Decay of Y^{95}†

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The decay of Y^{95} has been investigated with semiconductor and scintillation spectrometers. The half-life of this isotope was measured to be 10.7±0.2 min. Its total disintegration energy is 4.43±0.02 MeV. The beta decay to the ground state of Zr^{95} (82% of the total decay) is expected to be unique first-forbidden. However, the $\log f_1 t$ value of 7.45 is very low for this type of beta transition. Furthermore, the typical unique-first-forbidden shape has not been confirmed. The other β-ray branches excite a complex system of more than 20 levels in Zr^{95}, with γ-ray energies up to 4 MeV. The lower levels of this scheme agree with those observed by Cohen and Chubinsky with the $Zr^{94}(d,p)$ reaction. Using their spin assignments for the lower levels, it was possible to suggest spins and parities of some higher energy levels from the present work. Appendices are included with some new remarks on the decay of Y^{94}, a source contaminant, and on the decay of Cl^{38}, an isotope used for calibration purposes.

I. INTRODUCTION

UNTIL recently very little was known about the decay of Y^{95}. Studies of neighboring nuclides,[1,2] obtained as uranium-fission products, showed that Y^{95} is an emitter of highly energetic β rays and that it has a half-life of about 11 min, but almost no information was obtained about its beta decay and succeeding gamma radiation.

We investigated the decay with sources produced by the Zr^{96} (γ,p) reaction in the Iowa State University synchrotron. Our first results were obtained with conventional NaI(Tl) and plastic scintillation counters, and have been presented in a preliminary report.[3] These results indicated that the beta decay of Y^{95} is accompanied by a complex γ-ray spectrum, though the main part of the beta decay goes directly to the ground state of Zr^{95}.

In the present paper we describe more extensive experiments with improved detection techniques, more source material, and a larger number of sample activations. These resulted in 40 assignments for γ-ray transitions in Zr^{95} (some of which are tentative).

The natural objective of the present investigation is to obtain the level scheme of Zr^{95} observed from beta decay of Y^{95} and to obtain information on spins and parities of the levels. Cohen and Chubinsky[4] report a level scheme for Zr^{95} from the angular distributions in the (d,p) stripping reaction on Zr^{94}. The lowest levels reported there can be identified with those of the present work. In both investigations a high level density has been observed at higher energies, but above 1.7 MeV most of the individual levels do not correspond uniquely.

Another objective of this investigation is to study the beta decay from Y^{95} to the ground state of Zr^{95}. The shell model and the measured and proposed spins of most other odd-A yttrium isotopes suggest that the ground state of Y^{95} is $2p_{1/2}$. The ground state of Zr^{95} is expected to be $\frac{5}{2}^+$ from systematics of neighboring odd-A nuclides, and this assignment is supported by the results from (d,p) and (d,t) reactions of Ref. 4. The beta decay to the ground state of Zr^{95} is thus expected to be unique first-forbidden. Consequently, measurement of the $\log f_1 t$-value and of the shape of the β-ray spectrum near the end point is of importance. Since we were forced to use rather thick sources of low specific activity, shape measurements were feasible only because of the high energy of the β rays. At energies of more than 3 or 4 MeV, the influence of the finite source thickness was not too disturbing.

All sources were obtained by irradiating metallic zirconium samples with ~200 000 R/min bremsstrahlung from the ISU synchrotron, operating with 70-MeV electrons. The zirconium was obtained from the Oak Ridge National Laboratory (Stable Isotopes Division). It was enriched to 57.36% in Zr^{96} and contained 9.19% Zr^{90}, 2.02% Zr^{91}, 27.20% Zr^{92}, and 4.22% Zr^{94}. In the samples thus obtained the decay of Y^{95} is dominant, with respect to both β- and γ-ray activity, though the sources are not very pure. Several contaminants were easily identified, such as 4.3-min Zr^{89m} and 78-h Zr^{89} from Zr^{90} (γ,n), 50-min Y^{91m} from Zr^{92} (γ,p), and 20-min Y^{94} from Zr^{96} (γ,np). Following the irradiation, the decrease of activity was mainly determined by Y^{95} and 20-min Y^{94}, so that after a short waiting period the same sample could be activated again. After many irradiations, 65-day Zr^{95} and 35-day Nb^{95} accumulated in the sample, but remained minor impurities. Also observed were 10-h Y^{93} from Zr^{94} (γ,p), 2.7-h Sr^{92} from Zr^{96} (γ,α), and probably 3.2-h Y^{90m} from both Zr^{91} (γ,p) and Zr^{92} (γ,np).

During preparation of this manuscript Fiedler and Kennett[5] reported a Ge(Li) γ-ray spectrum of an

† Work was performed in the Ames Laboratory of the U. S. Atomic Energy Commission. Contribution No. 1940.
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[1] J. D. Knight, D. C. Hoffman, B. J. Dropesky, and D. L. Frasco, J. Inorg. Nucl. Chem. **10**, 183 (1959).
[2] K. Fritze, T. J. Kennett, and W. V. Prestwich, Can. J. Chem. **39**, 675 (1961).
[3] R. J. Hanson, J. Van Klinken, D. F. Boneau, and R. G. Clark, Bull. Am. Phys. Soc. **10**, 1117 (1965).
[4] B. L. Cohen and O. V. Chubinsky, Phys. Rev. **131**, 2184 (1963).
[5] H. J. Fiedler and T. J. Kennett, J. Inorg. Nucl. Chem. **28**, 1129 (1966).

$Y^{94}+Y^{95}$ source, obtained from fission products. Their samples contained, in contrast to ours, more Y^{94} than Y^{95}. They proposed 20 γ-ray transitions for Y^{95}, but according to the present data, some of these assignments (1.154, 2.230, and 2.433 MeV) appear to be misinterpretations of double-escape peaks while others (0.394, 1.564, and 1.703 MeV) do not occur in our samples and are probably due to impurities in their source material or to statistical fluctuations.

II. HALF-LIFE MEASUREMENTS

During this investigation several half-life measurements were performed using both γ-rays and parts of the β-ray spectrum. The most accurate results came from the high-energy part of the β-ray spectrum above 2.7 MeV. In that energy region we were left with essentially two components, namely ~11-min Y^{95} and ~20-min Y^{94}. The decay curve shown in Fig. 1 was analyzed by a FRANTIC computer program,[6] which was able to unfold a decay curve with up to four unknown activities and half-lives. As a first approach we treated the data with $t_{1/2}(Y^{94})$ supposedly unknown and found $t_{1/2}(Y^{94})=20.4\pm1.9$ min. This is consistent with the result of 20.35 ± 0.2 min of Fritze *et al.*,[2] but the latter is much more accurate since it was obtained with a source mixture enhanced in Y^{94} with respect to our sample. Using their value for Y^{94}, we obtain for Y^{95} $t_{1/2}=10.7\pm0.2$ min. This is consistent with $t_{1/2}=10.9\pm0.2$ min, the value which has also been reported by Fritze *et al.*[2] The present results are only slightly influenced by source contaminants. Figure 1 shows that these are weak and of much longer half-life. For the data of Fig. 1 the Y^{94} activity was slightly enhanced by irradiating the sample for 20 min, instead of for 10 or 11 min as was usually done for the measurements on Y^{95}.

III. Ge(Li) SPECTRUM OF GAMMA RAYS

The single γ-ray spectrum which showed most detail is shown in Fig. 2 and was obtained with a coaxially drifted 20 cc Ge(Li) detector purchased from Nuclear Diodes, Inc. The detector was operated at a bias of 900 V and had a resolution of 5 keV at 1.33 MeV. The linewidth in Fig. 2 is, however, slightly broader (~6 keV) because of electronic drift during the long accumulation time. This spectrum is the combined result of 18 sample irradiations accumulated in the following way. With our supply of enriched Zr^{96} divided into three samples, each about 80 mg, we performed the sequence: (1) irradiate sample 1 for 11 min, (2) wait about 5 min to allow for decay of 4.3-min Zr^{89m} and any 2.1-min O^{15}, (3) count for 11 min in 2048 channels of a Technical Measurement Corporation (TMC) 4096-channel analyzer, (4) count for a second period of 11 min in the second 2048-channel section of the TMC memory. The same sequence was then followed using sample 2, then sample 3. We added the events of all first 11-min counting periods to the first half of the memory and those of all second periods to the second half of the memory. After the first three irradiations the data were printed and plotted in a nondestruct mode. We then proceeded with the next irradiations of sample 1, then 2, then 3, etc., but usually without plotting and printing the intermediate results. By starting an irradiation during the previous second counting period (to save time), we allowed each sample about 1.5 h to decay. Nevertheless some "building up" of longer-lived activities like 78-h Zr^{89}, 50-min Y^{91m}, 3.5-h Y^{92}, and 2.7-h Sr^{92} could not be prevented, although Fig. 2 shows that their influence is minor and easy to recognize. This figure shows the results of the first counting period for the 18 irradiations. For clarity the results of the second counting period are not shown, but they plainly indicate the various decay times of contaminants. The ratios of the number of counts in a full-energy peak during the second to those during the first counting period were 0.49 for 10.7-min Y^{95} and ~0.18 and ~0.73 for 4.3-min Zr^{89m} and 20.3-min Y^{94}, respectively. Only for some weak lines like those at 0.084, 1.445, 1.798, and 1.814 MeV was there doubt as to whether or not the lines belong to Y^{95} or whether they might be statistical fluctuations.

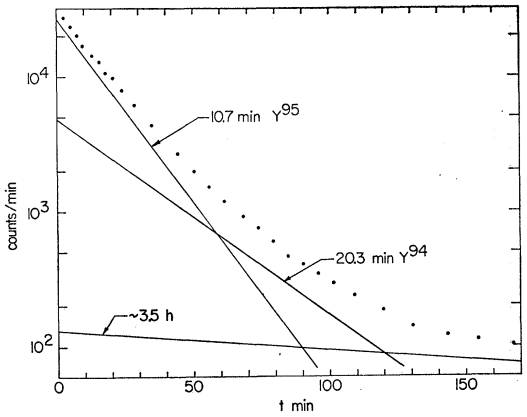

FIG. 1. The decay rate of the sample for β rays with $E\geq2.7$ MeV.

The electronic system consisted of a Tennelec TC 130 f.e.t. preamplifier and a TC 200 low-noise amplifier, which was connected directly to the TMC 4096-channel analyzer.

A Th^{228} source proved to be a useful tool for accurate energy calibration. Its 2.6145 ± 0.0001-MeV transition[7] is very close to both the 2.631-MeV line and the double escape peak of the 3.5756-MeV transition of the Y^{95} decay. Further calibration was obtained from other well-known lines from the Th^{228} source (583.14 ± 0.02

[6] P. C. Rogers, Massachusetts Institute of Technology, U. S. Atomic Energy Commission Report No. 76 (NYO-2303), 1962 (unpublished).

[7] G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. **63**, 353 (1965).

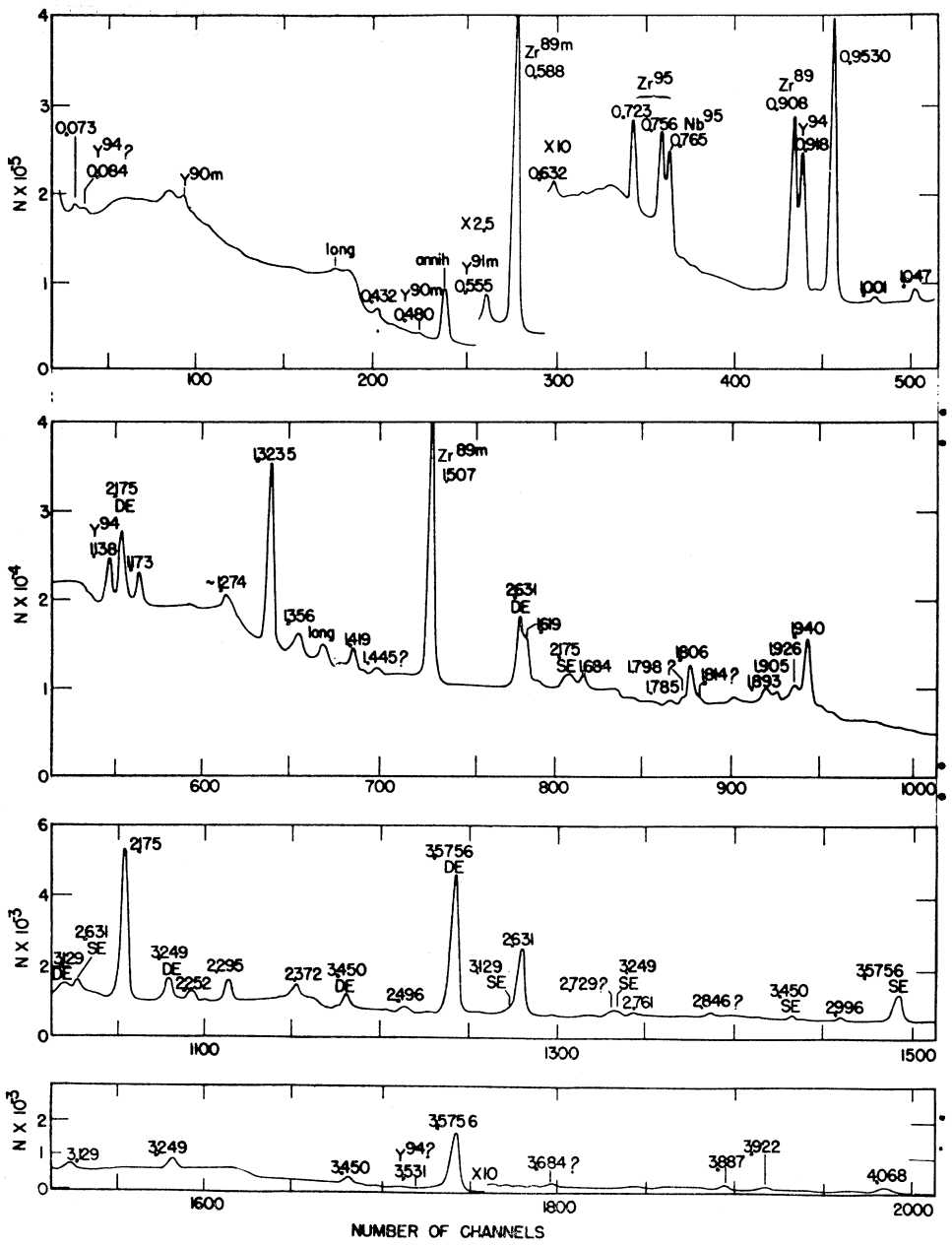

FIG. 2. Ge(Li) spectrum of γ rays accumulated during 18 irradiations. DE = double escape peak of indicated transition, SE = single escape peak of indicated transition. Single numbers indicate the energy in MeV of γ rays from the decay of Y^{95}. Transitions of source contaminants are indicated. Some weaker lines are hardly visible (or not at all, like the tentative 3.531-MeV line for Y^{94}), but were assigned from expanded plots.

and 238.62±0.02 keV) and from the annihilation radiation which was present in the samples themselves. Above 3 MeV we used the 3.5756-MeV line of Y^{95} (and its single escape peak) after establishing its energy by comparison of its double escape peak with the 2.6145-MeV line in the Th^{228} source. The channel number to energy conversion of the system was not quite linear, especially at energies below 0.511 MeV. There the correction for nonlinearity (also based on calibration with Th^{228}) added somewhat to the uncertainty in the quoted energy determination. We also measured the γ-ray spectrum with a smaller 1.5-cc Ge(Li) detector connected to another electronic system used for investigation[8] of the decay of Cu^{69}. This system showed no noticeable deviation from linearity, but the detector was of course less efficient. It did not show the weaker lines but gave energy values for the stronger transitions which were consistent with those of Table I.

The relative intrinsic full energy peak efficiency for the 20-cc Ge(Li) detector was measured by observing its response to Eu^{152} and Th^{228} sources and using their known relative γ-ray intensities. The accuracy of the

[8] J. Van Klinken, A. J. Bureau, G. W. Eakins, and R. J. Hanson, Phys. Rev. 150, 886 (1966).

TABLE I. Gamma rays. The energies and intensities were obtained mainly from an analysis of the spectrum given in Fig. 2. The remarks refer to various parts of the following text, especially to Sec. IV.

Energy (MeV)	Error (keV)	Intensity	Remarks
Used for decay scheme of Fig. 8:			
0.432	2	~8	+1.940≈2.372
0.632	2	~3	+1.619≈2.252
0.953	1	100	level, fed by (1.419), 2.175, 2.295, (2.496), 2.631, and 2.761
1.047	1	5	coincident with 1.323
1.173	1	4	coincident with high-energy betas → level?
1.323	1	26	level, fed by 1.047, 1.806, and 1.926
1.419	1	4	+0.953≈2.372
1.619	3	7	no clear coincidences (hints in 0.630 region)
1.684	2	1.5	+1.893≈3.576
1.785	4	1	+1.798 } ≈3.584
1.798	4	1	+1.785 }
1.806	2	8	coincident with 1.323
1.893	3	3	+1.684≈3.576
1.926	4	5	coincident with 1.323
1.940	1	14	β-γ and intensity → level, +0.432≈2.372
2.175	1	41	coincident with 0.953
2.252	2	3	1.619+0.632
2.295	2	6	coincident with 0.953
2.372	4	5	0.953+1.419, 1.323+1.047
2.496	2	3	+0.953≈3.450
2.631	1	22	coincident with 0.953 → 3.584
2.729	5	~1	tentative level
2.761	5	~1	coincident with 0.953 → 3.714
2.846	5	~1	level, since not coincident with 0.953
2.996	3	1	level, since not coincident with 0.953
3.129	1	3	level, 2.175+0.953
3.249	1	4	level, 2.295+0.953, 1.926+1.323
3.450	1	2	level, 2.496+0.953
3.576	1	22	level, 1.684+1.893
3.684	3	0.1	level
3.887	3	0.1	level
3.922	5	0.1	level
4.068	3	0.15	level
Not placed in decay scheme of Fig. 8:			
0.073	2	~1	
1.001	2	2	+2.252≈3.249?
1.274	5	3	+1.356 } ≈2.631 and level at 2.227 or at 2.309
1.356	3	4	+1.274 }
1.445	5	1	tentative
1.814	5	~2	+0.953 → new level 2.767?
1.905	4	~2	level?

relative intensity values in Table I is about 20% or somewhat better in favorable cases.

Of the many γ-ray transitions, some pairs add together within error limits to another listed value, which strongly indicates that they might be cascade transitions with a crossover γ ray. Many of these possible cascades are indicated in Table I, especially if they are confirmed by evidence from coincidence measurements.

IV. COINCIDENCE MEASUREMENTS

Measurements of β-γ and γ-γ coincidences were facilitated by the use of a TMC 16 384-channel analyzer in its multiparameter mode. We used this instrument several times to take eight coincidence spectra simultaneously. For the γ-γ coincidence spectra of Fig. 3 the 20 cc Ge(Li) detector and a 3 in.×3 in. NaI(Tl) detector were connected with a conventional fast-coincidence circuit (Sturrup modular equipment: 1401 and 1301 fast-slow coincidence base unit) which gated both the pulses coming from the NaI(Tl) detector going via a Sturrup 101 amplifier to an analog-to-digital converter, ADC (A), and the pulses coming from the Ge(Li) detector and going via a TC-200 amplifier to an ADC (B). Both ADC's were TMC model 217A. The ADC (B) was set for 1024 channel conversion, and its digital output went to a TMC model 245 spectrum sorter. With this sorter we selected the eight energy regions ("bands") of the Ge(Li) spectrum for gating of eight coincident NaI(Tl) spectra. These NaI(Tl) spectra were stored in eight 256-channel sections of the TMC memory during the initial counting period of 11 min.

Usually we took two bands for studying coincidences with one line in the Ge(Li) spectrum: one band set on the line itself, and the other immediately above to measure the background due to the Compton continuum beneath the line of interest. In Fig. 3, this second spectrum has been subtracted from the first one. The re-

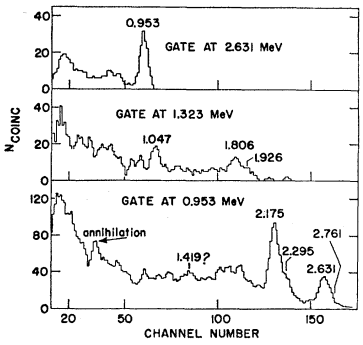

FIG. 3. Gamma-gamma coincidences, gated by Ge(Li) and observed with NaI-(Tl). The background from the Compton continuum has been subtracted.

sulting spectra were checked for their decay rates by storing, in another set of eight 256-channel sections, the NaI coincidence spectra for a second counting period immediately following the first one.

The γ-γ measurements showed for the following gate settings:

At 0.953 MeV: Coincidences at 2.175 and 2.295 MeV, which are suggested in Table I by the energy combinations $0.953+2.175\approx3.129$ and $0.953+2.295\approx3.249$. Furthermore, coincidences at 2.631 and probably at 2.761 MeV without observed crossover transitions.

At 1.323 MeV: Coincidences at 1.047, 1.806, and 1.926 MeV, which are also suggested in Table I by energy combinations.

At 2.631 MeV: Coincidences at 0.953 MeV, confirming the coincidences found with the gate setting at 0.953 MeV.

The coincidence spectra referred to above are shown in Fig. 3. Not shown are:

At 1.609 MeV, that is, double-escape peak of 2.631 MeV: The same coincidences at 0.953 MeV as found with the 2.631-MeV gate, plus here, of course, coincidences with annihilation quanta.

At 1.619 MeV: No clear coincidences, except perhaps in the region around 0.63 MeV.

At 2.175 MeV: Coincidences with only 0.953 MeV.

With these data, the major part of the decay scheme can be constructed. Taking into account the intensities quoted in Table I and the fact that the total decay energy E_0 is ~4.5 MeV (see Sec. V), we conclude the existence of levels at 0.953, 1.323, 1.619, 2.372, 3.129, 3.249, 3.584, and 3.714 MeV.

For some other lines the energy combination principle gives suggestions as listed in Table I. The absence of intense transitions below 0.953 MeV indicates that the 0.953-MeV level is probably the first excited state of Zr^{95}. Since none of the transitions above 2.761 MeV are observed to be in coincidence with the transitions of 0.953 or 1.323 MeV, it can be assumed ($E_0\cong4.43$ MeV) that they depopulate corresponding levels to the ground state of Zr^{95}.

The level scheme received further support and some more detail from β-γ coincidence measurements employing a plastic scintillator and a NaI(Tl) spectrometer. These measurements confirmed that the rather intense line at 1.940 MeV represents a level and suggested the same for the line at 1.173 MeV.

The information is summarized in the level scheme for Zr^{95} to be shown in Fig. 8.

V. ADDITIONAL OBSERVATIONS WITH NaI(Tl)-SPECTROMETERS

The poorer resolution of NaI(Tl) spectrometers prevented these crystals from adding any direct information about single γ-ray transitions. Because of their higher efficiency, however, they can give useful information if two coincident γ rays are detected at the same time and give rise to a sum peak in the γ-ray spectrum. [This summing effect was negligible for the Ge(Li) detector.] We placed our samples at various distances from a normal 3 in.×3 in. NaI(Tl) crystal and inside a 3 in.×3 in. well type NaI(Tl) crystal, both detectors having a resolution of about 8% at 0.662 MeV. Results from the well-type crystal confirm that the 2.175-MeV transition must be in coincidence with the 0.953-MeV transition ($0.953+2.175\approx3.129$), since the 3.129-MeV peak is enhanced and the 2.175 is strongly reduced. Little evidence was found for summing to any energy above 3.584 MeV, which indicates that the higher energy transitions (Fig. 2, Table I) go for the most part directly to the ground state.

In another experiment the source was brought inside the well-type crystal without an absorber for β rays. Since the walls of the well were thin (less than 30 mg/cm² Al), this yielded for the total disintegration energy 4.5 ± 0.1 MeV, but we will see (Sec. VII) that β-ray measurements with a plastic scintillator yield a more accurate value.

VI. FRACTION OF DIRECT BETA DECAY TO THE GROUND STATE OF Zr^{95}

A calibrated plastic scintillation spectrometer yielded for the β rays emitted by a thin activated sample a spectrum of which the main branch has an end point at 4.43 MeV (see Sec. VII). This main branch has a half-life of 10.7 min and obviously belongs to the decay of Y^{95}. Qualitatively, this spectrum shows that this beta branch must constitute a large fraction of the total beta decay.

However, it was not possible to measure quantitatively the intensities of Y^{95} β-ray branches with lower energies as various source contaminants contributed to the total spectrum below 1 MeV.

Therefore an independent measurement of the fraction of beta decay to the ground state of Zr^{95} was performed. A relatively thin source S (of ~30 mg/cm² Zr metal) was placed inside a plastic well-type scintillator as shown in Fig. 4. In this 4π-detector, nearly every

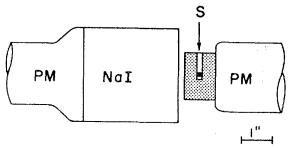

FIG. 4. Arrangement for measuring $N_{0.953}/N_{\text{tot}}$.

disintegration of Y^{95} gives rise to a pulse in the integrated spectrum. By following the decreasing decay rate of the spectrum integrated above ~50 keV, it was possible to analyze the decay curve into its main components (Fig. 1) and to isolate the dominant counting rate due to Y^{95}. This yields the total number of Y^{95} disintegrations $[N_{\text{tot}}(t)]$ per unit time at time t. With the NaI(Tl) spectrometer the number of counts in the pronounced peak around 0.95 MeV (N_F) was observed. From this follows the absolute number of γ-ray quanta of 0.953 MeV emitted during an equal unit of time at the same time t:

$$N_{0.953}(t)=\frac{N_F A}{\epsilon p}\frac{I(0.953)}{I(0.953)+I(0.908)+I(0.918)}, \quad (1)$$

where ϵ is the total absolute NaI(Tl) efficiency, p the peak to total ratio for the given geometry and energy,[9] and A a small correction for absorption of the γ rays in the plastic and light shields between the source and the NaI(Tl) crystal. The quantities $I(0.953)$, $I(0.918)$, and $I(0.908)$ are the relative intensities of the three[10] unresolved γ-ray transitions of Y^{95}, Y^{94}, and Zr^{89}. They were calculated from the Ge(Li) spectrum and were at $t=10$ min: 100, 47, and 15, respectively.

We found $N_{0.953}/N_{\text{tot}}=0.09\pm0.02$. Using the decay scheme derived so far, we obtain for the amount of beta decay to the ground state of Zr^{95}: $(82\pm5)\%$.

VII. BETA-RAY MEASUREMENTS

As mentioned in the Introduction, the intense β-ray branch to the ground state of Zr^{95} might well be a unique-first-forbidden transition. Since it is known that a unique-first-forbidden transition has typically a β-ray spectrum with enhanced intensity at higher energy, a shape measurement is very desirable. For such a measurement we took into account the following considerations which were characterized in the present decay and its investigation by: (1) high end-point energy, (2) low specific activity ($\lesssim 10^{-8}$ Ci/mg, which forced a compromise between source strength and source thickness), (3) short half-life, and (4) the existence of Y^{94} as a contaminant in the sample with only slightly higher end-point energy. For this situation a plastic scintillator was a suitable spectrometer. We designed an arrangement as shown in Fig. 5 and accumulated the spectrum using a 400-channel analyzer from Radiation Instrument Development Laboratory (RIDL). The thickness of the scintillator was matched with the range of about 5-MeV electrons. Its surface was made concave so that the β-ray particles will enter perpendicular to the surface when a sample is placed close to the detector. The resolution was 15% at 0.975 MeV. The γ-ray background was observed roughly by inserting a 4-mm thick brass plate between the source and the detector.

Several corrections, like those for backscattering events, bremsstrahlung escape, possible nonlinearity of the electronic system, source thickness, pile-up effects, etc., can be avoided if comparative measurements under the same conditions can be done with a well-known calibration source. Such a source could be Cl^{38}, for which Langer[11] proposed a unique-first-forbidden shape. However, the present knowledge about this decay is not without contradictions, as will be discussed in Appendix B. At present we assume:

$$E_0(Cl^{38})=4.915\pm0.008 \text{ MeV}, \quad (2)$$

but we will leave it an open question whether or not Cl^{38} has a unique-first-forbidden β-ray branch.

Comparative results for Y^{95} and Cl^{38} are given in Fig. 6. Shown first is a directly observed spectrum of Y^{95} (plus contaminants) which was analyzed into its components by an extensive program of following the half-lives for different sections of the spectrum. These sections are indicated by the horizontal bars through the measured values of the percentage of Y^{94}. The half-lives and strengths of the various source components were again obtained from the FRANTIC program.[6] Fortunately, at higher energies (above 2.7 MeV) only Y^{95} and Y^{94} contribute. The percentage of Y^{94} increases with higher energy because it has a somewhat higher end point energy. With decreasing energy there is an increasing number of other activities, which made analysis below ~1 MeV rather uncertain. Above 2.7 MeV, however, the analysis of Y^{95} and Y^{94} activity strength was accurate to within a few percent, and allowed accurate calculation of both Kurie plots.

Cl^{38} sources were obtained from neutron activation of NH_4Cl and were relatively thin (≈ 5 mg/cm^2). One such source gave the Kurie plot *b*. Plot *a* was obtained with a similar thin Cl^{38} source between two Zr foils of

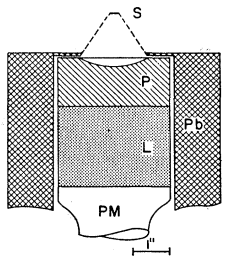

FIG. 5. Plastic scintillator for high-energy β rays. P: plastic scintillator, L: light pipe, PM: photomultiplier, Pb: lead shield.

[9] R. L. Heath, U. S. Atomic Energy Commission Report No. IDO-16880-1, 1964 (unpublished).

[10] Actually a fourth peak due to ~10-h Y^{93} was observable at 0.934 MeV, but its relative intensity (as seen in Fig. 2) was too small to be of any significance in (1).

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

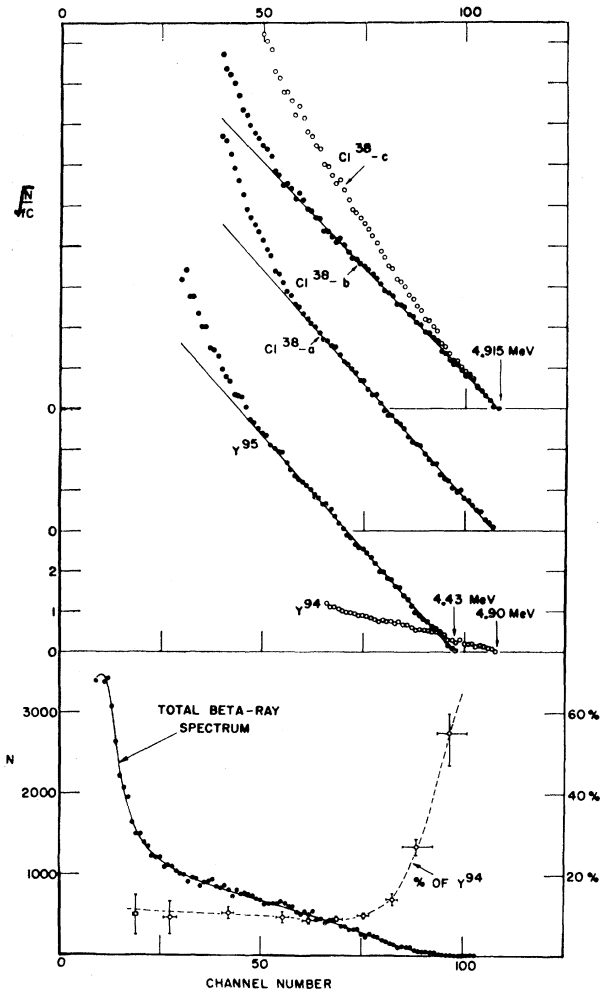

FIG. 6. Results of β-ray measurements. Bottom: (●) total spectrum at 20 min after an irradiation of 10 min, (○) percentage of Y^{94} at 8 min after an irradiation of 10 min. Top: various Kurie plots. Those for Y^{95}, Y^{94}, $Cl^{38}-a$, and $Cl^{38}-b$ are for a shape factor $C=1$, that for $Cl^{38}-c$ is for $C=(W^2-1)+(W_0-W)^2$. The plot $Cl^{38}-a$ is for a source of ~48 mg/cm², those for $Cl^{38}-b$ and $Cl^{38}-c$ are both ≈5 mg/cm².

~22 mg/cm² each. Thus the Cl^{38} source for plot *a* was slightly thicker than the Y^{95} ($+Y^{94}$) sample, which was 30 mg/cm². Care was taken that all three sources [Cl^{38} *a*, Cl^{38} *b*, and Y^{95} ($+Y^{94}$)] were of about equal strength, so that any small pile-up effect for the scintillator pulses was equal for all three cases. The Kurie plots have been corrected for the influence of the finite resolution of the detector. Without this correction the plots would show "tails" above the end point.[12]

In the decay of both Cl^{38} and Y^{95}, the possibility exists that a β-ray particle from a lower-energy branch and a Compton event from a coincident γ ray together give a spurious contribution at higher energy. However, this possibility is small above 3 MeV because the second highest β-ray branch is weak. With a brass absorber for β rays between source and plastic, we noticed that the response of the scintillator to γ rays is minor and occurs predominantly at lower energies.

Cl^{38} ends its second beta branch at 2.75 MeV, and Y^{95} has a branch ending at 3.48 MeV as follows from the constructed decay scheme, but it is very weak and is almost unobservable in the Kurie plot for Y^{95}. However, in order to avoid any doubt concerning possible interference of a beta branch going to the 0.953-MeV level, it might be better to make conclusions about the shape mainly from the part of the spectrum above 3 or 3.5 MeV.

The curves shown in Fig. 6 without any shape correction factor ($C=1$) are essentially straight for the upper parts of the spectra. In order to show the influence of possible unique forbiddenness we applied the shape correction factor for unique-first-forbidden beta decay on the data used for curve Cl^{38}-*b* and obtained the curve Cl^{38}-*c*. This factor is

$$C(W)=(W^2-1)+(W_0-W)^2. \tag{3}$$

It is clear that this procedure produces a nonlinearity which should be easily detectable with our spectrometer. Thus these plots strongly suggest a nonunique shape. However, for an *absolute* conclusion that the highest-energy β-ray branches of Y^{95} as well as of Cl^{38} are nonunique, we need more exact information concerning corrections mentioned previously in this section.

The present shape measurements were not undertaken to make *absolute* determinations. Primarily they were directed at Y^{95} *relative* to Cl^{38}. With only relative interpretation of the Kurie plots, we can be much more conclusive. In that case, the spurious effects are of negligible influence since the source conditions for Y^{95} and Cl^{38} were very similar. The relative measurement shows that *the high-energy β-ray branch of* Y^{95} *has essentially the same Kurie plot as the similar branch of* Cl^{38} and hence, these β-ray branches are either *both* unique or *both* nonunique.

Least-squares fits of the Kurie plots yield

$$E_0(Y^{95})/E_0(Cl^{38})=0.902\pm0.005, \tag{4}$$

which gives with (2)

$$E_0(Y^{95})=4.43\pm0.02 \text{ MeV}. \tag{5}$$

VIII. X-RAY AND CONVERSION ELECTRON MEASUREMENTS

Since most γ-ray transitions are of high energy (≥ 1 MeV), and since $Z=40$ is not a high atomic number, appreciable internal conversion is not expected, even if some γ-ray transitions were of higher multipolarity. While conversion x rays would be characteristic of Zr ($Z=40$), it is of interest to search for Y ($Z=39$) x rays as an indication of an isomeric state in Y^{95} or some other yttrium isotope.

X rays and low-energy γ rays were sought with a Reuter-Stokes (RSG-30A) proportional counter (which

[12] J. G. Cramer, Jr., B. J. Farmer, and C. M. Class, Nucl. Instr. Methods **16**, 289 (1962).

could distinguish yttrium from zirconium x rays) and a $\frac{1}{8}$-in.-thick NaI(Tl) crystal (with poor resolution but calculable efficiency). Zr^{96}-enriched sources of 25 mg/cm^2 were used behind a beta absorber of 1 g/cm^2 Be.

We saw no obvious yttrium x rays of half-life $\gtrsim 45$ sec, implying that no highly converted isomeric state of such a half-life is created (with reasonable strength) in Y^{94} or Y^{95}. Zirconium x rays were seen with an intensity roughly $\frac{1}{4}$ that of the 0.953-MeV transition (calculated as shown in Sec. VI) and a half-life in the 10–20-min region, though a considerable short-lived component was also present. A Cl^{38} source placed behind Zr foil was used to estimate the amount of Zr x rays excited by β rays. About half of the Zr x rays observed can be accounted for in this manner from the Y^{95} β rays alone. The various source impurities probably produced the rest so that it is difficult to estimate what part if any of the x rays could be due to internal conversion in the decay of Y^{95}. A 5-mm thick Si(Li) detector (operating at liquid-nitrogen temperature with 6-keV resolution at 0.975 MeV) was used to observe the β-ray spectrum between 0 and 2 MeV, and no clear evidence for conversion lines was found.

IX. DISCUSSION

For the ground state of Y^{95} the most obvious spin and parity assignment is $\frac{1}{2}^-$, with the odd proton in the $2p_{1/2}$ shell. The ground state of Zr^{95} should be $\frac{5}{2}^+$ as derived from the (d,p) and (d,t) reaction data of Cohen and Chubinsky[4] and as suggested by systematics of neighboring isotones. These assignments imply, as mentioned before, that the beta transition to the ground state of Zr^{95} is unique first-forbidden. However, the data do not confirm this unambiguously.

Let us first assume that this decay is indeed unique first-forbidden. In that case our observed logft value for Y^{95} of 6.82 is *very* low, as can be seen from the systematics given in a table in Ref. 13 and from a paper of Davidson.[14] The conventional logf_0t values (the index 0 for nonunique decay) for this category of transitions scatter from ~ 7 to ~ 10. The spread can be reduced by taking instead of f_0, the value

$$f_1 = f_0\{a(Z)(W_0^2-1)+b(Z)(W_0-1)\}, \qquad (6)$$

where $a(Z)$ and $b(Z)$ are defined and calculated in Ref. 14. The values of logf_1t scatter in a more narrow range from ~ 7.9 to 9.1, as is shown in the histograms of the known unique-first-forbidden transitions of odd-A nuclei (Fig. 7). It is quite obvious that the decay branch of Y^{95} to the ground state of Zr^{95} is anomalous, since it has log$f_1t = 7.45 \pm 0.05$.

Now let us assume that this decay branch is nonunique. Then decay of Cl^{38} is also nonunique (Sec. VII). This conclusion might be improbable, but cannot be considered impossible (see Appendix B). A nonunique decay would occur if the ground state of Y^{95} were not $\frac{1}{2}^-$, but $\frac{5}{2}^-$. The assignment $\frac{9}{2}^+$ seems impossible here since in that case the decay would be second-forbidden. We wonder whether $\frac{5}{2}^-$ can be the correct assignment, due to a lowering of the $p_{1/2}$ proton level in Y^{95} (caused by the large neutron excess) and perhaps to a small positive deformation of this nucleus. In case of a $\frac{5}{2}^-$ assignment, the relatively small beta branching to the 1.323- and 0.953-MeV levels is reasonable. The measured total decay energy of 4.43 ± 0.02 MeV does not agree with two values predicted by Everling,[15] one for the case that the ground state of Y^{95} is $\frac{9}{2}^+$ (3.60 MeV) and the other for the case that it is $\frac{1}{2}^-$ ($\sim$4.95 MeV). The measured value (4.43 MeV) lies in between those two predictions, which might be a suggestion for a $\frac{5}{2}^-$ assignment.

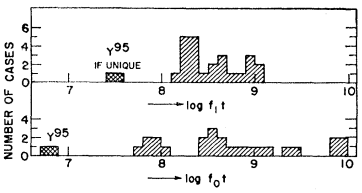

FIG. 7. Histograms of known values of logf_0t and logf_1t for unique first forbidden beta decay of odd-A nuclei.

At the present we can only say that further experimental or theoretical explorations are needed for definite conclusions about the two assumptions. Of special value would be a reinvestigation of the spectrum of Cl^{38} on whose exact shape our conclusions are so crucially dependent.

The logft values for other β-ray branches to the identified levels in Zr^{95} can be calculated from the constructed level scheme, using the measured intensities of the γ rays plus the intensity of the beta branch to the ground state of Zr^{95}. The logft values thus obtained are added to the decay scheme in Fig. 8. Some of them, such as those for the branches going to the 1.323- and the 0.953-MeV levels, are rather uncertain because these levels are fed by many γ-ray transitions, each with an uncertainty in its intensity. Possibly, allowed beta decay goes only to the close-lying levels at 3.576 and 3.584 MeV. These levels might be negative-parity states. Our measurements make the two tentative $(\frac{3}{2}^-)$ assignments of Cohen and Chubinsky[4] for the states at 2.29 and 2.48 MeV unlikely, since these levels are not favored by allowed beta decay.

The present information established the major part of the decay scheme for Y^{95}, as presented in Fig. 8.[15a] The weak lines at 0.073, 1.001, 1.274, 1.356, 1.445,

[13] K. Siegbahn, *Alpha-, Beta- and Gamma-Ray Spectroscopy* (North-Holland Publishing Company, Amsterdam, 1965), Vol. 2, p. 1378.

[14] J. P. Davidson, Jr., Phys. Rev. **82**, 48 (1951).

[15] F. Everling, Nucl. Phys. **36**, 228 (1962).

[15a] *Note added in proof*. After submission of this paper, a paper on Y^{95} was published by R. E. Larson and C. M. Gordon, Nucl. Phys. **88**, 481 (1966). They showed a complex gamma-ray spectrum obtained using NaI(Tl) scintillation detectors, and with the aid of gamma-gamma coincidence data and a beta scintillator a decay scheme was obtained in basically good agreement with the present decay scheme but lacking the detail which could be obtained with the good resolution of our Ge(Li) detectors. They report a ground-state beta branch of 40% which is in sharp contrast with our reported value of $(82 \pm 5)\%$.

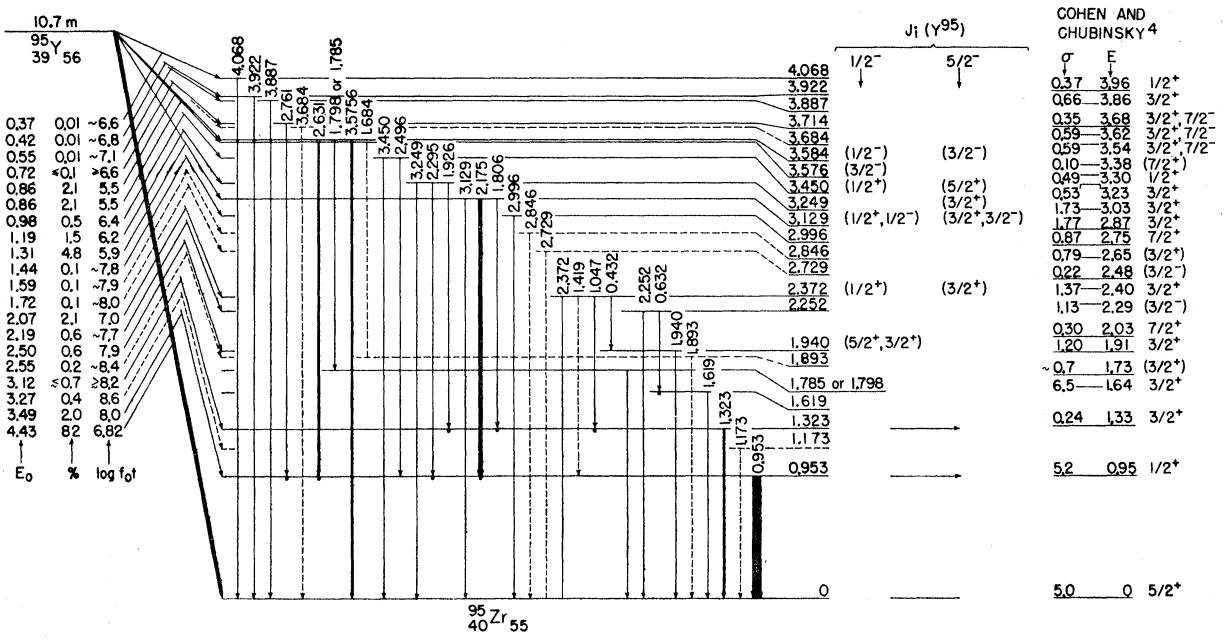

FIG. 8. The decay scheme of Y^{95}. The level structure is compared with the results of Cohen and Chubinsky (Ref. 4). Observed coincidences are indicated by a dotted arrowhead. Energies are given in MeV.

1.814, and 1.905 MeV are not included but indicate the existence of still more levels. If the spin assignments of Cohen and Chubinsky[4] for the lower levels in the scheme are adopted, then it is of interest to look at the branching ratios of transitions from higher levels going to two or more of these lower levels. As a combined result of (1) the selection rules for the feeding of a level by allowed or forbidden beta decay, and (2) the Weisskopf estimates, some spin and parity assignments can be suggested. They are shown in Fig. 8 for two assumptions: that the spin of Y^{95} is $\frac{1}{2}^-$, and that it is $\frac{5}{2}^-$.

ACKNOWLEDGMENTS

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APPENDIX A: SOME REMARKS ON THE DECAY OF Y^{94}

There have been several investigations which include Y^{94} as a fission product.[1,2,5,9] During the present experiments it was produced as a by-product of Y^{95} from the reaction $Zr^{96}(\gamma,np)$. Its relative strength in the integral β-ray spectrum (see Sec. VI) has been calculated with the FRANTIC program[6] and was usually about one-tenth of the strength of Y^{95}. Knight *et al.*[1] quote for the β-ray end point energy: $E_0=5.0\pm0.2$ MeV. We measure (see Fig. 6) $E_0=4.90\pm0.08$ MeV, using the end-point energy value 4.915 ± 0.008 MeV for Cl^{38}. Knight *et al.*[1] estimate that about half of the decay of Y^{94} goes directly to the ground state of Zr^{94}. We obtain no accurately measured value either, but find for the ratio $N_{0.918}/N_{\text{tot}}$ the value 0.7. From this the intensity of the beta branch to the ground state of Y^{94} (using the decay scheme of Ref. 1) is found to be $(30\pm10)\%$.

The Ge(Li) detector yielded more precise energy values for some of the γ-ray transitions: 0.918 ± 0.002 (100), 1.138 ± 0.002(12), and 3.531 ± 0.005 ($\sim$0.6) MeV, with relative intensities in parentheses. The rather weak transition at 3.531 MeV is assigned tentatively though its existence is denied in Ref. 5. However, its intensity is less than found in Refs. 1 and 9. It is possible that there was in these investigations some interference from Y^{95}, which is also produced as a fission product.

A coincidence spectrum gated by Ge(Li) pulses of the 0.918-MeV line showed peaks at $\sim$0.38, 0.55, 0.75, and 1.135 MeV. This supports the decay scheme proposed on the basis of energy fits by Fiedler and Kennett.[5]

APPENDIX B: SOME REMARKS ON Cl^{38}

We referred to the decay of Cl^{38} for both the shape measurements of the β-ray spectrum and for the deter-

mination of the beta end-point energy of Y^{95}. Unfortunately the data on Cl^{38} contain contradictions and unfortunately we have no other well investigated β-ray emitter with $E_0 \approx 4.5$ MeV at our disposal.

To our knowledge the best available investigation dates from 1950 and is that of Langer.[11] Still earlier reports are those of Hole and Siegbahn[16] and Watase and Itoh.[17] These three investigations yielded for the directly observed beta end-point energy: 4.81 ± 0.05,[11] 5.2 (no error quotation)[16] and 4.99 ± 0.06 [17] MeV, respectively. Langer concluded from his data that the highest energy group of Cl^{38} is of the unique-first-forbidden type, which means that the conventional Kurie plot curves towards the energy axis near the end point. This could explain his lower E_0 value, since the other investigators made a straight line extrapolation for their Kurie plots. A precise γ-ray energy measurement provides, however, an easy check on this discrepancy. This is because Langer obtained a five times more accurate end point value of 1.11 ± 0.01 MeV for the lowest energy beta group of Cl^{38}. For the two γ rays we measured with the Ge(Li) detector: 1.643 ± 0.001 and 2.168 ± 0.001 MeV (relative intensities 84 ± 5 and 100, respectively). Adding these values to 1.11, we obtain for the end point of the highest energy β-ray group 4.92 ± 0.01 MeV. A confirming value of 4.915 ± 0.008 MeV has been obtained independently from mass differences of stable nuclei as quoted by Mattauch *et al.*[18] This more accurate value should replace the old value of 4.81 MeV, but removes one of the sustaining arguments of Ref. 11 for a unique-first-forbidden shape. Taken together with our suggestion of a straight Kurie plot (Sec. 6), we conclude that a reinvestigation of the shape of Cl^{38} with a modern magnetic spectrometer is desirable.

A unique shape for Cl^{38} is in accordance with the expectations from shell model and systematics, however, since the ground state of Ar^{38} (the daughter nucleus) is 0^+ and the first Nordheim rule predicts 2^- for the ground state of Cl^{38}.

The energy and intensity determination of the two gamma transitions can be compared with results given in a recent paper by Robinson,[19] who quotes 1.598 ± 0.005, (85 ± 3) and 2.166 ± 0.005 MeV (100), respectively. The highest energy values of Ref. 19 and of the present work agree within limits of error, as do the relative intensities. But unfortunately, one of the values for the lower energy transition cannot be right. The present values were obtained after calibration of the Ge(Li) detector with the Pb^{208} line at 2.6145 ± 0.0001 MeV, and its single-escape (SE) and double-escape (DE) peak. We believe that the present value is correct (1) because the disputed line lies only 15 keV below the SE line of the undisputed transition of 2.168 MeV, (2) because the DE line of the disputed transition has been observed at 0.621 MeV, which is fairly close to the easily recognized annihilation line, and (3) the end-point energy for the ground-state beta decay derived from the present measurements agrees well with the previously mentioned mass-spectroscopic value.

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[17] Y. Watase and J. Itoh, Proc. Phys. Math. Soc. Japan **21**, 626 (1939).
[18] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 1 (1965).
[19] B. L. Robinson, Phys. Rev. **140**, B1529 (1965).