

## RESONANCES EXCITED BY THE ${}^9\text{Be}({}^6\text{Li},d){}^{13}\text{C}$ REACTION

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Alpha resonant states in  ${}^{13}\text{C}$  up to 15 MeV were excited by the  ${}^9\text{Be}({}^6\text{Li},d){}^{13}\text{C}$  reaction. The data were taken at a bombarding energy of 25.5 MeV employing the São Paulo-Pelletron-Engge Split Pole facility and the nuclear emulsion technique. The resolution of 50 keV allowed for the separation of the resonant contributions to the known  $7/2^-$  and  $(5/2^-)$  states near the  ${}^9\text{Be} + \alpha$  threshold both associated with an  $L = 4$  transfer. Several narrow alpha resonant states not previously measured were detected, in particular the one at the  $3\alpha + n$  threshold populated by an  $L = 2$  transfer, revealing a  ${}^9\text{Be} + \alpha$  component for the  $1/2^-$  cluster state candidate at this threshold.

### 1. Introduction

The investigation of the alpha cluster correlation, an important concept in the nuclear physics of light nuclei,<sup>1</sup> is the main purpose of the research program in progress, focusing  $x\alpha + \nu$  structures.<sup>2–4</sup> The  ${}^9\text{Be}({}^6\text{Li},d){}^{13}\text{C}$  reaction was used in the present work to investigate alpha resonant states in  ${}^{13}\text{C}$ . The reaction was measured at a bombarding energy of 25.5 MeV employing the São Paulo Pelletron Engge-Spectrograph facility and the nuclear emulsion technique. An excellent energy resolution of 50 keV was obtained and several narrow alpha resonant states up to 15 MeV of excitation, not previously measured, were detected. Recently,  ${}^{13}\text{C}$  has been the subject of cluster model calculations;<sup>5,6</sup> molecular structures and alpha particle condensation in some states are discussed.

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## 2. Experiment

The 25.5 MeV  ${}^6\text{Li}$  beam of the São Paulo Pelletron Accelerator bombarded a clean and uniform  $131\mu\text{g}/\text{cm}^2$   ${}^9\text{Be}$  target. The deuterons emerging from the  $({}^6\text{Li},d)$  reaction were momentum analyzed by the magnetic field of the Enge-Spectrograph and detected in emulsion plates (Fuji G6B,  $50\mu\text{m}$  thick). Spectra associated with seven scattering angles between  $3^\circ$  and  $20^\circ$  in the laboratory frame, each one along 100cm of the focal plane, were measured. The plates, after processing, were scanned in strips of  $200\mu\text{m}$  and a resolution of 50 keV was obtained. Due to the joint presence of tracks of deuterons and of elastically scattered  ${}^6\text{Li}$  (charge state of two) above approximately 13 MeV of excitation in  ${}^{13}\text{C}$ , the selective reading methodology was applied. The extracted spectra revealed previously unreported narrow resonances at 12.3, 13.5, 14.7 and 15.1 MeV of excitation and one not so narrow at 14.0 MeV.

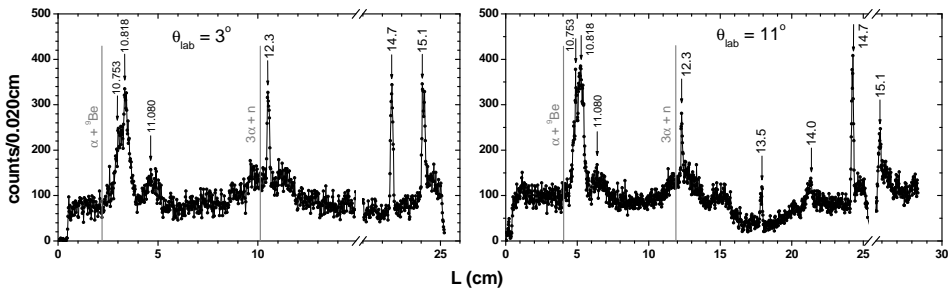


Fig. 1. Deuteron spectra for  $\theta = 3^\circ$  and  $\theta = 11^\circ$ . The excitation energies in MeV and the  $\alpha + {}^9\text{Be}$  and  $3\alpha + n$  thresholds are indicated.

The improvement of experimental conditions<sup>7</sup> allowed for the separation of the resonant contributions at 10.753 MeV and 10.818 MeV  ${}^{13}\text{C}$  excitation energies.<sup>8</sup> The known resonance at 11.080 MeV<sup>8</sup> corresponds to very low statistics peaks. Fig.1 shows the deuteron spectra corresponding to  $\theta_{\text{lab}} = 3^\circ$  and  $11^\circ$ , displaying the number of tracks per strip versus the position along the focal plane.

## 3. Results and Discussion

One step alpha transfer finite-range DWBA calculations, in this preliminary analysis, were performed to describe mainly the shape of the experimental angular distributions. The optical model used for the entrance and exit channels used the global parameter sets of Cook<sup>9</sup> and Daehnick *et al.*<sup>10</sup> respectively. The binding potential of Kubo and Hirata<sup>11</sup> was taken for the  $\alpha + d$  description of  ${}^6\text{Li}$  and, although  $\alpha$ -resonant, the states under consideration were assumed to be bound by 100 keV in a Woods-Saxon binding potential ( $r_0 = 1.25\text{fm}$ ,  $a = 0.65\text{ fm}$ ). Relative to the  ${}^9\text{Be}$  core,  $(1p)^4$  and  $(1p)^3(1d)$  single particle configurations were considered for negative ( $G=4$ ) and positive parity states ( $G=5$ ), respectively.<sup>12</sup>

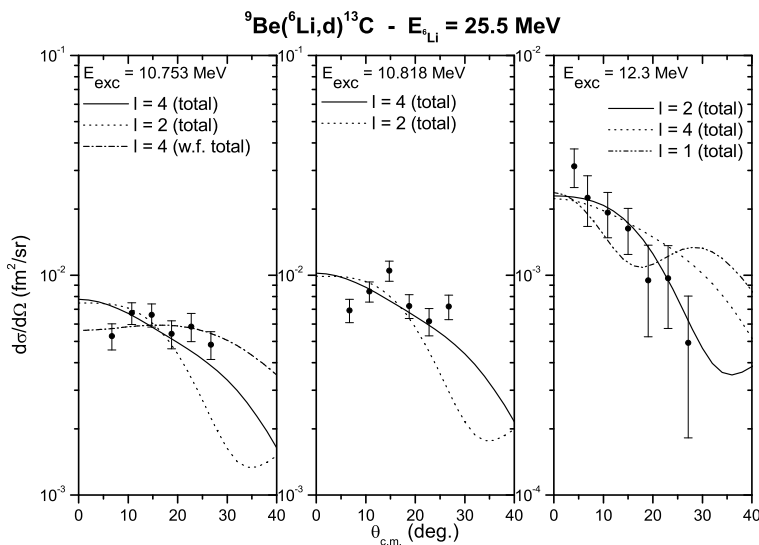


Fig. 2. Experimental angular distributions and DWBA predictions.

The experimental angular distributions associated with the alpha resonances near the  ${}^9\text{Be} + \alpha$  and  $3\alpha + n$  thresholds are presented in comparison with DWBA predictions in Fig. 2. Seen at the  ${}^9\text{Be} + \alpha$  threshold, a pure  $L=4$  transfer is indicated for each transition to the known states  $7/2^-$  at 10.753 MeV and  $(5/2^-)$  at 10.818 MeV,<sup>8</sup> instead of  $L=2$  obtained in the fit to the integrated contribution.<sup>7</sup> For the resonance at 10.753 MeV, the DWBA angular distribution, calculated considering the wave function predicted by a simplified description of  ${}^9\text{Be} + \alpha$  system,<sup>12</sup> is in very good agreement with the data. It is to be noted that for the resonance at 12.3 MeV, in comparison with  $L=2$  and  $L=4$  DWBA predictions, an  $L=2$  transfer is indicated. Also presented in the figure is, for further discussion, the DWBA  $L=1$  angular distribution.<sup>9</sup> The narrow alpha resonance seen at the  $3\alpha + n$  threshold shows an  ${}^9\text{Be} + \alpha$  component not previously measured. A large  $E0$  isoscalar transition, signature of a spatially developed  $1/2^-$  cluster-state<sup>13</sup> and reported by T. Kawabata,<sup>14</sup> was detected near this threshold by alpha inelastic scattering. The  $L=2$  transfer obtained in the excitation of the alpha resonant state at 12.3 MeV is in agreement with the  $1/2^-$  attribution.<sup>14</sup> The cluster structure of the  $1/2^-$  state predicted near the  $3\alpha + n$  threshold has been studied by Yamada and Funaki,<sup>5</sup> who performed the  $3\alpha + n$  orthogonality condition model (OCM) calculations and by Yoshida et al.,<sup>6</sup> in which the alpha-breaking effect is included. The OCM results<sup>5</sup> reveal that this state, although presenting a large component of the  ${}^{12}\text{C}(\text{Hoyle}) + n$  channel, contains also components of the  ${}^{12}\text{C}(2^+) + n$  and  ${}^9\text{Be}(\text{g.s.}) + \alpha$  channels. The presence of the last channel mentioned is confirmed by the excitation of the alpha resonance at 12.3 MeV through an  $L=2$  transfer. On the other hand, the  $1/2^+$  state near the  $3\alpha + n$  threshold, with a dilute alpha

condensate character,<sup>5</sup> was consistently not populated in the present experiment. In fact, the transfer of  $L = 1$  does not reproduce the shape of the experimental angular distribution (Fig. 2).

#### 4. Summary

The  ${}^9\text{Be}({}^6\text{Li},d){}^{13}\text{C}$  reaction was measured at a bombarding energy of 25.5 MeV to investigate alpha resonant states in  ${}^{13}\text{C}$  up to 15 MeV. The nuclear emulsion detection technique was employed and an energy resolution of 50 keV was obtained. The experimental angular distributions associated with the resonances detected just above the  ${}^9\text{Be} + \alpha$  and  $3\alpha + n$  thresholds are compared with DWBA predictions. Seen at the  ${}^9\text{Be} + \alpha$  threshold, a pure  $L = 4$  transfer is indicated for each transition to the known  $7/2^-$  and  $(5/2^-)$  states,<sup>8</sup> instead of  $L = 2$  obtained in the fit to the integrated contribution.<sup>7</sup> The DWBA angular distribution, calculated considering the wave function predicted for the  $7/2^-$  state<sup>8</sup> with a simplified description of the  ${}^9\text{Be} + \alpha$  system,<sup>13</sup> is in very good agreement with the data. Particularly interesting is the narrow resonance detected at 12.3 MeV of excitation, close to the  $3\alpha + n$  threshold and populated by an  $L = 2$  transfer revealing a  ${}^9\text{Be} + \alpha$  component not previously measured, for the  $1/2^-$  cluster state candidate<sup>5,14</sup> at this threshold. With the benefit of the use of the emulsion plates and applying the track selective reading methodology, at least three other narrow resonances not previously reported were detected and the analysis will appear elsewhere soon.

#### Acknowledgements

Partially supported by the Brazilian funding agencies FAPESP and CAPES.

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