Determination of the positive parity band for the $^{14}C + \alpha$ molecular rotation in $^{18}O$

Yanlin Ye
School of Physics and State Key Lab of Nuclear Physics and Technology, Peking University

at INPC2019, Glasgow
Collaborators

PHYSICAL REVIEW C 99, 064315 (2019)

Investigation of the $^{14}$C + $\alpha$ molecular configuration in $^{18}$O by means of transfer and sequential decay reaction


$^1$School of Physics and State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China

$^2$China Institute of Atomic Energy, Beijing 102413, China

$^3$Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

$^4$Institute of High Energy Physics, CAS, Beijing 100049, China

$^5$Research Center for Nuclear Physics, Osaka University, 10-1 Mihogaoka, Ibaraki 567-0047, Japan

$^6$RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

Chinese Physics C Vol. 43, No. 8 (2019) 084001

Spin determination by in-plane angular correlation analysis in various coordinate systems

Biao Yang(杨彪) Yan-Lin Ye(叶沿林)$^1$ Jian-Ling Lou(楼建玲) Xiao-Fei Yang(杨晓菲) Jing-Jing Li(李晶晶) Yang Liu(刘洋) Wei Liu(刘威) Han-Zhou Yu(余翰舟)
I. Introduction

II. Measurement

III. Results and discussion

IV. Summary
Expanding and clustering - the threshold effect

Fig. 1. Schematic figure for rich phenomena in nuclear systems.
Examples at high excitation

Members of the $K = 0^+_2$, $1^-_2$, and $0^+_4$ bands of $^{20}\text{O}$ (with tentative assignments) are marked by downward hatched (blue), filled (cyan), and upward hatched (red) areas, respectively.
Observation criteria

i) $E_x$ - spin systematics:
   high moment of inertia

ii) Large cluster decay width:
   large $\Gamma_{\text{Cluster}}/\Gamma ; \gamma^2_{\text{Cluster}} ; \theta^2_{\text{Cluster}}$

iii) Characteristic transition strength
   large $M(IS)$ !!

iv) Structural link in population and decay selective path

Cluster-decay: $E_x$ selectivity; AC/spin; BR/SF; decay-path
Reflection asymmetric systems

- symmetry breaking under reflection operation
- parity inversion doublet bands: almost parallel, separated by \( \sim 5 \text{ MeV} \)

\[
\phi_r = |^{14}\text{C} \otimes \alpha\rangle \quad (\alpha\text{-cluster right}) \\
\phi_l = |\alpha \otimes ^{14}\text{C}\rangle \quad (\alpha\text{-cluster left}) \\
\Phi^\pm = N(\phi_r \pm \phi_l).
\]

- observed in some even-even stable nuclei.

Question

M. L. Avila, PHYSICAL REVIEW C 90, 024327 (2014)

α-cluster structure of $^{18}$O

Resonant scattering; R-matrix analysis;

Finding:
- Previously classified molecular states are mostly with very small SF;
- The larger SFs are very much fragmented.

* Importance to determine the spins, cluster decay BRs (SFs) of the possible molecular states.
Outline

I. Introduction

II. Measurement

III. Results and discussion

IV. Summary
Reaction channel

\[ ^{13}\text{C} + ^{9}\text{Be} \rightarrow ^{18}\text{O} + \alpha \quad Q: 12.83 \text{ MeV} \]

\[ ^{14}\text{C} + \alpha \quad Q: 6.60 \text{ MeV} \]

- beam: \(^{13}\text{C}; 65\text{MeV}\)
- target: \(^{9}\text{Be}; 1.4\mu\text{m}\)
Detector setup

Combinations:

- $L0+R0$: $^{14}C + \alpha_{\text{dec.}}$
- $L0+R0/R2$: $\alpha_{\text{dec.}} + \alpha_{\text{rec.}}$
Outline

I. Introduction

II. Measurement

III. Results and discussion

IV. Summary
High resolution energy-spectra

$E_x(M)$:
7-19 MeV; 28 states;
New states $E_x > 14$ MeV

High resolution:
11.15/1.47/111.72 MeV,
12.38/12.58/12.94 MeV
Well resolved.

Branching Ratio

\[ BR = \frac{N_{IM}/\epsilon_{IM}}{100 \times N_{MM}/\epsilon_{MM}} \]

Obtained for 14 states

<table>
<thead>
<tr>
<th>IM/MeV</th>
<th>MM/MeV</th>
<th>Branching Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.28</td>
<td>10.3</td>
<td>0.37±0.13</td>
</tr>
<tr>
<td>11.13</td>
<td>11.1</td>
<td>0.65±0.22</td>
</tr>
<tr>
<td>11.47</td>
<td>11.8</td>
<td>&gt; 0.23±0.08</td>
</tr>
<tr>
<td>11.72</td>
<td>11.8</td>
<td>&gt; 0.89±0.29</td>
</tr>
<tr>
<td>12.38</td>
<td>12.5</td>
<td>&gt; 0.41±0.14</td>
</tr>
<tr>
<td>12.58</td>
<td>12.5</td>
<td>&gt; 0.79±0.26</td>
</tr>
<tr>
<td>12.94</td>
<td>13.1</td>
<td>&gt; 0.94±0.31</td>
</tr>
<tr>
<td>13.64</td>
<td>13.9</td>
<td>&gt; 0.07±0.02</td>
</tr>
<tr>
<td>13.87</td>
<td>13.9</td>
<td>&gt; 0.32±0.11</td>
</tr>
<tr>
<td>14.18</td>
<td>14.8</td>
<td>&gt; 0.16±0.05</td>
</tr>
<tr>
<td>14.69</td>
<td>14.8</td>
<td>0.08±0.03</td>
</tr>
<tr>
<td>15.88</td>
<td>15.9</td>
<td>&gt; 0.57±0.19</td>
</tr>
<tr>
<td>16.06</td>
<td>15.9</td>
<td>&gt; 0.09±0.03</td>
</tr>
<tr>
<td>16.20</td>
<td></td>
<td>&gt; 0.09±0.03</td>
</tr>
</tbody>
</table>
Angular correlation and spin

\[ a(A, B^* \rightarrow c + C)b, \]

Spin 0 for c & C

\[ W(\theta^* = 0^\circ, \psi' = \psi - \alpha \theta^*) \]

\[ \alpha = \frac{l_i - J}{J}, \]

\[ l_i = r_0(A_p^{1/3} + A_t^{1/3}) \sqrt{2 \mu E_{\text{c.m.}}} \]

\[ |P_J(\cos(\psi))|^2. \]

Fig. 3. (color online) Schematic diagram of the four symmetric reaction-decay processes in the chamber plane. (a) and (b) are parity-symmetric processes, while (c) and (d) are their axial-symmetric processes, respectively. All processes are identified by the angles \( \theta^* \) and \( \psi \) defined in various coordinate systems, as described in the text.
For the 10.3 MeV state

\( \alpha_{\text{dec.}} \) \((T0)^+\) \( \alpha_{\text{rec.}} \) \((T2)\) events

\( \theta_{\text{cm}}: \ 4^\circ \sim 15^\circ \)

\( ^{14}\text{C} \) beam

\( \alpha_{\text{rec.}} \)
Positive-parity band confirmed

Prediction (2010):

$0^+(3.63\text{MeV})$, bound;

$2^+(5.24\text{MeV})$, bound

$4^+(7.11\text{MeV})$, previously determined

$6^+(11.69\text{MeV})$, now separated

and large SF determined

---

Negative-parity band not confirmed

Prediction (2010):
1- (9.6MeV),
3- (9.8MeV),
5- (13.1MeV)
SF fragmented?

Present data based on precise coincident measurement.
PRC99(2019)064315

Ref. PRC90(2014)024327
Outline

I. Introduction

II. Measurement

III. Results and discussion

IV. Summary
Summary

- 28 α-decay states in $^{18}$O were observed with high precision, including a few new states.
- α-decay BR are extracted for 14 resonances, and their SF are deduced by using existing tentative spins.
- Spin-parity of 4$^+$ is determined for the 10.3 MeV state, by using the AC method.
- The positive parity band is confirmed for the $^{14}$C + α configuration in $^{18}$O, whereas the related negative-parity band is still questionable.
Thank you for your attention!
| $E_x$ (MeV) | $J^p$ | $\Gamma_{\text{tot}}$ (keV) | BR | $\theta_\alpha^2$ | $E_x$ (MeV) | $J^p$ | $\Gamma_{\text{tot}}$ (keV) | $\alpha$ (keV) | $\theta_\alpha^2$ | $E_x$ (MeV) | $J^p$ | $\Gamma_{\text{tot}}$ (keV) | $\alpha$ (keV) | $\theta_\alpha^2$ | $E_x$ (MeV) | $J^p$ | $\Gamma_{\text{tot}}$ (keV) | $\alpha$ (keV) | $\theta_\alpha^2$ | $E_x$ (MeV) | $J^p$ |
|------------|--------|----------------|-----|--------|------------|--------|----------------|--------|--------|------------|--------|----------------|--------|--------|------------|--------|----------------|--------|--------|------------|--------|--------|
| 7.11(3)$^a$ | h      | 8.96(1)        | (4$^+$) | 70(30) | 5(1)     | 0.20    | 8.93    | 9.35(2)        | 3$^-$   | 180(30) | 110(30) | 0.48    | 9.70    | 3$^-$   | 140(10) | 15(2) | 0.04    | 10.29(4)        | 4$^+$   | 29(4) | 19(2) | 0.09    | 10.29    | 3$^-$   | 4$^+$   | 5$^+$ | 0.10    | 10.30    | 4$^+$ |
| 7.62(3)$^b$ | 9.35(2)        | 3$^-$   | 180(30) | 110(30) | 0.48    | 9.70    | 1$^-$   | 140(10) | 15(2) | 0.04    | 10.29(4)        | 4$^+$   | 29(4) | 19(2) | 0.09    | 10.29    | 3$^-$   | 4$^+$   | 5$^+$ | 0.10    | 10.30    | 4$^+$ |
| 7.86(3)$^b$ | 9.70(1)        | 3$^-$   | 140(10) | 15(2) | 0.04    | 10.29(4)        | 4$^+$   | 29(4) | 19(2) | 0.09    | 10.29    | 3$^-$   | 4$^+$   | 5$^+$ | 0.10    | 10.30    | 4$^+$ |
| 8.57(4)$^c$ | 9.06(4)        | 3$^-$   | 140(10) | 15(2) | 0.04    | 10.29(4)        | 4$^+$   | 29(4) | 19(2) | 0.09    | 10.29    | 3$^-$   | 4$^+$   | 5$^+$ | 0.10    | 10.30    | 4$^+$ |
| 8.70(4)$^c$ | 9.27(4)        | 3$^-$   | 140(10) | 15(2) | 0.04    | 10.29(4)        | 4$^+$   | 29(4) | 19(2) | 0.09    | 10.29    | 3$^-$   | 4$^+$   | 5$^+$ | 0.10    | 10.30    | 4$^+$ |
| 8.90(4)$^c$ | 9.63(4)$^d$    | 4$^+$   | >0.37(0.03) | 0.07    | 10.29(4)        | 4$^+$   | 29(4) | 19(2) | 0.09    | 10.29    | 3$^-$   | 4$^+$   | 5$^+$ | 0.10    | 10.30    | 4$^+$ |
| 9.13(4)$^e$ | 11.13(5)$^f$   | 2$^+$   | >0.65(0.03) | <0.01 (if 2$^-$)$^g$ | 10.98(4)        | 2$^+$   | 280(130) | 20(10) | 0.01    | 11.43(1)        | 4$^+$   | 40(10) | 30(10) | 0.05    | 11.39 |
| 11.47(5)$^h$ | 61(14)        | >0.23(0.01) | 0.02 (if 4$^+$)$^j$ | 11.43(1)        | 4$^+$   | 40(10) | 30(10) | 0.05    | 11.39 |
| 11.57(5)$^h$ | 61(14)        | >0.23(0.01) | 0.02 (if 4$^+$)$^j$ | 11.43(1)        | 4$^+$   | 40(10) | 30(10) | 0.05    | 11.39 |
| 11.72(5)$^i$ | 32(5)        | >0.89(0.03) | 0.56 (if 6$^+$)$^j$ | 11.699(5)        | 6$^+$   | 23(2) | 12(1) | 0.23    | 11.62    | 5$^-$   | 11.63 |
| 12.32(5)$^i$ | 23(5)        | >0.89(0.03) | 0.56 (if 6$^+$)$^j$ | 11.699(5)        | 6$^+$   | 23(2) | 12(1) | 0.23    | 11.62    | 5$^-$   | 11.63 |
| 12.58(5)$^i$ | 23(5)        | >0.89(0.03) | 0.56 (if 6$^+$)$^j$ | 11.699(5)        | 6$^+$   | 23(2) | 12(1) | 0.23    | 11.62    | 5$^-$   | 11.63 |
| 12.94(5)$^i$ | 337(16)       | >0.94(0.04) | 0.10 (if 2$^-$)$^r$ | 12.90(3)        | 2$^+$   | 310(30) | 285(30) | 0.09    | 13.00    | (2,4)$^+$ | 13.11 |
| 13.64(6)$^i$ | 35(26)        | >0.07(0.01) | 0.02 (if 6$^+$)$^j$ | 13.69(1)        | 2$^+$   | 530(120) | 40(20) | 0.01    | 13.94 |
| 13.87(6)$^i$ | 37(26)        | >0.07(0.01) | 0.02 (if 6$^+$)$^j$ | 13.69(1)        | 2$^+$   | 530(120) | 40(20) | 0.01    | 13.94 |
| 14.16(6)$^i$ | 169(27)       | >0.16(0.01) | 0.02 (if 6$^+$)$^j$ | 13.89(1)        | 4$^+$   | 24(10) | 14(6) | 0.01    | 13.94 |
| 14.59(6)$^i$ | 44(10)        | >0.57(0.02) | 0.02 (if 6$^+$)$^j$ | 13.96(2)        | 3$^-$   | 150(50) | 80(10) | 0.03    | 14.59 |
| 16.04(6)$^j$ | 16.20 |
| 17.12(6)$^j$ | 17.40 |
| 17.42(7)$^j$ | 17.81(9)$^c$ | 17.40 |
| 18.25(9)$^c$ | 18.25(9)$^c$ | 17.40 |

$^a$From events with $^{14}C + \alpha_{\text{decay}}$ detected in the same telescope (L0/R0).
$^b$From events with $\alpha_{\text{decay}} + \alpha_{\text{recoil}}$ detected in two telescopes (L0+R0).
$^c$From events with $^{14}C + \alpha_{\text{decay}}$ detected in two telescopes (L0+R0).
$^d$Possible spin assignment from Ref. [24].
$^e$Possible spin assignment from Ref. [25].
$^f$Possible spin assignment from Ref. [26].
$^g$Possible spin assignment from Ref. [27].
$^h$Possible spin assignment from Ref. [28].
$^i$Possible spin assignment from Ref. [29].