# Angular correlation study of the $^{16}O(^{7}Li,t^{16}O)^{4}He$ reaction



1974 J. Phys. A: Math. Nucl. Gen. 7 1748

(http://iopscience.iop.org/0301-0015/7/14/007)

J. Phys. A: Math., Nucl. Gen., Vol. 7, No. 14, 1974. Printed in Great Britain. © 1974

# Angular correlation study of the $^{16}O(^{7}Li, t\,^{16}O)^{4}He$ reaction

A D Panagiotou†, J C Cornell, N Anyas-Weiss, P N Hudson, A Menchaca Rocha‡, D K Scott and B E F Macefield
Nuclear Physics Laboratory, Keble Road, Oxford, UK

Received 4 March 1974, in final form 20 May 1974

**Abstract.** Angular correlations between tritons and $^{16}O$ GS nuclei, produced in the sequential reaction $^{16}O(^{7}Li, t)^{20}Ne^{*}(\alpha)^{16}O$, have been measured for a number of levels in $^{20}Ne$. The tritons were detected at angles as large as 30° in the laboratory and the fits to the correlations suggested the existence of a symmetry axis for the decay of the intermediate state $^{20}Ne^{*}$. Taking the observed symmetry axis as the axis of quantization, the population of the magnetic substates $m = 0, \pm 1$ of levels of $^{20}Ne$ with known $J^{\pi}$ was deduced from the correlations. The data are best fitted by assuming at least 84% population of the $m = 0$ substate. These observations are consistent with the ($^{7}$Li, t) reaction being mainly a direct reaction, and consequently it can be used reliably to obtain spectroscopic information. The structure of two states at 12·56 and 15·36 MeV is discussed.

## 1. Introduction

The angular correlation study of sequential reactions, in which three particles are produced in the exit channel, is of considerable interest, since it can provide a sensitive tool for determining the reaction mechanism, as well as information on the spin, parity and polarization of the intermediate state. Such a reaction could be written as A(a, b)B*(c)C, if we assume that the process does not go via the formation of a compound nucleus. In the first stage, B* is produced in a state of well defined spin and parity $J^{\pi}$.

Such reactions have been observed to exhibit a symmetry axis for the sequential decay of the intermediate state B*. Lambert *et al* (1971) discussed a measurement of the angular correlation in the reaction $^{10}B(d, \alpha_1)^{8}Be^{*}(\alpha_2)^{4}He$. They observed an axis of symmetry for the decay of $^{8}$Be(2·9 MeV) $\rightarrow 2\alpha$, which, compared with the recoil directions associated with various possible mechanisms, provided the necessary information to select the reaction mechanism. Lang *et al* (1972) studied the reaction $^{12}C(d, n)^{13}N^{*}(p)^{12}C$, by detecting the neutrons at the peaks of their angular distribution, and obtaining an angular correlation of the decay protons. In a coplanar geometry, they observed an approximate symmetry for the $^{13}N^{*}$ decay, for neutron angles corresponding only to the stripping maxima. This axis was not identical with the $^{13}N^{*}$ recoil direction, but shifted by several degrees as a function of the neutron angle. In non-coplanar geometry no such axis was observed. DWBA calculations, which included interactions in the entrance and exit channels, fitted the data well and produced the correct shift of the approximate symmetry axis. Eichner *et al* (1973) analysed the angular distributions of the three particle reaction $^{10}B(\alpha_1, \alpha_2)^{10}B^{*}(\alpha_3)^{6}Li$, in which the $\alpha_2$ particles were detected at 40° with respect to the

† Present address: Nuclear Research Centre 'Demokritos', Aghia Paraskevi, Attikis, Greece.
‡ Supported by Consejo National de Ciencia y Technologia, Instituto Nacional de Energia Nuclear, Mexico.

beam direction. They fitted the distributions by taking as axis of quantization the observed symmetry axis, which was found to be $+6°$ and $+16°$ away from the direction of the $^{10}B^*$ recoil for the two states at 5·923 MeV and 4·774 MeV respectively.

The three studies mentioned above dealt with reactions initiated by light ions and were assumed to proceed via a direct mechanism. Regarding heavy ion projectiles, Artemov *et al* (1971), have used the reaction $^{12}C(^{6}Li, d)^{16}O^*(\alpha)^{12}C$ to obtain the spin and parity of some levels in $^{16}O$. The deuterons were detected at 10° in the laboratory system. They used as a quantization axis the recoil direction of $^{16}O$ and fitted the correlation by $[P_J(\cos\theta)]^2$, in the $^{16}O^*$ rest frame, by shifting the data points by 3° and 6° for the two incident energies of 30·7 and 26 MeV respectively. The direction of the shift was not mentioned.

We set out to do a more detailed and systematic study of the sequential reaction $^{16}O(^{7}Li, t)^{20}Ne^*(\alpha)^{16}O$, and to investigate the existence of a symmetry axis for the decay of $^{20}Ne^*$, as well as the alignment of this intermediate state.

The $(^{7}Li, t)$ reaction on light nuclei has been extensively studied over a wide range of energies (Bethge 1970), and has been thought to proceed, to a large extent, via direct transfer of four nucleons with $S = T = 0$, at energies well above the Coulomb barrier.

Comparison between DWBA and Hauser–Feshback calculations for the $^{12}C(^{7}Li, t)^{16}O$ reaction at 20 to 24 MeV have indicated (Puhlhofer *et al* 1970), that contributions from compound nucleus formation do not account for more than 10% of the differential cross section at forward angles for strong transitions. Furthermore, the angular correlation of $\gamma$ rays relative to tritons detected at 0° in the reaction $^{16}O(^{7}Li, t\gamma)^{20}Ne$ (with quantization axis taken along the beam direction) has shown (Balamuth 1971) that the $m = 0$ magnetic substate is dominant over the $m = \pm 1$, $\pm 2$ substates, suggesting that at 13–14 MeV incident energy the reaction $(^{7}Li, t)$ proceeds to a large extent by $\alpha$-particle transfer.

To investigate this reaction further we have studied the angular correlation in the reaction plane between the tritons and the $^{16}O$ nuclei produced in the sequential process

$$^{7}Li + ^{16}O \rightarrow t + ^{20}Ne^* \rightarrow ^{16}O_{gs} + \alpha.$$

## 2. Experimental procedure

$^{7}Li^{3+}$ beams of energy 20 MeV and 24 MeV and intensity 100 nA were used to bombard self-supporting films of $SiO_2$ of about 100 μg $cm^{-2}$. The tritons were detected at 25° and 30° to the lithium beam by a $(\Delta E - E)$ counter telescope of 50 μm and 2000 μm thickness respectively, with an angular acceptance of 2°. The identification of the tritons was performed using a conventional power law mass identifier (Fisher and Scott 1967). Once the position of the triton detector had been selected, a recoil direction was defined for the $^{20}Ne^*$ system, and the decay products of $^{20}Ne^*$ were constrained by momentum and energy conservation. For fixed triton angles in a coplanar geometry, the $^{16}O$ nuclei and $\alpha$ particles were detected by a position sensitive detector (PSD) with a curved grid in front. Sixteen different positions, corresponding to 16 angles in 1·7° intervals, were simultaneously obtained, covering an angular range of 27° in the laboratory. Due to the dynamics and kinematics of the decay products, when an $^{16}O$ nucleus was recorded by the PSD, the corresponding $\alpha$ particle was always off the detector and vice versa. The fast timing, incorporating a time to amplitude converter, was obtained between the signal of the $E$ counter of the telescope and the energy signal of the PSD. An overall timing resolution of about 40 ns was obtained for the total length of the PSD, which reduced to better than 5 ns for each of the sixteen positions. Each event, consisting of four coincident pieces of information, ie, the total energy of the triton ($E_t$), the energy ($E$) and position ($P \times E$) from the PSD and the timing ($TAC$), was written on tape, event by event, by the on-line PDP-7 computer. The division of ($P \times E$) by $E$ was also done on line and displayed. The analysis and data reduction followed the method discussed by Panagiotou *et al* (1972).

We chose to examine the (t, $^{16}O$) angular correlation instead of the customary (t, $\alpha$) because it has a number of practical advantages, eg the differential cross section is about 3–4 times larger in the laboratory system, due to the kinematics of the $^{16}O$ decay particle and the angular correlation is more compressed, resulting in a wider angular range in the $^{20}Ne$ centre of mass system for a relatively large detector to target distance of 10 cm.

The triton spectra for coincident events at the two incident energies are shown in figure 1. The energy resolution obtained was about 100 keV FWHM, due mainly to the kinematic broadening. In figure 1($b$) the tritons leading to the particle stable $4^+$ level at 4·25 MeV were detected in coincidence with the recoiling $^{20}Ne^*$, which were recorded by the PSD. The background under the peaks comes from the possible low-spin states, accidental coincidences and true (t–$^{16}O$) coincidences from the decay of the $^{19}F^*$ intermediate state. In obtaining the angular correlations the background was not subtracted, and it has thus contributed to the broadening of the correlations.

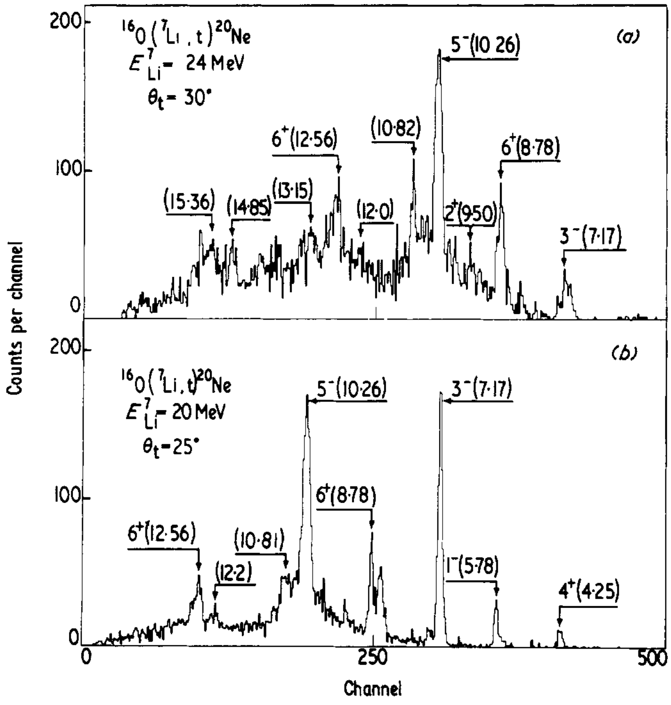


**Figure 1.** Coincident triton spectra obtained in the reaction $^{16}O(^7Li, t)^{20}Ne^*(\alpha)^{16}O$ at 24 MeV and 20 MeV incident energy.

## 3. Theoretical considerations

In a sequential reaction of the type A(a, b)B*(c)C, if the decay of the intermediate state B* is unperturbed by the scattering of particle b, ie, if the decay of B* is treated as an independent process, and if there is rotational symmetry in the decay of B*, the angular correlation of particles c, in the centre of mass frame of B* is (for coplanar geometry, $\phi = 0$) given by (Litherland and Ferguson 1961)

$$W(\theta) = \sum_{l\lambda} A_{l\lambda} P(\lambda) \frac{2l+1}{4\pi} \frac{(l-|\lambda|)!}{(l+|\lambda|)!} (P_l^{|\lambda|}(\cos\theta))^2 \quad (1)$$

where $A_{l\lambda}$ are real constants characterizing the decay of B* to C (with spin different from zero), $P(\lambda)$ are the magnetic substate population coefficients, describing the polarization of B*, $P_l^{|\lambda|}$ the associated Legendre functions and $(\theta)$ the angle of emission of the decay product c with respect to the frame of reference in which the $P(\lambda)$ are defined (ie, the B* rest frame). In the case in which the nucleus C has spin zero, the sum over $l$ has only one term and $l = J$, the spin of the intermediate state B*.

If the $^{16}O(^7Li, t)^{20}Ne^*$ reaction is considered a stripping process and if the interaction in the initial and final channels is neglected (PWBA), the direction of momentum transfer, which is equal to the recoil direction of $^{20}Ne^*$ in the laboratory system, is an axis of symmetry for the decay of $^{20}Ne^*$. This is the well known Treiman and Yang (1962) criterion for a reaction in which a particle of spin 0 or $\frac{1}{2}$ is transferred.

If we adopt this simple plane-wave view, the reaction $^{16}O(^7Li, t)^{20}Ne$ may be said to have an axial symmetry along the momentum transfer direction, as if a 'beam of $\alpha$ particles' was impinging upon the target along that direction. The direction of momentum transfer, of course, is not constant but varies with excitation energy of the residual nucleus. Using this symmetry axis as the quantization axis, $^{20}Ne^*$ should be formed (in the plane-wave approximation) in an $m = 0$ substate. However, distortion of the plane waves in the entrance and exit channels is indeed important and may cause departure from the simple approach, as discussed by Satchler (1960).

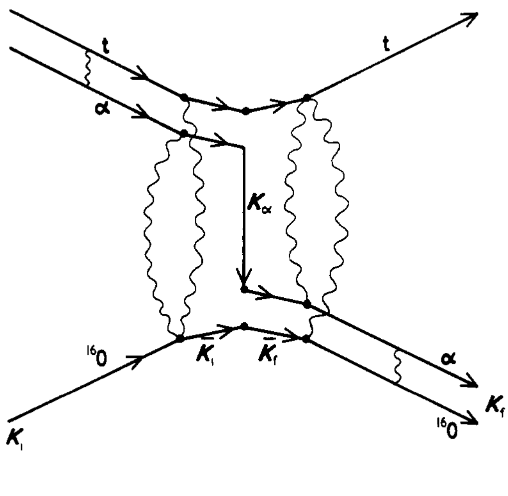


**Figure 2.** Schematic wavevector diagram for the reaction $^7Li + ^{16}O \rightarrow t + ^{20}Ne$ in the centre of mass frame. The particles $^7Li$ and $^{20}Ne$ are decomposed into ($\alpha + t$) and ($^{16}O + \alpha$) respectively, in order to show the possible interactions.

In figure 2 a schematic wavevector diagram is shown for the $^{16}O(^{7}Li, t)^{20}Ne$ reaction. At large separations between the $^{7}Li(=\alpha+t)$ and $^{16}O$ nuclei, the relative wavevector is $\boldsymbol{K}_i$. As the nuclei approach, the interaction becomes stronger, resulting in the distortion of the plane waves. The relative wavevector now becomes $\bar{\boldsymbol{K}}_i = \boldsymbol{K}_i + \Delta\boldsymbol{K}_i$. At this point the transfer of the $\alpha$ particle takes place with a wavevector $\boldsymbol{K}_\alpha$. In the exit channel a similar distortion takes place and the final wavevector at infinity becomes $\bar{\boldsymbol{K}}_f = \boldsymbol{K}_f + \Delta\boldsymbol{K}_f$. Thus

$$\boldsymbol{K}_\alpha = \bar{\boldsymbol{K}}_i - \bar{\boldsymbol{K}}_f = (\boldsymbol{K}_i - \boldsymbol{K}_f) + (\Delta\boldsymbol{K}_i - \Delta\boldsymbol{K}_f). \tag{2}$$

The first term of this relation is the plane-wave part and the second comes from the distortion of the plane waves by the interaction in the entrance and exit channels. This second term will cause departure from the simple picture of the transfer and could result in the population of magnetic substates other than $m = 0$, rotation of the symmetry axis away from the recoil direction and perhaps even total loss of the symmetry (Satchler 1960).

The distortion of the plane waves should depend on the energy of the incident $^{7}Li$ and outgoing tritons and on the angle of the emitted tritons as well. The magnitude of the quantities $\Delta\boldsymbol{K}_i$ and $\Delta\boldsymbol{K}_f$ are not known at present and a quantitative estimate of the change of the direction of $\boldsymbol{K}_\alpha$ from the plane-wave prediction is not given. One may, however, make the following valid assumptions:

(i) The (t, $\alpha$) interaction in the entrance channel is small. This may be understood on the basis of the $L = 1$ relative angular momentum of t and $\alpha$ and the small binding energy of $^{7}Li$(2·47 MeV).

(ii) The ($\alpha$, $^{16}O$) interaction, although it may be large, does not produce large rotation since it acts approximately along the recoil direction.

(iii) The 'only' effective interaction may be the (t, $^{16}O$) in the entrance channel and (t–$^{20}Ne$) in the exit channel; the magnitude may not be very large if we have a peripheral collision. This interaction in the entrance channel may cause a small change in the direction of the incoming $\alpha$ particle so that its angular momentum has now a small projection along the recoil direction of the $^{20}Ne^{*}(= {}^{16}O+\alpha)$ system. This will result in the population of magnetic substates with $m > 0$ in addition to $m = 0$. In the exit channel and before the intermediate state decays, the interaction may cause a small rotation of the symmetry axis for the decay of the ($^{16}O+\alpha$) system away from the plane-wave prediction (ie, the recoil direction of $^{20}Ne^{*}$).

Assuming then that the incoming '$\alpha$-particle beam' along the momentum transfer direction produces an axial symmetry, equation (1) was used to describe the angular correlation. The angle $\theta$ is now defined as the angle of emission of the decay product with respect to the observed axis of symmetry in the $^{20}Ne^{*}$ rest frame. The observed symmetry axis, which was taken as the quantization axis, was found by a search code, which performed a $\chi^2$ test for a given axis of quantization, an $l$ value and $\lambda = 0, \pm 1$. Since the contribution of the magnetic substates declines with larger $|\lambda|$, only up to $\lambda = \pm 1$ was included. The population parameters $P(\lambda)$ were deduced from the best fit to the correlation. A computer program produced fits to the data by varying the ratio $P(\pm 1)/P(0) \equiv Z^2$, as well as a normalization factor $A$, for a given axis of symmetry in the $^{20}Ne^{*}$ centre of mass system. $\chi^2$ values were calculated for each set of the variables, and the normalized $\chi^2$, defined as $\chi^2/(N-n)$, where $N$ is the number of data points and $n$ the number of variables, was compared with the 0·1 % confidence limit.

## 4. Results

In the present sequential reaction we have obtained the angular correlation with the decay products left in their ground state. In this case, since both $\alpha$ and $^{16}O_{gs}$ have $J^\pi = 0^+$, the $l$ in the expression (1) is equal to the spin $J$ of the intermediate state $^{20}Ne^*$, and $\lambda = m$, the magnetic substates of $^{20}Ne^*$.

The angular correlation for the $3^-$ level at 7·17 MeV excitation in $^{20}Ne$, obtained at 20 MeV incident energy and with the triton detector set at 25°, is shown in figure 3(*a*), in both the laboratory system and the $^{20}Ne$ centre of mass system.

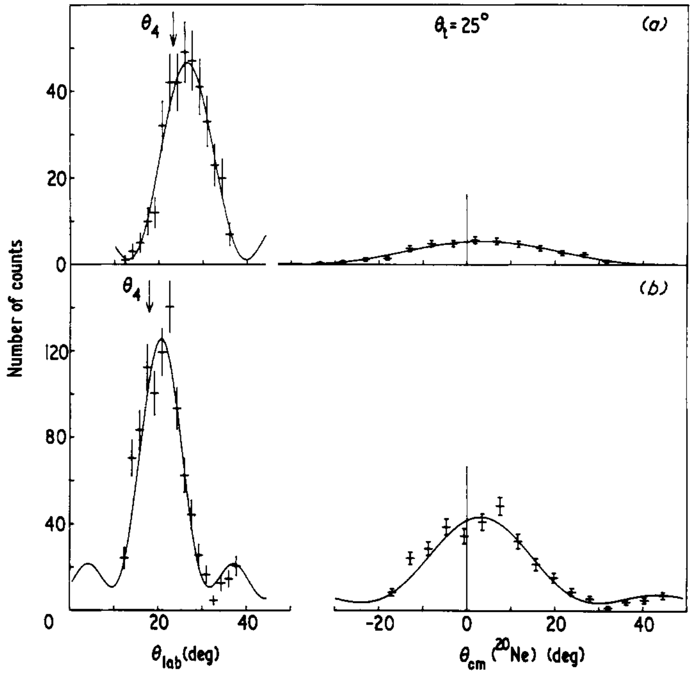


**Figure 3.** Experimental (t, $^{16}O$) angular correlations and best theoretical fits obtained for (*a*) the $3^-$ (7·17 MeV), and (*b*) the $5^-$ (10·26 MeV) levels at 20 MeV incident energy in both the laboratory and $^{20}Ne^*$ centre of mass systems. '$\theta_4$' is the fixed laboratory angle of the recoil $^{20}Ne^*$.

The best fit, deduced from a $\chi^2$ analysis, is obtained with population parameters $P(0) = 0{\cdot}96 \pm 0{\cdot}03$ and $P(\pm 1) = 0{\cdot}04 \pm 0{\cdot}02$. The population of $m = \pm 1$ is evidently very small. Since the background under this peak is almost zero (the $0^+$ level at 7·20 MeV is not expected to be populated (Middleton *et al* 1968)), the small broadening of the correlation can be assumed to be the result of the population of the $m = \pm 1$ substates. In figure 3(*b*) the correlation and fit for the $5^-$ level at 10·26 MeV is shown. The population parameters giving the best fit are $P(0) = 0{\cdot}84 \pm 0{\cdot}02$ and $P(\pm 1) = 0{\cdot}16 \pm 0{\cdot}02$. The larger value here of the $P(\pm 1)$ may be partially due to the larger background under the peak, which broadens the correlation.

The observed symmetry axis for the decay of the 7·17 MeV and 10·26 MeV states was found to be shifted by $+3{\cdot}5 \pm 0{\cdot}1°$ and $+3{\cdot}1 \pm 0{\cdot}1°$ respectively, from the corresponding direction of the $^{20}Ne^*$ recoil. This displacement is apparent in figures 3(*a*) and (*b*) (laboratory system) where the recoil direction of $^{20}$Ne* is denoted by '$\theta_4$'. In the $^{20}$Ne* rest frame these shifts correspond to $+10{\cdot}4 \pm 0{\cdot}2°$ and $+7{\cdot}4 \pm 0{\cdot}2°$ respectively.

The angular correlation for the $3^-$ level was also fitted for other spin values, $J = 2, 4$ and the results, together with the normalized $\chi^2$ values and the 0·1 % confidence limit are shown in figure 4. The $\chi^2$ test clearly shows that only the $J = 3$ spin value is acceptable.

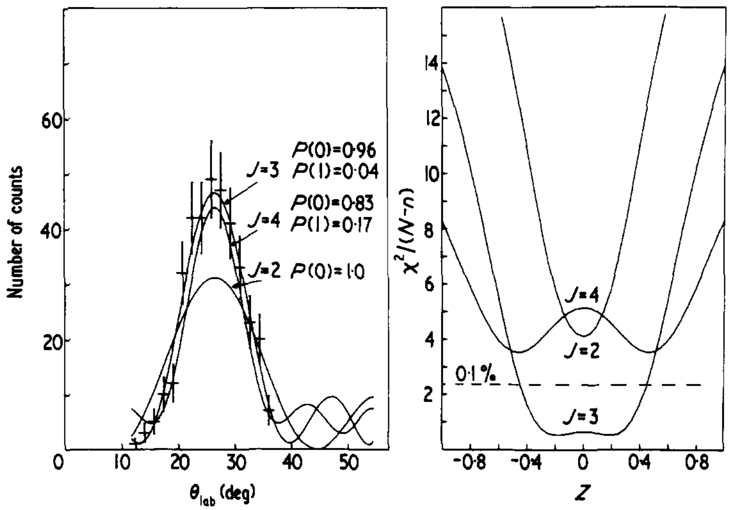


**Figure 4.** Theoretical fits to the angular correlation for the $3^-$, 7·17 MeV state, for $J = 2, 3, 4$ and the corresponding normalized $\chi^2$ values plotted as a function of the parameter $Z$, defined as $Z^2 \equiv P(\pm 1)/P(0)$.

Figure 5 shows the correlation obtained at 24 MeV incident energy, with the triton detector situated at 30° to the lithium beam. In figure 5(*a*) the correlation for the $5^-$ level at 10·26 MeV is shown. The best fit is obtained with population parameters $P(0) = 0{\cdot}84 \pm 0{\cdot}02$ and $P(\pm 1) = 0{\cdot}16 \pm 0{\cdot}02$. The correlation for the level at 12·56 MeV is shown in figure 5(*b*). Best fit was obtained with $P(0) = 0{\cdot}84 \pm 0{\cdot}03$ and $P(\pm 1) = 0{\cdot}16 \pm 0{\cdot}02$, for $J = 6$. Figure 5(*c*) shows the correlation for the broad level at 15·36 MeV. The best fit in this case is obtained with population parameters $P(0) = 0{\cdot}92 \pm 0{\cdot}03$ and $P(\pm 1) = 0{\cdot}08 \pm 0{\cdot}03$, for $J = 7$. (The obvious discrepancy of the fit to the second maximum may be caused by a strong $^{19}F^* \rightarrow t + {}^{16}O$ background group.)

At the incident energy of 24 MeV, the observed symmetry axis for the decay of the 10·26, 12·56 and 15·36 MeV states was shifted by $+4{\cdot}8 \pm 0{\cdot}1°$, $4{\cdot}7 \pm 0{\cdot}1°$ and $3{\cdot}6 \pm 0{\cdot}1°$ respectively from the corresponding direction of the $^{20}$Ne* recoil in the laboratory frame. In the $^{20}$Ne* rest frame these rotations correspond to $12{\cdot}2 \pm 0{\cdot}2°$, $11{\cdot}2 \pm 0{\cdot}2°$ and $8{\cdot}2 \pm 0{\cdot}2°$ respectively.

## 5. Discussion and conclusions

The results of the angular correlation study of the sequential reaction $^{16}O(^7Li, t)$-$^{20}Ne^*(\alpha)^{16}O$ have revealed a number of points. Firstly, the apparent existence of a

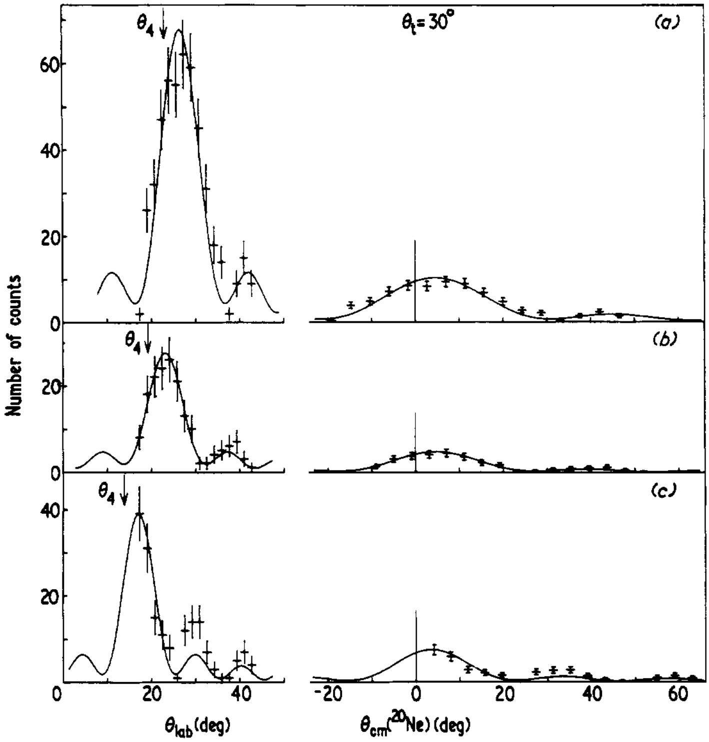


**Figure 5.** (t, $^{16}$O) angular correlations and best fits obtained at 24 MeV incident energy for (*a*) the $5^-$ (10·26 MeV), (*b*) the $6^+$ (12·56 MeV), and (*c*) the $7^-$ (15·36 MeV) levels in both the laboratory and $^{20}$Ne* centre of mass systems. '$\theta_t$' is the (fixed) angle at which the tritons were detected.

symmetry axis for the decay of the intermediate state $^{20}$Ne*, which is not readily predicted by the DWBA theory (strong interaction in entrance and exit channels) (D M Brink 1973, private communication). This may indicate that the assumption, that only the (t–$^{16}$O) effective interaction in the entrance and (t–$^{20}$Ne) in the exit channel is important, is qualitatively correct.

To obtain further qualitative insight into the spatial dependence of the (t–$^{20}$Ne) interaction in the exit channel, we have calculated the wavelength, $\lambda\!\!\!^{-}_f$, of the relative motion and the distance of closest approach, $d_f$, assuming an elastic (t–$^{20}$Ne) scattering with the appropriate energies and scattering angles. Table 1 exhibits this information together with the shift of the observed symmetry axis in both the $^{20}$Ne* centre of mass and laboratory systems. Column 6 in the table gives the ratio of the distance of closest approach to the wavelength of the relative motion, which may be considered as a relative measure for the (t–$^{20}$Ne) interaction. It is seen that the diplacement of the observed symmetry axis from the plane-wave recoil direction is inversely proportional to this ratio. That is, the smaller the ratio, ie the smaller the relative distance between t and $^{20}$Ne, the larger the shift. This may be the result of the stronger (t–$^{20}$Ne) interaction, which produces a greater distortion of the plane waves, and hence a larger displacement. It is also noted that this shift is in the same sense (positive) in all cases examined.

Regarding the alignment of the intermediate state of $^{20}$Ne* with respect to the observed symmetry axis, it is an almost pure $m = 0$ state, as this is inferred from the

**Table 1.** Calculated values for the wavelength, $\lambda_f$, and distance of closest approach $d_f$ (in fm) for the relative motion in the exit channel. The incident and excitation energies are in MeV.

| $E_{Li}$(lab) | $\theta_t$(lab) (deg) | $E^*_{^{20}Ne}$ | $\lambda_f$ | $d_f$ | $\left(\frac{d}{\lambda}\right)_f$ | $\Delta\theta$(cm) (deg) | $\Delta\theta$(lab) (deg) |
|---|---|---|---|---|---|---|---|
| 20 | 25 | 7·17 | 0·85 | 2·9 | 3·46 | 10·4±0·2 | 3·5±0·1 |
| 20 | 25 | 10·26 | 1·00 | 3·9 | 3·91 | 7·4±0·2 | 3·1±0·1 |
| 24 | 30 | 10·26 | 0·85 | 2·6 | 3·00 | 12·2±0·2 | 4·8±0·1 |
| 24 | 30 | 12·56 | 0·96 | 3·2 | 3·28 | 11·2±0·2 | 4·7±0·1 |
| 24 | 30 | 15·36 | 1·20 | 4·6 | 3·82 | 8·2±0·2 | 3·6±0·1 |

population parameters, $P(m)$, for the magnetic substates. This means that the spin $J$ of the intermediate state is almost perpendicular to the symmetry axis, and this supports the picture of an 'α-particle beam' along a direction very close to this axis. It is noted that, in a direct transfer of a spin-zero particle on a spin-zero target in a 0° geometry, the population parameters $P(m)$ are strictly zero for $m \neq 0$ in the plane-wave approximation.

The weak population of the magnetic substates with $|m| > 0$ is presumably the combined effect of the distortion of the plane waves, the contribution of non-direct processes and the finite angle ($\Delta\theta$) of the triton and $^{16}O$ detectors. At this stage a quantitative argument cannot be given on the relative contribution of the former two effects to the population of the $m = \pm 1$ substates. It is clear, however, that individually the two effects cause a very weak $m = \pm 1$ population. This could then indicate that at the incident energies of 20 and 24 MeV the contribution to the reaction mechanism (as observed at forward angles) by non-direct processes is almost negligible. This is true for strongly excited states which have large overlap with $^{16}O_{gs} + \alpha$ and which therefore belong to configurations built on a closed p shell, such as $(sd)^4$: the $K = 0^+$ band of the (80)$SU_3$ symmetry, $(sd)^3(fp)^1$: the (90)$K = 0^-$ band, $(sd)^2(fp)^2$: the (10, 0)$K = 0^+$ band, and $(fp)^4$: the (12, 0)$K = 0^+$ band. One has then an *a priori* knowledge of the possible structure of the excited states, which, together with α-reduced widths, could help to classify the levels in question into rotational bands.

The $6^+$ state at 12·56 MeV was seen to be strongly excited at 24 MeV and especially at 30 MeV (Bassani *et al* 1972), incident energy, and should therefore belong to one of the latter two $K = 0^+$ bands discussed above. Its α-reduced width to ($^{16}O_{gs} + \alpha$) is about 56% of a single-particle unit (Ajzenberg-Selove 1972). This compares well with the α-reduced width of about 43% of a single-particle unit of the $0^+$ level at about 8·4 MeV (Ajzenberg-Selove 1972) which is thought to have either $(sd)^2(fp)^2$ or $(fp)^4$ configuration (Fortune *et al* 1972). It is natural therefore, to classify the $6^+$ level at 12·56 MeV into the same rotational band as this $0^+$ state. Theoretically a $6^+$ level with $(fp)^4$ configuration has been predicted at about 13 MeV (D Strottman 1973, private communication). Furthermore, a study of the 2p-transfer reaction on $^{18}O$ (Strottman *et al* 1973), performed at high energy (~10 MeV/nucleon), strongly suggested that the $6^+$ level at 12·56 MeV does not have $(sd)^2(fp)^2$ configuration. We conclude therefore, that the 12·56 MeV $6^+$ state belongs to the $(fp)^4$ $K = 0^+$ band.

The $7^-$ level at 15·36 MeV is also very strongly populated by the ($^7Li$, t) reaction at 30 MeV incident energy (Bassani *et al* 1972) which indicates a large reduced width to the $^{16}O_{gs} + \alpha$ channel. (The weak population in our spectrum is only due to the low energy.) This compares favourably with the large α-reduced width of 66% of a single-particle unit of the $5^-$ level at 10·26 MeV and 36% of the $3^-$ at 7·17 MeV (Ajzenberg-Selove 1972), which are also very strongly excited, as can be seen in figure 1. The $7^-$ level then at 15·36 MeV may be unambiguously classified into the same rotational band, $K = 0^-$, with $(sd)^3(fp)^1$ configuration (see also Hunt *et al* 1967).

To summarize, the angular correlation study of the reaction $^7Li + {}^{16}O \rightarrow t + {}^{20}Ne^* \rightarrow {}^{16}O_{gs} + \alpha$ suggests that, for strongly excited states and forward angles, the contribution to the reaction mechanism from non-direct processes is almost negligible. It has also shown that despite the expectations of DWBA theory, a symmetry axis for the decay of $^{20}Ne^*$ seems to exist. This indicates that the distortion of the plane waves by the nuclear and Coulomb fields in the entrance and exit channels is not very strong (see also Neogy *et al* 1970†) and causes only a weak population of the $m = \pm 1$ substates and a small rotation of the symmetry axis away from the $^{20}Ne^*$ recoil direction. This demonstrates that the intermediate state, $^{20}Ne^*$, is aligned with respect to the observed symmetry axis in an almost pure $m = 0$ substate. Finally, this study shows that the departure from the 0° geometry does not seem to complicate the angular correlation in a direct transfer of a spin-zero particle onto a spin-zero target, if one takes as the quantization axis a direction very close to the recoil momentum of the intermediate state.

The spin and parity determination of states excited strongly in direct transfer reactions is a useful tool in classifying these levels into rotational bands, due to the small number of configurations available for excitation. This is in marked contrast to compound reactions which excite almost all possible configurations.

## Acknowledgments

We wish to thank Drs D M Brink, P S Fisher, B Buck and P Roussel for enlightening discussions and comments.

## References

Ajzenberg-Selove F 1972 *Nucl. Phys.* A **190** 1
Artemov K P *et al* 1971 *Phys. Lett.* **37B** 61
Balamuth D P 1971 *Phys Rev.* C **3** 1565
Bassani G *et al* 1972 *Proc. 1st Europ. Conf. on Nuclear Physics, Aix en Provence,* vol II-32 (Paris: Société Française de Physique, Geneva: EPS)
Bethge K 1970 *Ann. Rev. Nucl. Sci.* **20** 255
Eichner H *et al* 1973 *Nucl. Phys.* A **205** 249
Fisher P S and Scott D K 1967 *Nucl. Instrum. Meth.* **49** 301
Fortune H T, Middleton R and Betts R R 1972 *Phys. Rev. Lett.* **29** 738
Hunt W E *et al* 1967 *Phys. Rev.* **160** 782
Lambert J M *et al* 1971 *Phys. Rev. Lett.* **27** 820
Lang J *et al* 1972 *Phys. Rev. Lett.* **28** 623
Litherland A E and Ferguson A J 1961 *Can. J. Phys.* **39** 788
Middleton R *et al* 1968 *Phys. Rev. Lett.* **20** 118
Neogy P *et al* 1970 *Phys. Rev.* C **2** 2149
Panagiotou A D, Gove H E and Harar S 1972 *Phys. Rev.* C **5** 1995
Puhlhofer F *et al* 1970 *Nucl. Phys.* A **147** 258
Satchler G R 1960 *Nucl. Phys.* **18** 110
Strottman D *et al* 1973 *Phys. Lett.* **47B** 16
Treiman S B and Yang C N 1962 *Phys. Rev. Lett.* **8** 140

† In their plane-wave model treatment of the ($^7$Li, t) reaction, in which only Coulomb distortion was included which was produced by the Coulomb potential evaluated at a cut-off radius $R$, the large value of $R(\geqslant 7{\cdot}0\ \text{fm})$ was suggested to reflect the partial cancellation between Coulomb and nuclear distortions.