Aust. J. Phys., 1976, **29**, 355–62

Angular Correlations in ^{19}O

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Abstract

p–γ correlation measurements have been carried out on ^{19}O levels populated by the $^{18}O(d, p)$ reaction. A cryogenically cooled thin target of ^{18}O-enriched ice was used. Our data allow the following spin values: $J(2\cdot37) = 5/2$, $7/2$ or $9/2$; $J(2\cdot78) = 3/2^+$ or $7/2^+$; $J(3\cdot15) = 3/2$ or $5/2$. Previous spin assignments of 3/2 and 9/2 for the 2·37 and 2·78 MeV levels respectively are rigorously rejected. Mixing ratios measured for the $2\cdot37 \to 0$, $2\cdot78 \to 0$ and $3\cdot15 \to 0\cdot096$ MeV transitions agree with previous determinations. The results are discussed in terms of recent shell model and rotational model calculations on ^{19}O.

Introduction

Many of the theoretical calculations that have been carried out on the nucleus ^{19}O have assumed that the level at 2·78 MeV has a spin of 9/2 in order to determine model parameters. However, it has become clear that spin assignments of 3/2 and 9/2 for the 2·37 and 2·78 MeV levels respectively, made largely on the basis of

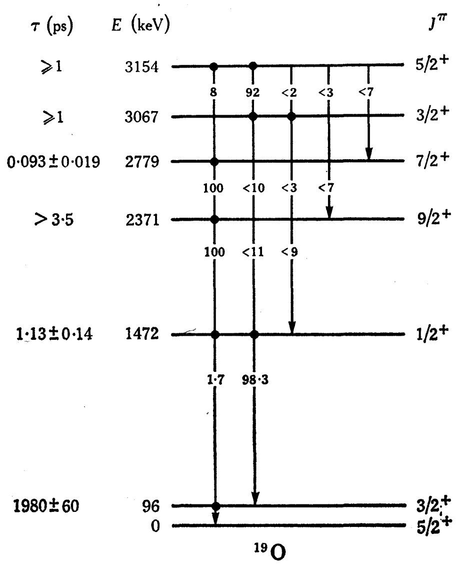

Fig. 1. Level scheme for ^{19}O. The level spins and energies are mostly from the Ajzenberg-Selove (1972) compilation. The branching ratios are weighted means of results quoted by Fintz *et al.* (1970) and Broude *et al.* (1971), with limits for weak branches from Fintz *et al.* and the present work. The branching ratios for the 3067 keV level are not known. Broude *et al.* (1971) and Hibou *et al.* (1971) report branches to the 1472 and 96 keV states respectively.

stripping results (Moreh 1965; Wiza and Middleton 1966; Fintz *et al.* 1969), are incorrect. The spins of these states are now believed to be 9/2 and 7/2, as indicated in Fig. 1. The evidence against the old assignments is given in detail by Broude *et al.* (1971), Hibou *et al.* (1971), Crozier *et al.* (1972) and Fasla and Beaumeveille (1972).

However, the only model-independent work to reject $J = 9/2$ as a possible spin for the 2·78 MeV level is that of Hibou *et al.* (1971). In view of the theoretical interest of this result it is important that it receive independent confirmation. In addition, recent calculations by Akiyama *et al.* (1969; see also Arima *et al.* 1971), Halbert *et al.* (1971), Allard *et al.* (1972) and Lambert *et al.* (1973) have included predictions of transition strengths, so that experimental data on γ-ray mixing ratios are of interest. We have therefore studied p–γ correlations from states in ^{19}O excited by the $^{18}O(d, p)$ reaction at a bombarding energy of 5 MeV. A preliminary report of this work begun in 1971 has already appeared (Southon *et al.* 1974).

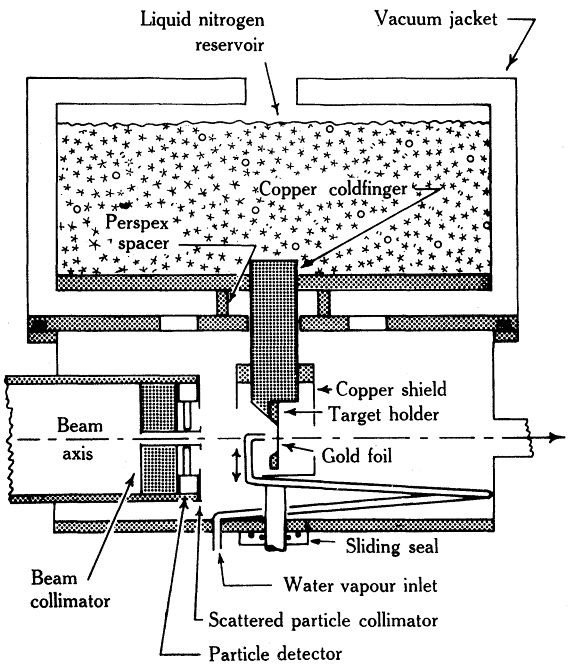

Fig. 2. Schematic diagram of the scattering chamber and cryogenic target used in the experiment, together with the arrangements for mounting the particle detector and applying water vapour to the target. The vapour inlet consisted of a spiral of thin copper tube and could be raised or lowered by means of an actuating rod which passed through a sliding seal in the floor of the chamber. The copper shield was used to minimize the contamination of the target due to the condensation of hydrocarbon and water vapour.

Experimental Method

The experimental arrangement of the scattering chamber and cryogenic target is shown in Fig. 2. Thin ^{18}O targets were made by freezing small amounts of approximately 60% ^{18}O-enriched water vapour onto a gold foil cooled with liquid nitrogen. The target and foil thicknesses were estimated from the reaction particle spectrum and were $\sim$100 and 300 $\mu g\,cm^{-2}$ respectively. Charged particles were detected in an annular silicon surface barrier subtending angles between 171° and 175° to the beam, and γ rays were observed with a 12·7 × 15·2 cm NaI(Tl) crystal mounted 25 cm from the target. Particle–γ coincidence events were detected by fast–slow coincidence electronics, and particle and γ-ray energy data and a real–random flag for each event were stored on magnetic tape with the aid of a computer-controlled data acquisition system. Data were recorded at γ-ray detector angles of 21°, 30°, 45°, 60° and 90° to the beam direction with runs at different angles taken in random order and each angle repeated at least once.

Analysis

The data tapes were played back to accumulate gain-stabilized coincident γ-ray spectra from portions of the energy matrix corresponding to ^{19}O states. The playback code also subtracted the random coincidence contribution which was typically 10% of the counts in peaks of interest. Peak areas were normalized to the yield of the $1 \cdot 38$ MeV γ ray from the decay of the spin 1/2 state (Ajzenberg-Selove 1972) at $1 \cdot 47$ MeV and the data for the different runs at each angle averaged to produce the angular correlations shown in Figs 3*a*–5*a*.

Theoretical correlation functions derived by Rose and Brink (1967) were fitted to the data to determine possible values of the initial and final level spins and the mixing ratio δ for each transition. Figs 3*b*–5*b* show plots of the normalized χ^2 from the fits as a function of $\arctan \delta$. Spins for which the minima of these plots lay above the $0 \cdot 1$% confidence level were rejected as possible solutions and error limits for mixing ratios were taken at the $31 \cdot 7$% confidence level. Finite detector size effects were evaluated using methods given by Litherland and Ferguson (1961), and the phase convention of Rose and Brink (1967) was used for mixing ratios.

Table 1. Results of angular correlation analysis

Transition $E_i \to E_f$ (MeV)	Legendre polynomial coefficients[A] A_2/A_0	A_4/A_0	Allowed spins of initial state	Mixing ratios[B] Present work	Hibou *et al.* (1971)	Adopted values
$2 \cdot 37 \to 0$	$0 \cdot 41 \pm 0 \cdot 04$	$-0 \cdot 30 \pm 0 \cdot 07$	5/2, 7/2, 9/2	$0 \cdot 02 \pm 0 \cdot 07$	$0 \cdot 02 \pm 0 \cdot 07$	$0 \cdot 02 \pm 0 \cdot 05$
$2 \cdot 78 \to 0$	$-0 \cdot 70 \pm 0 \cdot 05$	$-0 \cdot 11 \pm 0 \cdot 07$	$3/2^+$, $7/2^+$	$0 \cdot 9 \pm 0 \cdot 7$	$0 \cdot 8 \pm 0 \cdot 6$	$0 \cdot 8 \pm 0 \cdot 5$
$3 \cdot 15 \to 0 \cdot 096$	$-0 \cdot 48 \pm 0 \cdot 03$	$-0 \cdot 07 \pm 0 \cdot 04$	3/2, 5/2	$0 \cdot 03 < \delta < 2 \cdot 3$	$1 \cdot 4^{+1 \cdot 1}_{-1 \cdot 4}$	$0 \cdot 03 < \delta < 2 \cdot 3$

[A] Uncorrected for finite detector size. For the $2 \cdot 37 \to 0$ MeV transition $A_6/A_0 = -0 \cdot 14 \pm 0 \cdot 10$.
[B] Under the assumptions $J(2 \cdot 37) = 9/2$, $J(2 \cdot 78) = 7/2$ and $J(3 \cdot 15) = 5/2$.

Upper limits for the branching ratios of weak transitions were derived using peak areas from the spectra formed by summing all the data for each level. Limits which are more rigorous than those from the work of Fintz *et al.* (1970) have been included in the level scheme data in Fig. 1.

Results

The results of the angular correlation analysis are summarized in Table 1.

2·37 MeV Level

Our correlation analysis of the $2 \cdot 37 \to 0$ MeV transition (Fig. 3) gives results similar to those of Hibou *et al.* (1971), but the better statistics of our measurement allow us to reject $J = 3/2$. The fit for $J = 11/2$, $\delta = 0$ gives a χ^2 value above the $0 \cdot 1$% confidence level and the upper limit of 30 ns for the lifetime of the level (from our coincidence resolving time) requires $\delta = 0$ if $J = 11/2$; the spin must therefore be 5/2, 7/2 or 9/2.

2·78 MeV Level

Spins of 3/2 and 7/2 were allowed by a correlation analysis of the $2 \cdot 78 \to 0$ MeV transition. The mixing ratios of Fig. 4*a* and the mean lifetime of 93 ± 19 fs for the level (Broude *et al.* 1971) require M2 strengths in excess of 8 Weisskopf units (W.u.)

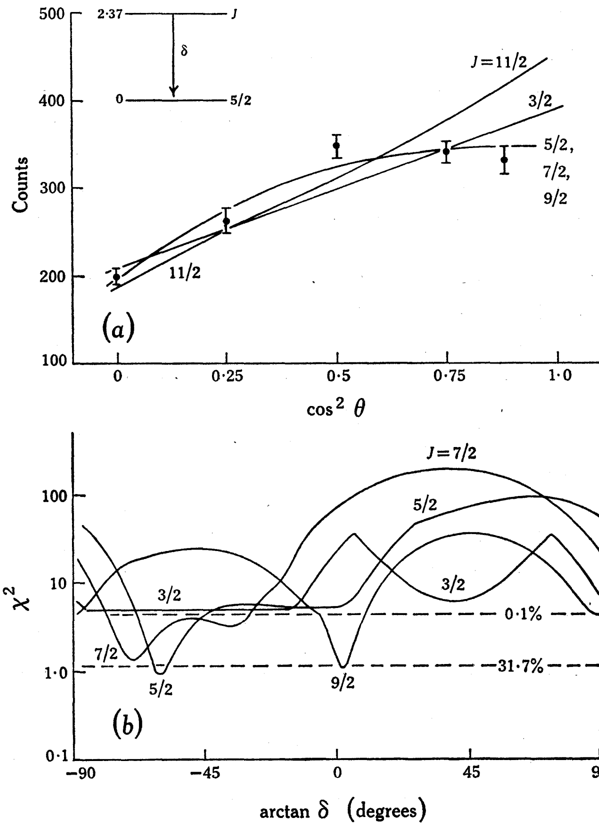

Fig. 3. Best fits (*a*) and plots of χ^2 versus arctan δ (*b*) for the $2\cdot37 \rightarrow 0$ MeV transition in ^{19}O. The probability of χ^2 exceeding the values indicated by the dashed lines, if the calculated correlation formulae are accurate representations of the experimental data, are $0\cdot1\%$ and $31\cdot7\%$ as shown. The fit for $J = 11/2$, $\delta = 0$ gave $\chi^2 = 11\cdot4$. The following mixing ratios were used in the theoretical distributions in (*a*):

J	3/2	5/2	7/2	9/2	11/2
δ	$-1\cdot0$	$-1\cdot8$	$-2\cdot6$	0	0

for this transition if the state has odd parity. We assume that the upper limit of 3 W.u. for M2 strengths found for $A = 21$–44 nuclei by Endt and van der Leun (1974) also applies in the present case and therefore assign even parity, in agreement with results from the stripping studies of Moreh (1965) and Fasla and Beaumeveille (1972).

3·15 MeV Level

A correlation analysis of the distribution from the major γ-ray peak in the spectra from this level (assuming that this peak was entirely due to the $3\cdot15 \rightarrow 0\cdot096$ MeV transition) allows $J = 3/2$ or $5/2$. Corrections for the contribution due to the weak ground state transition had little effect on the results. The $3\cdot15 \rightarrow 1\cdot47$ MeV transition reported by Broude *et al.* (1971) was not seen.

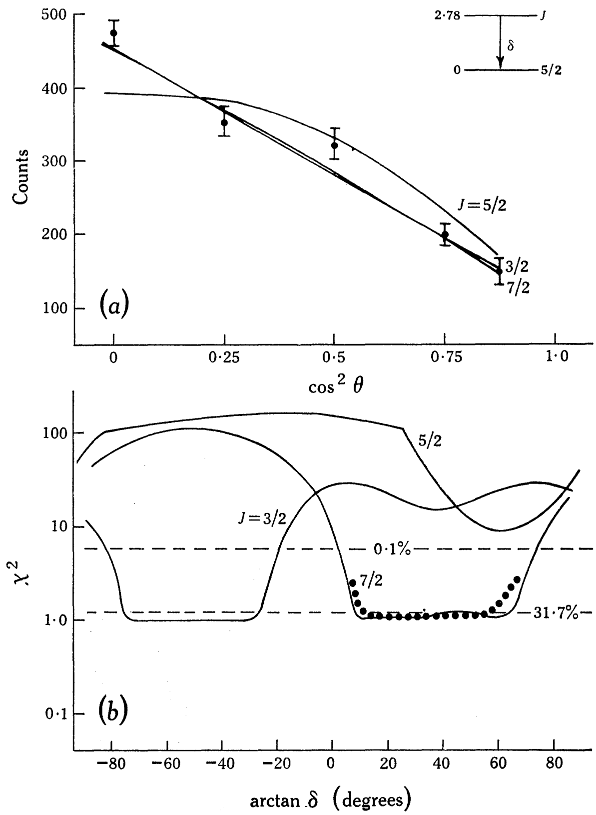

Fig. 4. Best fits (*a*) and χ^2 plots (*b*) for the $2\cdot78 \rightarrow 0$ MeV transition in ^{19}O. The effects of allowing a 3% population of the $|m_z| = 5/2$ substate of the initial level to allow for the finite particle detector size are shown by the dotted curve in (*b*). Data are shown only for spins which gave $\chi^2 < 10$. The theoretical distributions in (*a*) were calculated with $\delta = -1\cdot0$, $1\cdot7$ and $0\cdot6$ for $J = 3/2$, $5/2$ and $7/2$ respectively.

Discussion

Our results agree well with those of Hibou *et al.* (1971) and show clearly that the old spin assignments for the 2·37 and 2·78 MeV levels are incorrect. The stripping results of Crozier *et al.* (1972), together with these correlation data, indicate strongly that the spins of these states are 9/2 and 7/2 respectively.

Neither Fintz *et al.* (1970) nor the present group have observed the $3\cdot15 \rightarrow 1\cdot47$ MeV transition used by Broude *et al.* (1971) to derive the lifetime limit for the 3·15 MeV state. Moreh and Daniels (1965) also comment that different l_n values are found for (d, p) stripping to this level at different bombarding energies; clearly further clarification of the properties of this state is desirable.

The observed order of the 9/2 and 7/2 states is reproduced by the asymmetric rotor model of Allard *et al.* (1972) and by some of the Hamiltonians used by Halbert *et al.* (1971) in extensive shell model calculations. The asymmetric rotor model predicts a

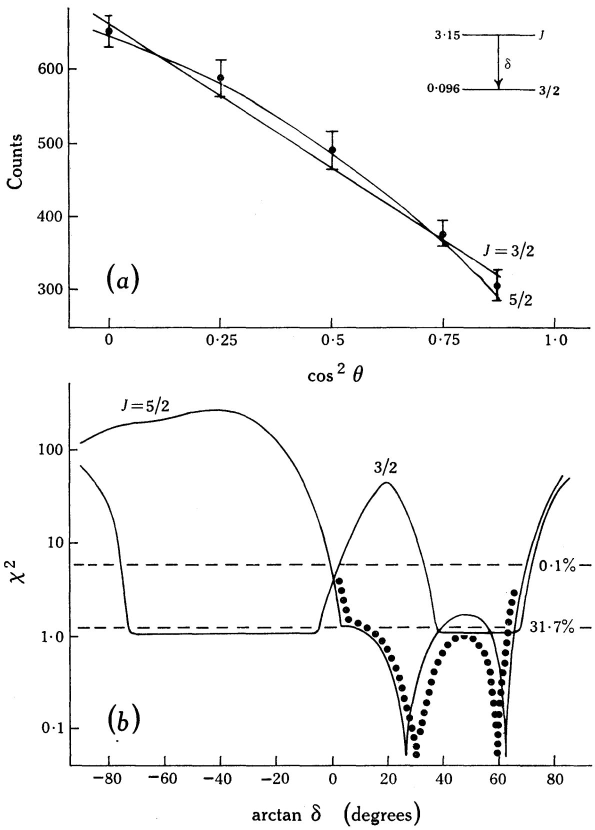

Fig. 5. Best fits (*a*) and χ^2 plots (*b*) for the $3\cdot15 \rightarrow 0\cdot096$ MeV transition in ^{19}O. It was assumed in this analysis that no other transitions contributed to the γ-ray peak at $\sim 3\cdot1$ MeV. The theoretical distributions in (*a*) were calculated with $\delta = 1\cdot0$ and $0\cdot5$ for $J = 3/2$ and $5/2$ respectively. The dotted curve in (*b*) shows the effect of allowing a 3% population of the $|m_z| = 5/2$ substate.

3/2 state at 2·5 MeV, for which no definite experimental evidence exists, but otherwise gives very good agreement with the experimental level scheme.

Experimental data on the transition rates are compared with theoretical predictions in Table 2. Few experimental results are available, as the lifetimes of several states and the branching ratios for weak decays are poorly determined. None of the calculations reproduce all the data shown, although the realistic interaction shell model calculation (II) of Halbert *et al.* (1971) gives the best overall agreement. The asymmetric rotor model (IV), while less successful, does reproduce some of the M1 transition rates.

The success of the asymmetric rotor model in predicting some features of the structure of ^{19}O is surprising, since the model requires a highly deformed nucleus; and other experimental evidence (e.g. the long lifetimes of the first two excited states as given in the Ajzenberg-Selove (1972) compilation) supports earlier calculations by Federman (1967) which indicate that the nucleus is spherical. However, the existence of strong deformations could explain the difficulties encountered by the more complex shell model calculations (Akiyama *et al.* 1969; Halbert *et al.* 1971), as attempts to account for a nonspherical nucleus by configuration mixing (i.e. by perturbation methods) must eventually fail for a sufficiently deformed shape. Models using effective interaction methods (Arima *et al.* 1967) have successfully predicted the structure of low-lying states. This could be explained by the ability of the effective interaction to absorb massive amounts of configuration impurity, as discussed by Arima *et al.* (1967).

Table 2. Comparison of experimental and theoretical transition strengths

Transition $2J_i \to 2J_f$	Experiment	Transition strengths[A] I	II	III	IV
	B(M1) $(10^{-2}\,\mu_0^2)$				
$3_1 \to 5_1$	$3\cdot24 \pm 0\cdot1$[B]	6	<1	0·7	2·1
$1_1 \to 3_1$	$0\cdot1 < B(\mathrm{M1}) < 2\cdot2$[B]	28	7	79	131
$7_1 \to 5_1$	$1\cdot7 \pm 0\cdot9$	5	3	14·8	1·3
$3_2 \to 5_1$	$<0\cdot2$	8	17	87	32[C]
$3_2 \to 3_1$	$<0\cdot22$	3·3	<1	13	3·3[C]
$3_2 \to 1_1$	$<1\cdot4$	0·7	—	—	1·4[C]
$5_2 \to 5_1$	$<0\cdot022$[D]	4	<1	49	—
$5_2 \to 3_1$	$<0\cdot11$[D]	57	17	65	—
	B(E2) $(e^2\,\mathrm{fm}^4)$				
$1_1 \to 5_1$	$1\cdot8 \pm 0\cdot3$	2·16	0·9	0·5	1·1
$9_1 \to 5_1$	$<3\cdot1$	—	2·6	2·8	11·7
$7_1 \to 3_1$	$<8\cdot0$	2·25	2·1	—	7·9
$5_2 \to 5_1$	$<0\cdot3$[D]	1·26	0·6	1·5	—
$5_2 \to 1_1$	$<1\cdot2$[D]	3·05	—	—	—

[A] Comparison of experimental data from Fig. 1 and Table 1 with (I) a shell model with phenomenological interactions (Akiyama *et al.* 1969), (II) a shell model with realistic interactions (Halbert *et al.* 1971), (III) the Nilsson model (Lambert *et al.* 1973) and (IV) an asymmetric rotor model (Allard *et al.* 1972).
[B] Mixing ratios from Allen *et al.* (1965).
[C] Allard *et al.* (1972) predict the second 3/2 state at an energy of 2·5 MeV. The experimental data in the second column are from the well-established 3/2 state at 3·07 MeV.
[D] For an assumed lifetime of the 3·15 MeV state of >1 ps (Broude *et al.* 1971). The γ ray from which this limit was derived was not seen in the present work.

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Manuscript received 25 June 1976