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HIGH-SPIN PROTON STATES OBSERVED IN THE $^{90}Zr(\alpha,t)^{91}Nb$ AND $^{92}Mo(\alpha,t)^{93}Tc$ REACTIONS AT 50 MeV*

M. S. Zisman and B. G. Harvey

Lawrence Radiation Laboratory
University of California
Berkeley, California 94720

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ABSTRACT

The $^{90}Zr(\alpha,t)^{91}Nb$ and $^{92}Mo(\alpha,t)^{93}Tc$ reactions have been investigated using a 50 MeV α-particle beam from the Berkeley 88-inch cyclotron. Comparisons are made with the results of (^{3}He,d) experiments on the same targets in order to locate high-spin ($\ell > 2$) levels in ^{91}Nb and ^{93}Tc. The ^{91}Nb (4.18 MeV) and ^{93}Tc (3.91 MeV) levels are probable $\ell = 4$ levels, in contrast to the (^{3}He,d) results. A difference in Q-values for the $^{90}Zr(\alpha,t)^{91}Nb$ and $^{91}Zr(\alpha,t)^{92}Nb$ reactions of 680±25 keV yields a Q-value for the $^{90}Zr(\alpha,t)^{91}Nb$ reaction of -14.643±.027 MeV, which is not consistent with the presently accepted mass excess of -86.750±.06 MeV for ^{91}Nb.

I. INTRODUCTION

In recent years there have been many studies[1-6] of proton configurations in the N = 50 nuclei ^{91}Nb and ^{93}Tc. The locations of these proton states are of interest for comparison with shell model calculations[7,8] and the centroid positions are useful in predicting energies of two-particle proton-neutron states in nearby odd-odd nuclei. The states expected in proton transfer to ^{90}Zr and ^{92}Mo are (suppressing radial quantum numbers) $g_{9/2}$, $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$, and possibly $h_{11/2}$. The (^{3}He,d) reaction, however, preferentially populates the lower angular momentum states (i.e., ℓ = 0, 2). Thus, it is not a very efficient method for locating high-spin states such as $g_{9/2}$, $g_{7/2}$, or $h_{11/2}$, particularly if these states are fragmented into many levels. In the ^{92}Mo(^{3}He,d)^{93}Tc reaction which has been studied in detail at 18 and 35 MeV,[1,5] no ℓ = 4 levels have been reported except for the ground state, although several have been seen in the ^{90}Zr(^{3}He,d)^{91}Nb experiments.[1,2,4,6] The (α,t) reaction, on the other hand, strongly populates the high-spin states due to the momentum mismatch for low ℓ-transfers ($\vec{Q} \times \vec{R} \approx 6$). A comparison of the relative strengths of various states observed in both the (^{3}He,d) and (α,t) reactions should, therefore, give some information on the location of high-spin (ℓ = 4 or 5) levels in ^{91}Nb and ^{93}Tc.

II. EXPERIMENTAL

The experiment was performed with a 50 MeV α-particle beam from the Berkeley 88-inch cyclotron at a beam resolution, ΔE/E, of 0.04%. The targets were self-supporting metal foils of ^{90}Zr (enriched to 97.8%) and ^{92}Mo (enriched to 98.3%), whose nominal thicknesses were 0.20 and 0.30 mg/cm^2, respectively. Due to large uncertainties in the target thicknesses, absolute cross sections for both reactions are accurate only to about ±50%. Relative cross sections for each target, however, should be correct to ±15%. Tritons were detected with two counter telescopes, each consisting of a 0.25 mm phosphorus-diffused Si ΔE and 5 mm Si(Li) E detector, and identified with a Goulding-Landis particle identifier.[9]

III. RESULTS

A. $^{90}Zr(\alpha,t)^{91}Nb$

Since the previously reported level energies from $^{90}Zr(^{3}He,d)^{91}Nb$ experiments[1,2,4,6] indicate rather substantial discrepancies, we remeasured them. [The energies reported in Refs. 1 and 6 are systematically higher than those found in Ref. 2, and the differences appear to increase with excitation energy. For example, the strongest peak in $^{90}Zr(^{3}He,d)^{91}Nb$ is assigned excitation energies of 3.360±.015[2], 3.395±.015[1], and 3.410±.010[6] MeV]. Our spectra were calibrated with the ^{17}F (g.s.) impurity peak and ^{91}Nb (g.s.) peak as a function of angle.[10] The Q-value for the $^{16}O(\alpha,t)^{17}F$ reaction, -19.2136 MeV, was taken from published tables.[11] However, recent results of various reactions leading to ^{91}Nb give conflicting results for the mass excess of that nucleus.

A $^{90}Zr(^{3}He,d)^{91}Nb$ experiment[6] gives a Q-value of -0.227±.020 MeV, which is essentially identical to the published[11] Q-value obtained from the mass table of Mattauch, Thiele, and Wapstra.[12] But the $^{91}Zr(p,n)^{91}Nb$ reaction[13] gives Q = -2.045±.006 MeV, which changes the mass excess of ^{91}Nb used in Ref. 11 by +120 keV. Our mass of ^{91}Nb comes from the relative Q-values of the $^{90}Zr(\alpha,t)^{91}Nb$ and $^{91}Zr(\alpha,t)^{92}Nb$ reactions, which were observed[14] simultaneously with a ^{91}Zr target containing about 5% ^{90}Zr impurity. The energy calibration of the $^{91}Zr(\alpha,t)$ data (using the ^{17}F (g.s.) and ^{92}Nb (g.s.) as a function of angle, with Q-values as given in Ref. 11) gives a difference in Q-values of 680±25 keV between the $^{90}Zr(\alpha,t)^{91}Nb$ and $^{91}Zr(\alpha,t)^{92}Nb$ reactions. Ball and Cates[15] found a difference in (^{3}He,d) Q-values for the two isotopes of 677±7 keV, which is essentially identical to our (α,t) results[14] and has a much lower uncertainty. The difference in Q-values obtained by Ball and Cates[15]

corresponds to a $^{90}Zr(^{3}He,d)^{91}Nb$ Q-value of -0.319 MeV (using the published $^{91}Zr(^{3}He,d)$ Q-value),[11] which is considerably different from the value of -0.227±0.020 MeV reported in Ref. 6. A summary of the relevant Q-values is given in Table I.

The change in the ^{91}Nb mass excess required by Ball and Cates[15] and our own data[14] is about +95 keV, which is slightly less than the value of +120 keV indicated by the $^{91}Zr(p,n)^{91}Nb$ data.[13] Perhaps the discrepancy is due to an error in the $^{91}Zr(^{3}He,d)$ and $^{91}Zr(\alpha,t)$ Q-values,[11] since the results[14,15] from the ^{91}Zr target are only relative to these numbers. However, the (α,t) calibration[14] is also consistent with the position of the $^{92}Zr(\alpha,t)^{93}Nb$ (g.s.) peak which would mean that this Q-value[11] must <u>also</u> be in error in order to agree with the results of Ref. 13. Based on these results, we feel that the $^{90}Zr(^{3}He,d)^{91}Nb$ Q-value determined in Ref. 6 is incorrect. The $^{90}Zr(\alpha,t)^{91}Nb$ Q-value used in our analysis is -14.643 MeV. This corresponds to the relative difference in (α,t) Q-values of 680 keV discussed above, and is slightly less negative than the value of -14.665 MeV which would be inferred from the $^{91}Zr(p,n)^{91}Nb$ results.[13]

Using a Q-value of -14.643 MeV for the $^{90}Zr(\alpha,t)^{91}Nb$ reaction, the excitation energies of ^{91}Nb states observed in this work are given in Table II. The results agree, in general, with those of Vourvopoulos <u>et al</u>.[2] and indicate that the excitation energies reported by Picard and Bassani[1] and Knöpfle <u>et al</u>.[6] are somewhat too high. Of course, our method of calibration gives excitation energies that depend on the choice of Q-value for the $^{90}Zr(\alpha,t)$ reaction. If the <u>published</u> $^{90}Zr(\alpha,t)$ Q-value[11] is used, the excitation energies correspond rather well to those of Ref. 6. The errors quoted in Table II reflect an uncertainty of ±27 keV in the Q-value used in our analysis, but must be considered in the context of any redetermination of this value.

A triton spectrum of the $^{90}Zr(\alpha,t)^{91}Nb$ reaction at $\theta_\ell = 30°$ is shown in Fig. 1. The resolution is 50 keV, full width at half-maximum (FWHM). The $g_{9/2}$ ground state is a factor of 15 more intense than any other single level in the spectrum. In the $^{90}Zr(^3He,d)^{91}Nb$ data at 30.9 MeV[4] the ground state has only about 1/3 the intensity of the 3.36 MeV $\ell = 2$ level. Based on the strength of the ground state ($g_{9/2}$), the spectroscopic factors from $(^3He,d)$[2,6] indicate that $\sigma_{9/2^+}/\sigma_{7/2^+} \approx 5$ for the (α,t) reaction.

Figures 2 and 3 show angular distributions of tritons leading to some of the stronger final states. The angular distributions of all strong triton groups show very little structure. One observable difference between the $\ell = 4$ (g.s.) and $\ell = 2$ (3.372 MeV) curves, displayed in Figs. 2 and 3, respectively, is the forward angle behavior: the $\ell = 2$ curve tends to flatten out near 10°, while the $\ell = 4$ curve is much steeper. The 4.770 MeV level, which is assigned $\ell = 4$ by the $^{90}Zr(^3He,d)$ reaction[2,6] also shows a very steep angular distribution at forward angles (see Fig. 2). The 4.179 MeV level, whose angular distribution is shown in both Figs. 2 and 3, has been assigned[2,6] $\ell = 2$ (the ℓ-value is bracketed in Ref. 2). The behavior of the (α,t) angular distribution seems to agree better with the $\ell = 4$ curves, although the differences are very slight.

A more serious discrepancy with the $\ell = 2$ assignment of the 4.179 MeV level comes from the strength of the state. The spectroscopic factors given for this level predict it to be weaker than the 3.372 MeV level by a factor of between 14 (Ref. 6) and 20 (Ref. 2), while the relative cross sections of the levels seen in the (α,t) data (Table II) show a difference of only a factor of 2. Thus, the 4.179 MeV level is between seven and ten times too strong to be consistent with the $\ell = 2$ spectroscopic factors of previous work.[2,6]

The level observed here at 4.892 MeV is presumably the same as the $\ell = 2$ level at 4.912 MeV seen in the 18 MeV $^{90}Zr(^{3}He,d)^{91}Nb$ experiment.[6] In this case as well, the (α,t) angular distribution (not shown) corresponds more closely to the $\ell = 4$ shape and the strength is too large relative to the 3.372 MeV level by a significant factor. The 6.01 MeV $\ell = 4$ level[2,6] is obscured by the ^{17}F (g.s.) impurity peak at most angles. However, it appears to have an intensity about equal to that of the 4.179 MeV state, i.e., about half that of the 4.770 MeV $\ell = 4$ state.

In the excitation energy region between 2.5 and 3 MeV there are several levels observed in the (α,t) which appear either weakly[1,6] or not at all[2,4] in the $(^{3}He,d)$ data. The many levels which are populated by both reactions makes it seem likely that these "new" proton levels, e.g., 2.301, 2.393, 2.526, 2.613, 2.770, 2.889, and 3.014 MeV are appearing in the $^{90}Zr(\alpha,t)^{91}Nb$ spectrum due to "angular momentum" reasons. That is, they are small fragments of, say, $g_{9/2}$ or $g_{7/2}$ (or $f_{5/2}$ or $f_{7/2}$ hole) states and thus would have an extremely low cross section in a reaction which does not populate high angular momentum states easily. The intensities of these states correspond to about 1-2% that of the $g_{9/2}$ ground state. In the highest energy $^{90}Zr(^{3}He,d)$ experiment,[4] at 30.9 MeV, this intensity would correspond to a peak cross section of about 30-60 μb/sr which would be difficult to observe with the short exposure times used in that experiment.

B. $^{92}Mo(\alpha,t)^{93}Tc$

A triton spectrum of the $^{92}Mo(\alpha,t)^{93}Tc$ reaction at $\theta_\ell = 15°$ is shown in Fig. 4. The resolution is 55 keV (FWHM). The intensity of the ground state ($g_{9/2}$) level is again much greater than that of any other level in the

spectrum. A summary of the levels observed in the $^{92}Mo(\alpha,t)^{93}Tc$ reaction compared with the $^{92}Mo(^{3}He,d)$ results[1,5] is given in Table III. The spectra were calibrated using the ^{17}F (g.s.) and ^{93}Tc (g.s.) peaks as a function of angle, with Q-values obtained from Ref. 11. As can be seen from Table III, the excitation energies determined in this work agree with those found previously,[1,5] with very few exceptions. The largest discrepancy occurs for the level observed in our data at 3.095 MeV. This level may correspond to the state observed at 3.170±.02 MeV[1] and 3.147±.015 MeV[5] in the (^{3}He,d) experiments but the different values for the excitation energy could also be caused by population of a high-spin (e.g., ℓ = 3 or 4) fragment near the 3.17 MeV state. The preference for large angular momentum transfers of the (α,t) reaction would enhance the cross section of the high-spin level relative to that of the ℓ = 2 level observed in the (^{3}He,d) data. The ℓ = 2 spectroscopic factor[5] for the 3.147 MeV level is only 1/23 that of the 3.343 MeV level. The 3.095 MeV level observed in the $^{92}Mo(\alpha,t)^{93}Tc$ reaction is weaker than the 3.36 MeV (ℓ = 2) level by about a factor of 4.

The 0.675 MeV state, which was populated weakly in both (^{3}He,d) experiments,[1,5] appears to be made more easily (see Fig. 4) in the (α,t) experiment, which suggests a high angular momentum assignment. Even in our experiment, however, the state is still quite weak, having only about 1% of the ground state intensity. Another weak level in the 18 MeV (^{3}He,d) data,[1] at 2.130 MeV, also appears more intense in the (α,t) data. In this case, the level is assigned ℓ = 3 ($f_{5/2}$) by the 35 MeV (^{3}He,d) experiment,[5] which is consistent with the stronger population in the (α,t) reaction. Two other levels, unreported in the (^{3}He,d) experiments,[1,5] are those at 1.42 and 3.58 MeV.

The former may be absent due to problems with resolving it from the 1.509 MeV state, but the latter level would presumably have been observed unless it was an unfavorable (high ℓ-transfer) transition. The level observed in the $^{92}Mo(\alpha,t)^{93}Tc$ experiment at 2.59 MeV probably corresponds to that seen at 2.56 MeV in the (^{3}He,d) data. It seems clear from our data that this level is in fact a multiplet, but our resolution is insufficient to adequately separate the states.

In the $^{92}Mo(\alpha,t)^{93}Tc$ data, as was the case with $^{90}Zr(\alpha,t)^{91}Nb$ (see above) there is one level, at 3.908 MeV, whose strength is inconsistent with the $\ell = 2$ assignment[1] from the (^{3}He,d) reaction. (The 3.890 MeV level is given a tentative $\ell = 2$ assignment in Ref. 5 as well, although it does not have a typical $\ell = 2$ angular distribution. This may be an indication that there exist two closely spaced levels at this energy but Kozub and Youngblood[5] found no combination of two ℓ-values which would yield the observed shape.) The angular distribution of the 3.908 MeV level, which is seen in Figs. 5 and 6, shows a forward-angle behavior similar to that of the ground state ($\ell = 4$); it does not appear to flatten out at forward angles as does the 3.359 MeV level in ^{93}Tc (and the 3.372 MeV level in ^{91}Nb). As mentioned above, this difference in angular distributions is very slight and would certainly not allow a determination of the ℓ-transfer by itself. The spectroscopic factors for this level from the (^{3}He,d) experiments[1,5] predict it to be weaker than the 3.359 MeV level by a factor of about 7, while ratio of (α,t) cross sections is about 1.6. The 3.908 MeV level observed in the $^{92}Mo(\alpha,t)$ data is, therefore, about four times too strong to be consistent with the $\ell = 2$ assignment of previous work.[1,5]

In the region near 4.5 MeV there are a number of levels observed in the (^{3}He,d) data[1,5] to which no ℓ-values are assigned. As can be seen in Fig. 4, these levels (mostly doublets) are excited more strongly in our (α,t) data than in the (^{3}He,d) reaction, which indicates that they are reached with large ℓ-transfers ($\ell > 2$). The appearance of $g_{7/2}$ levels at about this energy in ^{93}Tc seems in agreement with the existence of $\ell = 4$ transfers[2] (e.g., the 4.770 MeV state) in ^{91}Nb in this energy region. The angular distributions of the 4.366 and 4.898 MeV states, shown in Fig. 5, also appear to be similar to that of the $\ell = 4$ ground state transition.

The 5.978 MeV level seen in Ref. 5 probably is the same as the 6.01 MeV level seen in our (α,t) data. Figure 4 shows, however, that this state is part of a multiplet. These states do appear to stand out in the (α,t) data and could be $\ell = 5$ fragments as suggested tentatively in Ref. 5. Information on these states was difficult to obtain at backward angles since the ^{17}F (g.s.) impurity peak obscures the 6 MeV region beyond about 35° (lab).

IV. DISCUSSION

A. $^{90}Zr(\alpha,t)^{91}Nb$

A comparison of relative strengths of levels observed in both the (α,t) and $(^3He,d)$[1,2,4,6] experiments on ^{90}Zr indicates that the 4.179 MeV level observed in (α,t) is 7 to 10 times too strong to be consistent with an $\ell = 2$ assignment (based on its intensity compared to the 3.372 MeV $\ell = 2$ level). This discrepancy seems rather large since it has been verified[16] that (α,t) spectroscopic factors are, in general, the same as those obtained from $(^3He,d)$ experiments (within about a factor of two). Additional evidence for the existence of a high-spin state in this region comes from a recent study of the β-decay of ^{91}Mo.[17] This work indicates a level at 4.179±.001 MeV in ^{91}Nb which would be expected to have a spin of $7/2^+$, $9/2^+$, $11/2^+$ if populated with an allowed β-decay from the $9/2^+$ ground state. The shell model rules out an $11/2^+$ level if it is <u>strongly</u> populated in a proton transfer reaction and the high excitation-energy of the level favors a $g_{7/2}$ assignment although $g_{9/2}$ cannot be ruled out. A summary of the levels observed in the β-decay is included in Table II.

The β-decay experiment also provides an explanation for most of the levels near 3 MeV which are seen very weakly[1,6] in the $(^3He,d)$ data. Of the six levels seen in the (α,t) experiment between 2.39 and 3.01 MeV, only the 2.899 MeV level was not reported in the β-decay study. This supports our contention that these levels are high-spin states having at least some single-particle structure.

The 4.892 MeV level observed in the (α,t) experiment corresponds to a doublet at 4.85 and 4.90 MeV to which no ℓ-values are assigned in Ref. 2. A

level at 4.912 MeV was observed in a lower energy experiment[6] and assigned $\ell = 2$. As discussed above, the spectroscopic factor for this level would correspond to a cross section relative to the 3.372 MeV level of 1/16 as compared to the observed intensity ratio of 1/2.3, i.e., the 4.892 MeV level is 7 times stronger than its $\ell = 2$ assignment[6] would indicate. The ratio of ($\ell = 2$) spectroscopic factors for the 4.230 and 4.912 MeV levels given in Ref. 6 agrees quite well with the relative intensities of the two levels in (α,t), so that both levels are too strong by the same factor. Unfortunately, the β-decay of ^{91}Mo($9/2^+$) [17] can only populate ^{91}Nb levels up to about 4.4 MeV so it provides no additional information about the 4.892 MeV state.

The 5.144 MeV level seen in (α,t) has a strength which is roughly consistent with the 5.24 MeV $\ell = 2$ level, but the discrepancy in excitation energy is larger than the estimated uncertainties. Due to the large number of reported[2,6] levels in this region it is difficult to associate the 5.144 MeV level with a specific (^{3}He,d) state. The observed[2,6] levels at this energy, however, would not be as strong as the state seen here.

The intensity of the $\ell = 4$ level[2,6] near 6 MeV seems rather low in the (α,t) data. Knöpfle et al.[6] show a cross section ratio σ (6.04)/σ (4.82) $\approx$ 2 while our data give σ (5.95)/σ (4.77) $\approx$ 1/2. Unfortunately, the 6 MeV region of the spectrum is not visible at forward angles, so the intensity of the 5.95 MeV level is only approximate. Whether this apparent difference is related to the fact that the upper level is slightly unbound cannot be determined without DWBA calculations.

The appearance of these probable high ℓ-value levels is consistent with the general picture of the proton states in ^{91}Nb. As was pointed out in

Ref. 2, the number of $g_{7/2}$ levels observed is much smaller than expected compared to the considerable fragmentation of the $\ell = 0$ and $\ell = 2$ levels. However, the two observed[2] transitions already account for over 90% of the total $g_{7/2}$ strength so the appearance of these "extra" levels would require a renormalization of the spectroscopic strength if they are, in fact, $g_{7/2}$ fragments.

B. $^{92}Mo(\alpha,t)^{93}Tc$

In this case no high-resolution (^3He,d) data exists, so a detailed comparison is not possible. The strong levels in (α,t) at 3.908, 4.366, 4.67, 4.77, and 4.898 MeV are probable candidates for $\ell = 4$ levels based on their intensities relative to the 3.359 MeV $\ell = 2$ level. As mentioned above, the behavior of the 3.89 MeV level in the 35 MeV (^3He,d) data[5] may indicate a doublet at this energy in ^{93}Tc. The strength of the 3.908 MeV level in $^{92}Mo(\alpha,t)$ suggests that at least one of the states at this energy has a high spin. The tentative $\ell = 5$ assignment made by Kozub and Youngblood[5] for the 5.98 MeV level is in qualitative agreement with the observed group of strong levels in $^{92}Mo(\alpha,t)^{93}Tc$ near 6.01 MeV. The (^3He,d) experiment[5] finds the $d_{5/2}$ analog state at 8.4 MeV, which corresponds to a splitting between $T_>$ and $T_<$ centroids of about 4.7 MeV for the $d_{5/2}$ configuration. Recent $^{92}Mo(d,p)^{93}Mo$ experiments[18,19] show the existence of an $h_{11/2}$ neutron level at 2.30 MeV. Assuming the same splitting between $T_>$ and $T_<$ states for the $h_{11/2}$ configuration in ^{93}Tc would then give 6.0 MeV as the expected location of the $T_<$ $\ell = 5$ levels. The predicted $g_{7/2}$ centroid would be about 5.2 MeV (based on the neutron single-particle centroid from Ref. 18) which is somewhat higher than is indicated from the strong levels observed in our data. The data of

Vourvopoulos et al.[2] indicate that the $T_> - T_<$ splitting is about 1 MeV larger for the $g_{7/2}$ states than it is for the $d_{5/2}$ states in ^{91}Nb and a similar difference in ^{93}Tc would predict a $g_{7/2}$ centroid in reasonable agreement with the observed strong levels in ^{93}Tc between 3.9 and 4.9 MeV.

It is interesting to note that the ^{90}Zr(d,p) and (α,^{3}He) reactions[20] find the $g_{7/2}$ and $h_{11/2}$ centroids at the same energy in ^{91}Zr, which would suggest the existence of $T_<$ $\ell = 5$ states near 5 to 6 MeV in ^{91}Nb as well as ^{93}Tc, although none have been observed. (The 6 MeV levels observed in ^{91}Nb are not as strongly excited with (α,t) as those in ^{93}Tc and have been assigned $\ell = 4$ by the (^{3}He,d) reaction.[2,6])

V. CONCLUSIONS

The $^{90}Zr(\alpha,t)$ and $^{92}Mo(\alpha,t)$ reactions have been used to search for high-spin ($\ell > 2$) levels in ^{91}Nb and ^{93}Tc. Based on relative intensities of levels seen in both the (^3He,d) and (α,t) reactions, ^{91}Nb states at 2.39, 2.53, 2.61, 2.77, 2.90, 3.01, 4.18, 4.77, 4.89, and (5.14) MeV are probable candidates for levels with $\ell = 3$ or 4. The 4.18 MeV level is assigned $\ell = 2$ from (^3He,d)[2,6] but the large (α,t) strength and β-decay of $^{91}Mo(9/2^+)$ [17] indicate a $7/2^+$ or $9/2^+$ for this level. Levels near 6 MeV appear rather weakly in (α,t) although a strong $\ell = 4$ level was observed in the (^3He,d) experiments[2,6] at 6.01 MeV. From the position of the $h_{11/2}$ neutron centroid in ^{91}Zr it is expected that $\ell = 5$ proton levels may also exist in the 5 to 6 MeV region of ^{91}Nb, which could provide an explanation for some of the stronger levels observed in the (α,t) data in this region.

Possible high-spin levels in ^{93}Tc include the 0.68, (3.58), 4.37, (4.47), (4.67), 4.77, 4.90, 6.01 (multiplet), 6.17, and 6.44 MeV states. The states above 6 MeV may be $\ell = 5$ levels based on tentative results from the (^3He,d) experiment of Kozub and Youngblood.[5] The 3.91 MeV level, assigned $\ell = 2$ from the (^3He,d) studies[1,5] is populated too strongly in (α,t) to be consistent with the measured spectroscopic factors and is believed to have $\ell > 2$.

The Q-value used in our analysis of the $^{90}Zr(\alpha,t)^{91}Nb$ reaction, -14.643 MeV, corresponds to a change in the ^{91}Nb mass excess of +95 keV. This change is roughly consistent with a new Q-value determined for the $^{91}Zr(p,n)$ reaction[13] but contradicts a recent measurement of the $^{90}Zr(^3He,d)^{91}Nb$ Q-value[6] which confirms the ^{91}Nb mass excess of Mattauch, Thiele, and Wapstra.[12]

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FOOTNOTES AND REFERENCES

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1. J. Picard and G. Bassani, Nucl. Phys. A131, 636 (1969).
2. G. Vourvopoulos, R. Shoup, J. C. Fox, and J. B. Ball, in Nuclear Isospin, ed. by J. D. Anderson, S. D. Bloom, J. Cerny, and W. W. True, (Academic Press, Inc., New York, 1969), p. 205.
3. H. Ohnuma and J. L. Yntema, Phys. Rev. 176, 1416 (1968).
4. M. R. Cates, J. B. Ball, and E. Newman, Phys. Rev. 187, 1682 (1969).
5. R. L. Kozub and D. H. Youngblood, Bull. Am. Phys. Soc. 15, 1657 (1970), and to be published.
6. K. T. Knöpfle, M. Rogge, C. Mayer-Böricke, J. Pederson, and D. Burch, Nucl. Phys. A159, 642 (1970).
7. N. Auerbach and I. Talmi, Nucl. Phys. 64, 458 (1965).
8. J. Vervier, Nucl. Phys. 75, 17 (1966).
9. F. S. Goulding, D. A. Landis, J. Cerny, and R. H. Pehl, Nucl. Instr. Methods 31, 1 (1964).
10. Calculations were made with the data analysis program LORNA written by C. Maples.
11. C. Maples, G. W. Goth, and J. Cerny, Nucl. Data A2, 429 (1966).
12. J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. 67, 1 (1965).
13. H. J. Kim, R. L. Robinson, C. H. Johnson, and S. Raman, Nucl. Phys. A142, 35 (1970).
14. M. S. Zisman and B. G. Harvey, unpublished $^{91}Zr(\alpha,t)^{92}Nb$ data.
15. J. B. Ball and M. R. Cates, Phys. Letters 25B, 126 (1967).
16. P. Roussel, G. Bruge, A. Bussiere, H. Faraggi, and J. E. Testoni, Nucl. Phys. A155, 306 (1970).

17. K. Hesse and E. Finckh, Nucl. Phys. A141, 417 (1970).

18. J. B. Moorhead and R. A. Moyer, Phys. Rev. 184, 1205 (1969).

19. W. Booth, S. M. Dalgliesh, K. C. McLean, R. N. Glover, and F. R. Hudson, Phys. Letters 30B, 335 (1969).

20. C. R. Bingham and M. L. Halbert, Phys. Rev. C2, 2297 (1970).

Table I. Summary of Q-Values for Reactions Relating to ^{91}Nb

Reaction	Measured Q-Value (MeV)	Published Q-Value[a] (MeV)	^{91}Nb Mass Excess[b] (MeV)
^{91}Zr(^{3}He,d)^{92}Nb	---	0.358±0.011	---
^{91}Zr(α,t)^{92}Nb	---	-13.963±0.011	---
^{91}Zr(p,n)^{91}Nb[c]	- 2.045±0.006	- 1.925±0.060	-86.630±0.008
^{90}Zr(^{3}He,d)^{91}Nb[d]	- 0.227±0.020	- 0.225±0.060	-86.748±0.020
"	- 0.319±0.013[e]	"	-86.656±0.014
^{90}Zr(α,t)^{91}Nb	-14.643±0.027[f]	-14.545±0.060	-86.652±0.027

[a]Taken from Ref. 11, which uses a mass excess for ^{91}Nb (from Ref. 12) of -86.750±0.060 MeV.

[b]Calculated from the difference between the measured and published Q-values.

[c]Ref. 13.

[d]Ref. 6.

[e]Relative to ^{91}Zr(^{3}He,d)^{92}Nb Q-value listed above. Q-value difference from Ref. 15. (See text).

[f]Relative to ^{91}Zr(α,t)^{92}Nb Q-value listed above. Q-value difference from Ref. 14. (See text).

Table II. Levels Observed in the $^{90}Zr(\alpha,t)^{91}Nb$ Reaction at 50 MeV

No.	(α,t) Levels Observed[a] (MeV)	(α,t) Intensity[b] (mb)	(^{3}He,d) Levels Observed[c,d] (MeV)	(^{3}He,d) ℓ_p[d]	(^{3}He,d) C^2S[d]	^{91}Mo (g.s.) Decay Levels Observed[e] (MeV)
1	0.0	3.441	0.0	4	0.918	---
2	(0.103)[f]	0.144	0.103	1	0.430	
3	1.291	0.038[g]	1.31	1	0.048[h]	
						1.581
4	1.600	0.073	1.60	1	0.078[h]	1.637
						1.791
5	1.820	0.069[g]	1.84	3	0.058[h]	
6	1.950±.04	Weak	1.96	2[h]	0.014[h]	
7	2.301	0.043[i]	2.34	1	0.017[h]	
8	2.393±.03	Weak				(2.391)[j]
9	2.526	0.032[i]				2.531
10	2.613	0.023[k]	2.62[ℓ]		Weak[ℓ]	2.631
11	2.770	0.012[k]				2.792
12	2.899	0.074	2.92[ℓ]		Weak[ℓ]	

(continued)

Table II (continued)

No.	(α,t) Levels Observed[a] (MeV)	(α,t) Intensity[b] (mb)	(^{3}He,d) Levels Observed[c,d] (MeV)	(^{3}He,d) ℓ_p[d]	(^{3}He,d) C^2S[d]	^{91}Mo (g.s.) Decay Levels Observed[e] (MeV)
13	3.014	0.036[m]				3.028
			3.07	2	0.035	
14	3.120±.04	Weak	3.11			3.149
						3.187
15	3.372	0.218	3.36	2	0.388	
16	3.654±.04	0.027[k]	3.66	2[h]	0.023[h]	
						3.837
						3.886
			3.92[n]		Weak[n]	3.916
			3.95			
			3.99			
			4.11	0	0.055	
17	4.179	0.107	4.18	(2)	0.020	4.179
			4.23	(2)	0.008	
			4.30	2	0.023	
			4.39	0	0.160	

(continued)

Table II (continued)

	(α,t)		(^{3}He,d)			^{91}Mo (g.s.) Decay
No.	Levels Observed[a] (MeV)	Intensity[b] (mb)	Levels Observed[c,d] (MeV)	ℓ_p[d]	C^2S[d]	Levels Observed[e] (MeV)
			4.49	2	0.043	
			4.61	2	0.013	
			4.70	2	0.033	
18	4.770±.03	0.232[g]	4.77 } 4.80 }	4	0.343	
			4.85			
19	4.892±.03	0.096[g]	4.90			
			4.95 } 4.99 }	(0)	0.055	
20	5.020±.03	Weak	5.04	0	0.040	
21	5.144±.03	0.067[i]	5.17	(0)	0.080	
			5.24	2	0.133	
22	5.341±.03	Weak	5.33	0	0.090	
			5.44	2	0.165	
			5.57	(0)	0.035	
			5.64	0	0.060	

(continued)

Table II (continued)

No.	(α,t) Levels Observed[a] (MeV)	(α,t) Intensity[b] (mb)	(^{3}He,d) Levels Observed[c,d] (MeV)	(^{3}He,d) ℓ_p[d]	(^{3}He,d) C^2S[d]	^{91}Mo (g.s.) Decay Levels Observed[e] (MeV)
			5.74	0	0.020	
			5.80	0	0.120	
			5.86	0	0.045	
23	5.95±.05	(0.1)[o]	6.01	4	0.500	
24	6.09±.05	Weak	6.09	2	0.075	
			6.17	2	0.103	
			6.215[n]	(4)[n]	Weak[n]	

[a]Excitation energy ± 20 keV except as noted. The Q-value for the reaction was assumed to be -14.643 MeV. (See text).

[b]Integrated from $\theta_{c.m.}$ = 12.5 to 57° except as noted.

[c]Excitation energy ± 15 keV.

[d]Taken from Ref. 2 except as noted. All ℓ = 2 levels up to 5.44 MeV are assumed $d_{5/2}$. All ℓ = 4 levels except g.s. are assumed $g_{7/2}$.

[e]Taken from Ref. 17. Only those levels believed to be populated in the g.s. ($9/2^+$) decay are included. All energies ± 1 keV or less. The upper limit for the decay is about 4.4 MeV.

[f]Not resolved.

[g]Integrated from $\theta_{c.m.}$ = 12.5 to 52°.

(continued)

Table II (continued)

[h]Taken from Ref. 4. All $\ell = 1$ levels except 0.103 MeV are assumed $p_{3/2}$. The 1.85 MeV level is assumed $f_{5/2}$.

[i]Integrated from $\theta_{c.m.} = 12.5$ to $36.5°$.

[j]The existence of this level was uncertain.

[k]Integrated from $\theta_{c.m.} = 12.5$ to $42°$.

[ℓ]Taken from Ref. 1.

[m]Integrated from $\theta_{c.m.} = 12.5$ to $42°$.

[n]Taken from Ref. 6.

[o]Observed at only 3 angles. The average differential cross section ratio to the 4.179 MeV level (~ 0.9) was used in obtaining the intensity.

Table III. Levels Observed in the $^{92}Mo(\alpha,t)^{93}Tc$ Reaction at 50 MeV

	(α,t)		(^{3}He,d)[a]			(^{3}He,d)[b]		
No.	Levels Observed[c] (MeV)	Intensity[d] (mb)	Levels Observed (MeV)	ℓ_p	C^2S[e]	Levels Observed (MeV)	ℓ_p	C^2S[e]
1	0.0	3.709	0.0	4	0.67	0.0	4	0.50
2	0.385	0.118	0.390±.010	1	0.30	0.396±.005	1	0.28
3	0.675	0.040	0.660±.020		Weak	(0.66)		Weak
4	1.180	0.019	1.190±.015	1	0.03,0.01	1.21 ±.020	1	0.034,0.015
5	1.42±.03	0.037						
6	1.509	0.044	1.500±.015	1	0.10,0.04	1.500±.010	1	0.12, 0.052
7	1.781	0.055[f]	1.780±.020	1	0.12,0.05	1.788±.010	1	0.11, 0.048
8	2.140	0.097	2.130±.020		Weak	2.134±.015	3	0.045[g]
9	2.59±.04	0.082	2.565±.020	2	0.04,0.02	2.556±.015	2	0.037,0.019
10	3.095	0.091						
			3.170±.020	(2)		3.147±.015	2	0.034,0.018
11	3.359	0.390	3.360±.020	2	0.78,0.38	3.343±.015	2	0.78, 0.41
12	3.584	0.064						
13	3.908	0.245	3.910±.020	2	0.09,0.05	3.89 ±.020	(2)	(0.11, 0.06)
			4.110±.020	(0)	(0.15)	4.09 ±.030	0	0.23

(continued)

Table III (continued)

	(α,t)		(^{3}He,d)[a]			(^{3}He,d)[b]		
No.	Levels Observed[c] (MeV)	Intensity[d] (mb)	Levels Observed (MeV)	ℓ_p	C^2S[e]	Levels Observed (MeV)	ℓ_p	C^2S[e]
14	4.15±.04	0.059[f]						
15	4.366	0.192[f]	4.43			4.39 ±.040		
16	4.474	0.066[h]						
17	4.67±.03	0.07[i]						
18	4.77±.03	0.087[i]	4.79			4.76 ±.030		
19	4.898	0.166[i]	4.92			4.88 ±.030		
			5.02					
20	5.20±.03	0.097[h]	5.18			5.170±.015	1	0.23, 0.083
			5.33			5.302±.015	2	0.059,0.032
			5.49			5.50 ±.040	(2)	(0.051,0.028)
			5.65			5.64 ±.040	2	0.035,0.019
21	6.01±.03	0.16[h]				5.98 ±.040	(5)	(0.079)[j]
22	6.17±.03	0.17[h]				6.24 ±.040		
23	6.44±.04	0.11[h]						

(continued)

Table III (continued)

[a]Taken from Ref. 1. No spectroscopic information is given for levels above 4.110 MeV.

[b]Taken from Ref. 5.

[c]Excitation energy ± 20 keV, except as noted.

[d]Integrated from $\theta_{c.m.}$ = 12.5 to 57° except as noted.

[e]When two values are listed the first corresponds to $j = \ell - 1/2$, the second to $j = \ell + 1/2$.

[f]Integrated from $\theta_{c.m.}$ = 12.5 to 52°.

[g]Assumed $f_{5/2}$.

[h]Integrated from $\theta_{c.m.}$ = 12.5 to 36.5°.

[i]Integrated from $\theta_{c.m.}$ = 15.5 to 52°.

[j]Assumed $h_{11/2}$.

FIGURE CAPTIONS

Fig. 1. Triton energy spectrum from the $^{90}Zr(\alpha,t)^{91}Nb$ reaction at $\theta_\ell = 30°$.

Fig. 2. Angular distributions of tritons from the $^{90}Zr(\alpha,t)^{91}Nb$ reaction leading to the 0.0, 4.179, and 4.770 MeV levels. Statistical errors are shown for each point. The curves have no theoretical significance.

Fig. 3. Angular distributions of tritons from the $^{90}Zr(\alpha,t)^{91}Nb$ reaction leading to the 3.372 and 4.179 MeV levels. Statistical errors are shown for each point. The curves have no theoretical significance.

Fig. 4. Triton energy spectrum from the $^{92}Mo(\alpha,t)^{93}Tc$ reaction at $\theta_\ell = 15°$.

Fig. 5. Angular distributions of tritons from the $^{92}Mo(\alpha,t)^{93}Tc$ reaction leading to the 0.0, 3.908, 4.366, and 4.898 MeV levels. Statistical errors are shown for each point. The curves have no theoretical significance.

Fig. 6. Angular distributions of tritons from the $^{92}Mo(\alpha,t)^{93}Tc$ reaction leading to the 3.359 and 3.908 MeV levels. Statistical errors are shown for each point. The curves have no theoretical significance.

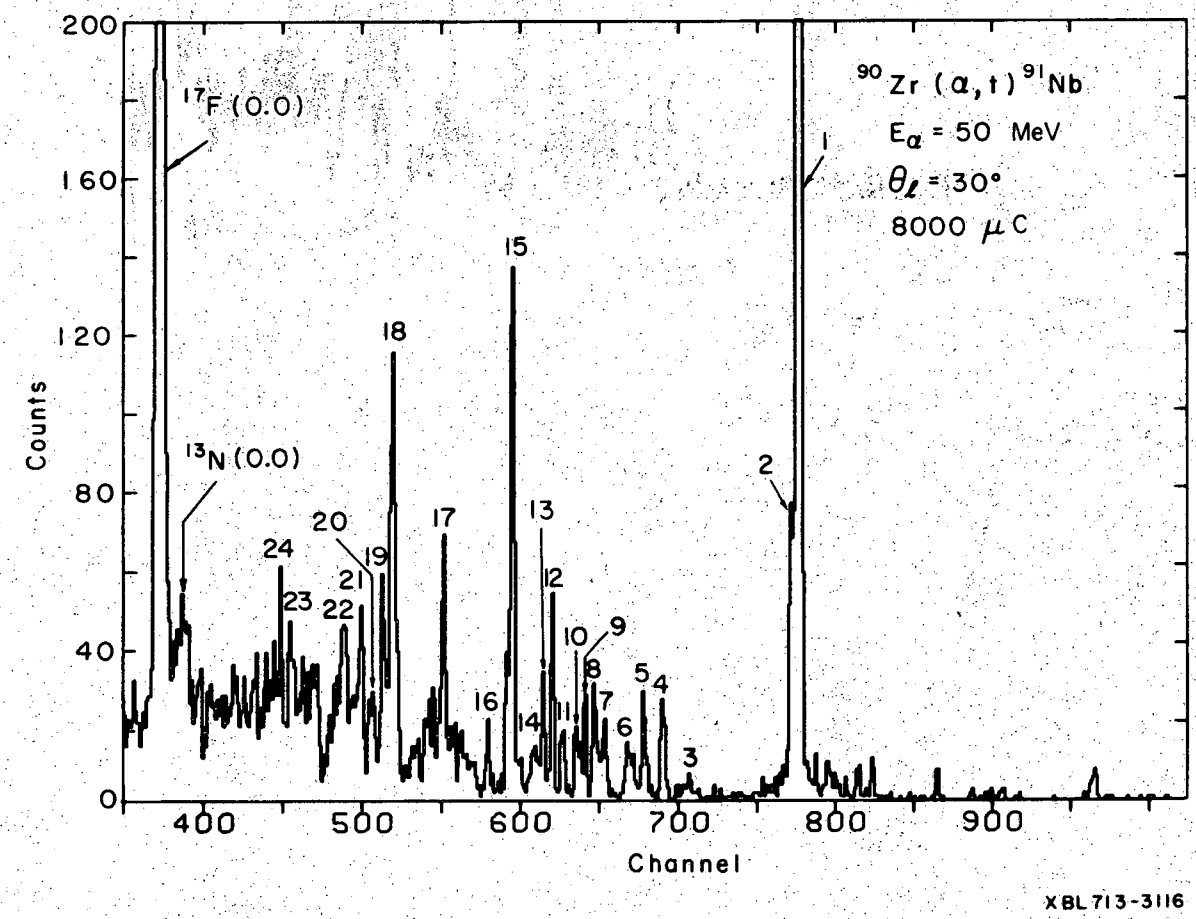

^{90}Zr (α, t) ^{91}Nb
E_α = 50 MeV
θ_ℓ = 30°
8000 μC
^{17}F (0.0)
^{13}N (0.0)
Counts
Channel
XBL713-3116

Fig. 1

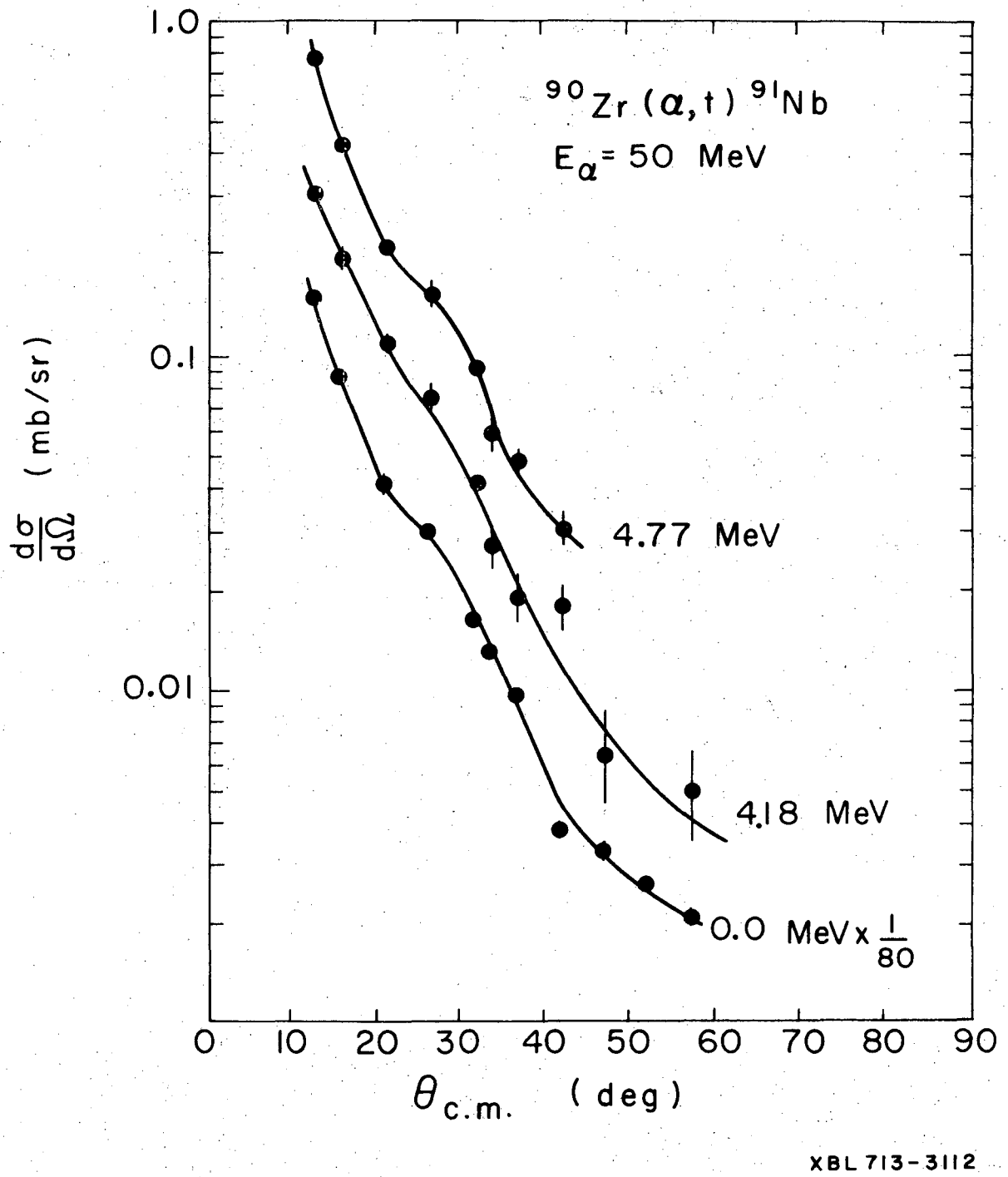
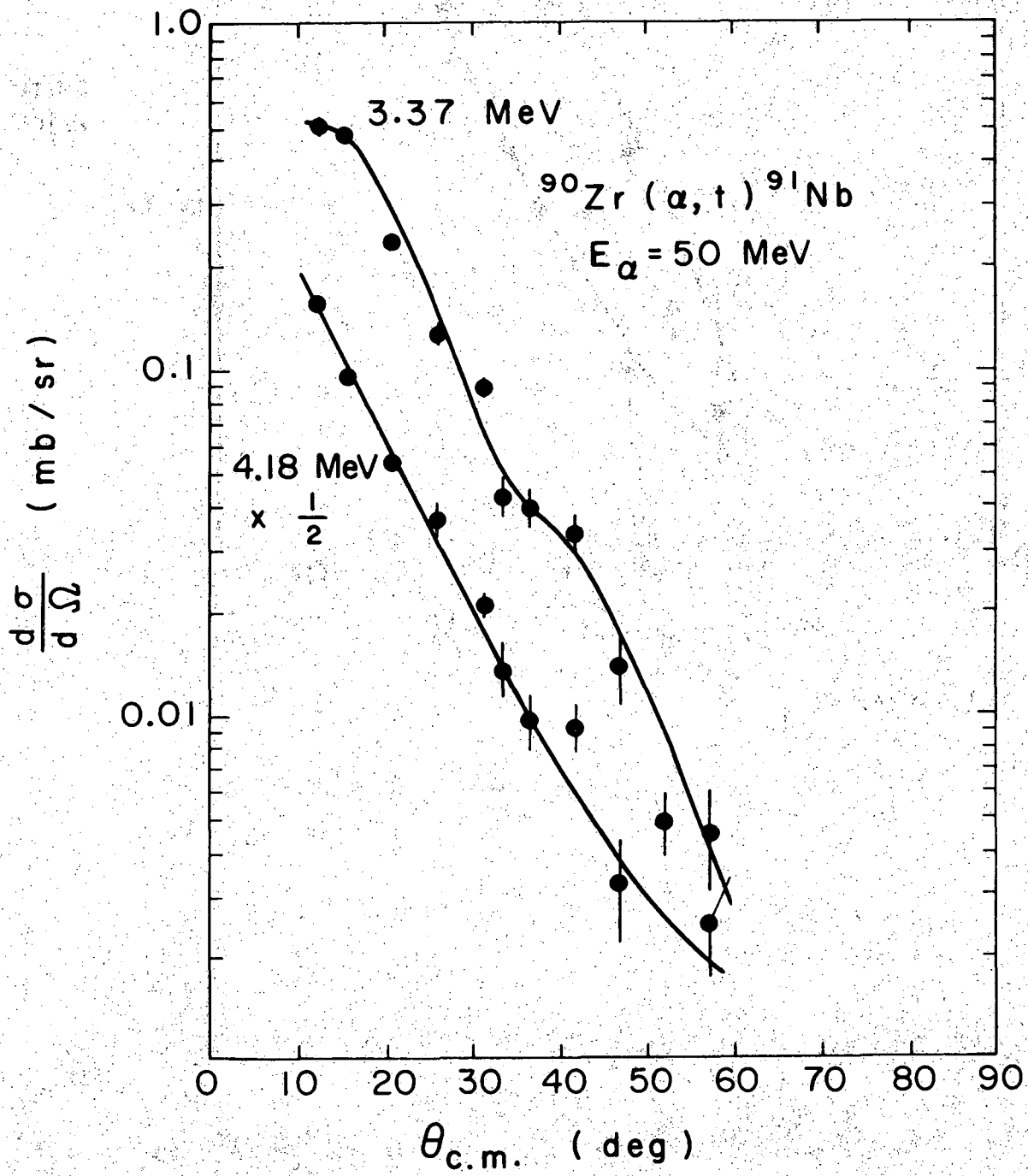

$^{90}Zr(\alpha,t)^{91}Nb$
$E_\alpha = 50$ MeV
4.77 MeV
4.18 MeV
0.0 MeV x $\frac{1}{80}$
$\frac{d\sigma}{d\Omega}$ (mb/sr)
1.0
0.1
0.01
0
10
20
30
40
50
60
70
80
90
$\theta_{c.m.}$ (deg)
XBL 713-3112

Fig. 2



XBL 713-3113

Fig. 3

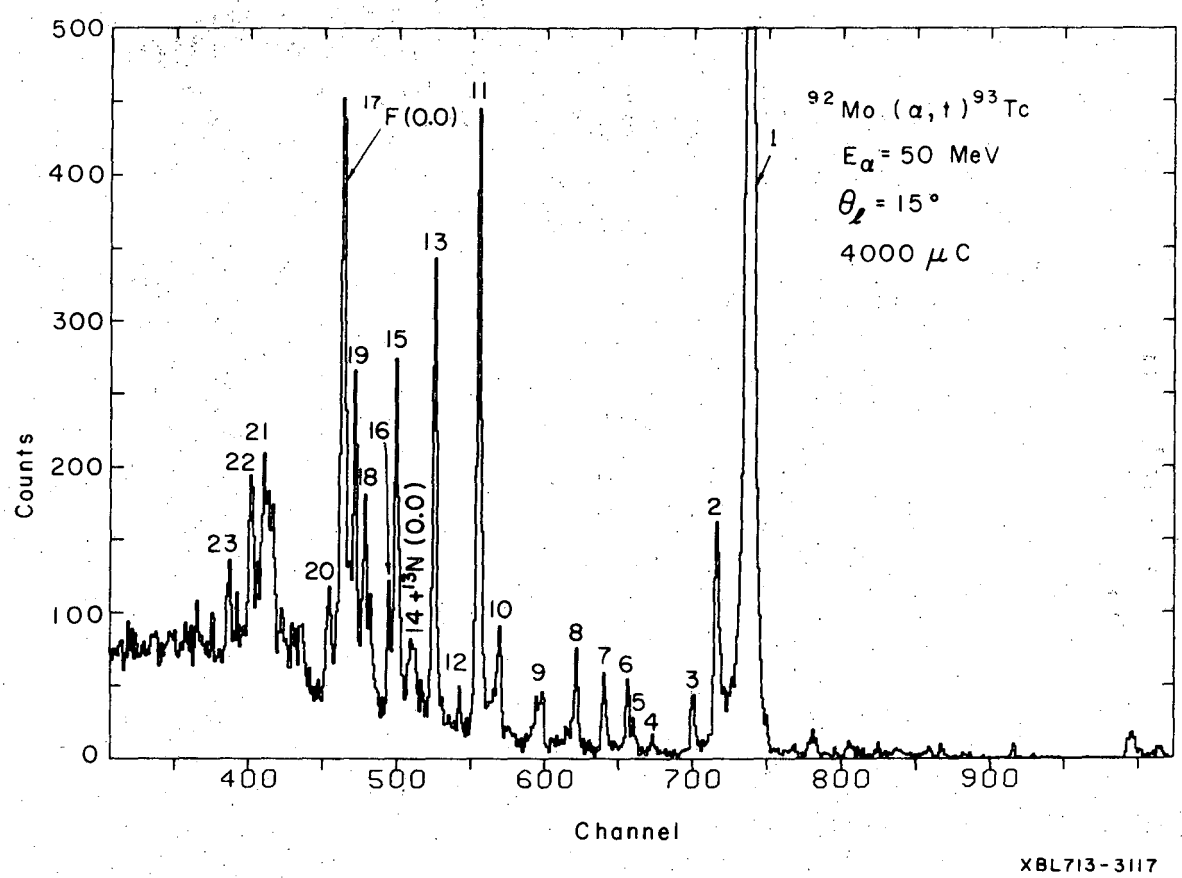

^{92}Mo (α, t) ^{93}Tc
E_α = 50 MeV
θ_ℓ = 15°
4000 μC
^{17}F (0.0)
14 + ^{13}N (0.0)
Counts
Channel
XBL713-3117

Fig. 4

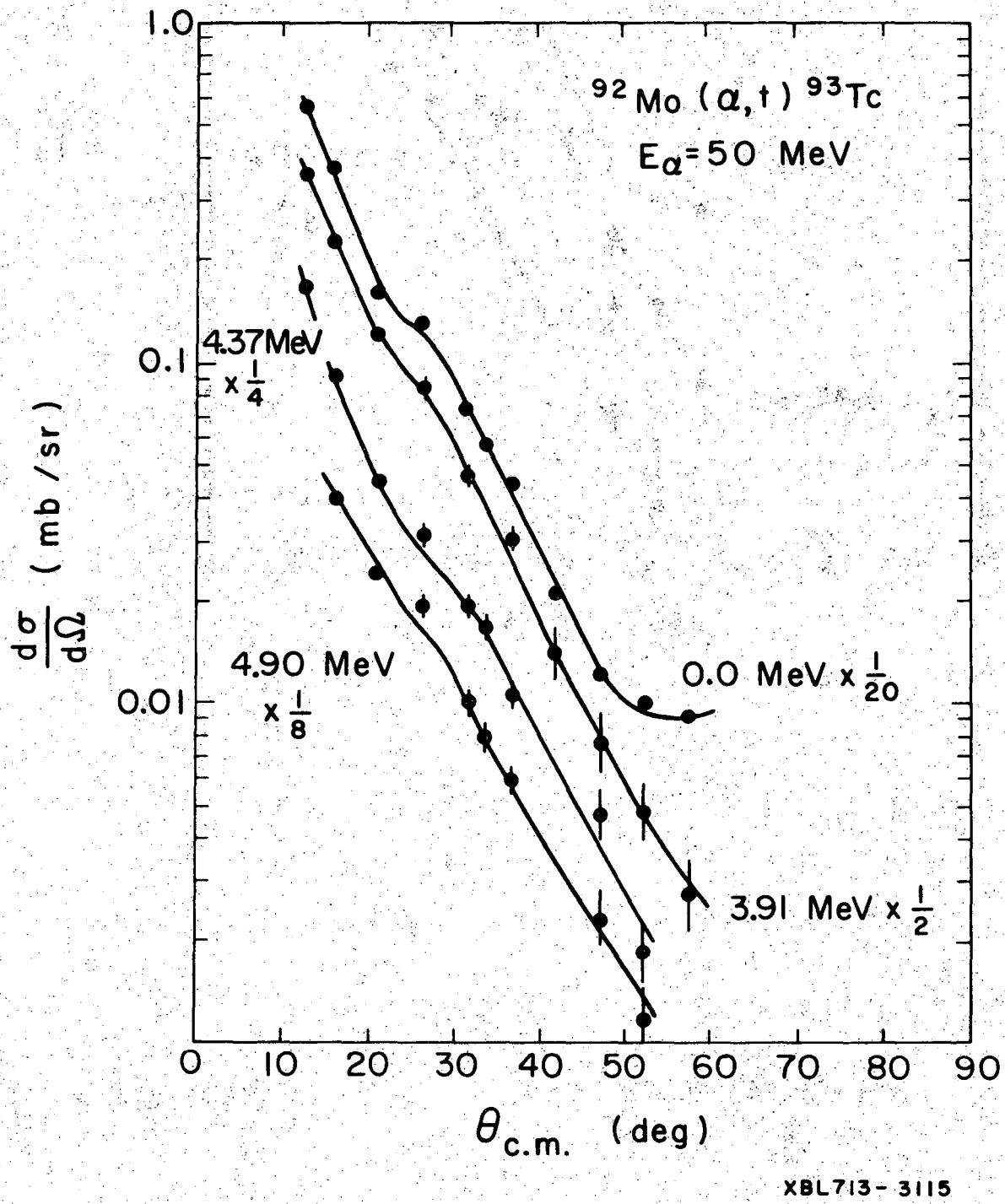
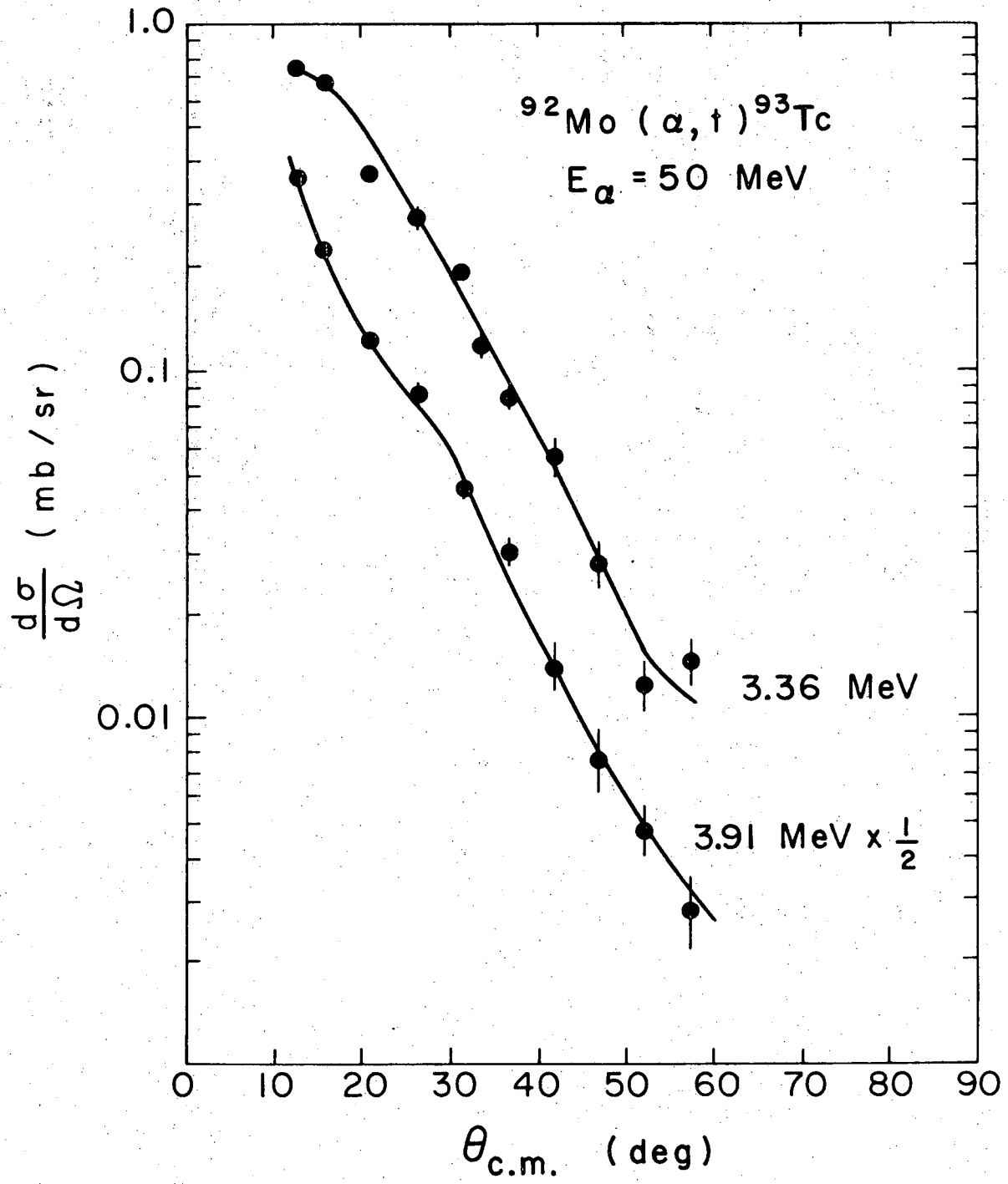

^{92}Mo (α,t) ^{93}Tc
E_α=50 MeV
4.37MeV
x 1/4
4.90 MeV
x 1/8
0.0 MeV x 1/20
3.91 MeV x 1/2
1.0
0.1
0.01
dσ/dΩ (mb/sr)
0
10
20
30
40
50
60
70
80
90
θc.m. (deg)
XBL713-3115

Fig. 5



XBL713-3114

Fig. 6

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TECHNICAL INFORMATION DIVISION
LAWRENCE RADIATION LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720