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Spins and spin alignments in $^{16}O + ^{16}O$ inelastic scattering

S. F. Pate,* R. W. Zurmühle, A. H. Wuosmaa,† and P. H. Kutt
Physics Department, University of Pennsylvania, Philadelphia, Pennsylvania 19104

M. L. Halbert, D. C. Hensley, and S. Saini
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

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Angular correlation measurements have been performed for the heavy-ion inelastic channel $^{16}O(^{16}O,^{16}O)^{16}O(3^-$, 6.13 MeV) over a wide energy range. The spin alignment was determined and the range of acceptable values of J has been narrowed down for several structures in the excitation function. Our results rule out the possibility of any correlation between the structures in this channel and those in the elastic and the 6.05 MeV (0_2^+) inelastic channel and are in conflict with an interpretation in terms of the band crossing model.

The spectroscopy of resonant structures in heavy-ion reactions has been a subject of investigation for many years but some of the most important questions regarding the nature of these structures remain still largely unanswered. One question of considerable interest is the degree of correlation that exists between the various channels. For example, in the elastic and inelastic channels in $^{16}O+^{16}O$ one observes intermediate width structure with a spacing of approximately 5 MeV in the elastic channel as well as in several inelastic channels in the energy range $E_{c.m.} = 20$–40 MeV. These inelastic channels include not only momentum matched and strongly excited channels like the 6.13 MeV (3^-) state but also the weakly excited and momentum mismatched 6.05 (0_2^+) state.

The shape of these structures indicates that they are not individual isolated resonances. The spacing between peaks suggests, however, that they may correspond to angular momentum windows in the bombarding energy, where the cross section is dominated by a single partial wave. Alternately, these structures can be interpreted as a series of quasimolecular resonances, each of them fragmented into several states. In $^{16}O+^{16}O$ the correlation between the excitation functions is suggestive of quasimolecular structure but the evidence is certainly not conclusive. Calculations based on the band crossing model[1,2] do make definite predictions about the positions and spins of resonances in the various channels. Similar predictions have been made by Tanimura and Tazawa,[3] using a coupled channel formalism with a folding model potential.

Experimental studies have led to tentative spin assignments for the elastic channel[4] and the weakly excited 6.05 MeV (0_2^+) channel[5] but not for the more strongly excited 6.13 MeV (3^-) channel which offers a more reliable test of the model calculations. Therefore, we decided to perform detailed cross section and particle-γ angular correlation measurements for this excitation. In the last few years such experiments[6,7] have yielded new information, not only with regard to the spins of resonances but also concerning the spin alignment in the exit channel, which is also quite sensitive to the reaction mechanism.

The experiment was performed at the Holifield Heavy-Ion Research Facility of Oak Ridge National Laboratory, with the Spin Spectrometer,[8] a 4π γ-detection device consisting of 72 NaI(Tl) counters. A recoil coincidence setup, very similar to that of Ref. 7, was used to detect charged particles. The targets were of self-supporting BeO, formed by oxidation of evaporated Be foils of 15 $\mu g/cm^2$, yielding a thickness of ~ 20 $\mu g/cm^2$ of ^{16}O. The spin alignment data were normalized to an excitation function measurement done at the University of Pennsylvania Tandem Accelerator Facility, in which normalization was obtained from small angle elastic yields using the optical parameters of Reilly *et al.*[9] These detailed excitation data are displayed in the bottom panel of Fig. 1 and in Fig. 3(b).

Once we have chosen an axis of quantization for angular momentum, the spherical symmetry of the Spin Spectrometer allows us to integrate over the ϕ_γ dependence of the γ-ray distribution. Then the angular distribution of γ rays is given by

$$W(\theta_\gamma) = \sum_m A_m W_m(\theta_\gamma) , \tag{1}$$

where A_m is the population parameter for magnetic substate m, and $W_m(\theta_\gamma)$ is the distribution due to substate m, given by

$$W_m(\theta_\gamma) = \sum_{k=0,2,\ldots}^{2J} (-1)^{J-m} (JJm-m\,|\,k0) \times \left[\frac{4\pi}{2k+1}\right]^{1/2} Q_k G_k R_k^{Jm} P_k(\cos\theta_\gamma) . \tag{2}$$

Here, Q_k is a finite-size coefficient, R_k^{Jm} a radiation coefficient, $P_k(\cos\theta_\gamma)$ a Legendre polynomial, and G_k is a hyperfine interaction attenuation coefficient. Due to the long lifetime of the 3^- state, $\tau = 26.6$ ps, there results a large dealignment of ions which have only one atomic electron. These coefficients are given by (Ref. 10)

$$G_k = 1 - \frac{k(k+1)}{(2J+1)^2}\varepsilon , \tag{3}$$

where ε is the fraction of ions with one electron; at our en-

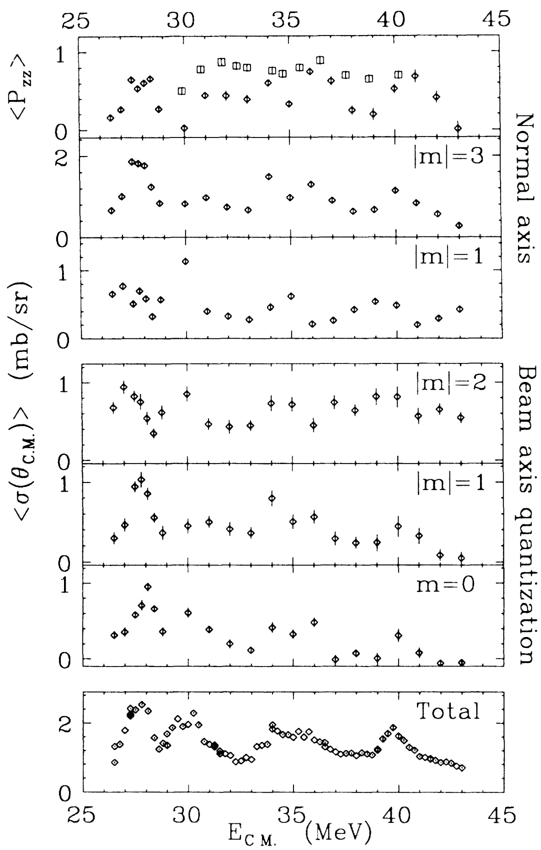

FIG. 1. Angle averaged excitation functions for the total cross section (bottom panel), for individual magnetic substates, and for the alignment (top panel). Alignment data from the Munich measurement (Ref. 11) are also shown (square points).

ergies, $\varepsilon \sim 0.5$. The other likely charge states, 6^+ and 8^+, undergo very little or no dealignment, respectively.

Figure 1 shows excitation functions for individual magnetic substates, for two quantization directions, as well as the total cross section. With quantization along the beam axis, all values of m are allowed, but we found that the contribution from $|m|=3$ was consistent with zero at every energy. The results shown come from a fit where σ_3 was fixed at zero (σ_m is the cross section for substate $\pm m$). The structures at 28, 35, and 40 MeV stand out well above the background in the excitations for $m=0$ and 1, but are only barely apparent above the background for $m=2$. (The slight misalignment of the peaks for $m=0$ and 1 for the 28 MeV peak may be caused by interference with the background.) The structure at 30 MeV, however, while only showing a weak excitation for $m=1$, seems to be strongly excited for $m=2$. For quantization along the axis normal to the scattering plane, symmetry only allows population of the $|m|=1,3$ substates. The results for this axis are shown, along with the angle averaged alignment P_{zz} on the top of Fig. 1. Results of alignment measurements by the Munich group[11] are also shown in this figure. Their data correspond to a larger range of angles ($21° < \theta_{lab} < 45°$) and therefore the two measurements cannot be directly compared. It is worth noting, however, that both sets of data have a similar energy dependence and show a low value for the alignment at $E_{c.m.}=30.0$ MeV.

Cross sections for the individual substates are listed in Table I for the four energies where the summed cross section exhibits a peak. The (gross) cross section given in this table is the peak value of the cross section at the given energy, or the average over the highest few points for the broader structures. We have estimated the nonresonant contribution to the cross section at each of these peaks. The net cross section that remains after subtraction of this estimate is listed. In addition, we give the fraction of the net cross section contributed by each substate. In the idealized situation of an isolated resonance which decays through a single l value, the fractional cross sections should be equal to the squares of the coefficients $(l3-mm|J0)$ (summed over $\pm m$, for $m\neq 0$). These are shown at the bottom of Table I. These values depend very weakly on the value of J if $J \gg 1$. While the numbers in Table I indicated that this idealized situation is not realized (small deviations can arise from the limited angle range), they do clearly favor the dominance of the aligned configuration. We see that σ_3 is very small as it should be for the aligned configuration and σ_1 is large while the nonaligned configuration would require σ_1 to be quite small. The fact that the structure at 30 MeV is not aligned is reflected in the small contribution from $|m|=1$ at this energy; on the other hand the $|m|=3$ cross section falls far below the prediction, and we conclude that interference effects between the different l values (and contributions from background) are important.

To extract spin values we subjected the angular distri-

TABLE I. Energy averaged cross sections for magnetic substates of the 3^- level.

$E_{c.m.}$ (MeV)	$m=0$	$\lvert m\rvert=1$	$\lvert m\rvert=2$	$\lvert m\rvert=3$
	Gross cross sections (mb/sr)			
28.1	0.77	0.92	0.69	0.00
30.0	0.60	0.45	0.86	0.00
35.0	0.41	0.62	0.69	0.00
40.0	0.30	0.43	0.80	0.00
	Net cross sections (mb/sr)			
28.1	0.56	0.52	0.28	0.00
30.0	0.43	0.06	0.45	0.00
35.0	0.32	0.40	0.28	0.00
40.0	0.29	0.31	0.40	0.00
	Fractional yields (net/total)			
28.1	0.41	0.38	0.21	0.00
30.0	0.45	0.07	0.48	0.00
35.0	0.32	0.40	0.28	0.00
40.0	0.29	0.31	0.40	0.00
	Fractional yields for isolated resonances			
Aligned[a]	0.34	0.48	0.16	0.02
Nonaligned[b]	0.20	0.02	0.38	0.40

[a] $l=19$ and $J=22$. [b] $l=19$ and $J=20$.

butions of all substates to a simultaneous fitting procedure. We assumed that the structures in the cross section are dominated by a single value of J; for an aligned configuration, then, the decay should proceed predominantly via a single value of l. But all four possible l values ($l=J\pm 1, \pm 3$) were included and freely varied in the calculations, using the result

$$\sigma_m(\theta_{\mathrm{c.m.}}) = \left| \sum_l a_l (l3-mm \mid J0) Y_{lm}(\theta_{\mathrm{c.m.}},0) \right|^2 + \text{background}. \tag{4}$$

We estimated the difference between Coulomb and hard-sphere phase shifts to vary by less than 2° between any two of the four l values and therefore we forced all amplitudes a_l to be real. We also required the cross section for $|m|=3$ to be small and that the fit represent an aligned configuration, except at 30 MeV where the measured alignment is very small. We have calculated fits with and without background terms. When included, an angle independent term, identical to the estimate used in Table I, was used for the background for each substate at each energy. This value was not varied to obtain the best fit and its inclusion does not affect our conclusions, but we did find that the inclusion of this term improved the fits. An isotropic term is not a completely accurate description of the background, but the off-resonance angular distributions are, in fact, nearly isotropic.[12] Results of our calculations for two energies are shown in Fig. 2. For the structure at 28 MeV, we can only obtain satisfactory fits for $J=20$, for all points within this structure. In the figure, we show the results for 28.1 MeV (the second best fit is for $J=22$). The nonaligned structure at 30.0 MeV (not shown in Fig. 2) has a very oscillatory $m=0$ angular distribution that suggests that $l=21$ is the dominant l value.[12] The $|m|=1$ angular distribution, on the other hand, is somewhat featureless which is consistent with the nonaligned nature of that structure (see Table I). At 36.0 MeV we obtain fits of comparable quality for $J=26$ and 28. However, the angular distribution changes very significantly across this rather broad structure (e.g., 2 MeV lower, at 34.0 MeV, the $m=0$ angular distribution is already rather featureless). It appears that at least two strong resonances contribute to this structure and a very tentative spin assignment of $J=26$ or 28 would belong to the member centered around 36 MeV, while no information can be extracted from our data for the lower member centered near 34 MeV. With regard to the structure at 40 MeV, insufficient statistics were collected to allow for a meaningful statement concerning its spin.

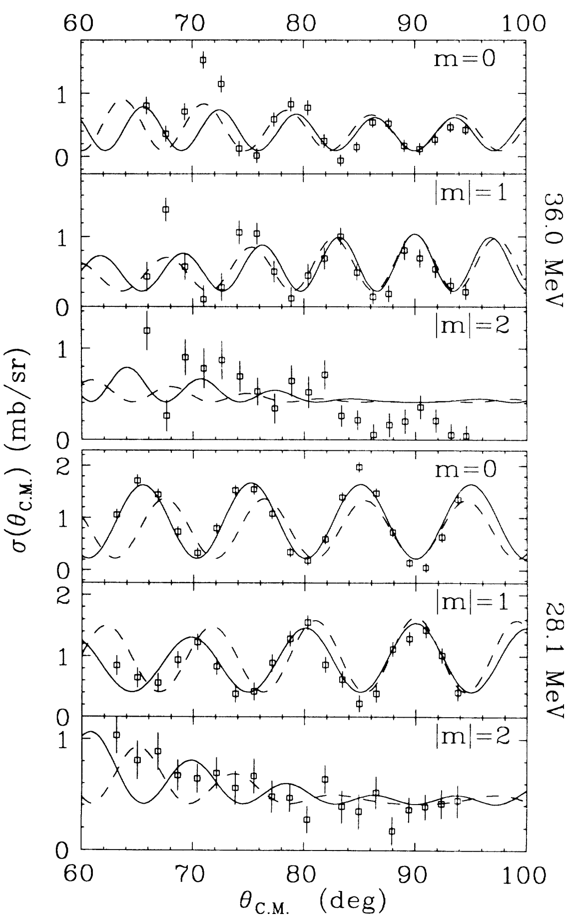

FIG. 2. Fits to the angular distributions (beam axis quantization). For 28.1 MeV, the solid curve assumes $J=20$, the dashed curve $J=22$. For 36.0 MeV, the solid curve assumes $J=28$, the dashed curve $J=26$.

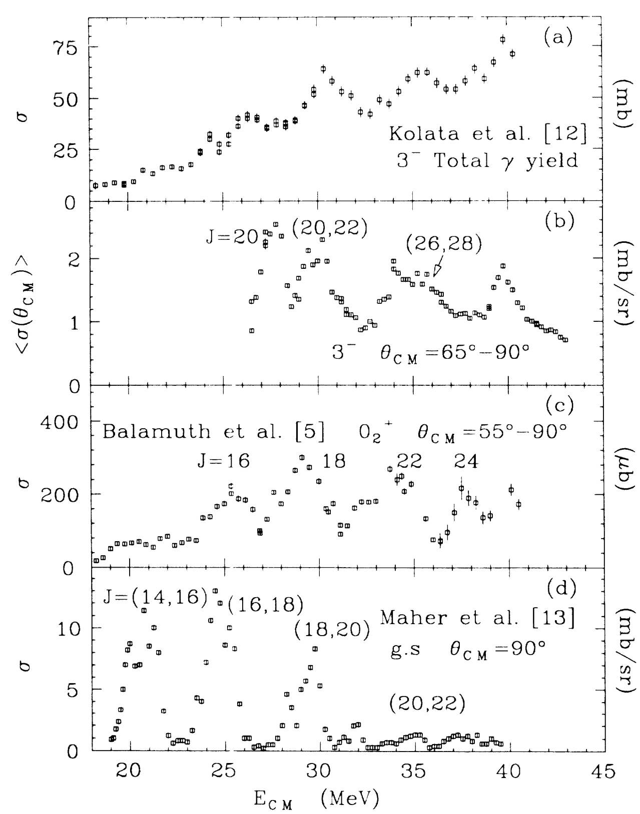

FIG. 3. (a) Total γ-ray yield for the 6.13 MeV transition (Ref. 13); (b) angle averaged cross section for the 3^- channel (this work); (c) cross section for the 0_2^+ channel and spin assignments (Ref. 5); (d) elastic cross section at 90° (Ref. 14) and suggested spins (Refs. 3, 4, and 15–17).

Figure 3(b) shows a summary of our results. For comparison, the total γ-ray yield from the 3^- excitation[13] is shown in Fig. 3(a). This total yield includes contributions from mutual excitations involving all bound and unbound excitations of the other interaction partner, hence it is not too surprising that the two excitation functions are not more alike. It is, however, remarkable that our strongest peak does not appear in the γ-ray yield data. Figures 3(c) and 3(d) show cross sections for the 6.05 (0_2^+) excitation[5] and for $\theta_{c.m.}=90°$ elastic scattering,[14] respectively. Several discussions of the spins of the structure in the elastic channel[3,15–17] have appeared in the literature, as well as a model dependent determination of spin values based on a careful analysis of the data;[4] these values and the previous tentative spin assignments are all within $2\hbar$ of each other. There is a hint of correlation between the positions and spins of the structures in the elastic channel and those seen in the 0_2^+ channel, while the structures in the 3^- channel exhibit no correlation in position or in spin with the elastic and 0_2^+ channels. The behavior of the cross section for the 3^- state is also in conflict with the band crossing model and any other model that predicts a simple rotational pattern for the resonances in this channel. Even without our tentative spin assignments, the lack of alignment of the structure at 30 MeV and the proximity of two pronounced separate structures at 34 and 36 MeV demand more refined calculations and provide a new challenge in the effort to formulate a theoretical description of the quasimolecular structure for this inelastic channel. With regard to our spin determination, we feel confident about the assignment of $J=20$ to the structure at 28 MeV, but the other spin values should be considered only tentative. Nevertheless, we feel that we have demonstrated that our angular correlation measurements, in combination with our analysis requiring simultaneous fits for all magnetic substates, represent a very powerful tool in elucidating the nature of high spin structures in heavy-ion inelastic scattering.

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*Present address: Indiana University Cyclotron Facility, Bloomington, IN 47405.

†Present address: Physics Division, Argonne National Laboratory, Argonne, IL 60439.

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