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The Non-statistical Population of the 11·10 MeV (4^+) State in ^{16}O by $^{12}C(^6Li, d)$

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Abstract

When compound nucleus calculations are normalized to the 13·88 MeV (4^+) $^{12}C(^6Li, d)^{16}O$ cross section it is found that the population of the 11·10 MeV (4^+) state is underpredicted by a factor of 4. This result means that the anomalous population of the 11·10 MeV (4^+) state in ^{16}O by the $^{12}C(^6Li, d)$ reaction is not compound nuclear in origin.

Introduction

The (^6Li, d) reaction has been used extensively to extract relative α spectroscopic factors in light nuclei. However, a particular concern in the use of the (^6Li, d) reaction is the fact that anomalous population of the 4^+ state at 11·096 MeV in ^{16}O was observed by Debevec *et al.* (1974). They showed that the 11·096 MeV (4^+) state observed with the $^{12}C(^6Li, d)^{16}O$ reaction at a bombarding energy of 32 MeV is populated at least 50 times more than expected for a single-step direct α transfer, and they suggested that a two-step mechanism is responsible for the population of this state. A subsequent analysis of this same reaction by Cobern *et al.* (1976) indicated that, if it was assumed that the 11·10 MeV ($4^+, 3^+$) doublet was populated, the cross section could be accounted for by statistical compound nuclear contributions, suggesting that most of the other $^{12}C(^6Li, d)^{16}O$ transitions observed had substantial compound nuclear contributions. This large uncertainty in the (^6Li, d) reaction mechanism makes structure conclusions drawn from (^6Li, d) studies of dubious value. The present work was undertaken to determine more carefully the upper limit of the statistical compound nuclear contribution to the $^{12}C(^6Li, d)$ reaction. An upper limit to this contribution must be known if present attempts to use the $^{12}C(^7Li, t)$ and $^{12}C(^6Li, d)$ reactions to extract spectroscopic information for use in stellar helium-burning calculations are to have any meaning (Becchetti *et al.* 1978).

Experimental Data

The forward angle $^{12}C(^6Li, d)^{16}O$ data used in the present work were taken at the Florida State University; the experimental details have been described in an earlier publication (Clark *et al.* 1978). The high resolution $^{12}C(^6Li, d)^{16}O$ data were taken with the Australian National University Pelletron accelerator. The reaction products were detected with a gas proportional counter (Ophel and Johnston 1977) after momentum analysis by an Enge spectrograph. The position and energy loss signals permitted

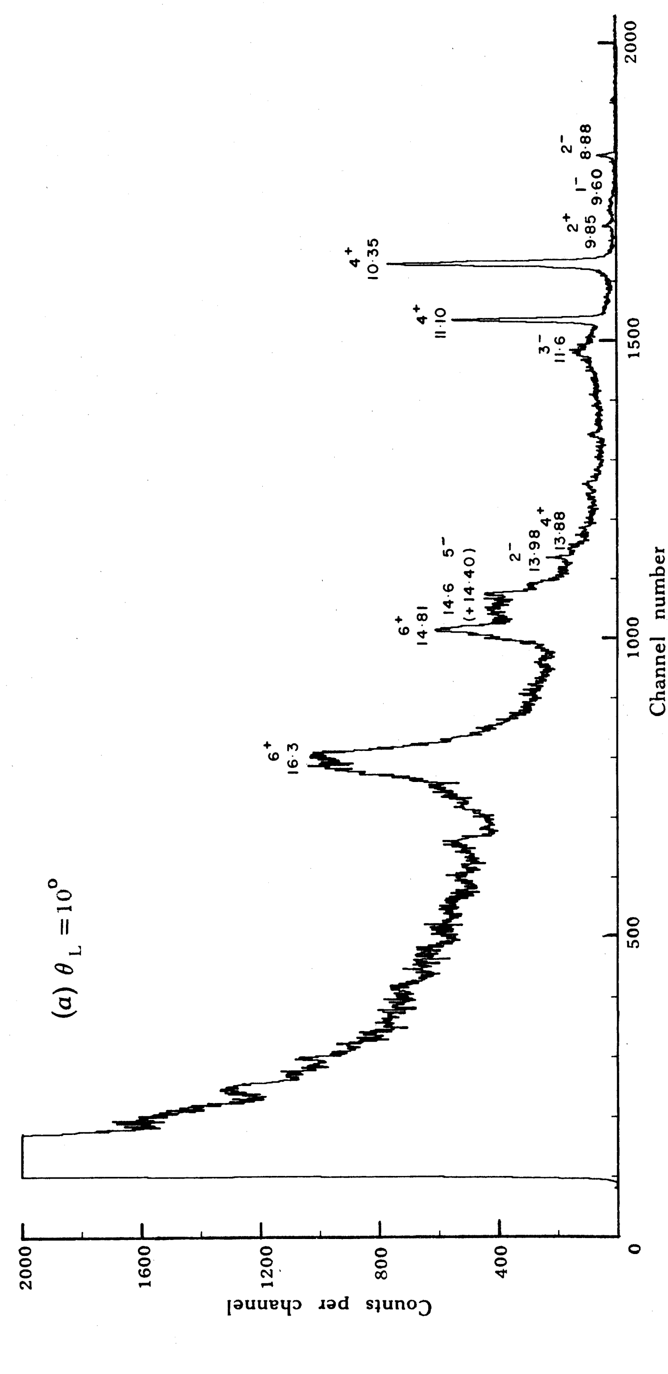
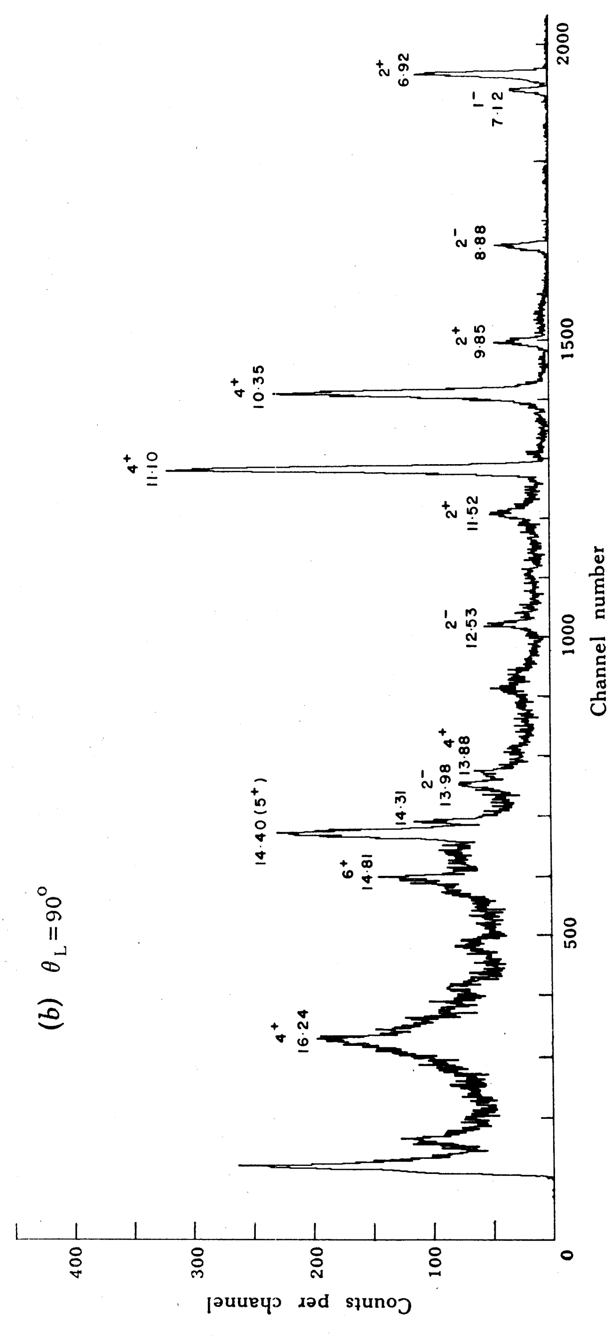

(a) $\theta_L = 10^{\circ}$
Counts per channel
0
400
800
1200
1600
2000
Channel number
500
1000
1500
2000
6+
16·3
6+
14·81
14·6
(+14·40)
5−
2−
13·98
4+
13·88
3−
11·6
4+
11·10
4+
10·35
2+
9·85
1−
9·60
2−
8·88

Fig. 1a



Figs 1*a* and 1*b*. Typical spectra for the $^{12}C(^{6}Li, d)^{16}O$ reaction at 35·5 MeV. As can be seen, the 13·88 MeV (4⁺) state is weakly populated compared with the 11·10 MeV (4⁺) state at both $\theta_L = 10°$ and 90°.

the deuterons to be distinguished from other reaction products. The absolute cross section for these data was obtained by normalizing to the forward angle data of Clark *et al.* (1978). Sample spectra for the $^{12}C(^{6}Li, d)^{16}O$ reaction taken with the ANU Enge spectrograph system are shown in Figs 1*a* and 1*b*.

Calculations

Because the magnitudes of the calculated statistical compound nuclear cross sections are extremely sensitive to the parameters used (Klapdor *et al.* 1976), the absolute compound nuclear cross sections for the $^{12}C(^{6}Li, d)^{16}O$ reaction have been found previously by normalizing the calculations to the 8·87 MeV (2^-) state in ^{16}O (Cobern *et al.* 1976; Becchetti *et al.* 1978; Cunsolo *et al.* 1978). These calculations have assumed no upper limit for the angular momentum that the compound system can have. As shown by Klapdor *et al.* (1976), the calculated cross section for the relative population of final states of different spins depends very strongly on the critical angular momentum of the system, so that the compound nucleus contributions determined for the $^{12}C(^{6}Li, d)^{16}O$ reaction could be in error by as much as a factor of 2 even if the assumption that the 2^- state is populated only by compound nuclear processes is correct.

If the population of the 11·10 MeV ($3^+, 4^+$) doublet is statistical compound nuclear in origin, then the 13·88 MeV (4^+) state in ^{16}O (Ajzenberg-Selove 1977) should be populated with a similar intensity. To determine the ratio expected from statistical compound nuclear population of the 11·10 MeV ($3^+, 4^+$) doublet and the 13·88 MeV (4^+) state, we have made calculations with the program HELGA (Penny 1974), which has been described by Gomez del Campo *et al.* (1974). The elastic, p, n, d, ^{3}He and α channels were included in the calculations. The optical model parameters for all channels except the elastic channel were taken from Perey and Perey (1972), while the $^{6}Li+^{12}C$ parameters were those of Schumacher *et al.* (1973). A level density parameter of $a \sim A/7{\cdot}8$ and a pairing energy of 5·1 MeV were used in the calculations. The results of the calculations predict that the 11·10 MeV ($3^+, 4^+$) doublet will have a 2·4 times larger cross section than the 13·88 MeV (4^+) state at $\theta_L = 10°$ and 90°. However, as can be seen in Fig. 1, the 13·88 MeV state is only weakly populated compared with the 11·10 MeV doublet at both $\theta_L = 10°$ and 90°. The natural width of the 13·88 MeV state is 85 keV, or roughly twice the present experimental resolution, and so this is not able to account for the difference in yields observed in the spectra of Fig. 1. The experimental ratio taken from the spectrum at $\theta_L = 90°$ in Fig. 1*b* is $7{\cdot}1 \pm 0{\cdot}6$. To make certain that the difference in yields at 90° was not a result of fluctuating cross sections, data were taken at 35 and 36 MeV, and the yields for all of the peaks in the spectra were constant to within the statistical uncertainty ($\pm 15\%$). In addition, forward angle yield curves reported by Cunsolo *et al.* (1978) show no evidence of gross fluctuations above $E(^{6}Li) = 28$ MeV.

Results and Discussion

Fig. 2 displays the angular distribution data and compound nucleus calculations for the 10·35 MeV (4^+) and 11·10 MeV ($4^+, 3^+$) transitions. The compound nucleus calculations were multiplied by 0·15 to normalize them to the 13·88 MeV cross section at 74° and 108° c.m. As can be seen, at 10° c.m. the compound nucleus calculations underpredict the measured 11·10 MeV cross section by a factor of 2·5 if it is assumed that both the 4^+ and 3^+ states at 11·10 MeV in ^{16}O are populated. A careful calibration of the present magnetic spectrograph data shows that it is the 11·10 MeV (4^+) state that is predominantly populated, in agreement with the conclusions of Debevec *et al.* (1974), so that the forward angle cross section is in fact underpredicted by at least a factor of 3·5 by the compound nuclear cross sections.

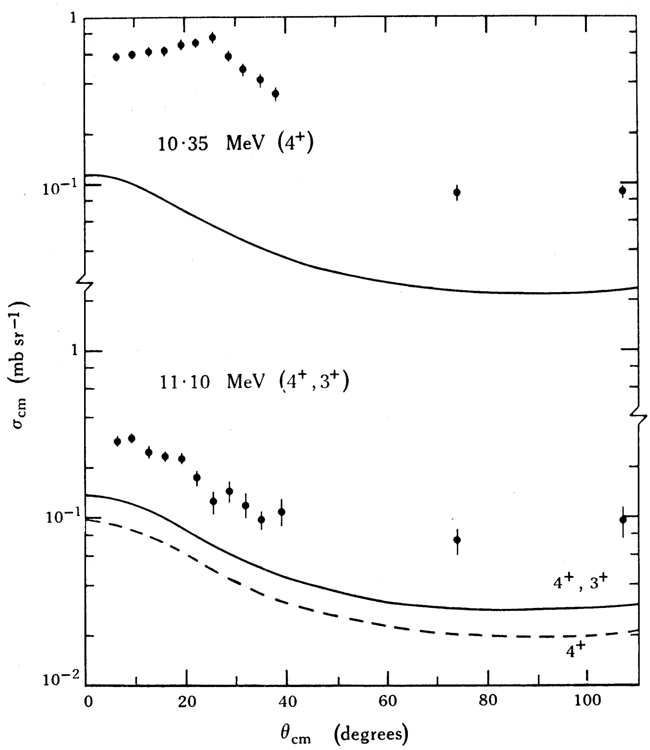


Fig. 2. Angular distributions for the $^{12}C(^6Li, d)^{16}O$ reaction at 35·5 MeV leading to population of the 10·35 MeV (4^+) and 11·10 MeV ($4^+, 3^+$) states. The curves are compound nucleus calculations that have been normalized to the 13·88 MeV (4^+) intensity.

Further support to the argument that compound contributions are small for the 11·10 MeV (4^+), 11·080 MeV (3^+) doublet is the narrow peak width ($\sim$30 keV and equal to the experimental resolution) observed in the 32 MeV work of Debevec *et al.* (1974).

In summary, when the 13·88 MeV (4^+) state of ^{16}O state is used to normalize statistical compound nucleus calculations for the $^{12}C(^6Li, d)^{16}O$ reaction, it is found that the compound nucleus mechanism is not responsible for the anomalous population of the 11·10 MeV (4^+) state, so that two-step processes may be important for the $^{12}C(^6Li, d)$ reaction, as suggested by Debevec *et al.* (1974). The strong population of the 11·10, 14·40, 14·81 and 16·24 MeV states observed in the spectrum at $\theta_L = 90°$ in Fig. 1*b* is very similar to that in the spectrum observed by Zisman *et al.* (1970)

for $^{14}N(\alpha, d)^{16}O$. This similarity in the two reactions suggests that sequential transfer, in addition to the normally assumed inelastic two-step process (Debevec *et al.* 1974), might be an important part of the $^{12}C(^{6}Li, d)$ cross section.

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