The Disintegration of Sr^{91} and Y^{91m}†

D. P. AMES,* M. E. BUNKER, L. M. LANGER,‡ AND B. M. SORENSON
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
(Received March 9, 1953)

The radiations from the fission product Sr^{91} (9.67-hr) and its daughter isomer Y^{91m} (50.3-min) have been studied using a magnetic lens spectrometer, a high resolution 180° focusing spectrometer, and a scintillation spectrometer. Coincidence measurements were made to check on certain genetic aspects of the decay scheme. Five beta-ray groups are observed with end-point energies and relative intensities of 2.665 Mev, 26.4 percent; 2.03 Mev, 4.1 percent; 1.359 Mev, 29.2 percent; 1.093 Mev, 33.1 percent; and 0.62 Mev, 7.2 percent. The 2.665-Mev group has a shape characteristic of a once forbidden transition involving a spin change of 2 units. Gamma-rays are found with energies of 1.413, 1.025, 0.93, 0.748, 0.645, and 0.5512 Mev. The 50.3-min isomeric level in Y^{91} decays only by gamma-emission to the ground state. The 0.5512-Mev gamma-ray associated with this transition has a $K/(L+M)$ internal conversion ratio of 6.00, which is consistent with an $M4$ assignment. A disintegration scheme is proposed.

INTRODUCTION

STRONTIUM-91 (9.67-hr) is formed in fission as the daughter of the two isomers of Rb^{91}.[1] Previous studies of the radiations from this isotope have been limited to absorption methods. The work of Finkle, Katcoff, and Sugarman[2] indicated that the beta-ray spectrum of Sr^{91} is complex and that there are two gamma-rays of approximate energy 1.3 and 0.61 Mev involved in the decay, the one of lower energy representing an isomeric transition in Y^{91}. The isomer Y^{91m} was found to have a half-life of 51 minutes. Their absorption measurements yielded an end point for the beta-spectrum of about 3.2 Mev. Thus, logft for the highest energy group was determined as ~8.0, suggesting the possibility that this group might exhibit the unique spectrum shape characteristic of $\Delta I=2$ (yes) transitions. This possibility was given further support by consideration of the nuclear shell model[3] which suggests $d_{\frac{5}{2}}$ and $p_{\frac{1}{2}}$ for the respective ground states of Sr^{91} and Y^{91}.

A further investigation of the radiations from Sr^{91} employing higher resolution seemed desirable in view of the suggested complexity of the decay and the possibility of establishing the forbidden character of the high energy beta-transition. It was soon discovered that the decay scheme was considerably more complex than had been indicated. However, study of the radiations in detail by various techniques has led to a consistent energy level diagram.

SOURCE PREPARATION

The Sr^{91} sources were produced by irradiating samples of 0.025 to 0.7 g of uranium enriched in U^{235} in a thermal column of the Los Alamos water boiler. The irradiation times ranged from 2 to 6 hours. The neutron flux at the sample position is estimated to be about 6×10^{11} n/cm^2 sec. Some of the uranium samples exhibited radioactivities of several hundred roentgens per hour shortly after irradiation.

Chemical separation of strontium from the fission product mixture was accomplished by using a modification of a procedure devised by Glendenin.[4] Strontium and barium were precipitated initially as nitrates from the gross fission product solution by the addition of fuming nitric acid. Then the rare earth fission products were decontaminated from the strontium and barium activities by the precipitation of iron (III) hydroxide from an ammoniacal solution. The precipitation of barium chromate from a buffered acetic acid solution served to separate the barium activity from the strontium activity. Additional iron (III) hydroxide decontamination steps were performed on the purified strontium fraction in order to remove any lanthanum activity resulting from barium decay prior to the barium separation. For the Sr^{91} work where it was necessary to have the sources as free of Y^{91m} as possible, an iron (III) hydroxide precipitation was made immediately preceding the source preparation. Strontium oxalate sources were used in the scintillation work. For the beta-spectrometer sources, the final strontium oxalate precipitate was dissolved in concentrated nitric acid and strontium nitrate was precipitated by the addition of fuming nitric acid. This precipitate was dissolved in a minimum amount of distilled water, and a portion of the resulting solution was evaporated on a rubber hydrochloride film.

Y^{91m} sources were prepared by allowing Sr^{91}, separated by the above procedure, to decay for a period of from two to three hours. Yttrium was separated initially from its strontium parent by the precipitation of yttrium hydroxide from an ammoniacal solution. Additional strontium decontaminations from the yttrium fraction

† Work performed under the auspices of the U. S. Atomic Energy Commission.
* Now at the University of Kentucky, Lexington, Kentucky.
‡ Indiana University, Bloomington, Indiana.
[1] O. Kofoed-Hansen and K. O. Nielsen, Phys. Rev. **82**, 96 (1951).
[2] Finkle, Katcoff, and Sugarman, *Radiochemical Studies: The Fission Products* (McGraw-Hill Company, Inc., New York, 1951), Paper No. 74, National Nuclear Energy Series, Plutonium Project Record, vol. 9, Div. IV.
[3] M. G. Mayer, Phys. Rev. **78**, 16 (1950).
[4] L. E. Glendenin, *Radiochemical Studies: The Fission Products* (McGraw-Hill Book Company, Inc., New York, 1951), Paper No. 236, National Nuclear Energy Series, Plutonium Project Record, Vol. 9, Div. IV.

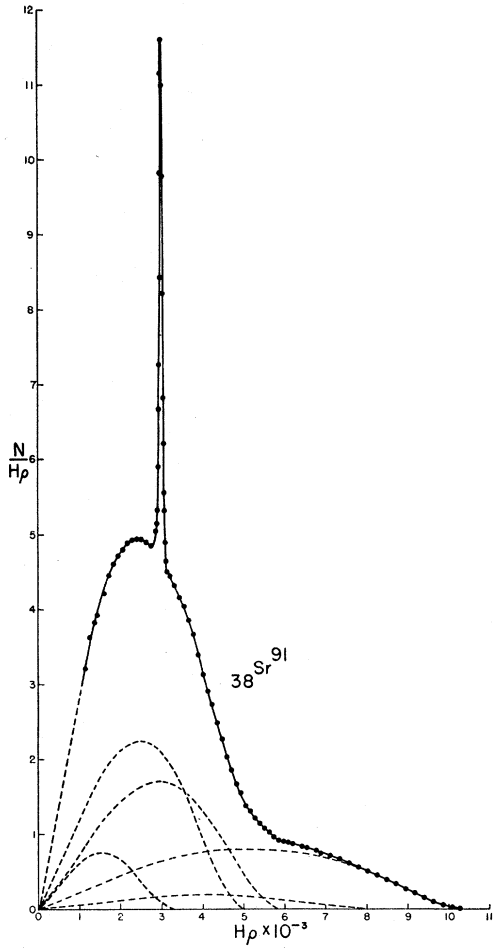

FIG. 1. Beta-spectrum of Sr^{91}. The partial spectra are determined from the Fermi plot analysis.

were performed by precipitating barium nitrate from a solution of the yttrium activity in fuming nitric acid. Then the yttrium activity was separated from the supernatant solution by the addition of concentrated hydrofluoric acid. The resulting yttrium fluoride was dissolved in a concentrated nitric acid—boric acid solution. An additional yttrium hydroxide precipitation was performed to reduce the total solid content of the solution. Following the dissolution of the precipitated hydroxide in dilute hydrochloric acid, yttrium oxalate was precipitated by the addition of a ammonium oxalate. This precipitate served as the Y^{91m} source material for both the scintillation and beta-spectrometer work.

The strontium separation was normally begun 30 to 40 hours after irradiation. This time lapse was necessary in order to effectively suppress Sr^{92}—Y^{92} contamination. A small amount of long-lived contamination resulting from Sr^{89} and Sr^{90} was unavoidable, however, and had to be taken into account. In order to check the purity of the strontium source material, decay data were taken over a period of several days, using a standard Geiger counter arrangement. When the contribution of the long-lived components was subtracted, a logarithmic decay curve was obtained which was linear and which, on the basis of the data taken during the first 36 hours, yielded a half-life for Sr^{91} of 9.67 ± 0.02 hours. Decay measurements were also made on a source of Y^{91m}, obtained by the above procedure. The logarithmic decay curve remained linear for more than two decades, yielding a half-life of 50.3 ± 0.25 minutes for Y^{91m}.

BETA-SPECTRA

Measurement of the composite beta-spectra of Sr^{89} (54-day), Sr^{90} (25-year), and Sr^{91} was begun as soon as feasible after the chemical separation. At the tiime of this measurement, the Sr^{91} activity amounted to roughly 75 percent of the total activity. A week later the spectrum was remeasured and the separate contributions of Sr^{89} and Sr^{90} were determined by a unique once forbidden Fermi analysis. These spectra were then corrected for decay and appropriately subtracted from the original composite distribution. The difference spectrum thus obtained is assumed to be that of Sr^{91}.

The beta-ray measurements referred to above were made with a large magnetic lens spectrometer.[5] An end-window Geiger tube having a 2.4-mg/cm² mica window and a 0.5-in. diameter aperture was employed as a detector. The spectrometer baffle system was adjusted so that the resolution was approximately 2.4 percent.

The beta-ray source consisted of approximately 0.2 mg of strontium nitrate spread over an area of 0.4 cm² on a backing of rubber hydrochloride 0.54 mg/cm² thick. The edge of the source was connected to ground by a narrow strip of aluminum foil.

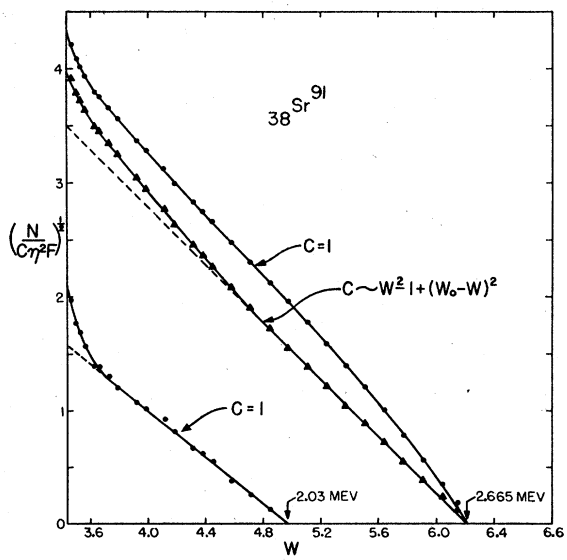

FIG. 2. Conventional and forbidden Fermi plots of the higher energy portion of the Sr^{91} data.

[5] L. M. Langer, Phys. Rev. **77**, 50 (1950).

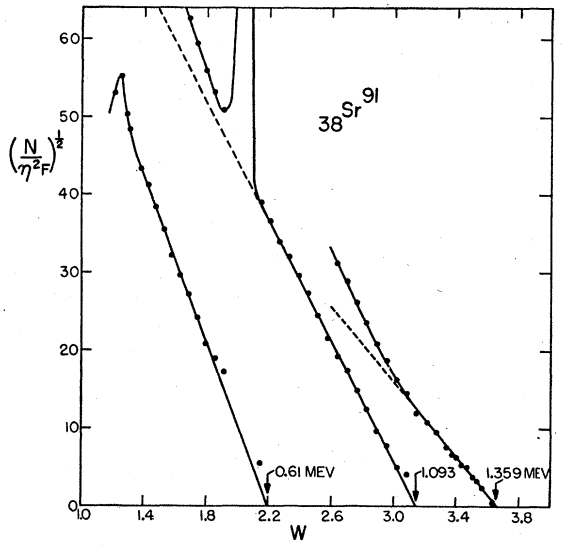

FIG. 3. Fermi plot of lower energy beta-groups of Sr^{91}. The continuous spectrum is obscured in the vicinity of $W=2.0$ by conversion lines of the 0.551-Mev gamma-ray.

The momentum distribution of the electrons from Sr^{91} is shown in Fig. 1. A statistical accuracy of about 1 percent was obtained on all points. The obviously complex spectrum has been resolved into five groups on the basis of a Fermi analysis of the data. Figure 2 shows the high energy portion of the Fermi plot. It is seen that the conventional plot of the highest energy group is concave toward the energy axis which, in conjunction with the calculated value of $\log[(W_0^2-1)ft]=9.65$, suggests that this transition is once forbidden with a spin change of 2 units.[6] In order to establish this assignment with greater certainty, the forbidden factor $a=W^2-1+(W_0-W)^2$, applicable to such transitions, has been appropriately applied to the data and yields the points plotted as triangles in Fig. 2. This "forbidden" plot is seen to be linear from near its end point of 2.665 Mev back to the end point of the next group at 2.03 Mev. The fact that the two points beyond $W=6.0$ lie slightly above the straight line is expected, since no correction was made for the finite resolution of the spectrometer.

The remainder of the Fermi plot analysis is shown in Fig. 3. The four inner groups are assumed to have the allowed shape. Unfortunately, the end point of the 0.61-Mev group is obscured by conversion electrons. However, in spite of the numerous subtractions, the data on this lowest energy group seem to be reasonably good, and the extrapolated end point is not thought to be in error by more than 20 kev. The rise of the Fermi plot below $W=1.4$ is a characteristic behavior of spectra emitted from a source of $\sim$0.5-mg/cm^2 surface density and is therefore not interpreted as indicating another group. The gamma-ray measurements further substantiate this assumption. The end-point energies, intensities, and logft values of the five observed groups are given in Table I.

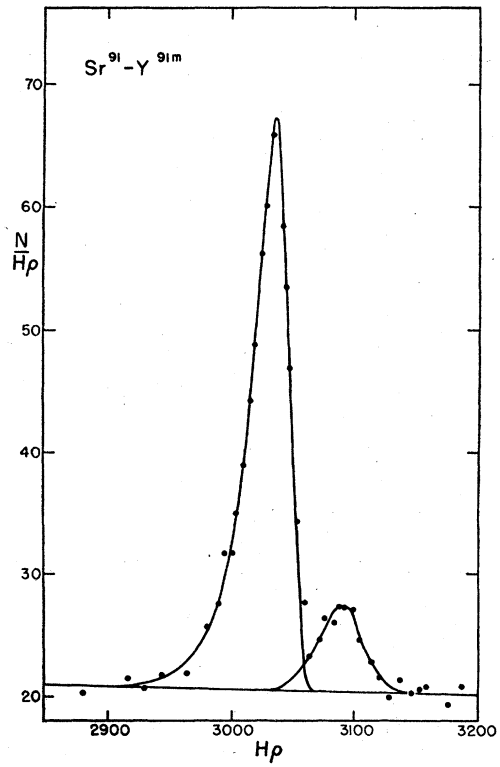

FIG. 4. K and $L+M$ internal conversion lines of the 551.2 kev isomeric transition in Y^{91}.

TABLE I. The beta-ray groups of Sr^{91}.

Group	End-point energy (Mev)	Intensity (%)	logft[a]
β_1	2.665±0.01	26.4	8.07
β_2	2.03 ±0.02	4.1	8.39
β_3	1.359±0.01	29.2	6.82
β_4	1.093±0.01	33.1	6.38
β_5	0.61 ±0.02	7.2	6.10

[a] Determined from the curves given by S. A. Moszkowski, Phys. Rev **82**, 35 (1951).

The strong conversion electron peak which appears in Fig. 1 arises from the decay of 50.3-min Y^{91m}. This peak could not be resolved into its separate K, L, and M components using the magnetic lens spectrometer. However, examination of a Sr^{91} source in a high resolution 180° focusing spectrometer[7] yielded the conversion electron spectrum shown in Fig. 4. The two peaks are, respectively, the K and $L+M$ lines of a 551.2±1.0 kev gamma-ray. The $K/(L+M)$ ratio is 6.00 which empirically classifies the transition as $M4$.[8] This classification is also suggested by the semi-empirical

[6] F. B. Shull and E. Feenberg, Phys. Rev. **75**, 1768 (1949).
[7] L. M. Langer and C. S. Cook, Rev. Sci. Instr. **19**, 257 (1948).
[8] Graves, Langer, and Moffat, Phys. Rev. **88**, 344 (1952).

lifetime-energy formulas given by Goldhaber and Sunyar.[9]

It was thought possible that Y^{91m} might be beta unstable. To check this point, an Y^{91m} beta-ray source was prepared by chemically extracting the yttrium from a Sr^{91} sample. Examination of the electron spectrum revealed only the conversion lines from the 551.2-kev gamma-ray.

GAMMA-SPECTRA

The photo- and Compton electrons ejected from a uranium radiator by the gamma-rays of Sr^{91} were examined with the magnetic lens spectrometer. The resulting spectrum is shown in Fig. 5. The source material was contained in a small brass capsule which had walls thick enough to stop 3-Mev beta-particles and which had attached to its front side a $\frac{3}{8}$-in. diameter, 33 mg/cm^2 disk of uranium.

A total of seven photoelectron lines were observed,

TABLE II. Photoelectron lines ejected from a uranium radiator by the gamma-rays of Sr^{91}.

Line	Energy (kev)	Converter thickness correction[a]	Binding energy (kev)	Gamma-energy (kev)	Gamma-best value (kev)
K_1	430.6	5.0	115.6[b,c]	551.2	
L_1	524.7	6.0	19.3[d]	550.0	551.2±1.0
K_2	524.7	6.0	115.6	646.3	645 ±5
K_3	625.4	7.2	115.6	748.2	
L_3	720.7	8.3	19.3	748.3	748 ±2
K_5	899.7	9.7	115.6	1025.0	
L_5	992.0	9.8	19.3	1021.1	1025 ±5
K_6	1288.8	9.0	115.6	1413.4	1413 ±5

[a] Hornyak, Lauritsen, and Rasmussen, Phys. Rev. **76**, 731 (1949).
[b] Y. Cauchois, J. phys. et radium **13**, 113 (1952).
[c] Hill, Church, and Mihelich, Rev. Sci. Instr. **23**, 523 (1952).
[d] A weighted average of the three L subshell binding energies given in reference *c*. Each shell was given a weight equal to the number of electrons it contains.

two of which are known to be superpositions of K and L lines. A summary of the energies and assignments of these lines is given in Table II. The K photoelectron line of the 551.2-kev gamma-ray (K_1) was used as a calibration. The peak which occurs at the approximate energy of the L line of this gamma-ray (L_1) was observed to have about twice the expected L_1 intensity, strongly suggesting that this peak is a composite of the L_1 line and a K line of about the same energy and intensity. Therefore, since the composite peak occurs at an energy of about 1 kev less than the calculated energy of the L_1 line, the K line (K_2) must have an energy of about 1 kev less than that of the peak. This is the reason why the energy of the gamma-ray responsible for K_2 is estimated in Table II to be 645 kev instead of 646.3 kev which one calculates from the observed (K_2, L_1) peak.

The Sr^{91} gamma-radiation was also studied with a

[9] M. Goldhaber and A. W. Sunyar, Phys. Rev. **83**, 906 (1951).

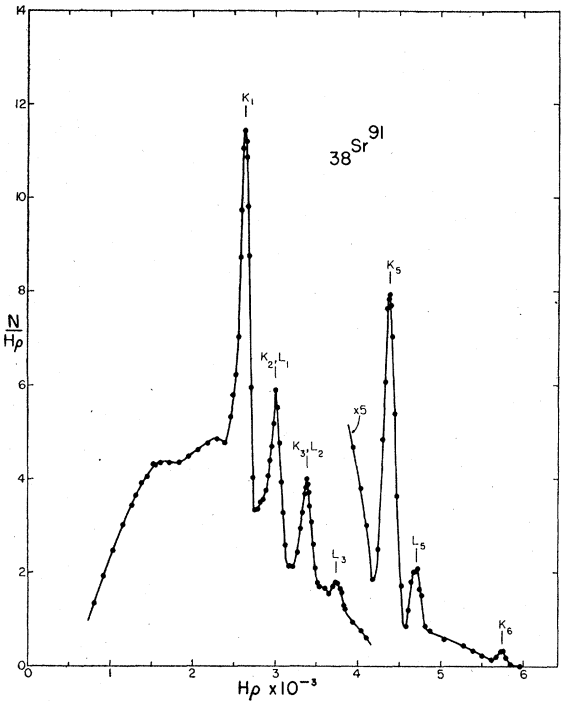

FIG. 5. Compton and photoelectrons ejected from a uranium radiator by the gamma-rays of Sr^{91}.

NaI(Tl) scintillation spectrometer. The phosphor, $1\frac{1}{2}$ in. in diameter and $1\frac{1}{2}$ in. high, was mounted on a Dumont K-1177 photomultiplier tube, and the amplified output pulses were sorted with a 10-channel pulse-height analyzer. A lead collimator 1 in. in diameter, and 4 in. long was placed between the source and detector.

A portion of the measured pulse-height distribution is shown in Fig. 6. Although a careful search was made down to energies as low as 20 kev, no photoelectron (or total energy) peaks of lower energy than 551 kev

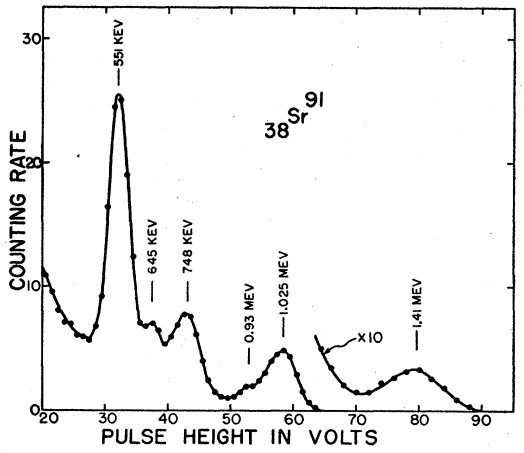

FIG. 6. Gamma-ray spectrum of Sr^{91} taken with a NaI(Tl) scintillation spectrometer. The 50.3-min Y^{91m} activity has been allowed to grow into secular equilibrium with the Sr^{91} activity.

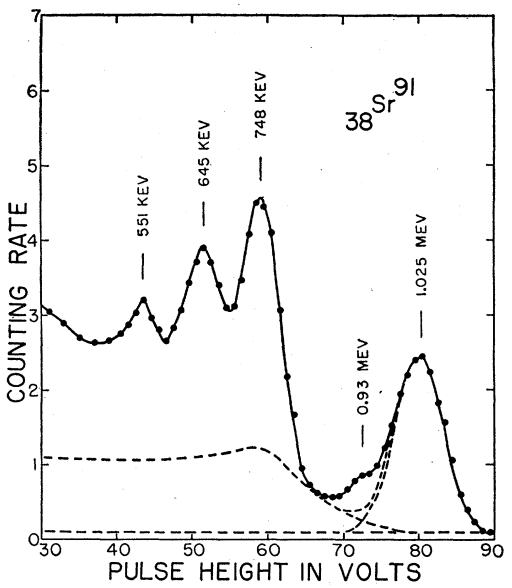

FIG. 7. A portion of the gamma-ray spectrum of Sr^{91} taken with a NaI(Tl) scintillation spectrometer approximately $3\frac{1}{2}$ minutes after chemically removing the Y^{91m} activity. The uppermost dotted line is an estimate of the sum of the spectra of the 1.025- and 1.41-Mev gamma-rays.

could be found. Five of the observed peaks agree in energy with the gamma-ray values listed in Table II. In addition, a weak line is in evidence at about 0.93 Mev which was not resolved in the secondary electron spectrum. Examination of an Y^{91m} source in the scintillation spectrometer proved that of the six observed gamma-rays, only the 551.2-kev transition is associated with the yttrium isomer. Therefore, this gamma-ray must be a ground-state transition.

The scintillation spectrum was used to estimate the relative intensities of the observed gamma-rays. In order to obtain a more reliable estimate of the intensity of the incompletely resolved 645-kev line, a Sr^{91} source was examined with the scintillation spectrometer approximately $3\frac{1}{2}$ minutes after an yttrium separation (which initially eliminates the 551-kev line). The spectrum obtained is shown in Fig. 7. The 551-kev line is sufficiently weak that a good estimate of the intensity of the 645-kev line could be made. The manner in which the scintillation data were analyzed is indicated by the dotted lines in Fig. 7, which show the estimated contribution to the spectrum of the 1.41- and 1.025-Mev gamma-rays. Guided by experimental data on monoenergetic lines of various energies, such curves were constructed for each gamma-ray. Gamma-ray intensity ratios were than calculated by correcting the areas under the photopeaks for crystal efficiency on the basis of an empirical efficiency curve for the $1\frac{1}{2}$-in. crystal. The results of this analysis are shown in Table III. The last column in Table III is discussed later in this report.

A gamma-gamma coincidence study was also made on the Sr^{91} gamma-radiation, using a pair of scintillation spectrometers. The resolving time of the coincidence circuit was about one microsecond. The experimental arrangement was very similar to that used by Bell *et al.*[10] With the so-called "gate" spectrometer set to count all pulses representing 400-kev energy or greater, the coincidence spectrum obtained is that shown in Fig. 8. This spectrum indicates that of the six known gamma-rays, only the 0.645-, 0.93-, and 1.41-Mev transitions are involved in prompt gamma-cascades. This fact was quite useful in the deciphering of the decay scheme.

DISCUSSION

A decay scheme for Sr^{91} can be deduced which is consistent with the various measurements described above. This is shown in Fig. 9. Consideration of energies and intensities alone would lead to this scheme. In addition, its validity is greatly strengthened by the information obtained in the gamma-gamma coincidence experiment. The strong 0.748- and 1.025-Mev gamma-rays do not appear in the coincidence spectrum since they both feed the isomeric level.

TABLE III. Sr^{91} gamma-ray data obtained with a NaI(Tl) scintillation spectrometer.

Gamma-energy (Mev)	Relative peak area	Crystal efficiency (arb. units)	Relative intensity (arb. units)	Normalized intensity[a] (%)
0.551	6.31[b]	0.308	20.5	59
0.645	1.39	0.267	5.2	15
0.748	2.15	0.234	9.2	27
0.93	0.21	0.192	1.1	3
1.025	1.84	0.177	10.4	30
1.41	0.25	0.138	1.8	5

[a] Relative to the total number of disintegrations.
[b] Corrected for internal conversion. The measured peak area was 6.02.

In order to convert the observed relative intensities of the gamma-rays to percentages relative to the total number of disintegrations, it was assumed that the sum of the intensities of the 1.025- and 0.93-Mev gamma-rays equals the intensity of the 1.093-Mev beta-ray group. The resulting normalized intensities are listed in Table III and also appear in Fig. 9. The fact that the intensity of the 0.748-Mev gamma-ray calculates to be slightly lower than expected and that of the 0.645-Mev gamma-ray slightly higher than expected suggests the possibility that there is a weak 0.654-Mev transition between the 1.299- and 0.645-Mev levels which is masked by the 0.645-Mev gamma-ray. However, the data are not good enough to decide this question. In this respect, it is interesting to note that if the spin assignments are correct, the 0.654-Mev gamma-ray would be an $M2$ transition and would not be expected to compete measurably with the 0.748-Mev $M1$ transition.

[10] Bell, Cassidy, and Kelley, Phys. Rev. **82**, 103 (1951).

From the 59 percent intensity of the 551.2-kev isomeric transition and the measured ratio of the area of its K conversion line to the area of the beta-spectrum, it is possible to calculate a value for the K internal conversion coefficient. This coefficient is found to be $(4.6\pm0.2)\times10^{-2}$, which is in excellent agreement with the theoretical value $(4.7)\times10^{-2}$ given by the tables of Rose *et al.*[11] for an $M4$ transition.

In regard to spin assignments, the beta-spectrum from 61-day Y^{91} has been identified as once forbidden $\Delta I=2$(yes),[12] and, since the measured ground state of Zr^{91} is $\frac{5}{2}$ (the shell model assignment is $d_{\frac{5}{2}}$), the ground state of Y^{91} must be $p_{\frac{1}{2}}$. Similarly, since the beta-transition from Sr^{91} to the Y^{91} ground state is also of the $\Delta I=2$(yes) type, the ground state of Sr^{91} must be $d_{\frac{5}{2}}$, which is consistent with shell model predictions. The $M4$ character of the isomeric transition makes the 0.551-Mev level a $g_{9/2}$ state. Thus, the reason there is no

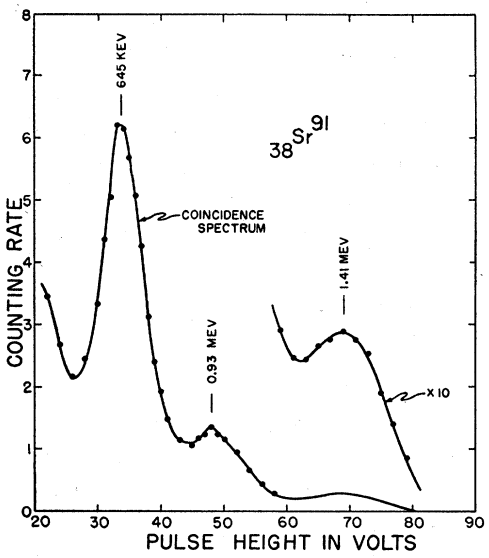

FIG. 8. Gamma-gamma coincidence spectrum of Sr^{91} obtained using coincident scintillation spectrometers. The pulses contributing to this spectrum are those that are in coincidence with pulses representing 400-kev energy or greater.

observed beta-emission to this level is that the transition is twice forbidden.

The rest of the spin assignments are less definite; but, as shown below, they provide a reasonable explanation of the experimental data consistent with beta-ray selection rules and gamma-ray transition probabilities. An attempt was also made to keep the assignments consistent with what might appear to be a reasonable extension of the one-particle shell model to the higher excited states. It is realized, of course, that the one-particle model is not necessarily applicable to highly excited states.

[11] Rose, Goertzel, Spinrad, Harr, and Strong, Phys. Rev. **83**, 79 (1951).

[12] L. M. Langer and H. C. Price, Jr., Phys. Rev. **76**, 186 (1949).

The beta-ray groups designated in Table I as β_2, β_3, and β_4 have logft values which suggest they are either once forbidden or l forbidden. Consequently, $p_{\frac{3}{2}}$, $g_{7/2}$, $f_{\frac{5}{2}}$, and $f_{7/2}$ seem to be the only shell model states available for assignment to the 0.645, 1.299, and 1.576 Mev levels. A $p_{\frac{3}{2}}$ assignment appears to be the best choice for the 0.645-Mev level for the following reasons: (1) there is no intermediate gamma-transition observed between the 0.645-Mev and the 0.551-Mev levels, which limits the choice to $p_{\frac{3}{2}}$ or $f_{\frac{5}{2}}$; (2) the choice of $f_{\frac{5}{2}}$ makes it difficult to explain the observed gamma-ray branching ratios from the upper levels to the 0.551- and 0.645-Mev levels.

The 1.299- and 1.576-Mev levels both decay predominantly to the 0.551-Mev, $g_{9/2}$ level. This fact eliminates $f_{\frac{5}{2}}$ as a possibility for either level, leaving only the choices $g_{7/2}$ and $f_{7/2}$. Now, it appears definite that there is a weak transition (0.93 Mev) between the 1.576-Mev level and the 0.645-Mev level, whereas it is questionable whether or not there is an observable transition to the $p_{\frac{3}{2}}$ level from the 1.299-Mev level. This suggests assignment of $f_{7/2}$ to the 1.576-Mev level and $g_{7/2}$ to the 1.299-Mev level, since it seems likely that a 0.93-Mev, $E2$ transition would compete more strongly with a 1.025-Mev, $E1$ transition than a 0.93-Mev, $M2$ transition would compete with a 1.025-Mev, $M1$ transition.

The data indicate that the 2.058-Mev level decays mainly to the 0.645-Mev, $p_{\frac{3}{2}}$ level. If β_5 is a once forbidden transition, an assignment of $f_{\frac{5}{2}}$ to the 2.058-Mev level seems to be the most likely possibility. This would make the 1.413-Mev gamma-ray an $M1$ (or $M1+E2$) transition. The fact that the higher energy $E2$ transition to the ground state does not compete detectably with the 1.413-Mev gamma-ray is not in contradiction with the empirical data on $M1$ and $E2$ transition probabilities.[9] There is some possibility that β_5 is an allowed transition, in which case the most logical assignment for

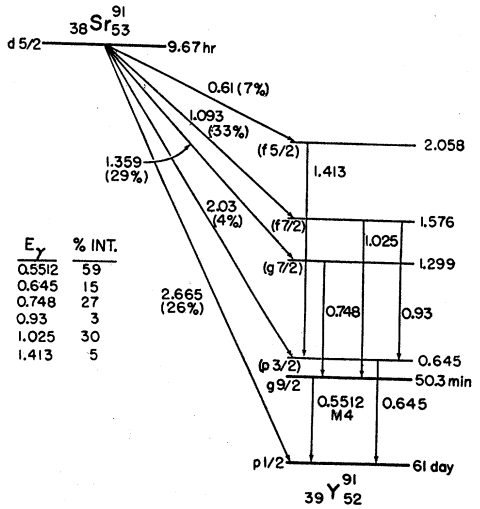

FIG. 9. Proposed disintegration scheme of Sr^{91}.

the 2.058-Mev level would be $d_{\frac{5}{2}}$. This assignment would be as consistent with the gamma-ray data as an $f_{\frac{5}{2}}$ assignment.

The fact that Y^{91m} does not exhibit detectable beta-emission leads to an interesting conclusion regarding the spacing of certain energy levels of Zr^{91}. The first excited state of Zr^{91} would be expected to be a $g_{7/2}$ state, and beta-emission to this level from Y^{91m} would be *allowed*. From the experimental data it is possible to to say that, if Y^{91m} does beta-decay to Zr^{91}, the intensity of the beta-transition must be less than 1.5 percent of that of the isomeric transition. From this fact and the fact that the logft values of allowed transitions have an empirical upper bound of about 6.0, it is possible to calculate an upper limit on the energy of the hypothetical Y^{91m} beta-transition. This value is found to be $\sim$0.75 Mev, which leads to the conclusion that the $g_{7/2}$ excited state of Zr^{91} is more than 1.34 Mev above the ground state. The same lower bound holds for the $g_{9/2}$ excited state. These conclusions are supported by the preliminary data of Shull and McFarland[13] on the Q values of the proton groups from the reaction $Zr^{90}(d,p)Zr^{91}$. The two proton groups they observed were found to have associated Q values of 5.03 and 2.93 Mev, suggesting that the first excited state of Zr^{91} is 2.1 Mev above the ground state.

We wish to extend our thanks to Mr. John W. Starner for his invaluable assistance with the scintillation experiments.

[13] F. B. Shull and C. E. McFarland, Phys. Rev. **87**, 216 (1952).

PHYSICAL REVIEW VOLUME 91, NUMBER 1 JULY 1, 1953

Gallium-64

BERNARD L. COHEN
Oak Ridge National Laboratory, Oak Ridge, Tennessee
(Received March 27, 1953)

A new isotope, 2.5-minute Ga^{64}, was produced by the (p,n) reaction on Zn^{64} and identified by measurement of the excitation function, by bombardment of separated isotopes, and by chemical separation. Its decay scheme includes gammas of 0.97 Mev, 3.8 Mev, and probably 2.2 Mev. The maximum energy of the principle beta is about 5 Mev. The threshold for Zn^{64} (p,n) is 8.1±0.5 Mev.

A PREVIOUSLY unidentified isotope, 2.5-min gallium 64, has been produced by bombarding zinc with high energy protons from the ORNL 86-in. cyclotron. The following tests were made to ascertain its identity.

(1) A rough excitation function for the various activities found from proton bombardment of zinc was measured by a stacked foil technique. The results, shown in Fig. 1, indicate that the 2.5-min activity has all the characteristics of a (p,n) reaction, as can be seen by comparing it with the 68-min (Ga^{68}) and 9.4-hr (Ga^{66}) activities which are known to be produced by (p,n) reactions. The ratio of the cross sections for production of the 2.5-min and 9.4-hr activities in natural zinc was found to be about 2:1 at 13 Mev, which is approximately the isotopic abundance ratio of Zn^{64} to Zn^{66}. After the excitation function was measured, all further investigation was carried out by bombarding under an absorber calculated to reduce the proton energy to 13 Mev.

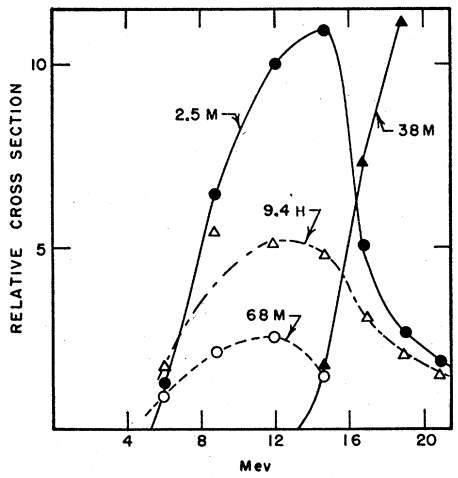

FIG. 1. Excitation functions for activities produced by proton bombardment of zinc. The 9.4-hr, 68-min, and 38-min activities are known to be produced by (p,n) reactions on Zn^{66} and Zn^{68}, and the (p,pn) reaction on Zn^{64}, respectively.

(2) A series of bombardments was made with isotopically enriched Zn^{64}.[1] This essentially eliminated the 68-min and 9.4-hr activities, but yielded very good intensities of the 2.5-min activity. Most of the spectroscopy was done with this isotopically enriched material.

(3) Chemical identification was obtained by ether extraction. The ratio of the 2.5-min to 9.4-hr activities in the ether fraction was found to be about the same as in an unprocessed zinc foil. By counting under a thick absorber to remove the 68-min activity, the decay could be followed above the 9.4-hr background through nine half-lives even after three half-lives had been con-

[1] Separated isotopes were obtained from the Stable Isotopes Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.