^{92}Nb using ^{89}Y(α, $n\gamma$)^{92}Nb and ^{92}Zr(p, $n\gamma$)^{92}Nb†

J. M. Davidson and D. M. Sheppard
Nuclear Research Centre, The University of Alberta, Edmonton, Canada

P. W. Green* and J. A. Kuehner
Tandem Accelerator Laboratory, McMaster University, Hamilton, Canada
(Received 16 August 1976)

The states of ^{92}Nb were studied using the reactions ^{89}Y($\alpha,n\gamma$)^{92}Nb and ^{92}Zr($p,n\gamma$)^{92}Nb. The level and decay scheme of ^{92}Nb up to 1.6 MeV excitation was deduced from excitation function and γ-γ coincidence data. Spins were deduced for many states from the analysis of γ-ray angular distribution and γ-γ angular correlation data. These include members of the $1g^{\pi}_{9/2} \otimes 2d^{\nu}_{5/2}$ sextuplet at 286 (J = 3) and 481 (J = 4) keV excitation, and the $(2p^{\pi}_{1/2})^{-1} \otimes 2d^{\nu}_{5/2}$ doublet at 226 (J = 2) and 390 (J = 3) keV excitation.

[NUCLEAR REACTIONS ^{89}Y($\alpha,n\gamma$), E=7.0–12.5 MeV, ^{92}Zr($p,n\gamma$), E=3.0–5.0 MeV; measured E_γ, $\sigma(E,E_\gamma)$, $\sigma(E_\gamma,\theta_\gamma)$, $\gamma\gamma$ coincidence; ^{92}Nb deduced levels, J, π, δ. Enriched and natural targets. Ge(Li) detectors.]

I. INTRODUCTION

The shell-model ground state of the odd-odd nucleus ^{92}Nb is normally pictured as having single unpaired nucleons in the $1g^{\pi}_{9/2}$ and $2d^{\nu}_{5/2}$ orbitals, outside a ^{90}Zr core. In this picture, the *jj* coupling of these nucleons forms a low-lying sextuplet of positive-parity states having spins from J=2 to J=7. In addition, the shell-model configuration coupling a $2p_{1/2}$ proton hole and a $2d_{5/2}$ neutron is expected to give rise to a low-lying negative parity doublet having spins 2 and 3.

The knowledge of the level scheme of ^{92}Nb up to 501 keV excitation as it stood at the beginning of this work[1] is summarized in Fig. 1. The parities of the eight levels pictured have been determined in various reaction studies.[2-8] The spin of the 136 keV level is probably J=2, as shown by its β^+ decay.[9] In assigning spins to these levels, it has been the tradition in previous works to assume *a priori* that they comprise the two *jj*-coupled multiplets and that an experiment need only determine the ordering of the spins *within the multiplets*. In the present work, spin assignments were deduced for these states, making only the minimal assumptions that: (i) the spin-parity of the 136 keV state is $J^\pi = 2^+$, and (ii) the parities and lifetimes[10] of the other seven states are as shown in Fig. 1. Higher-lying states of ^{92}Nb were also investigated in this work, because their properties may bear upon the assignments of spins in the low-lying group and because information on states in this region of excitation is rather limited.

The reactions used in this investigation were the ^{89}Y($\alpha,n\gamma$)^{92}Nb and ^{92}Zr($p,n\gamma$)^{92}Nb reactions. γ-ray excitation functions, angular distributions, and γ-γ angular correlations were measured for both reactions. The level and decay scheme of ^{92}Nb was deduced up to 1.6 MeV excitation. Unambiguous spin assignments were made for most of the low-lying levels. Spin assignments were also made for several states in the region from 0.5 to 1.6

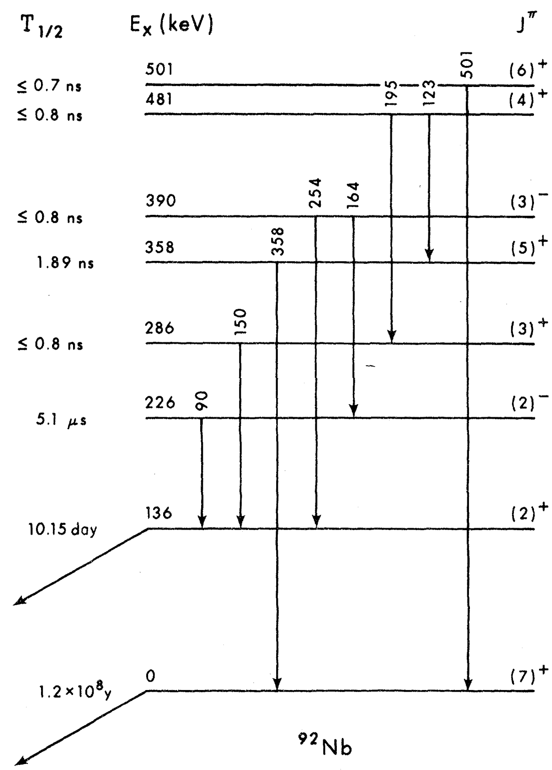

FIG. 1. Low-lying levels of ^{92}Nb at the beginning of the present work (Ref. 1).

MeV excitation. These results are compared with the results of previous charged-particle[2-8] and γ-ray[10-12] studies. Preliminary reports of this study have been already given.[13]

II. EXPERIMENTAL DETAILS

A. ^{89}Y($\alpha,n\gamma$)^{92}Nb reaction

Targets consisted of natural Y foils (100% ^{89}Y). For the measurements of γ-ray excitation functions, a 50 mg/cm^2 foil, which was thick enough to stop the beam, was used to improve the counting statistics in the peaks of interest, while for the angular distribution and angular correlation measurement, a 0.9 mg/cm^2 rolled Y foil, for which the beam energy loss was approximately 200 keV, mounted on a 0.127 mm Au backing was used.

The targets were bombarded with α particles from the McMaster University FN Van de Graaff accelerator. γ rays were detected with Ge(Li) detectors of active volumes and resolutions of 48 cm^3($\Delta E = 3$ keV at 1.33 MeV), 50 cm^3 ($\Delta E = 3$ keV at 1.33 MeV), and 14 cm^3 ($\Delta E = 1.4$ keV at 122 keV). Neutrons from the reaction were not observed.

γ-ray excitation functions were measured with the 50 cm^3 (positioned at $\theta = -55°$) and 14 cm^3 (positioned at $\theta = 90°$) Ge(Li) detectors, at incident energies from 7.0 to 12.5 MeV in steps of 0.5 MeV. Beam currents for these experiments were typically 100 nA of α^{++}, and each spectrum was collected for about 1 h. The excitation function data from both reactions were used only to establish that the approximate threshold for any particular γ ray was consistent with its assigned location in the ^{92}Nb decay scheme.

Angular distributions were measured at an incident energy of 12.0 MeV. From the study of the excitation functions, it was determined that even at such high bombarding energy, the contribution to the yield from the states below 0.5 MeV excitation due to cascade feeding from higher levels was small, and the effects on the alignment of the low-lying states due to such cascades was ignored in the analysis of the data. The effect of cascades between the low-lying states was generally small (although not negligible) and was taken into account.

The angular correlation measurements were also performed at an incident energy of 12.0 MeV. The 48 cm^3 Ge(Li) detector was fixed in the reaction plane at $\theta = 90°$, and the 50 cm^3 detector was rotated between 0° and 90°. Both detectors were 8.5 cm from the target. Coincidences between the two detectors were recorded event by event on magnetic tape. The data were then sorted off line, by placing digital windows on transitions observed in the fixed detector to generate the spectrum of coincident γ rays observed in the movable detector. In this way, angular correlations were obtained for both the $A1$ and $A2$ geometries[14] for several cascades in ^{92}Nb.

Sample ^{89}Y($\alpha,n\gamma$)^{92}Nb γ-γ coincidence spectra are shown in Fig. 2.

B. ^{92}Zr($p,n\gamma$)^{92}Nb reaction

Beams of 3.0 to 5.0 MeV H$^+$ ions were provided by the University of Alberta Van de Graaff accelerator. The target, except for the measurement of angular distributions, consisted of a fine granular deposit of ZrO_2 (> 95% ^{92}Zr) glued to a 0.25 mm thick Ta backing, which also served as the vacuum seal and end plate of the beam line. The target used in the measurement of γ-ray angular distributions was a rolled foil of Zr metal (> 95% ^{92}Zr) glued to a 0.025 mm thick Ag foil which was in turn glued to a 0.127 mm thick Ni backing which served as the vacuum seal and end plate on the beam line. The targets were mounted at an angle of 30° with respect to the beam direction. The Zr foil targets were 1.98 mg/cm^2 in thickness. γ-ray spectra were recorded using Ge(Li) detectors

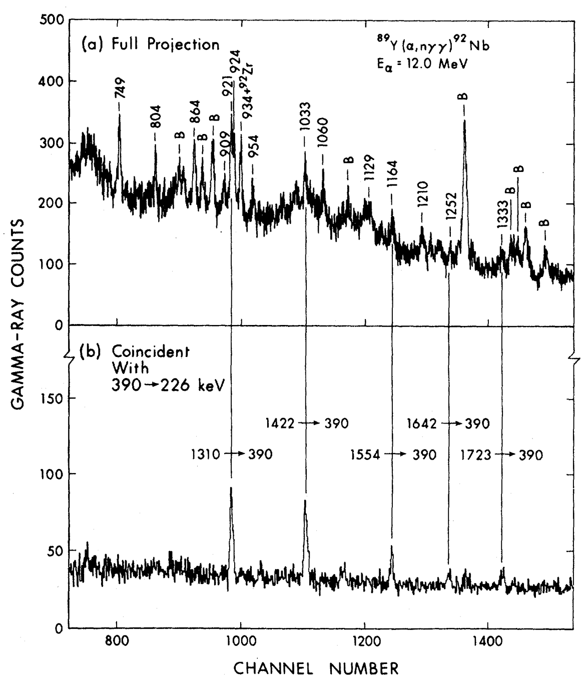

FIG. 2. Sample γ-γ coincidence spectra (background subtracted) from the ^{89}Y($\alpha,n\gamma$)^{92}Nb reaction. γ rays arising from other sources are identified by the γ-emitting final nuclei; unidentified background peaks are denoted by a B. For ^{92}Nb transitions, γ-ray energies (keV) are given in (a) and initial and final level energies (keV) are given in (b).

of high efficiency (8–10%) and resolution ($\Delta E \leq 3$ keV at $E_\gamma = 1.33$ MeV) in various configurations as described below; neutrons from the reaction were not observed. For all measurements in this work, two Ge(Li) detectors were used. One of these was always fixed at 90° with respect to the beam direction. The other Ge(Li) detector was fixed at $-55°$ for the measurement of the excitation functions and for the γ-γ coincidence measurements at $E_p = 4.8$ MeV. For the measurements of angular distribution and angular correlation data, it was allowed to move in the quadrant from 0° to 90° . Energy and efficiency calibration was performed using sources of ^{22}Na, ^{56}Co, and ^{133}Ba, for which the γ-ray energies and relative intensities are well known.[15,16] During all data recording, beam currents were maintained at such a level that the singles counting rate in each detector was no greater than 10 000 counts/s. Beam currents ranged from 50 to 300 nA. Signals from the Ge(Li) detectors were processed using *NIM* standard electronics and were analyzed and stored on line using a Honeywell DDP-516 computer.

In the measurement of excitation functions, spectra were recorded at 200 keV intervals from 3.0 to 5.0 MeV incident energy. The distance from the reaction site to the front face of each detector was about 10 cm. At each energy, run times of approximately two hours were necessary to obtain adequate statistics.

The γ-ray angular distributions were measured at incident energies of 3.34, 4.0, and 4.5 MeV. These energies were chosen to fall near the threshold for populating ^{92}Nb states of interest. The distance to the front face of each detector was 22 cm. These distributions were obtained with the moving detector positioned at up to seven different angles from 0° to 90°, with several angles repeated for each beam energy as a reproducibility check. The data collection time at each angle ranged from one hour to three hours.

In the measurement of γ-γ coincidences, data were collected at 4.8 and 4.5 MeV incident energies. These coincidence data were recorded in the event mode on magnetic tape. For the data taken at 4.8 MeV incident energy, the target-detector distance was approximately 2 cm, with the detectors fixed at $\theta = -55°$ and $\theta = 90°$. This configuration was used in an extended run of about 30 hours, with the objective of establishing the ^{92}Nb level and decay scheme with greater confidence than was possible with the measurement of excitation functions in singles. At 4.5 MeV incident energy, γ-γ angular correlations were recorded. The target-detector distance for this measurement was approximately 5 cm for each detector. The incident energy of 4.5 MeV was chosen to lie just above the threshold for populating the 1415 keV state of ^{92}Nb. This state is of particular interest because of its strong γ-ray branching to the 481 keV state, which connects it via cascade to all members of the $1g^{\pi}_{9/2} \otimes 2d^{\nu}_{5/2}$ sextuplet, except the 501 keV state. It was hoped that the simultaneous measurement of the various correlations involving the 1415 keV state would yield information on the ordering of spins in the lower-lying multiplet. In the course of the angular correlation measurements, data were recorded for seven different angle settings of the movable detector, with three angles repeated as a reproducibility check. The event recording during the angular correlation measurements enabled the simultaneous acquisition of data for both the *A*1 and *A*2 Ferguson geometries.[14] Because of the low data acquisition rate for coincidence measurements, run times of 12 hours per angle were necessary. After collection of the angular distribution and angular correlation data, the alignment of the correlation table was checked, using target radioactivity ($\tau_{1/2} = 10.2$ day) from the ^{92}Nb(β^+)^{92}Zr*(934 keV)^{92}Zr decay; a small anisotropy was noted and an appropriate correction was made to the data.

Sample ^{92}Zr($p,n\gamma$)^{92}Nb γ-γ coincidence spectra are shown in Fig. 3.

III. EXPERIMENTAL RESULTS AND ANALYSIS

Figure 4 shows the ^{92}Nb level and decay scheme established from the γ-γ coincidence data. The normalized angular distribution data for each transition were corrected for absorption in the target backing materials using known[17] photon cross sections and fitted to an even-order Legendre series up to order 4,

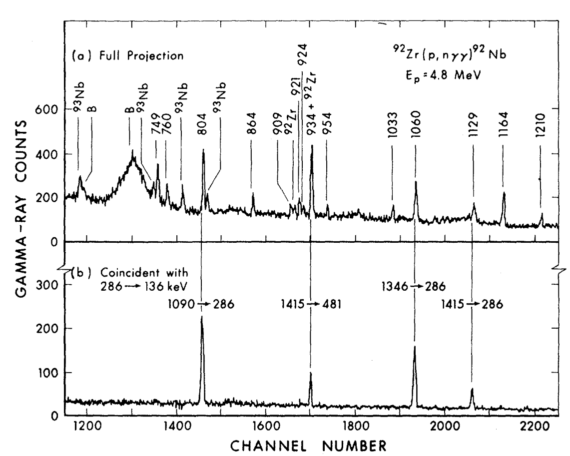

FIG. 3. Sample γ-γ coincidence spectra (background subtracted) from the ^{92}Zr($p,n\gamma$)^{92}Nb reaction. The notation is as described for Fig. 2.

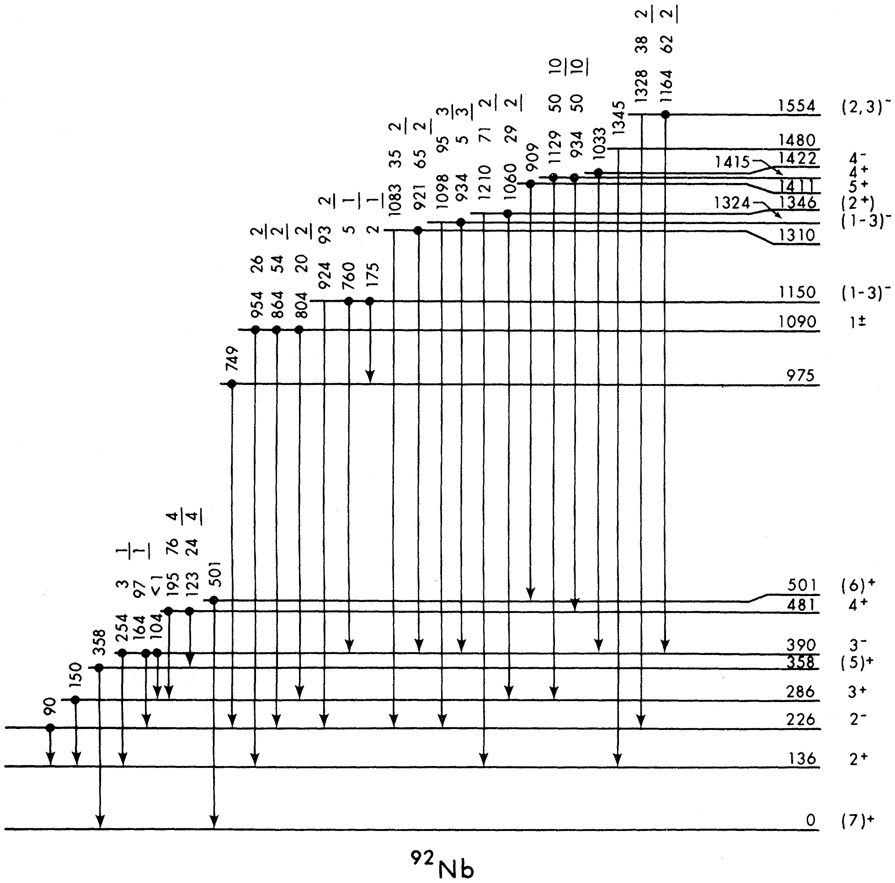

FIG. 4. The ^{92}Nb level and decay scheme as determined in the present work. The dot at the origin of a transition indicates that its existence was verified in γ-γ coincidence data. The γ-ray energy (keV), branching ratios (%) and errors in the branching ratios are indicated above each transition. The excitation energy (keV) and assigned spin and parity are given at the right hand side of each level. The notation for the errors is as defined in Table I.

$$y(\theta)=A_0[1+a_2P_2(\cos\theta)+a_4P_4(\cos\theta)].$$

The branching ratios indicated in Fig. 4 were determined where possible from the fitted values of A_0, corrected for the efficiency of the γ-ray detector. Otherwise they were determined from the coincidence data. A summary of the experimental values of a_2 and a_4 for both the angular distribution and angular correlation measurements is contained in Tables I and II for the ^{89}Y($\alpha,n\gamma$) and ^{92}Zr($p,n\gamma$) reactions, respectively.

Analysis of the angular distribution and angular correlation data was done using the statistical compound nuclear model (see, e.g., Refs. 18 and 19). For the incident and inelastic channels, the proton optical model parameters were those of Perey[20] and the α-particle parameters were those of Bingham, Halbert, and Quinton.[21] For the neutron channels, the real and imaginary well parameters were those of Wilmore and Hodgson.[22] The neutron spin-orbit parameters were those of Perey.[20] The computer code ABACUS[23] was used to calculate transmission coefficients for the various channels. Theoretical and experimental angular distributions were compared using a standard χ^2 test. Minima in χ^2 falling above the 0.1% confidence limit were ruled out as corresponding to possible combinations of J_i^π and δ for that transition.[24] Minima falling below this limit are listed in Table III for both reactions. The errors on the mixing ratios were calculated following the $\chi^2_{\rm min}+1$ rule.[25]

IV. DISCUSSION

A. States below 501 keV excitation

There are eight states in ^{92}Nb below 501 keV excitation. Unambiguous spin assignments are made in the present work for ^{92}Nb states at 226 (2$^-$), 286 (3^+), 390 (3^-), and 481(4^+) keV excitation (see Table III). The assignments for the 286, 390, and 481 keV states are made directly from χ^2 tests. In the case of the 226 keV state, spin-parities of $J^\pi = 2^-$ and $J^\pi = 4^-$ are both permitted from the analysis of the 390 → 226 keV transition. Of these, the choice of $J^\pi = 4^-$ is eliminated on the basis of the half-life of 5.6 μs for the 226 keV state which is consistent with the 226 → 136 keV transition being $E1$ ($2^- \to 2^+$) but not with its being $M2$ ($4^- \to 2^+$).[26,27] This consideration includes the contribution from conversion electron decay.[28] Thus, $J^\pi = 2^-$ is left as the only possible spin-parity assignment for the 226 keV state.

Unique spin assignments for the ^{92}Nb states at 0, 358, and 501 keV cannot be made from the present results; however, assignments of 7, 5, and 6, respectively, are strongly preferred. In the case of the 358 keV state, its spin is determined from the present work to be either 3 or 5. Of these, the choice of 3 is highly unlikely, because of the low spin (≤ 4) that would imply for the ^{92}Nb ground state. Such a low spin would require a retardation for the 136 → 0 keV transition of ≥ 10^{12} over the Weisskopf estimate and would lead to a logft value of ~ 14 for the then allowed β^+ decay of the ^{92}Nb ground state. Thus, the 358 keV state is assigned a spin of 5 with near certainty. Likewise, the ground state may be argued on the basis of γ- and β^+-decay lifetimes to have a spin of 6 or 7. Of these, the choice of 7 is strongly preferred, based on the combined evidence from charged-particle reaction studies,[2-8] theoretical calculations[29-33] and lifetime measurements.[9,10] If the ^{92}Nb ground state is taken to be $J = 7$, then the 501 keV state is assigned a spin of 6 or 8 from the 501 → 0 keV angular distribution measurements. As in the case of the ground state, the combined theoretical and experimental evidence makes the choice of 6 strongly preferred.

The results of the present work support the generally accepted picture in which the first eight states of ^{92}Nb comprise two jj-coupling multiplets (see Sec. I). However, there is some indication that a larger model space is required to give a complete description of these states. Since the $M1$ strengths of transitions between members of a jj-coupling multiplet are expected to be approximately equal to single-particle estimates, one estimates that arctan $|\delta| \leq 0.5°$ for these transi-

TABLE I. Angular distribution and angular correlation coefficients measured in the ^{89}Y($\alpha, n\gamma$) reaction.

Level energy[a]	γ-ray energy[a]	Angular distribution[b] a_2	a_4	Angular correlations[b] A1 geometry a_2	a_4	A2 geometry a_2	4
286	150	−0.16 1	0.02 1				
358	358	0.13 1	0.00 1				
390	164	−0.19 1	0.00 1				
	254	−0.17 2	0.00 2				
481	123, (358)	−0.12 1	0.03 1	0.02 3	0.04 3	0.17 4	0.07 4
	195, (150)	−0.14 2	0.02 2	−0.23 2	0.06 2	−0.23 2	0.00 2
501	501	−0.18 1	0.03 2				
975	749	−0.01 1	−0.01 1				
1090	804	0.05 3	−0.02 4				
	864	−0.04 1	0.01 1				
	954	−0.12 2	0.02 2				
1150	760	0.16 13	0.07 14				
	924	0.01 1	0.00 1				
1310	921, (164)	0.01 1	−0.02 1	0.14 11	0.11 12		
1324	1098	0.03 1	0.01 1				
1346	1060	−0.30 3	0.02 4				
	1210	−0.04 1	0.01 2				
1415	934, (195)			−0.01 11	0.12 11		
1554	1164, (164)	0.06 2	−0.07 3	−0.02 14	−0.02 14		

[a] Energies in keV from Ref. 11 and the present work. Uncertainties are ±0.5 keV. When given, the number in parentheses denotes the energy in keV of the second γ ray in the cascade for which angular correlation coefficients are quoted. The α-particle bombarding energy was 12.0 MeV for all measurements.

[b] The underlined numbers in all columns are uncertainties referring to the last quoted significant figure.

tions, assuming that the pure $E2$ 358→0 keV transition is representative of their $E2$ strength. Thus, it is interesting to note that the mixing ratios for the 286→136 keV ($3^+\to2^+$), 390→226 keV ($3^-\to2^-$), and 481→358 keV ($4^+\to5^+$) transitions are not consistent with zero (see Table III). These nonzero values are not due to any systematic error arising from the apparatus nor to any failure of the statistical compound nuclear model, as can be argued in the two following ways. First the values of mixing ratio, δ, measured independently in the two reactions are in agreement with each other, while each is separately inconsistent with a value of zero. Second, the experimental values of δ for the 358→0 keV ($5^+\to7^+$) and 390→136 keV ($3^-\to2^+$) transitions, both of which are constrained from reported lifetimes[10] to be zero,[27] are indeed consistent with $\delta=0$ for the results from both reactions. These deviations of δ from 0 for the three $E2/M1$ transitions as noted may indicate that a

TABLE II. Angular distribution and angular correlation coefficients measured in the ^{92}Z($p,n\gamma$)^{92}Nb reaction.

Level energy [a]	γ-ray energy [a]	Bombarding energy [b]	Angular distribution [c] a_2	a_4	Angular correlations [c] A1 geometry a_2	a_4	A2 geometry a_2	a_4
286	150	3.34	−0.33 2	0.01 2				
		4.00	−0.25 1	0.02 2				
358	358	3.34	0.15 5	−0.07 6				
		4.00	0.17 1	−0.04 2				
390	164	3.34	−0.38 2	0.03 2				
		4.00	−0.28 1	−0.02 1				
	254	4.00	−0.16 7	0.05 8				
481	123	4.00	−0.11 5	0.06 6				
		4.50	−0.14 2	−0.02 3				
	195	4.00	−0.26 2	0.01 2				
		4.50	−0.22 1	0.00 2				
501	501	4.50	−0.09 7	−0.11 8				
975	749	4.00	−0.03 2	0.00 2				
1090	804	4.00	−0.01 2	0.01 2				
		4.50	−0.02 1	0.00 2				
	864	4.00	−0.04 1	0.00 1				
		4.50	−0.03 1	0.00 1				
	954, (150)	4.00	−0.05 3	−0.01 3				
		4.50	−0.09 1	0.00 2	0.34 5	−0.08 6	0.15 6	0.02 7
1150	175	4.50	−0.14 3	−0.05 3				
	760	4.50	0.01 3	0.01 4				
	924	4.50	−0.01 1	−0.01 1				
1310	921, (164)	4.50	0.06 6	−0.06 6	0.20 11	0.12 13		
	1083	4.50	0.04 6	−0.14 7				
1324	1098	4.50	−0.02 2	0.00 2				
1346	1060	4.50	−0.21 2	0.01 2	−0.13 6	−0.09 7	−0.33 6	0.09 6
	1210	4.50	−0.04 1	−0.01 1				
1411	909	4.50	−0.22 6	−0.08 7				
1415	934, (195)	4.50			0.02 9	−0.20 12	−0.07 12	−0.17 14
	1129, (150)	4.50	0.12 3	−0.01 4	0.13 12	−0.03 15		
1422	1033, (164)	4.50	−1.00 6	0.19 6	−1.22 29	0.21 29		
1480	1345	4.50	0.00 1	−0.01 1				
1554	1164, (164)	4.50	−0.08 2	0.02 2	0.33 21	−0.30 27		
	1328	4.50	−0.08 2	0.02 3				

[a] Energies in keV from Ref. 11 and the present work. Uncertainties are ±0.5 keV. When given, the number in parentheses denotes the energy in keV of the second γ ray in the cascade for which angular correlation coefficients are quoted.

[b] Energies in MeV.

[c] The underlined numbers in all columns are uncertainties referring to the last quoted significant figures.

TABLE III. J^{π} values and mixing ratios in ^{92}Nb.

Level energy[a]	γ-ray energy[a]	$J_i^{\pi} \to J_f^{\pi}$	Arctanδ[b] $^{89}Y(\alpha,n\gamma)$	$^{92}Zr(p,n\gamma)$	Average
286	150	$3^+ \to 2^+$	4.0 10	4.0 15	4.0 8
358	358	$5^+ \to 7^+$	−0.5 20	−1.6 21	−0.7 12
390	164	$3^- \to 2^-$	8.5 15	6.1 22	7.7 13
	254	$3^- \to 2^+$	5 4	−3 9	3.5 5
481	123	$4 \to 5^+$	−2.5 15	−2.3 34	−2.5 14
	195	$4^+ \to 3^+$	−0.5 20	2.0 11	0.5 10
501	501	$6^+ \to 7^+$	−1 2	0 7	−1 2
975	749	$0^{\pm} \to 2^+$	0[c]	0[c]	
		$1^+ \to$	All	54 41	
		$1^- \to$	82 27	−76 23	−85 18
			−9 18	−30 23	−17 14
		$2^- \to$	22 8	28 8	26 6
			−88 8	86 8	87 6
		$3^- \to$	−9 2	−8 2	−8.5 15
1090	804	$1^{\pm} \to 3^+$	0[d]	0[d]	
	864	$\to 2^-$	All	−87 15	
				−19 15	
	954[e]	$\to 2^+$		−72 32	
				−34 32	
1150	175[e,f]				
	760	$1^{\pm} \to 3^-$	0[d]	0[d]	
		$2^- \to$	−23 to 77	9 9	
				72 13	
		$3^- \to$	−90 to 38	−73 5	
				22 5	
	924	$1^+ \to 2^-$	−4 to 77	−81 27	
				−26 27	
		$1^- \to$	−2 to 75	−12 14	
				85 14	
		$2^- \to$	15 5	22 4	19 4
		$3^- \to$	−11 2	−9.5 10	−11 2
1310	921	$1^{\pm} \to 3^-$	0[d]	0[d]	
		$2^- \to$	6 5	16 10	8 6
			75 5	71 8	74 4
		$3^- \to$	24 3	22 6	24 3
	1083[e]	$1^{\pm} \to 2^-$		All	
		$2^- \to$		−86 28	
				21 28	
		$3^- \to$		−10 6	
1324	1098	$1^- \to 2^-$	37 37	All	
		$2^- \to$	10 8	22 6	18 6
		$3^- \to$	−13 3	−10 2	−11 2
1346	1060	$2^+ \to 3^+$		−79 4	
				−21 4	
		$4^+ \to$	8 5	−2 1	3 5
	1210	$2^+ \to$	84 20	−88 3	−88 6
			30 12	24 3	24 3
1411	909[e]	$5^+ \to 6^+$		−86 5	
				−4 5	
1415	934[e]	$4^+ \to 4^+$		−68 18	
				42 18	
	1129	$4^+ \to 3^+$	−13 3	−13 2	−13 2
1422	1033[e]	$4^- \to 3^-$		42 8	
1480	1345[e]	$0^{\pm} \to 2^+$		0[c]	
		$1^{\pm} \to$		All	
		$2^+ \to$		−82 3	
				18 3	
		$3^+ \to$		−10 1	

TABLE III. (*Continued*)

Level energy [a]	γ-ray energy [a]	$J_i^\pi \to J_f^\pi$	^{89}Y(α, $n\gamma$)	Arctanδ [b] ^{92}Zr(p, $n\gamma$)	Average
1554	1164	$2^- \to 3^-$	3 to 76	−5 7	
		$3^- \to$	−69 8	−79 3	−78 6
			17 8	28 3	27 7
	1328	$2^- \to 2^-$		−5 6	
				85 6	
		$3^- \to$		−80 3	

[a] Energies in keV from Ref. 11 and the present work. Uncertainties are ±0.5 keV.
[b] Arctanδ is given in degrees. The underlined numbers give the uncertainties as defined in Tables I and II.
[c] Rigorously zero.
[d] Assumed pure quadrupole.
[e] Not measured in ^{89}Y(α, $n\gamma$).
[f] See Table IV.

small admixture of collective excitation in the core is necessary to give an accurate description of the wave functions of these low-lying states in ^{92}Nb.

B. States between 501 keV and 1600 keV excitation

Knowledge of the level structure of ^{92}Nb in this region of excitation is somewhat limited. The most complete level and γ-ray decay schemes thus far proposed are those of Kumabe *et al.*[11] and Kent and Blatt,[12] both of whom used the ^{92}Zr(p, $n\gamma$)^{92}Nb reaction in their studies. The level scheme proposed in the present work (see Fig. 4) is substantially in agreement with these works. Evidence for previously reported[6,7,11,12] levels at 1642 and 1723 keV excitation was also seen in the present work (see Fig. 2). However, these levels were too weakly populated to enable a conclusive verification of their existence or an analysis of the angular distributions of their γ-ray decays.

Few spin-parity assignments have been reported for ^{92}Nb levels in this region of excitation. Studies of the ^{91}Zr(^{3}He, d)^{92}Nb and ^{93}Nb(d, t)^{92}Nb reactions[6,7] have led to the assignment of parities and spin limits for some of these levels. The comparison[11] of ^{92}Zr(p, $n\gamma$)^{92}Nb excitation functions to Hauser-Feshbach predictions has also led to some spin assignments. In the present work, spins (or spin limits) and multipole mixing ratios have been assigned from the analysis of γ-ray angular distributions and correlations as described in Sec. III. A number of spin-parity combinations were rejected because the upper limit (≲ 10 ns) placed on the lifetime of all levels seen in the γ-γ coincidence measurements precludes the possibility in most cases of significant $M2/E1$ or $M3/E2$ mixing.[27]

1. Levels at 975 and 1150 keV

These states are linked by a weak (~5%) γ-ray decay branch. They are suggested by Kent and Blatt[12] to comprise a negative-parity doublet of spins 0 and 1 which is expected to occur near this excitation, based on the $(2p_{1/2}^{\pi})^{-1} \otimes 3s_{1/2}^{\nu}$ shell-model configuration. These results of the present work relating to these levels are summarized in Table IV. As this table shows, the present results are consistent with assignments of 0^- and 1^- for the 975 and 1150 keV levels, respectively, although a number of other combinations are permitted.

2. Level at 1090 keV

This level has strong decay branches to the 136 keV (2^+), 226 keV (2^-), and 286 keV (3^+) levels in the ground state multiplets. It was reported in ^{91}Zr(^{3}He, d)^{92}Nb to be populated by $l = 1$ transfer,[6] indicating negative parity. The somewhat anomalous character of the γ-ray decay and conflicting spin-parity assignments[8,11] have led to the sugges-

TABLE IV. Possible values of arctanδ (values of arctanδ and errors as defined in Table III) for the 1150 → 975 keV transition.

J_f^π	J_1^π: 1^-	2^-	3^-
$0^\pm$	0 [a]		
$1^\pm$	45 23	7 10	
2^-	−85 to −20	56 24	−3 4
			78 4
3^-		77 14	−89 9
		−23 14	38 9

[a] Rigorously zero.

tion[12] that this level may be a doublet. This possibility is very unlikely, however, in view of the fact that all three of the reported decay branches for the 1090 keV level are seen in the present work in coincidence with the 1642 → 1090 keV transition. In addition, the branching ratios measured at several energies in both reactions are equal within experimental errors, making the existence of a doublet most improbable. The analysis of γ-ray angular distribution and correlation data for the three strong decay branches from this level leads to the unique assignment of $J = 1$. This is in agreement with the assignment of Kumabe *et al.*[11] of $1^{\pm}$ from $^{92}Zr(p, n\gamma)^{92}Nb$. The present results combined with stripping data[6] would favor the assignment of an odd parity for this level, although this would imply a strength for the 1090 → 286 keV ($1^- \rightarrow 3^+$) transition of 0.5 (Weisskopf units), which would be most unusual for an $M2$ transition.

3. *Level at 1310 keV*

This level has not been reported in any previous studies of ^{92}Nb. The observation of the 1310 → 390 keV γ ray in coincidence with the 390 → 226 keV γ ray in the present work gives evidence of its existence. The combined angular distribution and angular correlation data in the present work lead to acceptable spin-parity values of $1^{\pm}$, 2^-, and 3^- for this level.

4. *Level at 1324 keV*

This level has been reported[6] in $^{91}Zr(^3He, d)^{92}Nb$ to have $l = 1$, indicating a negative parity. Its existence has also been reported by Kumabe *et al.*[11] and Kent and Blatt,[12] both from $^{92}Zr(p, n\gamma)^{92}Nb$. A weak (~ 5%) branch to the 390 keV (3^-) state is reported in the present work from γ-γ coincidence data; this branch is unreported in previous γ-ray studies[11,12] probably due to masking by the strong decay of the first excited state (934 keV) in ^{92}Zr. The combined results of the present work and stripping data[6] limit the spin-parity of this level to $(1-3)^-$, in disagreement with a previous assignment[11] of 4^-.

5. *Level at 1346 keV*

This level is reported by Bhatia, Daehnick, and Canada[7] in $^{93}Nb(d, t)$ to have $l = 2 + 4$, indicating a positive parity. The combined angular distribution and correlation data from $^{92}Zr(p, n\gamma)$ in the present work uniquely determine the spin-parity of this level to be $J^{\pi} = 2^+$, in disagreement with a previous assignment[11] of $(3, 4)^-$. However, the results from $^{89}Y(\alpha, n\gamma)$ are anomalous in that between the two observed γ-ray decay branches from this level, all spin assignments are ruled out. Thus, a value of 2^+ for the 1346 keV level is only tentatively assigned.

6. *Level at 1411 keV*

This level is reported by Bhatia *et al.*[7] in $^{93}Nb(d, t)^{92}Nb$ to have $l = 0$, indicating $J^{\pi} = (4, 5)^+$. This result, combined with that of the present work, leads to an unambiguous assignment of $J^{\pi} = 5^+$ for this level.

7. *Level at 1415 keV*

The results of the present work limit the spin-parity of this level to $J^{\pi} = (3, 4)^+$. If this level is identified with the 1407 ± 10 keV level reported by Bhatia *et al.*[7] in $^{93}Nb(d, t)^{92}Nb$ to have $l = 0$ and hence $J^{\pi} = (4, 5)^+$, then a unique assignment of $J^{\pi} = 4^+$ is possible.

8. *Level at 1422 keV*

This level was reported[6] in $^{91}Zr(^3He, d)^{92}Nb$ to have $l = 1$, indicating a negative parity. This is consistent with the results of the present work in which the strong anisotropy of the 1422 → 390 keV γ ray in both angular distribution and correlation measurements leads to a unique spin-parity assignment of $J^{\pi} = 4^-$.

9. *Level at 1480 keV*

This level has been previously[8,11] assigned $J^{\pi} = 1^+$ in agreement with the results of the present work, which permits a wide range of possible assignments. A tentative assignment[7] of $J^{\pi} = (4, 5)^+$ to a level at 1479 ± 10 keV, reported in $^{93}Nb(d, t)^{92}Nb$, is in conflict with the other evidence relating to this level. The existence of a doublet near this excitation is a possible explanation of this discrepancy.

10. *Level at 1554 keV*

The results of the present work limit this level to $J^{\pi} = (2, 3)^-$, in disagreement with a previous assignment[11] of $J^{\pi} = 1^{\pm}$.

V. CONCLUSION

Spin assignments have been made for several states below 501 keV excitation in ^{92}Nb, based on the minimal assumptions that the spin-parity of the 136 keV state is $J^{\pi} = 2^+$ and that the parities and lifetimes of the other seven states in this region are as reported previously. These assignments are in agreement with previous assignments which were based in part on the assumption that the states in this region comprise two *jj*-coupling multiplets based on the shell-model configurations $1g^{\pi}_{9/2} \otimes 2d^{\nu}_{5/2}$ and $(2p^{\pi}_{1/2})^{-1} \otimes 2d^{\nu}_{5/2}$. Thus, the results of the present work give further evidence of the shell-model nature of the first eight states in ^{92}Nb, although some degree of collective excitation in the core wave function is indicated.

The results of the present work either alone or in combination with previously reported results lead to assignments for higher-lying ^{92}Nb levels at 1090 ($1^{\pm}$), 1346 (2^{+}), 1411 (5^{+}), 1415 (4^{+}), and 1422 (4^{-}) keV excitation.

It should be noted that the assumption made in this work, that the 136 keV ^{92}Nb state is $J^{\pi} = 2^{+}$, is open to question. Applying the criteria for assigning J^{π} values from experimental log*ft* measurements proposed by Raman and Gove,[34] the spin of the 136 keV state is rigorously limited to only $J^{\pi} = 1^{+}$, 2^{+}, or 3^{+}. Thus, a definitive determination of the spin of this state, for example, using the $(\vec{d}, \alpha)$ technique of Kuehner *et al.*,[35] would be most useful.

We wish to thank the academic and technical staffs of the accelerator laboratories of the University of Alberta and McMaster University for their hospitality and assistance during the course of this study.

†Work supported in part by the Atomic Energy Control Board and the National Research Council of Canada.
*Present address: Nuclear Research Centre, The University of Alberta, Edmonton, Alberta, Canada.
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