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IN-BEAM GAMMA-RAY SPECTROSCOPY OF ODD-NEUTRON Mo AND Ru ISOTOPES†

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Abstract: Levels of Mo and Ru isotopes, excited by the reactions $^{94}Zr(\alpha,3n)^{95}Mo$, $^{96}Zr(\alpha,3n)^{97}Mo$, $^{92}Mo(\alpha,n)^{95}Ru$, $^{94}Mo(\alpha,n)^{97}Ru$, $^{98}Mo(\alpha,3n)^{99}Ru$, and $^{100}Mo(\alpha,3n)^{101}Ru$, have been studied by in-beam gamma-ray spectroscopic techniques (γ singles spectra, beam-γ delay, γγ-coincidence, and γ-ray angular distributions). A new isomer, $t_{1/2}$ = 8 ns, is found in ^{95}Ru. Much of the new information concerns high-spin states. In ^{95}Mo, number of these states are predicted by calculations for the configuration $(\pi p_{1/2})^2(\pi g_{9/2})^2(\nu d_{5/2})^3$, and most of the others can be accounted for qualitatively by inclusion of other neutron orbitals, primarily $g_{7/2}$ and $h_{11/2}$ for the high-spin states. Similar shell-model structures are inferred for some levels in $^{97,99,101}Ru$. In ^{101}Ru and ^{99}Ru we observed also sequences of high-spin, odd-parity states which can be characterized as phonon bands coupled to an 11/2- particle state.

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NUCLEAR REACTIONS $^{94,96}Zr$, $^{98,100}Ru(\alpha,3n\gamma)$, $^{92,94}Mo(\alpha,n\gamma)$, $^{92}Mo(\alpha,?\gamma)$; measured E_γ, I_γ, $\alpha\gamma(\theta)$, $\alpha\gamma(t)$, γγ-coin. $^{95,97}Mo$, $^{95,97,99,101}Ru$, ^{93}Ru or $^{94}Tc(?)$, deduced levels, J, π. ^{95}Ru deduced $t_{1/2}$ (level). Enriched targets. Ge(Li) detectors.

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

1. Introduction and Experimental Methods

In another paper[1]) we have described studies of excited states of even isotopes of Mo and Ru populated by the $(\alpha,2n\gamma)$ reaction. The present paper concerns some of the odd-neutron isotopes populated by the reactions $(\alpha,n\gamma)$ and $(\alpha,3n\gamma)$. The experimental data were obtained at the same time as the data pertaining to the even isotopes.

Since the methods and interpretation of the data are described in Ref. [1]), we give here only a brief summary. Targets of Zr and Mo, enriched in one of the stable isotopes, were bombarded with α particles at the Berkeley 88-inch cyclotron. In most cases the bombarding energy was 30 MeV, although a few measurements were made at 24 and 40 MeV. Although 30 MeV is close to an optimal energy for the $(\alpha,2n)$ reaction, the $(\alpha,3n)$ reaction competes to a considerable extent in bombardments of the neutron-rich targets ^{94,96}Zr and ^{98,100}Mo, whereas with the neutron-deficient targets ^{92,94}Mo, the (α,n) reaction competes.

Gamma-ray spectra and angular distributions relative to the incident beam direction were measured with small, planar Ge(Li) detectors. In bombardments of ^{92}Mo, nanosecond isomers were studied by measuring the decay of the γ rays relative to the arrival time of the natural beam bunches. Although the searches were less thorough, no isomers were found with the other targets; a limit of $\lesssim 10$ ns can be set on the lifetimes of excited states. Level schemes were constructed with the aid of γγ-coincidence measurements made with two large Ge(Li) detectors. The sensitivity of these measurements was lower in the early experiments, so that only the strongest of the observed lines could be assigned from data obtained with the ^{92}Mo target.

The accuracy of the γ-ray energy determinations is $\simeq 1.0$ keV unless otherwise noted. The stated errors on the angular distribution coefficients, A_2 and A_4, are standard deviations derived from least-squares fitting of the data.

While writing this paper, we received a preprint of a paper by Mesko, Nilsson, and Hjorth[2]) describing similar studies at the Research Institute for Physics (Stockholm) of the reactions $^{92}Zr(\alpha,n\gamma)$, $^{94}Zr(\alpha,3n\gamma)$, and $^{94}Zr(\alpha,n\gamma)$. We have included their results, which are in general agreement with our own, in the discussion of levels of ^{95}Mo and ^{97}Mo.

2. Experimental Results

2.1. $^{94}Zr(\alpha,3n)^{95}Mo$

The data and level scheme are given in table 1 and fig. 1. Mesko et al.[2]) recently studied the levels of ^{95}Mo from the same reaction and also from the reaction $^{92}Zr(\alpha,n)$. Their more detailed level scheme is in good agreement with the one proposed here. From their (α,n) measurements, they were also able to deduce a number of additional levels of relatively low spin. Our tentative level at 1073 keV is more firmly established in their work, as are the spins of some of the levels. Our coincidence results provide additional support for the 3635-keV level, which they assign tentatively.

Although the proposed placement of the 386.6-keV transition is supported by most of the coincidence data, this placement does not explain the observation of 386.6-152.1 coincidences. (We do not, however, observe 386.6-348.4 coincidences which are reported by Mesko et al.[2]). Mesko et al. also note a discrepancy between the singles and coincidence intensity for the 386.6-keV transition. It appears likely from both sets of experiments that the transition is a doublet, whose weaker component remains unplaced.

In fig. 2 we compare the levels, derived from our work and that of the Stockholm group, with the recent $^{94}Mo(d,p)$ scheme of Moorhead and Moyer[3]) and with levels populated [4,5]) from the decay of ^{95}Tc and ^{95m}Tc. The $(\alpha,xn\gamma)$ data clearly support the assignment 9/2+ for the 948-keV state, which is very probably the same as the state at 943 keV populated in the (d,p) reaction with $\ell_n = 4$, but assigned as 7/2+. The results of Mesko et al.[2]) lend somewhat weaker support to a 5/2+ assignment for the 1426-keV state, and suggest reassignment of the 1222-keV γ-ray proposed as a ground state transition in Ref. [4]). In other respects there is good agreement between the $(\alpha,xn\gamma)$, (d,p), and EC-decay results.

2.2. $^{96}Zr(\alpha,3n)^{97}Mo$

Our data (table 2) support the level scheme shown in fig. 3. There are some differences in this scheme from that proposed by Mesko et al.[2]) from their study of the reaction $^{94}Zr(\alpha,n)^{97}Mo$. The 566-keV transition, which they assign as feeding the 1116-keV level, in our scheme feeds the 1436-keV state. This placement is required by our observation that the 566- and 320-keV γ rays are fully coincident. Reassignment of this transition casts some doubt on the existence of a 1683-keV level proposed by Mesko et al.

Part of the intensity of the 1024.7-keV γ ray is in coincidence with γ rays of 117.0, 278.0, 658.3, and 751.9 keV. We therefore place a transition of this energy between levels at 2435 and 1410 keV, in addition to a 1024.7-keV ground state transition as proposed by Mesko et al. We find the (latter) transition to be coincident with a weak 259.0-keV γ ray, which probably connects the 1025-keV state with a state at 1284 keV proposed by the Stockholm group.

Of the alternative placements proposed[2]) for the 804-keV transition, feeding levels at 481 and/or 1116 keV, the latter is in agreement with our coincidence results, although the existence of a second transition of about the same energy is probable, from their measurements[2]). A number of additional levels of relatively low spin, deduced from the (α,n) data[2]), were not observed in our (α,3n) studies.

The ordering of the coincident 117.0- and 278.0-keV transitions is uncertain. The placement of the weak 919.2-keV transition shown in fig. 3 is likely from the observation of coincidences with these two γ rays; it would be analogous to the placement of the 902-keV transition in ^{95}Mo. We cannot exclude an alternative placement: between levels at 2435 and 1515 keV. However, this placement would be inconsistent with a spin of 15/2 for the 2435-keV state.

The (α,xnγ) and $^{97}Nb(\beta^-)$[6,7] level schemes are compared in fig. 4. The only major disagreement is the absence of the 1146-keV level in the former; Mesko et al. suggest reassignment of the 1146-keV γ ray to the decay of a 1628-keV state.

$^{96}Mo(d,p)$ spectra[8-10] support the assignment of levels at 680(1/2+), 719, 888(1/2+), 1284(3/2+), and 1436(11/2-) keV. A more detailed comparison awaits (d,p) spectra of higher resolution and sensitivity.

2.3. $^{92}Mo + \alpha$

Chikhladze[11] has reported K and L conversion lines from a (256 ± 4)-keV transition excited in the reaction $^{92}Mo(\alpha,n\gamma)^{95}Ru$. On the basis of its K/L ratio and an approximate K-conversion coefficient, he assigned the transition an M2 multipolarity and hypothesized the existence of a short-lived isomer in ^{95}Ru: 256 keV (11/2-) → ground state (7/2+). However, the ground state of ^{95}Ru has recently been shown by Ball[12] to have spin and parity 5/2+. The basis for the original (7/2+) assignment, which was the report[13] of an allowed ground-state β^+ transition from ^{95}Tc (9/2+), has also been refuted[14].

In bombardments of ^{92}Mo with 30-MeV α particles, we have observed a transition of 255-keV with a half-life of 8.3 ± 1.0 ns. This half-life is too short for an M2 transition; very probably the multipolarity is E2. The observation of two other transitions with the same half-life plus prompt components proves that, although the 255-keV transition is indeed isomeric, it is not a ground-state transition.

These results remove the disagreement between the proposed 11/2- M2 isomer and the 5/2+ ground-state assignment. Our proposed decay scheme is shown in fig. 5. The cascade of three transitions is confirmed by coincidence data. Another γ ray of 941 keV, not in strong coincidence with other γ rays, is placed as a ground state transition. All four lines are strongly enhanced when the bombarding energy is reduced to 23 MeV, which supports their assignment to ^{95}Ru. The levels at 941- and 1346 keV are also populated by the decay of ^{95}Rh [15]) and in the reaction ^{96}Ru(p,d) [12]).

The spin assignments of fig. 5 were made on the basis of the (p,d) data and the similar structure of ^{93}Mo. Alternative possible assignments, consistent with our results, are 11/2± and 15/2± for levels at 2024 and 2279 keV, respectively.

The observed cascade transitions do not have a long-lived component, such as would be expected if the 21/2+ level of ^{95}Ru were below the 17/2+ level, giving rise to an M4 isomer, as in ^{93}Mo. Preliminary theoretical calculations[16]) predict that the order of these levels should be reversed in ^{95}Ru.

The cascade depicted in fig. 6 was observed in the ^{92}Mo + 30-MeV α spectra. The transitions appear to have a half-life of ≈ 3 ns, although this value is close to the limit of our time resolution. They are possibly assignable to the reaction ^{92}Mo(α,3n)^{93}Ru, although their intensities relative to transitions in ^{94}Ru [1]) increase only slightly when the beam energy is increased to 40 MeV. An alternative assignment would be to the reaction ^{92}Mo(α,pn)^{94}Tc.

2.4. ^{94}Mo(α,n)^{97}Ru

The data and level scheme are given in table 3 and fig. 7. Placement of most of the transitions is strongly supported by coincidence data. These data do not yield unequivocal placements for the 189.2- and 255.9-keV γ rays, although they strongly suggest that the transitions do occur in ^{97}Ru. The 189.2-keV γ ray apparently occurs in the decay of ^{97}Rh also[17,18]), and has been placed tentatively as a ground state transition[17]).

With the assumption of a 5/2+ ground state for ^{97}Ru, the spins indicated for the excited states at 422 , 879 , and 1199 keV are well established by the angular distributions and decay patterns. Spins assigned to the states at 1845 and 2545 keV are probable. The angular distribution of the 193.7-keV γ ray favors a 21/2+ assignment for the 2739-keV state. However, this transition was not found to be isomeric ($t_{1/2} \lesssim 10$ ns); if it is an E2 transition, it must be enhanced considerably relative to the single-particle estimate. The 11/2- assignment for the state at 1821 keV is speculative; alternative possibilities are 11/2+ or 13/2+.

The decay of ^{97}Rh has been restudied recently by Anton'eva _et al._[17]). The only levels common to their study and ours are those at 422 and 879 keV.

2.5. ^{98}Mo(α,3n)^{99}Ru

The dominant cascade observed in this reaction is

$$2268(19/2-) \xrightarrow{(E2)} 1572\ 15/2(-) \xrightarrow{E2} 1070\ 11/2(-) \xrightarrow{(E1)} 720\ 9/2+ \xrightarrow{E2} \text{g.s. } 5/2+.$$

The ordering of the first two transitions, which is not determined unambigously from the singles intensities, is supported by coincidence data taken with a thicker target (which results in a lower effective beam energy). The angular-distribution data support the spin and multipolarity assignments. A spin of 7/2 for the 618-keV state, proposed by Kistner and Schwarzschild[19]) from Coulomb excitation experiments, is confirmed by the present measurements. Of their alternative assignments (7/2,9/2)+ for each of the levels at 340 and 720 keV, 7/2+ for the former and 9/2+ for the latter are in agreement with our angular distributions. Very weak population of the 321-keV state in the $(\alpha,3n)$ reaction favors a 5/2+ assignment over the alternative 7/2+ [19]).

Odd parity for the 1070-keV state is inferred from the absence of decay to either of the lower-lying 7/2+ states. Our results are summarized in table 4 and fig. 8, which also includes a comparison with the $^{99}Ru(\alpha,\alpha'\gamma)$ scheme[19]). A comparison with the decay schemes of $^{99,99m}Rh$ is given in Ref. [19]). A more recent study of ^{99}Rh (1/2-) decay[20]) reveals a number of additional, low-spin levels between 618 and 2059 keV.

2.6. $^{100}Mo(\alpha,3n)^{101}Ru$

As in ^{99}Ru, the most intense cascade observed in the $(\alpha,3n\gamma)$ reaction proceeds through the 11/2- state. In ^{101}Ru, this state lies below the lowest 9/2+ state, and consequently is isomeric, with a half-life of 17 μs [21,22]). Because of this long lifetime, placement of the 849.5— 663.9— 431.4-keV γ-ray cascade above the isomer could not be confirmed by the coincidence measurement, but intensity considerations allow only this placement or direct feeding of the ground state. The latter possibility can be ruled out, because it implies a 9/2+ level at 431.4 keV that almost certainly does not exist (e.g., no state at 431 keV was observed in Coulomb excitation[19]) of ^{101}Ru). As in ^{99}Ru, the transitions above the 11/2- state appear to form a stretched E2 cascade. A second, weaker cascade,

$$1861\ (15/2+) \xrightarrow{(E2)} 1001\ 11/2+ \xrightarrow{E2} 307\ 7/2+ \xrightarrow{M1} \text{g.s. } 5/2+,$$

is also constructed from the coincidence and angular distribution data.

Our data yield additional information about some of the levels populated by Coulomb excitation[19]. The spin of the 312-keV state (5/2) is confirmed; however, our data give strong preference to a spin of 9/2 rather than 7/2 for the 720-keV state. Of the spins 5/2 or 7/2 proposed[19] for the state at 545-keV, the latter is more probable from our measurements.

Table 5 and fig. 9 summarize our results and compare them with the ^{101}Ru(α,$\alpha'\gamma$) scheme[19]. Studies of the decay of ^{101}Tc and the two isomers of ^{101}Rh give evidence for additional levels at 639 and 843 keV [19].

3. Discussion

Even-parity levels of ^{95}Mo and ^{97}Mo have been calculated[23,24] for the configurations $(\pi p_{1/2})^2(\pi g_{9/2})^2(\nu d_{5/2})^3$ (^{95}Mo) and $(\pi p_{1/2})^2(\pi g_{9/2})^2(\nu d_{5/2})^{-1}$ (^{97}Mo). Calculated levels of ^{95}Mo [24] are included in fig. 2, and we have also indicated some correspondences with observed levels: solid lines connect the first or second level of a given spin with the corresponding calculated level; dashed lines represent a possible similarity between the n^{th} calculated state and the m^{th} observed state of a given spin, $n \neq m$.

One evident failure of the calculations is the prediction of too few levels below 1-MeV [23,24]. Another, involving the present results, is the prediction of lowest 7/2+, 11/2+, and 15/2+ states at too high an energy. A plausible explanation of these difficulties can be made in terms of neutron orbitals that are outside the configuration space of the calculations. The observed states 766-keV 7/2+, 1541 keV 11/2+, and 2233 keV (15/2+) can probably be assigned predominant configurations $(\nu d_{5/2})^2_{0+,2+,4+}(\nu g_{7/2})$.* Configurations of this type have been suggested by Mesko *et al.* from the decay patterns of the states[2]. The implied "$g_{7/2}$ single-particle" configuration for the 7/2+ state was previously rejected[24] because of weakness of the $\ell = 4$ (d,p) transition, which is largely masked by the strong $\ell = 0$ transition to the 786-keV state[9]. More recent (d,p) data[3] resolve the two transitions. The spectroscopic factor for the 7/2+ state is indeed low (0.18).

*Here and in the following discussion, we usually omit the configurations of paired particles.

However, $\sum S(d,p)$ for all 7/2+ states below $\approx$ 3.5 MeV is only 0.35 [3]), so that half of the observed $g_{7/2}$ strength is accounted for by the 766-keV state.

Other high-spin states observed in the present study are in good agreement with the calculated states.

Low-lying 1/2+ states at 786 and 1039 keV contain most of the $s_{1/2}$ strength (S(d,p) = 0.59 and 0.19, respectively[3]). The occurrence of at least one of these below the lowest calculated 1/2+ state is thus ascribable to neglect of the $\nu s_{1/2}$ orbital in the calculations. The 3/2+ states at 204 and 1370 keV and the (5/2+) state at 1426 keV appear to correspond with calculated states. All three have low (d,p) spectroscopic factors[3]), consistent with the prediction that they are predominantly seniority-3 states[24]). The state at 821 keV (probably 5/2+) is populated with moderate intensity by the (d,p) reaction (S = 0.17 compared to 0.59 for the ground state[3])). The state thus contains some single-particle $d_{5/2}$ strength, although the nature of larger components of the wave function is unknown.

The odd-parity states [1938 keV 11/2- and 2611 keV (15/2-)] may be assigned configurations $(\nu h_{11/2})(\nu d_{5/2})^2_{0+,2+} + (\nu d_{5/2})^3_{5/2,9/2}(\text{octupole vibr.})_{3-}$. The former type of configuration has been suggested by Mesko _et al_.[2]). The spectroscopic factor for the 11/2- state (S(d,p) = 0.26) indicates that it contains a considerable portion of the $\nu h_{11/2}$ single-particle strength.

Figure 4 includes levels of ^{97}Mo calculated by Bhatt and Ball[24]). One prominent discrepancy between the calculated and observed levels which was _not_ found in ^{95}Mo is the absence of the low-lying 3/2+ state in the calculated spectrum. This state, discovered by Mesko _et al_. in the $^{94}Zr(\alpha,n)$ reaction[2]), was not observed in the $^{96}Mo(d,p)$ reaction[3]), and should thus be a multiparticle state. It is very likely assignable to the same configuration as the first-excited state of ^{95}Mo, $(\nu d_{5/2})^3_{3/2+}$. Its existence is further evidence against good closure of the $d_{5/2}$ shell at N = 56 in Mo [23,9,25]. Occurrence of a probable 23/2+ state at about the same energy as the one in ^{95}Mo is also likely due to this effect, since 21/2 is the highest spin attainable with the configuration $(\pi g_{9/2})^2(\nu d_{5/2})^{-1}$. The marked overall resemblance of the level structure of ^{97}Mo to that of ^{95}Mo is strong evidence against a single $d_{5/2}$-hole configuration in ^{97}Mo.

In spite of the apparent inappropriateness of the neutron configuration $(d_{5/2})^{-1}$ for ^{97}Mo, the calculations based on this configuration predict rather closely the energies of the 13/2+, 17/2+, and 19/2+ states. This is not unexpected in view of the fact that the lowest calculated states of these spins in ^{95}Mo have predominant components of the type $(\pi g_{9/2})^2_{4+,6+,8+}(\nu d_{5/2})^3_{5/2+}$, that is, they are of seniority-one in the neutron component, and thus similar states should exist in ^{97}Mo. More surprising, in view of the above discussion of ^{95}Mo, is the rather good agreement for the 15/2+ state.

The observed levels of ^{97}Ru appear quite similar to those of the Mo isotopes, the only major difference being the observation of a probable 21/2+ state in place of the 19/2+ states of ^{95}Mo and ^{97}Mo. As discussed in the previous section, this spin assignment, based on an angular distribution, seems questionable on other grounds; a spin of 19/2 for the 2739-keV state of ^{97}Ru is by no means excluded. The occurrence of the lowest 7/2+, 11/2+, 15/2+, and 11/2- states at somewhat lower energies in ^{97}Ru is consistent with the above-suggested configurations for these states in ^{95}Mo and the reasonable supposition that the $\nu g_{7/2}$ and $\nu h_{11/2}$ quasiparticle energies are lower in ^{97}Ru.

Although the structures of ^{99}Ru and ^{101}Ru tend to be more collective, the same trends can also be seen in these nuclei. Thus the lowest 7/2+ states are connected to the ground states by small E2 matrix elements[19]), which suggests that they are $\nu g_{7/2}$ excitations rather than members of a phonon multiplet. The 11/2+ – 7/2+ and (in ^{101}Ru) 15/2+ – 11/2+ spacings are also similar to the ones observed in ^{95}Mo, consistent with assignments $(\nu d_{5/2})^{\pm 2}_{0+,2+,4+}(\nu g_{7/2})$ for the 7/2+, 11/2+, and 15/2+ states. The 13/2+ – 9/2+ spacings are also similar to those of ^{95}Mo. However, the lowest 9/2+ as well as the second 5/2+ and 7/2+ levels lie considerably lower in ^{99}Ru and ^{101}Ru than in the Mo isotopes; therefore these states are probably more collective than in Mo isotopes. This is analogous to the trend in the 2+ states of the neighboring even nuclei[1]).

The most notable difference between our results for ^{99}Ru and ^{101}Ru and those for the other nuclei is the predominant population of odd-parity states. This is undoubtedly due to the marked lowering of the $\nu h_{11/2}$ quasiparticle state and related excitations, which places these states below the even-parity states of the same spin.

The odd-parity sequences in ^{101}Ru and ^{99}Ru appear to be a good example of phonon-coupled bands (see fig. 10). The resemblance to the sequences 6+ ⟶ 4+ ⟶ 2+ ⟶ 0+ in ^{102}Ru and ^{100}Ru (even to the extent of similar angular distributions of the transitions) supports an interpretation of these states as (maximum-spin) one-, two-, and three-phonon excitations based on the $\nu h_{11/2}$ particle state. By contrast, Coulomb-excitation results indicate that the low-lying, even-parity states are not simply characterized by the weak-coupling model as one-phonon excitations based on the 5/2+ ground states[19]).

A plausible explanation of this difference is the dominance of the $(\nu d_{5/2})^{\pm 2}_{2+}$ configuration in the phonon, which would result in even-parity states whose character is intermediate between that of the weak-coupling description and a multiparticle, $(\nu d_{5/2})^3$ configuration, subject to the exclusion principle. On the other hand, the $(\nu h_{11/2})^2$ configuration is probably not a major component of the phonon structure, and thus the weak-coupling model should be more appropriate to the odd-parity states. This finding is also in accord with the prediction of Kisslinger[26]) that coupling of phonons to the high-spin, opposite-parity orbital of each major shell should be weak.

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Table 1. γ rays from the reaction $^{94}Zr(\alpha,3n\gamma)^{95}Mo$

E_γ(keV)	I_γ Relative	Angular Distribution A_2	A_4	Placement	Comment
102.5	2.0 ± 0.3	0.09 ± 0.05	0.10 ± 0.10		probably ^{95}Mo, coinc.
152.1	28 ± 2	-0.28 ± 0.03	0.10 ± 0.05	2733(19/2+) → 2581(17/2+)	
173.5	4.2 ± 0.5	-0.21 ± 0.06	0.12 ± 0.09	2233 15/2+ → 2058 13/2+	
204.0	13.2 ± 1.0	0.02 ± 0.05	0.16 ± 0.09	204 3/2+ → g.s. 5/2+	
348.4	50 ± 3	-0.04 ± 0.07	-0.11 ± 0.12	2581(17/2+) → 2233 15/2+	
386.6[a]	16 ± 2	-0.10 ± 0.05	-0.01 ± 0.08	1938 11/2- → 1552(9/2+)[a]	
593.2	48 ± 4	-0.25 ± 0.05	-0.03 ± 0.08	1541 11/2+ → 948 9/2+	
604.0	13 ± 4	0.31 ± 0.17	-0.16 ± 0.25	1552(9/2+) → 948 9/2+	
674 ± 2	≈ 8[b]			(2611(15/2-) → 1938 11/2-)	
691.8	85 ± 4	0.40 ± 0.06	0.01 ± 0.08	2233 15/2+ → 1541 11/2+	
766.0	50 ± 3	-0.10 ± 0.05	0.15 ± 0.09	766 7/2+ → g.s. 5/2+	
774.9	38 ± 5	0.47 ± 0.07	-0.14 ± 0.10	1541 11/2+ → 766 7/2+	
786 ± 2	≈ 7[b]			1552(9/2+) → 766 7/2+	
903 ± 2	≈ 5[b]			3635(23/2+) → 2733(19/2+)	
947.7	<u>100</u>	0.35 ± 0.04	-0.01 ± 0.06	948 9/2+ → g.s.5/2+	
1073.2	10 ± 4			(1073 7/2+ → g.s. 5/2+)	assigned to known level
1110.7	11 ± 6			2058 13/2+ → 948 9/2+	

(continued)

Table 1 (Continued)

[a] Transition is probably a doublet — see text.

[b] Transition observed and intensity measured in the coincidence experiment only.

Table 2. γ rays from the reaction $^{96}Zr(\alpha,3n\gamma)^{97}Mo$

E_γ (keV)	I_γ Relative	Angular Distribution A_2	A_4	Placement	Comment
117.0	17 ± 3	-0.29 ± 0.02	-0.04 ± 0.03	(2552(17/2+) → 2435(15/2+))[a]	
124.8	0.8 ± 0.4				probably ^{97}Mo, coinc.
259.0	3.6 ± 0.6			1284(3/2+) → 1025 7/2+	
278.3	18 ± 2	-0.30 ± 0.04	-0.11 ± 0.07	(2830(19/2+) → 2552(17/2+)[a]	
320.5	56 ± 3	-0.18 ± 0.02	-0.03 ± 0.03	1436 11/2- → 1116 9/2+	
566.0	31 ± 5	0.30 ± 0.05	-0.18 ± 0.07	2002(15/2-) → 1436 11/2-	
658.3	70 ± 3	-0.32 ± 0.03	-0.02 ± 0.05	658 7/2+ → g.s. 5/2+	
723.1[b]	20 ± 5[b]			2160 (13/2, 15/2 -) → 1436 11/2-	
751.9	51 ± 10[c]	0.20 ± 0.05	-0.01 ± 0.07	1410 11/2+ → 658 7/2+	
803.7	35 ± 3	0.21 ± 0.06	0.01 ± 0.07	1920(13/2+) → 1116 9/2+	
846.3 ?	8 ± 2				possibly ^{97}Mo, excit.
919.2	5.5 ± 1.5			(3749(23/2+) → 2830(19/2+))	
1024.7[d]	42 ± 3[d]	0.01 ± 0.05	-0.07 ± 0.06	{2435(15/2+) → 1410 11/2+; 1025 7/2+ → g.s. 5/2+} d	
1116.0	100	0.24 ± 0.05	-0.04 ± 0.07	1116 9/2+ → g.s. 5/2+	
1515.1	7 ± 2			(1515 → g.s. 5/2+)	known transition in ^{97}Mo

(continued)

Table 2 (Continued)

[a]Ordering of the 117.0- and 278.0-keV transitions is uncertain.

[b]From the coincidence measurement. γ ray is masked in the singles spectrum by a 722.8-keV transition in ^{98}Mo.

[c]Intensity derived from the coincidence measurement. This γ ray masks a 752.8-keV transition in ^{98}Mo.

[d]Doublet. From the coincidence measurement, $\approx 60\%$ of the intensity is assigned to the transition from the 2435-keV state.

Table 3. γ rays from the reaction $^{94}Mo(\alpha,n\gamma)^{97}Ru$

Energy (keV)	I_γ Relative	Angular Distribution A_2	A_4	Placement	Comment
189.2	11 ± 4	0.06 ± 0.04	0.12 ± 0.07		probably ^{97}Ru, coinc.
193.7	14 ± 5	0.37 ± 0.06	0.12 ± 0.07	2739(21/2+) → 2545(17/2+)	
215.8	9 ± 3				probably ^{97}Ru, coinc., excit.
255.9	17 ± 4				probably ^{97}Ru, coinc., excit.
319.9	19 ± 4	-0.35 ± 0.06	-0.03 ± 0.10	1199(11/2+) → 879(9/2+)	
421.9	100	-0.19 ± 0.06	0.08 ± 0.09	422(7/2+) → g.s.(5/2+)	
456.9	6 ± 2	-0.57 ± 0.15	0.01 ± 0.21	879(9/2+) → 422(7/2+)	
646.4	62 ± 7	0.41 ± 0.06	0.00 ± 0.09	1845(15/2+) → 1199(11/2+)	
700.0	26 ± 3	-0.30 ± 0.07	-0.02 ± 0.14	2545(17/2+) → 1845(15/2+)	
777.7	88 ± 8	0.34 ± 0.07	-0.12 ± 0.11	1199(11/2+) → 422(7/2+)	
878.8	54 ± 7	0.33 ± 0.07	-0.07 ± 0.11	879(9/2+) → g.s.(5/2+)	
911.5	13 ± 6			1333(7/2,9/2) → 422(7/2+)	
942.5	20 ± 10			1821(11/2-) → 879(9/2+)	
995.6	12 ± 5			996 → g.s.(5/2+)	

Table 4. γ rays from the reaction $^{98}Mo(\alpha,3n\gamma)^{99}Ru$

Energy (keV)	I_γ Relative	Angular Distribution A_2	A_4	Placement	Comment
89.4	2.4 ± 0.6			89 3/2+ → g.s. 5/2+	
277.1	2.7 ± 1.1			618 7/2+ → 341 7/2+	
299.0	1.8 ± 0.9				probably ^{99}Ru, excit.
321.4	5 ± 1	0.20 ± 0.14	0.03 ± 0.22	321(5/2+) → g.s. 5/2+	
328.1	3 ± 1			1048(11/2+) → 720 9/2+	
340.5	43 ± 3	-0.23 ± 0.02	0.02 ± 0.03	341 7/2+ → g.s. 5/2+	
349.8	60 ± 3	-0.34 ± 0.02	-0.02 ± 0.03	1070 11/2(-) → 720 9/2+	
360.0	3.3 ± 0.8				probably ^{99}Ru, excit.
378.2	5 ± 2			720 9/2+ → 341 7/2+	
430.7	5 ± 2			(1048(11/2+) → 618 7/2+)	placement possible, energy diff.
473.8	4 ± 2	-0.50 ± 0.10	-0.01 ± 0.17		probably ^{99}Ru, excit.
502.1	48 ± 3	0.39 ± 0.05	-0.09 ± 0.07	1572 15/2(-) → 1070 11/2(-)	
617.7	17 ± 2	-0.78 ± 0.06	-0.04 ± 0.10	618 7/2+ → g.s. 5/2+	
696.2	44 ± 3	0.20 ± 0.06	-0.01 ± 0.09	2268(19/2-) → 1572 15/2(-)	
707.5	25 ± 3	0.25 ± 0.10	0.08 ± 0.15	1048(11/2+) → 341 7/2+	
719.8	100	0.14 ± 0.03	-0.12 ± 0.05	720 9/2+ → g.s. 5/2+	

(continued)

Table 4 (Continued)

Energy (keV)	I_γ Relative	Angular Distribution A_2	A_4	Placement	Comment
777.2	23 ± 3	0.25 ± 0.04	−0.19 ± 0.10	1470(13/2+) → 720 9/2+	
844.1	14 ± 2	0.02 ± 0.10	−0.32 ± 0.20		probably ^{99}Ru, excit.
904.0	20 ± 2	0.29 ± 0.08	−0.09 ± 0.11		probably ^{99}Ru, excit.
931.6	12 ± 2	0.30 ± 0.07	−0.20 ± 0.11		probably ^{99}Ru, excit.
972.0	13 ± 2	0.38 ± 0.09	−0.15 ± 0.14	1313$\begin{pmatrix}9/2,+\\11/2\end{pmatrix}$ → 341 7/2+)	placement probable, coinc.

Table 5. γ rays from the reaction $^{100}Mo(\alpha,3n\gamma)^{101}Ru$

E_γ(keV)	I_γ Relative	Angular Distribution A_2	A_4	Placement	Comment
127.8	10 ± 2	0.01 ± 0.05	0.05 ± 0.07	128 3/2+ → g.s. 5/2+	
175.0	1.2 ± 0.3			720 9/2+ → 545(7/2+)	
179.4	1.0 ± 0.3			307 7/2+ → 128 3/2+	
184.1	8 ± 1	-0.21 ± 0.02	0.03 ± 0.03	312 5/2+ → 128 3/2+	
197.1	2.1 ± 0.3			325 1/2+ → 128 3/2+	
220.6	65 ± 3	a		528 11/2- → 307 7/2+	
238.0	0.6 ± 0.2			(545(7/2+) → 307 7/2+)	known transition in ^{101}Ru
281.2	0.9 ± 0.4			(1001 11/2+ → 720 9/2+)	placement probable, energy diff.
307.1	<u>100</u>	-0.21 ± 0.03	0.00 ± 0.04	307 7/2+ → g.s. 5/2+	
312.2	1.2 ± 0.4			312 5/2+ → g.s. 5/2+	known transition in ^{101}Ru
324.3	0.8 ± 0.4			325 1/2+ → g.s. 5/2+	known transition in ^{101}Ru
431.4	77 ± 4	0.37 ± 0.03	-0.09 ± 0.04	959 15/2- → 528 11/2-	
545.2	7.8 ± 1.0	-0.76 ± 0.12	0.33 ± 0.20	545(7/2+) → g.s. 5/2+	
616.1	3.4 ± 1.0			929 → 312 5/2+	
663.9	41 ± 2	0.40 ± 0.04	-0.12 ± 0.06	1623 19/2- → 959 15/2-	

(continued)

Table 5 (Continued)

E_γ(keV)	I_γ Relative	Angular Distribution A_2	A_4	Placement	Comment
693.3	10 ± 3	0.22 ± 0.04	-0.10 ± 0.06	1001 11/2+ → 307 7/2+	
671.8	4.1 ± 1.0				probably ^{101}Ru, excit.
719.9	15 ± 1	0.33 ± 0.05	-0.10 ± 0.07	720 9/2+ → g.s. 5/2+	
780.8	9 ± 1	0.41 ± 0.06	-0.18 ± 0.09		probably ^{101}Ru, coinc., excit.
844.5	4.5 ± 1.0				probably ^{101}Ru, coinc., excit.
849.5	16 ± 1	0.38 ± 0.05	-0.09 ± 0.07	2473 23/2- → 1623 19/2-	
860.4	6.1 ± 1.0	0.33 ± 0.12	-0.26 ± 0.20	1861(15/2+) → 1001 11/2+	
877.3	5.9 ± 1.0	0.46 ± 0.08	-0.15 ± 0.14		probably ^{101}Ru, excit.
928.9	2.3 ± 0.5			929 → g.s. 5/2+	known transition in ^{101}Ru

[a] Fully attenuated (17 μs half-life).

FIGURE CAPTIONS

Fig. 1. Levels of ^{95}Mo observed in the present experiments. Spins in brackets are those given in Ref. [2]).

Fig. 2. Comparison of ^{95}Mo levels observed in (α,xnγ) reactions (present measurements and Ref. [2])), the ^{94}Mo(d,p) reaction[3]), radioactive decay[4,5]), and calculated[24]). The indicated correspondence between observed and calculated levels is discussed in section 3.

Fig. 3. Levels of ^{97}Mo observed in the present measurements. Spins in brackets are those given in Ref. [2]).

Fig. 4. Comparison of ^{97}Mo levels observed in (α,xnγ) reactions (present measurements and Ref. [2])), radioactive decay[6,7]), and calculated[24]). The indicated correspondence between observed and calculated levels is discussed in section 3.

Fig. 5. Levels of ^{95}Ru observed in the reaction ^{92}Mo(α,nγ).

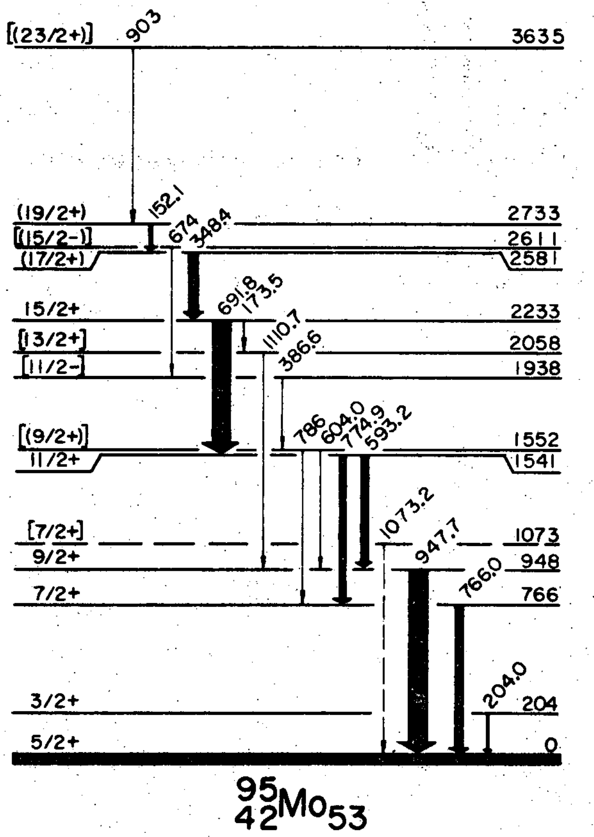
Fig. 6. Levels of (^{93}Ru or ^{94}Tc(?)) deduced from γ-ray measurements in bombardments of ^{92}Mo with 30-MeV α particles.

Fig. 7. Levels of ^{97}Ru observed in the reaction ^{94}Mo(α,nγ).

Fig. 8. Levels of ^{99}Ru observed in the reactions ^{98}Mo(α,3nγ) (present results) and ^{99}Ru(α,$\alpha'\gamma$) (Ref. [19])).

Fig. 9. Levels of ^{101}Ru observed in the reactions ^{100}Mo(α,3nγ) (present results) and ^{101}Ru(α,$\alpha'\gamma$) (Ref. [19])).

Fig. 10. Comparison of odd-parity "phonon" bands in ^{101}Ru and ^{99}Ru with the ground-state bands of the neighboring even nuclei.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903
3635
(19/2+)
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(17/2+)
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674
348.4
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2611
2581
15/2+
[13/2+]
[11/2-]
691.8
173.5
1110.7
386.6
2233
2058
1938
[(9/2+)]
11/2+
786
604.0
774.9
593.2
1552
1541
[7/2+]
9/2+
7/2+
1073.2
947.7
766.0
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766
3/2+
5/2+
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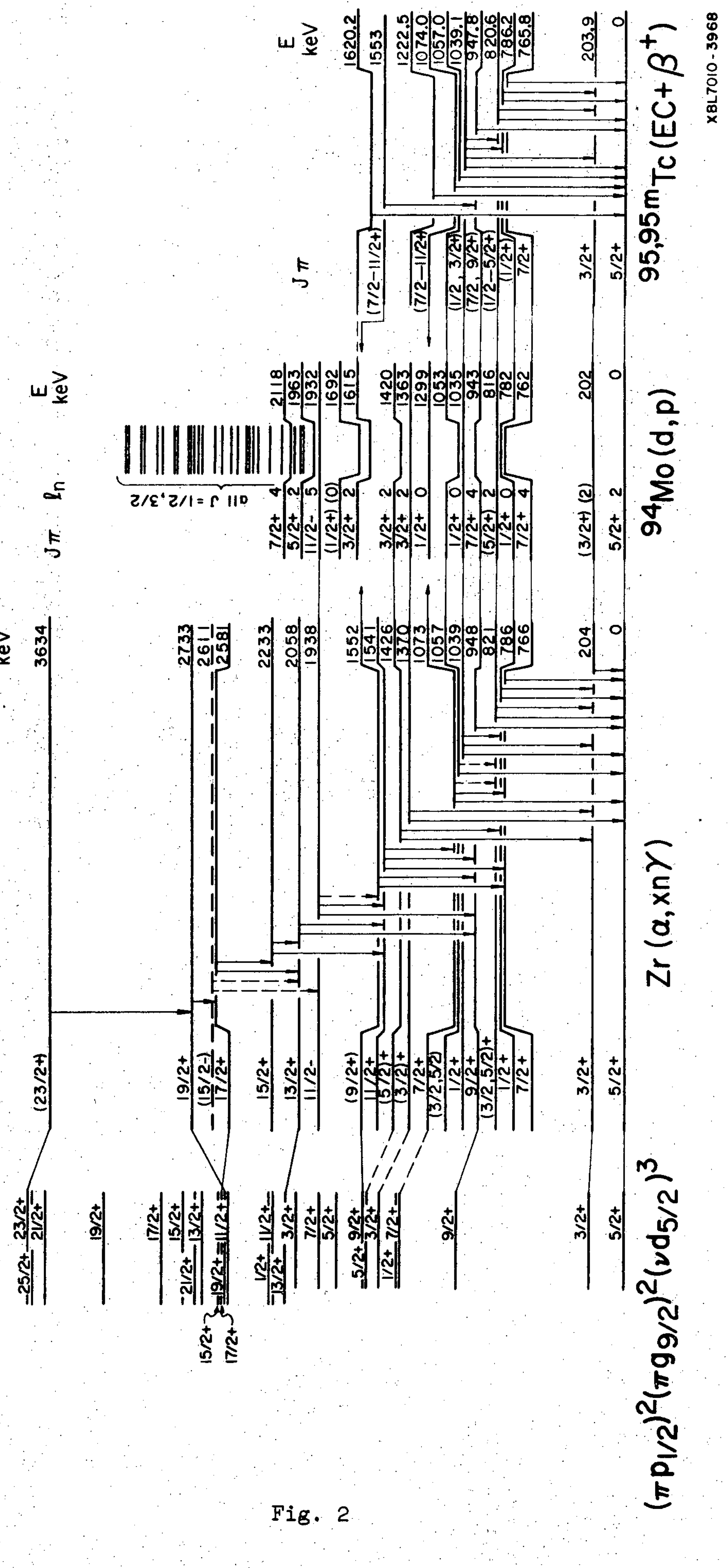
204
0
95
42 Mo 53
XBL7010-3998

Fig. 1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Zr (α,xnγ)
^{94}Mo(d,p)
95,95mTc(EC+β+)
XBL7010-3968

Fig. 2

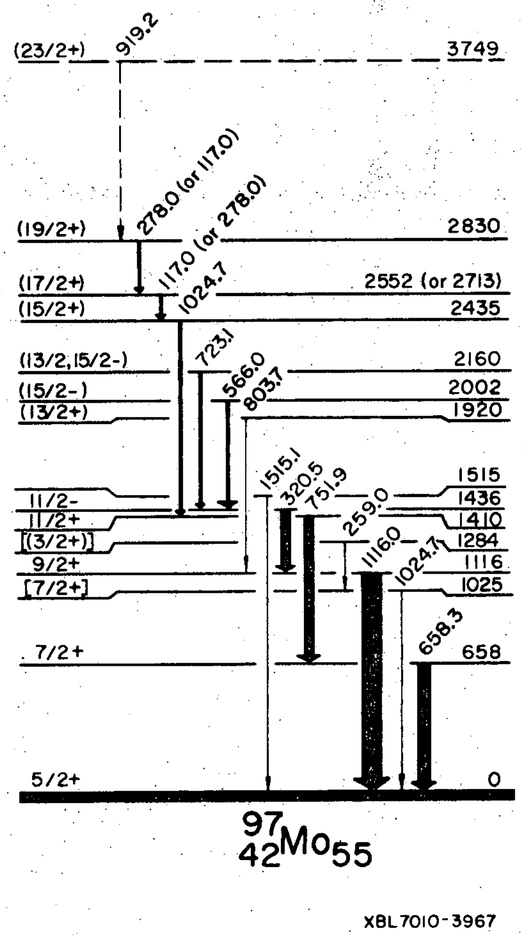

(23/2+)
919.2
3749
278.0 (or 117.0)
117.0 (or 278.0)
(19/2+)
2830
(17/2+)
1024.7
2552 (or 2713)
(15/2+)
2435
(13/2,15/2-)
723.1
2160
(15/2-)
566.0
2002
(13/2+)
803.7
1920
1515.1
1515
11/2-
320.5
1436
11/2+
751.9
1410
[(3/2+)]
259.0
1284
9/2+
1116.0
1116
[7/2+]
1024.7
1025
7/2+
658.3
658
5/2+
0
$^{97}_{42}Mo_{55}$
XBL 7010-3967

Fig. 3

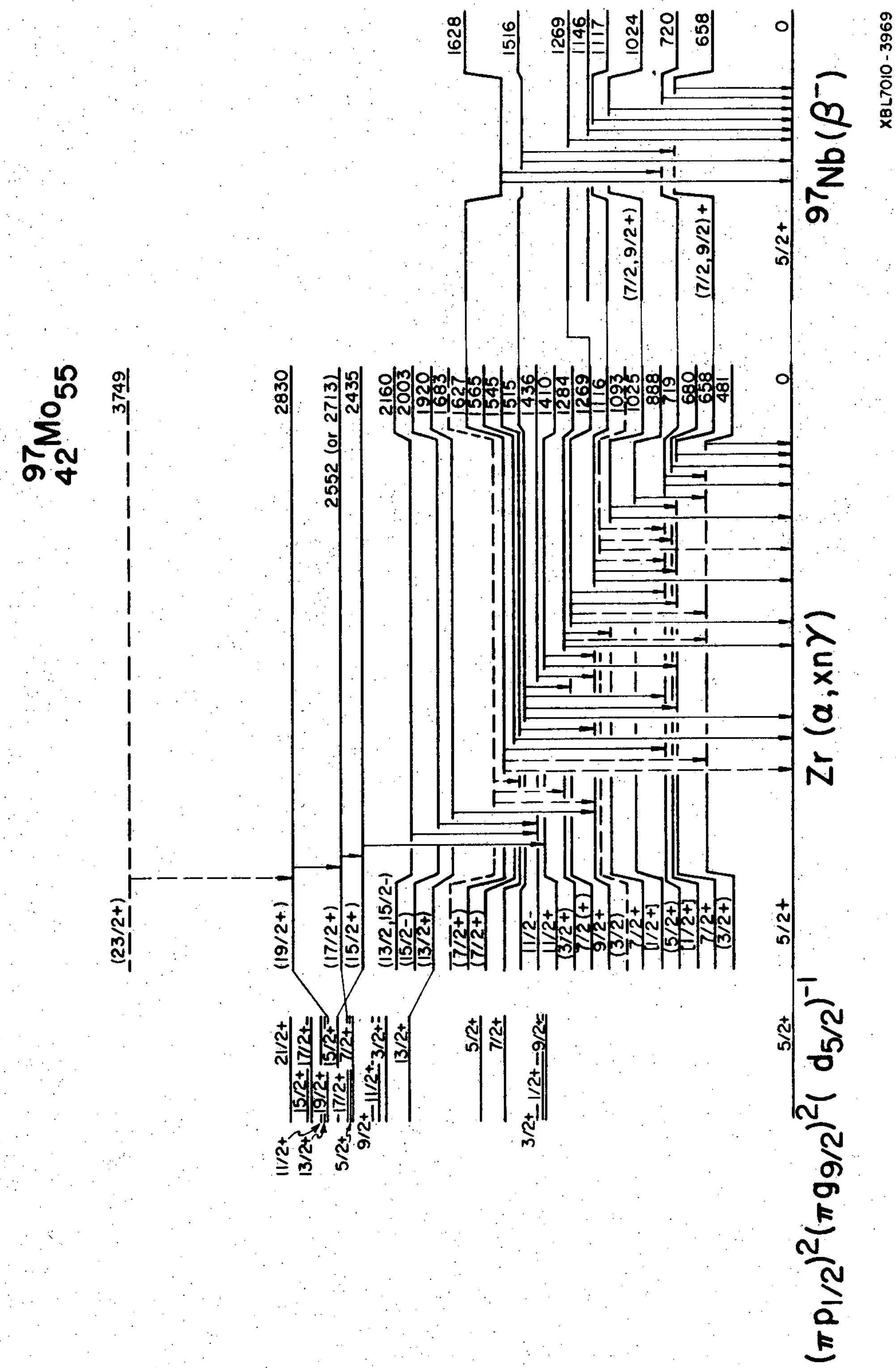
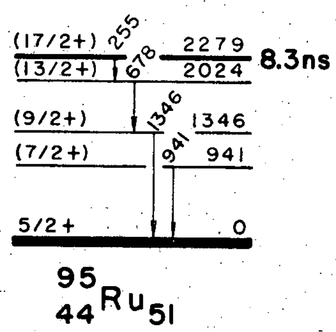
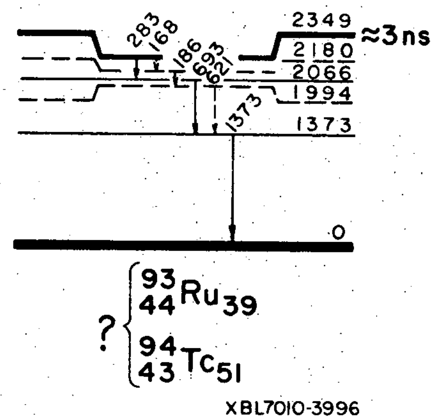


Fig. 4



XBL7010-3997

Fig. 5


2349
≈3ns
2180
2066
1994
1373
0
283
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693
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1373
?
93 44 Ru 39
94 43 Tc 51
XBL7010-3996

Fig. 6

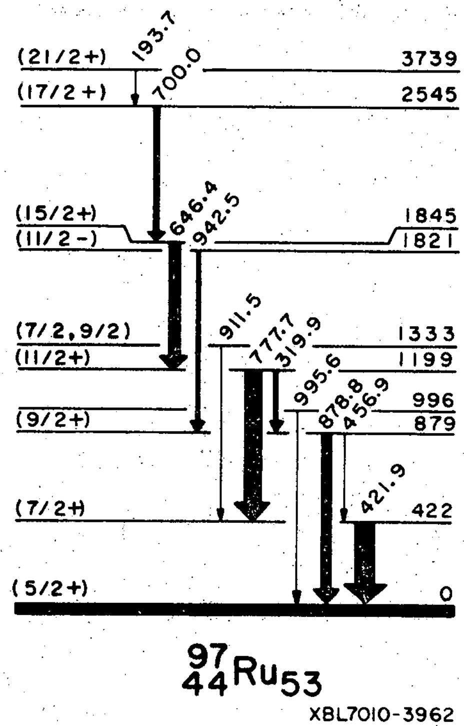
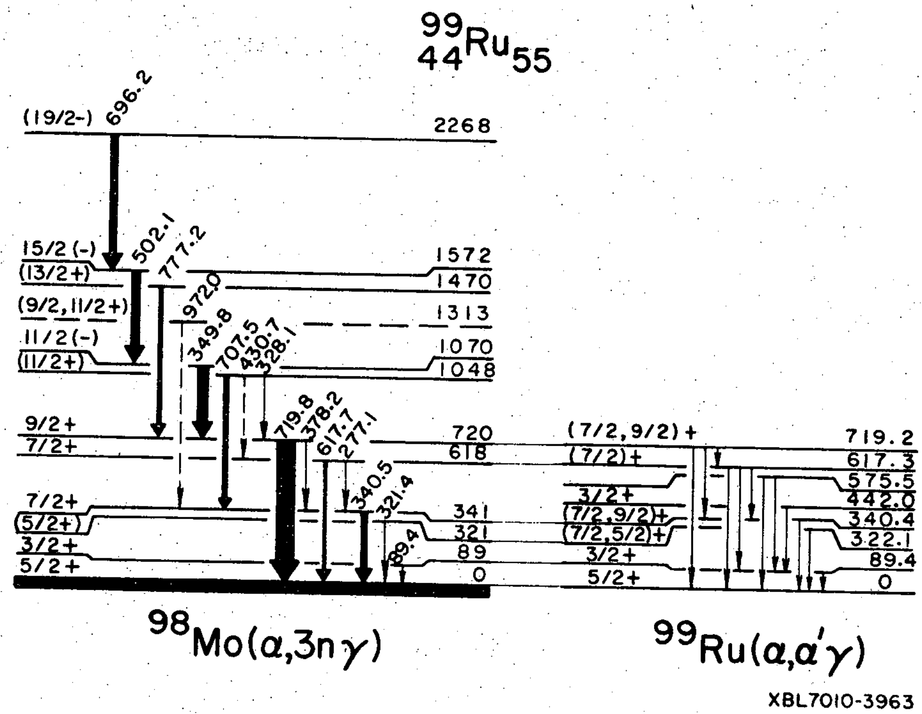

(21/2+)
193.7
700.0
3739
(17/2 +)
2545
(15/2+)
(11/2 -)
646.4
942.5
1845
1821
(7/2, 9/2)
(11/2+)
911.5
777.7
319.9
1333
1199
995.6
878.8
456.9
996
879
(9/2+)
(7/2+)
421.9
422
(5/2+)
0
$^{97}_{44}Ru_{53}$
XBL7010-3962

Fig. 7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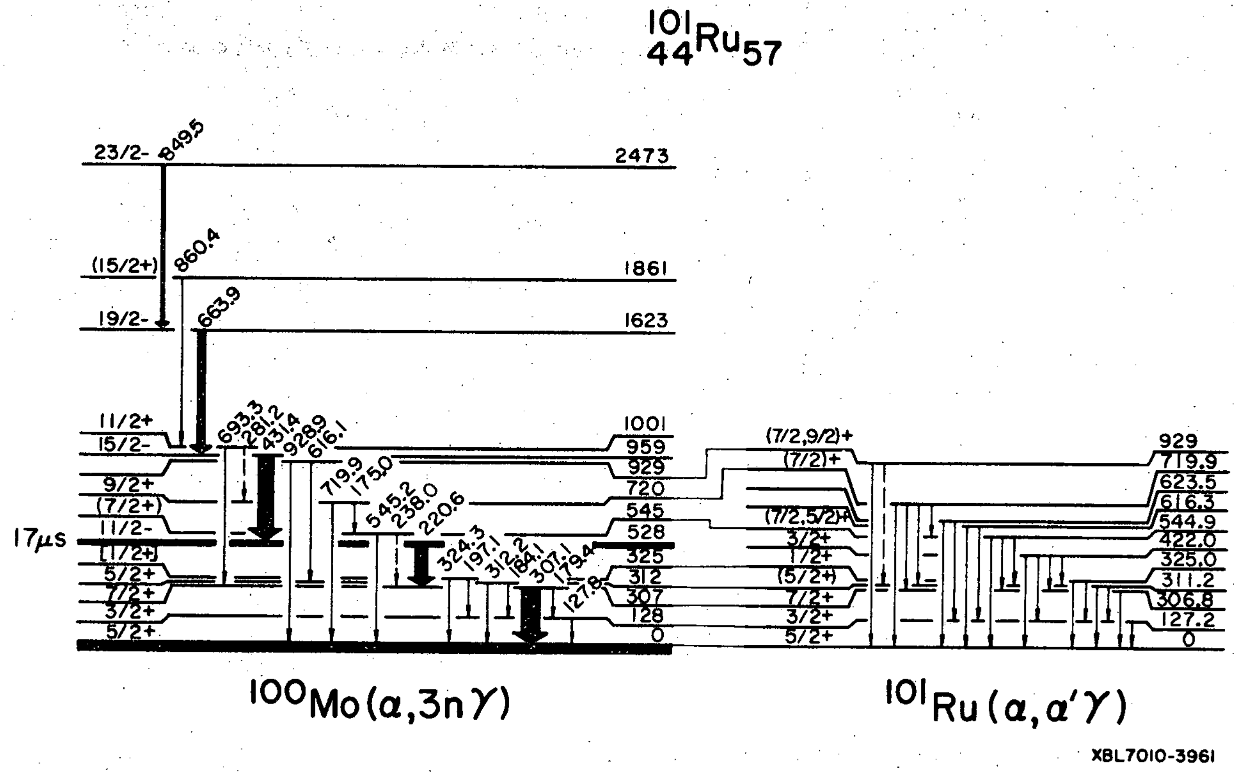
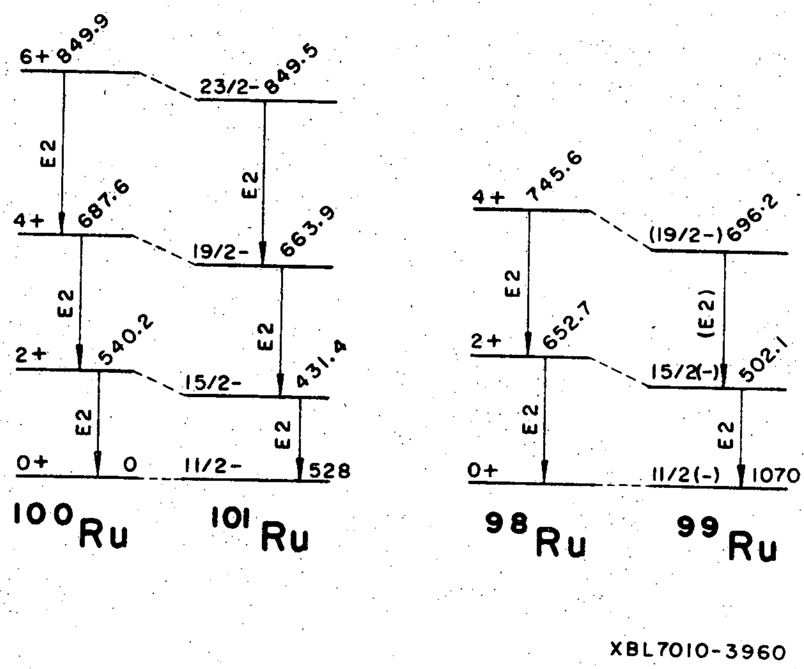
(19/2-) 696.2
2268
15/2(-)
(13/2+)
502.1
777.2
1572
1470
(9/2,11/2+)
972.0
1313
11/2(-)
(11/2+)
349.8
707.5
430.7
328.1
1070
1048
9/2+
7/2+
719.8
378.2
617.7
277.1
720
618
7/2+
(5/2+)
3/2+
5/2+
340.5
321.4
89.4
341
321
89
0
(7/2,9/2)+
(7/2)+
3/2+
(7/2,9/2)+
(7/2,5/2)+
3/2+
5/2+
719.2
617.3
575.5
442.0
340.4
322.1
89.4
0
$^{98}Mo(\alpha,3n\gamma)$
$^{99}Ru(\alpha,\alpha'\gamma)$
XBL7010-3963

Fig. 8



$^{101}_{44}Ru_{57}$
23/2-
849.5
2473
(15/2+)
860.4
1861
19/2-
663.9
1623
11/2+
1001
15/2-
959
9/2+
929
(7/2+)
720
11/2-
545
17μs
528
[1/2+]
325
5/2+
312
7/2+
307
3/2+
128
5/2+
0
693.3
281.2
431.4
928.9
616.1
719.9
175.0
545.2
238.0
220.6
324.3
197.1
312.2
184.1
307.1
179.4
127.8
(7/2,9/2)+
(7/2)+
(7/2,5/2)+
3/2+
1/2+
(5/2+)
7/2+
3/2+
5/2+
929
719.9
623.5
616.3
544.9
422.0
325.0
311.2
306.8
127.2
0
$^{100}Mo(\alpha,3n\gamma)$
$^{101}Ru(\alpha,\alpha'\gamma)$
XBL7010-3961

Fig. 9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23/2- 849.5
E2
4+ 687.6
19/2- 663.9
2+ 540.2
15/2- 431.4
0+ 0
11/2- 528
100Ru
101Ru
4+ 745.6
(19/2-) 696.2
(E2)
2+ 652.7
15/2(-) 502.1
0+
11/2(-) 1070
98Ru
99Ru
XBL7010-3960

Fig. 10

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