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Low-lying levels of ^{94}Nb†

E. C. Hagen, B. D. Kern, F. D. Snyder,* and D. E. Miracle
Department of Physics and Astronomy, University of Kentucky, Lexington, Kentucky 40506
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The low-lying low-spin levels of ^{94}Nb have been investigated; these levels were populated via the ^{94}Zr$(p,n\gamma)^{94}$Nb reaction with a separated isotope ^{94}Zr foil target (96% ^{94}Zr). Excitation functions of γ rays were obtained at incident proton energies from 1.688 to 3.700 MeV. γ-γ coincidences were observed at E_p=3.0 MeV. The existence of additional levels at 301.5, 450.3, 666.2, and 785.0 keV has been established. Computed Hauser-Feshbach (p,n') cross sections have been fitted to experimental cross sections deduced from the γ-ray data with the resulting best-fit spin-parities: 140.4-keV level, 2^-; 301.5, 2^-; 334.2, 3^+; 396.3, 4^-; and 450.3, 3^+.

[NUCLEAR REACTIONS ^{94}Zr$(p,n\gamma)$, E=1.688–3.700 MeV; measured E_γ, I_γ, γ-γ coincidence spectra. ^{94}Nb deduced levels, J^π. Ge(Li) detectors. Enriched target.]

I. INTRODUCTION

Properties of many levels of ^{94}Nb have been established by Gruber *et al.*,[1] Jurney *et al.*,[2] Prestwich, Corté, and Hla,[3] and Chrien, Rimawi, and Garg[4] using the ^{93}Nb$(n,\gamma)^{94}$Nb reaction. Neutron capture by ^{93}Nb, whose ground state spin is $\frac{9}{2}$, populates highly excited high-spin states ($E_{exc} \geq 7.228$ MeV; $J=4, 5$) of ^{94}Nb. While this reaction allows precise measurement of the energies of the γ-rays, the placement of the γ-rays in the level scheme is sometimes uncertain. Several low-lying levels populated by the ^{94}Zr$(p,n)^{94}$Nb reaction[5] were not observed in the neutron capture studies,[1,2] nor were they observed in studies with the (d,p) (Refs. 6 and 7) and (α,d) (Ref. 8) reactions. The endothermic ^{94}Zr$(p,n)^{94}$Nb reaction is especially suited for further study of ^{94}Nb, since it preferentially populates low-spin levels; also, one can sequentially populate levels by raising the proton bombarding energy to just above their thresholds.

II. EXPERIMENTAL PROCEDURES

The excited states of ^{94}Nb examined in this study were populated through the ^{94}Zr$(p,n)^{94}$Nb reaction (Q_0= −1.681 MeV).[9] The University of Kentucky model CN Van de Graaff accelerator provided proton beams of 1.688- to 3.700-MeV incident energy. The beam current was limited to less than 0.8 μA to prevent deterioration of the 0.9-mg/cm^2 foil which was isotopically enriched to 96.1% in ^{94}Zr. The target chambers employed were of thin walled aluminum construction, with either gold or carbon beam stops.

The experiment proceeded through two phases, the first being the acquisition of γ-ray excitation functions and the second being a γ-γ coincidence measurement at E_p = 3.0 MeV. Two γ-ray detectors were used for both phases of the experiment; one was a 35-cm^3 coaxial Ge(Li) detector with a resolution at 1.33 MeV of 2.0 keV and the other a 5-mm planar Ge(Li) detector of 1.0-keV resolution at 99 keV.

γ-ray excitation functions

As the ^{94}Zr$(p,n)^{94}$Nb reaction is endothermic, only those states for which the incident proton energy is above threshold will be populated. By observing the number of γ-ray decays as a function of E_p it is possible to associate each γ ray with a region of excitation in ^{94}Nb. If the energy of the level to which the excited state is decaying is accurately known, or if the members of a cascade to an accurately known level can be identified, the energy of the excited state can be accurately inferred from the γ-ray energy.

γ-ray energy spectra were obtained as a function of proton bombarding energy from E_p = 1.688 to 3.700 MeV. The data were taken in 50-keV steps. Individual γ-ray photopeak yields in each spectrum were extracted after background subtraction and were then corrected for dead time in the detection electronics. As the square roots of the yields were found to be linear in E_p near thresholds, each threshold energy was determined by least-squares fitting a straight line to the square roots and extrapolating it to zero yield. A typical spectrum is shown in Fig. 1. Examples of the

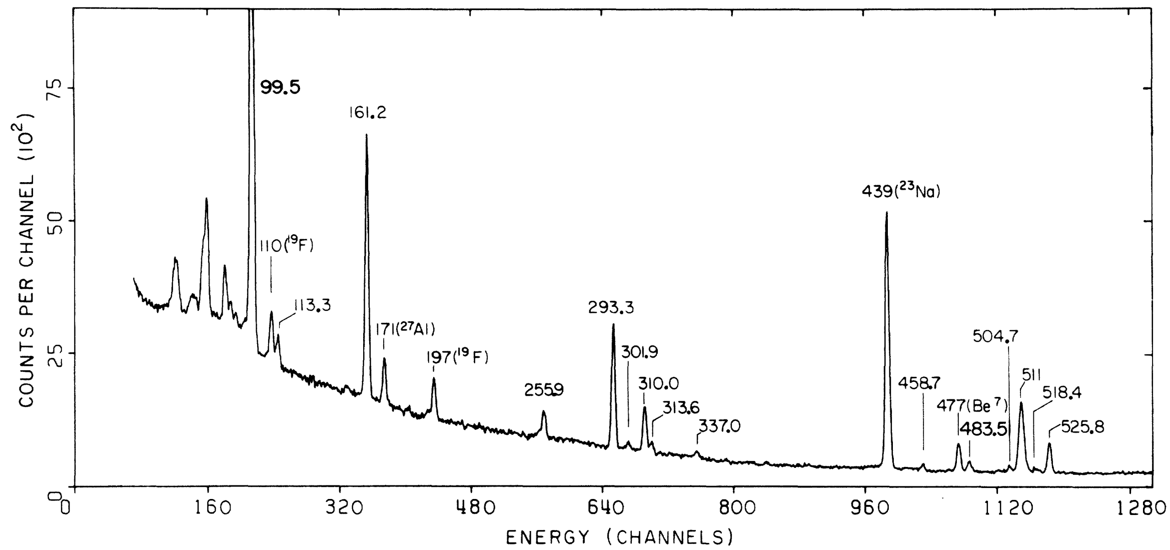

FIG. 1. A typical spectrum of γ rays due to the ^{94}Zr$(p,n\gamma)^{94}$Nb reaction. The incident proton energy was 3.25 MeV.

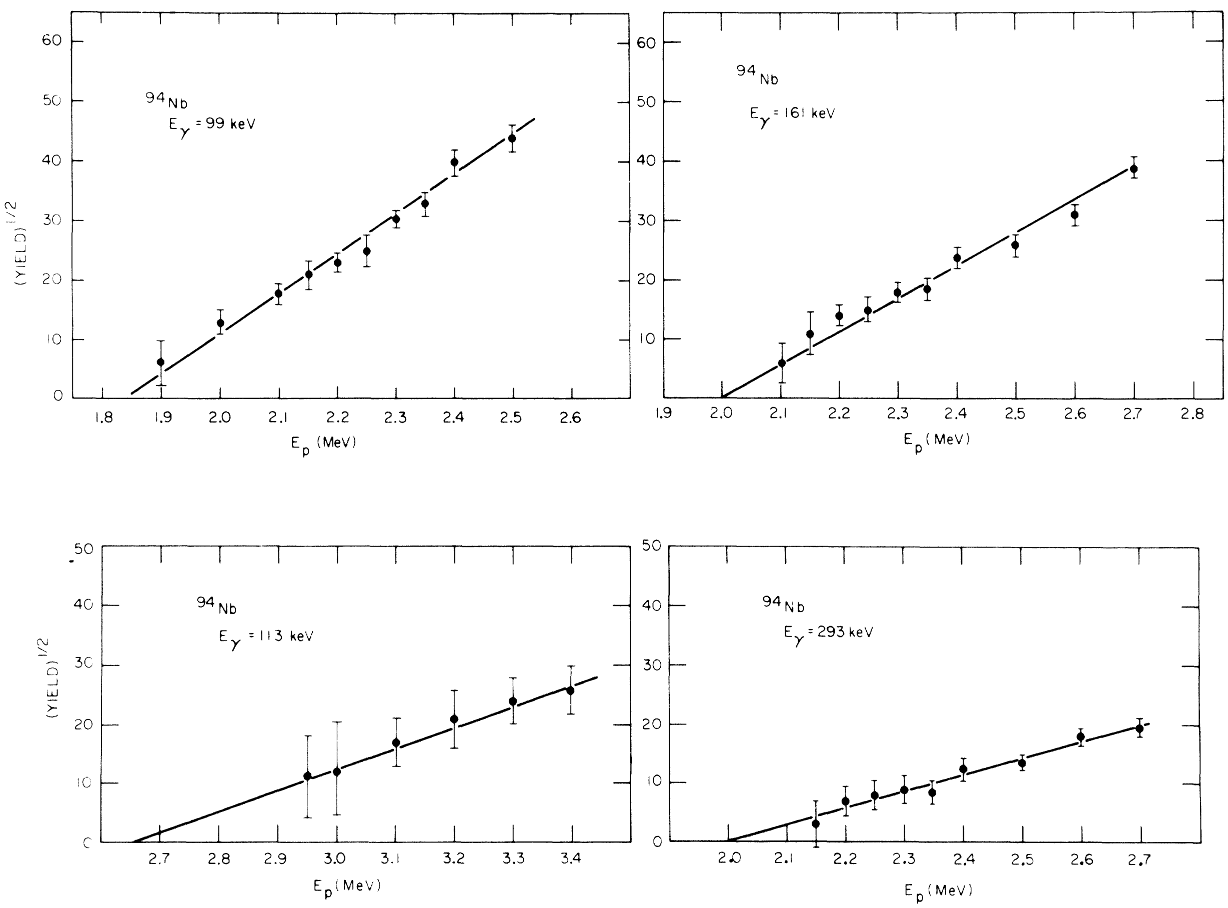

FIG. 2. Typical excitation curves for γ rays from the ^{94}Zr$(p,n\gamma)^{94}$Nb reaction. The square roots of the measured yields are plotted.

TABLE I. Energies and thresholds of γ rays observed in the $^{94}Zr(p,n\gamma)^{94}Nb$ reaction. The calculated E_{th} are based on the known Q value and the level to which each γ ray has been assigned.

E_γ	$\pm\Delta E_\gamma$	Observed E_{th} (MeV)	$\pm\Delta E_{th}$	Calculated E_{th} (MeV)
99.5	0.2	1.85	0.05	1.84
113.3	0.7	2.6	0.2	1.81 [a]
161.2	0.2	2.01	0.06	2.01
255.9	0.2	2.28	0.07	2.10
293.3	0.2	1.98	0.06	2.03
301.9	1.7	2.6	0.2	2.64
310.0	0.5	2.00	0.05	2.16
313.6	1.6	2.3	0.2	•••
458.7	1.0	2.4	0.2	2.49
483.5	0.5	2.24	0.07	2.48
504.7	1.0	2.7	0.09	•••
518.4	1.5	2.7	0.1	2.34 [a]
525.8	0.5	2.27	0.06	2.37

[a] Since the observed threshold is higher than this, we conclude that the γ-emitting level is populated by a cascade from a higher energy level.

excitation functions are shown in Fig. 2. Since the Q value of the $^{94}Zr(p,n)^{94}Nb$ reaction is well known, it was possible to associate each threshold energy with an excitation energy in the final nucleus ^{94}Nb. The γ-ray energies were determined by comparison with the energies of standard γ rays, which were in this case ^{85}Kr, ^{139}Ce, and ^{60}Co. Since the energies of some of the transitions in ^{94}Nb have been determined to high precision,[1-4] an internal calibration was also possible using these lines. A listing of the γ-ray energies observed and the uncertainty in these energies is given in Table I. The measured proton energy thresholds are listed in column 3.

γ-γ coincidences

For the coincidence measurements the 35-cm^3 and 5-mm detectors were located, respectively, at approximately 25 and 15 cm from the target, each at an angle of 90° relative to the beam axis. Standard slow-fast coincidence techniques were used, with the time resolution being 4.6 ns full width at half maximum. During data acquisition, a 25-ns window was placed around the time peak, and only those γ-ray events falling within this window were presented to the analog to digital converters. Coincidence pairs were stored event by event on magnetic tape for later off-line analysis. A background spectrum consisting of random coincidences was also obtained with a very small random count; no conflicting γ rays were observed.

The coincidence data were analyzed on the PDP-8/I computer. For each photopeak of interest in the energy spectrum of one detector, a window was set about the peak and another window of equal width was set over a region slightly greater in energy. The data tape was then searched for events in the other detector in coincidence with either of these regions. Thus spectra were obtained having γ rays associated with a photopeak and with the underlying Compton background. The Compton-gated spectrum was then subtracted from the photopeak-gated spectrum and photopeak yields obtained. Table II lists the energies of photopeaks seen in coincidence with the photopeaks listed in column 1.

Differential cross sections

The differential cross sections for γ-ray production at 90° have been calculated from the mea-

TABLE II. Observed γ-γ coincidences due to the $^{94}Zr(p,n\gamma)^{94}Nb$ reaction.

Gating γ ray (keV)	γ rays in coincidence (keV) 99	113	161	256	293	302	310	459	484	505	518	526
99			C	C			C		C			C
113											C	
161	C								C			
256	C											
293								?				
302												
310	C											
459					?							
484	C		C									
505	?											
518		C										
526	C											

sured yields. The γ-ray angular distributions of the decays of the 140- and 301-keV levels were observed at $E_p = 2.20$ and 2.45 MeV. These distributions were found to be isotropic to ±8% in all cases. The angular distributions of the weaker decays were not measured.

Total neutron production cross sections for the levels were deduced from the 90° γ-ray cross sections. The cross sections were corrected for cascades and for internal conversion. These total neutron production cross sections were compared with those computed according to the Hauser-Feshbach model using the computer code ALTE.[10] For the purpose of comparison the transitions for which the angular distributions are unknown were assumed to be isotropic. An additional 25% error has been added to the experimental error in these cases.

The parameters used in the above calculation were those of Perey[11] for the incident protons and those of Wilmore and Hodgson[12] for the exiting neutrons. The first eight levels of ^{94}Zr were included as active proton channels and the first 12 levels of ^{94}Nb were included as the neutron channels. The spins and parities of the levels in ^{94}Zr and the spins and parities of the first five levels in ^{94}Nb were held constant during the fitting procedure. The spin-parities of the next seven levels were individually varied from 0^+ to 4^-. The best over-all fit to the data for five of these seven levels is shown in Fig. 3. The effect of alternative spin-parity assignments on the computed 334-keV level cross sections is shown in Fig. 4. Throughout the fitting procedure, no normalization of the computed to the experimental cross sections was made. It should be noted that the calculated cross sections are interdependent, since changing the spin-parity of any individual level requires the redistribution of the outgoing flux through the remaining levels.

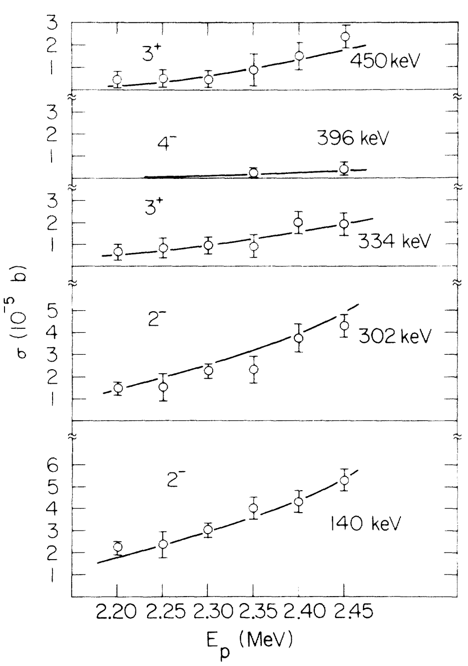

FIG. 3. The best over-all fit of the computed Hauser-Feshbach (p,n') cross sections to the data for five levels.

III. DISCUSSION

The low-lying level structure and prominent γ decays of ^{94}Nb are shown in Fig. 5. The level energies inferred by Buchs *et al.*[5] from the study of neutron time of flight with the ^{94}Zr$(p,n)^{94}$Nb reaction are also shown. The spins of the levels observed in both experiments are, with one exception, $J \leq 4$. The one level of higher spin that was observed in this study was only indirectly populated by a γ-ray cascade.

The most intense line observed had an energy of 99.5 keV and was the transition between the level at 140.35 keV and the $J^\pi = 3^+$ level at 40.95 keV. Several other γ-rays were observed in coincidence with this transition as noted in Table II. The transition had an observed threshold of 1.85(±0.05) MeV which agrees well with the calculated value of 1.838 MeV. The γ decay of the 5^+ level at 113.404 keV was observed in this study, but only above a proton energy of 2.6(±0.2) MeV. A weak 518.4(±1.5)-keV radiation was observed above $E_p = 2.7$ MeV and in coincidence with the 113.4-keV γ decay. These γ-ray energies and the

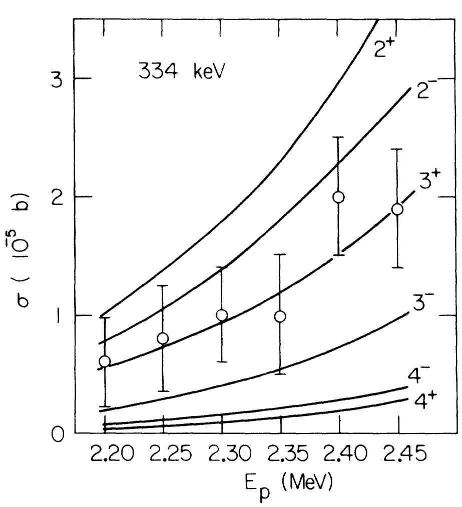

FIG. 4. The effect of alternative choices of spin-parity on the computed Hauser-Feshbach (p,n') cross sections for the 334-keV level.

threshold information imply the existence of a level at 631.7(±1.7) keV. γ decays of 161, 518, and 113 keV were observed in the study of Gruber *et al.*,[1] and these decays were assigned to the levels at 793, 631, and 113 keV, respectively. In this work the 161-keV decay of the 793-keV state was not observed. A γ ray of that energy was not in coincidence with either the 518- or the 113-keV decays. However, as the strongest branch[1] of the decay of the 793-keV level (459.0 keV) was only weakly observed in the singles phase of this study, no definite statement can be made about the absence of the 161-keV branch. A 161.2(±0.2)-keV radiation observed in this work originates from a different level and will be discussed below.

The 255.9(±0.2)-keV transition between the level at 396.28 keV and the level at 140.35 keV was observed only weakly in this study, both in coincidence with the 99.5-keV radiation and in the excitation function measurements. The observed threshold of 2.28(±0.07) MeV was in fair agreement with the calculated threshold of 2.10 MeV.

A weak transition of 301.9(±1.7) keV was observed above $E_p = 2.6$ MeV. This is probably the decay of the $J^\pi = (4^+, 5^+)$ level[1] at 935.13 keV populating the $J^\pi = 4^+$ level at 631.68 keV. The intensity of this radiation was too low for coincidence observation. Several other γ-rays that do not fit into the adopted level scheme of Ref. 13 were observed. A 161.2(±0.2)-keV γ ray was observed to have a proton threshold of 2.01(±0.06) MeV. This is far below the threshold of the 793-keV level mentioned above as a source of a 161.285-keV radiation, which decays[1] through the 113-keV

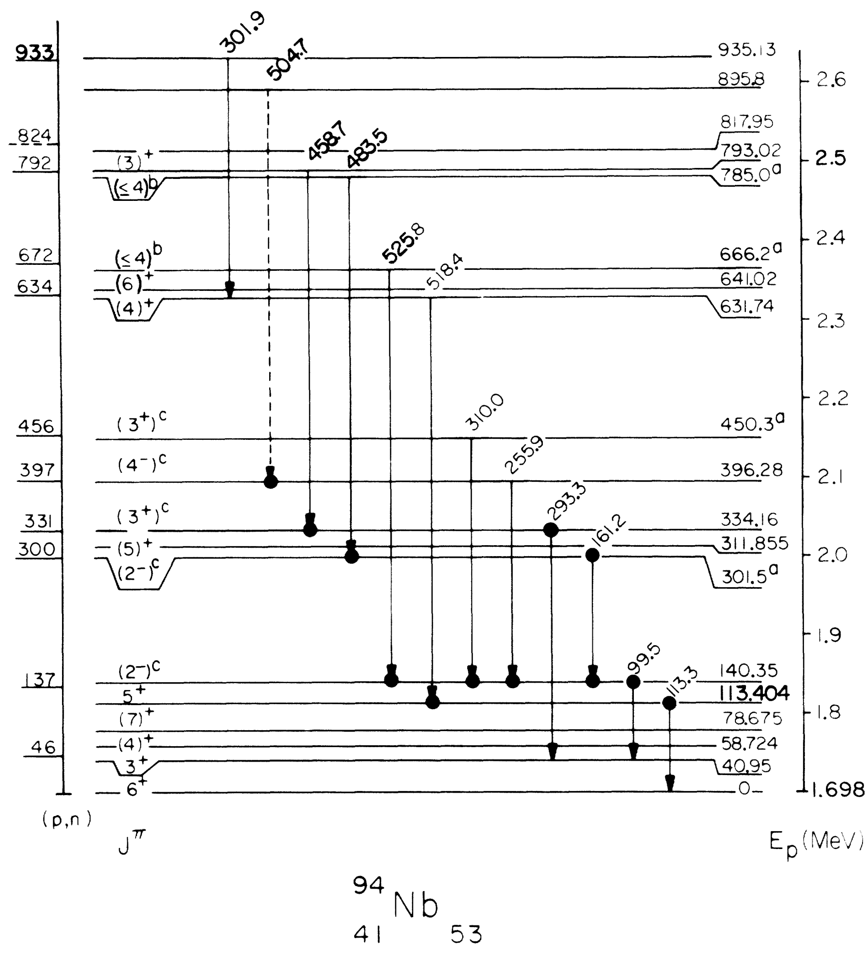

FIG. 5. Low-lying levels of ^{94}Nb. Levels which are added due to the presently reported work have the superscript (a) on the level energy. Other level energies are from Ref. 1. The left-hand column gives the energies (±8 keV) which were reported in Ref. 5. The right-hand column gives the threshold energy scale. The J^π are those adopted by Ref. 13, except for those superscripted (b) to which we set upper limits. The spin-parities of the levels marked (c) have been tentatively assigned on the basis of a Hauser-Feshbach calculation. Meaning of the symbol: ●, observed in coincidence spectra; otherwise, observed in singles spectra only.

level. However, the neutron time-of-flight study of Buchs *et al.*[5] places 12 levels at energies shown in Fig. 5, with uncertainties of ±8 keV. The threshold of the 161.2-keV radiation observed in this study corresponds to an excitation energy of 300 keV. This γ ray was observed in coincidence with the 99.5-keV γ ray and not with the 113.3-keV γ ray. This evidence suggests the placement of a level at 301.5(±0.3) keV which decays to the 140.35-keV level.

A 310.0(±0.5)-keV transition observed in coincidence with the 99.5-keV γ-ray had a proton threshold of 2.00(±0.05) MeV. This is most probably the decay of a level at 450.3(±0.6) keV. A level of this energy has been reported,[5] and it would have a proton threshold of 2.16 MeV.

The reports of Refs. 1–4 place two levels in the region of 600 keV excitation, one at 631.74 keV and one at 641.02 keV, tentatively identified as having $J^\pi = 4^+$ and 6^+, respectively. Buchs *et al.*[5] have placed a level at 634(±8) keV and one at 672(±8) keV. The decay of the 631.74-keV level was observed in this study as described above. However, as the most intense branch of the decay of the 641.02-keV level (562.1 keV[1]) was not observed in this work, this level is assumed not to be populated. A 525.8(±0.5)-keV transition was observed during the excitation function measurements above a proton energy of $E_p = 2.27(\pm 0.06)$ MeV which would place it in this region. As the 641-keV level was not populated this γ ray could not be the 527.1-keV decay[1] of this state. Since this γ ray was observed in coincidence with the 99.5-keV γ ray, it originates from the decay of a level at an energy of 666.2(±0.6) keV. Thus the neutron groups observed by Buchs *et al.*[5] are most probably identified with levels at 631.74 and 666.2 keV and not with the 641-keV state.

IV. CONCLUSIONS

Four additional levels have been added to the spectrum of levels of ^{94}Nb; they are identified in Fig. 5 by the superscript a. The systematic behavior of the levels of the low-lying odd-Z–odd-N nuclei in this nuclear mass region indicates that the low-lying even-parity levels of ^{94}Nb may be described as configurations of the form $[\pi(g_{9/2})\nu(d_{5/2})^3]_{J^\pi=2^+-7^+}$. The members of this group with spins 5–7 should not be populated by the $^{94}Zr(p,n)^{94}Nb$ reaction with enough strength to be observed, as the target nucleus has ground state spin $J=0$ and the penetrabilities of protons and neutrons favor low angular momentum change. In fact, the decays of the 7^+ level at 78 keV, the 5^+ levels at 113 and 311 keV, and the 6^+ level at 641 keV were not observed, with the exception of the 113-keV level which was only indirectly populated. Thus these previous spin assignments are consistent with present data. Conversely, all the levels populated directly in this study for which the spin is unknown probably have $J \leq 4$. Three odd-parity doublets (1^--2^-, 2^--3^-, and 4^--5^-) arise from the $[\pi(p_{1/2})^{-1}{}_{1/2}(g_{9/2})^2{}_0\nu(d_{5/2})^3{}_{3/2,5/2,9/2}]$ configurations. The lowest-lying of these is expected to be the 2^--3^- doublet.[2] Neither the 3^- member of this doublet, nor the 2^+ member of the positive-parity multiplet has been identified in this study.

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*Present address: Physics Department, University of Pittsburgh, Pittsburgh, Pennsylvania 15260.

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