High-Spin Isomers in ^{91}Nb and ^{91}Zr via ^{6}Li-Induced Reactions*

B. A. Brown,† P. M. S. Lesser,‡ and D. B. Fossan
State University of New York at Stony Brook, Stony Brook, New York 11794
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High spin levels in ^{91}Nb and ^{91}Zr have been studied with the reactions ^{88}Sr(^{6}Li, $3n$)^{91}Nb and ^{88}Sr(^{6}Li, $p2n$)^{91}Zr by pulsed-beam–γ, γ-γ, and γ-$W(\theta)$ measurements. Isomers were found which agree with theoretical predictions: a $\tau = 5.42 \pm 0.18$-μsec state at 2035 keV in ^{91}Nb, $|(g_{9/2})^2 p_{1/2}, \frac{17}{2}^-\rangle$, and a $\tau = 6.15 \pm 0.50$-μsec state at (3183) keV in ^{91}Zr, $|(g_{9/2})^2 \times d_{5/2}, \frac{21}{2}^+\rangle$. The $|g_{9/2} p_{1/2} d_{5/2}, \frac{15}{2}^-\rangle$ state in ^{91}Zr was located at 2288 keV by a 28.1-keV decay γ ray.

The effective interaction and electromagnetic operators for valence nucleons of a specific configuration are necessary for the understanding of its nuclear structure. These operators, which are also of intrinsic interest, can be determined with accuracy from studies of the usually pure high-spin states which are formed uniquely within the configuration. A level-scheme identification (E_{ex}, J^{π}) of these high-spin states yields the effective interaction operators while γ-ray transition strengths (lifetimes) yield the effective electromagnetic operators. Little information is available regarding the high-spin states of the odd nuclei in the $A \approx 90$ region with $N = 50$ and 51 neutrons. This information together with that for the even nuclei is crucial for an effective-operator study. In this region, the neutrons form a closed shell of $N = 50$ with the valence neutrons being in the $2d_{5/2}$ orbital, and the valence protons outside the $^{88}_{38}$Sr$_{50}$ core in the $1g_{9/2}$ and $2p_{1/2}$ orbitals. For those nuclei with the simplicity of three valence nucleons, $^{91}_{41}$Nb$_{50}$ is expected to have proton configurations of $(g_{9/2})^2 p_{1/2}$ and $(g_{9/2})^3$ with maximum spins $J^{\pi} = \frac{17}{2}^-$ and $\frac{21}{2}^+$, while in $^{91}_{40}$Zr$_{51}$, the configurations $g_{9/2} p_{1/2} d_{5/2}$ and $(g_{9/2})^2 d_{5/2}$ have maximum spins of $\frac{15}{2}^-$ and $\frac{21}{2}^+$, respectively.[1-3] Prior to the present experiment, this $\frac{17}{2}^-$ state in ^{91}Nb and the $\frac{15}{2}^-$ and $\frac{21}{2}^+$ states in ^{91}Zr, which were predicted to be isomers,[1,3] along with other high-spin states had not been observed, although numerous attempts had been made. In this Letter, experimental results obtained via previously unexploited ^{6}Li-induced fusion-evaporation reactions on ^{88}Sr are presented. These reactions gave the proper high-spin selectivity for γ-ray spectroscopy in $\Delta Z \leq 3$ nuclei. The above ^{91}Nb and ^{91}Zr high-spin states including the isomers were found. These results represent a significant increase in knowledge with respect to a complete effective-operator interpretation. In particular, comparisons of these results and those for even nuclei indicate a sensitivity to small configuration admixtures, namely proton holes. A report on final data for the ^{91}Nb isomer has been made.[4]

To study the population of these high-spin states in ^{91}Nb and ^{91}Zr, a thick natural Sr metal target was bombarded with ^{6}Li ions over an energy range of 20–35 MeV. The resulting γ-ray yields showed a significant cross section to these states from the reactions ^{88}Sr(^{6}Li, $3n$)^{91}Nb and ^{88}Sr(^{6}Li, $p2n$)^{91}Zr (3:1 ratio) at a ^{6}Li energy of 34 MeV. In these reactions,[5] the heavy ion takes a large orbital angular momentum l into the fused compound system; the subsequent evaporation of low-energy nucleons, which carry away only small angular momenta, populates high-spin states in the residual nuclei. The dominant decay mode of these states is via stretched γ-ray cascades $J \rightarrow J - L$ down through the yrast levels (lowest E_J). Because l is perpendicular to the beam, the high-spin states excited are strongly aligned in low-m substates resulting in anisotropic γ-ray angular distributions which are characteristic of the multipolarity L.

In order to establish the level scheme and the decay properties of the high-spin states in the residual nuclei, the following set of experiments using Ge(Li) and Si(Li) detectors were performed: (1) pulsed-beam–γ timing, (2) γ-γ coincidence, and (3) γ angular distribution measurements. (1) The observation of delayed γ rays with pulsed-beam timing allows the location of isomeric states and the study of their decay modes. These experimental results also yield a determination of the lifetimes involved. Measurements using time resolutions of ~5 nsec were made for pulse repetition periods ranging from 250 nsec to 32 μsec. (2) Because of the complex nature of the γ-ray spectra from these reactions involving several residual nuclei, γ-γ coincidence measurements with a Ge(Li)-Ge(Li) detector combination were required to identify the γ-ray cascades. Ge(Li)-Si(Li) coincident spectra were

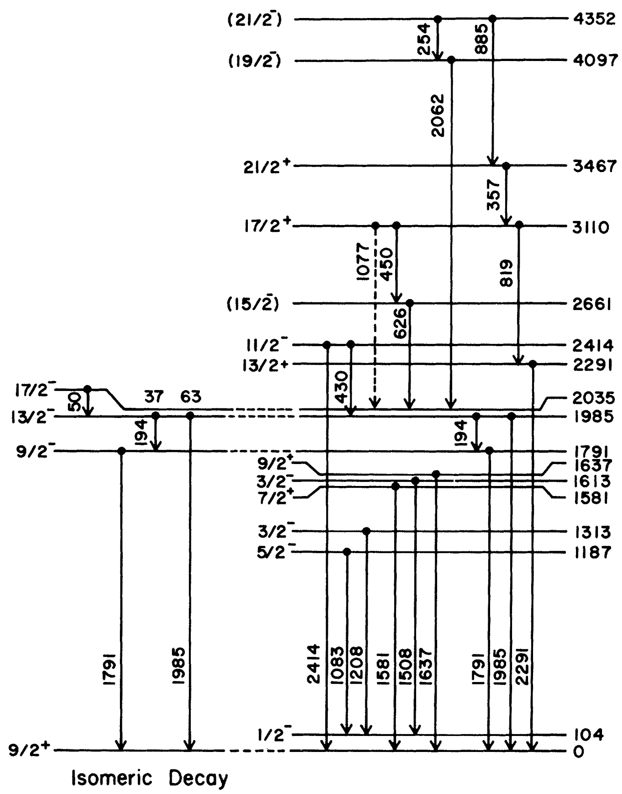

FIG. 1. The γ-ray decay scheme for ^{91}Nb observed in the present study with the reaction ^{88}Sr(^{6}Li, $3n$)^{91}Nb. The levels and J^π assignments are from the present and previous studies. The isomeric decay scheme observed for the $\frac{17}{2}^-$ 2035-keV level ($\tau = 5.42 \pm 0.18$ μsec) is shown on the left.

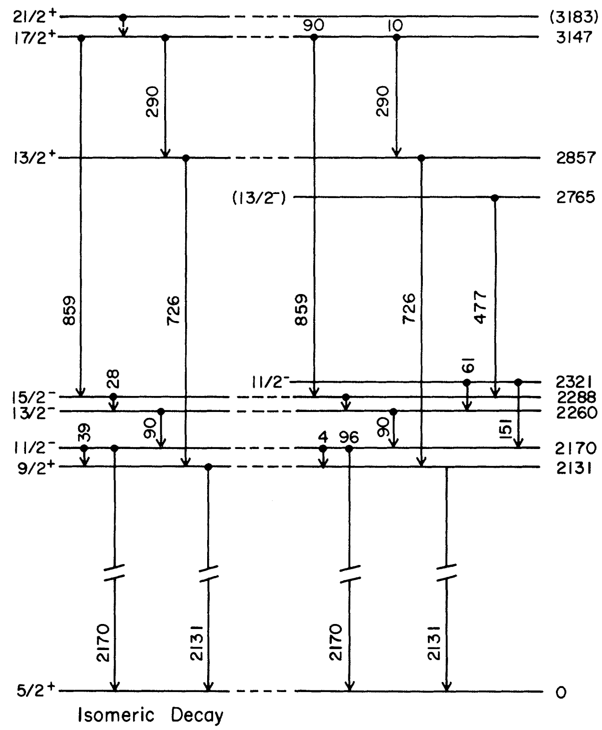

FIG. 2. The γ-ray decay scheme for ^{91}Zr observed in the present study with the reaction ^{88}Sr(^{6}Li, $p2n$)^{91}Zr. The levels and J^π assignments are from the present and previous studies. The isomeric decay scheme observed for the $\frac{21}{2}^+$ 3183-keV level ($\tau = 6.15 \pm 0.50$ μsec) is shown on the left.

also measured in order to include the low-energy γ rays. (3) To obtain information on the spins of the levels and the γ-ray multipolarities as well as the γ-ray intensities I_γ, the γ-ray angular distributions were measured in singles at seven angles between 0° and 90°. The photopeak areas were extracted and fitted to $W(\theta) = I_\gamma[1 + A_2P_2 + A_4P_4]$. In this way, the A_2 and A_4 coefficients of the Legendre polynomials and the intensities I_γ corrected for efficiency were obtained. Strong J assignments were obtained from $W(\theta)$, lifetime, and I_γ (electron-conversion) results under the argument[5] that yrast levels are populated (low-m substates) and that they decay via stretched $J \rightarrow J - L$ γ transitions.

The γ-ray decay scheme for ^{91}Nb observed in the present study from the reaction ^{88}Sr(^{6}Li, $3n$)^{91}Nb is shown in Fig. 1 and that for ^{91}Zr from the reaction ^{88}Sr(^{6}Li, $p2n$)^{91}Zr is shown in Fig. 2. The isomeric decays which are the focus of the present Letter are separated to the left in both figures. The levels and J^π assignments listed are from the present and previous studies. Previously, ^{91}Nb and ^{91}Zr have been investigated with light-ion reactions.[6-11]

In the present experiment, three γ rays with energies of 194, 1791, and 1985 keV, that were known to be from ^{91}Nb (see Fig. 1), appeared with large intensities in the microsecond-delayed γ spectrum all displaying a similar time dependence. These γ rays are associated with $\frac{13}{2}^- \rightarrow \frac{9}{2}^-$, $\frac{9}{2}^- \rightarrow \frac{9}{2}^+$, and $\frac{13}{2}^- \rightarrow \frac{9}{2}^+$ transitions, respectively, on the basis of the present as well as previous[9,7] measurements. The mean lifetime obtained from fits to these delayed γ rays is $\tau = 5.42 \pm 0.18$ μsec. In addition, a less intense new γ ray of 50 keV was observed to be delayed with the same lifetime. In the γ-γ data, the 50-keV γ ray was found to be coincident with the 1985- and the 194-keV γ rays. A precise energy of 50.1 ± 0.2 keV was determined with a Si(Li) detector. The above results including τ and I_γ give strong evidence for this being the $\frac{17}{2}^-$ 2035 → $\frac{13}{2}^-$ 1985 $E2$ transition [internal conversion coefficient (ICC), 13.9] as shown in Fig. 1. The lifetime $\tau = 5.42 \pm 0.18$ μsec is then associated with the $\frac{17}{2}^-$ 2035-keV level in ^{91}Nb. This level is expected to be the $|(g_{9/2})^2 p_{1/2}, \frac{17}{2}^-\rangle$ state which was predicted[3] to be isomeric and at about this energy. The resulting $B(E2)[\frac{17}{2}^- \rightarrow \frac{13}{2}^-] = (32.0 \pm 1.1)e^2$ fm^4 implies an effective proton charge $e_p = 1.45$, which is interestingly ~30% smaller than that for the ^{90}Zr $8^+ \rightarrow 6^+$ $E2$ transition. A fit of theoretical "rates"[3] for $N = 50$ nuclei gave $e_p = 1.72$. The influence of $p_{3/2}$ or $f_{5/2}$ holes is suggested.

In addition to the above isomeric delays, the same three γ rays (194, 1791, and 1985 keV) also exhibited in the present data a shorter delayed component consistent with $\tau \approx 15$ nsec. In a previous ^{89}Y(α, 2n)^{91}Nb experiment,[7] a mean lifetime of $\tau = 14.4 \pm 0.5$ nsec was observed for the 1985-keV γ ray and attributed to another cascade γ ray of similar delay which was subsequently found to be a contaminant. Thus, in agreement with the present experiment, their result[7] of $\tau = 14.4 \pm 0.5$ nsec is associated with the 1985-keV $\frac{13}{2}^-$ level. The g-factor measurement obtained in the same experiment,[7] $g = 1.25 \pm 0.04$, is exactly that expected for the $|(g_{9/2})^2 p_{1/2}, \frac{13}{2}^-\rangle$ state. The present $W(\theta)$ results for the 194-keV γ ray agree with a $\frac{13}{2}^- \rightarrow \frac{9}{2}^-$ $E2$ transition and yield a branching of (63 ± 1)% for the 1985-keV transition. After branching corrections, the lifetime of the $\frac{13}{2}^-$ 1985-keV level is consistent with the expected $E2$ strength.

Although the prompt γ rays will not be emphasized here, three coincident γ rays of 357, 819, and 2291 keV in ^{91}Nb (see Fig. 1) which were observed in the present data and also with the reaction ^{90}Zr(α, p2n)^{91}Nb,[8] have been assigned to the stretched $E2$ cascade $\frac{21}{2}^+ \rightarrow \frac{17}{2}^+ \rightarrow \frac{13}{2}^+ \rightarrow \frac{9}{2}^+$ on the basis of the I_γ and $W(\theta)$ results. The energies of the upper three states in this cascade agree with those expected[1-3] for the $(g_{9/2})^3$ configuration in ^{91}Nb.

In ^{91}Zr (see Fig. 2) a 90-, a 2170-, and a new 859-keV γ ray, that were in coincidence from the γ-γ data, appeared in the microsecond-delayed time spectrum with significant intensity. All three yielded a consistent mean lifetime of $\tau = 6.15 \pm 0.50$ μsec. The 90- and 2170-keV γ rays also contained a shorter delayed component ($\tau \approx 50$ nsec). Previously with the reaction ^{88}Sr(α, n)^{91}Zr, these two γ rays were assigned to the $\frac{13}{2}^- \rightarrow \frac{11}{2}^- \rightarrow \frac{5}{2}^+$ cascade and measured to have a time dependence of $\tau = 41.8 \pm 1.2$ nsec which was attributed to an unobserved $\frac{15}{2}^- \rightarrow \frac{13}{2}^-$ cascade $E_\gamma < 80$ keV.[7] In the present experiment, a 28.1 ± 0.1-keV γ was found to be in coincidence with the 859- and 2170-keV transitions by a Si(Li)-Ge(Li) γ-γ measurement. The 28-keV γ ray has been assigned to a $\frac{15}{2}^-$ 2288 → $\frac{13}{2}^-$ 2260 $M1$ transition on the basis of the γ-γ data, the I_γ (ICC, 8.9), the lifetime,[7] and the good energy agreement with levels observed in (p, p') $\Delta l = 5$ transfer data of Blok.[11] This result then defines the position of the $|g_{9/2} p_{1/2} d_{5/2}, \frac{15}{2}^-\rangle$ state at 2288 keV in ^{91}Zr which is in disagreement with the predictions[1] of its energy and thus its isomeric decay.

The coincident 859-keV γ ray, which feeds the $\frac{15}{2}^-$ 2288-keV level, thus originates at 3147 keV which is consistent with a level at 3143 ± 9 keV observed[11] in the (p, p') work. The 859-keV γ ray showed a negative A_2 characteristic of a dipole transition and its time spectra contained a 35% prompt component. These experimental facts strongly imply that the 3147-keV level in ^{91}Zr is the $\frac{17}{2}^+$ member of the $(g_{9/2})^2 d_{5/2}$ configuration with the 859-keV $\frac{17}{2}^+ \rightarrow \frac{15}{2}^-$ $E1$ transition giving the observed prompt component. The $\frac{17}{2}^+$ state also decays by a 10% branch via a $\frac{17}{2}^+ \rightarrow \frac{13}{2}^+ \rightarrow \frac{9}{2}^+ \rightarrow \frac{5}{2}^+$ $E2$ cascade through lower spin members of the $(g_{9/2})^2 d_{5/2}$ configuration yielding 2857 keV for the $\frac{13}{2}^+$ energy. The $|(g_{9/2})^2 d_{5/2}, \frac{21}{2}^+\rangle$ state, which had been predicted[1] to lie slightly below the $\frac{17}{2}^+$ state, is not the 3147-keV level since a $\frac{21}{2}^+ \rightarrow \frac{15}{2}^-$ $E3$ transition has a positive A_2 with an estimated $\tau = 165$ μsec. Thus, the isomeric nature of the 859-keV and subsequent γ rays most probably results from a $\frac{21}{2}^+ \rightarrow \frac{17}{2}^+$ $E2$ transition of low energy. On the basis of the ^{90}Zr $8^+ \rightarrow 6^+$ $E2$ strength, the energy which is consistent with a $\tau = 6.15$ μsec, $\frac{21}{2}^+ \rightarrow \frac{17}{2}^+$ $E2$ transition is 32 keV (ICC, 66). A γ ray of 36.3 keV observed in the Si(Li) singles and total coincidence spectra had the right intentisy (an ICC of 42) for this transition; however, the large ICC prevented a definite Si(Li)-Ge(Li) coincidence result. Assuming 36.3 keV, a consistent $B(E2)[\frac{21}{2}^+ \rightarrow \frac{17}{2}^+] = 49.0e^2$ fm^4 is obtained. With $E_\gamma \leq 36$ keV the $|(g_{9/2})^2 d_{5/2}, \frac{21}{2}^+\rangle$ level in ^{91}Zr is located at 3183 keV or a few keV less. A recent calculation communicated by Gloeckner[3] predicted the $\frac{21}{2}^+$ state to be 20 keV above the $\frac{17}{2}^+$ state.

In summary, high-spin states involving $g_{9/2} p_{1/2}$ protons and $d_{5/2}$ neutrons have been found in ^{91}Nb and ^{91}Zr. From the energies of these pure states, an improved determination[3] of the effective interaction operators can now be obtained. The transition strengths deduced from the isomeric lifetimes also determine effective electromagnetic operators; an $E2$ effective-charge analysis for the $A \approx 90$ nuclei similar to those for the Pb and Ca regions[12] is planned.

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†Present address: University of Tokyo, Tokyo, Japan.

‡Present address: Brooklyn College, City University of New York, New York, N. Y. 11234.

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Experimental Measurement of the Form Factors of the Decay $K_L^0 \to \pi^\pm e^\mp \nu$†

R. Blumenthal,* S. Frankel, J. Nagy,‡ L. Resvanis, O. Van Dyck,§ and R. Werbeck§
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19174

and

R. Winston
Department of Physics, University of Chicago, Chicago, Illinois 60637

and

V. Highland
Department of Physics, Temple University, Philadelphia, Pennsylvania 19122

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We have analyzed 25 000 K_{e3} decays, reconstructed to the center of mass by measurement of the K_L^0 momentum from time of flight and measurement of the π and e momenta with a spark-chamber–magnet spectrometer. Using the linear parametrization of the vector form factor $f_+(q^2) = 1 + \lambda_+(q^2/m_\pi^2)$ we find $\lambda_+ = 0.0270 \pm 0.0028$. Upper limits for the scalar (f_s) and tensor (f_t) form factors at the 68% confidence level are $f_s/f_+ < 0.04$, $f_t/f_+ < 0.23$, corresponding to intensity ratios $I_s/I_v < 0.3\%$ and $I_t/I_v < 0.4\%$.

As part of an experimental study of K_L^0 decays we have made a new measurement of the vector form factor $f_+(q^2)$, and set new limits on the scalar (f_s) and tensor (f_t) form factors in K_{e3} decay ($K_L^0 \to \pi^\pm e^\mp \nu$). These data serve to resolve discrepancies in published results for the K_{e3}^0 vector form factor and provide definitive data relating to the equality of K_{e3}^0 and K_{e3}^+ form factors.[1] This experiment utilized the rf structure of the proton beam of the Princeton-Pennsylvania Accelerator to determine the momenta of the decaying K_L^0 mesons, thus allowing for event reconstruction to the K_L^0 center-of-mass system and kinematic suppression of possible $K_{3\pi}$ contamination.

The vertical view of the apparatus (Fig. 1) is self-explanatory. Charged secondaries of the decays $K \to \pi e \nu$, $K \to \pi \mu \nu$, and $K \to \pi^+ \pi^- \pi^0$ inside the vacuum region were recorded in magnetostrictive spark chambers located before and after