Study of the $Nb^{93}(n_{res},\gamma)Nb^{94}$ Reaction*

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The high-energy γ-ray spectra following capture in one s-wave and three p-wave resonances in Nb have been observed with a Ge(Li) detector. The low-lying energy levels of Nb^{94} inferred from the data are consistent with those previously reported on the basis of (d,p) and low-energy (n,γ) data. From the observed decay properties of the intial states, the spin assignments for the resonances are inferred to be $J_r^\pi = 5^-$ (35.8 eV), 4^+(119.2 eV), 4^- or 5^-(42.3 eV), 3^- or 4^-(94.3 eV). The distribution of partial radiative widths for the three p-wave resonances is consistent with that predicted by the statistical compound-nucleus model.

I. INTRODUCTION

THE resonances in the total neutron cross section of Nb^{93} were first observed by Bollinger *et al.*[1] The first detailed study was made by Saplakoglu *et al.*[2] The latter observed that the distribution of reduced neutron widths for this nucleus could be interpreted as consisting of two components. They suggested that the resonances corresponding to the component with smaller mean neutron width result from p-wave interactions. On this basis, they were able to obtain the first experimental value for the p-wave neutron strength function determined from the average parameters of individual low-energy resonances. Their suggestion was essentially confirmed by the work of Jackson[3] on the capture γ-ray spectra from these resonances. He found that the resonances could be classified into two groups according to the shape of their corresponding spectra. The difference between the two groups of spectra is reflected in the relative yield of the high-energy primary transitions, and the interpretation is consistent with the requirement that the two corresponding sets of resonances have opposite parity. In more recent studies,[4] the parities of many resonances in niobium have been assigned on the basis of shape analysis. This has not been possible for the resonances in the energy region below 200 eV because of their extremely small neutron widths. For the same reason, it has not been possible to determine the spins of resonances in this energy region.

The spectrum of primary transitions following thermal-neutron capture in niobium was first observed by Bartholomew and Kinsey,[5] who identified three transitions. More recently, a detailed study of the thermal spectrum has been reported by Slaughter and Harvey.[6] In a study of the $Nb^{93}(d,p)Nb^{94}$ reaction, Sheline *et al.*[7] observed 47 states extending to an excitation energy of about 3.3 MeV. The spectrum of thermal-neutron-capture γ rays in the energy region of 50–95 keV was measured by Gruber *et al.*,[8] who used a bent-crystal spectrograph. The level scheme deduced from the (d,p) and (n,γ) data by these authors is reproduced in Fig. 1. The energy and spin sequences are in substantial agreement with a theoretical description of the multiplet arising from the $(\pi g_{9/2})(\nu d_{5/2})^3$ configuration. A detailed treatment is given in Refs. 7 and 8.

In the present experiment, high-energy neutron-capture γ rays from the decay of some of the Nb resonances below 200 eV have been observed with a lithium-drifted germanium detector. The high resolution attainable with such a detector makes possible the identification of individual transitions in the resonance spectra—in contrast to the previous NaI data.[3] However, because of the much lower detection efficiency of the Ge(Li) counter, the accumulation of a statistically significant sample of events was very time consuming.

II. EXPERIMENTAL PROCEDURE

A rectangular target of Nb metal, 5 cm×8 cm and 0.0714 atoms/b thick, was irradiated in the pulsed neutron of the Argonne fast-chopper facility.[9] The sample was oriented so that it intercepted the beam at an angle of approximately 30°. The flight path was 6.49 m and the chopper rotated at 15 000 rpm. The neutron time-of-flight resolution width was 300 nsec/m —considerably poorer than the 80 nsec/m reported in

* Work performed under the auspices of the U. S. Atomic Energy Commission.
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[1] Data of L. M. Bollinger, D. A. Dahlberg, and R. R. Palmer, in U. S. Atomic Energy Commission Report No. AECU-2040, Suppl. 3, 1954 (unpublished).
[2] A. Saplakoglu, L. M. Bollinger, and R. E. Coté, Phys. Rev. **104**, 1258 (1958).
[3] H. E. Jackson, Phys. Rev. **131**, 2153 (1963).
[4] G. Le Poittevin, S. De Barros, V. C. Huynh, J. Julien, J. Morgenstern, F. Netter, and C. Samour, Nucl. Phys. **70**, 497 (1965); Kim Hi San, L. B. Pilkener, K. H. Sirazhet, and E. I. Sharapov, Zh. Eksperim. i Teor. Fiz. **49**, 410 (1965) [English transl.: Soviet Phys.—JETP **22**, 288 (1966)]; H. V. Muradyan and Yu V. Adamchuk, in *International Conference on the Study of Nuclear Structure with Neutrons, Antwerp, 1965*, edited by M. Nève de Mévergnies, P. Van Assche, and J. Vervier (North-Holland Publishing Co., Amsterdam, 1966), p. 570.
[5] G. A. Bartholomew and B. B. Kinsey, Can. J. Phys. **31**, 1025 (1953).
[6] G. G. Slaughter and J. A. Harvey, Oak Ridge National Laboratory Report 3778, 1964 (unpublished), pp. 44–53; Bull. Am. Phys. Soc. **10**, 499 (1965).
[7] R. K. Sheline, R. T. Jernigan, J. B. Ball, K. H. Bhatt, Y. E. Kim, and J. Vervier, Nucl. Phys. **61**, 342 (1965).
[8] U. Gruber, R. Koch, B. P. Maier, O. W. B. Schult, J. B. Ball, K. H. Bhatt, and R. K. Sheline, Nucl. Phys. **67**, 433 (1965).
[9] L. M. Bollinger, R. E. Coté, and G. E. Thomas, in *Proceedings of the Second International Conference on Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 14, p. 239.

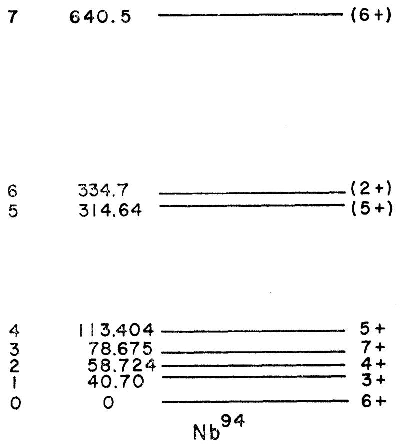

FIG. 1. Low-lying levels of Nb^{94} as given in Refs. 7 and 8. The energies of all levels are given in keV and, except for the 40.7-keV level, are based on the precision measurements of Ref. 8. The levels are identified according to the numbers in the far left column of the figure.

the previous work,[3] in which a large NaI detector was used with the 25-m flight path. The shorter flight path was necessary in the present experiment—in spite of the accompanying sacrifice in resolution—in order to obtain the higher neutron intensity made necessary by the much lower efficiency of our detection system. The γ rays were detected in a Ge(Li) counter of 15 cc active volume. The distance from the center of the sample to the face of the detector was 5 cm. An 8-mm-thick B^{10} absorber was placed over the face of the detector to absorb scattered neutrons. The detector was shielded from the reactor environment by a housing of lead and borated polyethylene.

The pulses from the detector were amplified and shaped with a standard Tennelec low-noise linear system, and processed in a biased amplifier. The neutron energy was determined from the flight time measured as the time difference between a start pulse generated upon opening the chopper slits and a stop pulse generated from the Ge(Li) detector. The time and pulse-height information was recorded with the Argonne three-parameter analyzer[10] in a data field consisting of 256 time channels and 1024 pulse-height channels. Each time channel covered a 0.5-μsec time interval. The gain and bias of the biased amplifier were adjusted so that the pulse-height range analyzed corresponded to the region of double-escape peaks from transitions in the interval from 4.7 to 7.7 MeV. In a parallel arrangement, the integrated γ-ray yield above 1 MeV was recorded as a function of time of flight in 2048 channels (0.5 μsec) of a separate time analyzer.

The counting rate for events in the energy and time region selected for two-parameter analysis was only 2 sec^{-1}. The low event rate is due to the characteristically small neutron widths of the Nb resonances in the region of usable neutron flux.[5] In order to obtain data of good enough statistical quality for a meaningful analysis, it was necessary to accumulate events for a period of 19 days. The short-term resolution width of the detector, full width at half-maximum (FWHM), at 6.6 MeV is 6.5 keV. However, because of electronic instabilities, the resolution width obtained over the long counting period used increased to 13 keV at 6.6 MeV.

III. EXPERIMENTAL RESULTS

The total γ-ray yield curve in the region of interest is shown in Fig. 2(a). The niobium resonances at 94, 106, and 119 eV are only partially resolved. In addition to the resonances shown in the figure, six resonances were observed in the region below 25 eV. The energies of five of these (those at 4.3, 10.3, 13.8, 20.3, and 23.7 eV) agree within error with well-known resonances in tantalum. A sixth resonance at 18.4 eV corresponds in energy to the lowest-energy resonance in W^{186}.

In a separate experiment, the transmission of the sample used was measured at a resolution width of 40 nsec/m. The resonances observed were all found to have energies in excellent agreement with those reported for tungsten, tantalum, and niobium. Using the latest resonance parameters,[11] it was possible to obtain a measure of the contaminant levels in our sample. These were determined to be 0.063 and 2×10^{-4} at.% for Ta and W, respectively.

In order to obtain the relative partial radiative widths for transitions from different resonances, it is necessary to normalize the observed intensities to give the same integrated yields.[12] To obtain the normalizing constants, the total yield curve was first resolved into six main components, superimposed upon a linearly varying background, as shown in Fig. 2(a). The relative contributions from tantalum to the apparent yields for the various niobium resonances were calculated by use of the latest resonance parameters.[11] The maximum tantalum contribution is for the 106-eV resonance—namely, 14%.

As a check on this procedure, the relative yields of high-energy γ rays were determined and compared with the previous work.[3] The γ-ray yield as a function of time of flight was determined from the two-parameter data integrated over the pulse-height region from 5.3 to 6.7 MeV. In this region the spectrum is dominated by the double-escape peaks corresponding to transitions in the energy range from 6.3 to 7.7 MeV, and the Compton continua from transitions with energies greater than approximately 5.6 MeV. The total energy release from the $Ta^{181}(n,\gamma)Ta^{182}$ reaction is known[13] to

[10] C. C. Rockwood and M. G. Strauss, Rev. Sci. Instr. **32**, 1211 (1961).

[11] *Brookhaven National Laboratory Report BNL*-325 (U. S. Government Printing and Publishing Office, Washington, D. C., 1960), 2nd ed., Suppl. No. 2.

[12] R. T. Carpenter, Argonne National Laboratory Report ANL 6589, 1962 (unpublished).

[13] J. R. Erskine and W. W. Buechner, Phys. Rev. **133**, B370 (1964); O. A. Wasson, M. A. Lone, M. R. Bhat, R. E. Chrien, H. R. Meuther, and M. Beer, Bull. Am. Phys. Soc. **12**, 596 (1967).

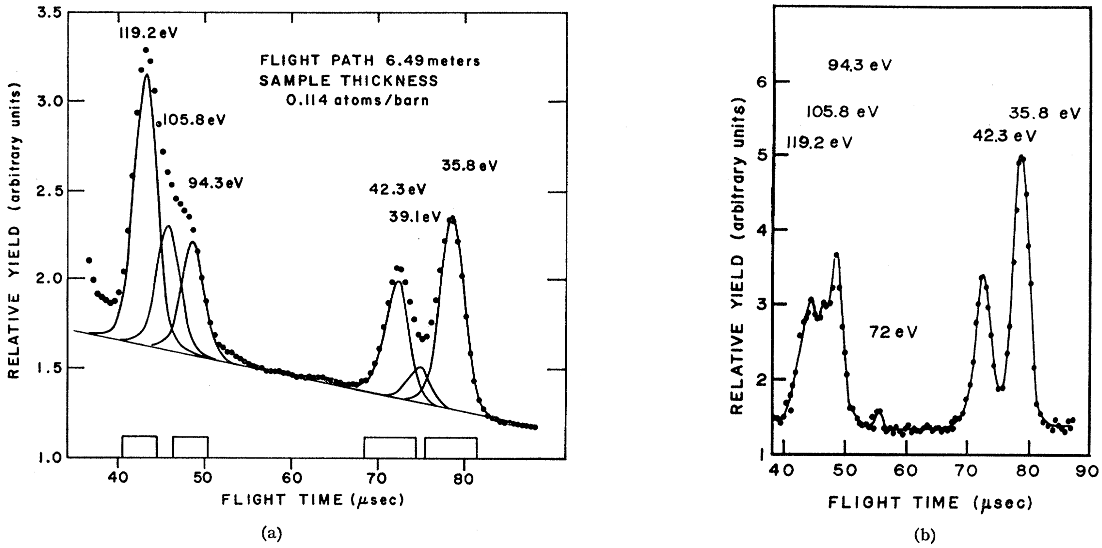

FIG. 2. (a) The total γ-ray yield as a function of time of flight. The curve was analyzed into the components shown by use of a least-squares procedure. The peak at 39.1 eV is due to a tantalum impurity. γ-ray spectra were observed for the four time regions indicated. (b) The γ-ray yield in the energy region $E_\gamma > 5.3$ MeV as a function of time of flight. The small peak at 72 eV has been tentatively assigned to Nb.

be less than 6.2 MeV, so that the contribution from tantalum γ rays in this region is strongly suppressed. The results are shown in Table I and Fig. 2(b), where they are compared with those of the previous work.[3] It can be seen from the table that the results are in good agreement, despite the fact that it was not possible to reproduce exactly the conditions used by Jackson.[3]

In addition to the resonances observed in the total-yield curve, when the pulse height is required to be in the range 5.3–6.7 MeV we observe a small resonance at 72±2 eV that is 7% as intense as the 35.8-eV resonance in Nb. A peak of this magnitude cannot be formed by possible undetected resonances in either tantalum or tungsten. Also, the relative intensity of the γ rays in the range 5.3–6.7 MeV is consistent with the values given in Table I for p-wave resonances of Nb. Hence, we tentatively assign the 72-eV resonance to be a p-wave Nb resonance, with a neutron width of roughly 10^{-5} eV.

The pulse-height spectra corresponding to the time regions near the 35.8- and 119-eV resonances are compared in Fig. 3. The absolute energy calibration was determined from a gain calibration and the positions of the γ rays corresponding to capture in iron,[14] which is the major contributor to the off-resonance background.

As can be seen from Fig. 3, these two spectra display a marked difference in over-all shape, as observed in the previous NaI work.[3] While the spectrum corresponding to the p-wave resonance at 35.8-eV is quite flat over the entire energy range shown, the intensity in the

TABLE I. Relative high-energy γ-ray yields.

Resonance energy (eV)	Neutron orbital angular momentum	Relative intensity[a] of all transitions with $E_\gamma > 6.5$ MeV	Relative integrated yield[b] for $E_\gamma > 5.3$ MeV
35.8	1	1.2±0.1	1.0±0.1
42.3	1	0.8±0.1	0.8±0.1
94.3	1	0.8±0.1	0.9±0.1
106	0	0.3±0.1	0.4±0.1
119	0	0.1±0.1	0.2±0.1

[a] From Ref. 3.
[b] The region $E_\gamma > 5.3$ MeV in the Ge(Li) detector includes the double-escape peaks for $E_\gamma > 6.3$ MeV and the Compton continua for $E_\gamma > 5.6$ MeV (approximately).

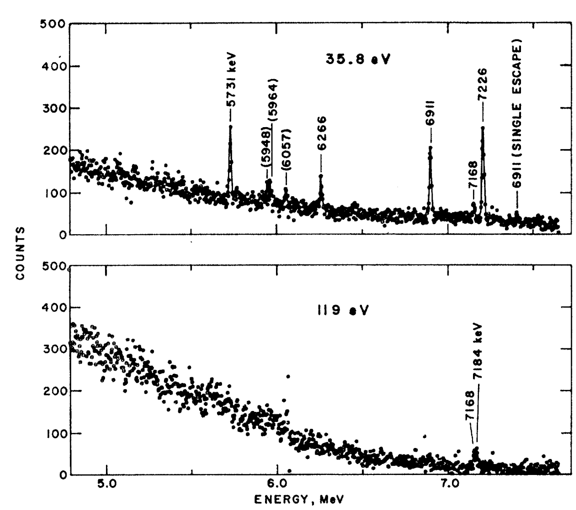

FIG. 3. Comparison of the γ-ray spectra of s- and p-wave resonances. The upper spectrum is that corresponding to capture in the 35.8-eV p-wave resonance. The lower spectrum is that obtained for the s-wave resonance at 119 eV. The energy scale has been adjusted so that the position of the double-escape peak occurs at the energy of the corresponding γ ray.

[14] H. E. Jackson, A. I. Nameson, and G. E. Thomas, Phys. Rev. Letters **17**, 324 (1965).

Table II. γ-rays observed following capture in the 35.9-eV resonance.

E_γ(keV)	Relative intensity	Excitation energy (keV) From[a] (S_n-E_γ)	From[b] (d,p)	J^π	E_γ(keV) thermal[c]
7226±6	1000	0	0	6^+	7229±10
7168±6	140±30	58.2±1	59	4^+	7167
6911±6	780±60	314.6±1	314	5^+	6917
6266±6	360±40	960 ±2	960		
6057±6	190±40[d]	1169 ±2	1168		6067
5964±6	200±80[d]	1262 ±2			5964
5948±6	130±60[d]	1278 ±2	1278		5954
5731±6	570±140	1495 ±3	1496		5732

[a] With $S_n=7226$ keV. The errors include the estimated uncertainties in gain and peak positions.
[b] Reference 6. Only the reported levels with excitation energies near those observed in this work are listed.
[c] Reference 6. Only those transitions corresponding to the ones observed in this work are included in the table.
[d] The assignment of any fraction of these intensities to transitions in Nb^{94} is uncertain because of the energy coincidence between these transitions and transitions in tantalum, a known impurity in the sample used in the present work.

spectrum due to the s-wave resonance at 119 eV increases with decreasing energy in the region below 6 MeV. Unfortunately, the statistical quality of the data for the 119-eV resonance, as for the s-wave resonances in general, was too poor to allow a meaningful analysis in terms of individual transitions with energies less than 7 MeV.

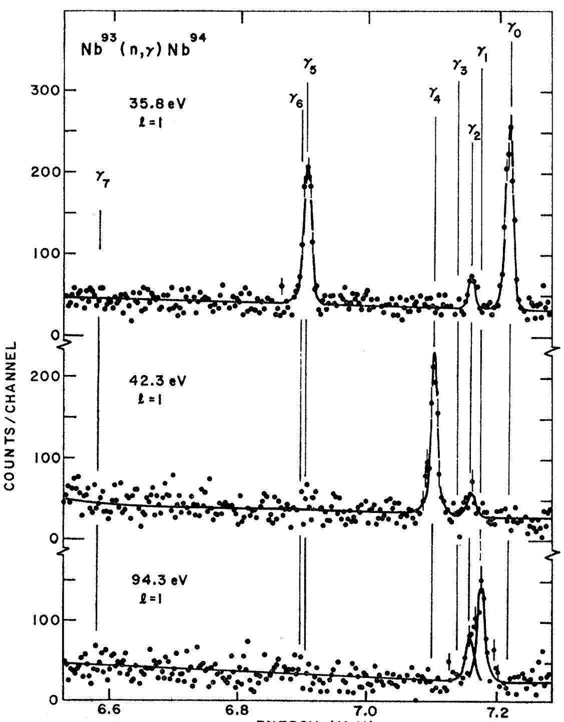

Fig. 4. Comparison of the spectra for the three p-wave resonances. The relative positions of all possible primary transitions populating the ground state and seven excited states of Nb^{94} as reported in Refs. 7 and 8 are indicated in the figure. The energy scale has been adjusted so that the position of the double-escape peak corresponding to a given transition coincides with the full energy of that transition.

The relative intensities were determined from the areas of the corresponding double-escape peaks, corrected for the energy dependence of the counter efficiency. The results for the 35.8-eV resonance are shown in Table II. The highest transition energy observed is 7226±6 keV. The value for the neutron separation energy of this reaction, based on the (d,p) data,[7] is 7231±12 keV. This transition is therefore interpreted as populating the ground state of Nb^{94}. Table II also lists the differences between this separation energy S_n and the energies E_γ of all lower-energy transitions, and compares these differences with some of the energy levels observed in previous (d,p) studies.[7,8] The excellent agreement between the energies of the excited states observed in the two types of experiments is adequate justification of this interpretation. The γ-ray data for this resonance appear to indicate the existence of a level at 1262 keV not observed in the (d,p) reaction.

The energies of the transitions observed in this work are all in agreement with corresponding energies observed in the thermal spectrum.[6] These authors also find evidence for a state at 1265 keV. The highest energy observed in the thermal spectrum is 7229±10 keV, in excellent agreement with the value of 7226±6 keV measured in this work.

Because of the known presence of tantalum in the sample, the energies of the transitions observed were compared with those measured[15] for the thermal capture spectrum of Ta. The three transitions at the energies 6057, 5964, and 5948 keV agree within error with transitions at the energies 6062, 5965, and 5948 keV observed in tantalum. Hence the transitions at 6057 and 5948 keV can be equally well explained as primary transitions leading to states at 1168 and 1278 keV in Nb^{94} or as transitions in Ta^{182}. The assignment of any fraction of the strengths of these three transitions to Nb must therefore be considered tentative. These three transitions have also been observed in the thermal spectrum.[6]

Figure 4 compares the spectra following capture in the three lowest-energy p-wave resonances. Vertical lines give the expected positions of transitions to the first eight levels of Nb^{94}. The analysis was restricted to a consideration of the intensity at these positions only. The spectra were analyzed as above, and the results obtained are given in Table III. The relative partial radiative widths were determined from the relative intensities of the observed transitions, each normalized by the integrated yield for the corresponding resonance. In the case of the 94.3-eV resonance, a 37% contribution to the over-all spectrum comes from the 106-eV resonance, from which it is only partially resolved. In the region above 6.3 MeV, however, this contribution is reduced to 16%, and it has been assumed that the intensities of the only two transitions observed are entirely due to the 94.3-eV resonance.

[15] H. H. Bolotin (private communication).

TABLE III. Relative radiative widths of transitions to the first eight levels observed in $Nb^{93}(d,p)Nb^{94}$.

Transition	E_γ (keV)[a]	Excitation energy (keV) From[b] (S_n-E_γ)	Previous value[c]	J^π	$\Gamma_{\gamma i}$ (arbitrary units) 35.8 eV	42.3 eV	94.3 eV	119 eV
γ_0	7226	0	0	6^+	1000	7±24	22±35	4±12
γ_1	7184	41.5±1	40.7	3^+	10±14	20±24	470±63	85±20
γ_2	7168	58.2±1	58.724	4^+	140±30	150±42	300±50	75±20
γ_3	(7147)[d]		78.675	7^+	<18	<27	<35	<20
γ_4	7112	114.3±1	113.404	5^+	5±19	700±90	−12±35	−15±20
γ_5	6911	314.6±1	314.64	(5^+)	780±60	43±34	−24±35	<20
γ_6	(6891)[d]		334.7	(2^+)	<18	<27	<35	3±30
γ_7	(6589)[d]		640.5	(6^+)	<18	<27	<35	<30

[a] The absolute energies are uncertain by 6 keV.
[b] With $S_n=7226\pm6$ keV.
[c] Obtained from the results of Ref. 7.
[d] These possible transitions were not observed in any of the spectra. The corresponding energies were calculated from the level energies of Ref. 7.

IV. DISCUSSION

Since the ground-state spin of Nb^{93} is $\frac{9}{2}^+$, the capture of an s-wave neutron leads to Nb^{94} resonances with spin and parity of 4^+ or 5^+. In the case of p-wave capture, however, resonances with negative parity and spins from 3 to 6 may be formed. Since all but one of the observed low-lying states of Nb^{94} are of even parity, it is possible for the p-wave resonances to decay to the low-lying states by electric-dipole radiation, while the s-wave resonances can decay to these same states only by $M1$ radiation or radiation of higher multipolarity. From the systematics of neutron-capture radiation,[16] it is known that the primary transitions from the capture state are predominantly dipole in nature. On this basis, the relation between the spin J_i of the initial state and the spins J_f of the final states to which transitions are observed is

$$J_f-1\leqslant J_i\leqslant J_f+1.$$

For the 35.8-eV resonance, transitions are observed to the ground state and to the 58.7-keV state, for which $J_f^\pi=6^+$ and 4^+, respectively. The 35.8-eV resonance is therefore assigned to be $J_i^\pi=5^-$. For the 119-eV ($l=0$) resonance, the observation of the 7184-keV transition leading to the first excited state for which $J_f^\pi=3^+$, suggests that this resonance be assigned a spin and parity of 4^+. By similar arguments, the spins of the 42.3- and 94.3-eV p-wave resonances are limited to $J_i^\pi=4,5^-$ and $3,4^-$, respectively.

Gruber *et al.*[8] have tentatively assigned $J_f^\pi=5^+$ and 2^+ for the states at 314.6 and 334.7 keV, respectively. This spin sequence is also predicted for the $(\pi g_{9/2})\times(\nu d_{5/2})^3$ multiplet. The relatively strong decay of the 35.8-eV resonance to the 314.6-keV state requires that the spin be 4, 5, or 6. The lack of any observable intensity for a transition to the 334.7-keV state in the 35.8- and 42.3-eV spectra is consistent with the previously suggested 2^+ assignment. In all three spectra, no transitions are observed to the 78.7- or 640.5-keV states. For the 78.7-keV state, electric-dipole radiation is not allowed from an initial state with J_i^π 5^-. In the case of the 640.5-keV level, for which an assignment of $J_f^\pi=6^+$ has been suggested, $E1$ radiation from the 35.8-eV resonance is allowed.

The observation that normally allowed primary transitions often have unmeasurably small radiative widths is consistent with the predictions of the statistical model.[17] The model predicts that the partial radiative widths fluctuate in magnitude according to the Porter-Thomas distribution—a χ^2 distribution with $\nu=1$, where ν is the number of degrees of degrees of freedom.

The predicted distribution of widths has been confirmed experimentally[18] in some detail for s-wave capture, but virtually no widths for p-wave resonances have been reported. Thus, even though the decay of the compound state is expected to be independent of its mode of information, it seems worthwhile to examine

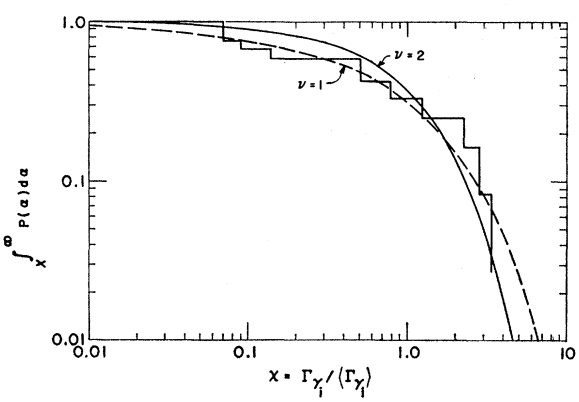

FIG. 5. The integral distribution observed for twelve partial γ-ray widths of the three p-wave resonances in Nb. The distribution has been normalized to have unit area, and is qualitatively consistent with a χ^2 distribution with $\nu=1$.

[16] G. A. Bartholomew, Ann. Rev. Nucl. Sci. **11**, 259 (1961).

[17] C. E. Porter and R. G. Thomas, Phys. Rev. **104**, 483 (1956).

[18] R. E. Chrien, H. H. Bolotin, and H. Palevsky, Phys. Rev. **127**, 1680 (1962); L. M. Bollinger, R. E. Coté, R. T. Carpenter, and J. P. Marion, *ibid.* **132**, 1640 (1963).

the distribution of the small sample ($N=12$) of p-wave widths measured in this investigation.

The distribution of the measured radiation widths for the p-wave resonances is shown in Fig. 5. Only the data for those transitions that were thought to be allowed are included. In addition, it was necessary to assume that all the transitions were sampled from a common distribution. The widths were corrected for the dependence of the mean value on the spin of the initial state, the spins $J_i=5$, $\frac{9}{2}$, and $\frac{7}{2}$ being used for the 35.8-, 42.3-, and 94.3-eV resonances, respectively. No corrections were made for any possible energy-dependent factors. As can be seen from the figure, the experimental distribution follows the $\nu=1$ curve, although it is consistent with $\nu=2$. Using the formula[19]

$$\nu_{\text{eff}}=\frac{2\langle\Gamma\rangle^2}{\langle\Gamma^2\rangle-\langle\Gamma\rangle^2},$$

[19] L. Wilets, Phys. Rev. Letters **9**, 430 (1962).

$\nu_{\text{eff}}=1.4$. These results indicate that the data are qualitatively consistent with the general predictions of the statistical compound-nucleus model of the neutron-capture reaction.

The thermal spectrum exhibits a strong 6830-keV transition to a level at 399 keV. This transition was not observed in the 119-eV s-wave resonance. This result is consistent with the observed Porter-Thomas distribution for s-wave partial radiative widths, for which the most probable value is zero. It indicates that the 119-eV resonance is probably not the dominant contributor to thermal capture.

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Test of Time-Reversal Invariance via a β-γ-γ Angular Correlation in ^{106}Rh-^{106}Pd†

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A measurement of the relative phase angle η between the $E2$ and $M1$ reduced matrix elements in the 1.050-MeV transition of ^{106}Pd has been made by means of a β-γ-γ angular correlation. Instrumental and background asymmetries in the data were carefully measured and found to be negligible. A value $\sin\eta=+0.004\pm0.018$ was obtained. Time-reversal invariance requires $\sin\eta\equiv0$; thus, the present result is consistent with no violation of time-reversal invariance.

THE observation of CP nonconservation in neutral K-meson decay[1] has led Bernstein, Feinberg, and Lee[2] to postulate the the CP violation may be due to C (or T, assuming CPT invariance) violation in the electromagnetic interaction of the hadrons. As a result of such T or C noninvariance, all nuclear matrix elements in either β or γ transitions may contain a T-violating amplitude. Henley and Jacobsohn[3] have discussed in detail various tests of T invariance in processes involving γ-ray transitions. In each case, T invariance is tested by observing the relative phase factor ($e^{i\eta}$) of the reduced matrix elements in a mixed multipole transition. If T invariance holds, the relative phase factor must be real, i.e., $\sin\eta\equiv0$;[4] any deviation of $\sin\eta$ from zero indicates failure of T invariance.[5]

We have chosen to measure the relative phase factor in the mixed $E2$-$M1$ 1.050-MeV transition in ^{106}Pd. The initial 2^+ state at 1.562 MeV in ^{106}Pd is populated via an allowed Gamow-Teller β^- decay (2.0 MeV endpoint) from the 1^+ ground state of ^{106}Rh ($T_{1/2}=30$ sec), which in turn is populated via a 39-keV β^- transition from the ground state of ^{106}Ru($T_{1/2}=367$ days). The 1.050-MeV mixed transition leads to a 2^+ state at 0.512 MeV which decays ($T_{1/2}=12$ psec) via a pure $E2$ transition to the 0^+ ground state of ^{106}Pd. In this case the angular correlation distribution has the form[3]

$$W=A+B\sin\eta,$$

$$A=1+|\delta|^2+(0.25+0.732|\delta|\cos\eta-0.077|\delta|^2)\times P_2(\hat{k}_1\cdot\hat{k}_2)+0.327|\delta|^2P_4(\hat{k}_1\cdot\hat{k}_2),$$

$$B=0.366P|\delta|(\hat{k}_1\cdot\hat{k}_2)(\hat{k}_1\times\hat{k}_2)_z,$$

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters **13**, 138 (1964).

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