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Distorted wave Born approximation analysis for the $^{16}O(^{3}He, \alpha)^{15}O$ reaction

F El-Bedewi and M Shalaby

Physics Department, Faculty of Science, Ein Shams University, Cairo, Egypt

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Abstract. Angular distributions for the $^{16}O(^{3}He, \alpha)^{15}O$ reaction induced by 15 MeV ^{3}He particles have been measured. Distributions characterized by single-nucleon pickup have been compared with the local zero range form of the DWBA. A normalization factor of 14·2 has been estimated and absolute spectroscopic factors have been extracted for excited states in ^{15}O up to 10 MeV. A discussion for the odd and even parity states has been given in the weak-coupling model. Neutron filling probabilities for the $1d_{5/2}$–$2s_{1/2}$ and $1d_{3/2}$ orbits have been calculated for the ^{16}O ground state.

1. Introduction

Extensive theoretical and experimental investigations have been recently performed to study the structure of the ^{15}O nucleus. From the simple shell model, neutron pickup from the closed ^{16}O nucleus can leave a hole in the p shell and accordingly the $\frac{1}{2}^-$ ground state and $\frac{3}{2}^-$ excited state at 6·18 MeV have usually been regarded as $1p_{1/2}$ and $1p_{3/2}$ single hole states respectively. However the presence of additional negative parity states and other low-lying positive parity states has indicated complexity in the structure of that nucleus which could be related to some particle–hole admixture in the ^{16}O ground state. Recently, the weak-coupling model developed by Ellis and Engeland (1970) was successfully used by Lie *et al* (1970) and Lie and Engeland (1971) in calculating, for $A = 15$ nuclei, the energy locations of the possible particle–hole excitations within the framework of the spherical shell model. Applying such weak coupling between particles in the s–d shell and holes in the p shell, both positive and negative parity states were theoretically obtained and found to be in good agreement with the corresponding energy levels below 8·6 MeV in the ^{15}O and ^{15}N mirror nuclei. However the correspondence seems uncertain for states lying within the upper 3 MeV region and the situation still requires more experimental investigations to correlate fully the theoretical suggestions for such higher excited states.

Earlier measurements of neutron pickup from ^{16}O have been made by Kavaloski *et al* (1963) and Warburton *et al* (1965) via (p, d) and ($^{3}He, \alpha$) reactions respectively. Both of these studies observed only the negative parity $1p_{3/2}$ and $1p_{1/2}$ hole states. The succeeding studies of Snelgrove and Kashy (1969) for (p, d) and Bohne *et al* (1968) for ($^{3}He, \alpha$) reactions were limited mainly to the low-lying excited states. The present experiment was performed to serve the dual purposes of covering a wider range of excitation energies in ^{15}O and to get an estimation for the excitation strength out of the p shell in the ^{16}O ground state wavefunction.

2. Experimental procedure and measurements

A beam of $^{3}He^{++}$ particles accelerated to 15 MeV by the tandem accelerator at the University of Pennsylvania was allowed to enter a ^{16}O gas cell characterized by no entrance window (Middleton 1969). The gas was continuously leaked into the cell at a stabilized pressure of 15 Torr. To maintain the purity of the gas it was allowed to pass, during its recirculation process, through a liquid molecular sieve cooled by liquid nitrogen.

The outgoing α particles were allowed to pass through an exit window consisting of 184 $\mu g\,cm^{-2}$ paralyne C. They were then momentum analysed at angular intervals of 7·5° over an angular range from 7·5°–157·5° using a multiangle magnetic spectrograph designed by Middleton and Hinds (1962). The analysed α particles were detected by 21 nuclear emulsion plates each of 40 in, placed along the corresponding focal planes of the magnets. Scanning and analysis of these plates have been carried out at Ein Shams University, Cairo, and a typical α particle spectrum recorded at angle $22\frac{1}{2}°$ is presented in figure 1. As shown in this spectrum, twenty-seven α particle groups were identified to correspond to states of ^{15}O covering excitation energies up to 11·995 MeV as shown in table 1.

The reaction energy, Q_0, was found to be $4{\cdot}917 \pm 0{\cdot}010$ MeV in agreement with the value $4{\cdot}910 \pm 0{\cdot}002$ MeV derived on the basis of the mass difference tables given by Ajzenberg (1970). In the compilation given by the latter author, the ^{15}O energy levels were found to agree with the observed excited states with the exception of a level at 11·960 MeV which may be considered new.

3. Angular distribution analysis

Analysis of the experimental angular distributions was performed using the local zero range form of the DWBA code of Smith (1967) after being adjusted to run on the ICL 1905 E computer at Cairo University. For the (^{3}He, α) reaction on a spin zero target, the experimental cross section is related to the theoretical DWBA cross section $\sigma_{lj}(\theta)$ by the expression

$$\sigma_{\mathrm{exp}}(\theta) = NC^2 S_{lj} \sigma_{lj}(\theta)$$

where l, j are the quantum numbers of the transferred particle and C is the isospin coupling coefficient which is equal to $\frac{1}{2}$ for a (^{3}He, α) reaction on a $T = 0$ target leading to $T = \frac{1}{2}$ final states. N is a normalization factor which includes the overlap of the ^{3}He and α internal wavefunctions and S_{lj} is the spectroscopic factor.

In selecting the appropriate optical model parameters to be used in the entrance and exit channels; a set successfully used by Garrett *et al* (1970) has been tried. This set represents a combination of average optical model elastic scattering parameters on light nuclei by ^{3}He (Gray *et al* 1970, Fortune *et al* 1969, Drisko *et al* 1967 (see Tamura 1967)) and α particles (Gray *et al* 1970, H T Fortune and B Zeidman (see Garratt *et al* 1970), Dehnhard *et al* 1969). In trying this set, the fits between theoretical and experimental angular distributions were in general unsatisfactory with the exception of the backward angles of the ground state angular distribution as shown in figure 2. However, recent elastic scattering measurements of 15 MeV ^{3}He particles on ^{16}O were reported by Zurmühle and Fou (1969) and their optical model parameters have been used to

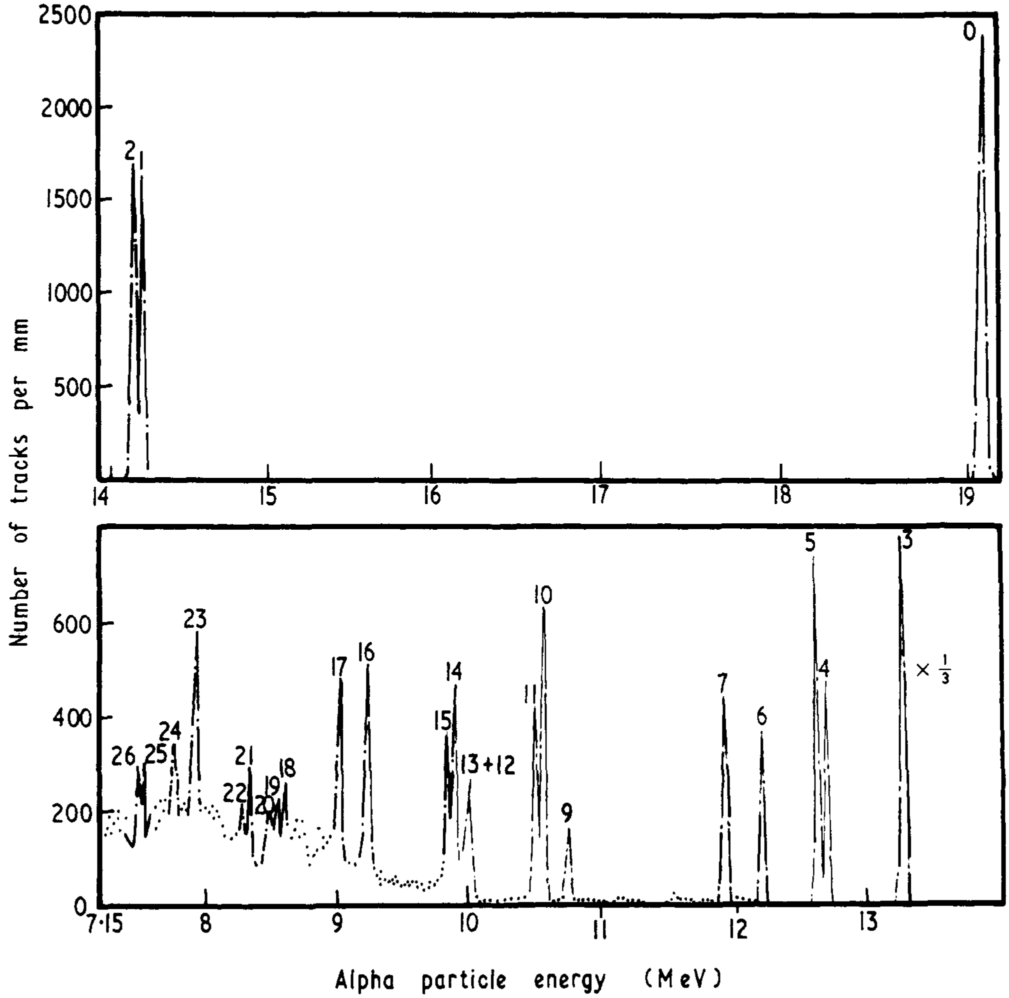

Figure 1. Typical α particle spectrum recorded at an angle of 22·5° for the $^{16}O(^3He, \alpha)^{15}O$ reaction at $E_{^3He} = 15$ MeV.

replace the above-mentioned entrance channel parameters. This choice has been found to give reasonable agreement with the experimental angular distributions particularly for forward angles. Table 1 represents the adopted optical model parameters for the present calculations together with the trial ones. It is to be noted that the absorptive α particle potential (W) could be taken as a constant value of 8·75 MeV or as energy dependent $W = 9{\cdot}25 - 0{\cdot}5E_x$ (Gray *et al* 1970). Both cases have been tried and the corresponding theoretical distributions showed no significant differences except at backward angles where the cross section in the case of $W(E_x)$ was found to be larger than that for constant W. With respect to the bound state wavefunction, a Woods–Saxon potential with $r_0 = 1{\cdot}26$ fm, $a = 0{\cdot}60$ fm and potential well depth adjusted by the program to match the neutron binding energy were used. The value of the spin–orbit coupling v_{so} was taken as 6·0 MeV, which is equivalent to the use of a Thomas spin–orbit strength of $\lambda = 25$ in the DWUCK program.

Table 1. Optical model parameters used in the DWBA analysis.

Channel	v (MeV)	r (fm)	a (fm)	W (MeV)	r_1 (fm)	a_1 (fm)	References
Adopted set I							
$^{16}O+{}^3He$	158	0·96	0·80	6·75	2·25	0·65	A
$^{15}O+\alpha$	194·9	1·32	0·604	9·25†	1·60	0·488	C
Trial set II							
$^{16}O+{}^3He$	170	1·14	0·723	20·0	1·5	0·800	B
$^{15}O+\alpha$	194·9	1·32	0·604	9·25†	1·60	0·488	C

A, Zurmühle and Fou (1969); B, Gray *et al* (1970), Fortune *et al* (1969), Drisko *et al* (1967); C, Gray *et al* (1970), Fortune and Zeidman (1970), Dehnhard *et al* (1969).
† $W = 9{\cdot}25 - 0{\cdot}5E_x$ (Gray *et al* 1970).

The present experimental angular distributions, corresponding to energy levels in ^{15}O up to 10 MeV, are presented together with their appropriate DWBA curves in figures 2, 3, 4 and 5. Table 2 includes E_x, l_n and J^π assignments for these levels. A brief discussion of these parameters for the observed odd and even parity states is given as follows.

3.1. *Odd parity states*

Two strong transitions corresponding to the ground and the 6·175 MeV states and three relatively weak transitions to the excited states at 8·985, 9·611 and 9·668 MeV have been fitted with $l_n = 1$ DWBA calculations as shown in figure 2. Among these distributions, the ground state transition is of considerable interest and a satisfactory fitting for its distribution at forward angles ($\leqslant 60°$) is achieved with $1p_{1/2}$ neutron pickup DWBA calculations using set I of the optical model parameters. With regard to the excited states 6·175, 8·985 and 9·611 MeV, $1p_{3/2}$ DWBA calculations have been used to fit their corresponding experimental angular distributions. Such fitting is in accordance with the J^π assignment of $\frac{3}{2}^-$ to these excited states as experimentally established by a variety of reactions (Ajzenberg 1970, Amokrane *et al* 1972). Moreover these states are considered as the three lower $\frac{3}{2}^-$ model states theoretically predicted by the application of the weak-coupled model to the negative parity states of the $A = 15$ nuclei reported by Lie and Engeland (1971).

In the case of the excited state at 9·668 MeV, the best probable fitting for the corresponding experimental angular distribution has been achieved by using a $1p_{1/2}$ DWBA calculation. This state was previously suggested to have a spin and parity of $(\frac{7}{2}^-)$ or $(\frac{9}{2}^-)$ in the analysis of the $^{14}N(p, p)^{14}N$ reaction (Lambert and Durand 1967) and theoretically predicted by Lie and Engeland (1971) to have $J^\pi = \frac{7}{2}^-$. However, the present experimental angular distribution shows no indication of the $l_n = 3$ pickup pattern which could be expected for the population of $\frac{7}{2}^-$ or $\frac{9}{2}^-$ states, but rather a possible $l_n = 1$ pattern. The present J^π assignment of $\frac{1}{2}^-$ to this state might confirm the value obtained recently by Etten and Lenz (1972) in the study of the $^{13}C(^3He, n)^{15}O$ reaction, and accordingly this state cannot be the analogue of the $\frac{7}{2}$ 9·83 MeV state in

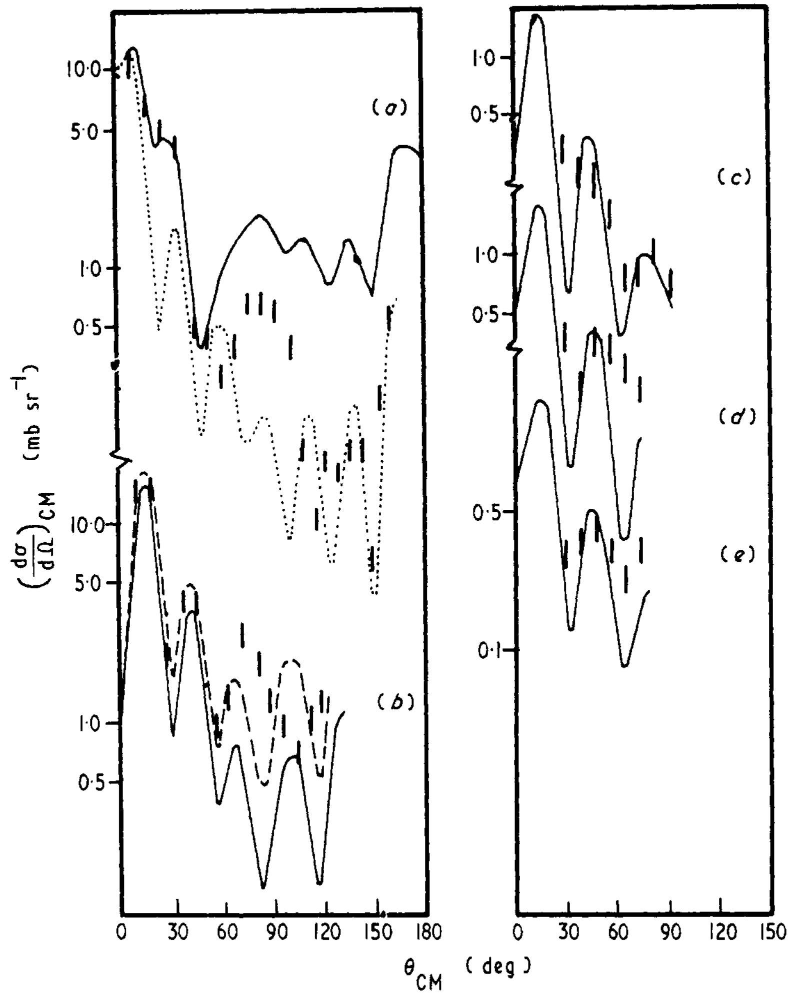

Figure 2. Angular distributions for $l_n = 1$ transitions. Full and broken curves represent the appropriate DWBA calculations using set I of optical model parameters with an α particle potential (W) taken as constant or energy dependent respectively. The dotted curve represents the use of the trial set II of the optical model parameters. (*a*) $E_x = 0{\cdot}0$ MeV, $J^{\pi} = \frac{1}{2}^{-}$; (*b*) $E_x = 6{\cdot}175$ MeV, $J^{\pi} = \frac{3}{2}^{-}$; (*c*) $E_x = 8{\cdot}985$ MeV, $J^{\pi} = \frac{3}{2}^{-}$; (*d*) $E_x = 9{\cdot}611$ MeV, $J^{\pi} = \frac{3}{2}^{-}$; (*e*) $E_x = 9{\cdot}668$ MeV, $J^{\pi} = \frac{1}{2}^{-}$.

^{15}N as suggested by Amokrane *et al* (1972) but may correspond to the $(\frac{1}{2}, \frac{3}{2})^{(+)}$ state at 9·93 MeV in ^{15}N.

3.2. Even parity states

The observed even parity states in ^{15}O have been analysed by direct DWBA pickup calculations of even l_n neutrons from the ^{16}O ground state which is assumed to contain admixtures of $1d_{5/2}$ and $2s_{1/2}$ and $1d_{3/2}$ neutrons. A brief discussion for the observed l_n transitions is given as follows.

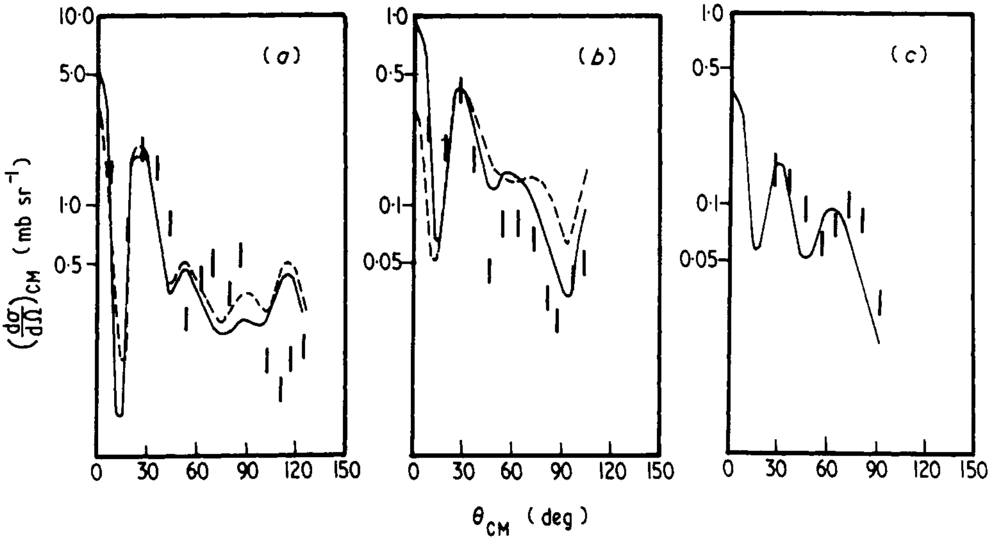

Figure 3. Angular distributions for $l_n = 0$ transitions. Full and broken curves represent the appropriate DWBA distributions using set I of optical model parameters with an α particle potential (W) taken as constant or energy dependent respectively. (a) $E_x = 5{\cdot}182$ MeV, $J^\pi = \frac{1}{2}^+$; (b) $E_x = 7{\cdot}557$ MeV, $J^\pi = \frac{1}{2}^+$; (c) $E_x = 8{\cdot}744$ MeV, $J^\pi = \frac{1}{2}^+$.

3.2.1. The $l_n = 0$ transitions. The intense experimental angular distribution corresponding to the excited state at 5·182 MeV was found as shown in figure 3 to be well fitted with an $l_n = 0$ DWBA curve using a cut-off radius of zero, rather than the value of 4·9 fm which has been used in the PWBA and DWBA calculations of Hinds and Middleton (1959) and Bohne *et al* (1968) respectively. Moreover the α particle angular distributions corresponding to the excited states at 7·557 and 8·744 MeV are considered to be new and could also be fitted with $l_n = 0$ DWBA curves. These three excited states might then have spin–parity $\frac{1}{2}^+$ which is consistent with the experimental results reported in the compilation of Ajzenberg (1970) as well as the theoretical predictions of Lie *et al* (1970) who considered these states as representing, in order, the three lower $\frac{1}{2}^+$ model states.

3.2.2. The $l_n = 2$ transitions. $1d_{5/2}$ and $1d_{3/2}$ DWBA calculations have been carried out to fit the experimental angular distributions corresponding to the excited states at (5·241, 6·861) and (6·791, 8·290, 8·924) MeV respectively as shown in figure 4. These calculations are in accordance with the spin–parity assignments which have been established for these states (Ajzenberg 1970 and Etten and Lenz 1972). Moreover, one can point out that while the states at 5·241 and 6·861 MeV represent the first and second $\frac{5}{2}^+$ model states, the third one expected by Lie *et al* (1970) to be around 9 MeV could be taken as the new 8·95 MeV level recently observed in the $^{14}N(p, \gamma)^{15}O$ reaction (P D Kunz 1972, see Edwards *et al* 1973) and might have $J^\pi = \frac{5}{2}^+$ (Etten and Lenz 1972). The excited state at 10·286 MeV has been assigned a spin–parity of $\frac{5}{2}^+$ or greater in the spectroscopic study of ^{15}O by use of the $^{13}C(^3He, n)^{15}O$ reaction (Georgopulos *et al* 1972) and might be considered as the fourth $\frac{5}{2}^+$ model state in the theoretical work of Lie *et al* (1970). Unfortunately the experimental angular distribution data for this state are not adequate for a DWBA analysis but could only be used for estimating the corresponding transition strength.

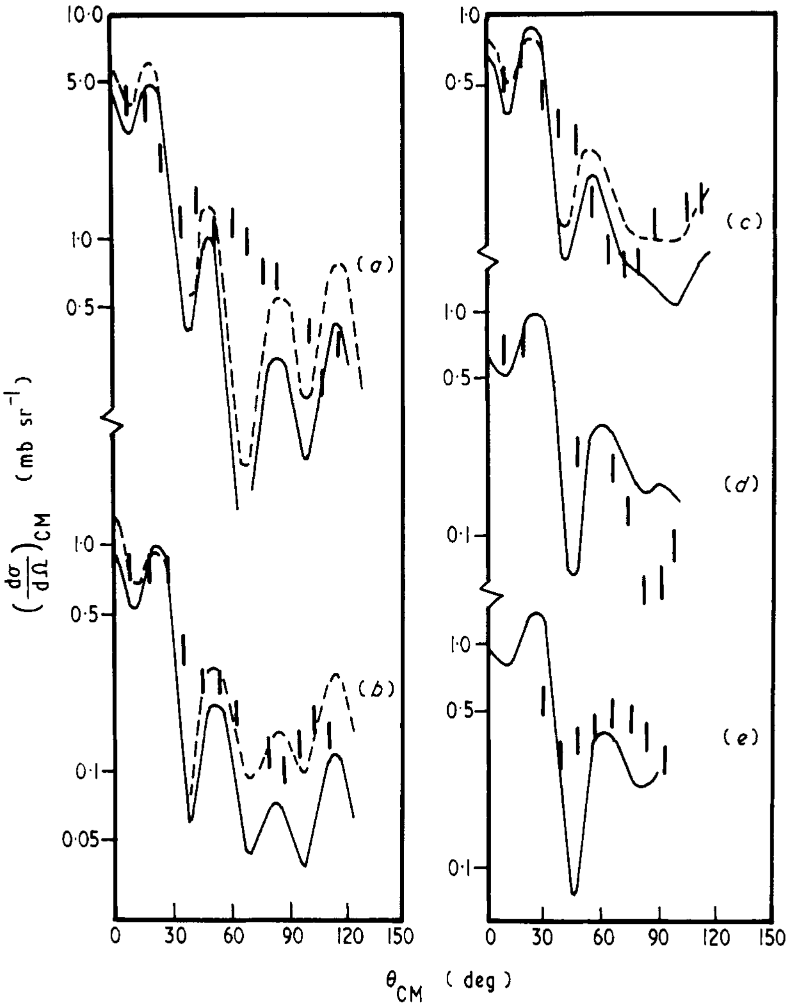

Figure 4. Angular distributions for $l_n = 2$ transitions. Full and broken curves represent the appropriate DWBA calculations using set I of optical model parameters with α particle potential (W) taken as constant or energy dependent respectively. (a) E_x = 5·241 MeV, $J^\pi = \frac{5}{2}^+$; (b) E_x = 6·861 MeV, $J^\pi = \frac{5}{2}^+$; (c) E_x = 6·791 MeV, $J^\pi = \frac{3}{2}^+$; (d) E_x = 8·290 MeV, $J^\pi = \frac{3}{2}^+$; (e) E_x = 8·924 MeV, $J^\pi = \frac{3}{2}^+$.

3.2.3. The l_n = 4 transition. The experimental angular distribution corresponding to the excited state at 7·278 MeV was found to be considerably peaked at about 35° which might suggest an l_n = 4 pickup pattern as shown in figure 5. This level was considered to be the mirror of the 7·56 MeV level in ^{15}N which has an established spin–parity assignment of $\frac{7}{2}^+$ (Ajzenberg 1970). So, it was encouraging to carry out the present $1g_{7/2}$ DWBA calculations on the assumption that this level was excited via a direct reaction mechanism corresponding to the pickup of a $1g_{7/2}$ neutron. This treatment may be in agreement with the theoretical calculations of Lie *et al* (1970) which predicted such a $\frac{7}{2}^+$ level with a wavefunction having an almost pure 1p–2h configuration with 98 % of the strength allocated to it and the remaining 2 % to the 3p–4h configuration. It should be mentioned that the potential well for such a $\frac{7}{2}^+$ (7·278 MeV) level adjusted by the

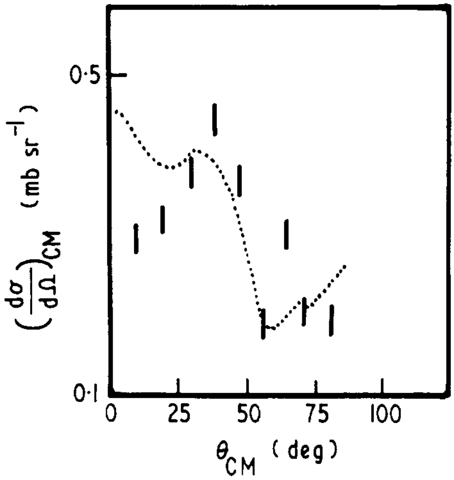

Figure 5. Angular distribution for $l_n = 4$ transition ($E_x = 7{\cdot}278$ MeV) (DWUCK program).

applied DWUCK program to match the neutron binding energy was found to be 220 MeV which is quite high

An alternative description for the excitation of this level might be, as suggested by Snelgrove and Kashy (1969), via a two-step process in which the 6·13 MeV 3^- level of ^{16}O is first excited and probably followed by the pickup of a $1p_{1/2}$ neutron.

4. Spectroscopic factor analysis

In order to extract spectroscopic factors, the theoretical angular distributions (W constant) are normalized to the largest forward peak of the experimental data for estimating the ratio $\sigma_{exp}(\theta)/\sigma_{lj}$. Although relative spectroscopic factors NS_{lj} could be achieved by this process as represented in table 2, yet for determining absolute values for S_{lj} one has to adjust an appropriate value for the normalization factor N. Unfortunately, this factor is not well determined for (^{3}He, α) reactions since previous theoretical and experimental estimates vary from approximately 10 to 50 (Bray and Nurzynski 1969, Gray *et al* 1970, Lim 1970). However, one can estimate the normalization factor N on the basis of the ^{16}O ground state wavefunction of Brown and Green (1966) which has the form:

$$|^{16}O_{gs}\rangle = 0{\cdot}874|0p\text{–}0h| + 0{\cdot}469|2p\text{–}2h| + 0{\cdot}130|4p\text{–}4h\rangle.$$

Such a function can give a value of 5·75 for the sum of the pickup 1p spectroscopic factors which could be taken to be equal to the value $\Sigma NS_{lj}(1p) = 81{\cdot}5$ experimentally determined in the present investigation. Accordingly the normalization constant is estimated as $N = 14{\cdot}2$ and thus could be used in deriving absolute spectroscopic factors. For strong excitations, the estimated uncertainty in the spectroscopic factors amounts to about 15% while for weak excitations the uncertainty may be up to 30%. It is to be noted that the derived value of N is in close agreement with that derived as $N = 14$ by Edwards *et al* (1973), applying the procedure of normalizing the sum of the $f_{7/2}$ strengths for (^{3}He, α) and (p, d) reactions on Ni which is then renormalized to satisfy the sum rule limit $\Sigma f_{7/2} = 8$.

Table 2. Angular momentum transfer and spectroscopic factors for levels observed in the $^{16}O(^{3}He, \alpha)^{15}O$ reaction.

Level number	E_x† (MeV)	l_n‡	J^π§	Spectroscopic factors	
				NS_{lj}	S_{abs} (N = 14·2)
0	0	1	$\frac{1}{2}^-$	16·3	1·15
1	5·182	0	$\frac{1}{2}^+$	4·8	0·34
2	5·241	2	$\frac{5}{2}^+$	9·7	0·68
3	6·175	1	$\frac{3}{2}^-$	35·0	2·46
4	6·791	2	$\frac{3}{2}^+$	3·5	0·25
5	6·861	2	$\frac{5}{2}^+$	4·2	0·30
6	7·278	(4)	$\frac{7}{2}^+$	0·98	0·07
7	7·557	0	$\frac{1}{2}^+$	1·7	0·12
8	8·290	2	$\frac{3}{2}^+$	5·6	0·40
9	8·744	0	$\frac{1}{2}^+$	0·90	0·06
10	8·924	2	$\frac{3}{2}^+$	4·2	0·30
11	8·985	1	$\frac{3}{2}^-$	8·8	0·62
12	9·493‖				
13	9·535‖				
14	9·611	1	$\frac{3}{2}^-$	10·9	0·77
15	9·668	1	$\frac{1}{2}^-$	10·5	0·74
16	10·286	(2)	$\frac{5}{2}^+$	4·00	0·28
17	10·469				
18	10·900‖				
19	10·945‖				
20	11·010				
21	11·158				
22	11·217‖				
23	11·578				
24	11·470‖				
25	11·960‖				
26	11·995‖				

† The estimated uncertainty in excitation energies (E_x) is 10 keV except for those marked ‖ where the uncertainty is doubled.

‡ Uncertain values indicated in parentheses.

§ Established or most favourable spin assignment (as discussed in text).

As the ground state of ^{16}O contains admixtures of neutrons from 2s–1d orbits which accounts for the observed excitation of even parity states, one would expect the ratio of the summed $1p_{3/2}$ spectroscopic factors to that of $1p_{1/2}$ to be greater than 2. In the present investigation this ratio was found to be 2·04 : 1 which is in agreement with the ratio 2·19 : 1 theoretically determined from the calculations of Wong (1968). Moreover the absolute spectroscopic factors experimentally determined for the even parity states could be used to evaluate the neutron filling probabilities (%) to the $1d_{5/2}$, $2s_{1/2}$ and $1d_{3/2}$ orbits in the ^{16}O ground state. For these orbits, the corresponding summed spectroscopic factors are found to be 1·26, 0·52, and 0·95 respectively and accordingly the calculated neutron filling probabilities are 21 %, 26 % and 24 % respectively.

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References

Ajzenberg F 1970 *Nucl. Phys.* A **152** 1–221
Amokrane A, Allab M, Beaumevieille H, Faid B, Bersillon O, Chambon B, Drain D and Vidal J L 1972 *Phys. Rev.* C **6** 1934–45
Bohne W, Homeyer H, Morgenston H and Scheer J 1968 *Nucl. Phys.* A **113** 97–103
Bray K H and Nurzynski J 1969 *Nucl. Phys.* A **127** 622–34
Brown G E and Green A M 1966 *Nucl. Phys.* **75** 401–17
Dehnhard D, Williams N and Yntema J L 1969 *Phys. Rev.* **180** 967–70
Drisko R M, Roos P G and Bassel R H 1967 *Proc. Int. Conf. on Nuclear Structure* and private communication to T Tamura
Edwards F M, Kraushaar J J and Ridley B W 1973 *Nucl. Phys.* A **199** 463–80
Ellis P J and Engeland T 1970 *Nucl. Phys.* A **144** 161–90
Etten M P and Lenz G H 1972 *Nucl. Phys.* A **179** 448–64
Fortune H T, Gray T G, Trost W and Fletcher N R 1969 *Phys. Rev.* **179** 1033–46
Garrett J D, Middleton R and Fortune H T 1970 *Phys. Rev.* C **2** 1243–54
Georgopulos P D, Lochstet W A and Bleuler E 1972 *Nucl. Phys.* A **183** 625–39
Gray T J, Fortune H T, Trost W and Fletcher N R 1970 *Nucl. Phys.* A **144** 129–45
Hinds S and Middleton R 1959 *Proc. Phys. Soc.* A **73** 727–32
Kavaloski C D, Bassani G and Hintz N M 1963 *Phys. Rev.* **132** 813–22
Lambert M and Durand M 1967 *Phys. Lett.* **24B** 287–90
Lie S and Engeland T 1971 *Nucl. Phys.* A **169** 617–28
Lie S, Engeland T and Dahll G 1970 *Nucl. Phys.* A **156** 449–64
Lim T K 1970 *Nucl. Phys.* A **148** 299–311
Middleton R 1969 *Proc. Int. Conf. on Nuclear Reactions Induced by Heavy Ions, Heidelberg* (Amsterdam: North Holland) pp 263–76
Middleton R and Hinds S 1962 *Nucl. Phys.* **34** 404–23
Smith W R 1967 *Oxford University, Nuclear Physics Laboratory Report* No 36
Snelgrove J L and Kashy E 1969 *Phys. Rev.* **187** 1246–58
Tamura T 1967 *Phys. Rev.* **165** 1123–5
Warburton E K, Parker P D and Donovan P F 1965 *Phys. Lett.* **19** 397–8
Wong S S M 1968 *Nucl. Phys.* A **120** 625–44
Zurmühle R W and Fou C M 1969 *Nucl. Phys.* A **129** 502–12