Gamma Decay of Low-lying Levels in ^{93}Nb

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Mean lifetimes for four levels in ^{93}Nb have been measured by the Doppler-shift attenuation method. γ-ray angular distributions have been measured for the γ decay of excited levels in ^{93}Nb up to 1127 keV in excitation. The levels were excited by the ^{90}Zr$(\alpha, p\gamma)^{93}$Nb reaction at a bombarding energy of 14.77 MeV. Spectra of γ rays in coincidence with protons were obtained with a 55-cm^3 Ge(Li) detector. Spin assignments obtained from the present results for the low-lying positive-parity levels in ^{93}Nb are in agreement with previous assignments. A J^π of $\frac{3}{2}^-$ has been assigned to a level at 685 keV in excitation and a J^π of $\frac{5}{2}^-(\frac{3}{2}^-)$ has been assigned to an 809-keV negative-parity level. γ-ray mixing ratios measured for the γ decay of excited low-lying levels in ^{93}Nb have been combined with lifetime measurements to calculate the electromagnetic transition strengths. The experimental $E2$ transition strengths are shown to be consistent with those predicted by a weak-coupling model.

NUCLEAR REACTIONS ^{90}Zr$(\alpha, p\gamma)$, E = 14.77 MeV; measured τ, E_γ, pγ coin, $I_\gamma(\theta)$, δ. ^{93}Nb deduced levels J, π, Γ.

I. INTRODUCTION

The low-lying levels in ^{93}Nb have been studied in the past primarily by inelastic neutron scattering experiments.[1-8] The properties of these levels as well as the existence of a number of the levels have not been well established by the ^{93}Nb$(n, n'\gamma)^{93}$Nb work. For example, a level located at 685 keV in excitation was first observed in the ^{94}Mo$(d, {}^3$He$)^{93}$Nb reaction[9] and the ^{92}Zr$({}^3$He$, d)^{93}$Nb reaction.[10] Later, after a more careful study of the γ-ray yield as a function of the neutron excitation energy, the existence of this level was confirmed by the Texas Nuclear group.[5] Furthermore, the existence of a doublet at 808 and 809 keV in excitation was not clearly established until Rogers *et al.*[7] made a comparison of the Coulomb-excitation yields for the respective levels.

The only low-lying positive-parity levels in ^{93}Nb for which consistent spin assignments have been made from the ^{93}Nb$(n, n'\gamma)^{93}$Nb work are the 744-keV ($\frac{7}{2}^+$) and the 809-keV ($\frac{5}{2}^+$) levels. Recently some Coulomb-excitation measurements on ^{93}Nb by Stelson *et al.*[11] and Kregar and Seaman[12] have reduced the number of discrepancies that previously existed for the spins of the remaining low-lying positive-parity levels.

A J^π of $\frac{3}{2}^-$ was tentatively assigned to the 685-keV level in ^{93}Nb from the ^{94}Mo$(d, {}^3$He$)^{93}$Nb reaction studies,[9] while $\frac{1}{2}^-$ or $\frac{3}{2}^-$ was assigned to this level by Cates, Ball, and Newman[10] from the ^{92}Zr$({}^3$He$, d)^{93}$Nb angular distribution. Beghian *et al.*[4] observed a 780-keV γ ray which they assigned to a 808 → 28-keV transition in ^{93}Nb. They tentatively assigned a J^π of $\frac{3}{2}^-$ to the 808-keV level from inelastic neutron scattering excitation function studies. In a more recent ^{93}Nb$(n, n'\gamma)^{93}$Nb experiment, Gobel, Feicht, and Vonach[8] tentatively assigned a J^π of $\frac{3}{2}$ or $\frac{5}{2}^-$ to an 810-keV level from which they observed a 780-keV γ ray decaying to a 30-keV level. In view of the discrepancies mentioned above and the absence of electromagnetic-decay information for the low-lying negative-parity levels in ^{93}Nb, we decided to investigate the properties of the low-lying levels by measuring the lifetimes of the excited levels and the γ-ray angular distributions resulting from the decay of these levels.

In this paper we report the lifetimes measured for the 685- and the 744-keV levels and the 809-keV doublet in ^{93}Nb by the Doppler-shift attenuation method. γ-ray angular distributions measured for the decay of levels up to 1127 keV in excitation are presented. Spin and parity assignments as well as transition probabilities are discussed for these levels in light of a weak-coupling model.

II. EXPERIMENTAL PROCEDURES AND DATA ANALYSIS

The ^{90}Zr$(\alpha, p\gamma)^{93}$Nb reaction was used to populate the levels in ^{93}Nb at an α bombarding energy of 14.77 MeV. The α beam was supplied by the Ballistic Research Laboratories tandem Van de Graaff accelerator. A 1-mg/cm^2 enriched (97.65%) ^{90}Zr self-supporting foil purchased from the Oak Ridge Isotope Division was used for both the Doppler-shift-lifetime and the angular-distribution measurements. γ rays in coincidence with protons detected with a 300-μm annular surface-barrier detector mounted at 180° with respect to the beam direction and subtending an angle from 162 to 175° at the target were detected with a 55-cm^3 true-coaxial Ge(Li) detector. The resolution of the Ge(Li) detector was <3 keV on the 1.33-MeV ^{60}Co peak. The Ge(Li) detector was mounted in an angular-distribution lid specifically designed to fit in the top of a 43-cm-diam ORTEC scattering chamber. A vacuum sliding seal in the angular-distribution lid allowed the Ge(Li) detector to be rotated about the target as well as positioned radially. The Ge(Li) detector angle and radial distance could be accurately read from vernier scales. Throughout this experiment the front face of the Ge(Li) detector was positioned 7 cm from the target.

An aluminum foil 34 mg/cm^2 thick was placed over the front of the annular detector to stop the elastically scattered α particles. Excitation functions for the levels of interest in ^{93}Nb studied over the range from 14 to 16 MeV showed no large variations with the α bombarding energy. These excitation functions were studied with a 500-μg/cm^2 enriched (97.65%) ^{90}Zr self-supporting foil. Although we were not able to resolve individual states in the proton spectrum, the excited levels in ^{93}Nb below the 1297-keV level were grouped into one large peak such that an energy window in the backward scattered proton spectrum could be placed on the low-lying states for the coincidence measurements. An α-particle bombarding energy of 14.77 MeV was finally chosen for the lifetime and angular-distribution measurements as this energy corresponded to the largest yield for the reaction in the energy range over which excitation functions were obtained.

The coincidence electronics employed in these measurements consisted of constant fraction fast-timing discriminators and standard slow-coincidence logic and gating modules. A pulse-height stabilizer set on a pulser peak was used during the lifetime measurements in order to insure gain stability against electronic drifts. Throughout these measurements beam currents of 50 nA were used on target. Approximately 16 h of data collection were required at each angle with these beam currents in order to obtain adequate statistics.

A typical coincidence γ-ray spectrum taken at $\theta_\gamma = 45°$ during the angular-distribution measurements is shown in Fig. 1. This spectrum has been compressed four to one in channel number for display purposes. γ-ray peak centroids and areas in each of the coincidence spectra were determined by fitting with a Gaussian peak shape and a linear background. Random coincidence γ-ray spectra taken for each of the angular-distribution measurements were not subtracted from the true-coincidence spectra, since the former showed no peaks or Compton edges in the region of interest.

Due to some nonlinearities in the ADC, and count-rate shifts between the coincidence counting rate and a source calibration counting rate, we were unable to make absolute γ-ray energy measurements. Instead, we determined the energies of the γ rays originating from the negative-parity levels by using an internal calibration in which the γ-ray energies measured by Gobel, Feicht, and Vonach[8] and Stelson *et al.*[11] for the positive-parity levels were fitted with a quadratic equation. The energies quoted in this paper for the positive-parity levels are those of Stelson *et al.*[11] The uncertainites associated with the γ-ray energies from the negative-parity levels measured in this work are estimated to be ±0.8 keV. Since the negative-parity levels studied all decay through the (30 ± 2)-keV $(\frac{1}{2}^-)$ level[13] of ^{93}Nb, the energy uncertainty associated with this level combined with the γ-ray energy uncertainties made the over-all uncertainty for the negative-parity level positions on the order of 2.3 keV. Presumably, the 30.4-keV energy quoted in Ref. 14 for the position of the $\frac{1}{2}^-$ isomeric level in ^{93}Nb is more accurate than that of Ref. 13, but we were not able to find the uncertainties associated with this value.

The lifetimes of the low-lying levels in ^{93}Nb were measured in this work by the Doppler-shift attenuation method.[15-17] Preliminary results of

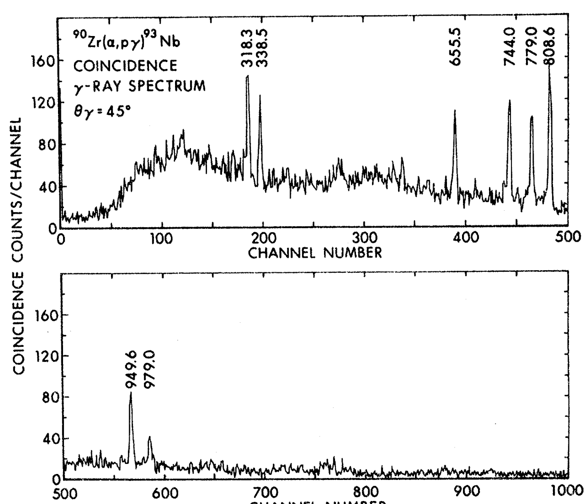

FIG. 1. Coincidence γ-ray spectrum taken with a 55-cm^3 Ge(Li) detector at $\theta_\gamma = 45°$. The spectrum has been compressed four to one in channel number for this display. The proton energy window included levels in ^{93}Nb from 695 to 1127 keV in excitation. Energies in keV are shown above the peaks.

these measurements were reported in Ref. 18. Doppler shifts measured for the levels were obtained from coincidence γ-ray spectra taken at angles of 45, 90, and 135°. The adopted shifts for each level were extracted from a least-squares fit to the angular dispersion of the measured centroid positions for the three angles. The measured Doppler shifts were then used to obtain the experimental attenuation factors, which represent the ratio of the observed Doppler shift in the γ-ray energy for an excited nucleus slowing down in the target, to full Doppler shift expected for recoiling into a vacuum. Since 15% of the excited nuclei were able to escape into the vacuum by recoiling out the back of the (1-mg/cm^2) ^{90}Zr target, the measured lifetimes were corrected according to the procedure outlined in Ref. 19 using an effective recoil slowing-down time. Doppler-shift attenuation factors $F(\tau)$ were calculated as a function of the lifetime using the stopping-power theory of Lindhard, Scharff, and Schiott (LSS).[20] Large-angle scattering corrections were made according to the Blaugrund method.[21] The expression for the nuclear stopping power was the same as that used in an earlier paper,[22]

$$\left.\frac{d\epsilon}{d\rho}\right|_n = \frac{\epsilon^{1/2}}{0.67+2.07\epsilon+0.03\epsilon^2},$$

which represents an empirical fit to the (LSS) nuclear stopping-power curve.[23]

Angular-distribution coincidence γ-ray spectra were taken at 30, 45, 60, 70, and 90°. The measured angular distributions were then analyzed using a χ^2 test. The angular-distribution formalism and spin convention followed Method II of Litherland and Ferguson[24] as developed by Poletti and Warburton.[25] In this particular reaction, with protons being detected near 180°, only magnetic substates of $\pm\frac{1}{2}$ were populated except for a small amount of $\pm\frac{3}{2}$ population due to the finite size of the annular counter. We have estimated the $\pm\frac{3}{2}$ impurity to be 10% of the $\pm\frac{1}{2}$ substate population. Finite solid-angle corrections for the Ge(Li) detector[26] were included in the angular-distribution analysis. The χ^2 results were plotted as a function of the arctangent of the mixing ratio. These plots were then used to obtain the most probable spin and the corresponding mixing ratio. The error limits in the mixing ratio were obtained by increasing the unnormalized χ^2 by 1, which corresponds to one standard deviation.

III. RESULTS AND DISCUSSION

A. Doppler-Shift Lifetimes

The results of the Doppler-shift-lifetime measurements are shown in Table I. The spins assigned to the negative-parity levels are the results of the present measurements. A detailed discussion of these levels as well as others will be given later in the text. Except for the 685-keV level, the lifetimes measured are merely lower limits. The errors associated with the lifetimes include only the statistical error. Since there are no experimental data available for the stopping cross sections of Nb ions in Zr, no attempt was made to correct for any deviations from the LSS stopping-power theory. Since most of these lifetimes are only lower limits, no additional uncertainties for the stopping cross sections were included in the final lifetime uncertainties. In view of these uncertainties, the lifetime limits measured in the present work for the positive-parity levels are consistent with lifetimes deduced from Coulomb excitation.[11] Stelson *et al.*[11] obtained a lifetime of 0.8 psec for the 744.0-keV ($\frac{7}{2}^+$) level and 9.0 psec for the 808.6-keV ($\frac{5}{2}^+$) level from their Coulomb-excitation measurements.

B. Angular Distributions

685-keV Level

The γ-ray angular distribution measured for the decay of the 685-keV level to the 30-keV level is shown in Fig. 2. As a result of fitting the distribution with a Legendre-polynomial expansion of the

TABLE I. Doppler-shift lifetimes in ^{93}Nb.

Level (keV)	J^π	Transition (E_i and E_f in keV)	Measured Doppler shift (keV)	Measured $F(\tau)$	τ (psec)
685	$\frac{3}{2}^-$	685 → 30	1.6 ± 0.7	0.34 ± 0.15	$0.41^{+0.69}_{-0.20}$
744.0 [a]	$\frac{7}{2}^+$	744.0 → 0	0.5 ± 0.6	0.09 ± 0.11	>1
808.6 [a]	$\frac{5}{2}^+$	808.6 → 0	0.0 ± 0.4	0.0 ± 0.07	>4
809	$\frac{5}{2}^-, (\frac{3}{2}^-)$	809 → 30	0.3 ± 0.6	0.05 ± 0.11	>1.5

[a] Energies quoted from Ref. 11.

form $W(\theta)=A_0+A_2P_2$, the A_2/A_0 coefficient was measured to be -0.61 ± 0.14. This coefficient as well as all other Legendre-polynomial coefficients presented in this paper have been corrected for the finite solid-angle attenuation factors of the Ge(Li) detector. From the χ^2 analysis also shown in Fig. 2 a spin of $\frac{3}{2}$ can unambiguously be assigned to the 685-keV level. The dashed line indicates the χ^2 analysis associated with a ten percent $\pm\frac{3}{2}$ substate population. For a spin of $\frac{3}{2}$, the χ^2 analysis yields two possible $E2/M1$ mixing ratios; $\delta=+0.13^{+0.14}_{-0.09}$ or $\delta=+1.33\pm0.35$. These mixing ratios include our estimate of the finite-size

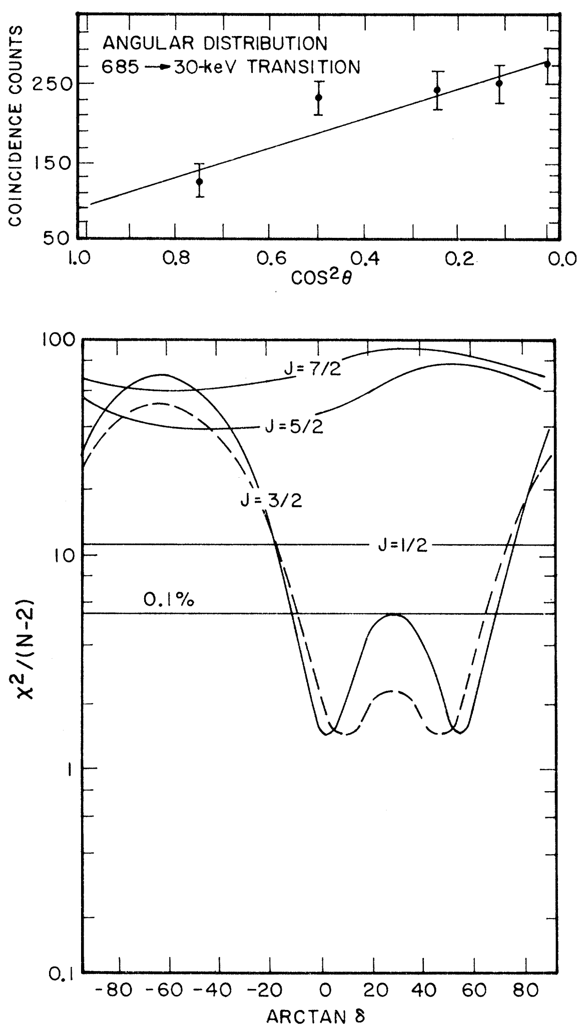

FIG. 2. Measured angular distribution and χ^2 vs arctangent δ for the 685→ 30-keV transition. The solid line through the data points represents the Legendre-polynominal fit to the data. The χ^2 distribution is divided by $(N-2)$, where N is the number of data points. The dashed line indicates a 10% $\pm\frac{3}{2}$ substate population due to the finite size of the annular counter.

effects. The parity of the 685-keV level has been established as being negative from the $l=1$ transfer measured in the ^{94}Mo(d, ^{3}He)^{93}Nb,[9] ^{92}Zr(^{3}He, d)-^{93}Nb,[10] and the ^{96}Mo(p, α)^{93}Nb[27] angular distributions. Combining our lifetime measurement $\tau=0.41^{+0.69}_{-0.20}$ psec with the $E2/M1$ mixing ratio $\delta=+0.13^{+0.14}_{-0.09}$, we obtain an $E2$ transition strength of $11^{+35}_{-10.5}$ W.u. (Weisskopf units). This value is consistent with other collective $E2$ transition strengths measured for nuclei in this region[11,12] and strongly suggests that there is collective enhancement for the transition. The second root for the $E2/M1$ mixing ratio $\delta=+1.33\pm0.35$ can be excluded on the basis that it gives an $E2$ strength >200 W.u. which is entirely too large.

744.0- and 1082.5-keV Levels

In the previous ^{93}Nb(n, $n'\gamma$)^{93}Nb experiments the 1082.5-keV level was observed to have a branch to the 744.0-keV level as well as a ground-state branch. Recently, Stelson *et al.*[11,28] measured the relative yield of the 1082.5→ 744.0-keV branch to be 2.5 times the ground-state branch. They also observed a branch to the 979.0-keV level on the order of 10%. In the present work, only a 338.5-keV γ ray resulting from the decay of the 1082.5-keV level to the 744.0-keV level was observed; branches to the ground state and the 979.0-keV level were too weak to be observed within the 16-h data collection times. The coefficients obtained from the Legendre-polynomial fit to the measured angular distribution for the 338.5-keV γ ray are $A_2/A_0=-0.60\pm0.15$ and $A_4/A_0=-0.13\pm0.26$. A J^π of $\frac{7}{2}^+$ has been assigned to the 744.0-keV level from neutron inelastic scattering experiments. Gobel, Feicht, and Vonach[8] assigned a J^π of $\frac{7}{2}^+$ to this level while reserving a $\frac{9}{2}$ possibility. Coulomb-excitation experiments[11,12] have been in agreement with a J^π of $\frac{7}{2}^+$ for the level.

Assuming a J^π of $\frac{7}{2}^+$ for the 744.0-keV level, the χ^2 analysis of the measured angular distribution for the 338.5-keV γ ray yielded a spin of $\frac{9}{2}$ for the 1082.5-keV level, in agreement with a $J^\pi=\frac{9}{2}^+$ assignment deduced from the earlier Coulomb-excitation works.[11,12] Cates, Ball, and Newman[10] have also assigned a J^π of $\frac{9}{2}^+$ to the 1082.5-keV level from the $l=4$ transfer observed in the ^{92}Zr-(^{3}He, d)^{93}Nb angular distribution. With the parity of the level clearly established as positive, the $E2/M1$ mixing ratio presently measured for the 1082.5→ 744.0-keV transition is $\delta=+0.12^{+0.09}_{-0.07}$. The above spin assignment is also in agreement with the ^{96}Mo(p, α)^{93}Nb angular distribution measured at this laboratory for the 1082-keV level.[27]

The angular distribution measured for the 744.0-keV γ ray yielded Legendre-polynomial coefficients of $A_2/A_0 = -0.52 \pm 0.15$ and $A_4/A_0 = +0.17 \pm 0.25$. Since protons from the 1082.5-keV level were included in the proton energy window, the angular distribution for the 744.0-keV level was analyzed taking into account this feeding. The mixing ratio δ, for the 1082.5 → 744.0-keV cascade transition was fixed at a value of 0.12. The percentage direct and cascade feeding to the 744.0-keV level was varied along with the mixing ratio considered for the particular spin sequence. The mixing ratio was found to be insensitive to the percentage of cascade feeding over a wide range (e.g., 0–50%). The χ^2 analysis yielded spins of $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{11}{2}$ with nearly equal acceptance probability for this level. An $E2$ strength of <11 W.u. obtained with a J^π of $\frac{7}{2}^+$, a measured $E2/M1$ mixing ratio of $\delta = -0.25^{+0.06}_{-0.09}$, and a lifetime of $\tau > 1$ psec is consistent with the Coulomb-excitation value of 8.4 W.u.[11] A $J^\pi = \frac{5}{2}^+$ assignment for this level is not very likely in view of a rather large $M3/E2$ mixing ratio of $\delta = +1.0$. For $J^\pi = \frac{11}{2}^+$, the measured $E2/M1$ mixing ratio is $\delta = +0.12 \pm 0.05$. Using our lower lifetime limit we obtain an $E2$ transition at least 5 times smaller than that measured by Coulomb excitation.[11, 12]

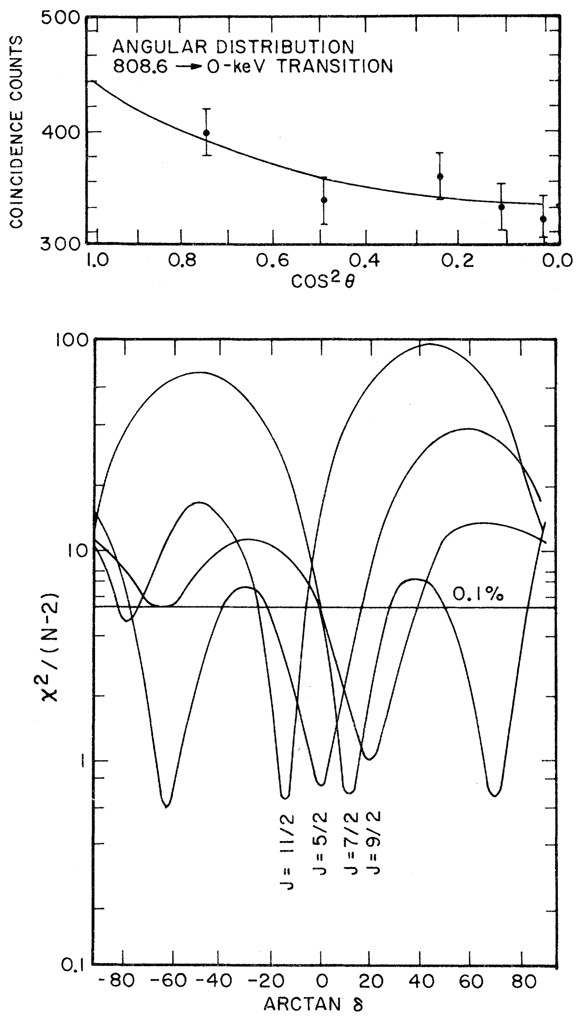

FIG. 3. Measured angular distribution and χ^2 vs arctangent δ for the 808.6 → 0-keV transition. Finite-size effects due to the annular counter were negligible, hence they are not shown.

808.6-keV Positive-Parity Level

Nearly all of the previous J^π assignments made from neutron inelastic scattering experiments have been in agreement with a $J^\pi = \frac{5}{2}^+$ for the 808.6-keV level. Gobel, Feicht, and Vonach[8] remain an exception to this in that they have assigned a spin of $\frac{7}{2}^+$, $\frac{9}{2}$, or $\frac{11}{2}^-$ to this level. Cates, Ball, and Newman[10] assigned a J^π of $\frac{5}{2}^+$ to an 807-keV level from the $^{92}Zr(^3He, d)^{93}Nb$ angular distribution. Stelson *et al.*[11] assigned a J^π of $\frac{5}{2}^+$ to the level from Coulomb-excitation studies and measured a $B(E2)$ reduced transition probability for excitation of 159 $fm^4 e^2$. Recently, Kregar and Seaman[12] measured the $B(E2)$ for this transition and obtained agreement with this value. However, they tentatively assigned a J^π of $\frac{11}{2}^+$ to the 809-keV level on the basis that it gives a reduced transition probability for core excitation in the weak-coupling model in better agreement with the average $B(E2)$ for core excitations in ^{93}Nb.

The angular correlation shown in Fig. 3 measured for the 808.6-keV level is fitted with the Legendre coefficients $A_2/A_0 = +0.19 \pm 0.09$ and $A_4/A_0 = +0.08 \pm 0.15$. As can be seen from the χ^2 analysis shown in Fig. 3, it was impossible to determine a unique spin for the 808.6-keV level from the angular-distribution measurement. Spins ranging from $\frac{5}{2}$ through $\frac{11}{2}$ all have nearly the same acceptance probability. We have measured a lower lifetime limit for this level of $\tau > 4$ psec. Stelson *et al.*[11, 28] measured a lifetime of $\tau = 8$ psec for the 808.6-keV level from a Doppler-broadened peak-shape analysis, in agreement with a lifetime deduced from their $B(E2)$ transition probability. In light of the $J^\pi = \frac{5}{2}^+$ assignment made by Stelson *et al.*,[11] the $M3/E2$ mixing ratio measured in this work is $\delta = +0.03^{+0.08}_{-0.06}$. Combining this with the 8-psec lifetime, we obtain an $E2$ strength of 11.8 W.u. in agreement with the $B(E2)/B(E2)_{sp} = 10.5$ W.u. measured by Stelson *et al.*[11] The second root for the $M3/E2$ mixing ratio is not significant as this would imply a large $M3$ contribution. A branch for the decay of the 808.6-keV level to the 744.0-keV level on the order of 1% was observed by Stelson *et al.*[11, 28] This branch was not observed in the present work because of its low intensity and low energy. As for the other spins indicated by our χ^2 analysis shown in Fig. 3 we were not able to rule these out except to indicate that for $J^\pi = \frac{11}{2}^+$ the $E2$ transition strength is less than 2 W.u.

809-keV Negative-Parity Level

A doublet existing at 809 keV in excitation having a separation on the order of 1 keV was first suggested by Beghian *et al.*[4] from ^{93}Nb$(n, n'\gamma)^{93}$Nb excitation-function studies using a high-resolution Ge(Li) detector. They tentatively assigned a J^π of $\frac{3}{2}^-$ to a 808-keV level which decayed to the 28-keV ($\frac{1}{2}^-$) level with a 780-keV γ ray. Previous inelastic neutron scattering measurements by Williams and Morgan[3] suggested that the 780-keV γ ray originated as a branch from the 809-keV ($\frac{5}{2}$) level. Rogers *et al.*[7] confirmed the existence of a doublet by showing that the relative yield between the 780- and the 809-keV γ rays was different for Coulomb excitation from that obtained by inelastic scattering of neutrons. More recently, Gobel, Feicht, and Vonach[8] observed a 780-keV γ ray decaying from a level at 810 keV in excitation to the 30-keV ($\frac{1}{2}^-$) level in their inelastic neutron scattering experiments. They assigned a spin of $\frac{3}{2}$ or $\frac{5}{2}^-$ to this level.

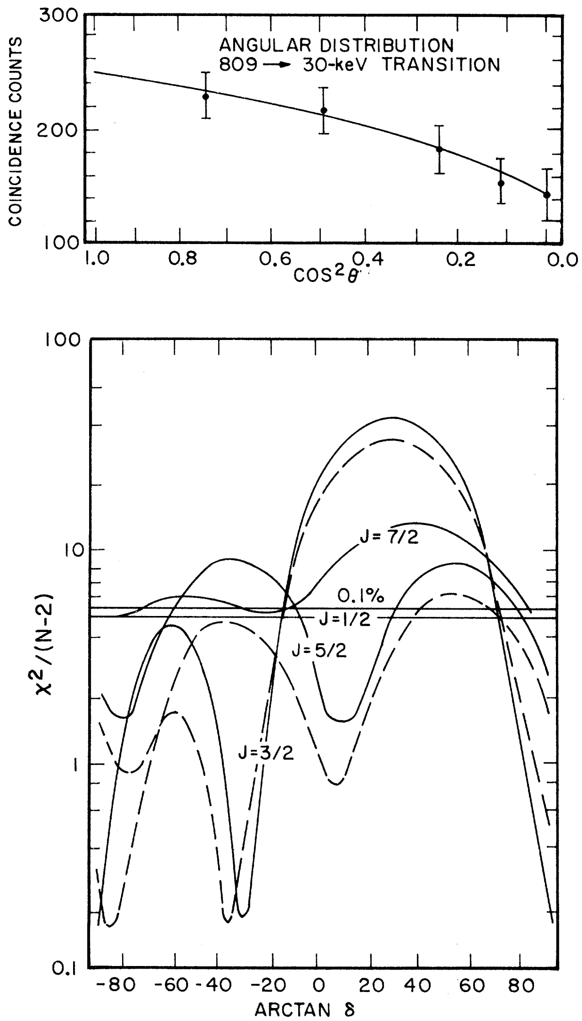

FIG. 4. Angular distribution and χ^2 vs arctangent δ for the 809→30-keV transition. Dashed lines in the χ^2 distribution plot indicate finite-size effects of the annular counter.

The angular distribution measured for the decay of a 779-keV γ ray from the 809-keV level to the 30-keV ($\frac{1}{2}^-$) isomeric state in ^{93}Nb is shown in Fig. 4. The Legendre coefficients are $A_2/A_0 = +0.48 \pm 0.16$ and $A_4/A_0 = -0.11 \pm 0.24$. From the χ^2 analysis spins of $\frac{3}{2}$ and $\frac{5}{2}$ are possible for this level. The dashed lines in Fig. 4 represent the finite-size effects of the annular counter. Although a level located at 1127 keV in excitation was observed to decay to the 809-keV level with emission of a 318-keV γ ray, the cascade feeding due to this level did not have an appreciable effect on the 779-keV γ-ray angular correlation owing to the nearly isotropic angular distribution measured for the 318-keV γ ray. (See discussion of the 1127-keV level.) Negative parity has tentatively been assigned to one member of the 809-keV doublet from previous neutron inelastic scattering experiments.[4,8] Recently, a ^{96}Mo$(p, \alpha)^{93}$Nb angular distribution measured at this laboratory[27] yielded a J^π assignment of $\frac{5}{2}^-$ ($\frac{3}{2}^-$) for a level located in this doublet. In these (p, α) angular distributions the 744.0-keV ($\frac{7}{2}^+$) and the 808.6 ($\frac{5}{2}^+$) levels were weakly populated. Considering the previous assignments, the $J^\pi = \frac{5}{2}^+$ assignment for the 808.6-keV level, and the observed decay of the 809-keV level to the 30-keV ($\frac{1}{2}^-$) level, we believe the parity of the 809-keV level to be negative. Thus for $J^\pi = \frac{3}{2}^-$, the $E2/M1$ mixing ratio is $\delta = -0.64^{+0.12}_{-0.17}$. Using our lower lifetime limit of $\tau > 1.5$ psec, we obtain an $E2$ strength of <26 W.u. For $J^\pi = \frac{5}{2}^-$, the $M3/E2$ mixing ratio $\delta = 0.15 \pm 0.20$, when combined with the lower lifetime limit, gives an $E2$ strength of <76 W.u. In view of the lower lifetime limit and considerations of a weak-coupling model for the low-lying negative-parity levels, we have tentatively assigned a $J^\pi = \frac{5}{2}^-$ to the 809-keV level. A J^π of $\frac{5}{2}^-$ was also tentatively favored in the ^{96}Mo$(p, \alpha)^{93}$Nb angular-distribution measurement mentioned above.

949.6-keV Level

The Legendre coefficients obtained from the measured angular distribution for the decay of the 949.6-keV level to the ground state of ^{93}Nb are $A_2/A_0 = +0.40 \pm 0.21$, $A_4/A_0 = -0.75 \pm 0.40$, and A_6/A_0

$=+0.21\pm0.42$. Spins of $\frac{9}{2}$ and $\frac{13}{2}$ were obtained from the χ^2 analysis of the measured distribution. The lifetime of this level has been measured by Stelson *et al.*[11,28] from Doppler peak-shape analysis to be 6 psec. Combining this lifetime with the $E2/M1$ mixing ratio of $\delta=-1.04^{+0.34}_{-0.44}$ for a J^π of $\frac{9}{2}^+$ we obtain an $E2$ transition strength of 3.6 W.u. For a $J^\pi=\frac{13}{2}^+$, the measured $M3/E2$ mixing ratio of $\delta=+0.18\pm0.18$ when combined with the above lifetime gives an $E2$ transition strength of 6.9 W.u. in good agreement with the Coulomb excitation $E2$ strength of 6.6 and 7.0 W.u. measured by Stelson *et al.*[11] and Kregar and Seaman,[12] respectively. We, therefore, conclude that the J^π of this level is $\frac{13}{2}^+$ in agreement with previous asssignments, as well as with a recent assignment of $\frac{13}{2}^+$ made from the ^{96}Mo(p, α)^{93}Nb angular-distribution analysis.[27]

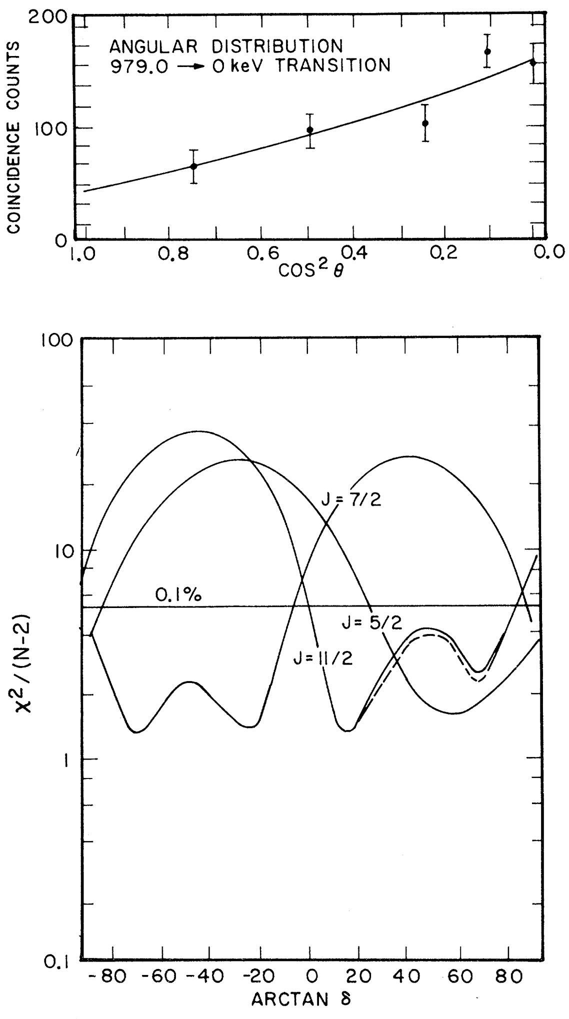

FIG. 5. Angular distributions and χ^2 vs arctangent δ for the 979.0→ 0-keV transition. The dashed line indicates finite-size effects. Spins for which the χ^2 distributions were above the 0.1% confidence level are not included on the figure.

979.0-keV Level

The Legendre-polynominal coefficients obtained from fitting to the angular distribution shown in Fig. 5 for the decay of the 979.0-keV level to the ground state are $A_2/A_0=-0.80\pm0.25$ and $A_4/A_0=+0.09\pm0.38$. Of the spins $\frac{5}{2}$ through $\frac{13}{2}$ considered for this level only those having a χ^2 distribution below the 0.1% confidence limit are shown in Fig. 5. A J^π of $\frac{5}{2}^+$ as suggested by Ref. 12 for this level is quite unlikely, since the χ^2 analysis shown in Fig. 5 indicates that a $J^\pi=\frac{5}{2}^+$ would require a very large $M3/E2$ mixing ratio. Using a lifetime of 0.5 psec for this level as measured by Stelson *et al.*[11,28] from Doppler broadening, we obtain an $E2$ transition strength of 14.0 W.u. for a J^π of $\frac{7}{2}^+$ with an $E2/M1$ mixing ratio of $\delta=-0.49^{+0.17}_{-0.24}$. For $J^\pi=\frac{11}{2}^+$ the $E2/M1$ mixing ratio $\delta=+0.27^{+0.13}_{-0.09}$, when combined with the above lifetime, results in an $E2$ transition strength of 4.9 W.u. Stelson *et al.*[11] obtained a J^π of $\frac{11}{2}^+$ for the 979.0-keV level from γ-γ angular correlations and measured an $E2$ transition strength of 5.7 W.u. Thus, the present $E2$ strength for a J^π of $\frac{11}{2}^+$ is in good agreement with that determined from Coulomb excitation. A $l=1$ transfer measured by Cates, Ball, and Newman[10] from the ^{92}Zr(^{3}He, d)^{93}Nb angular distribution for a level at 970 keV in excitation does not agree with the J^π assignment of $\frac{11}{2}^+$ for the 979.0-keV level nor with the $\frac{13}{2}^+$ assignment of the 949.6-keV level. The decay of such a level was not observed in this work. Furthermore, recent ^{96}Mo(p, α)^{93}Nb angular distributions measured at this laboratory[27] give no indication of a level having a J^π of $\frac{1}{2}^-$ or $\frac{3}{2}^-$ located around 970 keV in excitation.

1127-keV Level

A level located at 1127 keV in excitation in ^{93}Nb has recently been established from the γ-γ coincidence measurements by Gobel, Feicht, and Vonach,[8] in which they observed a 318-keV γ ray in coincidence with a 780-keV γ ray resulting from the decay of the 810-keV level to the 30-keV ($\frac{1}{2}^-$) level. From neutron inelastic scattering excitation functions Gobel, Feicht, and Vonach assigned spins of $\frac{5}{2}^+$ or $\frac{7}{2}$ to the 1127-keV level. Previous γ-ray energy measurements resulting from neutron inelastic scattering experiments[1,5–7] assigned a 316-keV γ ray to the 1296→ 980-keV transition. Stelson *et al.*[11,28] observed a 318.3-keV γ ray resulting from the decay of the 1297.3-keV level to the 979.0-keV level following Coulomb excitation of the 1297.3-keV level. They also observed a branch to the 744.0-keV level and a ground-state branch. Stelson *et al.*[11,28] measured the relative γ-ray yield of the 553.3-keV γ ray to the 1297.3-keV γ ray to be 55% and the relative yield of the 318.3-keV γ ray to the 1297.3-keV γ ray to be 31%. With the above information, we assigned all of the yield observed in the present work for a 318-keV γ ray to the decay of the 1127-keV level on the basis that we did not observe any yield for the 553.3- or the 1297.3-keV γ-ray branches of the 1297.3-keV level. The angular distribution measured for the 318-keV γ ray was nearly isotropic as indicated from the Legendre-polynomial coefficients of $A_2/A_0 = +0.07 \pm 0.16$ and $A_4/A_0 = +0.07 \pm 0.23$. Spins ranging from $\frac{1}{2}$ through $\frac{9}{2}$ were tested in a χ^2 analysis assuming the spin of the 809-keV level to be $\frac{5}{2}^-$. Only a spin of $\frac{9}{2}$ could be eliminated with the present measurement. An analysis of the angular distribution for the 318-keV γ ray assuming a spin of $\frac{3}{2}^-$ for the 809-keV level yielded possible spins of $\frac{1}{2}$, $\frac{3}{2}$, and $\frac{5}{2}$ for the 1127-keV level. With the present information we were not able to make a spin assignment for the 1127-keV level.

The parity of this level has not been determined since the level has not been observed in any direct-reaction work. Positive parity would not be expected because of the observed γ decay to the 809-keV $\frac{5}{2}^-$ ($\frac{3}{2}^-$) level. For spins of $\frac{1}{2}^-$, $\frac{3}{2}^-$, and $\frac{5}{2}^-$

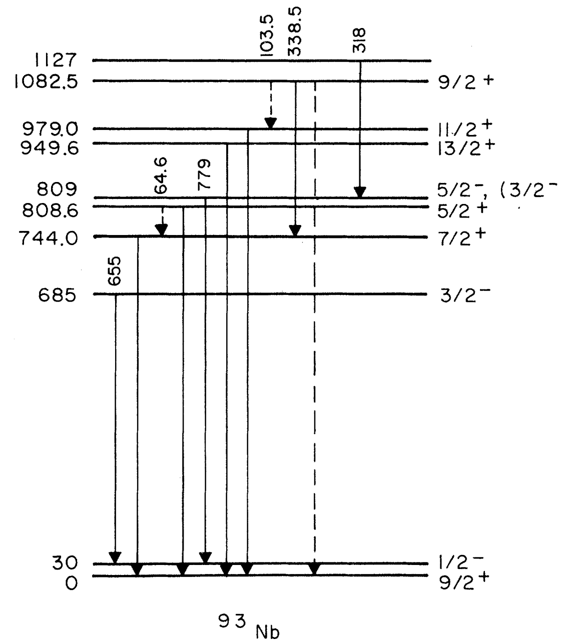

FIG. 6. Energy-level diagram and decay scheme for levels in ^{93}Nb up to 1127 keV in excitation. The level energies quoted to the nearest tenth of a keV are those of Ref. 11. Spin assignments are discussed in the text. The dashed lines indicate transitions observed by the investigators of Ref. 11, but not observed in the present work due either to their low energies or low intensities.

TABLE II. Electromagnetic decay properties of levels in ^{93}Nb.

Level (keV)	J^π	Transition (E_i and E_f in keV)	τ (psec)	δ	ML	$\lvert M\rvert^2$ (W.u.) Present work	$\lvert M\rvert^2$ (W.u.) Stelson *et al.*[a]
					$E2$	$11^{+35}_{-10.5}$	
685	$\frac{3}{2}^-$	685→30	$0.41^{+0.69}_{-0.20}$	$+0.13^{+0.14}_{-0.09}$			
					$M1$	$0.27^{+0.26}_{-0.17}$	
					$E2$	<11	8.4
744.0[b]	$\frac{7}{2}^+$	744.0→0	>1	$-0.25^{+0.06}_{-0.09}$			
					$M1$	<0.075	0.095
808.6[b]	$\frac{5}{2}^+$	808.6→0	>4	$+0.03^{+0.08}_{-0.06}$	$E2$	<23	10.5
809	$\frac{5}{2}^-$	809 →30	>1.5	$+0.15 \pm 0.20$	$E2$	<76	
	($\frac{3}{2}^-$)			$-0.64^{+0.12}_{-0.17}$	$E2$	<26	
					$M1$	<0.036	
949.6[b]	$\frac{13}{2}^+$	949.6→0		$+0.18 \pm 0.18$	$E2$		6.6
979.0[b]	$\frac{11}{2}^+$	979.0→0		$+0.27^{+0.13}_{-0.09}$	$E2$		5.7
1082.5[b]	$\frac{9}{2}^+$	1082.5→744.0		$+0.12^{+0.09}_{-0.07}$	$M1$		0.095
1127		1127→809					

[a] From Coulomb-excitation measurements of Ref. 11.
[b] Energies quoted from Ref. 11.

TABLE III. Comparison of experimental $E2$ transition strengths with the weak-coupling-model predictions.

Level (keV)	J^{π}	Transition (E_i and E_f in keV)	ML	$\lvert M\rvert^2$ (W.u.) Present work	$\lvert M\rvert^2$ (W.u.) Stelson *et al.* [a]	$\lvert M\rvert^2$ (W.u.) Weak-coupling model
685	$\frac{3}{2}^-$	685→ 30	$E2$	$11^{+35}_{-10.5}$		22
744.0 [b]	$\frac{7}{2}^+$	744.0→ 0	$E2$	<11	8.4	6.5
808.6 [b]	$\frac{5}{2}^+$	808.6→ 0	$E2$	<23	10.5	6.5
809	$\frac{5}{2}^-$	809→ 30	$E2$	<76		22
	$(\frac{3}{2}^-)$		$E2$	<26		22
949.6 [b]	$\frac{13}{2}^+$	949.6→ 0	$E2$		6.6	6.5
979.0 [b]	$\frac{11}{2}^+$	979.0→ 0	$E2$		5.7	6.5
1082.5 [b]	$\frac{9}{2}^+$	1082.5→ 0	$E2$		1.0	6.5

[a] From Coulomb-excitation measurements of Ref. 11.
[b] Level energies quoted from Ref. 11.

one may expect to observe transitions to the 30-keV ($\frac{1}{2}^-$) isomeric level; however, a direct transition to this level was not observed in the present work. The fact that we observed no strong decay of the 1127-keV level to the 685-keV ($\frac{3}{2}^-$) level indicates that for a spin of $\frac{7}{2}^-$ the transition has little, if any, collective component.

IV. SUMMARY AND CONCLUSION

A summary of the electromagnetic decay properties measured in the present work for levels up to 1127 keV in excitation in ^{93}Nb are tabulated in Table II. The transition strengths expressed in terms of an enhancement over single-particle units are compared with recent Coulomb-excitation measurements. An energy-level diagram and decay scheme for levels up to 1127 keV in excitation in ^{93}Nb is shown in Fig. 6. The γ-ray and level energies quoted to the nearest tenth of a keV are those of Ref. 11. The dashed lines indicate transitions observed by the investigators of Ref. 11 but not observed in the present work.

The positive-parity levels in ^{93}Nb observed in Coulomb excitation[11,12] have been described in terms of a weak-coupling model in which a $g_{9/2}$ proton is coupled to the ^{92}Zr core. As can be seen in Table III there is good agreement between the experimental $E2$ transition strengths for the low-lying positive-parity levels and those predicted by the weak-coupling model with the exception of the transition from the 1082.5-keV ($\frac{9}{2}^+$) level. Kregar and Seaman[12] have shown in a first-order weak-coupling approximation that a mixing of the first excited $\frac{9}{2}^+$ state with the $\frac{9}{2}^+$ ground state of ^{93}Nb is required in order to bring the predicted $E2$ strength of the first excited $\frac{9}{2}^+$ level into better agreement with experiment.

We have assigned a $J^{\pi}=\frac{3}{2}^-$ to the 685-keV level of ^{93}Nb and have tentatively indicated that an assignment of $\frac{5}{2}^-$ is favored for the 809-keV negative-parity level. In view of a weak-coupling model, a multiplet of $\frac{3}{2}^-$ and $\frac{5}{2}^-$ results from coupling the $2p_{1/2}$ proton-hole state to the ^{94}Mo (2^+) core. The collective enhancement suggested by the measured $E2$ transition strengths shown in Table III for the negative-parity levels would tend to indicate that a weak-coupling model may be appropriate for explaining these low-lying levels. Furthermore, recent assignments[29] of $\frac{1}{2}^-$ for a 39.0-keV level, $\frac{3}{2}^-$ for a 646.3-keV level, and ($\frac{5}{2}^-$) for a 927.9-keV level in ^{95}Tc support a weak-coupling model in which a negative-parity multiplet results from coupling a $2p_{1/2}$ proton-particle state to the ^{94}Mo core.

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