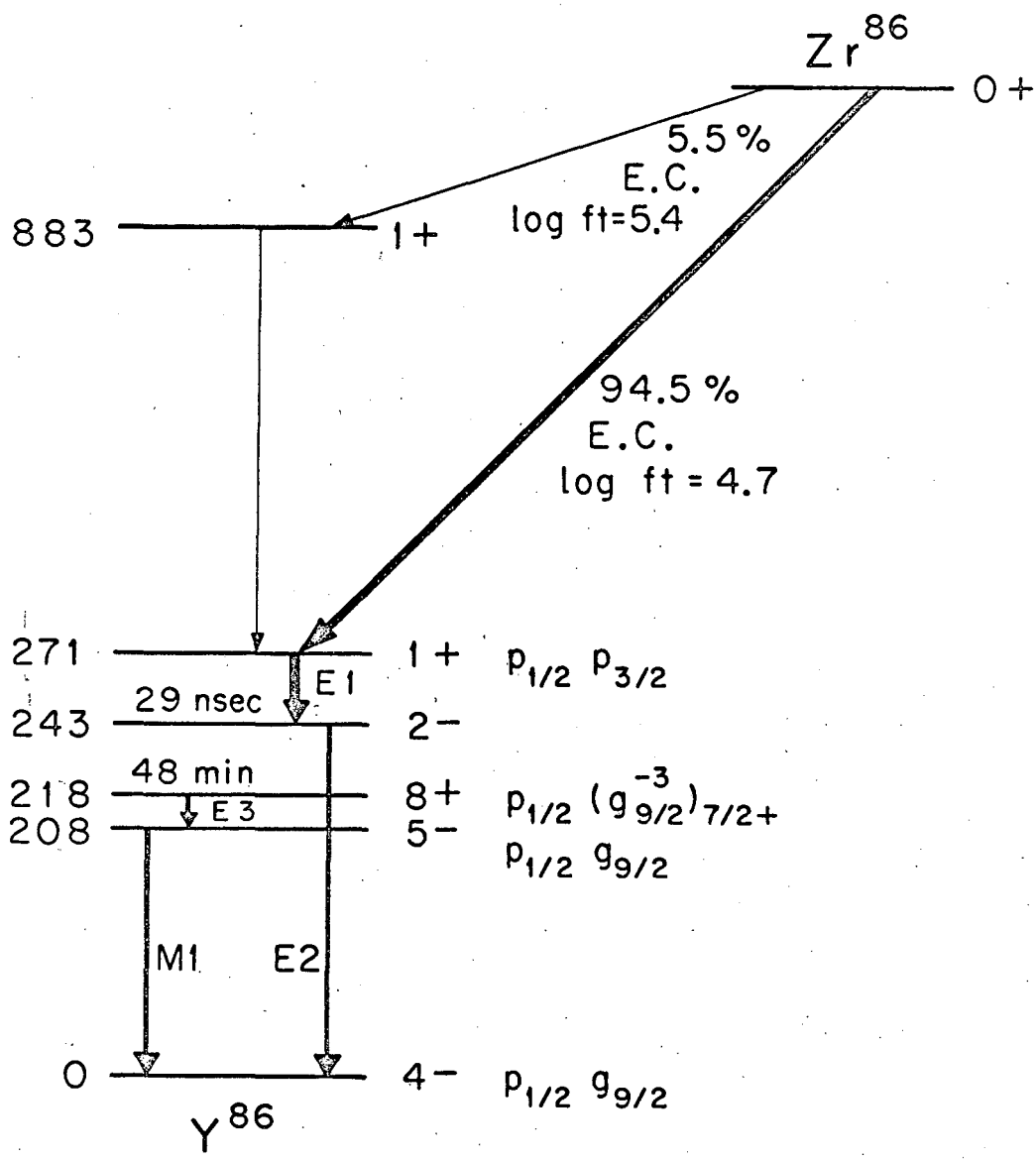

Coincidence
spectrum
Si (Li)
15-keV gate
15-keV
X-ray
28 keV
1400
1200
1000
800
600
400
200
0
0
20
40
60
80
100
Channel number
MUB-7884

Fig. 7



MUB-7881

Fig. 8



MUB-7880

Fig. 9

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