1.57-MeV State in Mo^{94}*

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In an attempt to make an unambiguous spin assignment to the 1.57-MeV state in Mo^{94}, the gamma radiation following the decay of 20 000-yr Nb^{94} and 6.6-min Nb^{94m} has been studied. In the decay of the former activity, an upper limit of $\approx 0.03\%$ has been placed on the intensity of a 1.57-MeV crossover transition relative to that of the cascade transition. This was obtained from a comparison of calculations of the coincidence summing effect in NaI(Tl) crystals with the observed variation of the intensity of the 1.57-MeV peak with source-detector distance. It has been found that approximately 0.2% of the decays of the 6.6-min state in Nb^{94} are by beta emission to the 872-keV state in Mo^{94}. Evidence for the existence of a beta branch from the 6.6-min state in Nb^{94} to the 1.57-MeV state in Mo^{94} is presented. The intensity of this branch, relative to that feeding the 872-keV state, is approximately 1 %. The directional correlation of the 703–872-keV gamma-ray cascade de-exciting the 1.57-MeV state has been measured. The results of this measurement are consistent with a spin-4 assignment to this state, or a spin-2 assignment with $\delta \approx -0.2$ for the 703-keV transition. Arguments favoring the former assignment are presented. On the basis of a spin-4 assignment, consistent spins are assigned to the two states in Nb^{94}. Several possible configurations for the low-lying states in Nb^{94} are briefly discussed.

I. INTRODUCTION

PREVIOUS studies[1,2] of the 2.0×10^4-yr ground state of Nb^{94} have shown that all of its measurable decay is by beta emission to a state in Mo^{94} at 1.57 MeV which de-excites by the emission of cascade gamma rays of 0.70 and 0.87 MeV. Several investigations of the decay of the 6.6-min isomeric state of Nb^{94} have also been made.[3–5] This state decays predominantly by an isomeric transition[3,4] having an energy of 41.5 keV.[4] In addition, a 1.3-MeV beta transition and a 0.9-MeV gamma ray were observed in the decay of the isomeric state.[5,6] The intensity of this beta transition has been reported[6] as approximately 0.1% of the decays of the isomeric state.

From Coulomb excitation experiments,[7,8] it has been established that the spin and parity of the 0.87-MeV first excited state of Mo^{94} is 2+. The spin of the state at 1.57 MeV, however, has not yet been unambiguously assigned. In order to establish the spin and parity of this state, Bernstein and Forster[9] measured the directional correlation of the 0.70–0.87-MeV gamma-ray cascade which de-excites it. This measurement did not provide a unique assignment, since spins of 2 and 4 were allowed by the data. It would appear that the 2+ assignment reported in the literature[10] was largely based on the presumed existence of a crossover transition. The original evidence for this transition was based upon an analysis of the pulse spectrum from a NaI(Tl) scintillation spectrometer. A 1.57-MeV peak appearing in this spectrum was interpreted[1] as a crossover transition. A subsequent investigation[2] revealed that this interpretation was in error and that this peak arose, not from a real gamma ray, but rather from coincidence summing of the 0.70- and 0.87-MeV cascade gamma rays in the scintillation crystal. Since this argument in favor of a 2+ assignment is thus in question, it was decided to study the radiations which excite and de-excite the 1.57-MeV state in Mo^{94} in an attempt to arrive at an unambiguous assignment.

The results of the present investigation, together with information previously available[11] on the decay of the two Nb^{94} activities, are included in the proposed decay scheme shown in Fig. 1. In addition to measure-

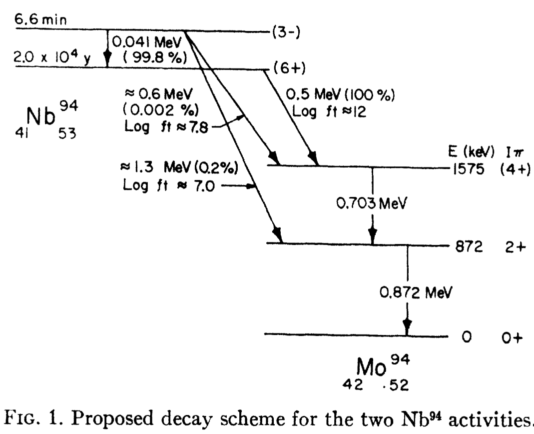

FIG. 1. Proposed decay scheme for the two Nb^{94} activities.

* Work performed under the auspices of the U. S. Atomic Energy Commission.
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2 R. P. Schuman and P. Goris, J. Inorg. Nucl. Chem. **12**, 1 (1959).
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5 E. der Mateosian, Phys. Rev. **83**, 223 (1951).
6 M. Goldhaber and R. D. Hill, Rev. Mod. Phys. **24**, 179 (1952).
7 G. M. Temmer and N. P. Heydenburg, Phys. Rev. **104**, 967 (1956).
8 P. H. Stelson and F. K. McGowan, Phys. Rev. **110**, 489 (1958).
9 H. Bernstein, and H. H. Forster, Bull. Am. Phys. Soc. **6**, 50 (1961); and Nucl. Phys. **24**, 601 (1961).
10 D. Strominger, J. M. Hollander, and G. T. Seaborg, Rev. Mod. Phys. **30**, 585 (1958).
11 K. Way *et al.*, *Nuclear Data Sheets* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.).

ments of the directional correlation of the 0.70–0.87-MeV gamma-ray cascade in Mo^{94}, the investigation described below includes a study of the gamma-ray spectra from 20 000-yr Nb^{94} and 6.6-min Nb^{94m}. The analysis of scintillation spectra from the ground-state activity provides no evidence for the existence of a 1.57-MeV crossover transition. The analysis of the spectra from the latter activity, together with the results of a gamma-gamma coincidence experiment, establishes the presence of a weak 0.70-MeV gamma ray and thus suggests the existence of a weak beta branch from the 6.6-min state in Nb^{94} to the 1.57-MeV state in Mo^{94}. Also, from the spectrum of the 6.6-min activity, the intensity of the K x-ray from the internal conversion of the 41.5-keV isomeric transition relative to that of the 0.87-MeV gamma ray was measured. From this ratio, the relative number of beta rays and isomeric transitions from the decay of this state was obtained.

The results of the present investigation, together with data[12] from the decay of Tc^{94}, favor the assignment of 4+ to the 1.57-MeV state in Mo^{94}. On this basis, spin and parity assignments for the two states in Nb^{94} are made.

II. EXPERIMENTAL TECHNIQUES AND RESULTS

A. Source Preparation

The 20 000-yr Nb^{94} activity was produced by neutron irradiation of spectroscopically pure niobium metal powder in the Materials Testing Reactor. The integrated flux to which the sample was exposed was $\approx 1.2\times 10^{22}$ n/cm^2. After irradiation, the sample was allowed to decay for approximately 5 yr in order to insure that it contained no Nb^{95} activity ($T_{1/2}=35$ days). Anion-exchange techniques[13] were used to remove the remaining radioactive contaminants (mainly Ta^{182} and Co^{60}).

The 6.6-min Nb^{94m} activity was produced by neutron irradiation of milligram quantities of pure niobium foil or "Specpure" Nb_2O_5 powder for several minutes in the Materials Testing Reactor. No chemical purification of the irradiated samples was attempted. An examination of the gamma-ray spectra from several of these samples after the 6.6-min activity had decayed away gave no evidence for the presence of any 20 000-yr Nb^{94}.

B. Gamma-Ray Measurements

The gamma radiation emitted by the two Nb^{94} activities was studied using 3in.×3 in. cylindrical NaI(Tl) detectors. Energy calibration of the scintillation spectrometers was accomplished by the method of internal comparison. For the 20 000-yr Nb^{94} activity, the 569.7- and 1064-keV gamma rays from the decay of Bi^{207} were used as a comparison; for the 6.6-min activity, the 661.6-keV gamma ray from Cs^{137} was used. In both cases, the procedure was as follows.[14] First, a spectrum was taken of the Nb source and the comparison source together. For these data, the full-energy peaks of the various gamma rays were each fit to a Gaussian function by a least-squares method. From such an analysis, the relative pulse heights of these peaks can be established with considerable precision. The energies were then obtained by comparing these pulse heights with a standard pulse height vs energy curve obtained for the scintillation spectrometer used in the experiment. Such a comparison is necessary in view of the nonlinear energy response of NaI(Tl).

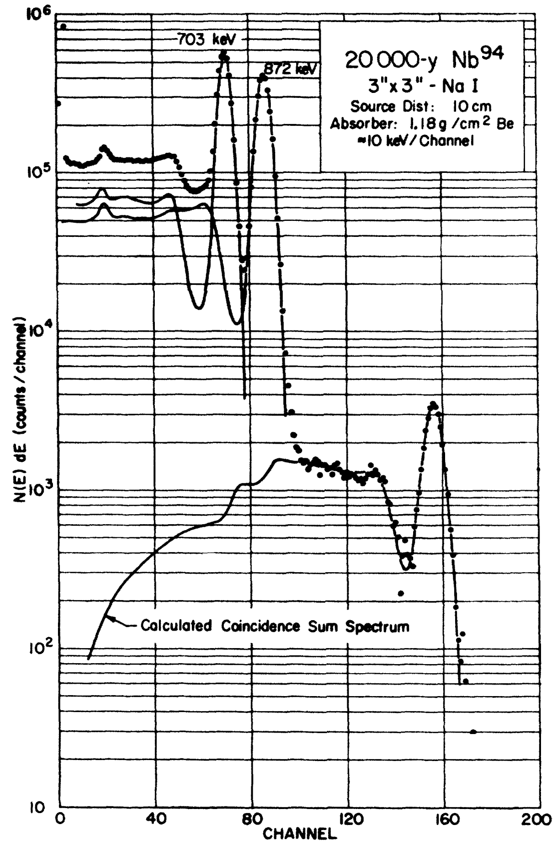

FIG. 2. Gamma-ray spectrum from 20 000-yr Nb^{94}. The shape and magnitude of the coincidence sum spectrum were calculated as described in the text.

1. 20 000-yr Nb^{94}

The gamma-ray spectrum of 20 000-yr Nb^{94} is shown in Fig. 2. In addition to the x ray from 12-yr Nb^{93m} (present as a contaminant), peaks at 0.70, 0.87, and 1.57 MeV appear in the spectrum. The first two peaks correspond to the previously reported Mo^{94} gamma rays. The energy-calibration procedure described above

[12] H. Medicus, P. Preiswerk, and P. Scherrer, Helv. Phys. Acta **23**, 299 (1950).

[13] K. A. Kraus and G. E. Moore, J. Am. Chem. Soc. **73**, 9 (1951).

[14] For a detailed description of these techniques, see: R. L. Heath, Nucleonics **20**, No. 5, 67 (1962); and R. L. Heath, IRE Trans. on Nuclear Science, **NS-9**, No. 3, 294 (1962).

yielded energy values of 703±2 and 872±2 keV. The relative photopeak intensities of these two gamma rays were obtained by successive subtraction of calculated pulse-height distributions[14,15] representing the response of the detector to monoenergetic radiation for the source-detector configuration used in the measurement. The relative gamma-ray intensities were then obtained using calculated detector efficiencies and experimentally determined peak-to-total ratios.[16] These intensities were found to be the same to within ≈1%.

For the reasons stated in the introduction, the origin of the 1.57-MeV peak in the gamma-ray spectrum is important. That it arises at least predominantly from coincidence summing is evidenced by the fact that its intensity relative to the two prominent gamma rays varies with the source-detector distance. Gamma-ray spectra were measured at nine different source-detector distances ranging from ≈0.6–90 cm. There typical spectra obtained are shown in Fig. 3. The normalization of these spectra is to a constant intensity of the photopeak of the 872-keV gamma ray. In the gamma-ray spectrum taken at 90 cm (not shown) there was no evidence for any peak above background in the region of 1.57 MeV.

The effects of coincidence summing are frequently important in the analysis of gamma-ray spectra obtained using scintillation spectrometers.[17] However, many of the gamma-ray spectra encountered are of sufficient complexity or the corresponding decay schemes are not known in sufficient detail that a detailed study of this effect can be meaningfully made. Since the gamma-ray spectrum from 20 000-yr Nb^{94} contains only two coincident gamma rays of equal intensity, it was believed that this provided an excellent case to investigate the accuracy with which a coincidence sum spectrum can be calculated. The first step in the procedure, as described previously,[15,17,18] was the calculation of the response of the detector to each of the single gamma rays. Each response shape was generated with a normalization of one disintegration of the source, so that the magnitude of the function in a given channel gave directly the probability that an event would be recorded in that channel. The magnitude $G(c)$ of the normalized sum spectrum in channel c was then generated according to the formula $G(c)=\sum_n G_1(n)G_2(c-n)$, where $G_1(n)$ is the magnitude in channel n of the response function for gamma ray 1 and $G_2(c-n)$ is the corresponding quantity in channel $(c-n)$ for gamma ray 2. In order to compare this calculated sum spectrum with the data in Fig. 2, the number of source disintegrations

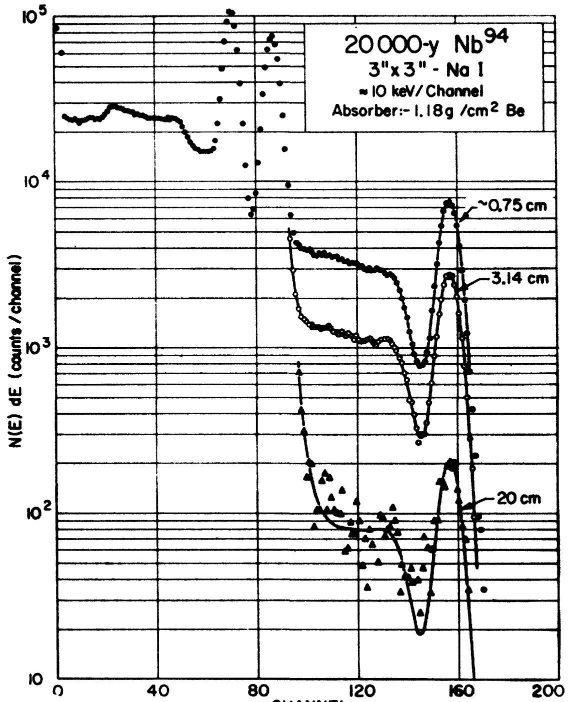

FIG. 3. Gamma-ray spectra of 20 000-yr Nb^{94}, taken at three different source-detector distances. The normalization of the three spectra has been to a constant number of events in the photopeak of the 872-keV gamma ray. The observed variation of sum-peak intensity with source-detector distance agrees with what one would calculate, assuming that all of the 1.57-MeV peak arises from coincidence summing.

N_d necessary to produce the spectrum shown there was calculated. This number was obtained from the number of events N_{p1} in the photopeak of gamma ray 1 by means of the expression

$$N_d=N_{p1}/(\epsilon PA)_1[1-(\epsilon A)_2\bar{W}(0°)]. \qquad (1)$$

In this expression, ϵ, P, and A are the total absolute efficiency, peak-to-total ratio, and absorber transmission, respectively. The subscripts 1 and 2 indicate that the quantities refer to gamma rays 1 and 2, respectively. For convenience in the analysis, gamma ray 1 was taken to be the higher energy gamma ray. The factor in square brackets in the denominator corrects for the loss of events from the photopeak of gamma ray 1 to the sum spectrum. $\bar{W}(0°)$ is the directional correlation of the cascade, averaged over the solid angle subtended by the detector. The number of source disintegrations given in Eq. (1), multiplied by $\bar{W}(0°)$, is the factor by which the calculated sum spectrum must be multiplied before one can compare it with the experimental spectrum. After this normalization was applied to the calculated sum spectrum, the number of events in the sum peak was compared with the number actually observed. These two numbers agreed to within 1%, an agreement which is perhaps somewhat surprising in view of the uncertainties in the peak-to-total ratios (≈2%) and

[15] R. L. Heath, in "Proceedings of the Total Absorption Gamma-Ray Spectrometry Symposium, May 10–11, 1960" [Atomic Energy Commission Report TID-7594 (unpublished)].

[16] S. H. Vegors, Jr., L. L. Marsden, and R. L. Heath, Atomic Energy Commission Report IDO-16370 (unpublished).

[17] C. W. Reich, R. P. Schuman, J. R. Berreth, M. K. Brice, and R. L. Heath, Phys. Rev. 127, 192 (1962).

[18] E. C. Yates, R. L. Heath, and C. S. Pea, MTR-ETR Technical Branches Quarterly Report, July 1–September 30, 1960, IDO-16658 (unpublished), p. 31.

absolute efficiencies ($\approx 2\%$) used in the calculation. It does serve to illustrate, however, that coincidence summing effects in scintillation spectrometers can be calculated with a reasonable degree of accuracy, if the parameters of the spectrometer and the decay scheme of the nuclide in question are known.

The variation of the sum-peak intensity with source-detector distance was also calculated. It was found that this calculated dependence on source-detector distance agreed quite well with that observed experimentally. The results of this study of the coincidence summing effect indicate an upper limit of $\lesssim 0.03\%$ for the intensity of the crossover transition, substantiating the previously reported value.[2]

2. 6.6-min Nb^{94m}

The gamma-ray spectrum from 6.6-min Nb^{94m} is shown in Fig. 4. The energy of the prominent gamma ray was measured, as described above, to be 872 ± 2 keV. An inspection of this spectrum revealed that the high-energy edge of the Compton distribution differed from the shape expected for a single gamma ray of this

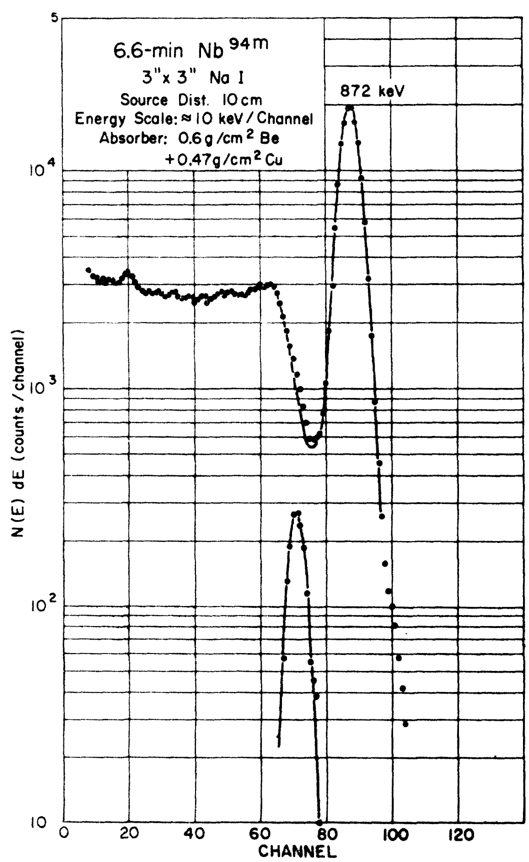

FIG. 4. Gamma-ray spectrum from 6.6-min Nb^{94m}. The 0.47 g/cm² Cu absorber was used to attenuate the intense K x rays from the isomeric transition. The result of the subtraction of the calculated shape for an 872-keV gamma ray from the experimental points is also indicated.

energy, indicating the possible presence of another gamma ray. Consequently, the pulse-height distribution representing the response of the detector to a gamma ray of 872 keV was calculated, normalized to fit the observed photopeak, and subtracted from the data. The results of this analysis, as shown in Fig. 4, indicated the presence of an ≈ 0.70-MeV photopeak.

While the presence of another gamma ray in the spectrum was thus indicated, it was believed that additional experimental evidence was necessary before it could be placed in the level scheme. Accordingly, a spectrum of gamma radiation in coincidence with the 872-keV gamma ray was obtained. A source of 20 000-yr Nb^{94} was used to set up the timing relationships of the fast-slow coincidence circuit. The coincidence spectrometer, a conventional 20-channel discriminator-type analyzer, was set to span the region of the two gamma-ray photopeaks. Because of the short half-life of the activity and the low coincidence rates involved, only this region of the coincidence spectrum was investigated. Brass absorbers, $\frac{1}{16}$ in thick, were placed on each detector to absorb the intense x rays from the isomeric transition. For the "real" coincidence run, four separate samples of niobium foil were irradiated, and at least three determinations of the coincidence rate as a function of time were made of each sample. A similar procedure, using three separate samples, was used in obtaining a random coincidence spectrum. The results of this experiment, together with a spectrum of 20 000-yr Nb^{94}, taken for comparison, are shown in Fig. 5. In the real coincidence spectrum, the presence of a gamma ray of ≈ 0.70 MeV is clearly indicated. No attempt was made to estimate its intensity relative to that of the 872-keV gamma ray from the coincidence experiment. For a given sample, the coincidence rate of this 0.70-MeV gamma ray was proportional to the counting rate in the single-channel analyzer, while that of the 0.87-MeV gamma ray was proportional to the square of this rate. The 0.70-MeV peak was thus interpreted as arising from real coincidences with the 0.87-MeV gamma ray, while the 0.87-MeV peak in the spectrum was interpreted as arising from random coincidences. A gamma-ray spectrum of one of the samples, taken approximately 70 h after the experiment, contained no observable contribution from 20 000-yr Nb^{94}. Since no states other than that at 1.57 MeV are reported[11] in this region of excitation in Mo^{94}, it was concluded that the 0.70-MeV gamma ray observed here originates from the same state as the 703-keV gamma ray observed in the decay of the long-lived Nb^{94} activity. A beta branch from the 6.6-min Nb^{94} state to the 1.57-MeV state in Mo^{94} is thus indicated. The intensity of this branch, relative to that feeding the 872-keV state, was found from an analysis of the spectrum shown in Fig. 4 to be $\approx 1\%$. It should be emphasized that this value is quite sensitive to details of the shape of the detector response function in the region of the valley and leading edge of

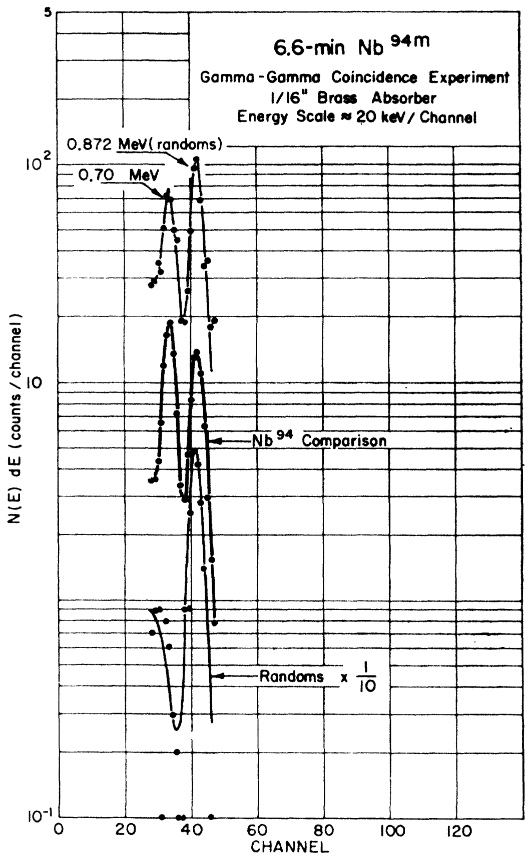

FIG. 5. The results of a coincidence experiment to establish the presence of a 0.70-MeV gamma ray in the spectrum from 6.6-min Nb^{94m}. The upper curve represents the sum of all the coincidence events recorded in the 20-channel analyzer during the "reals" experiment. The lower curve represents a similar sum (multiplied by a factor of $\frac{1}{10}$) for the "randoms" run. For purposes of comparison, a spectrum from 20 000-yr Nb^{94}, taken before the experiment, is shown. The ordinates of the three curves are not directly comparable.

the Compton distribution. It is, therefore, difficult to assign an uncertainty to this intensity.

In order to obtain a value for the relative number of beta particles and isomeric transitions from the 6.6-min Nb^{94} state, the intensity of the 872-keV gamma ray relative to the K x ray was measured. A value of 1.1×10^{-2} was obtained for this ratio. The major uncertainty in this number lies in the uncertainty in the attenuation of the x rays by the aluminum-oxide reflector which lines the inside of the can surrounding the scintillation crystal.[19] It is estimated that the thickness of the can and aluminum oxide is equivalent to ≈ 10 mils of aluminum, for which the transmission for niobium K x rays was measured to be 0.67. The ratio of beta transitions to isomeric transitions may be obtained by multiplying the measured ratio of 872-keV gamma rays to niobium K x rays by the factor $\alpha_K/(1+\alpha_t)$. The internal-conversion coefficients were obtained by interpolation from the tables of Sliv and Band[20] (L subshells) and Rose[21] (K and M shells). An $E3$ assignment (see the Discussion) for the isomeric transition was assumed. The values used were 160, 8.5, 190, 265, and 250 for the K, $L_{\rm I}$, $L_{\rm II}$, $L_{\rm III}$, and M shells, respectively. (The K-shell value is somewhat uncertain due to the curvature of the plot of log α_K vs log E in this energy region.) From these values, the ratio of beta transitions to isomeric transitions from the 6.6-min state in Nb^{94} was calculated to be 2.0×10^{-3}. The uncertainty to be associated with this number is believed to be $\approx 20\%$, not including the uncertainty in the internal-conversion coefficients used in the calculation, and may be as large as $\approx 50\%$ inlcuding this latter uncertainty.

III. DIRECTIONAL CORRELATION MEASUREMENTS

Two measurements of the directional correlation of the 703–872-keV gamma-ray cascade were made. The techniques and general procedures used at this laboratory for carrying out such measurements have been described previously.[17] The Nb^{94} activity, in HF solution, was contained in a thin-walled lucite holder $\frac{1}{16}$ in. i.d.$\times\frac{3}{8}$ in. high. In each measurement, at least seven determinations of the coincidence counting rate were made at each angle. This number of observations allowed the making of a meaningful comparison of the observed variance of the coincidence rate with that calculated from the statistical uncertainties only. The agreement between the variances calculated in these two ways was consistent with the statistical uncertainties involved. The results of one of these measurements are shown in Fig. 6. The measured Legendre-polynomial expansion coefficients are given in Table I. They are seen to be in quite good agreement with those expected for an assignment of spin 4 to the 1.57-MeV state in Mo^{94}. The other possible assignments may conveniently be obtained from an inspection of the A_4 vs A_2 plot shown in Fig. 7. The spin sequences illustrated here are those for which the final transition takes place

TABLE I. Directional correlation results for the 703–872-keV gamma-ray cascade in Mo^{94}.

Run	A_2[a]	A_4[a]
1	$+(0.0988\pm0.0034)$	$+(0.0156\pm0.0055)$
2	$+(0.1035\pm0.0047)$	$+(0.0085\pm0.0067)$
Average	$+(0.101\pm0.003)$	$+(0.0121\pm0.0043)$
Theoretical values for 4(2)2(2)0 cascade:	$+0.102$	$+0.0091$

[a] Corrected for the finite solid angle of the detectors.

[19] For details of the detector configuration, see R. L. Heath, Atomic Energy Commission Report IDO-16408 (unpublished).

[20] L. A. Sliv and I. M. Band, Leningrad Physico-Technical Institute Reports, 1956 [translation: Reports 57 ICCKl and 58 ICCLl, Physics Department, University of Illinois, Urbana Illinois (unpublished).]

[21] M. E. Rose, *Internal Conversion Coefficients* (North-Holland Publishing Company, Amsterdam, 1958).

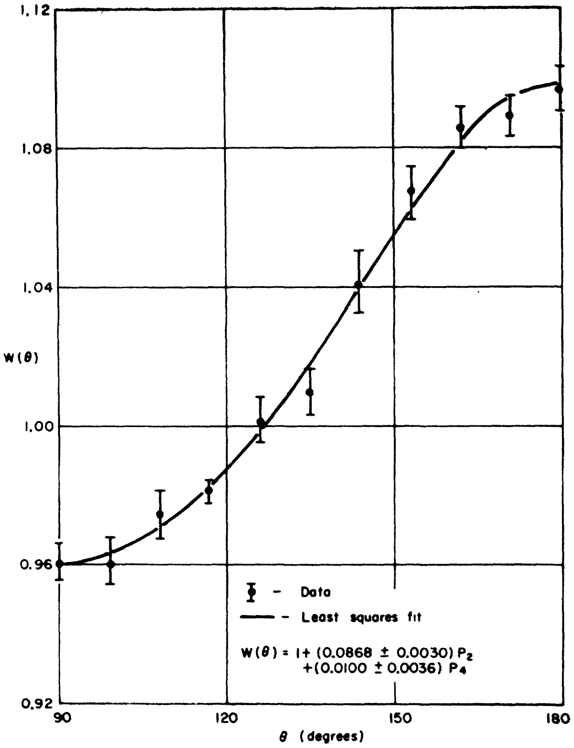

FIG. 6. One of the measurements of the directional correlation of the 703–872-keV gamma-ray cascade in Mo^{94}. The Legendre-polynomial coefficients shown in the figure are the measured ones with no correction for the finite angular resolution of the detectors.

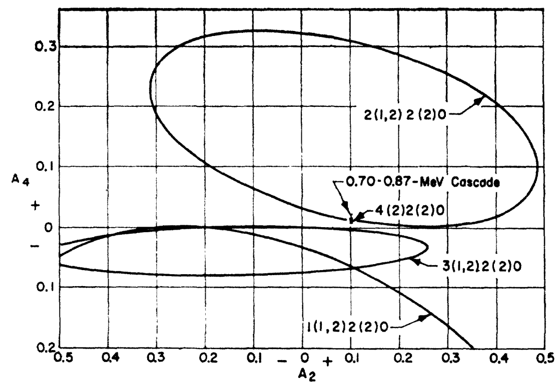

FIG. 7. Plot of A_4 vs A_2 for various spin sequences in which the final transition takes place from a state of spin 2 to a state of spin 0. The experimental point, corresponding to the measured Legendre-polynomial expansion coefficients of the directional correlation of the 703–872-keV gamma-ray cascade in Mo^{94}, is also indicated. It appears that only a spin-2 or a spin-4 assignment to the 1.57-MeV state is consistent with this measurement.

from a state of spin 2 to a state of spin 0. In addition to the spin-4 assignment, it is evident that a spin-2 assignment (with a mixing parameter, δ, ≈ -0.20 in the 703-keV transition) is consistent with the measured correlation. The data appear to rule out all other reasonable spin assignments.

IV. DISCUSSION

The directional correlation results presented above are in essential agreement with those of Bernstein and Forster.[9] Unfortunately, these results are not sufficient in themselves to provide an unambiguous angular momentum assignment to the 1.57-MeV state. Several arguments in favor of a spin-4 assignment can be made, however. In addition to the known 2+ state at 0.87 MeV in Mo^{94}, the decay of Tc^{94} feeds states at 2.73 and 3.27 MeV.[10–12] Since ground-state transitions from these states are observed, they are presumably of low spin (1 or 2). If the 1.57-MeV state were also 2+, it would be somewhat difficult to explain the absence of any feeding of this state in the Tc^{94} decay.

Under the assumption that the 1.57-MeV state is 2+, one may also calculate the various reduced transition probabilities for the transitions from it. From Coulomb excitation experiments, Stelson and McGowan[8] have shown that the reduced transition probability for the de-excitation ($B(E2,2\rightarrow 0)$) of the first excited state is about 21 times as large as the single-particle value. They have also shown,[22] albeit for nuclei somewhat farther from the closed shell than Mo^{94}, that the ratio $B(E2,2'\rightarrow 2)/B(E2,2\rightarrow 0)$ is approximately equal to unity. (The 2′ and 2 represent the second and first 2+ states, respectively.) For these nuclei, they also show that the reduced transition probability $B(E2,2'\rightarrow 0)$ is approximately equal to the single-particle value or a little smaller. Assuming that these same features are valid for Mo^{94} and using the mixing ratio required for the 703-keV transition and the upper limit on the intensity of the crossover transition, one may show that $B(E2,2'\rightarrow 0)$ must be smaller than the single-particle estimate by a factor of over 300. If this argument is valid, this large discrepancy indicates that a 2+ assignment for the 1.57-MeV state is unlikely.

The assignment of spin 4, for the reasons mentioned above, is preferred. An even parity is indicated, since low-lying 4− states are not observed in even-even nuclei. On the basis of a 4+ assignment to the 1.57-MeV state and the multipolarity of the isomeric transition, reasonable spin assignments to the two Nb^{94} states may be made. Beta branches to both the 0.872- and 1.57-MeV states in Mo^{94} are observed in the decay of the 6.6-min Nb^{94} activity. The log *ft* values (7.0 and 7.8, respectively) for these transitions are consistent with $\Delta I=0,1$ (yes). Thus, the most reasonable assignment for this state is 3−. If the assignment were 4−, the beta transition to the 872-keV state would be unique first forbidden. In such a case, one would expect the log *ft* value to be somewhat larger than the observed value of 7.0 The argument against a 2− assignment is somewhat weaker. If the assignment were 2−, the beta transition to the 1.57-MeV state would be unique first forbidden, for which the observed log *ft* value of 7.8 is perhaps not too small. However, for this assignment the

[22] P. H. Stelson and F. K. McGowan, Phys. Rev. **121**, 209 (1961).

beta transition to the ground state of Mo^{94} would also be unique first forbidden. The ground-state beta transition should be considerably more intense than that to the 1.57-MeV state if the log *ft* values for the two transitions are comparable. No beta transition to the Mo^{94} ground state has been reported.[10,11] The isomeric transition has been assigned an $E3$ character,[23] presumably on the basis of its reported[4] K/L ratio (≈ 0.31) and the gamma-ray lifetime of the 6.6-min state in Nb^{94}. This lifetime is consistent with a multipolarity of either $M3$ or $E3$. Since the K/L ratios for these two assignments are calculated to be ≈ 1.6 and ≈ 0.34, respectively, the $E3$ assignment appears to be the more likely one. The value of the quantity SM_{E3}^2, as defined by Moszkowksi,[24] for a 41.5-keV $E3$ transition in Nb^{94} is calculated to be $\approx 3\times 10^{-3}$. This value is in good agreement with those reported for other $E3$ transtions and indicates that the transition is considerably slower than the single-proton estimate. From the measured half-life[2] and beta energy,[1] a log *ft* of approximately 12 is calculated for the beta transition from the Nb^{94} ground state. This value is consistent with $\Delta I = 2,3$ (no). Thus, an assignment of 1+, 2+, 6+, or 7+ for the Nb^{94} ground state is indicated. The absence of beta transitions to the ground state and first excited state rules out the first two possibilities. Since the isomeric transition is $E3$, an assignment of 6+ to the ground state of Nb^{94} is indicated. This set of spin assignments is consistent with all of our experimental data.

With reference to these spin assignments, several remarks should be made concerning the nucleon configurations of the states in Nb^{94}. The ground states of Mo^{95} and Zr^{93}, both of which have 53 neutrons, are $5/2+$.[10] It is thus reasonable to consider the 53rd neutron as being in a $d_{5/2}$ state, in agreement with the predictions of the nuclear shell theory.[25] Some information on the states available to the 41st proton is provided by the low-lying levels of Nb^{93}. The ground state of Nb^{93} is $9/2+$.[10] A 30-keV isomeric state with a probable assignment of $\frac{1}{2}-$ is also reported.[10] Thus $g_{9/2}$ and $p_{1/2}$ states are expected for the 41st proton, also in agreement with the shell theory. The assumption of a $(g_{9/2}d_{5/2})$ configuration for the Nb^{94} ground state and a $(p_{1/2}d_{5/2})$ configuration for the isomeric state apparently leads to some difficulties. If this were the case, the isomeric transition should be a single-proton $M4$ transition, which is inconsistent with the multipolarity assignment of $E3$. The existence of an $E3$ transition in this region, in which a large number of $M4$ isomers is observed, is in itself interesting. It is possible that the isomeric transition does not go directly to the Nb^{94} ground state, but rather excites an intermediate state which in turn decays to the ground state. If the energy of this state were of the order of 20 keV or less, any transitions from it to the ground state would probably not have been observed in this experiment. It should be pointed out that, while there is, at present, no direct experimental evidence for the existence of such a low-lying state in Nb^{94}, the possibility of its existence should be considered. The existence of such a state would require a reconsideration of the spin assignments to the Nb^{94} states and the beta-ray branching ratios. It would appear that further studies are necessary before any definite configuration assignments can be made to the states in Nb^{94}. In particular, a direct measurement of the ground-state spin of this nuclide would be desirable.

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[24] S. A. Moszkowski, Phys. Rev. **89**, 474 (1953).
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