The beta- and gamma-ray energies and relative intensities are listed in Table I.

Since it is known that an appreciable fraction of the decay of the 5.5-hour state goes by way of the 170-kev isomeric transition to the 22-minute state,[2] it is likely that the beta rays we have observed from the 5.5-hour state in reality represent the decay of the 22-minute state. The lack of similarity between the gamma-ray spectra associated with the two isomers, however, implies some degree of beta-ray branching directly from the 5.5-hour state.

PHYSICAL REVIEW VOLUME 118, NUMBER 5 JUNE 1, 1960

Beta Decay of Y^{91}†

O. E. JOHNSON AND W. G. SMITH
Physics Department, Purdue University, Lafayette, Indiana
(Received January 11, 1960)

The decay of Y^{91} was studied using NaI(Tl) scintillation counters and a 4π beta-ray scintillation spectrometer. A single gamma ray with a measured energy of 1.208±0.010 Mev was observed. The shape and end-point energy of the weak (~0.3%) beta group in coincidence with the 1.208-Mev gamma ray was measured. The end-point energy was determined to be 0.319±0.010 Mev. The experimental shape factor is clearly in disagreement with that predicted for a once-forbidden unique transition, $\Delta I=2$ (yes). The 0.319-Mev beta spectrum yields a shape factor which may, within experimental accuracy, be interpreted as a statistical shape. These measurements yield a Y^{91}-Zr^{91} mass difference of 1.527±0.014 Mev.

INTRODUCTION

THE decay schemes for Y^{91}, $t_{\frac{1}{2}}\sim 60$ days, as proposed in recent compilations of nuclear data[1,2] are in good agreement in so far as the major features are concerned. In Fig. 1, for reference purposes only, is given the decay scheme and "accepted" data as proposed by Way et al.[2] The ground-state beta group has been identified as a once-forbidden unique transition, $\Delta I=2$ (yes),[3] and the ground-state spin of Zr^{91} has been measured to be $\frac{5}{2}$.[4] Taken together, this information requires a spin of $\frac{1}{2}$ for the ground state of Y^{91} with parity opposite to that of the Zr^{91} ground state. The assignments of even parity for the ground state of Zr^{91} and odd parity for the ground state of Y^{91} are consistent with shell model predictions. Further, the even parity assignment for the ground state of Zr^{91} is supported by the measured magnetic moment of −1.3 nuclear magnetons[5] when compared with the Schmidt limits. The weak (~0.3%) beta transition ($E_{max}\sim 0.33$ Mev) populating a 1.22-Mev excited state of Zr^{91} as well as the 1.22-Mev gamma transition to the ground state was first reported by Bunker, Mize, and Starner[6] and later reported by Kahn and Lyon.[7]

The proposed decay scheme of Bunker et al.[6] includes an assignment of $\frac{5}{2}+$ for the 1.22-Mev state of Zr^{91}. These investigators point out that the logft value is somewhat large for a once-forbidden transition of the type $\Delta I=0$, 1 (yes). They also call attention to the possible unusual character of this state since the reaction $Zr^{90}(d,p)Zr^{91}$ seems to give no evidence for a level in Zr^{91} at 1.22 Mev.[8] This implies that the beta group populating the 1.22-Mev state would be a once-forbidden unique transition, $\Delta I=2$ (yes). However, Bunker et al., having measured this beta group, state that the poor resolution of the scintillation spectrometer used does not allow a conclusion as to whether the shape is statistical or of the once-forbidden unique type. On the other hand, the spin and parity assignment for this state proposed by Way et al.,[2] presumably based on the low values of the corrected comparative half-lives of the electron decay of Y^{91} and the electron capture transition of Nb^{91} to the 1.22-Mev state, is $\frac{1}{2}+$ or $\frac{3}{2}+$.

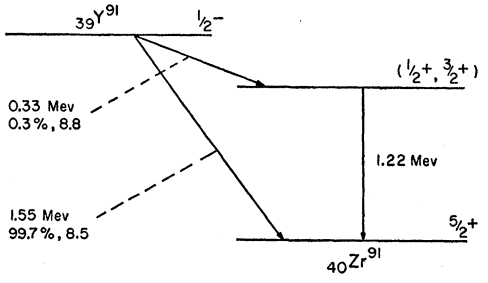

FIG. 1. The decay scheme of Y^{91} as proposed by Way et al., see reference 2, based on compiled nuclear data.

† Work supported in part by the U. S. Atomic Energy Commission.

[1] D. Strominger, J. M. Hollander, and G. T. Seaborg, Revs. Modern Phys. **30**, 585 (1958).

[2] *Nuclear Level Schemes*, $A=40-A=92$, compiled by K. Way, R. W. King, C. L. McGinnis, and R. van Lieshout, Atomic Energy Commission Report TID-5300 (U. S. Government Printing Office, Washington, D. C., 1955).

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

[4] O. H. Arroe and J. E. Mack, Phys. Rev. **76**, 873 (1949).

[5] S. Suwa, J. Phys. Soc. Japan **8**, 734 (1955).

[6] M. E. Bunker, J. P. Mize, and J. W. Starner, Phys. Rev. **94**, 1694 (1954).

[7] B. Kahn and W. S. Lyon, Phys. Rev. **98**, 58 (1955).

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

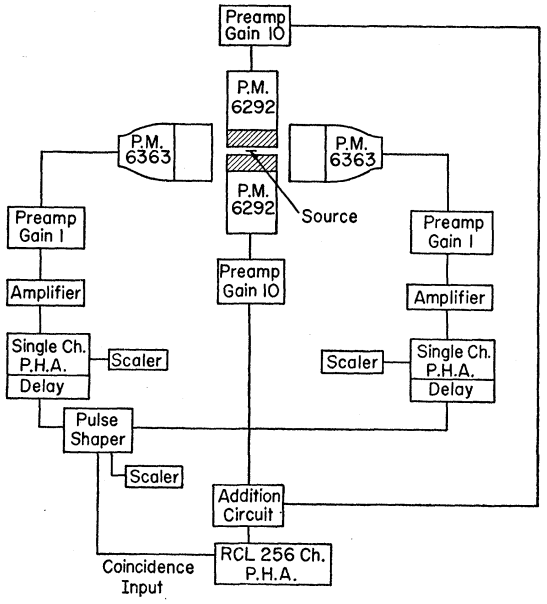

FIG. 2. Schematic diagram of the 4π beta-ray scintillation spectrometer.

The present experiment was undertaken in an effort to measure the 0.33-Mev beta group associated with the decay of Y^{91} with high enough precision to determine whether or not the experimental shape factor is consistent with that theoretically predicted for a once-forbidden unique transition.

EXPERIMENTAL APPARATUS

A schematic diagram of the 4π beta-ray scintillation spectrometer used in this investigation is shown in Fig. 2. The spectrometer system is basically the same as the one developed and described by Johnson et al.,[9] and extended in application by Robinson and Langer.[10] This is the same instrumental configuration used in the successful measurement of the weak 0.687- and 0.335-Mev beta groups associated with the Cd^{115m} decay.[11] The source, mounted on a transparent, thin Zapon lacquer film is sandwiched between two cylindrical Pilot-*B* plastic phosphors each 0.875 inches in diameter and 0.188 inches thick. The phosphors were optically coupled with Dow Corning 200 silicone fluid to DuMont 6292 photomultiplier tubes. The beta pulses from the gain-of-ten preampliers go to a linear addition circuit, gain one, and then into the linear amplifier of a 256-channel differential pulse-height analyzer. The resolution obtained for the 0.624-Mev internal conversion line of Ba^{137m} was between 10.5 and 11% for all experimental measurements. The linearity and stability of the beta system was checked periodically by measuring several internal conversion lines with energies between 61 and 974 kev and by using a precision mercury relay pulser. The energy calibration of the beta system was maintained constant to $\pm 1\%$ and the individual gains of the beta detectors matched by adjusting the high voltage.

Each of the two independent gamma-channels consisted of a 3×3-in. NaI(Tl) crystal mounted on a DuMont 6363 photomultiplier tube. The gamma detectors were placed adjacent to the beta phosphors with their axes perpendicular to that of the beta phosphors. The gamma pulses, after amplification, were analyzed in single channel differential discriminators. The discriminator windows were adjusted to accept a fixed fraction of the full-energy peak from the 1.22-Mev gamma ray associated with the decay of Y^{91}. The positions of the analyzer windows were checked periodically using an Y^{91} gamma source and the window widths were checked with the precision pulser. The suitably delayed output pulses of the differential discriminators were shaped and fed into the delayed coincidence input of the 256-channel pulse-height analyzer. The resolving time of the coincidence system is ~ 1.5 μsec. The use of the two independent gamma-channels served to double the rate at which data could be accumulated without introducing any additional complications.

The performance of this spectrometer system had been established previously by measuring certain well known beta spectra. These tests and their results have been discussed in part elsewhere.[3]

The gamma-ray spectrum of Y^{91} was measured using a 3×3-in. NaI(Tl) crystal with a 0.25-in. Lucite absorber adjacent to the crystal. The source to crystal distance was 10 cm. The resolution of this system was 8.4% for the 0.662-Mev gamma ray associated with the decay of Cs^{137}.

SOURCE PREPARATION

The Y^{91} used in this study was purchased from Oak Ridge National Laboratory. It had been chemically processed, carrier-free, from a fission products solution.

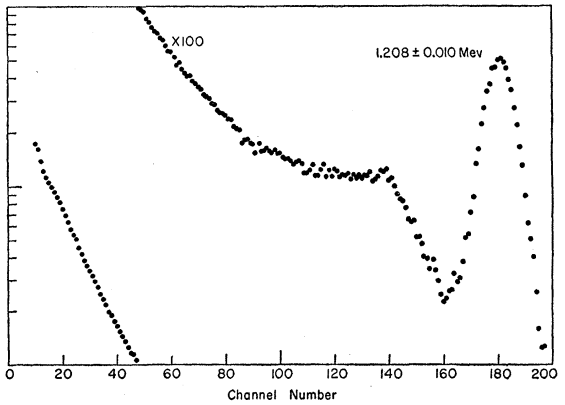

FIG. 3. A typical gamma-ray spectrum of Y^{91} measured using a 3×3 NaI(Tl) crystal.

[9] R. G. Johnson, O. E. Johnson, and L. M. Langer, Phys. Rev. **102**, 1142 (1956).
[10] R. L. Robinson and L. M. Langer, Phys. Rev. **109**, 1255 (1958).
[11] O. E. Johnson and W. G. Smith, Phys. Rev. **116**, 992 (1959).

In order to further assure the chemical purity of the source material, the following chemistry was performed. Approximately one milligram of La^{+++} was added to carry the yttrium activity. LaF_3 precipitations were made, with and without the presence of Zr^{++++} hold-back carrier. $La(OH)_3$ was precipitated and then dissolved in conc HCl; this solution was then passed through an anion exchange resin column. The La^{+++} carrier and yttrium activity were separated by eluting with lactic acid from an ethylene trichloride, boiling point 87°C, heated cation exchange resin column. The source was prepared by evaporating an $8M$ HCl solution containing the carrier-free activity on the Zapon backing.

EXPERIMENTAL RESULTS

A typical gamma-ray spectrum measured as described above is shown in Fig. 3. An energy of 1.208±0.010 Mev was obtained for the gamma transition from the first excited state to the ground state. The energy calibration was made using gamma radiations from Na^{22}, Mn^{54}, Zn^{65}, Sn^{113}, and Cs^{137}. The over-all internal consistency of the gamma calibration was about 1%. However, at higher energies, ~1.5 Mev, the least squares fitted calibration reproduced the energy to ~0.5%. The assigned error is based on the internal consistency of the energy calibration and the uncertainty due to finite resolution associated with the location of the experimental full-energy peak. No evidence was found in the pulse-height distributions for any other gamma rays except the one discussed above. This confirms the results of Bunker et al.,[6] and serves as further experimental evidence for "source purity."

A conventional Fermi plot of the beta spectrum measured in coincidence with the 1.208-Mev gamma ray is shown in Fig. 4. The spectrum was corrected using an experimentally determined chance coincidence spectrum from the same source as well as the coincidence spectrum due to general background. At the maximum in the beta spectrum the true to chance ratio was greater than 13.

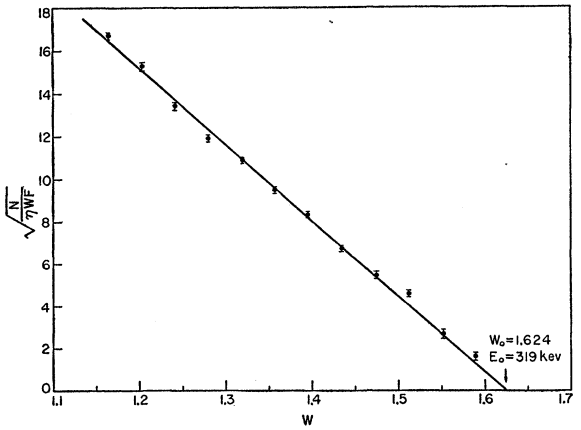

FIG. 4. A conventional Fermi plot of the beta spectrum measured in coincidence with the 1.208-Mev gamma ray.

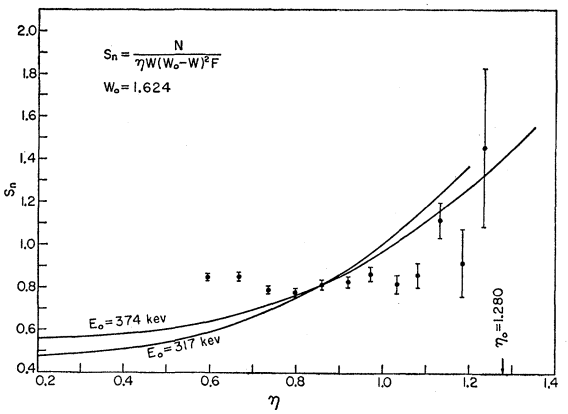

FIG. 5. The experimental shape factor calculated from the beta spectrum measured in coincidence with the 1.208-Mev gamma ray and using $W_0=1.624$. The solid lines represent the theoretical once-forbidden unique shape factors for two values of the end-point energy.

The error bars in Fig. 4 indicate counting statistics only. The straight line is least squares fitted to those experimental points corresponding to $1.164 \leq W \leq 1.473$. The finite resolution correction of Palmer and Laslett[12] was used to correct the three points corresponding to $1.551 \leq W \leq 1.628$. The body-correction was negligible. The experimental runs were programmed such that errors arising from an uncertainty in the half-life were of no significance. The linearity of the Fermi plot in Fig. 4 and the experimental shape factor in Fig. 5 makes the linear extrapolation of the least squares straight line to determine an end-point energy of 0.319±0.010 Mev seem reasonable. The error assigned to the measured end-point energy is based on the internal consistency of the energy calibration and a statistical analysis of the least squares fitted line.

In Fig. 5 is shown an experimental shape factor $S_n=N/[\eta W(W_0-W)^2F]$ obtained using an end-point energy $W_0=1.624$ and the experimental points. In addition, the once-forbidden unique shape factors $a_1=9L^2L_0+9L_1$ for two end-point energies corresponding to maximum beta kinetic energies of 0.374 and 0.317 Mev are shown. These energies correspond to the extreme values of the maximum beta kinetic energy that can be obtained using various reported end points for the ground-state transition and the reported gamma transition energy from the first excited state. The theoretical curves are normalized to the experimental point at $\eta=0.86$. The three points with $1.1<\eta<1.3$ have been end point corrected to be consistent with a linear Fermi plot since the end-point correction assumes the shape of the spectrum in the vicinity of the end point. This fact coupled with the very large statistical uncertainty in the last three points makes their comparison with the theoretical shape factors practically meaningless. However, it can be clearly seen that the remaining 9 experi-

[12] J. P. Palmer and L. J. Laslett, Iowa State College Report ISC-174, December, 1950 (unpublished).

mental points are not in agreement with the shape factor predicted for a once-forbidden unique transition. It should be pointed out that small changes in the end-point energy used in the calculation of the experimental shape factor will not alter the above conclusion.

CONCLUSIONS

The gamma-ray measurements of the present work are in essential agreement with that of other investigators.[6,7] The single gamma-ray energy was measured to be 1.208±0.010 Mev and is to be compared with 1.22±0.01 Mev[6] and 1.190±0.005 Mev[7]; with no evidence for any other gamma transitions.

The beta spectrum measured in coincidence with the 1.208-Mev gamma is in agreement with that expected for a single beta-group having a maximum electron energy of 0.319±0.010 Mev. The maximum electron energy as determined by other experimenters is reported to be 0.33±0.01 Mev[6] and 0.36±0.02 Mev.[7] The present measurement supports the conclusion that the 0.319-Mev transition is not a once-forbidden unique transition. Within the statistical accuracy of the experiment, the shape of this weak beta group corresponds to a statistical or allowed shape. This conclusion together with a comparative half-life of 8.8 suggests that the transition is a nonunique once-forbidden transition which would support the proposed alternative assignments of $\frac{1}{2}+$ or $\frac{3}{2}+$ of Way et al.,[2] for the first excited state of Y^{91}. These measurements yield a Y^{91}-Zr^{91} mass difference of 1.527±0.014 Mev in agreement with the measured beta-ray end point of 1.537±0.007 Mev by Langer and Price.[3]

ACKNOWLEDGMENT

The authors wish to thank Professor R. W. King for helpful discussions related to this investigation.

PHYSICAL REVIEW VOLUME 118, NUMBER 5 JUNE 1, 1960

Low-Energy Photodisintegration of H^3 and He^3 and Neutron-Deuteron Scattering*

L. M. DELVES†
Clarendon Laboratory, Oxford, England

(Received December 11, 1959; revised manuscript received January 4, 1960)

The cross sections for electric dipole photodisintegration of H^3 and He^3 at low energies are expressed in terms of the effective range parameters of the doublet *n-d* scattering matrix. Agreement with the experimental results is possible for either set of *n-d* scattering lengths.

I. INTRODUCTION

DIRECT elastic scattering experiments do not define the neutron-deuteron doublet and quartet scattering lengths uniquely, but lead to the two alternative sets[1]

$$\text{(A)}\quad {}^2a=0.8\pm0.3,\quad {}^4a=6.2\pm0.1, \qquad \text{(B)}\quad {}^2a=8.3\pm0.2,\quad {}^4a=2.4\pm0.2 \text{ fermis},$$

and theoretical arguments have been advanced for both sets (A)[2–4] and (B).[5–8] It is therefore of interest to point out that the low-energy H^3 and He^3 photodisintegration cross sections can be expressed in terms of the *n-d* doublet effective range. This in turn is determined, if we neglect higher terms in the effective range expansion, by the doublet scattering length and the binding energy of the last neutron in H^3. Then the large difference between the doublet scattering lengths of sets (A) and (B) leads to very large differences in the predictions for the photodisintegration cross sections. These differences do not disappear on consideration of higher terms in the expansions, but do so if, as is not unlikely, $k\cot\delta$ has a pole on the imaginary axis between zero and the triton bound state. The existence of such a pole is necessary to give agreement between the observed $d(p,\gamma)He^3$ cross section and calculations pointing to set (A) as the correct set of scattering lengths.

II. BOUND STATES AND THE EFFECTIVE RANGE EXPANSION

For any system the scattering matrix $\mathbf{S}$ referring to open channels only is, if the representation is suitably chosen, unitary and symmetric; then $\mathbf{S}$ can be diagonalized:

$$\mathbf{S}=\mathbf{T}^{-1}\exp(2i\boldsymbol{\delta})\mathbf{T}, \qquad (1)$$

* This work is supported in part by funds provided by the U. S. Atomic Energy Commission, the Office of Naval Research, and the Air Force Office of Scientific Research.

† Now at the Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, Massachusetts.

[1] D. G. Hurst and N. Z. Alcock, Can. J. Phys. **29**, 36 (1957); E. O. Wollan, C. G. Shull, and W. C. Koehler, Phys. Rev. **83**, 700 (1951).
[2] R. S. Christian and J. L. Gammel, Phys. Rev. **91**, 100 (1953).
[3] L. Motz and J. Schwinger, Phys. Rev. **58**, 26 (1940).
[4] A. S. Davidov and G. F. Filippov, J. Exp. Theoret. Phys. U.S.S.R., **4**, 267 (1957).
[5] A. Troesche and M. Verde, Helv. Phys. Acta **24**, 39 (1951).
[6] M. M. Gordon, Phys. Rev. **80**, 111 (1950).
[7] F. G. Prohammer and T. A. Welton, Oak Ridge National Laboratory Report ORNL-1005 (unpublished).
[8] L. M. Delves and D. Brown, Nuclear Phys. **11**, 439 (1959).