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## The $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C})^{16}\text{O}$ reaction : an insight into the reaction mechanism by particle correlation measurements

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**Résumé.** — La réaction  $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C})^{16}\text{O}$  a été étudiée par des mesures de corrélations angulaires de particules. Cette expérience a démontré : i) que le mécanisme de double excitation en voie de sortie est un phénomène très important, ii) que l'alignement du noyau résiduel  $^{16}\text{O}$  est très fort.

**Abstract.** — The  $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C})^{16}\text{O}$  reaction was studied by particle correlation measurements. It is shown : i) that the double excitation mechanism is very important in the exit channel, ii) that the alignment of the residual nucleus  $^{16}\text{O}$  is very strong.

### 1. Introduction.

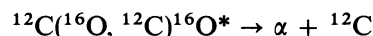
In the past few years a large amount of experimental and theoretical works have been devoted to the study of heavy ion induced transfer reactions. In particular the alpha particle transfer has been extensively studied using different targets and projectiles and was proved to be a good tool to populate high spin states in light even-even nuclei [1]. But in most cases it has not been possible to extract quantitative spectroscopic information for these states from simple angular distributions.

A part of the reaction mechanism is not yet well understood and not yet well described by reaction mechanism theories. One of the open problems is the importance of the ejectile excitation and of the double excitation (ejectile + residual nucleus) mechanism.

A deeper insight on these problems can be reached by correlation measurements. In a previous work on the  $^{16}\text{O}(^{16}\text{O}, ^{12}\text{C})^{20}\text{Ne}$  reaction [2] we have shown that the polarization measurement of the residual nucleus was a stringent test of the reaction models and the  $^{20}\text{Ne}$  polarization was found to be very strong.

In the present experiment we have measured particle-particle correlations in the four-nucleon trans-

fer reaction :



where the  $^{16}\text{O}^*$  levels are selected by the energy of the associated  $^{12}\text{C}$ .

The aim of this work was :

- to determine the alignment of the  $^{16}\text{O}$  residual nucleus in order to compare it to previous experiments ;
- to evaluate the part of ejectile and double excitation in this reaction, this problem being still open at this date.

### 2. Experimental set-up.

The experimental set-up has been described in details in a previous paper [2]. We chose to detect the  $^{12}\text{C}$  resulting from the  $^{16}\text{O}$  decay instead of the  $\alpha$  for the optimization of the efficiency.

The  $^{16}\text{O} 7^+$  beam from the Orsay MP Tandem is focussed on  $^{12}\text{C}$  targets ( $50 \mu\text{g}/\text{cm}^2$ ) and stopped in a Faraday cup. The energy and the position of the decay products from the  $^{16}\text{O}^*$  excited nucleus are obtained in a silicon position sensitive detector (PSD) 5 cm long, placed in the reaction chamber 7 cm away from the target. The  $^{12}\text{C}$  particles from the two body reaction are analysed by a  $n = 1/2$  spectrometer and are localized in two position sensitive gas counters which provide the ray tracing [3] at the exit of the magnet. The ion identification is

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unambiguously achieved with a  $\Delta E$ ,  $E$  ionization chamber [4].

For each event, nine primary signals are generated, namely : S1, S2, S3, S4 from the two ends of the position counters,  $\Delta E$ ,  $E$  from the ionization chamber,  $E'$  and  $P'E'$  the energy and position signals from the PSD, and the TAC which operates between timing signals coming from  $E'$  and the first gaz counter. These signals are processed through a computer which provides for several on line visualizations and puts the data on tape for an off line treatment.

### 3. Results.

**3.1  $^{12}\text{C}$  ENERGY SPECTRA FROM THE  $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C})^{16}\text{O}$  REACTION.** — The  $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C})^{16}\text{O}$  reaction has been studied at 100 MeV incident energy. Spectra obtained for this reaction are shown in figure 1a and 2a. These spectra exhibit a strong selectivity. The populated states are members of the  $K^\pi = 0^+$  (6.05 MeV  $0^+$ , 6.92 MeV  $2^+$ , 10.35 MeV  $4^+$ , 16.3 MeV  $6^+$ ) and  $K^\pi = 0^-$  (9.63 MeV  $1^-$ , 11.60 MeV  $3^-$ , 14.67 MeV  $5^-$ ) alpha cluster bands. The same states are selectively populated in the ( $^7\text{Li}$ , t) [5] and ( $^{12}\text{C}$ ,  $^8\text{Be}$ ) [1] reactions.

The main problem in the study of the ( $^{16}\text{O}$ ,  $^{12}\text{C}$ ) reaction is the important overlap between the  $^{16}\text{O}$  ground state wave function and the  $^{12}\text{C}^*$  (4.43 MeV  $2^+$ )  $\otimes$   $\alpha$  wave function. Thus the population of this  $2^+$  excited state is expected to be large. This peak is clearly observed in the spectra in spite of the Q mismatch. The remaining problem is the contribution of this state ( $^{12}\text{C}^*(2^+)$ ) in the higher excitation energy peaks. In fact, several excitation energies of the populated states correspond to a possible double excitation. For example, the  $4^+$  state of  $^{16}\text{O}$  at 10.36 MeV can be mixed with the double excitation peak coming from 6.05 MeV ( $0^+$ ) of  $^{16}\text{O}$  + 4.43 MeV ( $2^+$ ) of  $^{12}\text{C}$  and so on.

**3.2 CORRELATION MEASUREMENTS ; PROBLEM OF THE EJECTILE EXCITATION.** — One way to solve this problem is to observe the deexcitation of the residual nucleus in the outgoing channel. Figures 1b and 2b display the outgoing  $^{12}\text{C}$  spectra measured with a coincidence between a  $^{12}\text{C}$  at the exit of the magnet and a decaying particle coming from the  $^{16}\text{O}$  residual nucleus. The detailed analysis of these spectra together with the bidimensional energy-position spectra obtained in the PSD permit to precise the mode of deexcitation of each level under study and to evaluate the contribution of the double excitation in simple spectra.

— Peak around 10.40 MeV.

Figure 3 shows in details the area in the energy spectrum around 10.40 MeV. The plot (1) is the energy spectrum gated by a coincidence with a signal in the PSD. Plot (2) is the one obtained with a window put around the recoil events (the 4.44 MeV ( $2^+$ ))

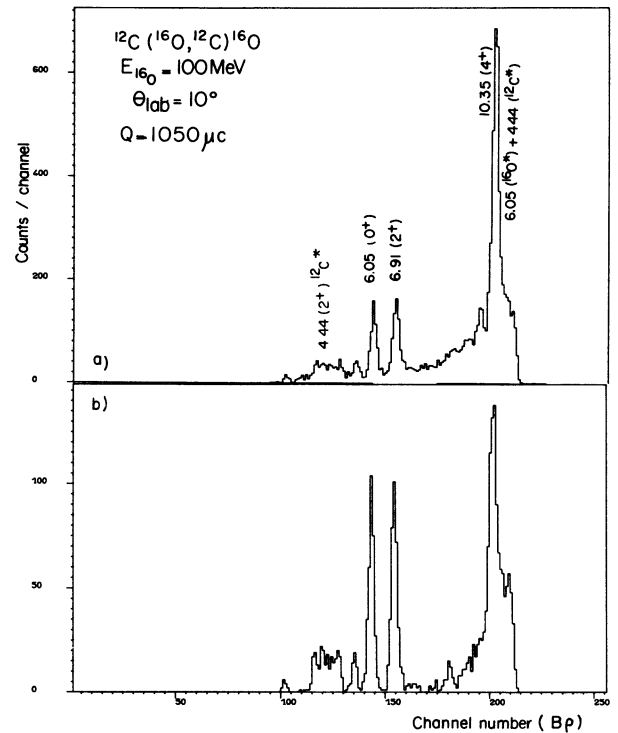


Fig. 1. — a)  $^{12}\text{C}$  energy spectrum observed in the  $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C})^{16}\text{O}$  reaction at 100 MeV incident energy. This spectrum corresponds to the first exposure of the magnet. b) Same spectrum but gated by a coincidence between a  $^{12}\text{C}$  event at the exit of the magnet and an event in the position sensitive detector set in the reaction chamber.

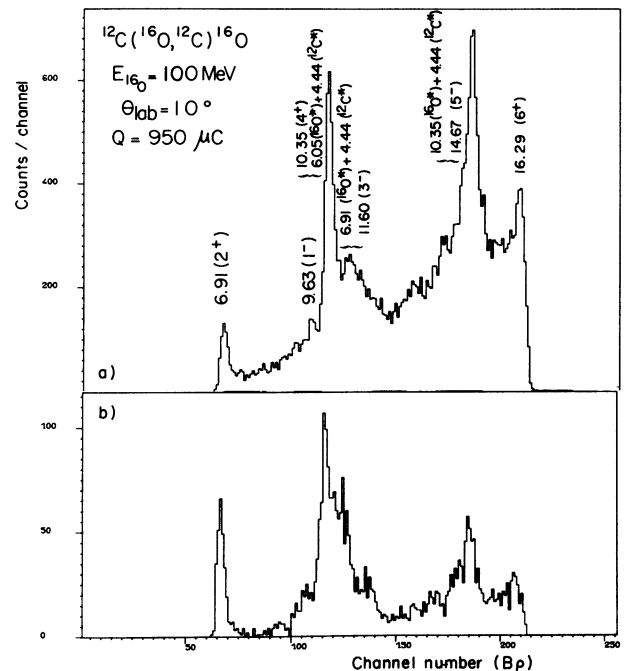


Fig. 2. — a)  $^{12}\text{C}$  energy spectrum observed in the  $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C})^{16}\text{O}$  reaction at 100 MeV incident energy. This spectrum corresponds to the second exposure of the magnet. b) Same spectrum but gated by a coincidence between a  $^{12}\text{C}$  event at the exit of the magnet and an event in the position sensitive detector set in the reaction chamber.

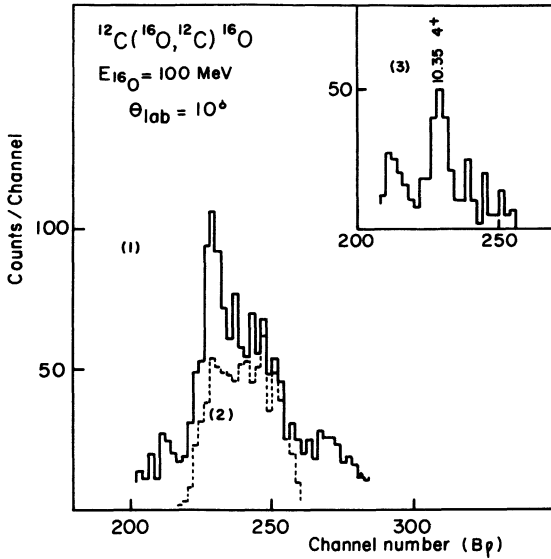


Fig. 3. — Detail of the  $^{12}\text{C}$  energy spectrum in the area around 10 MeV. See text to have explanation for the different plots (1) (2) and (3).

level of  $^{12}\text{C}$  decaying by  $\gamma$  emission gives a recoil nucleus which is detected in the PSD and gives a well defined group of events at a given angle and energy). Plot (3) corresponds to a window put on the correlation plot  $^{16}\text{O}^* 10.35 \text{ MeV } (4^+) \rightarrow \alpha + ^{12}\text{C}$  corresponding to these three-body kinematics. The first thing to note is that peak (3) well corresponds to the difference between peak (1) and peak (2). This checks that there is no other background.

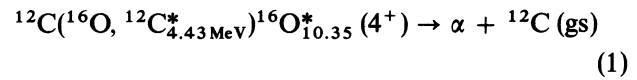
The bump observed in (2) corresponds to the two double excitation peaks 4.44 MeV ( $2^+$ )  $^{12}\text{C}^*$  + 6.05 ( $0^+$ ) MeV and 6.91 MeV ( $2^+$ )  $^{16}\text{O}^*$ . These peaks are broadened by  $\gamma$  Doppler effect. The ratio of the double excitation cross section to the  $4^+$   $^{16}\text{O}$  state was estimated to be

$$N = \frac{d\sigma/d\Omega(D.E)}{d\sigma/d\Omega(10.35 \text{ MeV } 4^+)} = 3.0 \pm 0.5.$$

— Peak around 14.7 MeV.

This broad peak can be attributed to the  $5^-$  state of  $^{16}\text{O}$  at 14.67 MeV or (and) to the double excitation 4.44 MeV ( $2^+$ )  $^{12}\text{C}^*$  + 10.35 MeV ( $4^+$ )  $^{16}\text{O}^*$ . One can observe (Fig. 2) that the ratio of this peak to the peak around 10.4 MeV is not the same in the single spectrum (a) and in the coincidence spectra (b). This is due to the fact that the PSD was not set at an angle where the recoil nucleus  $^{12}\text{C}^*$  coming from the double excitation could be detected.

The distribution of the particles detected in the PSD gated by the coincidence with the peak around 14.7 MeV in the two-body reaction spectrum is shown in figure 4. The full line is the kinematical line corresponding to the deexcitation of  $^{16}\text{O}^*$  in the two different sequential reactions :



and

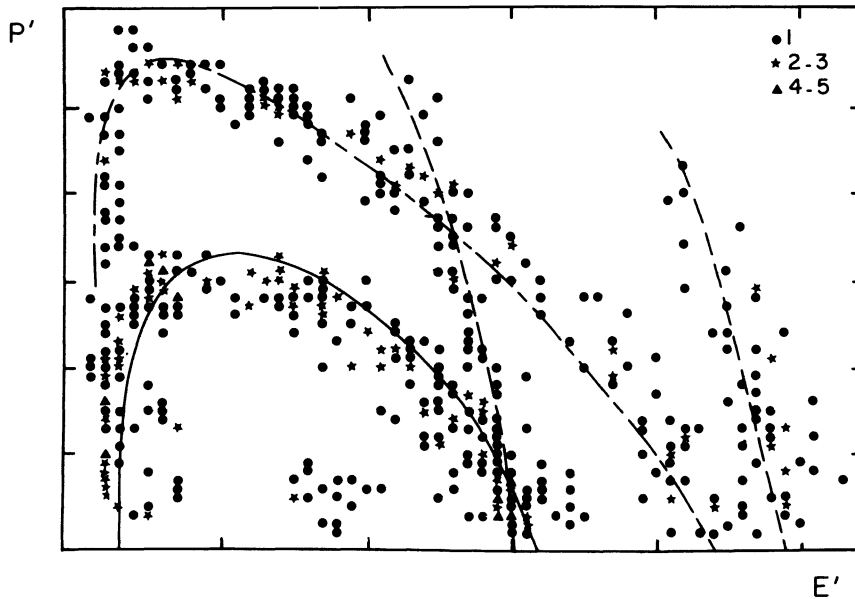
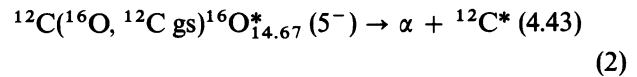
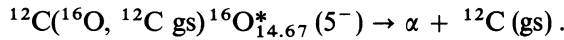


Fig. 4. — Distribution of the  $^{12}\text{C}$  and  $\alpha$  particles detected in the PSD and gated by the coincidence with  $^{12}\text{C}$  at the exit of the magnet, corresponding to the peak at 14.7 MeV. The full line is the kinematical line corresponding to the deexcitation of the  $^{16}\text{O}^*$  in  $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C}^*(2^+))^{16}\text{O}^*(4^+) \rightarrow \alpha + ^{12}\text{C}(\text{gs})$  and  $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C})^{16}\text{O}^*(5^-) \rightarrow \alpha + ^{12}\text{C}^*(2^+)$ . The dotted line is the kinematical line corresponding to the deexcitation of the  $5^-$   $^{16}\text{O}^*$  state at 14.67 MeV.  $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C})^{16}\text{O}^*(5^-) \rightarrow \alpha + ^{12}\text{C}(\text{gs})$ . The other lines correspond to the detection of the  $\alpha$  coming from the same decays.

The three-body kinematics are exactly the same and the only way to distinguish these two reactions would be to detect the  $^{12}\text{C}$  recoil nucleus after  $\gamma$  emission in reaction (1).

Nevertheless when a gate is put on this correlation and the energy spectrum is observed, the obtained peak is broad ( $\sim 1$  MeV). This indicates that the reaction (1) corresponding to the double excitation is largely dominant.

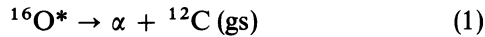
The dotted line is the kinematical line corresponding to the deexcitation of the  $5^-$   $^{16}\text{O}$  state at 14.67 MeV :



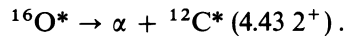
The contribution of this  $5^-$  state was evaluated to be only 30 % of the whole peak around 14.6 MeV.

— Peak around 16.3 MeV.

This peak cannot contain any double excitation process. But there are two decay channels for this  $^{16}\text{O}(6^+)$  state, namely :



and



These two channels were also clearly distinguished in the correlation figure. The first decay channel is dominant and is evaluated to be 65 %, of the decay mode. This result is in agreement with that obtained by S. S. Sanders *et al.* [1].

**3.3 CORRELATION FUNCTIONS AND ALIGNMENT OF THE  $^{16}\text{O}$  RESIDUAL NUCLEUS.** — Correlation functions between  $^{12}\text{C}$  (at the exit of the magnet) and  $^{12}\text{C}$  (coming from the  $^{16}\text{O}$  decay) have been measured in the reaction plane ( $\theta = \frac{\pi}{2}$ ) for a  $^{12}\text{C}$  lab. angle of  $10^\circ$  with an aperture of  $1^\circ$ . A sample of correlation functions obtained for some levels is displayed in figure 5. It is seen that for the  $^{16}\text{O}$  states decaying to  $\alpha + ^{12}\text{C (gs)}$ , rather regular oscillations are observed. Their number is equal to the spin of the level in the  $\varphi$  range of  $0^\circ$  to  $180^\circ$ . This is not true for the  $6^+$  decaying to  $\alpha + ^{12}\text{C} (2^+)$ . In this case the shape of the correlation function is very different with no regular oscillations. This is due to the fact that, only in the first cases, all the particles involved have spin zero (with the exception of the residual nucleus).

In our previous work it was shown [2, 6] that the population of the different magnetic substates could be extracted from the experimental correlation functions. Two different methods can be used [2]. In this work we used the extraction from the average value of the correlation function. Only the alignment, that is to say the sum,  $|p_j^+|^2 + |p_j^-|^2$  can be deduced from this method.

It is recalled that, for a level with a given spin  $J$ , the correlation function, in the reaction plane  $W(\pi/2)$ ,

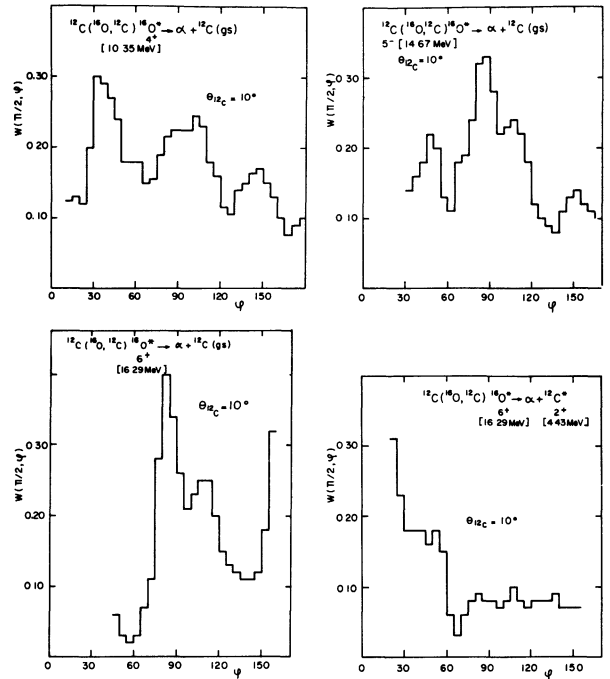


Fig. 5. —  $^{12}\text{C}$ - $^{12}\text{C}$  angular correlations measured in the  $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C})^{16}\text{O}^* \rightarrow \alpha + ^{12}\text{C}$  at 100 MeV incident energy for different  $^{16}\text{O}^*$  states. The correlations are observed in the reaction plane ( $\theta = \frac{\pi}{2}$ ) for a  $^{12}\text{C}$  lab. angle of  $10^\circ$ .

averaged over  $\varphi$  can be written as

$$\langle W_j \rangle = \sum_{M \geq 0} (|p_j^M|^2 + |p_j^{-M}|^2) \langle W_{JM} \rangle$$

where  $\langle W_{JM} \rangle$  is the contribution, with weight  $|p_j^M|^2 + |p_j^{-M}|^2$  of the two magnetic substates  $M$  and  $-M$  to the average value of the correlation function.

In table I, the values of the partial average value  $\langle W_{jj} \rangle$ , that is to say the average value of the correlation function if only the two magnetic substates  $M = \pm J$  are populated, are compared to the experi-

Table I. — Values of the calculated partial average  $\langle W_{jj} \rangle$  compared to the experimental average values for the three different studied  $^{16}\text{O}$  states.

$^{16}\text{O}$ states	$\langle W_{jj} \rangle$ calculated values	$\langle W_j \rangle$ experimental values
10.35 MeV ( $4^+$ )	0.19	0.17
10.67 MeV ( $5^-$ )	0.22	0.18
16.29 MeV ( $6^+$ )	0.24	0.21

mental values for different  $^{16}\text{O}$  levels. It is seen that the experimental values are very close to calculated maximum values. The results show the strong  $^{16}\text{O}$  alignment since the contributions of the magnetic substates  $|M| = J$  are predominant. One can estimate that the  $^{16}\text{O}$  alignment is of the same order of magnitude that as that obtained for  $^{20}\text{Ne}$  in our previous work, that is to say an alignment of  $85 \pm 5\%$ .

#### 4. Summary.

The aim of this work was to study the  $^{12}\text{C}(^{16}\text{O}, ^{12}\text{C})^{16}\text{O}$  reaction mechanism by particle angular correlation measurements. The reaction exhibits a strong selectivity. The two alpha cluster bands  $K = 0^+$  and  $K = 0^-$  are preferentially populated.

The correlation measurements have allowed us to obtain two results.

i) The double excitation ( $^{12}\text{C}^*(4.43 \text{ MeV}, 2^+) +$  residual nucleus) process is very large and contributes for 70% to the differential cross section of the peaks at 10.35 MeV and 14.7 MeV.

ii) The alignment of the  $^{16}\text{O}$  residual nucleus has been deduced and found to be very strong, comparable to that obtained for  $^{20}\text{Ne}$  in a previous work [2]. So this strong alignment seems to be a general characteristic of such an  $\alpha$  transfer reaction on light targets.

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