High-spin three-quasiparticle states of ^{93}Nb populated in the beta decay of $21/2^+$ ^{93}Mo^m†

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Thirteen γ rays with the 6.85-h half-life of ^{93}Mo^m have been identified using singles and Compton suppression Ge(Li) spectrometers. The known levels of ^{93}Nb at 949.82 ($13/2^+$), 1335.20 ($17/2^+$), and 1491.10 ($15/2^+$) keV are populated by γ rays from two levels at (logft in parenthesis) 2753.15 (5.1) and 2180.2 keV (7.5), with possible spin values of $21/2^+$ and $19/2^+$, respectively. The 2753-keV level is discussed within the framework of a $\pi(g_{9/2})\nu(g_{7/2}d_{5/2})$ three-quasiparticle configuration.

[RADIOACTIVITY ^{93}Mo^m [From ^{90}Zr(α,n) and ^{92}Zr$(\alpha,3n)$] measured $E\gamma, I\gamma$; deduced logft. ^{93}Nb deduced levels, J,π. Ge(Li) and Compton suppression spectrometer.]

INTRODUCTION

The 6.85-h isomer[1] of ^{93}Mo was first identified by Kundu, Hult, and Pool.[2] Since then Alexander and Scharff-Goldhaber[3] have identified additional γ rays that represent the population of a $\frac{7}{2}^+$ level at 1363 keV. Their relative γ-ray-intensity ratios were confirmed by Naqvi, Bubb, and Wolfson,[4] even though the use of these intensities and the known multipolarities of the 684- and 1477-keV γ rays[1,5] lead to higher population than depopulation of the levels. The assignment of an $E4$ multipolarity for the 263-keV isomeric transition has been made by conversion electron measurements.[6,7] The J^π value of $\frac{21}{2}^+$ was confirmed by low-temperature, anisotropic angular distribution measurements,[8] which substantiated a

$$\tfrac{21}{2}^+ \xrightarrow{(E4)} \tfrac{13}{2}^+ \xrightarrow{(E2)} \tfrac{9}{2}^+ \xrightarrow{(E2)} \tfrac{5}{2}^+$$

cascade. This same work measured the magnetic moment of the $\frac{21}{2}^+$ level and thereby confirmed the $[\pi(g_{9/2})^2\nu(d_{5/2})]_{21/2^+}$ assignment suggested by Alexander and Scharff-Goldhaber[3] and discussed by Peker.[9] Other high-spin levels of Mo have been identified by transfer,[1,10] radioactive decay,[1] and $(d,p\gamma)$ studies.[11,12]

The levels of ^{93}Nb have been studied by $(n,n'\gamma)$ techniques,[13,14] Coulomb excitation,[15] and in-beam γ-ray[16] studies. The possible positive parity levels identified to date are shown in Fig. 1 along with the known yrast levels of neighboring even-even core nuclei.[17,18] Presumably, all five members of the $g_{9/2}$-first-phonon multiplet have been identified. Although the 6^+ yrast level of ^{92}Zr has not been identified, it might be expected to occur at approximately 2400 keV as for ^{94}Mo. Thus, a multiplet of levels ranging from $\frac{3}{2}^+$ to $\frac{21}{2}^+$ could be expected to be centered at approximately 2400 keV.

The adopted Q_{EC} value for ^{93}Mo^g decay is 398 ± 4 keV.[1] The 2424.84-keV energy of the isomer in ^{93}Mo provides a Q_{EC} value of 2823 ± 4 keV for ^{93}Mo^m decay to ^{93}Nb. This value and the known levels of Nb suggest the possibility of electron capture or β^+ branch for ^{93}Mo^m decay. Presumably, previous attempts to identify this have failed mostly because the γ ray from the $\frac{13}{2}^+$ level at 949.82 keV has been masked by the 948.34-keV sum peak of the intense 263.67- and 684.67-keV γ rays. Here, we report on studies which have led to the identification of eight γ rays in the Nb nucleus, which can be assigned to the decay of three known levels and two new levels. The highest level is suggested to be the $\frac{21}{2}^+$ member of a three-quasiparticle state with a $\pi(g_{9/2})\nu(g_{7/2}d_{5/2})$ configuration.

EXPERIMENTAL PROCEDURES

The ^{93}Mo^m sources were produced by the ^{90}Zr(α,n) reaction on enriched ^{90}Zr targets, and the ^{92}Zr$(\alpha,3n)$ reaction on enriched ^{92}Zr targets. The latter targets were dissolved in a mixture of HNO_3 and HF acid; then Mo carrier was added. The Mo was isolated by solvent extraction techniques. The sources were mounted on Lucite planchets and sealed for counting.

Several Ge(Li) spectrometers were used. Five large-volume Ge(Li) spectrometers were used at varying gains with no absorber and with absorbers of up to 12.5 mm of Pb. Source-to-detector distances up to 60 cm were used to reduce summing effects to a minimum. A thin Ge(Li) detector was

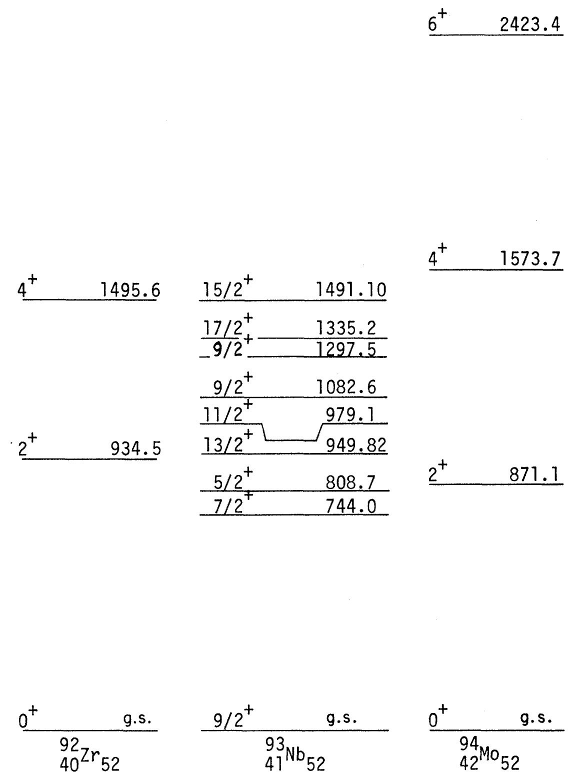

FIG. 1. Known levels of ^{92}Zr, ^{93}Nb, and ^{94}Mo. (Taken from Refs. 1 and 13–18.)

used to measure the γ rays below 400 keV. Particular attention was paid to the relative intensities of major γ rays. Two Compton suppression spectrometers[19] were used in the course of this study, one with a peak to Compton ratio of 200 to 1 and the other with a 600 to 1 ratio. All sources were measured a number of times over the course of several half-lives. The γ-ray energies were calibrated by simultaneously counting the ^{93}Mo^m with standards[20] at gains of 0.1 keV per channel on a 4096-channel low-energy photon spectrometer and gains of 0.25- and 0.50-keV channel on large-volume Ge(Li) spectrometers. All spectra were analyzed using the code **GAMANAL**[21] on CDC 7600 computers.

RESULTS AND DECAY SCHEME

The observed γ rays with a 6.85-h half-life are presented in Table I, and a spectrum of chemically isolated ^{93}Mo^m is shown in Fig. 2. In Fig. 3 we present the decay scheme deduced from our γ-ray measurements and known levels of ^{93}Nb and ^{93}Mo. The intensities of the cascade γ rays in ^{93}Mo are consistent with the measured conversion coefficients.[1] The conversion to absolute intensities was calculated by assuming no direct β-decay branch to ^{93}Nb^g and a total conversion coefficient of 2×10^{-3} for the 684-keV γ ray.[1,5,6]

The known levels of Nb, which were populated by γ rays from higher levels, have been identified by several different studies. The 949.82-keV $\frac{13}{2}^+$ level has been observed in $(\alpha, p\gamma)$,[16] $(n, n'\gamma)$,[13,14] and Coulomb excitation[15] studies. The 1335.20-keV $\frac{17}{2}^+$ level was known to decay by a single 385.4-keV γ ray from $(n,n'\gamma)$[13,14] studies, and the 1491.1-keV $\frac{15}{2}^+$ level was known to be depopulated by a 541.2-keV γ ray.[1,13,14] We have identified an additional γ ray of 155.84 keV and have placed it as representing the 1491.1- to 1335.2-keV level transition. We do not observe the 1491.1-keV γ ray as suggested by Rogers *et al.*[13] However, this is in agreement with Göbel *et al.*[14] We assign the remaining γ rays to the decay of two levels, one at 2180.2 keV and the other at 2753.1 keV with $\log ft$ values of 7.5 and 5.1, respectively. The $\log ft$ values were determined by using the half-life and Q values[22] adopted by Kocher[1] and the tables of Gove and Martin.[23] The β-decay rules of Raman and Gove[24] require the decay to the 2753-keV level to be allowed, thus limiting the J^π value to $\frac{19}{2}^+$, $\frac{21}{2}^+$, or $\frac{23}{2}^+$. The $\frac{23}{2}^+$ is excluded because of decay to the $\frac{17}{2}^+$ level. We prefer the $\frac{21}{2}^+$ assignment because of its γ-ray decay branching and lack of

TABLE I. The γ rays measured in the decay of ^{93}Mo^m.

$E\gamma(\Delta E\gamma)$	$I\gamma(\Delta I\gamma)$ [a]	Assignment
114.024 (9)	6.8 (1)	Mo 1477 1363
155.841 (90)	0.10 (3)	Nb 1491 1335
263.062 (5)	569 (8)	Mo 2424 2161
385.375 (85)	0.6 (1)	Nb 1335 949
541.220 (65)	0.6 (1)	Nb 1491 949
572.760 (63)	0.5 (1)	Nb 2753 2180
684.672 (9)	1000 (3)[d]	Mo 2161 1477
689.070 (49)	0.7 (1)	Nb 2180 1491
844.900(200)	0.2 (1)	Nb 2180 1335
949.817 (30)	1.2 (1)	Nb 949 g.s.
1363.023 (32)	7.9 (1)	Mo 1363 g.s.
1417.900(200)	0.3 (1)	Nb 2753 1335
1477.113 (20)	994 (15)	Mo 1477 g.s.
Limits		
511	<0.05	β^+ decay
826[b]	<0.05	Mo 2305 1479
979.0[c]	<0.06	Nb 979 g.s.

[a] For absolute intensities, multiply by 9.968×10^{-4} and incorporate a 2% error for the knowledge of the efficiency of the Ge(Li) detector.
[b] This would represent possible population of the known $\frac{11}{2}^-$ level in ^{93}Mo at 2305 (see Refs. 10 and 12).
[c] This would represent possible population of the known $\frac{11}{2}^+$ level at 979 keV in ^{93}Nb (see Refs. 13, 14, and 18).
[d] Fiducial: error represents reliability of peak shape fit plus statistical error only (see footnote a).

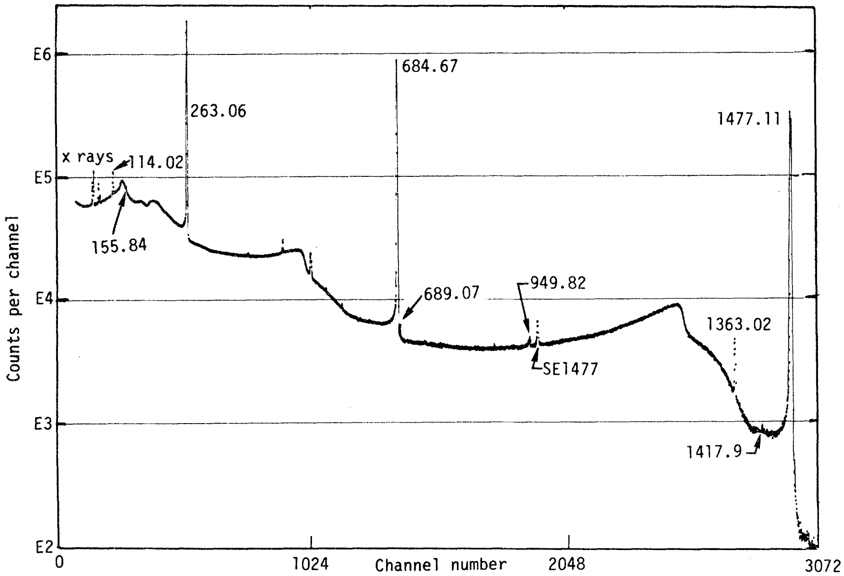

FIG. 2. The γ-ray spectra of chemically purified $^{93}Mo^m$ taken at a source-to-detector distance of 33 cm.

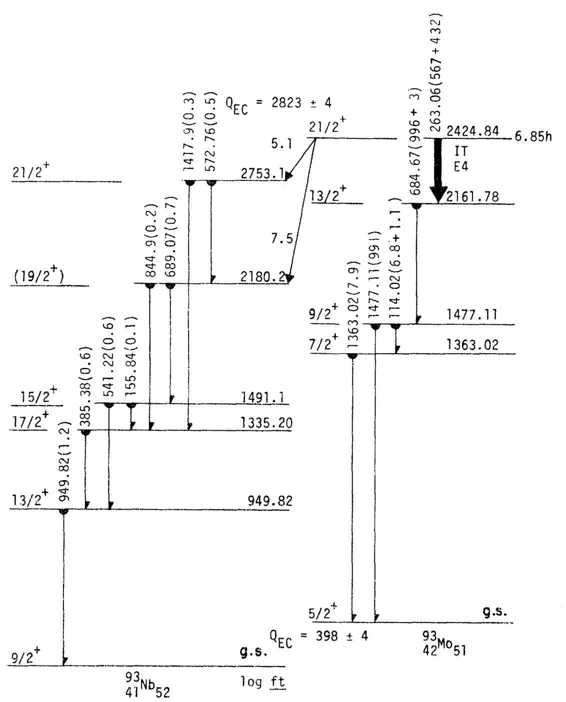

FIG. 3. Decay scheme of $^{93}Mo^m$ (*note bene* the number given in parentheses after the γ-ray energy is the intensity per 1 000 decays of the isomer and is given as γ-ray intensity *plus* conversion electron intensity when the latter contributes to a significant degree. The conversion electron data were taken from Ref. 1 and works cited therein).

transitions to the 949-keV level. Although no unique value can be determined for the 2180-keV level, we suggest a tentative J^π value of $\frac{19}{2}^+$ based on strong feeding from the positive parity 2753-keV level and decay to the 1335- and 1491-keV levels only.

It is possible to set limits on two γ rays that represent the decay of two levels known from other types of studies. One is in ^{93}Mo, the other in ^{93}Nb. Both $^{93}Nb(n, n'\gamma)$ studies[13,14] and the $^{90}Zr(\alpha, p\gamma)$ studies[16] identify a level at 979.1 keV with J^π of $\frac{11}{2}^+$. This level might be expected to be populated by cascade from the 1491-keV level; however, we place a limit of 60 parts in a million decays or less. The other level is the lowest $\frac{11}{2}^-$ level identified in ^{93}Mo by (d, p) studies.[10] Dünnweber *et al.*[12] showed that this 2305-keV level decayed primarily by a 826-keV γ ray. A small but measurable $\frac{21}{2}^+ \rightarrow \frac{11}{2}^-$ $E5$ transition could compete with the $E4$ isomeric transition. However, we set a limit of less than 50 parts per million decays of the $^{93}Mo^m$.

DISCUSSION

The level at 2753 keV populated in the electron capture $^{93}Mo^m$ may be a member of a multiplet arising from the $\pi(g_{9/2})\nu(g_{7/2}d_{5/2})$ three-quasiparticle configuration. Some support from this comes from considering the known configuration of $^{93}Mo^m$ and the speed of the β decay in ^{93}Mo and in ^{95}Mo.

Kaindl *et al.*[8] have shown that the $^{93}Mo^m$ configuration is $[\pi(g_{9/2}g_{9/2})\nu(d_{5/2})]_{21/2^+}$. Any decay that proceeds with a logft value of 5.05 ± 0.08 from this state, as does decay to the 2753-keV level, must proceed by an allowed path. The only channel open is the $\pi(g_{9/2})\rightarrow\nu(g_{7/2})$ decay. Such a decay has a logft of 5.1 in ^{95}Mo.[25-27] The dominant deexcitation of the 2753-keV level by a 572-keV transition to the 2180-keV level rather than by a 1417-keV transition to the 1335-keV level suggests a similar nature for the 2180-keV level. However, the high logft value of 7.5 is inconsistent with this level being a member of the multiplet. Measurement of the magnetic moment of the 2753-keV level would be useful in confirming a $\pi(g_{9/2})\nu(g_{7/2}d_{5/2})$ configuration for this level.

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