PHYSICAL REVIEW C VOLUME 23, NUMBER 2 FEBRUARY 1981

Decay of ^{89}Mo^g to levels of ^{89}Nb

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(Received 19 August 1980)

The 9/2$^+$ ground state of ^{89}Mo has been found to decay with a half-life of 2.15 ± 0.20 min to the ground state and levels at 658.6, 1155, and 1272 keV in ^{89}Nb. Spin and parity assignments are discussed as are the levels of the $N = 48$ and $N = 52$ odd Z isotones.

[RADIOACTIVITY ^{89}Mo^g from ^{92}Mo$(p,p3n)$, measured $t_{1/2}, E_\gamma, I_\gamma$. ^{89}Nb deduced levels. Ge detector. Enriched target.]

I. INTRODUCTION

In a recent paper, we reported the results of an investigation of the decay of the 190 msec $\frac{1}{2}^-$ isomer of ^{89}Mo.[1] In that paper we recounted the previous efforts to establish the decay properties of ^{89}Mo and ^{88}Mo and discussed the properties of the $N=47$ isotones. As isomer ratio studies[2] of ^{96}Mo (p, xn) reactions gave σ_h/σ_L values > 1, we could be assured that we were also producing substantial quantities of ^{89}Mo^g. We therefore continued our search for the decay of ^{89}Mo^g as well as ^{89}Tc isomers and report the results of these studies in this paper.

II. EXPERIMENTAL PROCEDURES

Because the studies of Hagenauer *et al.*[3] indicated an upper limit of ~2 min for the half-life of the $\frac{9}{2}^+$ isomer, our initial experiments were designed to search for an activity in the 15–30 sec range. Levels in ^{89}Nb at 0.83, 1.01, 1.16, 1.55, 1.70, 1.80, 2.05, and 2.20 MeV were observed[4] in a study of the ^{92}Mo$(p, \alpha)^{89}$Nb reaction. Spalek *et al.*[5] observed a number of γ rays in ^{89}Nb in a study of the ^{89}Y$(^3$He, $3n\gamma)$ ^{89}Nb reaction. In addition to finding the $\frac{13}{2}^+$, $\frac{17}{2}^+$, $\frac{21}{2}^+$, and higher yrast sequence, unlikely to be populated in the decay of $\frac{9}{2}^+$ ^{89}Mo^g, they also listed a number of unplaced γ rays including those at 495, 658, 718, 803, and 835 keV that cannot be assigned to other nuclides. We, thus, focused our search of the spectra we obtained on these energy values.

In the experiment aimed at a 15–30 sec half-life, the rotating beam chopper system described earlier[1,6] was operated by a switch to provide for 45 sec irradiations of an enriched (96%) ^{92}Mo target with 60-MeV protons and a 300 sec counting period between irradiations. A 10% Ge(Li) detector with a full width at half maximum (FWHM) of 4.3 keV was located 15 cm from the target and utilized to collect 8192 channel spectra. The ten spectra collected during the 300 sec counting period consisted of four 15 sec counts followed by four 30 sec counts and two 60 sec counts. The 658.6-keV γ ray noted above was observed and decayed with a half-life of ~2 min.

This experimental arrangement was also used to search for the decay of ^{89}Tc isomers. A 75-MeV proton beam was used. Any $\frac{1}{2}^-$ ^{89}Tc would be expected to decay to the 220 msec $\frac{1}{2}^-$ ^{89}Mo^m, which would in turn decay by the 268.5- and 118.6-keV γ rays.[1] Any $\frac{9}{2}^+$ ^{89}Tc could decay to the $\frac{7}{2}^+$ state at 118.6 keV or to any of several levels observed in ^{89}Mo by deBoer *et al.*[7] who studied the ^{90}Zr$(^3$He, $4n\gamma)^{89}$Mo reaction. In either case, the presence of 118.6-keV γ rays would indicate the presence of ^{89}Tc decay.

Additional experiments were performed using a procedure in which enriched ^{92}Mo targets were irradiated for 30 sec and transferred to an 18% Ge detector with a 1.7 keV FWHM. The transfer took place manually and required ~90 sec. The ten 8192-channel spectra collected consisted of four 30 sec spectra, four 2-min spectra, and two 5-min spectra. Most of the data were collected using a 60 MeV proton energy, and additional data were taken at 40, 50, 70, and 75 MeV to establish threshold values.

III. RESULTS

A. ^{89}Tc

No 118.6-keV γ rays were observed in any experiment at any beam energy. The low yields observed at 40, 50, 60, 70, and 75 MeV for ^{90}Tc and ^{91}Tc isomers indicate that very little ^{89}Tc is produced by the ^{92}Mo$(p, 4n)$ reaction. These cross sections are reduced because of the decreasing proton binding energies and increasing neutron binding energies that render proton evaporation quite competitive with neutron evaporation.

B. ^{88}Mo

Earlier conflicting half-lives of 27.3 and 8.6 min were proposed by Butement and Qaim,[8] and Doron and Blann,[9] respectively. At 60 MeV very weak evidence for the 3 γ rays proposed by Doron and Blann[9] at 80, 131, and 171 keV is observed. These peaks are much more prominent at 75 MeV and are found to follow an 8.6 ± 0.7 min half-life, fully consistent with the work of Doron and Blann.

C. ^{89}Mo^g

The most extensive data are those taken at 60 MeV. Each sample was counted for 20 min. The data were analyzed by measuring the γ ray energies of all peaks, determining which peaks were present in the first two minutes of counting and absent in the last 5 min of counting and assigning as many as possible to known nuclides. The γ rays from 50-sec ^{90}Tc, 1.4-min ^{86}Nb met this criterion, and sharp count rate drops were observed for the γ rays from the 3.1 and 3.3 min ^{91}Tc isomers, and the 2.6- and 3.7-min ^{87}Nb isomers. In addition to the 658.6-keV peak, sharp reductions in peaks near 1155 and 1272 keV were observed. Although these latter peaks were initially assigned[10] to the 1153.05 ± 0.10 keV peak from 14-h ^{86}Y decay, the 1270.364 ± 0.013 keV peak from 14.6-hr ^{90}Nb decay, and the 1271.3 ± 0.6 keV peak from 5.67 h ^{90}Mo decay, both peaks showed shifts of position in time and each peak showed a 2-min component.

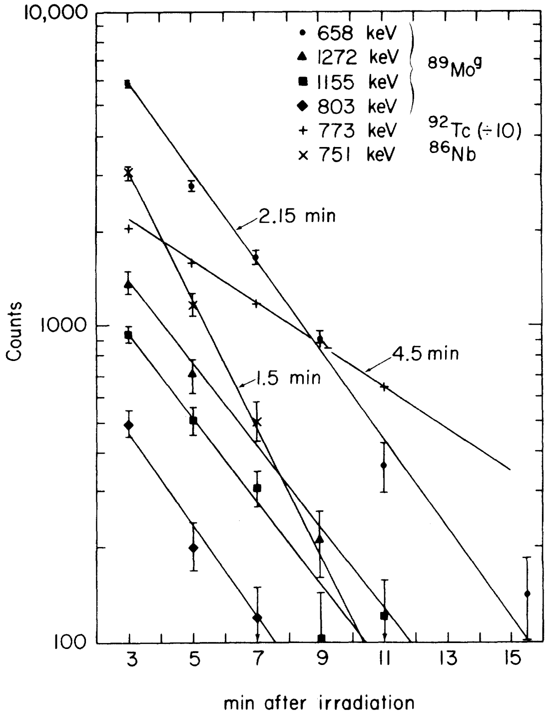


FIG. 2. Plots of peak area versus time for a number of γ rays observed following the irradiation of ^{92}Mo by 60-MeV protons.

In Fig. 1 we show the 658-keV peak region at three times after irradiation and show the plot of the time dependence of the peak areas in Fig. 2. In Fig. 3, we show the first 2-min count and the last 5-min count for both the 1155- and 1272-keV regions. The peak areas are also plotted against time in Fig. 2. For comparison we also show the peak areas versus time for the 752-keV γ ray of 1.4-min ^{86}Nb and the 733-keV γ ray of 4.4 min ^{92}Tc. We show the 658-keV peak area at 40, 50, and 70 MeV for the first two minutes of counting in Fig. 4. The 1155 and 1272 keV peak areas main-

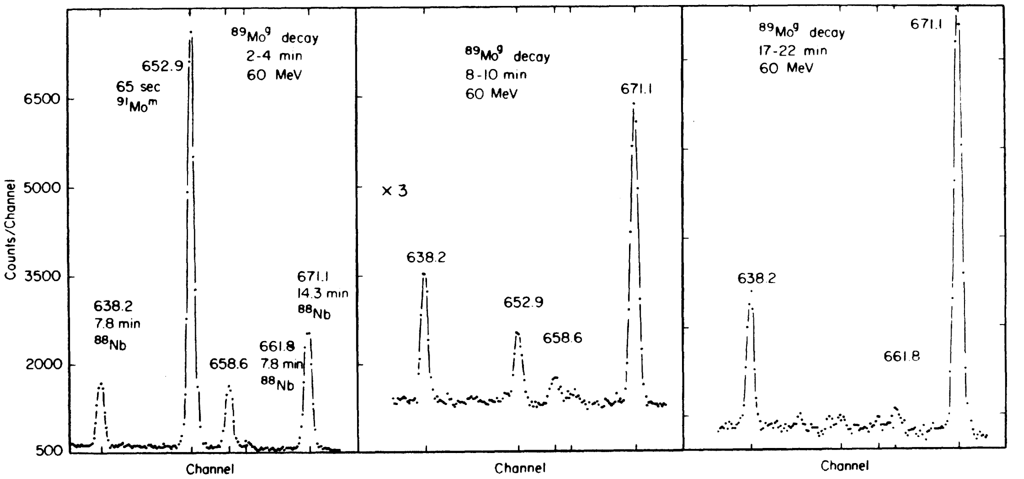


FIG. 1. The 650-keV region of the γ-ray spectra taken from 2–4, 8–10, and 17–22 min after irradiation of ^{92}Mo by 60-MeV protons.

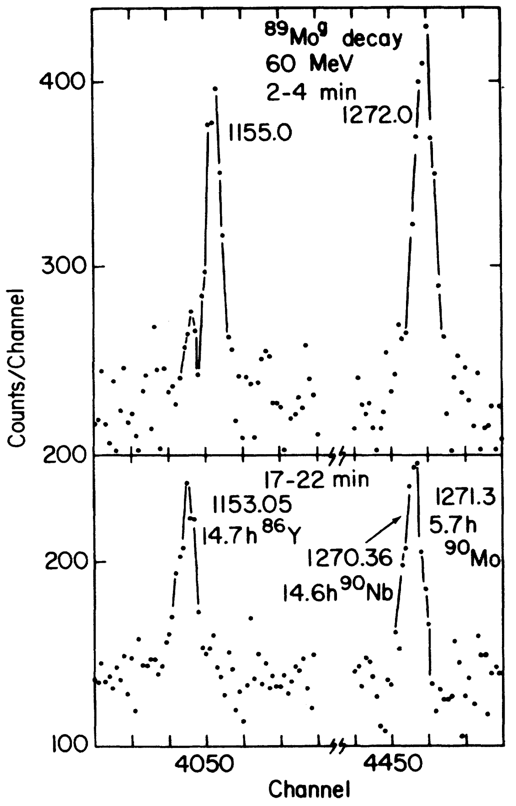


FIG. 3. The 1150- and 1270-keV regions of the γ ray spectra taken from 2–4 and 17–22 min after irradiation of ^{92}Mo by 60-MeV protons.

tained the same ratio within the uncertainty limits with the 658.6-keV peak at 50 and 70 MeV.

We also observed a number of other weak γ ray peaks whose half-lives could not be determined with great accuracy. Peaks at 803 and 997 keV did give indications of a 2-min half-life and could not be assigned to the decay of any other nuclides that were produced.

IV. DISCUSSION

The 2.15 ± 0.20 min half-life we attribute to ^{89}Mo^g is at the upper edge of the limits set by Hagenauer *et al.*[3] and slightly below a value of 2.6 ± 0.2 reported by Della Negra *et al.*[11] No mention in the latter report was made of what radiations showed the 2.6 ± 0.2 min half-life. It should be noted[10] that there is a 2.6 ± 0.1 min isomer in ^{87}Nb.

The recent measurement of the -75.003 MeV mass excess of ^{89}Mo by Pardo *et al.*,[12] in a study of the ^{92}Mo(^{3}He, ^{6}He)^{89}Mo reaction combined with the earlier measurement of the -80.64 mass excess of ^{89}Nb by Serduke and Henning in a study[4] of the ^{92}Mo(p, α)^{89}Nb reaction, fix $Q_{\beta^+/\mathrm{EC}}$ at 5.64 MeV for the decay of ^{89}Mo^g. As $\log f$ is 3.2 for a Q value[13] of 5.6 MeV, a $\log ft$ value of 5.3 can be calculated for the β^++EC decay from the $\frac{9}{2}^+$ ^{89}Mo^g to the $\frac{9}{2}^+$ isomer in ^{89}Nb (assuming a nearly 100% ground-to-ground decay branch). This value is consistent with the trend[10] observed for the decay of isotonic $^{85}_{38}$Sr (6.1) and $^{87}_{40}$Zr (5.6), and less than the value of 6.1 found for $^{91}_{42}$Mo^g decay.

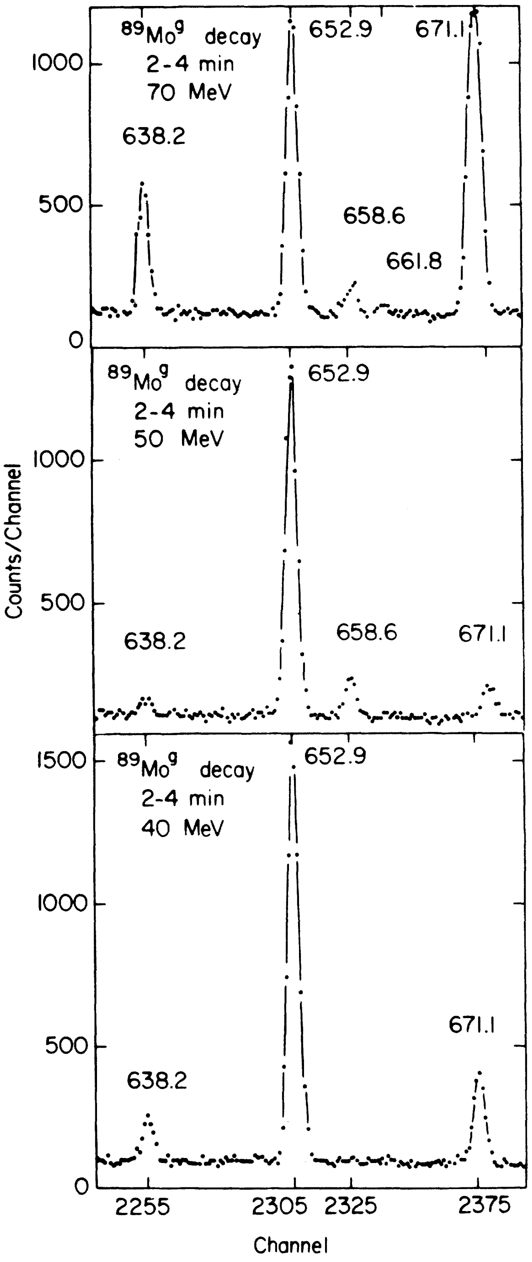


FIG. 4. The 650-keV region of the γ-ray spectra taken from 2–4 min after irradiation of ^{92}Mo with 40-, 50-, and 70-MeV protons.

We show in Fig. 5 a partial decay scheme for ^{89}Mo^g. As the 803-keV γ ray was one of those also observed by Spalek *et al.*[5] and not assigned

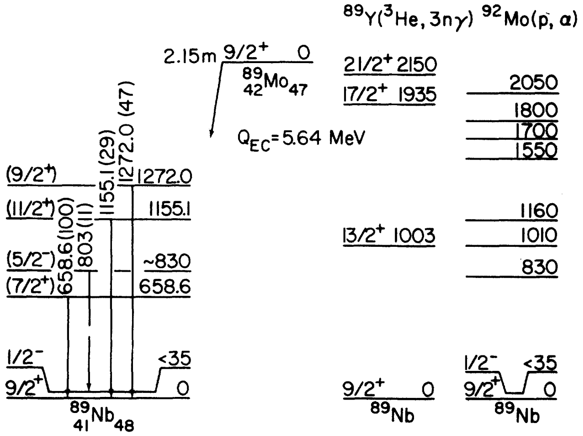
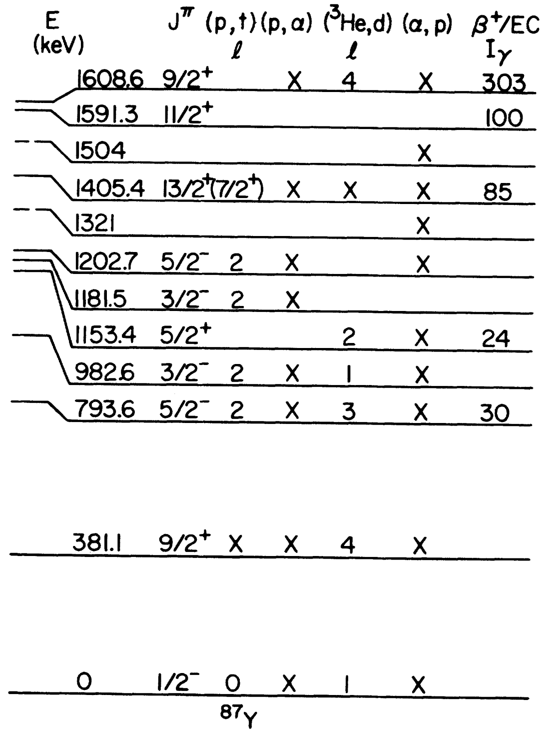


FIG. 5. The partial decay scheme of $^{89}Mo^g$ to levels of ^{89}Nb. Also shown are the levels observed in ^{89}Nb in the $^{92}Mo(p,\alpha)$ reaction (Ref. 4) and the $^{89}Y(^3He, 3n\gamma)$ reaction (Ref. 5).

to any other nuclide, we have included it in this scheme and suggest that it may represent the $\frac{5}{2}^-$ to $\frac{1}{2}^-$ transition from the possible $\frac{5}{2}^-$ level at 830 keV observed in the $^{92}Mo(p, \alpha)$ reaction study.[4]

We show in Fig. 6 the low-lying level structure observed for isotonic ^{87}Y. These levels have been observed in a number[14,15] of experiments including (p, α), (p, t), $(^3He, d)$, (p, γ), (α, p), $(p, 2n\gamma)$, and $(\alpha, 2n\gamma)$ as well as in the decay of ^{87}Zr. The (p, t) reactions on $\frac{1}{2}^-$ ^{89}Y are particularly useful for locating the negative parity states resulting from $(p_{1/2}\times 2^+)$ and $(p_{1/2}\times 4^+)$ configurations. The strong $l=2$ and $l=4$ transfer strength in the $(^3He, d)$ study establishes $\frac{5}{2}^+$ and $\frac{9}{2}^+$ as the spin and parity values for the 1155- and 1608-keV levels, respectively. The recent in-beam γ-ray studies of Fields *et al.*[15] clearly establish $\frac{11}{2}^+$ and $\frac{13}{2}^+$ spin and parity values for the 1590 and 1404 keV levels, respectively.



E (keV)	J^π	(p,t) l	(p,α)	$(^3He,d)$ l	(α,p)	β^+/EC I_γ
1608.6	9/2+		X	4	X	303
1591.3	11/2+					100
1504					X	
1405.4	13/2+(7/2+)		X	X	X	85
1321					X	
1202.7	5/2-	2	X		X	
1181.5	3/2-	2	X			
1153.4	5/2+			2	X	24
982.6	3/2-	2	X	1	X	
793.6	5/2-	2	X	3	X	30
381.1	9/2+	X	X	4	X	
0	1/2-	0	X	1	X	

FIG. 6. The properties of the low-lying levels of ^{87}Y. The data are taken from Refs. 10, 14, and 15.

Several aspects of the ^{87}Y levels are important to the interpretations of the data available for ^{89}Nb. First, the levels observed below 1 MeV in the $^{90}Zr(p, \alpha)^{87}Y$ reaction are identified as the low-lying $\frac{3}{2}^-$ and $\frac{5}{2}^-$ levels. Thus, it is likely that the levels at 830 and 1010 keV observed in the $^{92}Mo(p, \alpha)^{89}Nb$ reaction are also negative parity levels.

In the study of the $^{85}Rb(\alpha, 2n\gamma)^{87}Y$ reaction,[15] the cascade down the negative parity yrast levels led to substantial intensity for the 793.6-keV $\frac{5}{2}^-$ to $\frac{1}{2}^-$ γ ray. As the 803-keV γ ray was observed by Spalek *et al.*[5] in the $(^3He, 3n\gamma)$ reaction, additional support exists for placing the 803-keV γ ray as the $\frac{5}{2}^-$ to $\frac{1}{2}^-$ transition in ^{89}Nb.

Spin and parity assignments for the 1155 and 1272-keV levels are difficult to establish. Comparison with the levels observed in the decay of ^{87}Zr to levels of ^{87}Y would suggest a $\frac{9}{2}^+$ assignment for the 1272-keV level and an $\frac{11}{2}^+$ assignment for the 1155-keV level, as the $\frac{9}{2}^+$ level is the more strongly fed in β decay. An inverse argument could also be made on the basis of the (p, α) population of a level at 1160 keV in ^{89}Nb. If that 1160-keV level is the 1155-keV positive parity level that we propose, then it would be analogous to the (p, α) population of the $\frac{9}{2}^+$ level at 1608.6 keV in ^{87}Y and support a $\frac{9}{2}^+$ spin and parity assignment. However, the 1160-keV peak observed in the $^{92}Md(p, \alpha)^{89}Nb$ reaction could also be a negative parity state or doublet corresponding to either or both the 1181.5- and 1202.7-keV levels observed in the $^{90}Zr(p, \alpha)^{87}Y$ reaction.

The spin and parity of the 658-keV level is most simply assigned as $\frac{7}{2}^+$ in view of the intensity of 658-keV γ ray. In Fig. 6, we note, however, the sizable γ ray intensity attributed to both the $\frac{5}{2}^+$ level at 1153.4 keV and the $\frac{13}{2}^+$ level at 1405.4 keV in the decay of ^{87}Zr to levels of ^{87}Y. As the $\frac{5}{2}^+$ and $\frac{13}{2}^+$ levels cannot be fed directly in the β^+/EC decay of $\frac{9}{2}^+$ ^{87}Zr, evidence for substantial indirect feeding may exist. We suggest, however, that the 1405-keV level in ^{87}Y is a doublet with the $\frac{13}{2}^+$ state fed in the in-beam γ ray studies, while the $\frac{7}{2}^+$ member is observed in the β^+/EC decay of ^{87}Zr *and* in the (p, α), (α, p), and par-

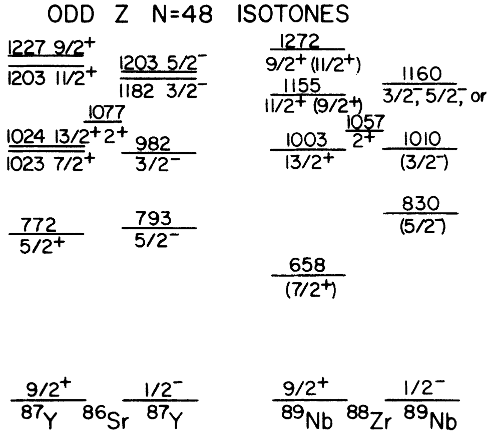


FIG. 7. The low-lying levels of the $N=52$ isotones of ^{39}Y, ^{41}Nb, and ^{43}Tc. The data are largely taken from Ref. 10 with spin and parity assignment for ^{91}Y taken from Ref. 16. The positive and negative parity states are normalized to the $\frac{9}{2}^{+}$ and $\frac{1}{2}^{-}$ states, respectively.

ticularly the (^{3}He, d) transfer reactions. It is highly unlikely that adequate $i_{13/2}$ strength would be present to permit population in a (^{3}He,d) reaction. The numerous γ-ray branchings from higher lying levels that are fed in the β^{+}/EC decay of $\frac{9}{2}^{+}$ ^{87}Zr would be more likely for a $\frac{7}{2}^{+}$ level than a $\frac{13}{2}^{+}$ level, and the tentative[14] 251-keV γ feeding to the $\frac{5}{2}^{+}$ level at 1154 keV impossible for a $\frac{13}{2}^{+}$ level. Eight of the higher-lying levels feed the 1405-keV level whereas only two feed the $\frac{11}{2}^{+}$ level at 1591.3 keV and four feed the $\frac{9}{2}^{+}$ level at 1608.6 keV.

Additional support for $\frac{7}{2}^{+}$ assignments for both the 658-keV ^{89}Nb level and one of the 1405-keV levels in ^{87}Y may be derived from the odd Z $N=52$ isotones shown in Fig. 7. There we see that most of the particle $\otimes 2^{+}$ states move slowly as protons are added relative to the adjacent 2^{+} core, except for the $\frac{7}{2}^{+}$ state. As the occupancy of the $g_{9/2}$ orbital increases, the mixing of $(g_{9/2})^{3}{}_{7/2}$ cluster character clearly brings down the $\frac{7}{2}^{+}$ level. The $\frac{7}{2}^{+}$ (and other) assignments proposed for ^{87}Y and ^{89}Nb that we show on Fig. 8 are consistent with the $N=52$ isotones. The increased $(g_{9/2})^{3}$ cluster character required in ^{89}Nb to bring down the $\frac{7}{2}^{+}$ level can also account for the sharp increase in β^{+}/EC decay strength.

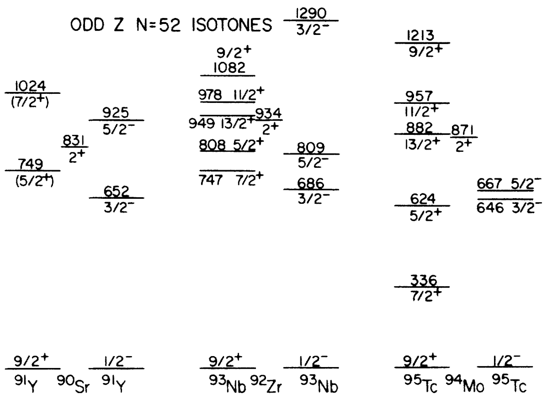


FIG. 8. The low-lying levels of the $N=48$ isotones of ^{39}Y and ^{41}Nb. The data are taken from this work and Refs. 4, 5, 10, 14, and 15. The positive and negative parity states are normalized to the $\frac{9}{2}^{+}$ and $\frac{1}{2}^{-}$ states, respectively.

ACKNOWLEDGMENTS

We wish to express our appreciation to Professor D. L. Hendrie and Mr. John Brett of the Maryland Cyclotron for their cooperation and efficiency in producing the various proton beams required in these experiments. This work was funded in part by the National Science Foundation whose support we greatly appreciate.

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