Decay of Y^{92} and Nb^{92}†

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(Received March 26, 1962)

The radiations of $_{39}Y^{92}$ (3.50 h) and $_{41}Nb^{92}$ (10.1 day) have been studied with the help of scintillation spectrometers and a solenoidal beta spectrometer. Analysis of the experimental results indicates that the Y^{92} decay scheme involves six excited states of $_{40}Zr^{92}$, which have the following energies (MeV), spins, and parities: 0.932 (2+), 1.380 (0+), 1.492 (4+), 1.836 (2+), 2.05 (2+), and 2.33 (3−). The spectrum of the 3.64-MeV beta transition from Y^{92} to the Zr^{92} ground state has a unique first-forbidden shape, identifying Y^{92} as a 2− state. Nb^{92}, which decays only to the 1.836- and 0.932-MeV levels of Zr^{92}, is postulated to have spin and parity 2+. Several features of the level structure of Zr^{92} appear to be manifestations of simple shell-model phenomena. It is proposed that the main components of the 1.380- and 1.836-MeV states are excited proton configurations, whereas the dominant components of the levels at 0.932, 1.492, and 2.05 MeV are excited neutron configurations.

I. INTRODUCTION

The present work represents a detailed re-examination of the Y^{92} and Nb^{92} decay schemes.

Previous studies of the radiations of Y^{92} have yielded little information about the level structure of Zr^{92}. Moreover, the present authors were aware of numerous discrepancies between published results[1–3] on Y^{92} and data previously obtained at this laboratory.[4] As discussed below, most of these discrepancies have now been resolved, and we have been able to make definite spin and parity assignments for the first six excited states of Zr^{92}.

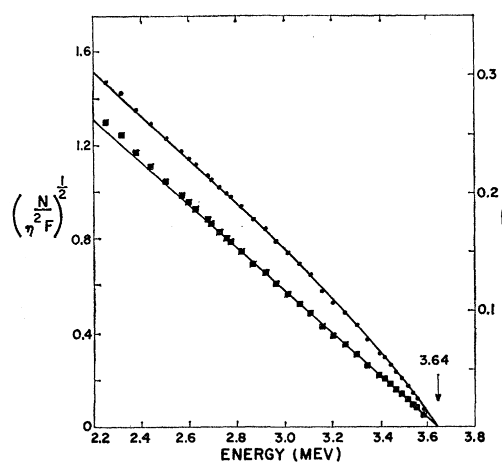

FIG. 1. Fermi–Kurie plots of the high-energy portion of the Y^{92} beta spectrum. The upper curve is a conventional plot (left ordinate), and the lower curve is a shape-corrected unique first-forbidden plot (right ordinate).

Although the radiations of Nb^{92} (10 day) have been well studied,[5,6] it became evident from the proposed Y^{92} decay scheme and from $\Delta J,\Delta\pi$ selection rules that several previously unobserved transitions were possible in the decay of Nb^{92}. Furthermore, it seemed desirable to verify the previous[6,7] angular correlation measurements which indicate that there is a $2+\rightarrow 2+$ transition in Zr^{92} which is essentially pure $M1$. In addition to experiments on the 10-day activity, a search was made for another isomer of Nb^{92}. The results of this search were negative.

II. DECAY OF Y^{92}

A. Source Preparation

The Y^{92} source material was produced by decay of Sr^{92} which had been isolated from uranium fission products. The fission product mixture, produced by irradiating 20-mg U^{235} samples for 10–30 min in a reactor, was allowed to stand for about 90 min to permit complete decay of Sr^{93}, and the strontium and barium were then isolated and stripped free of yttrium and lanthanum. A small amount of lanthanum carrier was added, and after a growth period of 1–2 h the carrier was precipitated as the hydroxide, carrying with it the yttrium activities from decay of strontium and the lanthanum activities from decay of barium. After reprecipitation, the active material was dissolved in 0.1N HCl and transferred to a Dowex-50 cation resin column; the yttrium activity was then selectively eluted, carrier-free, with α-hydroxyisobutyric acid. In the samples so prepared, the only detectable activities, other than Y^{92}, were 50-min Y^{91m} and 59-day Y^{91}. The Y^{92} half-life, as determined from decay measurements on both β and γ radiations, was 3.50±0.05 h.

† Work done under the auspices of the U. S. Atomic Energy Commission.

[1] W. A. Cassatt, Jr., and W. W. Meinke, Phys. Rev. **99**, 760 (1955).

[2] D. G. Gardner, thesis, University of Michigan, 1957 (unpublished); quoted in reference 3.

[3] *Nuclear Data Sheets*, National Academy of Sciences, National Research Council (U. S. Government Printing Office, Washington, D. C.).

[4] D. P. Ames, M. E. Bunker, and J. W. Starner (private communication, November, 1954); quoted in reference 3 and in *Nuclear Level Schemes*, $A=40-92$, compiled by K. Way, R. W. King, C. L. McGinnis, and R. van Lieshout, U. S. Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C.).

[5] R. W. Hayward, D. D. Hoppes, and H. Ernst, Phys. Rev. **98**, 231 (1955); oral report.

[6] H. I. West, Jr., L. G. Mann, and G. M. Iddings, Phys. Rev. **113**, 881 (1959); **114**, 1652 (E) (1959).

[7] C. F. Coleman, Nuclear Phys. **7**, 488 (1958).

B. Beta Spectrum

The source for β-spectrum measurement was prepared from a source solution which had been put through an extra resin-column treatment to free it of foreign dissolved solids. The final solution obtained, about 0.1 cc in volume, was evaporated to dryness as a ~2-mm-diam spot on a backing of 0.00025-in. aluminized Mylar.

A solenoidal β spectrometer, set for 0.8% momentum resolution, was used for investigation of the β spectrum. Measurement of the gross spectrum continued for 12 h after the source was prepared. Two days later, further data were taken to establish the Y^{91} contribution to the spectrum.

As observed previously,[4] a conventional Fermi–Kurie plot of the Y^{92} β spectrum showed, at the high-energy end, the characteristic "α" shape indicative of a unique first-forbidden transition (Fig. 1). Application of the $\Delta J=2$ (yes) spectral shape correction factor,[8] $a_1 = q^2L_0+9L_1$, yielded a linear plot with an end-point energy of 3.64±0.02 MeV. Departure of the shape-corrected plot from linearity below about 2.7 MeV indicated the presence of lower-energy β groups, but their low intensities precluded useful analysis. Instead, all other β-group intensities were deduced from γ-spectrum analyses.

The only conversion lines observed were those from the 551.2-keV Y^{91m} (50 min) isomeric transition.[9] Careful examination of the Y^{92} β spectrum in the vicinity of 1.36 MeV revealed no evidence for a K-conversion line from the possible 1.380-MeV $0+\rightarrow0+$ monopole transition (see decay scheme, Fig. 9). The estimated upper limit on the intensity of the monopole transition is $\leq 1\%$ of the intensity of the 0.448-MeV γ ray.

C. Scintillation Measurements

1. Gamma-Ray Spectrum

The single-crystal γ-ray spectrum of Y^{92}, taken at a source-to-crystal distance of 10 cm, is shown in Fig. 2. This spectrum was recorded approximately 10 h after the resin-column separation of the yttrium activity so that there would be no interference from 50-min Y^{91m}. Spectra observed as early as 30 min after the yttrium separation appeared identical to that of Fig. 2 except for an intense Y^{91m} peak at 0.551 MeV. The detector used in these measurements was a 3 in.×3 in. NaI(Tl) crystal mounted on a DuMont 6363 photomultiplier tube, and its resolution at 662 keV was 7.6%. A beryllium absorber was used to stop the β rays. Data were recorded with a 100-channel analyzer.

A careful "unfolding" of the spectrum of Fig. 2 revealed photopeaks at 0.448, 0.49, 0.560, 0.84, 0.932, 1.12, 1.395, 1.83, and 2.06 MeV. The unfolding procedure involved the use of the measured pulse-height distributions associated with monoenergetic γ rays whose energies were similar to the Y^{92} γ-ray energies. To avoid confusion, only the Gaussian photopeak portion of each pulse-height distribution is shown in Fig. 2. The peak shown at 0.90 MeV was resolved only in coincidence experiments (described below). The general rise of the spectrum with decreasing energy is caused by an underlying bremsstrahlung distribution associated with the high-energy β-ray groups.

Detailed examination of spectra taken at higher amplifier gain revealed no additional γ rays with energies below 0.448 MeV. In particular, no evidence was found for the reported[2,3] transitions of energy 0.070, 0.14, and 0.29 MeV. The γ rays with energies of 0.21 and 0.48 MeV observed by Cassatt and Meinke[1] and also Gardner[2,3] are now known to have been associated with the decay of 3.1-h Y^{90m},[10–14] an activity which was not present in our yttrium sample.

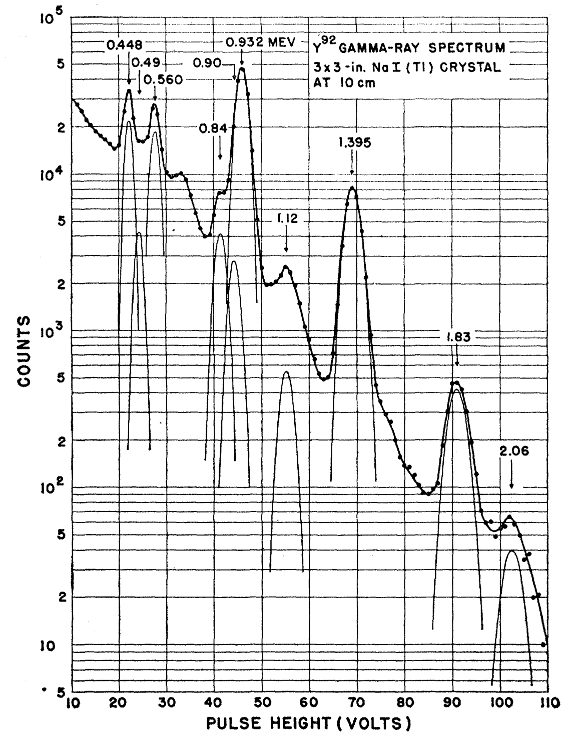

FIG. 2. Gamma-ray spectrum of Y^{92} taken with a 3×3-in. NaI(Tl) crystal.

A careful search for the reported[1–3] 2.4-MeV γ ray yielded negative results. In this experiment, the source-

[8] M. E. Rose, C. L. Perry, and N. M. Dismuke, Oak Ridge National Laboratory Report ORNL-1459 Special (unpublished).
[9] D. P. Ames, M. E. Bunker, L. M. Langer, and B. M. Sorensen Phys. Rev. **91**, 68 (1953).

[10] R. L. Heath, J. E. Cline, C. W. Reich, E. C. Yates, and E. H. Turk, Phys. Rev. **123**, 903 (1961).
[11] W. L. Alford, D. R. Koehler, and C. E. Mandeville, Phys. Rev. **123**, 1365 (1961).
[12] W. S. Lyon, J. S. Elridge, and L. C. Bate, Phys. Rev. **123**, 1747 (1961).
[13] L. Haskin and R. Vandenbosch, Phys. Rev. **123**, 184 (1961).
[14] C. Carter–Waschek and B. Linder, Nuclear Phys. **27**, 415 (1961).

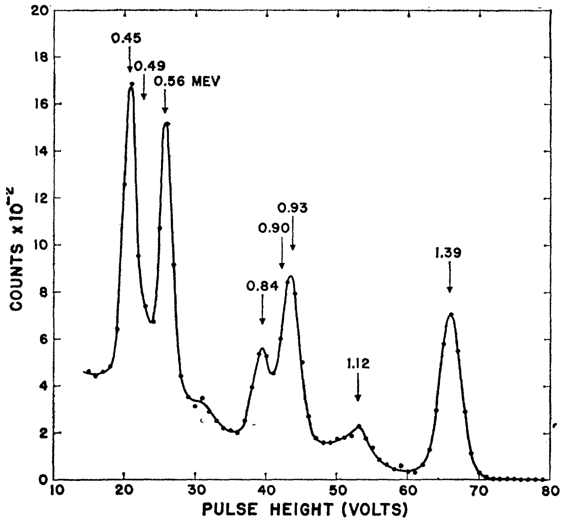

FIG. 3. Gamma-ray spectrum of Y^{92} observed in coincidence with pulses corresponding to the energy interval 0.88–0.98 MeV. Both gamma-ray detectors were 2×2-in. NaI(Tl) crystals.

to-crystal distance was increased to 24 cm and a $\frac{1}{2}$-in. thick lead absorber was introduced behind the usual β-ray absorber, both changes designed to suppress summing of the intense (1.395–0.932)-MeV cascade. The results indicate an upper limit of 5×10^{-4} for the intensity of γ rays in the 2.4-MeV region relative to the intensity of the 0.932-MeV γ ray.

Our "best" values for the energies and intensities of the observed γ rays are listed in Table I. Photopeak areas were converted to relative intensities through the use of the 3×3-in. crystal response curves prepared by Heath.[15]

2. Gamma-Gamma Coincidence Experiments

The detectors used for γ–γ coincidence measurements were either the 3 in.×3 in. scintillator assemblies described above or were 2 in.×2 in. NaI(Tl) crystals mounted on RCA-6342 photomultiplier tubes. All coincidence spectra were recorded with the 100-channel analyzer, which was gated with a coincidence circuit having a resolving time 2τ of $\sim4\times10^{-7}$ sec. In most of the experiments, the source was placed between two crystals which were oriented at 180° to one another and were situated as close together as the β absorbers would permit. In the few cases where we anticipated that γ–γ summing or Compton scattering might introduce noticeable background effects, the source-crystal distances were increased to 10 cm and the detectors were oriented at 90°, with 1-in. thick lead shielding between the crystals.

TABLE I. Summary of Y^{92} γ-ray data.

(1) E_γ (MeV)	(2) Relative intensity	(3) γ rays observed to be coincident with transition in column (1) (MeV)
0.448±0.002	16.5±1.3	0.932
0.49 ±0.01	3.3±0.4	0.932, 1.83
0.560±0.002	19.0±1.5	0.84, 0.932
0.84 ±0.01	8.0±1.0	0.560, 0.932
0.90 ±0.01[a]	6.0±0.7[b]	0.932
0.932±0.002	100	0.448, 0.49, 0.560, 0.84, 0.90, 1.12, 1.395
1.12 ±0.01	1.7±0.2	0.932
1.395±0.010	34 ±2	0.932
1.83 ±0.01	2.8±0.3	0.49
2.06 ±0.02	0.3±0.1	

[a] Evidence for this transition was found only in coincidence spectra.
[b] Value based on the relative intensities of the 0.90- and 1.83-MeV γ rays observed in the decay of Nb^{92}.

[15] R. L. Heath, Atomic Energy Commission Report IDO-16408 (unpublished).

The γ-ray spectrum observed in coincidence with pulses corresponding to the energy interval 0.88–0.98 MeV is shown in Fig. 3. This spectrum indicates that the 0.45-, 0.49-, 0.56-, 0.84-, 1.12-, and 1.39-MeV γ rays are coincident with the 0.932-MeV transition. In view of the established (0.932-1.12)-MeV and (0.932–1.39)-MeV coincidences, it is evident that the peak at 0.93 MeV is at least partially the result of coincidences between 0.932-MeV γ rays and (0.88–0.98)-MeV Compton pulses from the 1.12- and 1.39-MeV γ rays. However, comparison of the data of Fig. 3 with the spectrum coincident with pulses in the (0.99–1.09)-MeV region revealed that only half of the 0.93-MeV peak in Fig. 3 can be explained in this way. The remainder of the 0.93-MeV peak is attributed to (0.90–0.932)-MeV γ–γ coincidences. Although the postulated 0.90-MeV peak could not be separately resolved, it is evident from the Nb^{92} decay scheme that a (0.90–0.932)-MeV cascade must occur in the Y^{92} spectrum with an intensity 2.13 times that of the 1.83-MeV transition (see Table II), yielding a relative strength for the 0.90-MeV transition of 6.0 on the intensity scale of Table I. From the observed ratio of the areas of the (0.90+0.932)- and 1.39-MeV coincidence peaks in Fig. 3, corrected for the known angular correlations (see Secs. II C 3 and III B 4), we obtain an intensity of 6.7±1.3 for the 0.90-MeV transition, in reasonable agreement with the value of 6.0 predicted above.

Many other coincidence experiments were performed, each similar to the ones described above in that a narrow "gate" interval was set to span an energy region of particular interest, usually a photopeak. Three of the observed spectra are shown in Fig. 4. Comparison of the two upper curves indicates that the 0.45- and 0.56-MeV γ rays are not in coincidence; the occurrence of photopeaks at 0.45 and 0.56 MeV results entirely from coincidence of these two γ rays with Compton pulses from higher-energy γ rays, principally the 0.932-MeV transition. The fact that the intensity of the 0.93-MeV peak (relative to the 0.45- and 0.56-MeV peaks) is greater in the upper spectrum than in the middle spectrum is mainly the result of the strong anisotropy of the (0.45–0.93)-MeV cascade (see Sec. II C 3). From intercomparison of the three spectra of Fig. 4, it can be seen that the 0.84-MeV transition is in coincidence with the

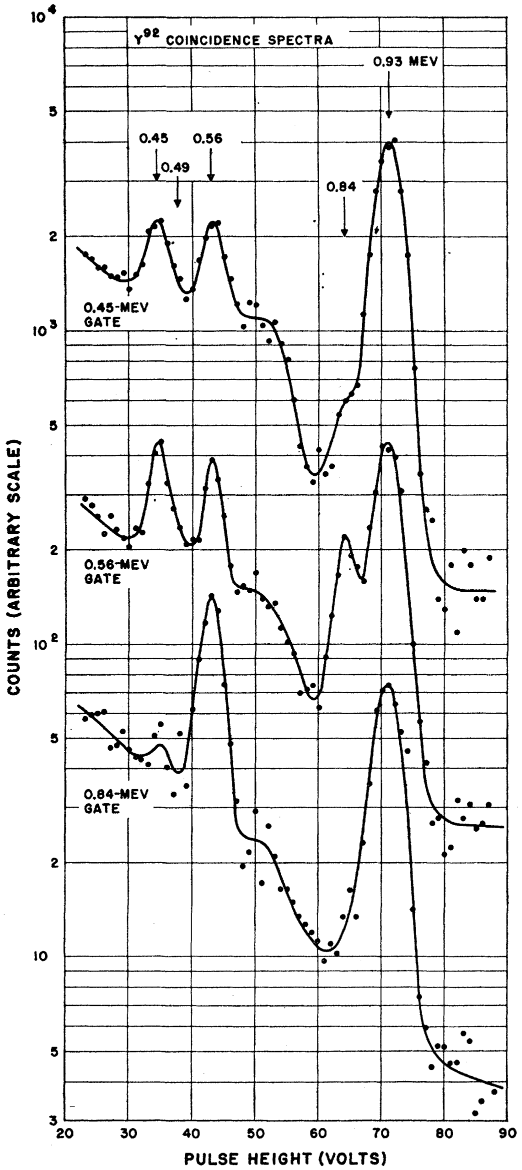

FIG. 4. Y^{92} gamma-gamma coincidence spectra obtained when a narrow gate interval was centered, in turn, on the energies 0.45, 0.56, and 0.84 MeV. The total number of counts at the peak of the 0.93-MeV photopeak was $\sim$400 in the two upper spectra and $\sim$100 in the bottom spectrum.

0.56-MeV transition, but is not in coincidence with the 0.45-MeV transition.

A summary of all γ–γ coincidence relationships established by the measurements described above is given in Table I. Intensity analysis of the observed coincidence spectra gave results which in all cases were in quantitative agreement with the proposed decay scheme (Fig. 9).

3. *Angular Correlation Measurements*

The coincidence and intensity data indicate that the strong transitions of energy 0.448, 0.560, and 1.395 MeV are in direct cascade with the 0.932-MeV ground-state transition. Each of these cascades gave a coincidence counting rate high enough to permit measurement of the angular correlation, thus providing information about the spin assignments of the Zr^{92} levels of energy 1.380, 1.492, and 2.33 MeV.

The (0.448–0.932)-MeV and (0.560–0.932)-MeV angular correlations were measured simultaneously. The "gate" channel of the coincidence circuit was set to span the energy range 0.90–1.00 MeV, and the "analyzer" channel was set to span the energy range from 0.25 to 0.80 MeV. The 2 in.$\times$2 in. crystals were used, in an experimental arrangement similar to that described previously,[16] with the source-to-crystal distances each 8.4 cm. The Y^{92} sources consisted of 20 to 50 μl of yttrium solution as obtained from the resin column. Each count was run for 30 min, at the end of which time the coincidence pulse-height spectrum was recorded, the angle was changed, and the amplifier gains were checked. The angular correlation data were obtained by "unfolding" the coincidence spectrum of each run and dividing the respective photopeak areas by the net number of Y^{92} counts recorded by the gate-channel scaler.

The (0.448–0.932)-MeV angular correlation results are shown in Fig. 5, where each data point represents

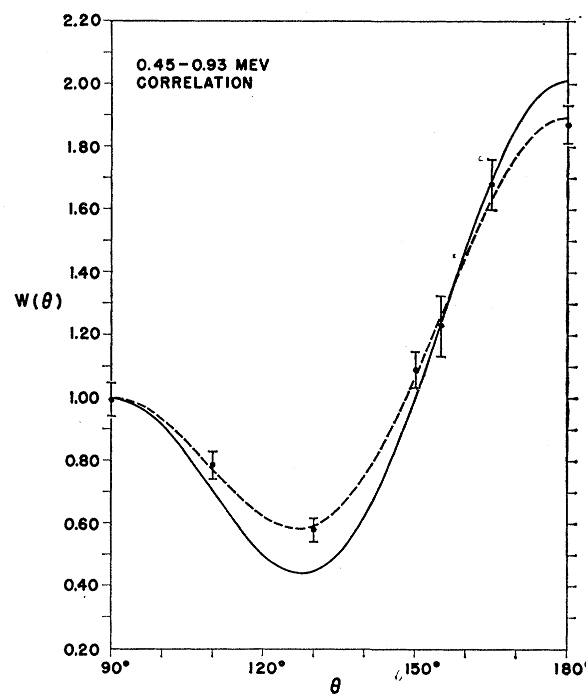

FIG. 5. Gamma-gamma angular correlation results on the (0.45–0.93)-MeV cascade. The dashed curve is the least-squares fit to the experimental data. The solid curve is the "true" correlation, obtained by correcting the observed $W(\theta)$ for finite-geometry effects. The corrected curve is practically indistinguishable from the theoretical 0–2–0 correlation.

[16] M. E. Bunker, J. P. Mize, and J. W. Starner, Phys. Rev. **105**, 227 (1957).

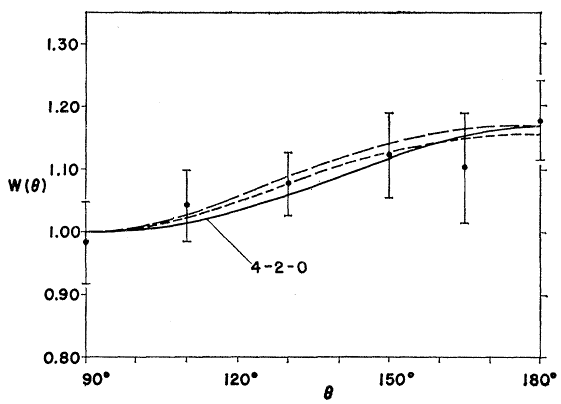

FIG. 6. Gamma-gamma angular correlation results on the (0.56–0.93)-MeV cascade. The curve with short dashes is the least-squares fit to the experimental data. Correction of the observed $W(\theta)$ for finite-geometry effects yields the upper curve (long dashes). The solid curve is the theoretical $4(Q)2(Q)0$ correlation.

the weighted average of all observations at that angle. The observed data were fitted by a least-squares procedure[17] to a function of the form $W(\theta)=1+A_2P_2\times(\cos\theta)+A_4P_4(\cos\theta)$, which yielded the dashed curve. Correction of the observed $W(\theta)$ for finite-geometry effects[18] gave the solid curve, which should correspond to the true correlation. The corrected values of the angular correlation coefficients are $A_2=0.366\pm0.055$ and $A_4=1.147\pm0.081$. The only correlation of the type J-2-0 which has coefficients that fall within these limits is 0-2-0, for which the theoretical coefficients are $A_2=0.357$ and $A_4=1.143$. The spin of the 1.380-MeV level, depopulated by the 0.448-MeV transition, is thus established as 0.

The angular correlation results for the (0.560–0.932)-MeV cascade are shown in Fig. 6. The corrected correlation (long dashes) was calculated to be $W(\theta)=1+(0.112\pm0.057)P_2(\cos\theta)-(0.016\pm0.077)P_4(\cos\theta)$. This $W(\theta)$ is consistent with the spin sequences $1(D,Q)2(Q)0$, $2(D,Q)2(Q)0$, $3(D,Q)2(Q)0$, or $4(Q)2(Q)0$. For reasons given later in this paper, the 1.492-MeV state is assigned a spin of 4. The theoretical $4(Q)2(Q)0$ correlation, for which $A_2=0.102$ and $A_4=0.009$, is shown in Fig. 6 for comparison.

The (1.395–0.932)-MeV angular correlation was measured in a manner similar to that described above except that 3 in.×3 in. NaI(Tl) crystals were used, with source-to-crystal distances of 10.7 cm. The results of these measurements are shown in Fig. 7. Analysis of the observed data gave a corrected correlation (long dashes) of $W(\theta)=1-(0.086\pm0.016)P_2(\cos\theta)-(0.005\pm0.026)\times P_4(\cos\theta)$. This angular distribution is consistent with a spin sequence of either $1(D,Q)2(Q)0$ or $3(D,Q)2(Q)0$. A spin of 1 for the 2.33-MeV level can be excluded, however, by the fact that there is a relatively strong γ-ray transition (0.84 MeV) from this level to the 1.492-MeV level, which is assigned as 4+ (see Sec. IV A 2). The absence of an observable 2.33-MeV ground-state transition supports this conclusion. The experimental values of A_2 and A_4 indicate a quadrupole admixture in the $3(D,Q)2$ transition of $Q=0.0003_{-0.0003}^{+0.0012}$, as shown graphically in Fig. 8.

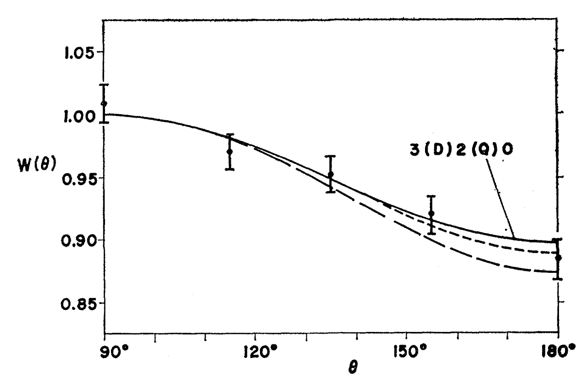

FIG. 7. Gamma-gamma angular correlation results on the (1.39–0.93)-MeV cascade. The curve with short dashes is the least-squares fit to the experimental data. Correction of the observed $W(\theta)$ for finite-geometry effects yields the lower curve (long dashes). The solid curve is the theoretical $3(D)2(Q)0$ correlation.

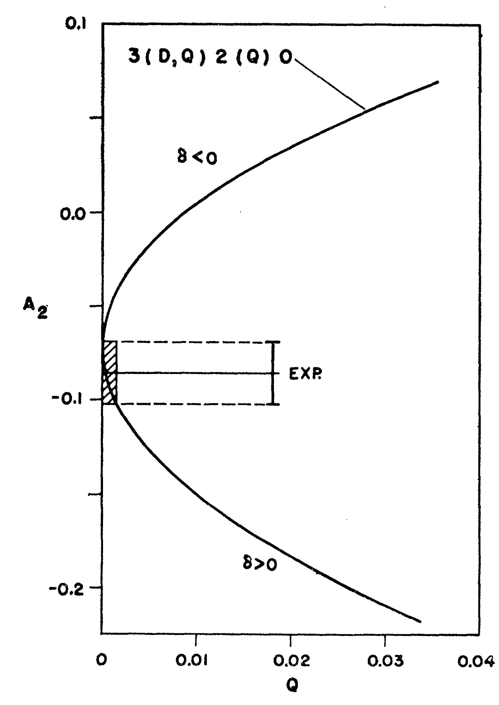

FIG. 8. The solid curve is a plot of A_2 vs Q, the quadrupole intensity, for a $3(D,Q)2(Q)0$ sequence. The shaded area shows the range of values of Q consistent with the experimental values of A_2 and A_4 obtained from analysis of the (1.39–0.93)-MeV gamma-gamma angular correlation. The fact that A_2(exp) also intersects the $3(D,Q)2(Q)0$ curve at about $Q=0.98$ can be ignored since A_4(exp) limits the value of Q to the range 0.0–0.38.

[17] M. E. Rose, Phys. Rev. **91**, 610 (1953).

[18] M. L. Wiedenbeck, University of Michigan Research Institute Technical Report 2375-3-T, February, 1959 (unpublished).

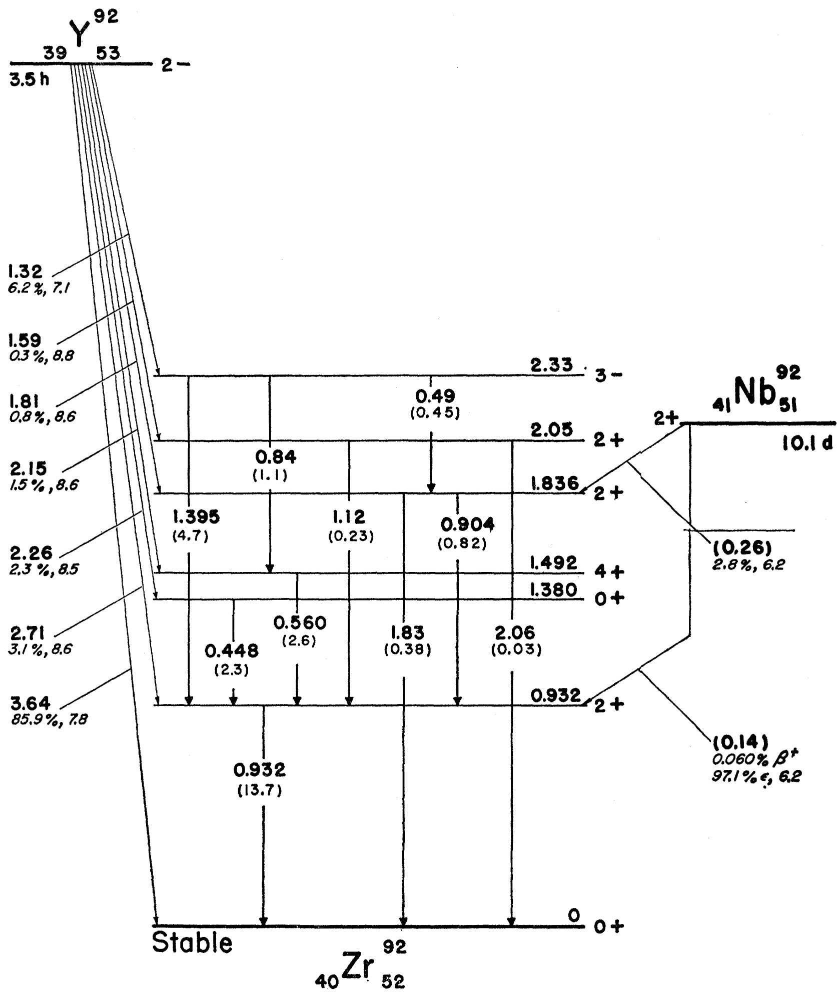

FIG. 9. Decay schemes of Y^{92} and Nb^{92}. The gamma-ray intensity values (in parentheses) correspond to numbers of quanta pr 100 disintegrations of Y^{92}. Numbers listed after the beta-branch percentages are log ft values. Energies in MeV.

D. Decay Scheme

Consideration of the coincidence results and the γ-ray intensity data given in Table I leads directly to the decay scheme shown in Fig. 9.

Normalization of γ-ray intensities to a "per disintegration" scale was accomplished by measuring the number of (0.90+0.932)-MeV γ rays per beta particle. For this measurement, a calibrated thin-window beta-proportional counter was used to determine the β-disintegration rate of a $\sim 10\mu g/cm^2$ source, and a NaI(Tl) detector with known photopeak efficiency was used to determine the source emission rate of (0.90+0.932)-MeV γ rays. The value for the above ratio was found to be $I_\gamma(0.90+0.932)/\beta = 0.145 \pm 0.010$. Using this value and the relative intensities of Table I, one can obtain I_γ/β values for all γ-ray transitions, from which one can then calculate all β-group intensities. The log ft values shown in Fig. 9 were determined from the graphs prepared by Moszkowski.[19]

[19] S. A. Moszkowski, Phys. Rev. **82**, 35 (1951).

III. Nb^{92} EXPERIMENTS

A. Source Preparation

The Nb^{92} source material was prepared by 15-MeV α-particle bombardment of an yttrium oxide target, followed by chemical isolation of the niobium fraction as the hydrated oxide. The only radioactive contaminant detected was a very small amount of 62-day Nb^{91m}, observed after the 10-day Nb^{92} had decayed for many half-lives.

A portion of the source material was set aside and counted once a week for a period of three months with a standardized NaI(Tl) scintillation counter. A least-squares analysis of the decay data in terms of two components, with the half-life of the longer-lived component (Nb^{91m}) assumed to be 62.0 days, gave a value for the Nb^{92} half-life of 10.16 ± 0.03 days.

B. Gamma-Ray Measurements

1. Gamma-Ray Spectrum

The γ-ray spectrum was examined with a 3 in.×3 in. NaI(Tl) detector. The source-to-crystal distance was

20 cm, and no absorbers were used. The only radiations observed were zirconium K x rays and γ rays of energy 0.932 and 1.83 MeV. The intensity ratio $I_\gamma(1.83)/I_\gamma(0.932)$ was determined to be $(0.90\pm0.05)\times10^{-2}$, in good agreement with the value of $(0.84\pm0.10)\times10^{-2}$ quoted by West *et al.*[6]

2. Gamma-Gamma Coincidence Experiments

In all coincidence experiments on Nb^{92}, use was made of a "fast-slow" coincidence circuit ($2\tau\simeq1.3\times10^{-8}$ sec) similar to the one described by Bell *et al.*[20] Unless otherwise noted, 2 in.×2 in. NaI(Tl) crystals were used as detectors.

With the lower and upper bounds of the "gate" channel set at 0.86 and 1.10 MeV, the coincidence spectrum exhibited photopeaks at 0.511 and 0.918 MeV. The 0.511-MeV peak, which is produced by annihilation radiation, was barely detectable. The intensity of the positron branch responsible for the annihilation radiation was measured in a separate experiment, described below. The 0.918-MeV peak results from the known[5,6] (0.90–0.932)-MeV cascade. The observed energy of this composite peak indicates that the ~0.90-MeV transition has an energy of (0.904 ± 0.008) MeV.

The ratio of the intensities of the 0.904- and 0.932-MeV transitions was determined by comparing the number of (0.904+0.932)-MeV photopeak coincidence counts (per gate pulse) with the coincidence ratio observed with a Sc^{46} source. Sc^{46} is a good comparison source for this experiment because >99.9% of the disintegrations give rise to a (1.12–0.89)-MeV cascade.[3] In the Sc^{46} run, the "gate" bounds were set to bracket the 1.12-MeV photopeak, and the number of counts in the 0.89-MeV coincidence photopeak (per gate pulse) was recorded. The Nb^{92} and Sc^{46} sources were examined in the same geometry—namely, our standard angular correlation geometry for 2 in.×2 in. crystals, with the angle between crystal axes set at 122°.[21] After certain obvious corrections were applied to the results of the above measurements, direct comparison of the Nb^{92} and Sc^{46} data yielded a ratio of intensities $I_\gamma(0.904)/I_\gamma(0.932)=(1.92\pm0.10)\times10^{-2}$. West *et al.*[6] obtained a value of 1.8×10^{-2} for this ratio.

The total decay energy of $Nb^{92}\rightarrow Zr^{92}$ may be as high as 2.14 MeV,[3,6] with the consequent possibility of electron-capture decay to the known 2.05-MeV level of Zr^{92}. Accordingly, a careful search was made for evidence of (1.12–0.932)-MeV γ–γ coincidences. The geometry used was the same as that described in the preceding paragraph. There was no indication of a 1.12-MeV peak in the coincidence spectrum accumulated during a 70-h run. From these data, an upper limit of 1.3×10^{-4} was obtained for the intensity ratio $I_\gamma(1.12\text{ MeV})/I_\gamma(0.932\text{ MeV})$.

TABLE II. Gamma-ray transitions associated with Nb^{92} decay.

γ-ray energy (MeV)	Relative intensity
1.83 ± 0.10	0.90 ± 0.05
0.932 ± 0.008	100
0.904 ± 0.008	1.92 ± 0.10
(1.12)[a]	$<1.3\times10^{-2}$
(0.45)[a]	<0.2
(0.34)[a]	<0.4

[a] Unobserved. Intensity quoted is an upper limit.

A search was also made for possible weak transitions from the 1.836-MeV level of Zr^{92} to the 1.492- and 1.380-MeV levels, which would give rise, respectively, to (0.34–0.56)-MeV and (0.45–0.45)-MeV γ–γ cascades (see Fig. 9). The geometry used in these experiments was the same as that described above except that the angular setting was $\theta=90°$. The coincidence spectrum obtained during a 35-h run, with a narrow "gate" region centered on 0.45 MeV, failed to reveal any evidence for (0.45–0.45)-MeV coincidences. Similarly, with the "gate" region centered on 0.56 MeV, no evidence was found for (0.34–0.56)-MeV coincidences. Upper limits on the intensities of these transitions are given in Table II.

3. Positron Experiment

West *et al.*[6] observed that Nb^{92} is a weak positron emitter and that most, if not all, of these positrons are associated with decay to the 0.932-MeV state. We remeasured the positron branch intensity by direct comparison of the number of (0.511–0.511) coincidences per 0.932-MeV γ ray with the number of (0.511–0.511) coincidences per 1.275-MeV γ ray from a Na^{22} source. The two Lucite source holders were of the same design, with wall thickness sufficient to stop 0.6-MeV positrons. Our standard angular correlation geometry for 2 in.×2 in. crystals was used, with source-to-crystal distances of 7.3 cm and $\theta=180°$. The intensity of the positron branch was calculated to be $(6.0\pm0.6)\times10^{-4}$ positrons/disintegration, in good agreement with West's value of $(5.6\pm0.6)\times10^{-4}$.

4. Angular Correlation Measurement

The (0.904–0.932)-MeV angular correlation was measured with 2 in.×2 in. NaI(Tl) detectors, used in conjunction with the fast-slow coincidence system. The source-to-crystal distances were each 7.3 cm. The source consisted of several milligrams of Nb_2O_5 precipitate, pressed into a cavity $\frac{1}{8}$ in. in diameter and $\frac{1}{4}$ in. high in the end of a Lucite rod.

The gate-channel "window" was set to correspond to the energy interval 0.60–1.02 MeV, and the analyzer-channel "window" spanned the energy interval 0.25–

[20] R. E. Bell, R. L. Graham, and H. E. Petch, Can. J. Phys. **30**, 35 (1952).

[21] Note: At $\theta=122°$, no angular correlation corrections are required if the cascades being compared are of the type $W(\theta)=1+A_2P_2(\cos\theta)$. In the present experiment, $A_4\ll A_2$ for both cascades; consequently, angular correlation corrections could be neglected.

1.15 MeV. At the beginning of the experiment, the measured ratio of true to chance coincidences was ~ 20. Each counting period was 2 h in duration. At the end of the count the data were recorded, calibrations were checked, and the angle was changed. The angular correlation datum from each run was obtained by dividing the net number of counts in the (0.904+0.932)-MeV coincidence spectrum between 0.30 and 1.02 MeV by the net Nb^{92} counts recorded by the "gate" scaler. The small contribution ($\sim 4\%$) from the 0.511-MeV spectrum was subtracted as an isotropic background.

The data accumulated in ~ 60 h of counting are shown in Fig. 10. Each experimental point represents the weighted average of all observations at that angle. After correction for the finite solid angles subtended by the detectors, the experimental angular distribution was found to be $W(\theta)=1+(0.217\pm0.013)P_2(\cos\theta)-(0.001\pm0.019)P_4(\cos\theta)$, which is consistent with previous measurements.[6,7] This angular correlation indicates a sequence of either $2(D,Q)2(Q)0$ or $3(D,Q)2(Q)0$. However, a spin of 3 for the upper state can be eliminated on the basis of the observed competition between the 0.904-MeV transition and the 1.83-MeV crossover transition. The above values of A_2 and A_4 indicate that the 0.904-MeV, $2(D,Q)2$ transition has a dipole content of $(99.8_{-0.2}^{+0.1})\%$. [Note: For a pure $2(D)2(Q)0$ correlation, $A_2=0.250$, $A_4=0$.]

IV. DISCUSSION

A. Spin and Parity Assignments

1. Y^{92}

The spectrum of the 3.64-MeV β transition from Y^{92} to the Zr^{92} ground state has a unique first-forbidden shape, identifying Y^{92} as a 2− state.

2. Zr^{92}

The 0.932-MeV level is known to be 2+ from Coulomb excitation experiments.[3]

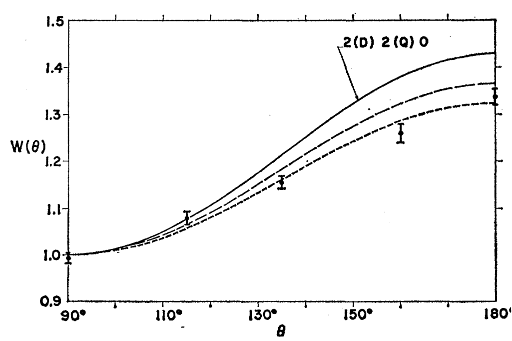

FIG. 10. Gamma-gamma angular correlation results on the (0.90–0.93)-MeV cascade. The curve with short dashes is the least-squares fit to the experimental data. Correction of the observed $W(\theta)$ for finite-geometry effects yields the middle curve (long dashes). The solid curve is the theoretical $2(D)2(Q)0$ correlation.

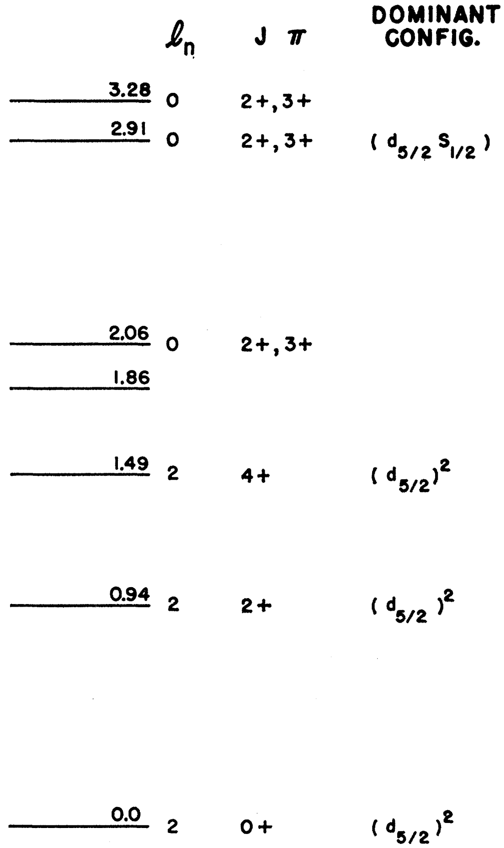

FIG. 11. Levels of Zr^{92} excited in the $Zr^{91}(d,p)Zr^{92}$ reaction. These results are quoted in reference 22.

The 1.380-MeV level, whose spin is uniquely determined as 0 by the (0.448–0.932)-MeV angular correlation, must have positive parity in view of the log *ft* value (8.5) of the 2.26-MeV β transition.

The 1.492-MeV level is assigned as 4+ for the following group of reasons: (1) Although the (0.560–0.932)-MeV angular correlation is consistent with a spin of 4, 3, 2, or 1 for the initial state, the choice of 3, 2, or 1 would imply a (D,Q) mixing ratio for the 0.560-MeV transition of just the right magnitude to make the correlation look like $4(Q)2(Q)0$, a possible but improbable circumstance; (2) The recent $Zr^{91}(d,p)Zr^{92}$ results of Martin *et al.*[22] (see Fig. 11) indicate positive parity and a probable spin of 4 for the 1.49-MeV level; (3) The $Zr^{92}(n,n')$ experiments of Day[23,24] suggest $J=4$ for this level; (4) From systematics, a 4+ level is expected in Zr^{92} somewhere below 2.3 MeV, and the 1.492-MeV level is the only possible candidate; (5) The absence of

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[22] H. J. Martin, Jr., M. B. Sampson, and R. L. Preston, Phys. Rev. **125**, 942 (1962).
[23] R. B. Day, *Proceedings of the International Conference at Moscow, November, 1957* (U.S.S.R. Academy of Sciences, Moscow, 1958), p. 149; R. B. Day and D. A. Lind (private communication; cited in reference 3).
[24] R. B. Day (private communication).

a ground-state γ-ray transition is consistent with the proposed 4+ assignment.

The 2+ assignment for the 1.836-MeV state is based on the (0.904–0.932)-MeV angular correlation and the relative strength of the ground-state transition (see Sec. III B 4).

Martin's[22] (d,p) results indicate a (2,3)+ assignment for the 2.05-MeV level. In view of the relative strength of the 2.06-MeV ground-state transition, this level is assigned as 2+. A measurement of the (1.12–0.932)-MeV angular correlation gave results which were consistent with the theoretical correlation $2(D,Q)2(Q)0$; however, the experimental errors were sufficiently large that these data do not constitute a strong argument for the 2+ assignment.

As mentioned earlier, the 2.33-MeV level can have a spin of 1 or 3 on the basis of the (1.395–0.932)-MeV angular correlation data, but a spin of 1 would not be consistent with the observation of a transition to the 4+ level or with the absence of a ground-state transition. A convincing argument for assignment of negative parity to the 2.33-MeV level comes from the recent $Zr^{91}(n,\gamma)Zr^{92}$ data of Bartholomew.[25] His results strongly suggest that the 6.30-MeV γ ray which proceeds to the 2.33-MeV level[3,26] from the neutron-capture level is an $E1$ transition. From the fact that Zr^{91} is a $\frac{5}{2}+$ state, which limits the assignment of the capture level to 2+ or 3+, it then follows that the 2.33-MeV state must have negative parity. Angular correlation measurements[25] on capture-γ-ray cascades which involve the 2.33-MeV level support the proposed 3− assignment for this state.

3. Nb^{92}

The fact that Nb^{92} (10 day) decays only to levels having spin and parity 2+, with the capture branches having log ft values of $\sim$6.2, strongly suggests that it is a 2+ state. The possibility of a 2− assignment can be rejected for the following reasons: (1) all known 2− $\rightarrow$(first 2+ level) beta transitions in the mass region $A=70$–120 have log ft values ≥ 7; (2) there would probably be observable positron decay to the Zr^{92} ground state if the parent state were 2−.

B. Interpretation of Level Structure

There is good reason to believe that all levels of Zr^{92} up to 2.33 MeV are shown in Fig. 9. Four other levels are shown in reference 3; however, (1) the 1.69- and 1.90-MeV levels were based on γ-ray transitions which are now known to be unrelated to the decay of Y^{92} (see Sec. II C 1), and (2) results of a reanalysis of the Zr^{92} (n,n') data indicate that the γ rays on which the 2.16- and 2.27-MeV levels were based[3,23] are probably not associated with Zr^{92}.[24] It is noteworthy that Day,[24] from analysis of the observed (n,n') cross sections as a function of neutron energy, has arrived at the same spin assignments for the 0.93-, 1.38-, 1.49-, and 1.83-MeV levels as shown in Fig. 9.

The Zr^{92} level structure exhibits several properties which are not predicted on the basis of vibrational (or collective) models. This is undoubtedly related to the fact that Zr^{92} has only 2 neutrons beyond a closed shell and 2 protons beyond a closed subshell. The properties referred to include the following: (1) the ratio of the energy of the second excited state to that of the first is considerably less than 2.0, (2) the second 2+ state decays to the first 2+ state by a nearly pure $M1$ transition, rather than by the nearly pure $E2$ transition expected if the states involved were both collective, and (3) the observed competition between the $E2$ component of the 0.904-MeV transition and the 1.83-MeV $E2$ transition yields a ratio of reduced transition probabilities $B(E2;\,2'\rightarrow 2)/B(E2;\,2'\rightarrow 0)\approx 0.14$, whereas in most medium-weight even-even nuclei this ratio is >10.[27] The possibility of explaining these and other features of the level scheme from a shell-model point of view is explored in the following paragraphs.

First of all, the 0.932-, 1.492-, and 2.05-MeV states are so strongly excited in the (d,p) reaction that there can be little doubt that they correspond primarily to excited neutron configurations. Martin *et al.*'s[22] results indicate that the dominant configuration of the 0.932- and 1.492- MeV levels is $(d_{5/2}^2)$. The configurational description of the 2.05-MeV level is less certain, but it seems evident that this state must have a sizeable admixture of $(d_{5/2}s_{1/2})$ since the proton angular distribution indicates $l_n=0$.

The fact that the (d,p) reaction does not observably excite the 1.380-MeV (0+) level[22] suggests the possibility that this level corresponds to an excited proton configuration. Another reason for pursuing this idea is that in ${}_{40}Zr_{50}{}^{90}$, whose low-energy levels are undoubtedly proton states, the first excited state has spin and parity 0+ and an excitation energy of 1.75 MeV, not greatly different than the 1.380-MeV energy of the Zr^{92} 0+ state. The level structure of Zr^{90} has been analyzed theoretically by Talmi and Unna,[28] and if their calculational methods are applied to Zr^{92}, one obtains a theoretical energy separation of the two $J=0$ states of the $(p_{1/2}^2)$ and $(g_{9/2}^2)$ configurations of 1.42 MeV[29,30]; i.e., this model predicts a 0+ excited state in Zr^{92} at about 1.4 MeV. The good agreement between the calculated and observed energies of the Zr^{92} 0+ level

[25] G. A. Bartholomew, Chalk River Report PR–P-48 (unpublished); G. A. Bartholomew and J. F. Verrier, Bull. Am. Phys. Soc. **6**, 237 (1961); G. A. Bartholomew (private communication).

[26] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. **31**, 1051 (1953).

[27] D. M. Van Patter, Nuclear Phys. **14**, 42 (1959).

[28] I. Talmi and I. Unna, Nuclear Phys. **19**, 225 (1960).

[29] I. Talmi, private communication (to be published).

[30] In this calculation, the reduction in energy difference between the two $J=0$ states in going from Zr^{90} to Zr^{92} is directly related to the drop in $p_{1/2}-g_{9/2}$ single-particle splitting observed in the adjacent odd nuclei; in the Zr^{90} calculation, a $p_{1/2}-g_{9/2}$ difference of 0.915 MeV was used (from ${}_{39}Y_{50}{}^{89}$), and in the Zr^{92} calculation, the $p_{1/2}-g_{9/2}$ difference was taken to be 0.551 MeV (from ${}_{39}Y_{52}{}^{91}$).

strongly supports the hypothesis that this state can be characterized mainly as an excited proton configuration.

The fact that the 1.836-MeV 2+ level is weakly excited in the (d,p) reaction[22] and decays to the first 2+ level by an $M1$ transition suggests that this state may also correspond to a proton excitation, namely, $(g_{9/2}{}^2)_{2+}$. In the Talmi–Unna analysis of Zr^{90},[28] the *unperturbed* separation of the 0+ and 2+ states of the $(g_{9/2}{}^2)$ configuration in Zr^{90} is found to be $\sim$0.9 MeV, and this separation ought to be roughly the same in Zr^{92}. If the 1.836-MeV level of Zr^{92} is considered to be the $(g_{9/2}{}^2)_{2+}$ state, the $(g_{9/2}{}^2)_{0+}-(g_{9/2}{}^2)_{2+}$ *unperturbed* separation turns out to be $\sim$1.1 MeV,[29] which agrees reasonably well with the Zr^{90} value.

If completely pure configurations are assumed, there should be no transitions between the neutron and proton systems of levels. However, small configuration admixtures will make such transitions possible. In particular, if the 2+ levels at 0.932 MeV and 1.836 MeV are slightly admixed, so that each level has components of both $[(g_{9/2}{}^2)_0(d_{5/2}{}^2)_2]_{2+}$ and $[(g_{9/2}{}^2)_2(d_{5/2}{}^2)_0]_{2+}$, then $M1+E2$ transitions can take place between them. It is significant that the observed $M1/E2$ ratio ($\sim$500) for the 0.904-MeV γ-ray transition closely agrees with the theoretical single-particle estimate[31] ($\sim$520), suggesting that collective effects play a minor role in this transition. The fact that the reduced transition probability of the $E2$ component of the 0.904-MeV transition is considerably smaller than that of the 1.83-MeV $E2$ transition is consistent with the assumption that the 0.904-MeV transition occurs only through impurities of the states considered, whereas the 1.83-MeV transition proceeds between major components, namely, $[(g_{9/2}{}^2)_2(d_{5/2}{}^2)_0]_{2+} \to [(g_{9/2}{}^2)_0(d_{5/2}{}^2)_0]_{0+}$. The $E2$ transitions from the 1.83-MeV level to the 1.492- and 1.380-MeV levels would be expected to have reduced transition probabilities comparable to that of the $E2$ component of the 0.904-MeV transition, which satisfactorily explains why these transitions were not observed in the Nb^{92} experiments.

The 3− level at 2.33 MeV is believed to be an octupole vibrational state. The fact that this level is strongly excited in the $Zr^{92}(d,d')$ reaction[32] attests to its collective character. The energy of this state fits in well with the systematics of 3− states in medium-weight even-even nuclei.[33,34] The hindrance of the allowed β-ray transition to the 2.33-MeV level is a natural consequence of the collective nature of the daughter state.

The principal configuration of ${}_{39}Y^{92}{}_{53}$ (3.50 h) is undoubtedly $(p_{1/2}d_{5/2})_{2-}$. The single-particle description of the $\Delta J=2$ beta transitions would, therefore, be $d_{5/2}\to p_{1/2}$. In the 2− →2+ beta transitions, there may be large contributions from $\Delta L=1$ transitions (e.g., $s_{1/2}\to p_{3/2}$), which proceed through small impurities in the two states.

Y^{92} could reasonably be expected to have a high-spin isomer resulting from the configuration $(g_{9/2}d_{5/2})$, as is observed in Y^{90}.[10] However, no evidence for such an isomer was found during the present experiments.

The only reasonable configuration for ${}_{41}Nb_{51}{}^{92}$ (10 day) is $(g_{9/2}d_{5/2})_{2+}$. This "anti-Nordheim" coupling of the odd proton and odd neutron is of common occurrence.[35] The two observed electron-capture branches cannot proceed via the transition $g_{9/2}\to d_{5/2}$, which is second forbidden; consequently, these two transitions must involve admixtures of other states. The most likely possibility appears to be $[(g_{9/2}{}^3)(g_{7/2})]_{2+}\to[(g_{9/2}{}^2)(g_{7/2}{}^2)]_{2+}$. Since it is well established that the $g_{7/2}$ neutron single-particle state lies $\sim$2.2 MeV above the $d_{5/2}$ level in ${}_{40}Zr_{51}{}^{91}$,[9,34,36] it would seem that there should be very little $g_{7/2}$ admixture in the Nb^{92} parent state. The calculated $\log ft$ values of $\sim$6.2 are compatible with this point of view. There is little point in discussing the nonobservation of an electron-capture transition to the 2.05-MeV level since the total decay energy of $Nb^{92}\to Zr^{92}$ is estimated to be 2.07±0.07 MeV,[3] i.e., the transition may not be energetically possible.

V. SEARCH FOR OTHER ISOMERS OF Nb^{92}

Since most of the niobium isotopes have isomeric states, it is reasonable to expect that Nb^{92} will also exhibit isomerism. In fact, a (13±2)-h activity has previously been assigned to Nb^{92},[37] having supposedly been produced by the reaction Nb^{93}(14-MeV p, pn) Nb^{92m}. However, the reported radiations of the 13-h activity do not include any of the γ-ray transitions observed in the decay of Y^{92} or Nb^{92} (10 day).

We looked for evidence that a 13-h activity was present in our sample of Nb^{92}, produced by the reaction Y^{89}(15-MeV α,n), by following the decay of both the K x rays and the 0.932-MeV γ ray with a NaI(Tl) detector. [Note: Since the spin of the 13-h state would be expected to be 6 or 7, resulting from the configuration $(g_{9/2}d_{5/2})$, it seems likely that any γ-ray cascade in Zr^{92}, following electron-capture decay of the isomer, would involve the 0.932-MeV transition.] The results obtained during the time interval 4–24 h after bombardment revealed only the 10-day component. Also, the only γ rays observed in the energy range 0.010–3.0 MeV were those known to accompany the 10-day activity.

If Nb^{92} is assumed to have a 13-h isomer, the decay data indicate that the ratio of the cross sections of formation, σ(10-day)/σ(13-h), must be $\geq$500, which seems unlikely. On the other hand, if one makes the assumption that the formation cross sections (by the

[31] S. A. Moszkowski, in *Beta- and Gamma-Ray Spectroscopy*, edited by Kai Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 391.

[32] B. L. Cohen (private communication).

[33] A. M. Lane and E. D. Pendlebury, Nuclear Phys. **15**, 39 (1960).

[34] B. L. Cohen, Phys. Rev. **125**, 1358 (1962).

[35] C. J. Gallagher, Jr., and S. A. Moszkowski, Phys. Rev. **111**, 1282 (1958).

[36] R. L. Preston, H. J. Martin, Jr., and M. B. Sampson, Phys. Rev. **121**, 1741 (1961).

[37] R. A. James, Phys. Rev. **93**, 288 (1954).

α,n reaction) of Nb^{92}(10 day) and Nb^{92m} do not differ by more than a factor of 2, then the half-life of Nb^{92m} must be <1 h or >350 yr. The latter value is based on observation of the γ-ray spectrum for a period of 130 days.

An attempt was also made to produce Nb^{92m} by the reaction $Nb^{93}(\gamma,n)$, using the beam from a 22-MeV betatron. The only niobium activity detected in the irradiated sample was 10-day Nb^{92}. Silva *et al.*[38] have reported a similar result. The reported 5.9-μsec, 0.088-MeV level of Nb^{92},[39] which is excited in the reaction $Nb^{93}(\gamma,n)$ is probably a 2− state, resulting from the configuration $(p_{1/2}d_{5/2})$.[40]

[38] E. Silva, J. Goldemberg, P. B. Smith, and L. Marquez, Nuovo cimento **9**, 17 (1958).
[39] R. B. Duffield and S. H. Vegors, Jr., Phys. Rev. **112**, 1958 (1958).
[40] *Note added in proof*. The reported 13-h niobium activity has recently been shown to result from an impurity (communication from E. T. Bramlitt and R. W. Fink to the Nuclear Data Group; reported in *Nuclear Data Pink Sheet* No. 3, February, 1962).

It is quite possible that the expected low-lying high-spin isomer, with configuration $(g_{9/2}d_{5/2})_{6+,7+}$, is the ground state of Nb^{92}, analogous to the case of Nb^{94}, which has a 6+ ground state. If this were the situation, the dominant decay mode would be an electron-capture transition to the 1.492-MeV (4+) level of Zr^{92}. This second-forbidden transition would be expected to have a half-life of $\geq 5\times 10^5$ yr.

VI. ACKNOWLEDGMENTS

We wish to express our appreciation to D. C. Hoffman and C. J. Orth for advice and assistance with the chemical procedures, to D. R. F. Cochran for providing the cyclotron bombardment, and to J. E. Schlosser for performing the betatron irradiation.

We are indebted to I. Talmi for communicating to us his shell-model analysis and calculations pertaining to Zr^{92}, which contributed greatly to our understanding of the level structure.

PHYSICAL REVIEW VOLUME 127, NUMBER 3 AUGUST 1, 1962

Decay of Sr^{85}†

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A gamma ray of 0.878 MeV was found in the decay of Sr^{85} in addition to the well-known 0.514-MeV gamma ray. The half-lives of both gamma rays were measured. The half-life of the 0.878-MeV gamma ray was found to be 64.9±1.99 days and the half-life of the 0.514-MeV gamma ray was found to be 63.9±0.27 days. There is good evidence of a gamma ray of 0.356±0.015 MeV in coincidence with the 0.514-MeV gamma ray. The 0.878-MeV gamma ray has also been found to be in coincidence with the characteristic x ray of Rb due to orbital electron capture. The relative intensities of the 0.878-, 0.356-, and 0.514-MeV gamma rays are about 1.07×10^{-4}, 0.2×10^{-4}, and 1.0, respectively. A decay scheme is proposed on the basis of these results.

INTRODUCTION

THE ground state of Sr^{85} decays to Rb^{85} by orbital electron capture usually followed by emission of a 0.514-MeV gamma ray.[1,2] The detection of any weak gamma ray of energy lower than 0.514 MeV is very difficult because of the predominance of the 0.514-MeV gamma ray. It is also difficult to discern weak gamma rays of energy less than 1.02 MeV in Sr^{85}. The use of a strong source to look for such gamma rays results in a "pile up" phenomenon; two 0.514-MeV gamma rays strike the detector simultaneously and appear as a 1.02-MeV gamma ray in a spectrometer. This effect is proportional to the square of the source strength.

† This work was supported by the U. S. Atomic Energy Commission.
[1] W. S. Emmerich and J. D. Kurbatov, Phys. Rev. **85**, 148 (1952).
[2] A. W. Sunyar, J. W. Mihelich, G. Scharff-Goldhaber, and M. Goldhabe, Phys. Rev. **86**, 1023 (1952).

The investigation of a 1-mC sample of Sr^{85} indicated[3] possible gamma radiation above the known 0.514-MeV gamma ray but because of the pile-up phenomenon it was difficult to discern the intensity or the energy of this radiation. Moving the source from the detector definitely indicated pile up, as the intensity of the 1.02-MeV photopeak decreased as the inverse fourth power of the distance from the source to the detector. A gamma ray of 0.878 MeV appeared as the source was moved further back from the detector. Its intensity fell off only as the square of the distance from the source to the detector. When an appropriate quantity of lead absorber was placed between the source and the detector, the 1.02-MeV "pile-up photopeak" could be caused to disappear and again a 0.878±0.012-MeV gamma ray did appear.

[3] All Strontium samples used in this investigation were purchased from the Oak Ridge National Laboratory.