Cluster structures of $^{18}$O and $^{20}$O up to 20 MeV excitation energy from the ($^7$Li,p)-reaction

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Abstract. We studied the band structure of $^{18}$O and $^{20}$O using the ($^7$Li,p)-reaction at an incident energy of 44 MeV on $^{12}$C and $^{14}$C targets. Spectra have been measured from the ground state up to 20 MeV excitation energy. We found 27 and 38 new states for $^{18}$O and $^{20}$O, respectively. The even-parity bands have been analysed up to now, i.e., some bands were extended by further members. The $0^+$ band head of the molecular band in $^{18}$O at 7.796(5) MeV was identified for the first time.

1. Introduction

Cluster structures in light nuclei have recently attracted much interest, in particular $\alpha$-clustering. The cluster states based on $\alpha$-particles and other strongly bound substructures are observed especially at excitation energies near the separation energies to these clusters, as described by the Ikeda diagram [1]. In neutron-rich light nuclei molecular-like states with a two-centre structure can be produced where, e.g., an $\alpha$-particle is bound by valence neutrons to the core. Such clusters and states are for example well-known in beryllium and carbon isotopes [2, 3, 4, 5].

The $^{18}$O nucleus has been studied in the past with many reactions [6, 7, 8]. However detailed knowledge of the cluster and, in particular, of the molecular structures is still missing. The different structures of this nucleus can be characterized by the configurations (i) $^{16}$O$\otimes$2n, (ii) $^{14}$C$\otimes$$\alpha$, (iii) $^{14}$C$\otimes$$^6$He, (iv) $^{12}$C$\otimes$2n$\otimes$$\alpha$ etc. All these structures can be populated in the $^{12}$C($^7$Li,p)$^{18}$O reaction, which we used in our investigation. In this case we transfer $^6$He or rather an $\alpha$-particle and 2 neutrons to the $^{12}$C target. The configuration (i) is characterized by 2-particle-0-hole (2p-0h) states with even parity. Another possibility is a (2p-2h) proton excitation of the $^{16}$O-core, which leads to (4p-2h) states with a strong parentage to the $^{14}$C$\otimes$$\alpha$ configuration. There also exists the molecular $^{12}$C$\otimes$2n$\otimes$$\alpha$ structure consisting of a $^{12}$C-core and an $\alpha$-particle, which is bound by two valence neutrons in $2h\omega$ orbits. In an equivalent shell model description this corresponds to a (6p-4h) configuration with 2 protons and 4 neutrons in the $(sd)$ shell. An odd-particle-odd-hole excitation produces odd parity states by excitation from the $(1p)$ shell to the $(sd)$ shell. Similar considerations apply to the $^{20}$O nucleus.
These cluster structures usually correspond to large deformations of the nucleus. Strongly deformed asymmetric cluster configurations, as we are dealing with in $^{18}$O, lead to doublets of parity-split bands [9]. Several cluster bands are already known in the oxygen isotopes $^{18}$O and $^{20}$O. The $^{14}$C⊗$\alpha$ band in $^{18}$O is known up to the $8^+$ state [6, 7]. The three members $2^+$, $4^+$ and $6^+$ of the $^{12}$C⊗$2n$⊗$\alpha$ molecular band are also already known [8, 10]. The missing $0^+$ band head was predicted by Fortune [10] at 7.11 MeV, but we have localized it at a different place (see below). This nucleus has also been studied in the microscopic cluster model in the GCM framework by Descouvemont [11]. Concerning $^{20}$O, only little is known about cluster structures. The (4p-0h) ground state band and three members $0^+$, $2^+$ and $4^+$ of the (6p-2h) cluster band with the equivalent $^{16}$C⊗$\alpha$ configuration were identified by LaFrance [12]. GCM calculations have also been performed for $^{20}$O by Descouvemont [13] using the $^{16}$O⊗$2n$⊗$2n$ configuration.

2. Experiment
The ($^7$Li,p)-reaction has been measured at the Q3D magnetic spectrograph of the Maier-Leibnitz-Laboratory in Garching using an incident energy of 44.0 MeV. The measurements have been performed at three scattering angles $10^\circ$, $20^\circ$ and $30^\circ$. The $^7$Li$(3^+)$-beam intensity was typically about 200 nA. The target thicknesses were 100 $\mu$g/cm$^2$ for $^{12}$C and 70 $\mu$g/cm$^2$ for $^{14}$C. Furthermore, we used a V$_2$O$_5$ target to identify contamination lines from $^{16}$O in both carbon targets (it turned out, that the oxygen content was negligibly small). The outgoing protons were detected in the focal plane of the spectrograph in a detector system described in [14]. For each isotope spectra have been measured from the ground state up to 20 MeV excitation energy with a resolution of 45 keV. To cover this wide energy range it was necessary to measure the ($^7$Li,p)-reaction at ten magnetic field settings. For each isotope the resulting ten parts of spectra were joined together in the overlapping regions, and the counting rates were adjusted to a common scale. The spectra have been calibrated using known states of $^{18}$O and $^{20}$O, respectively. A part of the full $^{18}$O spectrum between 6.2 MeV and 13.7 MeV excitation energy is shown in Fig. 1.

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Spectrum of the $^{12}$C($^7$Li,p)$^{18}$O reaction measured at 44.0 MeV incident energy and $\theta_{\text{Lab}} = 10^\circ$. Known spin and parity assignments [15] are indicated. The small gap in the spectrum marked by the asterisk results from a shielding plate to suppress the elastic scattering, which enters the focal plane at this point.

In the analysis of the spectra the lines have been fitted using Gaussians and, above particle...
thresholds, Breit-Wigner line shapes. The flat background in Fig. 1 corresponds to the 3-body phase-space distribution (cyan) for the three particles $p$ (detected), $n$ and $^{17}$O (both not detected). At about 12.8 MeV the 4-body phase-space distribution ($p + n + n + ^{16}$O) (pink line) becomes visible. Full spectra for $^{18}$O also exist at 20° and 39°. Similar spectra were obtained for $^{20}$O at 10°, 20° and 39°. As an example a part of the spectrum of the $^{14}$C($^7$Li,p)$^{20}$O reaction up to 6 MeV excitation energy is shown in Fig. 2. Since the $^{14}$C targets contained some $^{12}$C, the spectrum measured on the $^{12}$C target was used in the fit also as a background in this case.

![Figure 2. Spectrum of the $^{14}$C($^7$Li,p)$^{20}$O reaction up to 6.4 MeV excitation energy measured at 44.0 MeV incident energy and $\theta_{Lab}=10^\circ$. Shown spin and parity assignments were taken from the literature [16]. $^{18}$O lines resulting from $^{12}$C are indicated.](image)

3. Results and Discussion

The excitation energy $E_x$ of the members of a rotational band depends on the angular momentum $J$ of these states as follows: $E_x = (h^2/\Theta) \cdot J(J+1) + E_0$. Here $\Theta$ is the moment of inertia of the deformed nucleus in a given cluster configuration and $E_0$ is the offset energy. We present here first results for the bands, where some members are already known, and extend these by further band members using the given relation between $E_x$ and $J$ and further information from the cross sections and their angular dependences. Tentative assignments of the new members of the rotational bands have been made in this way.

3.1. $^{18}$O rotational bands

All members of the well-known ground state band of $^{18}$O are observed [6]: 0$^+$ at 0.00 MeV, 2$^+$ at 1.98 MeV and 4$^+$ at 3.36 MeV. We also observe the $^{14}$C⊗$\alpha$ cluster band based on the 0$^+$ band head at 3.64 MeV and the members at 5.26 MeV (2$^+$), 7.12 MeV (4$^+$), 11.70 MeV (6$^+$) and 17.60 MeV (8$^+$) [17]. The three known members [8, 10]: 2$^+$ at 8.22 MeV, 4$^+$ at 10.29 MeV and 6$^+$ at 12.55 MeV of the $^{12}$C⊗2$n$⊗$\alpha$ molecular band are also identified. The 0$^+$ band head, suggested by Fortune at 7.11 MeV [10], has now been identified for the first time at 7.796(5) MeV. Furthermore, using the $J(J+1)$ rule for the excitation energy and taking into account, that the states of this molecular band should be strongly populated in our reaction, we extended this band by tentatively assigned states $J^2=8^+$ at 15.80 MeV and $10^+$ at 20.38 MeV.
Figure 3. Even-parity bands of $^{18}$O studied in the present work. Solid circles refer to the members of the (2p-0h) ground state band, solid squares to the $^{14}$C⊗α cluster band and solid triangles to the $^{12}$C⊗2n⊗α molecular band. The lines indicate a linear fit to the data.

Fig. 3 shows these results in a plot of excitation energy $E_x$ versus $J(J+1)$ for the states of the ground state band (solid circles), the α-cluster band (solid squares) and the molecular band (solid triangles) in $^{18}$O. One can see, that the excitation energies for the α-cluster band follow quite well the $J(J+1)$ dependence. Concerning the molecular band, the known 2$^+$, 4$^+$ and 6$^+$ states, the suggested 8$^+$ and 10$^+$ members and the new 0$^+$ state at 7.8 MeV also lie all along a straight line in the plot. Theoretical calculations of Descouvemont and Baye [11] using a $^{14}$C⊗α structure are in a good agreement with the experimental data for the cluster band, but for the ground state band they are 5 MeV below the experimental values and for the known three members of the molecular band 2 MeV above the data.

The $^{12}$C⊗2n⊗α rotational band has a very small slope parameter $\hbar^2/\Theta = 0.114$ MeV (for comparison: the slope for the $^{16}$O⊗4n ground state band is 0.330 MeV and for the $^{14}$C⊗α cluster band 0.183 MeV). This means that the molecular band has a very large moment of inertia $\Theta$, which corresponds to a strong deformation of the structure and a large distance between the $^{12}$C-core and the α-particle in this configuration.

3.2. $^{20}$O rotational bands
States in $^{20}$O are known up to about 13 MeV [12, 18]. To investigate the cluster structure of this isotope we have measured the $^{14}$C($^7$Li,p)$^{20}$O reaction up to 20.2 MeV excitation energy. The analysis has been performed in same way as for $^{18}$O. In $^{20}$O all members of the $^{16}$O⊗4n ground state band [12] are observed: 0.00 MeV (0$^+$), 1.67 MeV (2$^+$) and 3.57 MeV (4$^+$). We identify also the three known members of the $^{16}$C⊗α cluster band based on the 0$^+$ band head at 4.46 MeV with the members 5.24 MeV (2$^+$) and 7.75 MeV (4$^+$). Furthermore, we extended this band suggesting states with $J^\pi = 6^+$ at 10.92 MeV and $J^\pi = 8^+$ at 15.72 MeV. We have also indications for the $^{14}$C⊗2n⊗α molecular band in $^{20}$O based on the 0$^+$ band head at 9.77 MeV.

4. Summary and Outlook
The spectra of $^{18}$O and $^{20}$O have been measured from the ground state up to 20 MeV excitation energy and many new states were found. The band structure has been analyzed and, as a first result, the known even-parity cluster bands were extended by new members. In $^{18}$O the 0$^+$ band head could be identified at 7.796 MeV. Further results are expected in the ongoing analysis for odd-parity states and for the corresponding band structures. They will give additional information for parity-split bands and asymmetric molecular structures.
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6. References
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