Coester and J. M. Jauch[6] and fully equivalent to those given by various authors, especially by Racah.[7]

The author is greatly indebted to G. Racah for a long series of discussions.

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Nuclear Levels Associated with Zirconium 95 and Niobium 95†

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Using sources of zirconium 95, both as a fission product and as derived from neutron capture in enriched Zr^{94}, in magnetic spectrometers, a study has been made of the beta- and gamma-energies and of the half-lives associated with the radioactive decay. Zirconium 95 emits three beta-rays of energy about 910, 405, and 360 kev, each followed by a gamma-transition leading to a radioactive daughter product, niobium 95. The gamma-energies are 758, 725, and 235.2 kev. The niobium 95 decays by beta-emission, of energy 165 kev, to molybdenum 95 with accompanying gamma-energies of 753 and 768 kev. The observed transitions are found to fit a level scheme that is not incompatible with shell theory.

A LONG-LIVED radioactivity in zirconium, obtained as a fission product from uranium, was first observed[1] in 1940 by Grosse and Booth. Contemporary studies determined[2] the half-life of the activity to be 63 days and associated it with the isotope of mass 93. Subsequent investigations have shown that the activity is more likely in zirconium 95, which decays to radioactive daughter products in niobium 95. Many measurements have been made of the beta- and gamma-energies in the decay processes, with a rather wide divergence in the expressed values, as shown in Table I.

Table I. Previous data relative to Zr^{95} and Nb^{95}.

Item	Half-life	PE[a]	RW[b]	MSK[c]	HL[d]	N[e]	F[f]	Z[g]
		Energy in Mev						
Zr^{95} β_1	65 days	0.80			0.887	1.00		
β_2		0.29			0.400	0.39		
γ_1		0.85		0.91		0.92		
γ_2					0.708	0.73		0.73
Nb^{95} γ_3	90 hr				0.216	0.23		
Nb^{95} β_1	35 days	0.14		0.14	0.146	0.15	0.163	
γ_1		0.78	0.75	0.92	0.758	0.77	0.771	0.76

[a] M. Pool and J. Edwards, Phys. Rev. 67, 60 (1945).
[b] W. Rall and R. Wilkinson, Phys. Rev. 71, 321 (1947).
[c] Mandeville, Scherb, and Keighton, Phys. Rev. 74, 888 (1948).
[d] J. Hugdens and W. Lyon, Phys. Rev. 75, 206 (1949); *Radiochemical Studies: The Fission Products* (McGraw-Hill Book Company, Inc., New York, 1950), Paper No. 90.
[e] V. Nedzel, National Nuclear Energy Series, Plutonium Project Record, Vol. 9, Div. IV and earlier papers in Plutonium Project Reports.
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In the present investigation specimens of Zr^{95} have been obtained both as a fission product and as produced in the pile by neutron capture in enriched (92 percent) zirconium 94. The gamma-energies have been determined from electron lines derived from internal conversion and from photoemission in lead radiators. Photographic magnetic spectrometers of high resolution have been employed and it is believed that the reported results are accurate to plus or minus 0.2 percent. The decay of Zr^{95} has been followed for more than a year and its half-life appears to be 65.2±1 days. A metastable state of niobium 95 with a half-life of 90

Table II. Electron energies associated with Zr^{95} and Nb^{95}.

Electron energy, kev	Interpretation	Energy sum, kev
216.1	K (41)	235.1
232.6	L (41)	235.3
235.0	M (41)	235.5
706.3	K (41)	725.3
722.7	L (41)	725.4
733.0	K (42)	753.0
739.6	K (41)	758.6
748.6	K (42)	768.6
765.8	L (42)	768.7
678	K (Pb)	766

Table III. Gamma energies due to transitions in Nb^{95} and Mo^{95}.

Nucleus	Energy, kev	K/L ratio
Nb^{95}	235.2	4.5±0.6
	725	5.0±1.0
	758	—
Mo^{95}	753	—
	768	7.6±0.6

† This investigation received the joint support of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

[1] A. V. Grosse and F. Booth, Phys. Rev. 57, 664 (1940).
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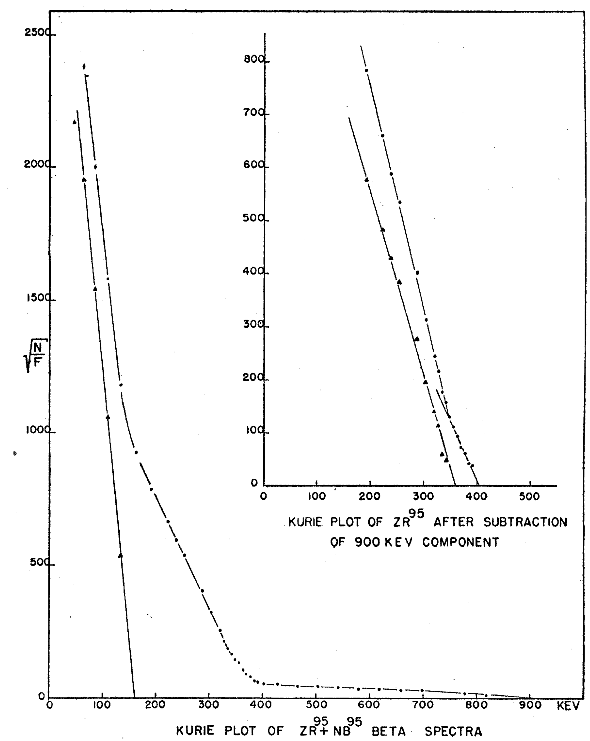

FIG. 1. Resolution of the beta-spectrum of zirconium 95.

hours had been reported. Beta-emission from the ground level of niobium leads to molybdenum 95. The half-life of this decay had been reported to be 35 days, and the radiation was believed to consist of a beta-ray followed by a single gamma.

The electron lines observed from the Zr^{95} source indicated the existence of more gamma-rays than had been previously reported. In order to identify the electron lines associated with the daughter product, a chemical separation of the niobium from the parent activity was kindly made by the Oak Ridge National Laboratory. Spectrograms obtained with this separated material allowed a complete resolution of the composite spectrum. The observed electron energies together with their interpretations are shown collected in Table II. The energies of the gamma-rays are given in Table III. The half-life of the separated niobium appears to be 35±0.5 days.

It is of interest that of the many transitions assigned to the molybdenum 95 nucleus, from a study of the *K*-capture decay in technetium 95, only one, namely, the gamma-ray at 768 kev, is found to be present in the niobium radiation.[3]

The K/L ratios, shown in Table III, for three of the gamma-rays have been evaluated from densitometer traces of the photographic plates made with a Leeds and Northrup recording microphotometer. For the other two gamma-rays only the *K* lines were observed so the K/L ratios must be large compared to unity. It is apparent that absorption methods could never resolve the many gamma-rays with energies so nearly alike, nor could the proper assignments be made without the chemical separation.

In order to determine the proper arrangement of the three gamma-transitions in the niobium 95 nucleus a careful re-examination has been made of the beta-emission. The double focusing magnetic spectrometer of 40 cm diameter was employed in this study. The G-M tube was provided with a very thin zapon window and the metallized zapon backing of the source was as near massless as possible. The observed electron distribution is shown graphically on a "Kurie" plot in Fig. 1. The high energy component comprises only about two percent of the total number of electrons, and consequently is not subject to the best statistics.

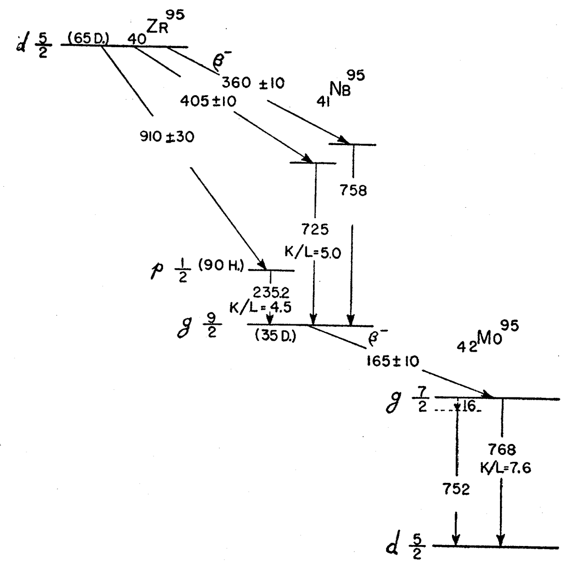

FIG. 2. Proposed nuclear level scheme for the radioactive decay of zirconium 95.

The upper energy limit appears to be about 910±30 kev with a log *ft* value of 9.7. On the subtraction of this high energy component it seems quite certain that the resulting "Kurie" line is resolvable into two betas differing by about 40 kev at an energy around 400 kev. The exact end points and the relative percentage of each depend to some extent upon the choice of slope. The most probable energy values appear to be 405 and 360 kev, each with a log *ft* value of about 6.5. The beta-spectrum of niobium is also present as a low energy component, shown resolved in Fig. 1. The chemically separated source was also studied, confirming that the spectrum has an allowed shape with an upper energy limit of 165±10 kev and a log *ft* of 5.0.

The gamma- and beta-energies may be arranged in a decay scheme as shown in Fig. 2. In the arrangement as shown, a low energy gamma-ray of about 16 kev might be expected. This energy is too low to produce

[3] Medicus, Preiswerk, and Scherrer, Helv. Phys. Acta 23, 299 (1950).

conversion electrons observable in our spectrometers. There is evidence from an observation of the absorption in aluminum that some very low energy gamma-radiation is present.

The ground state of the molybdenum nucleus has been found to be $d_{5/2}$. For the first excited level of the odd-even nucleus with 53 neutrons, from shell theory, a $g_{7/2}$ level is expected. This is in good agreement with present observations if the 768-kev transition is magnetic dipole, and it also satisfies the allowed 165-kev beta-transition from a $g_{9/2}$ level. The 235-kev radiation in niobium is by virtue of its long radiation lifetime and its high conversion coefficient interpreted as an $M4$ transition. If, then, the upper level is a $p_{1/2}$ state and the initial zirconium level, like the molybdenum ground state, is characterized as $d_{5/2}$, it would follow that the 910-kev beta-transition would be forbidden, as observed. No transition from the initial $d_{5/2}$ level to the niobium $g_{9/2}$ level would be expected.

Note added in proof:—A recent report by V. Shpinel (USSR) Zhur. Eksptl. i Teort. Fiz. 21, 1370 (1951), treats these radioactivities. Two gamma-rays are evaluated from photoelectrons and others are postulated to exist from differences in observed beta-energies. These are not in agreement with our observed energies.

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Radiochemical Studies on the Photofission of Thorium*

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The relative yields of thirteen products resulting from the photofission of Th^{232} have been determined radiochemically. Photofission was induced by a 69-Mev synchrotron bremsstrahlung beam. The photofission yield curve was shown by these data to have two peaks, occurring approximately at nucleon numbers 91 and 138 with values of 6.9 percent. The peak-to-valley ratio was 10 and the half-width of the peaks was 12. Symmetry of the curve about nucleon number of 114.5 indicated the average emission of approximately three neutrons. The results were compared with other photofission data and the yield curves of other fission processes.

I. INTRODUCTION

In the photoexcitation of heavy nuclei at moderate energies, fission may occur in excited states of target nuclei. At higher energies, the fission may be preceded by the loss of one or more neutrons. In any event, the nuclei undergoing fission are generally different from those which are excited by neutron capture or by charged-particle bombardment. A study of photofission, therefore, extends the knowledge concerning the general fission process. This is of particular interest in the case of Th^{232} and U^{238} because neutron yields from spontaneous fission have been determined for the ground states of these two nuclides.[1–3]

Present information of photofission product yields from various fissionable materials is not nearly so comprehensive as that available for the yields from neutron fission reported by the Plutonium Project[4] and by subsequent workers.[5,6] Photofission yield curves have been estimated for Bi^{209} irradiated by 85-Mev x-rays[7] and for U^{235} irradiated by 22-Mev x-rays.[8] Also available are some preliminary results of a current study by Richter[9] and Coryell[10] involving the irradiation of natural uranium with 16-Mev x-rays.

In this paper are reported the radiochemically determined yields of thirteen nucleon (mass) numbers produced by the irradiation of thorium with 69-Mev bremsstrahlung. From the photofission cross section curve of thorium given by McElhinney[11] and Ogle[12] and the characteristics of the bremsstrahlung spectrum, it is apparent that the preponderant majority of fission events resulted from the relatively moderate excitation energies of 10–20 Mev. Therefore it is not surprising that a yield curve of the familiar "twin-peaked" form was produced. The data were sufficient to give a fairly reliable indication of the width of the peaks at half-height, the ratio of the yield of the most probable mode

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