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Levels in ^{94}Tc up to an excitation of 4.5 MeV were populated by means of the ^{92}Mo(^{3}He,p) ^{94}Tc reaction at $E_{^3He}$=25 MeV . DWBA analysis of the proton angular distributions lead to spin and parity assigments for several levels. It was not possible to reproduce the angular distributions to the 1^+ and 0^+ final states on the basis of a direct one-step transfer. Coupled-channel calculations seem to improve the fits when both one-and two-step mechanisms are included. A possible 0^+ state at 2.72 MeV excitation is suggested to be the T_{lower} antianalog in ^{94}Tc .

NUCLEAR REACTIONS ^{92}Mo(^{3}He,p), E=25 MeV ;measured σ (Ep,θ),θ=5^0-50^0,$\Delta\theta$=5^0, enriched target, split-pole spectrograph. ^{94}Tc deduced levels, L_{np} , J^{π} ;one- - and two-step mechanism for (p-n) transfer.

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I - INTRODUCTION

Very little is known about the nuclear structure of the odd-odd nuclei in the 90-110 mass region. The $(^3He,p)$ reaction provides a convenient means of investigating these final states. The low-lying spectra of these nuclei constitute proton-neutron multiplets and may yield useful information on the effective proton-neutron interaction.

In this article the results of a study of the ^{94}Tc nucleus by means of the $^{92}Mo(^3He,p)$ reaction are presented. Twelve levels are known in ^{94}Tc up to an excitation energy of 960 keV from previous measurements of β^+-decay of ^{94}Ru[1], and the charge-exchange reactions $(p,n\gamma)$[2] and $(^3He,t)$[3]. An (α,d) experiment with 50 keV resolution has also been reported[4]. In the present work about 50 levels have been observed up to an excitation energy of 4.5 MeV, of which the proton angular distributions and subsequent DWBA analysis permit spin and parity assignments for more than thirty levels.

Bhatt and Ball[5] and Vervier[6] have reported shell-model calculations using effective nucleon-nucleon interactions. The known positive parity levels below 1 MeV excitation are in good agreement with the predicted spectra.

Although the strongest transitions observed are characteristic of $L_{np}=0$ or (0+2) transfer, displaying a sharp drop in cross section with increasing scattering angle in the forward angle region, it was not possible to reproduce the observed angular distributions on the basis of a direct one-step (p-n) transfer. While the calculated distributions have a well-defined minimum around $\theta=30^{\circ}$, the measured angular distributions to the levels assigned $J^{\pi}=1^{+}$ show a less pronounced diffraction pattern, with the cross sections remaining more or less constant. A similar behaviour has been observed previously for the $0^{+}\rightarrow 1^{+}$ (^{3}He,p) transitions in $f_{7/2}$ nuclei[7,8], but no systematic investigations of this reaction exist beyond the (f-p) shell region. A possible explanation could be that the (p-n) transfer process, at least in part, proceeds through a sequential mechanism. The results of the calculations with a two-step mechanism, viz., the (^{3}He,d) (d,p) process are also presented.

II - EXPERIMENTAL METHODS AND RESULTS

The incident ^{3}He beam of 25 MeV was obtained from the Orsay MP tandem accelerator. The thickness of the enriched self-supporting ^{92}Mo target was about 270 $\mu g/cm^{2}$ and was responsible for a large part of the energy resolution of 45 keV (FWHM) obtained. The outgoing protons were analysed with a split-pole magnetic spectrometer and were detected using position-sensitive surface-barrier detectors placed in the focal plane of the spectrograph.

The proton angular distributions were measured in steps of 5^{0} between 5^{0} and 50^{0} . A typical spectrum of the measured proton groups is shown in Fig. 1 . Level energies up to an excitation of

4.5 MeV, the transferred orbital angular momenta obtained from the DWBA analysis of the proton angular distributions and the resulting spin and parity assignments are displayed in Table 1. The measured angular distributions are compared with the DWBA predictions in Figs. 2 and 3 . For the 0^+ and 1^+ distributions (Fig. 4) the results of the coupled-channel calculations taking into account the two-step contributions are also presented. In Table 1 ,the excitation energies are accurate to within 10-15 keV. Levels for which only the excitation energies are quoted had, in general, differential cross sections of the order of 10 μb/sr ,and displayed structureless angular distributions within experimental errors.

III - THE ANALYSIS OF ANGULAR DISTRIBUTIONS

A . THE DWBA ANALYSIS

The optical-model parameters for the ^{3}He and proton channels were obtained from the systematic analysis of Becchetti and Greenlees[9] and are shown in Table 2 . The zero-range DWBA calculations were performed with the code DWUCK-4[10] using the direct two-nucleon transfer option and assuming pure shell-model configurations for the (p-n) multiplets. This code calculates the 2 nucleon bound-state wave functions according to the Bayman and Kallio prescription[11] . The binding energies for the transferred proton and neutron were taken to be $|S_p|-1/2\ E_x$ and $|S_n|-1/2\ E_x$, respectively, where Sp and S_n are the proton and neutron separation energies in ^{94}Tc and E_x is the excitation energy of the final state.

Transitions from a $J^{\pi}=0^{+}$ target to unnatural parity final states (1^{+}, 2^{-}, 3^{+},...) may proceed with mixed L_{np} contributions (0+2, 1+3, 2+4,...). The resulting shape of a given angular distribution depends on the relative amplitudes of the two L components. These amplitudes are governed by the j-j to L-S recoupling coefficient[12]

$$\begin{Bmatrix} \ell_1 & s_1 & j_1 \\ \ell_2 & s_2 & j_2 \\ L & S & J \end{Bmatrix}$$

where the two non-identical nucleons are transferred in the configuration $\left[\pi\ell_1 j_1, \nu\ell_2 j_2\right]_{J^{\pi}}$; $s_1=s_2=1/2$,such that S may take the values 0 or 1 .The present calculations were performed assuming S=1 transfer for all the transitions with the exception of the possible $J^{\pi}=0^{+}$ level at 2.72 MeV, considered as due to an L=S=0 transfer. When contributions from more than one L value were present, the computations were performed using the direct two-nucleon transfer option permitted by the code CHUCK[13], taking into account the relative amplitudes of the two L components. In addition, the product of the light particle spectroscopic amplitudes $S^{1/2}$ and the zero-range strength D_o was taken to be -1920 and-1100 for S=1 and S=0 transfers, respectively. These values are equivalent to utilizing a zero-range normalization factor of 244.

B . THE COUPLED-CHANNEL CALCULATIONS

The $L_{np}=0$ and $L_{np}=0+2$ angular distributions could not be well reproduced by the direct one-step DWBA calculations. As a result, Coupled Reaction Channel Calculations were made assuming a two-step (He,d)(d,p) process and also allowing for the interference between the one- and two-step mechanisms. The code CHUCK[13] which numerically solves the appropriate set of coupled differential equations, was used to calculate the coherent sum of the contributions due to the two processes.

The same optical parameters as in the DWBA calculations were used for the ^{3}He and p channels . For the (^{3}He,d)(d,p) path, the optical-potentials for the deuteron are needed and these were obtained from the compilation of optical-model parameters[14] and are included in Table 2, together with the parameters for the binding well. The binding energy of the transferred proton in the (^{3}He,d) channel was taken to be (5.49)+Q(^{3}He,d), where the Q-value refers to the (^{3}He,d) transition to the intermediate level assumed. Thus for the ($\pi 1g_{9/2}$) proton transfer the ground state of ^{93}Tc with the measured[15] spectroscopic factor of $C^2S_p \simeq 0.5$, and for the ($\pi 2\ d_{5/2}$) transfer, the 3.35 MeV level strongly excited[15] in the ^{92}Mo(^{3}He,d) ^{93}Tc reaction ($C^2S_p \simeq 0.8$) were taken to be the intermediate levels. For the (d,p) reaction the binding energy of the neutron was set to be Q(d,p) + 2.226 MeV, taking into account, in the case of the $\pi(2d_{5/2})\ \nu\ (2\ d_{5/2})$ configuration, the fact that the intermediate ^{93}Tc level is at an excitation energy of 3.35 MeV. The C^2S_n value for the transferred neutron was always set to be unity. In the two--step calculations with CHUCK, the product of the light particle spectroscopic amplitude $S^{1/2}$ and the zero-range strength D_o again enters both in the (^{3}He,d) and the (d,p) transitions. These values were -225 and 122.5, which correspond to the usual DWBA normalizations of 3.33 and 1.5 for the proton and the neutron transfers, respectively. The paths taken into account in the CHUCK calculations are indicated together with the comparison between the experimental and calculated angular distributions for the 1+ and 0+ levels in Fig. 4, while the values of $\sigma^{exp.}/\sigma^{theory}$ for these levels are listed in Table 3 .

IV - DISCUSSION

A . THE 1^+ LEVELS

Of the six levels assigned $J^\pi=1^+$ in the present work two (respectively at 440 and 960 keV) had been tentatively assigned 1^+ by previous radioactivity measurements[1].Later (p,nγ) measurements[2] also indicated 1^+ for the 440 keV level, although in a more recent (^{3}He,t) work[3] the angular distribution to this level could not be fitted well to any of the typical shapes.

In the present work in addition to these two states, a level at 1412 keV and a group of 3 levels around an excitation energy of 2.2 MeV, all show angular distributions of an L_{np}= 0+2 transfer. The measured cross sections drop sharply in the very forward angles indicating an L_{np}=0 contribution and for scattering angles of $\theta \gtrsim 15^0$ the calculated cross sections are much lower than the measured ones for a pure L_{np}=0 transfer. On the other hand, the DW angular distributions computed for an L_{np}=0+2 transfer, on the basis of a direct (p-n) transfer mechanism display a deep minimum around 30^0 not observed experimentally (dashed curves in fig.4) . Also shown in fig.4 are the results of coupled- channel calculations for a pure two-step transfer (dash-dot curves) as well as when both the one- and two-step mechanisms are considered (continuous curve). For the calculations all six levels were assumed to be of the $(\pi 1g_{9/2})(\nu 1g_{7/2})$ configuration. The calculated angular distributions reproduce the experimental data somewhat better, when the interference between the one- and two-step processes is taken into account,but the resulting fits are still far from excellent. The ratios of the experimental to theoretical cross sections for a direct one-step mechanism varies from 5 to 10, except for the 2124-keV level for which this ratio is 2.4. This fact might be taken to indicate the presence of other configurations in the wave functions of these levels. In fact the calculated direct one-step cross section for a $(2d_{5/2})^2_{1^+}$ configuration is an order of magnitude higher and a small admixture of this configuration may drastically alter the results of the calculations.

B . THE POSSIBLE 0^+ LEVEL AT 2719 KeV

The level at 2719 keV has an angular distribution different from those of the states assigned 1^+ .While the sharp drop in cross section in the forward angles is still present, a well difined minimum appears around $\theta \approx 25^0$, where the cross sections for the 1^+ levels tend to remain flat. The fits shown in fig.4 are the results of calculations assuming a $\left[\pi(2d_{5/2})\nu(2d_{5/2})\right]J^{\pi}=0^+$ configuration. It should be remarked that the interference calculations do reproduce the position of the minimum at 25^0, in contrast with the 1^+ angular distributions. Based on these observations the 2.719 keV level is suggested to have $J^{\pi}=0^+$. If this assigment is correct this level is a likely candidate for the antianalog configuration in ^{94}Tc . The excitation energy at which the analog of the g.s. of ^{94}Mo should occur may be calculated from the relation

$$E_x(\text{IAS}) = \Delta E_c - \delta_{np} + \Delta M(^{94}\text{Tc} - {}^{94}\text{Mo}) ,$$

where $\Delta M(^{94}\text{Tc} - {}^{94}\text{Mo})$ is the difference between the mass excess of ^{94}Tc and ^{94}Mo nuclei, and δ_{np} is the neutron-proton mass difference. The coulomb energy difference ΔE_C is calculated from the semi-empirical relation[16]

$$\Delta E_C = b_1\left(\bar{Z}/A^{1/3}\right) + b_2$$

where $\bar{Z}=Z_< + \frac{1}{2}$ is the average charge of the analog pair, $b_1=1430\pm 2.6$ and $b_2=-992\pm 22.6$.

The energy splitting ΔE of the IAS-AIAS doublet is given, to a first approximation, by

$$\Delta E \simeq \frac{(T_A+1)}{A} \langle lj|V_1(r)|lj\rangle$$

in terms of the radial matrix element of the isovector potential

$V_1(r)$[17]. Here, in the case of the (He,p) transitions, A and T_A refer to the target viz., ^{92}Mo. If the 2.72 MeV level is indeed the AIAS configuration, this leads to a value of 85 MeV for the radial matrix element, very close to the usually accepted value for nuclei in the $f_{7/2}$ region[18]. Recently Fortune et al.[19], have observed a possible 0^+ state at 3.49 MeV in ^{90}Y by means of the ^{88}Sr(^{3}He,p)^{90}Y reaction. A similar calculation as above again yields a value of 85 MeV for the radial matrix element of $V_1(r)$.

In addition three more levels at 3756, 3889 and 4036 keV excitation could possibly be due to L_{np}=0 or 0+2 transfers, but due to large experimental errors and missing data points no definite conclusions could be drawn from their angular distributions.

C . OTHER LEVELS

The lowest energy levels in ^{94}Tc belong to the $\pi(1g_{9/2})\nu(2d_{5/2})$ multiplet, giving rise to spins ranging from 2^+ to 7^+. Except for the unresolved 3^+ and 6^+ levels at 108 keV, the other members of the multiplet have been seen in the present work, with angular distributions consistent with their known spins. The only negative parity levels, also previously known, are the 2^- and 3^- levels, respectively at 326 and 470 keV. Their angular distributions have been calculated assuming a $\pi(2p_{1/2})\,\nu(2d_{5/2})$ configuration, which implies the presence of 2 holes in the $p_{1/2}$ proton- orbit in the ground state of the ^{92}Mo target.

No information was available in ^{94}Tc above an excitation energy of 1 MeV. Several angular distributions have been measured, all of which have been reproduced by $L_{np}=2$ or (2+4) transfers leading to $J^{\pi}=2^{+}$ or 3^{+} states. The calculated cross sections for all these levels are for direct one-step (p-n) transfer, assuming a $\pi(1g_{9/2})$ ν $(1g_{7/2})$ configuration and are, in general, lower than the observed values, expecially for the states for which assignments of $J^{\pi}=3^{+}$ have been made. This is evidently due to the fact that the wave functions of these levels are much more complicated than the simple shell-model configurations assumed in the calculations. Unfortunately there exist no theoretical calculations for the levels in ^{94}Tc above 1 MeV.

V - CONCLUSIONS

In the absence of other experimental data and the lack of knowledge of the wave functions involved, especially for excitation energies above 1 MeV, the present spin assignments should be regarded as tentative, even in cases where the angular distributions compare reasonably well with the experiment. This is due to the observation made earlier that even small admixtures in the wave functions could result in appreciable changes in the calculated angular distributions.

The present work makes it clear that the odd-odd nuclei of the A~90-110 region thus require further studies both from an experimental and a theoretical point of view. As could be seen, even the reaction mechanism of the (p-n) transfer has not been well-explored in this mass region. In the particular case of the 0^+ and 1^+ final states, although these are the strongest transitions, the direct one-step mechanism fails to reproduce the experimental data and it appears that a two-step mechanism does play a nonneglible role in these transitions.

It has been found[18] from even-target (^{3}He,p) reactions in the Ca-Fe region that the 0^+, T_{lower} states are excited with much less strength than expected from isobaric-spin coupling rules. Systematic studies of these antianalog configurations in the odd-odd nuclei of A~100 region would be highly desirable.

ACKNOWLEDGEMENTS

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FIGURE CAPTIONS

Figure 1 : Spectrum of proton groups from the ^{92}Mo (^{3}He,p) ^{94}Tc reaction.

Figures 2 and 3 : Proton angular distributions from the ^{92}Mo (^{3}He,p) ^{94}Tc reaction. The curves are the results of DW calculations (one-step direct transfer).

Figure 4 : Proton angular distributions for the 1^{+} and 0^{+} levels.

TABLE 1 - Results from the ^{92}Mo (^{3}He,p)^{94}Tc reaction at $E_{^3He}$=25 MeV

No	E_x(keV)	L_{np}	J^{π}	σ^{Exp}/σ^{DW} ($\theta \simeq 5°$)
1	G.S.	6	7^+	0.09
2	72	2	2^+	0.77
3	108 [a]			
4	210	4+6	5^+	0.44
5	238	4	4^+	1.05
6	326	1+3	2^-	0.12
7	432	0+2	1^+	6.4
8	470	3	3^-	0.06
9	815 [a]			
10	908			
11	955	0+2	1^+	7.5
12	1031	2+4	3^+	3.44
13	1250	2+4	3^+	10.1
14	1289			
15	1349			
16	1412	0+2	1^+	4.9
17	1523	2	2^+	1.15
18	1743			
19	1783	2+4	3^+	7.29
20	1871	2+4	3^+	6.28
21	2124	0+2	1^+	2.4
22	2186	0+2	1^+	10.1
23	2252	0+2	1^+	8.5
24	2341			
25	2397			
26	2504			
27	2719	0	0^+	0.8
28	2960	2+4	3^+	28.0
29	3082	2+4	3^+	24.7
30	3144	2 2+4	2^+ 3^+	3.3 14.3
31	3187	2 2+4	2^+ 3^+	3.7 17.1
32	3261			
33	3310			
34	3363			
35	3431			
36	3499			
37	3574			
38	3627	2^+ 2+4	2^+ 3^+	5.1 20.3
39	3677	2 2+4	2^+ 3^+	4.6 14.2
40	3756 [b]			
41	3792	2+4	3^+	12.2
42	3840	2+4	3^+	8.25
43	3889 [b]			
44	3956	2+4	3^+	11.52
45	4036 [b]			
46	4071	2	2^+	2.18
47	4132	2+4	3^+	11.46
48	4227	2+4	3^+	14.58
49	4272			
50	4356			
51	4427			

a possible doublets

b Angular distribution could be of L_{np}=0 or 0+2 shape, but no assignments possible because of missing data points and large error bars.

TABLE 2 - Optical-Model parameters used in the analysis of the $^{92}Mo(^{3}He,p)^{94}Tc$ reaction. Lengths are in fm and strengths in MeV .

Channel	V	r_0	a	W	$W'=4W_D$	r'_0	a'	V_{so}	r_{so}	a_{so}	r_{oc}
^{3}He	a)	1.20	0.72	a)	0	1.40	0.88	2.5	1.20	0.72	1.30
p	b)	1.17	0.75	b)	b)	1.32	0.51	6.2	1.01	0.75	1.25
d	100.8	1.099	0.835		52.56	1.344	0.747	6.53	1.099	0.835	1.30
Bound State	c)	1.25	0.65					7.5	1.25	0.65	1.25

a) $V = 151.9 - 0.17E + 50(N-Z)/A$

$W = 41.7 - 0.33E + 44(N-Z)/A$

b) $V = 54.0 - 0.32E + 24(N-Z)/A + 0.4(Z/A^{1/3})$

$W = 0.22E - 2.7$ or zero, whichever is greater

$W_D = 11.8 - 0.25E + 12(N-Z)/A$ or zero, whichever is greater.

c) See section III of text .

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$W = 0.22E - 2.7$ or zero, whichever is greater

$W_D = 11.8 - 0.25E + 12(N-Z)/A$ or zero, whichever is greater.

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25	2397			
26	2504			
27	2719	0	0^+	0.8
28	2960	2+4	3^+	28.0
29	3082	2+4	3^+	24.7
30	3144	2 2+4	2^+ 3^+	3.3 14.3
31	3187	2 2+4	2^+ 3^+	3.7 17.1
32	3261			
33	3310			
34	3363			
35	3431			
36	3499			
37	3574			
38	3627	2^+ 2+4	2^+ 3^+	5.1 20.3
39	3677	2 2+4	2^+ 3^+	4.6 14.2
40	3756 [b]			
41	3792	2+4	3^+	12.2
42	3840	2+4	3^+	8.25
43	3889 [b]			
44	3956	2+4	3^+	11.52
45	4036 [b]			
46	4071	2	2^+	2.18
47	4132	2+4	3^+	11.46
48	4227	2+4	3^+	14.58
49	4272			
50	4356			
51	4427			

a possible doublets

b Angular distribution could be of L_{np}=0 or 0+2 shape, but no assignments possible because of missing data points and large error bars.

TABLE 2 - Optical-Model parameters used in the analysis of the $^{92}Mo(^3He,p)^{94}Tc$ reaction. Lengths are in fm and strengths in MeV .

Channel	V	r_0	a	W	$W'=4W_D$	r'_0	a'	V_{so}	r_{so}	a_{so}	r_{oc}
^3He	a)	1.20	0.72	a)	0	1.40	0.88	2.5	1.20	0.72	1.30
p	b)	1.17	0.75	b)	b)	1.32	0.51	6.2	1.01	0.75	1.25
d	100.8	1.099	0.835		52.56	1.344	0.747	6.53	1.099	0.835	1.30
Bound State	c)	1.25	0.65					7.5	1.25	0.65	1.25

a) $V = 151.9 - 0.17E + 50(N-Z)/A$

$W = 41.7 - 0.33E + 44(N-Z)/A$

b) $V = 54.0 - 0.32E + 24(N-Z)/A + 0.4(Z/A^{1/3})$

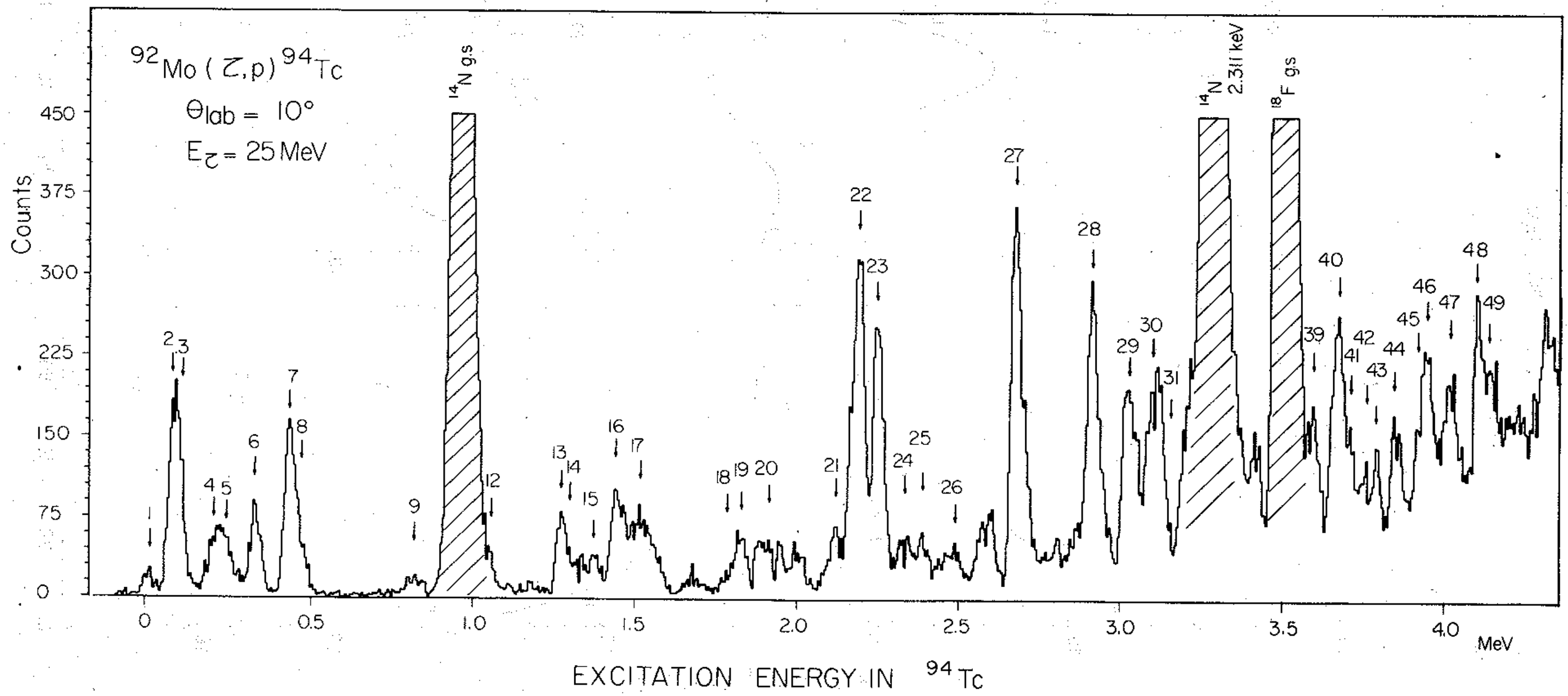
$W = 0.22E - 2.7$ or zero, whichever is greater

$W_D = 11.8 - 0.25E + 12(N-Z)/A$ or zero, whichever is greater.

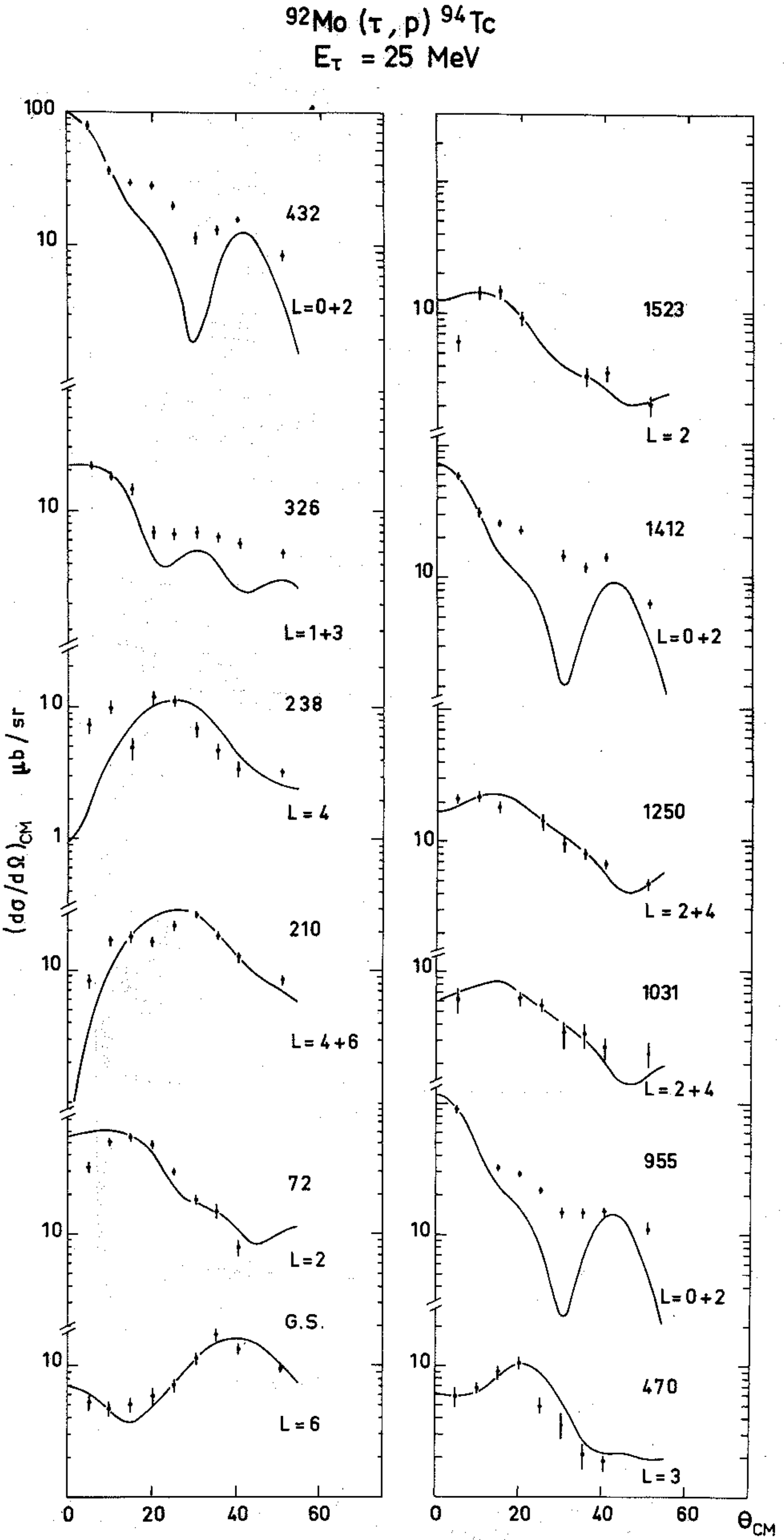
c) See section III of text .

TABLE 3 - The ratios of experimental to calculated cross sections for the 0^+ and 1^+ levels.

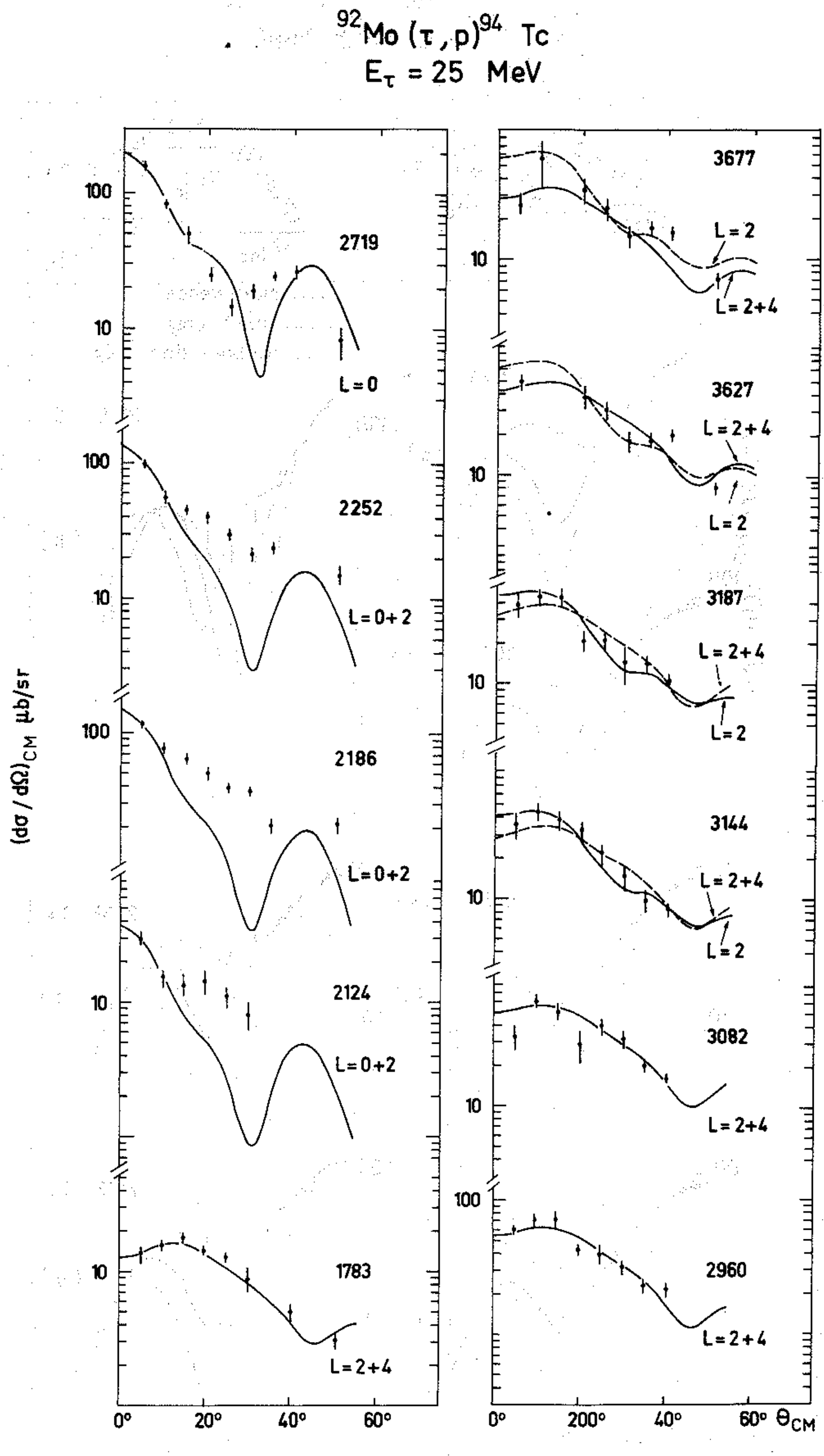
E_x (KeV)	L_{tr}	J^π	$\sigma^{exp}/\sigma^{calc}$ (5°) Direct only	Two-step only	interference
432	0+2	1^+	6.4	15.4	4.15
955	0+2	1^+	7.5	19.0	4.5
1412	0+2	1^+	4.9	11.6	3.2
2124	0+2	1^+	2.5	7.6	1.61
2186	0+2	1^+	10.1	30.0	6.33
2252	0+2	1^+	8.5	25.4	5.03
2719	0	0^+	0.8	0.3	0.3



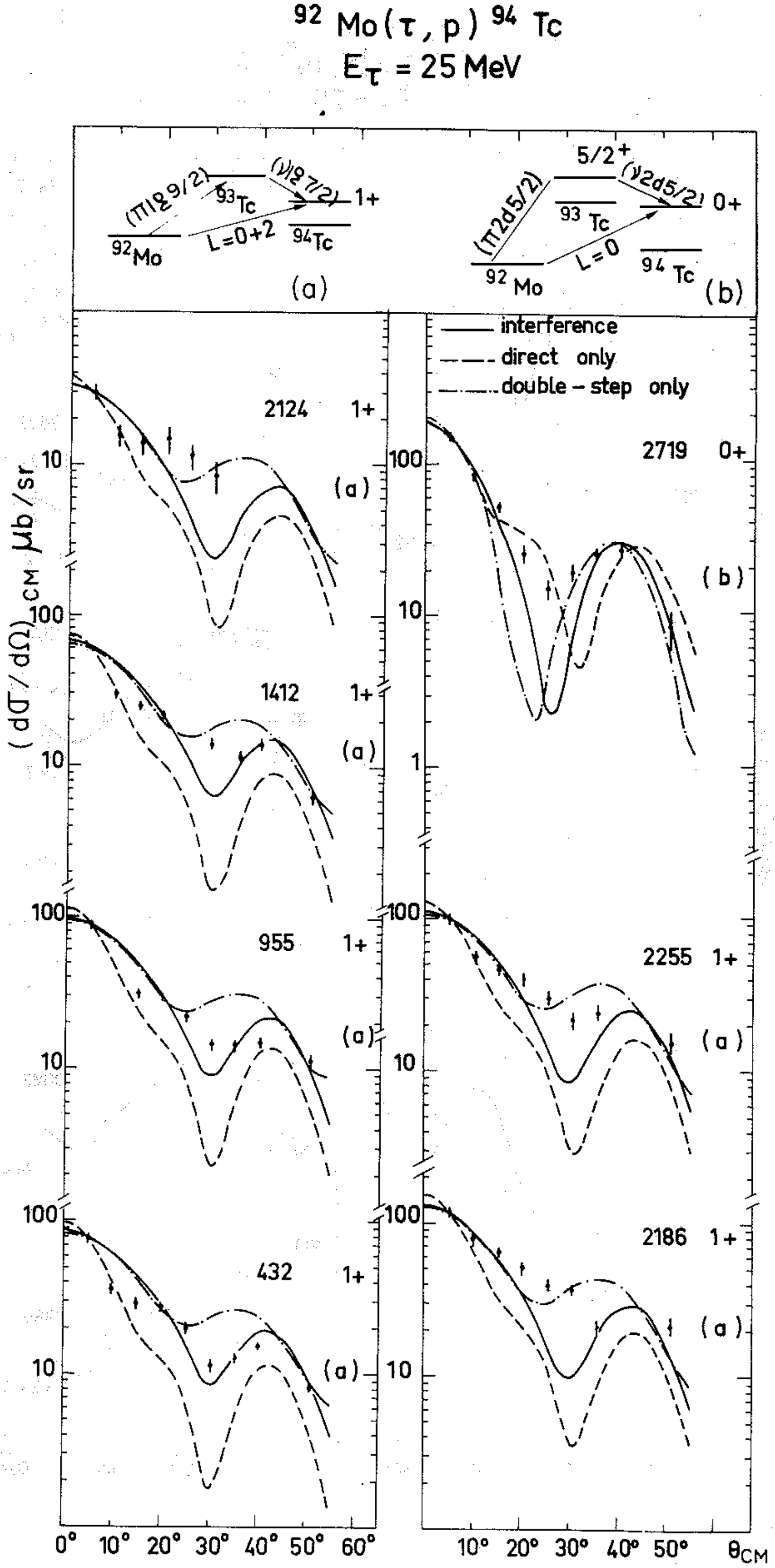
$^{92}Mo(\mathcal{C},p)^{94}Tc$
$\Theta_{lab} = 10°$
$E_{\mathcal{C}} = 25$ MeV
Counts
^{14}N g.s
^{14}N 2.311 keV
^{18}F g.s
EXCITATION ENERGY IN ^{94}Tc
MeV



$^{92}Mo\ (\tau, p)\ ^{94}Tc$
E_τ = 25 MeV
100
10
432
L=0+2
10
326
L=1+3
10
238
1
L = 4
10
210
L = 4+6
72
10
L=2
G.S.
10
L = 6
$(d\sigma/d\Omega)_{CM}$ μb/sr
10
1523
L = 2
1412
10
L=0+2
1250
10
L = 2+4
10
1031
L = 2+4
955
10
L=0+2
10
470
L = 3
0
20
40
60
0
20
40
60
θ_{CM}



$^{92}Mo(\tau,p)^{94}Tc$
$E_\tau = 25$ MeV
$(d\sigma/d\Omega)_{CM}$ µb/sr
2719
L=0
2252
L=0+2
2186
L=0+2
2124
L=0+2
1783
L=2+4
3677
L=2
L=2+4
3627
L=2+4
L=2
3187
L=2+4
L=2
3144
L=2+4
L=2
3082
L=2+4
2960
L=2+4
Θ_{CM}



^{92}Mo(τ, p) ^{94}Tc
$E_τ$ = 25 MeV
(πlg9/2)
^{93}Tc
(ν)g7/2)
1+
^{92}Mo
L=0+2
^{94}Tc
(a)
5/2+
(π2d5/2)
(ν)2d5/2)
0+
^{93}Tc
^{92}Mo
L=0
^{94}Tc
(b)
interference
direct only
double – step only
2124 1+
1412 1+
955 1+
432 1+
2719 0+
2255 1+
2186 1+
(dσ/dΩ)$_{CM}$ μb/sr
θ$_{CM}$