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Evidence for a $7/2^+$ State in Mo^{93}†

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The recent shell-model calculations by Bhatt and Ball and by Auerbach and Talmi concerning the level locations and transition probabilities in Mo^{93} have prompted us to perform an experimental examination of the Mo^{93} level scheme. This level scheme was studied through the decays of Mo^{93m}(7 h), Tc^{93m}(44 min), and Tc^{93}(2.8 h). The gamma-ray spectra produced in these decays were examined with a Ge(Li) detector and with Ge(Li)-NaI(Tl) coincidence techniques. A new transition of 114 keV, observed in the decay of Mo^{93m}, populates a level in Mo^{93} at (1365±3) keV. A spin-parity $\frac{7}{2}+$ is assigned to this level. The γ ray previously reported at 1.5 MeV in the spectrum of Tc^{93}(2.8 h) was shown to consist of a doublet at 1.477 and 1.521 MeV, and a new γ ray at 2.734 MeV was observed. The absence of transitions of 2030 and 2440 keV, which were previously reported to exist, is also of interest. An interpretation of these results in terms of the shell-model computations is discussed.

1. INTRODUCTION

THE $21/2^+$ isomeric state of Mo^{93m} (7.0 h) has long been recognized as a case of "core isomerism."[1] In this case the odd neutron, probably in a $d_{5/2}$ state, couples to the excited $g_{9/2}{}^2$ proton pair from the even-even core. Other examples of high-spin core isomerism have been observed in the deformed region of the periodic table.[2] The isomer Mo^{93m} decays through a cascade of three transitions $21/2^+$ (263 keV) $\rightarrow 13/2^+$ (685 keV) $\rightarrow \frac{9}{2}^+$ (1477 keV) $\rightarrow \frac{5}{2}^+$, the ground state of Mo^{93}. On the basis of the proton-neutron configuration suggested above, one can construct in excess of 20 shell-model levels ranging in spin from $\frac{1}{2}$ to 21/2. The question then arises as to why "spin gaps" exist between the Mo^{93} levels of spin 21/2, 13/2, $\frac{9}{2}$, and $\frac{5}{2}$, if there are available numerous other levels of intermediate spin to which these states may decay.

Using information on the effective interaction obtained from the level locations in Nb^{92} and Mo^{92}, Auerbach and Talmi[3] have attempted to answer the above question by computing the expected location of levels in Mo^{93}. The results of their calculation are presented in Fig. 1. As may be seen from this figure, their results are qualitatively in good agreement with the observed decay scheme of Mo^{93m}. However, their level scheme also indicates the possibility of weak transitions in this decay, to and from the levels predicted at 1.29 MeV ($\frac{7}{2}^+$), 1.34 MeV ($\frac{5}{2}^+$), and 2.16 MeV ($11/2^+$).

Bhatt and Ball[4] have performed a calculation similar to that of Auerbach and Talmi; the results are also given in Fig. 1. The small differences in level placement between the two schemes are essentially due to the difference in the choice of n-p effective interaction. It may be noticed that the level order given by Bhatt and Ball excludes the population of the $\frac{5}{2}^+$ level (located at 1.58 MeV) in the decay of Mo^{93m}.

It is of interest to establish experimentally which of the various possible Mo^{93} levels are populated and what the exact locations of these levels are. The relative intensities of transitions to and from such levels will help to confirm or rule out the predicted spin-parity assignments. The experimental information on the Mo^{93} level scheme prior to this experiment is summarized in Fig. 2(a), showing the Mo^{93} levels given in the *Nuclear Data*

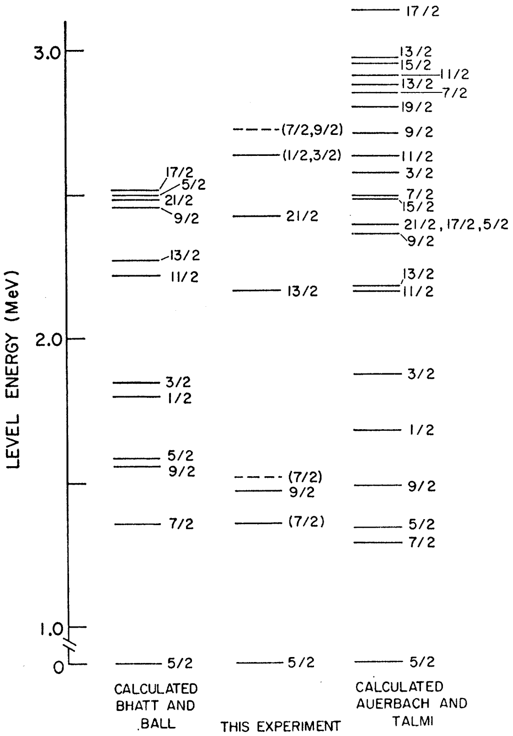

FIG. 1. Comparison of experimentally observed [see Fig. 2(b)] and theoretically calculated level locations in Mo^{93}.

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[1] M. Goldhaber, Phys. Rev. 89, 1146 (1953).

[2] See, e.g., P. Alexander, F. Boehm, and E. Kankeleit, Phys. Rev. 133, B284 (1964).

[3] N. Auerbach and I. Talmi, Phys. Letters 9, 153 (1964).

[4] K. H. Bhatt and J. B. Ball, Nucl. Phys. 63, 286 (1965). [See also the extensive study by J. Vervier, Nucl. Phys. 75, 17 (1966), which arrived after the completion of the present manuscript.]

Sheets,[5] and also levels reported in a more recent reference.[6] Additional Mo^{93} low-spin levels have been observed in (d,p) experiments[7] but are not shown in this figure.

We have examined the Mo^{93} level structure by studying the decays of Mo^{93m} (7 h), Tc^{93m} (44 min), and Tc^{93} (2.8 h). The use of Ge(Li) detectors for the study of gamma-ray spectra and of gamma-gamma coincidences from these decays has led to the observation of several new transitions in Mo^{93}. On the other hand, we find no evidence to support the existence of several transitions previously assigned to Mo^{93} and shown in Fig. 2(a). The accuracy afforded by Ge(Li) detectors in gamma-ray energy and intensity measurements allows a meaningful comparison with the theoretical predictions.

2. RADIOACTIVE SOURCES

Radioactive sources of Mo^{93m} (7.0 h) were produced by the $Nb^{93}(d,2n)$ reaction using 20-MeV deuterons from the 60-in. Brookhaven cyclotron. Pure Mo was separated from the target material by an ether-extraction technique.

Tc^{93}(2.8 h) and Tc^{93m} (44 min) activities were both produced by the $Mo^{92}(d,n)$ reaction with the 60-in. cyclotron, using a Mo^{92} sample enriched to 97.6%, which was obtained from Oak Ridge National Laboratory. Tc was chemically separated from the Mo target material by distillation.

3. EXPERIMENTAL RESULTS

A. Mo^{93} Singles Spectrum

The decay of Mo^{93m} (7.0 h) was investigated using a 2.4-cm^3 Ge(Li) detector to study the gamma-ray spectrum and a 2-mm×0.8-cm^2 Si(Li) detector to examine the internal-conversion electron spectrum. The general features of the Mo^{93m} gamma-ray spectrum are shown in Fig. 3. The well-established cascade transitions[5] are prominent at 263, 685, and 1477 keV. A two-quantum escape peak due to the 1477-keV transition is visible at 455 keV. In addition to these lines we have also observed two new transitions of (114.0 ± 0.5) keV and (1365 ± 3) keV. Energy and relative gamma-ray intensity values for these lines as established in this experiment are given in Table I. A careful analysis was made of the spectrum of Fig. 3 in order to reveal any additional weak transitions in the decay of Mo^{93m}. No transitions with relative gamma-ray intensities greater than 0.1–1.0, other than those listed in Table I, were observed. The variation in the value of this upper-intensity limit is a function of the location of a possible line. If, for example, we were attempting to establish an upper

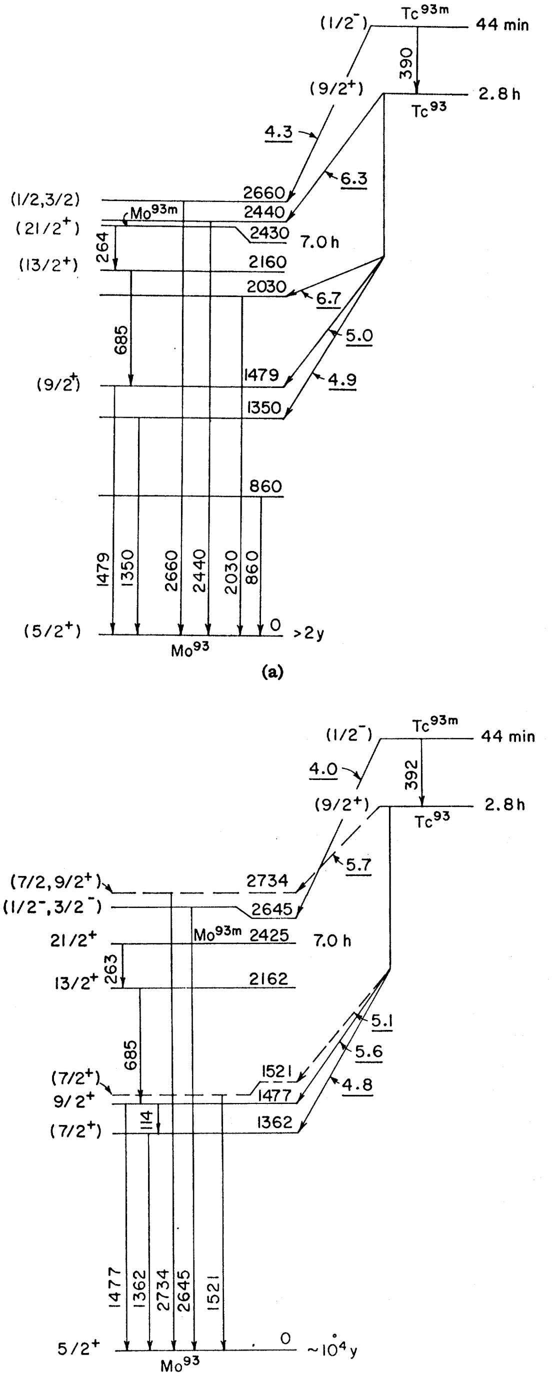

FIG. 2. (a). Scheme showing the decay of 44-min Tc^{93m}, 2.8-h Tc^{93}, and 7.0-h Mo^{93m}. Transitions and spin assignments as established by Refs. 5 and 6 are shown. A number of the transitions shown were not observed in this experiment. The underlined figures denote log*ft* values. (b). Scheme showing the decay of 44-min Tc^{93m}, 2.8-h Tc^{93}, and 7.0-h Mo^{93m} as established in this experiment. The lines at 114, 1521, and 2734 keV have not previously been reported in the decay of 2.8-h Tc^{93}. It is probable that the 1521- and 2734-keV transitions depopulate levels at those energies. The spin-parity assignments, with the exception of those for the levels at 1362, 1521, and 2734 keV, are taken from Ref. 5. The underlined figures denote log*ft* values.

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[5] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.), NRC 60-5-91.

[6] G. B. Vingiani, S. Monaro, R. A. Ricci, and R. van Lieshout, Nuovo Cimento 23, 729 (1962).

[7] S. A. Hjorth and B. L. Cohen, Phys. Rev. 135, B920 (1964).

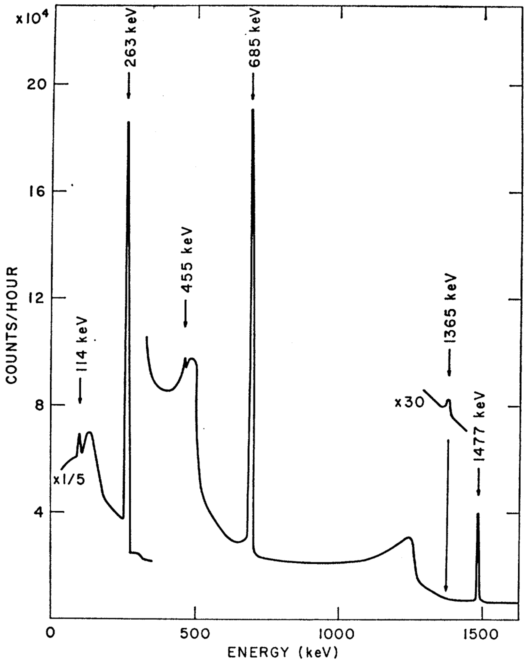

FIG. 3. Gamma-ray spectrum of Mo^{93} as observed with a Ge(Li) detector. The line at 455 keV is the two-quantum escape peak from the 1477-keV transition.

limit for a line superimposed on a low-energy Compton edge, the value 1.0 would apply.

Examination of the internal conversion electron spectrum of Mo^{93m} using a Si(Li) detector indicates that the relative intensities of the 263-, 685-, and 1477-keV conversion electron lines are in good agreement with previously published results.[5] This measurement also established an upper limit for the K internal-conversion intensity of the 114-keV transition relative to that of the 263-keV transition. The intensity of the 263-keV K-conversion line is found to be >550 times the intensity of the 114-keV K line.

TABLE I. Energies and relative intensities of gamma rays observed in the decay of 7.0-h Mo^{93}, 44-min Tc^{93m}, and 2.8-h Tc^{93}.

Mo^{93m} (7 h) Energy (keV)	Mo^{93m} (7 h) Rel. int.	Tc^{93m} and Tc^{93} Energy (keV)	Tc^{93m} and Tc^{93} Rel. int. Tc^{93m} (44 min)	Tc^{93m} and Tc^{93} Rel. int. Tc^{93} (2.8 h)
114.0 ± 0.5	1.2 ± 0.3	115.4 ± 1.2		0.078 ± 0.01
262.5 ± 0.5	100			
		391.5 ± 1.0	2.5 ± 0.5	
685.0 ± 0.5	174 ± 25			
1365 ± 0.5	1.5 ± 0.6[c]	1362.4 ± 1.0[b]		100
1477 ± 1[a]	192 ± 38	1477.2 ± 1.0		11.3 ± 0.5
		1521.0 ± 1.0[b]		36.0 ± 1.0
		2645 ± 2.0[b]	1	
		2734 ± 1.0[b]		0.8 ± 0.2

[a] The two-quantum escape peak from this transition is observed at 455 keV.

[b] The two-quantum escape peaks from the 1362-, 1521-, 2645-, and 2734-keV transitions are observed at 340, 498, 1622, and 1712 keV, respectively.

[c] After many half-lives have elapsed contributions to this peak arise from the 1368-keV line of Na^{24}. This activity is produced in the Al cyclotron-target block and very small amounts are carried over in the chemical separation.

B. Gamma-Ray Coincidences from Mo^{93m}

A variety of coincidence measurements were performed with Mo^{93m} (7.0 h). These included γGe(Li)-γNaI(Tl) coincidences, γGe(Li)-γGe(Li) coincidences, and γGe(Li)-Mo K x-ray NaI(Tl) coincidences. These measurements were performed using two Ge(Li) detectors, each 5-mm×5-cm², a 1.5-×1.5-in. NaI(Tl) detector, and a thin window $\frac{1}{8}$-in.×1-in. NaI(Tl) detector. A single-parameter 1600-channel and a dual-parameter 16 384-channel pulse-height analyzer were used in these experiments. Conventional fast-slow electrons were employed to supply gate pulses to the single- and dual-parameter analyzers. The coincidence resolving time in the fast circuit was set for 75 nsec. The low-energy (<300 keV) gamma-ray spectrum was studied using the γGe(Li)-γGe(Li) coincidence technique, while the higher energy portions of this spectrum were examined using γGe(Li)-γNaI(Tl) coincidences.

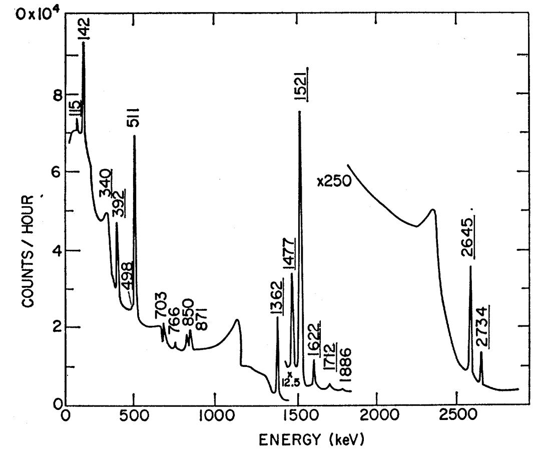

FIG. 4. Germanium (Li) gamma-ray spectrum of Tc chemically separated after production by (d,n) reaction on 97.6% enriched Mo^{92}. Gamma-ray energies are given in keV. The underlined lines at 115, 340, 392, 498, 1362, 1477, 1521, 1622, 1712, 2645, and 2734 keV are associated with the decays of Tc^{93} and Tc^{93m} (see Table I). The peaks at 340, 498, 1622, and 1712 keV are two-quantum escape peaks.

The new transition at 114 keV is found to be in coincidence with the 263-, 685-, and the 1365-keV transitions, but not with the 1477-keV transition. The transitions of 263, 685, and 1477 keV are observed to be mutually coincident. Gamma Ge(Li)-Mo K x-ray NaI(Tl) coincidence measurements show all of the above gamma rays to be in coincidence with Mo K x rays. This result was obtained through use of a set of matched critical absorbers interposed between the source and the thin-window NaI(Tl) detector. No additional γ-γ coincidences were observed over any portion of the Mo^{93m} spectrum between 50 keV and 2.5 MeV.

C. Tc^{93} and Tc^{93m} Singles Spectrum

Shortly after bombardment, γ rays from a number of Tc isotopes were observed in the chemically separated

Tc source. Figure 4 shows this spectrum as seen with a Ge(Li) detector. Included are lines from the decays of Tc^{93} (2.8 h) and Tc^{93m} (44 min), Tc^{94} and Tc^{94m} (52.5 min and 4.8 h),[8] Tc^{96} (4.35 day), and Tc^{99m} (6.0 h). If the scale of this figure were expanded, at least eight additional lines would become visible. After 10–20 h, activities from trace amounts of various impurities carried over in the chemical separation became dominant. Transitions arising from the decays of Tc^{93} and Tc^{93m} were identified in the gross spectrum of Fig. 4 by following all lines for several half-lives. Some of the more intense lines in the decay of Tc^{93} (2.8 h) were followed for 9 half-lives.

A list of those transitions found to decay with the half-lives of Tc^{93} and Tc^{93m} is presented in Table I; The lines at 391.5 and 2645 keV belong to the Tc^{93m} (44-min) activity. A two-quantum escape peak due to the 2645-keV transition may be observed at 1622 keV in Fig. 4.

Five of the transitions in the spectrum of Fig. 4 were observed to decay with the 2.8-h half-life of Tc^{93}. These lines have energies of 115.4, 1362.4, 1477.2, 1521.0, and 2734 keV. An accurate half-life determination of the line at 115 keV is difficult because soon after irradiation this line becomes "lost" in the massive low-energy Compton distribution. The half-life of the two-quantum escape peak at 1712 keV was found to agree with that of the full-energy peak at 2734 keV. The escape peaks at 340 and 498 keV due to the transitions at 1362 and 1521 keV are so weak that no half-life estimate was undertaken. The line observed at (115.4±1.5) keV in the decay of 2.8-h Tc^{93} has a gamma-ray intensity (0.007±0.001) times that of the 1477-keV line. As mentioned above, in the Mo^{93m} decay, a line is observed at (114.0±0.5)keV with a gamma intensity (0.006 ±0.002) times that of the 1477-keV line. We therefore believe that the 115.4- and the 114.0-keV lines are identical.

TABLE II. Upper-intensity limits for transitions reported in the decay of Tc^{93} which were not observed in this experiment.

Energy (keV)	Reported intensity[a] Vingiani *et al.*[b]	Max. possible int. This experiment
860	4.0	<1.0[c]
2030	0.57	<0.25
2440	0.55	<0.4

[a] Using the same intensity normalization as in Table I.
[b] See Ref. 6.
[c] A transition with half-life of ~4.5 h was observed at 850.6 keV.

In Table II we summarize the results of a search in the Tc^{93} (2.8 h) gamma-ray spectrum for gamma rays of 860, 2030, and 2440 keV recently reported by Vingiani *et al.*[6] We were unable to observe the transitions of 2030 and 2440 keV. We did see a gamma transition of 870.6 keV. This line, however, appears to have a half-life 50% greater than that of Tc^{93} (2.8 h), and is therefore ascribed to 4.5-h Tc^{94m}. [The 850-keV line decays with the half-life of Tc^{96} (~4.4 day).]

TABLE III. Total positron-plus-electron-capture branchings to levels in Mo^{93} from the decay of 2.8-h Tc,[3].

Level energy (keV)	Percent per decay This experiment[a]	Vingiani *et al.*[b]
1362	68	65
1477	8	34
1521	23.5	...
2734	0.5	...

[a] Computed using the gamma-ray intensity values of Table I and Rose's internal-conversion coefficients.
[b] See Ref. 6.

Using the gamma-ray intensity data of Table I and the theoretical internal conversion coefficients of Rose,[9] we have calculated the total positron–plus–electron-capture branches populating the various levels of Mo^{93} in the decay of Tc^{93} (2.8 h). These results are presented in Table III. Also presented for comparison in this table are the results of Vingiani *et al.*[6]

D. Tc^{93} Coincidence Studies

The theoretical calculations of Refs. 3 and 4 predict an $11/2^+$ level at ~2.2 MeV in Mo^{93}. If such a state exists at this energy it may be populated from the Tc^{93} ground state and decay preferentially to the $\frac{9}{2}^+$ Mo^{93} level at 1477 keV. We were unable to observe any transitions from a level at 2.2 MeV which were in coincidence with the 1477-keV ground-state transition. The upper relative intensity limit for such a transition is <2. Likewise, no gamma rays were observed to be in cascade with the 1521- or 2734-keV gamma rays.

4. CONCLUSIONS

A. The Level at 1362 keV

The Mo^{93} level at 1362 keV is depopulated by a ground-state transition observed both in the decay of Tc^{93} (2.8 h) and of Mo^{93m} (7.0 h). In the former case, this level is populated primarily directly from the $\frac{9}{2}^+$ Tc^{93} ground state [see Fig. 2(b)]; in the latter case the 1362-keV level is fed entirely by a 114-keV gamma-ray transition from the spin-$\frac{9}{2}^+$ level at 1477 keV. The strong positron and electron-capture feeding of the 1362-keV level (as indicated in Table III) relative to the feeding of the $\frac{9}{2}^+$ level at 1477 keV, suggests that the spin-parity of the 1362-keV level is either $\frac{7}{2}^+$, $\frac{9}{2}^+$, or $11/2^+$. Accordingly, the 114-keV transition should then have multipolarity $M1$, $M1+E2$, or $E2$. This assignment is con-

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[8] S. Monaro, G. B. Vingiani, R. A. Ricci, and R. van Lieshout, Physica **28**, 63 (1962); J. M. Matuszek, Jr., and T. T. Sugihara, Nucl. Phys. **42**, 582 (1963).

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

sistent with the upper limit we found for the internal-conversion electrons of the 114-keV transition. The assignment $11/2^+$ is excluded, since 114 keV–1365 keV coincidences were observed in the decay of Mo^{93m}. The assignment $\frac{9}{2}^+$ is highly improbable, since such a state would be populated from the $13/2^+$ state at 2160 keV.

Auerbach and Talmi[3] predict a Mo^{93} $\frac{7}{2}^+$ state at 1.29 MeV and a $\frac{5}{2}^+$ state at 1.34 MeV (see Fig. 1). Bhatt and Ball[4] locate the $\frac{7}{2}^+$ state at 1.36 MeV and the $\frac{5}{2}^+$ state at 1.58 MeV. A $\frac{5}{2}$ level has been observed in stripping reactions[7] at 1.7 MeV. On the hypothetical assumption that the 1362-keV level observed in this work is the $\frac{5}{2}^+$ level, Ball[10] computes a gamma-ray branching ratio

$$I(114\text{ keV } E2\ \tfrac{9}{2}\rightarrow\tfrac{5}{2})/I(1477\text{ keV } E2\ \tfrac{9}{2}\rightarrow\tfrac{5}{2})=5\times10^{-6},$$

whereas if the 1362-keV level is the $\frac{7}{2}^+$ state, the predicted branching ratio is

$$I(114\text{ keV-}M1\ \tfrac{9}{2}\rightarrow\tfrac{7}{2})/I(1477\text{ keV-}E2\ \tfrac{9}{2}\rightarrow\tfrac{5}{2})=0.02.$$

Both these branching ratios are only expected to be valid within a factor of 3.[10] The experimental value for this ratio is 0.006±0.002, yielding reasonable agreement with the branching-ratio prediction for a spin $\frac{7}{2}$ assignment. On the basis of these considerations it is most probable that the character of the Mo^{93} level at 1362 keV is $\frac{7}{2}^+$.

B. The Proposed 2734- and 1521-keV Levels

The fact that we were unable to locate any gamma rays in coincidence with the 2734-keV transition leads us to suggest that this may be a ground-state transition from a level at that energy. This proposed level may correspond to one of the $\frac{7}{2}^+$ or $\frac{9}{2}^+$ levels calculated to lie at about this energy.

Since no transitions were observed in coincidence with the 1521-keV line, it is probable that also this transition is a ground-state transition. This proposed level appears to be directly fed from the Tc^{93} ground state (spin $\frac{9}{2}$), three times more strongly than the adjacent 1477-keV $\frac{9}{2}$ level (see Table III). The strong feeding of the 1521-keV level from the $\frac{9}{2}^+$ ground state of Tc^{93} suggests that the spin of this level is $\frac{7}{2}$, $\frac{9}{2}$, or $11/2^+$. If, however, the spin of this level were $\frac{9}{2}$ or greater, the level would probably be fed in the decay of Mo^{93} (7 h). We are unable to relate this proposed $\frac{7}{2}^+$ level to any of those resulting from the calculations of Refs. 3 or 4.

C. The Calculated 2.2-MeV $11/2^+$ and 2.5-MeV $17/2^+$ Levels

Auerbach and Talmi[3] have proposed an 11/2 Mo^{93} level at 2.16 MeV. Bhatt and Ball[4] place this level at 2.22 MeV. As discussed in Sec. 3(d), we were unable to observe transitions from this state in the Tc^{93} (2.8 h) decay. The $17/2^+$ level, if existing, would not have been observed in the experiments described above.

D. The Transitions Reported at 2440, 2030, and 860 keV

Levels in Mo^{93} at 2440, 2030, and 860 keV depopulated by transitions of the same energies and populated from the Tc^{93} ground state have been reported in the literature.[5,6] The difficulty of extracting any information concerning these lines from the gross NaI(Tl) spectrum is illustrated in Fig. 4 of Ref. 6. In Fig. 4 we present the corresponding Ge(Li) spectrum, in which we find no evidence to support the existence of the 2030- and 2440-keV lines (see Table II for upper-intensity limits). We cannot exclude a weak line at ~870 keV, since a line of that energy from Tc^{94} and Tc^{94m} (52 min and ~4.5 h) obscures this position in the spectrum.

5. SUMMARY

In Fig. 2(b) we present a level scheme for Mo^{93} consistent with our experimental data from the study of the decay schemes of Mo^{93m} (7 h), Tc^{93} (2.8 h), and Tc^{93m} (44 min). We were able to detect a new transition of (114±0.5) keV in the decays of Mo^{93m} and Tc^{93} populating the 1362-keV state previously known from the decay of Tc^{93}. Since this level is not populated from the $13/2^+$ level at 2.162 MeV in the decay of Mo^{93m} and is therefore presumably not $\frac{9}{2}^+$, we conclude that it is probably the $\frac{7}{2}^+$ level computed to lie at 1.29 MeV by Auerbach and Talmi[3] and at 1.36 MeV by Bhatt and Ball. (See Fig. 1.) The intensity ratios I_{114}/I_{1477} are in good agreement: 0.006±0.002 for Mo^{93m} and 0.007±0.001 for Tc^{93}. They support the assignment $\frac{7}{2}^+$, since the predicted intensity ratio, 0.02, is expected to be valid only within a factor of 3.[10]

A new transition of 1.521 MeV was found in the decay of Tc^{93} (previously the 1477–1521 doublet was not resolved), which appears to proceed to the ground state of Mo^{93}. If this is the case, the 1.521-MeV level is probably also $\frac{7}{2}^+$,[11] although only one $\frac{7}{2}^+$ level—tentatively identified here with the 1362-keV level—follows from the assumptions used for the above-mentioned calculations.

No $11/2^+$ level, predicted to lie at ~2.2 MeV, was observed, although such a level might be expected to be populated from the $\frac{9}{2}^+$ ground state of Tc^{93}.

Finally, no transitions to a $\frac{5}{2}^+$ level were observed.

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[10] J. B. Ball (private communication).

[11] The low log *ft* value of 5.1 for the *K*-capture–positron transition to the 1521-keV level indicates that this transition is probably allowed. However, it is difficult to find possible configurations for this $\frac{7}{2}^+$ level, e.g., a level with the configuration $(\pi g_{9/2}{}^2)_0(\nu g_{7/2})_{7/2}$ should have been populated in the reaction Mo$^{92}(d,p)$, but was not seen (Ref. 7), while a $((\pi g_{9/2}{}^2)(\nu s_{1/2}))_{7/2}$ level is expected to lie at a considerably higher energy (Ref. 9).

This, however, does not necessarily support the level scheme given by Bhatt and Ball[4]—who have placed this level above the $\frac{9}{2}^+$ level—in preference to the one presented by Auerbach and Talmi,[3] where the order of these two levels is reversed, because as was pointed out by Ball,[10] even if the $\frac{5}{2}^+$ level were lower, the transition $\frac{9}{2}^+$ (1.48 MeV) $\rightarrow \frac{5}{2}^+$ (1.34 MeV) would probably be unobservably weak (see Sec. 4.A).

ACKNOWLEDGMENTS

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Analysis of Proton Scattering from Zr^{92} and Zr^{94} at 19.4 MeV*

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Elastic and inelastic angular distributions for 19.4-MeV protons scattered from Zr^{92} and Zr^{94} were measured. Several deuteron and triton groups from the (p,d) and (p,t) reaction were observed and angular distributions obtained. The inelastic distributions were analyzed using the real and complex collective-model form factor to obtain level-structure information. Angular distributions for several states of Zr^{92} and Zr^{94} were compared with distorted-wave calculations using shell-model wave functions for the initial and final nuclear states. An effective internucleon potential, which was found from the analysis of proton scattering from Zr^{90}, was used, and consisted of a Yukawa potential with a range of 1 F and a depth of approximately 200 MeV. This model was successful in predicting the magnitude and shape for the Zr^{92} and Zr^{94} cross sections for states having the $(d_{5/2})^2$ and $(d_{5/2}d_{3/2})$ configurations in Zr^{92} and the $(d_{5/2})^{-2}$ configuration in Zr^{94}.

I. INTRODUCTION

THE nuclei Zr^{92} and Zr^{94} have 40 protons and additional neutrons in the $2d_{5/2}$ shell above the closed shell of 50 neutrons. For this reason the low-lying states are expected to be dominated by the $(2d_{5/2})^2$ neutron configuration for Zr^{92} and by $(2d_{5/2})^{-2}$ for Zr^{94}. Talmi[1] has shown on theoretical grounds that the energy-level spacings of the resulting 0+, 2+, and 4+ states should be the same for Zr^{92} and Zr^{94}.

The level structure and shell-model configurations of Zr^{92} have been studied with a variety of experiments.[2–6] Recently Jolly[3] has reported the results of inelastic deuteron scattering on Zr^{92}. The Q values were determined up to an excitation of 5.5 MeV and assignments to several states were made. Previously, the spin and parity assignments to the first six excited states had been determined from the beta-decay studies of Bunker *et al.*[4] The possible shell-model configurations have been investigated by Martin *et al.*[5] and also by Cohen and Chubinsky[6] using the $Zr^{91}(d,p)Zr^{92}$ reaction. As anticipated, their work shows that the Zr^{92} 0.92-MeV, 2+ state and the 1.47-MeV, 4+ state have predominantly the $(2d_{5/2})^2$ neutron configuration. Cohen and Chubinsky[6] have also obtained the orbital angular momentum of the stripped neutron for many states for which spin and parity assignments have not been determined.

The previous work on Zr^{94} is not nearly as extensive.[7] Jolly, Lin, and Cohen,[8] studying inelastic deuteron scattering from Zr^{94}, have identified a 3^- state at 2.06 MeV and have given indications of parity assignments by use of the Blair phase rule. A 4+ state at 1.47 MeV has been suggested by Lind and Day[9] from the $Zr^{94}(n,n'\gamma)$ reaction.

The fact that only three assignments have been made for states in Zr^{94} and that only those below 2.5 MeV in Zr^{92} are certain provided one motivation for the present experiment.

In addition, there recently has been a distorted-wave analysis of inelastic proton scattering from Zr^{90} using shell-model wave functions for the initial and final

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