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THE (d, ${}^6\text{Li}$) REACTION ON LIGHT NUCLEI[†]

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The (d, ${}^6\text{Li}$) reactions on ${}^{12}\text{C}$, ${}^{16}\text{O}$, ${}^{20}\text{Ne}$, ${}^{24}\text{Mg}$, and ${}^{25}\text{Mg}$ have been studied at 55 MeV incident energy. Some features of the data appear consistent with an alpha-particle pickup model of the reaction. The ${}^{24}\text{Mg}(d, {}^6\text{Li}){}^{20}\text{Ne}$ results complement previously published ${}^{16}\text{O}({}^7\text{Li}, t){}^{20}\text{Ne}$ work and support the Elliot SU_3 classification scheme for low-lying states of ${}^{20}\text{Ne}$.

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The ground states of ${}^6\text{Li}$ and ${}^7\text{Li}$ have approximate (alpha + deuteron) and (alpha + triton) cluster model representations corresponding to the $(1s)^4(1p)^{A-4}$ shell model configurations [1]. This structure suggests that the $({}^6\text{Li}, d)$ and $({}^7\text{Li}, t)$ reactions

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or their inverse may selectively populate states related to the target nucleus by transfer of four nucleons having the $(2T+1), (2S+1) L_J [f] = 11 S_0 [4]$ structure of an "alpha particle" where $[f] = [4]$ denotes the totally symmetric space partition. Published data from the $({}^6\text{Li}, d)$ and $({}^7\text{Li}, t)$ reactions have exhibited the qualitative selectivity associated with alpha-particle-like transfer. In particular, the latter reaction has recently been utilized to investigate states in ${}^{16}\text{O}_2$, ${}^{20}\text{Ne}_3$, ${}^{18}\text{F}$, and ${}^{22}\text{Ne}$ [4].

The $(d, {}^6\text{Li})$ and $(d, {}^7\text{Li})$ reactions on several light nuclei were analyzed in the distorted-wave born approximation about four years ago by Denes, et al [5]; however, the low incident deuteron energy (15 MeV) precluded observation of transitions to high-lying residual states. In the present experiment 55 MeV deuterons from the Berkeley 88-inch cyclotron have been used to investigate these reactions on ${}^{12}\text{C}$, ${}^{16}\text{O}$, ${}^{20}\text{Ne}$, ${}^{24}\text{Mg}$, and ${}^{25}\text{Mg}$ targets. In this letter the $(d, {}^6\text{Li})$ data are interpreted within the framework of selection rules based on the assumed alpha-particle quantum numbers of the transferred nucleons. The results from the ${}^{20}\text{Ne}$ and ${}^{24}\text{Mg}$ targets complement the earlier [2,3] $({}^7\text{Li}, t)$ studies on ${}^{12}\text{C}$ and ${}^{16}\text{O}$.

Self-supporting ${}^{12}\text{C}$, ${}^{24}\text{Mg}$, and ${}^{25}\text{Mg}$ foil targets and ${}^{16}\text{O}$, ${}^{20}\text{Ne}$ gas targets were used in the experiment. Two semi-conductor $\Delta E-E$ telescopes, coupled to Goulding-Landis particle identifiers and conventional electronics were used to collect ${}^6\text{Li}$ and ${}^7\text{Li}$ energy spectra. The resolution varied from about 140 keV for the ${}^{24}\text{Mg}$ target to about 300 keV for the gas targets. Angular distributions from 15° to 60° or 70° cm were obtained for ${}^{12}\text{C}$, ${}^{16}\text{O}$, and ${}^{24}\text{Mg}$, while spectra at only four angles were collected for the ${}^{20}\text{Ne}$ and ${}^{25}\text{Mg}$ targets. Typical spectra are shown in figs. 1 and 2.

The angular distributions were found to have reasonable direct reaction shapes. The cross sections decreased rapidly with increasing angle, while the rate of decrease was typically smaller for transitions involving large angular momentum transfers. The cross sections for many of the states apparent in the spectra are tabulated in table 1.

The largest components of the ^{12}C and ^{16}O target wave functions can be characterized [8] by the [44] and [444] space-symmetry partitions of the p-shell with $S = 0$, $T = 0$. Thus, only the 0^+ , 2^+ , and 4^+ $S = 0$, $T = 0$ states of ^8Be and ^{12}C having the [4] and [44] partitions are expected to have large cross sections within the context of the simple pickup model. The observed strong population of these states as indicated in the table is therefore consistent with the model. The 7.66 MeV 0^+ and 9.63 MeV 3^- states of ^{12}C are also evident, but these states, which have large non p-shell components [9], may be formed via known [10] 2 particle-2 hole and 4 particle-4 hole admixtures in the ^{16}O ground state. The population of the 16.63 MeV and 16.93 MeV (unresolved) 2^+ states of ^8Be is seemingly more difficult to reconcile with the simple pickup model since intermediate-coupling calculations [8] indicate these states have the dominant $S = 1$, [31] structure, whereas the ^{12}C ground state has only a small $S = 1$, [431] component. A quantitative understanding of these 2^+ transitions is certainly required before the validity of the pickup model can be definitely established.

According to the calculations of Brown and Green [11] the 0^+ , 2^+ , and 4^+ states of ^{16}O at 6.06, 6.92, and 10.36 MeV are $K = 0$ rotational states built on the 4 particle-4 hole structure of the 6.06 MeV state, and the 9.85 MeV 2^+ state is the lowest member of a $K = 2$ rotational band. Arima et al. [6] have proposed a weak-coupling model for these states based on 4-hole states of ^{12}C

coupled to 4-particle states of ^{20}Ne . The latter scheme is indicated in the table. Bethge et al. [2] observed that the first three states discussed above were populated in the $^{12}\text{C}(^7\text{Li},t)^{16}\text{O}$ reaction whereas the 9.85 MeV state was only weakly populated in apparent agreement with either model. Provided $(d,^6\text{Li})$ reactions proceed via alpha-particle pickup, and the weak coupling scheme is realistic, the populations of the two 2^+ states ought to be reversed compared to the $(^7\text{Li},t)$ results. In fact they are populated about equally in the present work. This suggests that the weak-coupling model is inadequate for these 2^+ states. We note that if ^{20}Ne is characterized by a larger deformation than ^{12}C , then $K=2$ rotational states in ^{16}O may be more likely to be formed by alpha-particle pickup than by alpha-particle stripping. Unfortunately no population information can be extracted for the 6.06 MeV 0^+ state since it is not resolved. While the 10.36 MeV 4^+ state is populated only weakly, the observed cross section ratio compared to the 2^+ states is about the same as the ratio found for the 4^+ and 2^+ states in the $^{16}\text{O}(d,^6\text{Li})^{12}\text{C}$ reaction at 20° . Therefore the weak population of the 4^+ state (comparable to that for the 8.88 MeV 2^- state which is forbidden in an alpha-particle pickup reaction due to angular momentum-parity conservation) does not necessarily support the weak-coupling scheme for this state.

The $^{24}\text{Mg}(d,^6\text{Li})^{20}\text{Ne}$ data show strong transitions for only the 0^+ , 2^+ , and 4^+ members of the ground state rotational band and the 3^- 5.63 MeV member of the $K=2$ negative parity band based on the 2^- 4.97 MeV state [12]. The relatively weak transition strength for this unnatural-parity state is consistent with the alpha pickup model. These results complement the work of Middleton et al. [3] on the $^{16}\text{O}(^7\text{Li},t)^{20}\text{Ne}$ reaction. It is pointed out that within the

framework of the SU_3 classification [7], only states belonging to the $(\lambda\mu) = (80)$ and (90) bands are expected to be populated in an alpha-stripping reaction. The $(\lambda\mu)$ quantum numbers [7] for low-lying states of ^{20}Ne are listed in table 1. Conversely, in an alpha-pickup reaction the (80) and (82) bands may be formed, assuming the ground state of ^{24}Mg has $(\lambda\mu) = (84)$. The (90) and (82) negative-parity bands are thought to be built on the $(1s)^4(1p)^{12}(2s,1d)^3(1f,2p)^1$ and $(1s)^4(1p)^{11}(2s,1d)^5$ configurations, respectively. Both the stripping and pickup reactions populate the (80) band as expected. In the $(^7\text{Li},t)$ reaction the 1^- 5.80 MeV state is strongly populated, but the 3^- 5.63 MeV state is only weakly populated. In the $(d,^6\text{Li})$ reaction, the relative populations are reversed. These results support the Elliot scheme for these states and are consistent with an analysis [13] of the alpha-particle decay widths of these negative-parity states.

The $(d,^7\text{Li})$ data will not be discussed except to point out that at 20° cm, the ground state cross sections for formation of ^7Li in the ground plus first excited states range from about 1/3 to 1/30 the ground state cross sections for ^6Li formation on the same target. It is particularly interesting to note that the $^{25}\text{Mg}(d,^7\text{Li} + ^7\text{Li}^*)^{20}\text{Ne}$ cross section is only about 1/50 the $^{24}\text{Mg}(d,^6\text{Li})^{20}\text{Ne}$ cross section to the same final states. Since the Q-values, momentum transfers, and statistical factors for both reactions are quite similar, this small ratio supports the hypothesis of the direct nature of the $(d,^6\text{Li})$ reactions.

In summary, many features of the $(d,^6\text{Li})$ data appear consistent with the alpha-particle pickup hypothesis, although the weak populations of some unnatural-parity states indicate more complicated mechanisms also contribute to the reactions.

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Table 1: (d, ${}^6\text{Li}$) Cross Sections on ${}^{12}\text{C}$, ${}^{16}\text{O}$, ${}^{20}\text{Ne}$, and ${}^{24}\text{Mg}$.*

${}^{12}\text{C}(d, {}^6\text{Li}){}^8\text{Be}$			${}^{16}\text{O}(d, {}^6\text{Li}){}^{12}\text{C}$			${}^{20}\text{Ne}(d, {}^6\text{Li}){}^{16}\text{O}$				${}^{24}\text{Mg}(d, {}^6\text{Li}){}^{20}\text{Ne}$			
Exc. (MeV)	J^π	$\sigma(\mu\text{b})^a$	Exc.	J^π	$\sigma(\mu\text{b})^a$	Exc.	J^π	$d\sigma/d\Omega(\mu\text{b}/\text{sr})^b$	$[{}^{12}\text{C} \times {}^{20}\text{Ne}]^c$	Exc.	J^π	$\sigma(\mu\text{b})^d$	$(\lambda\mu)^e$
g.s.	0^+	410	g.s.	0^+	460	g.s.	0^+	80		g.s.	0^+	240	(80)
2.9	2^+	$\leq 1640^\dagger$	4.43	2^+	1370	6.06	0^+	45	$[0^+ \times 0^+]$	1.63	2^+	140	(80)
11.4	4^+	$\leq 1740^\dagger$	7.66	0^+	100	6.13	3^-				4.25	4^+	160
16.6	2^+	≤ 470	9.63	3^-	110	6.92	2^+	20	$[0^+ \times 2^+]$	4.97	2^-	40	(82)
16.9	2^+		14.08	4^+	410	7.12	1^-	weak		5.63	3^-	340	(82)
						8.88	2^-	4.0		5.80	1^-	weak	(90)
						9.59	1^-	weak					
						9.85	2^+	21	$[2^+ \times 0^+]$				
						10.36	4^+	3.5	$[0^+ \times 4^+]$				

* Absolute uncertainty $\pm 30\%$ for each target.

† Upper limit—no three-body continuum corrections has been made.

^a Integrated from 15° to 60° cm.

^b Differential cross sections at 20° cm.

^c Weak coupling scheme of Arima, et al. [6].

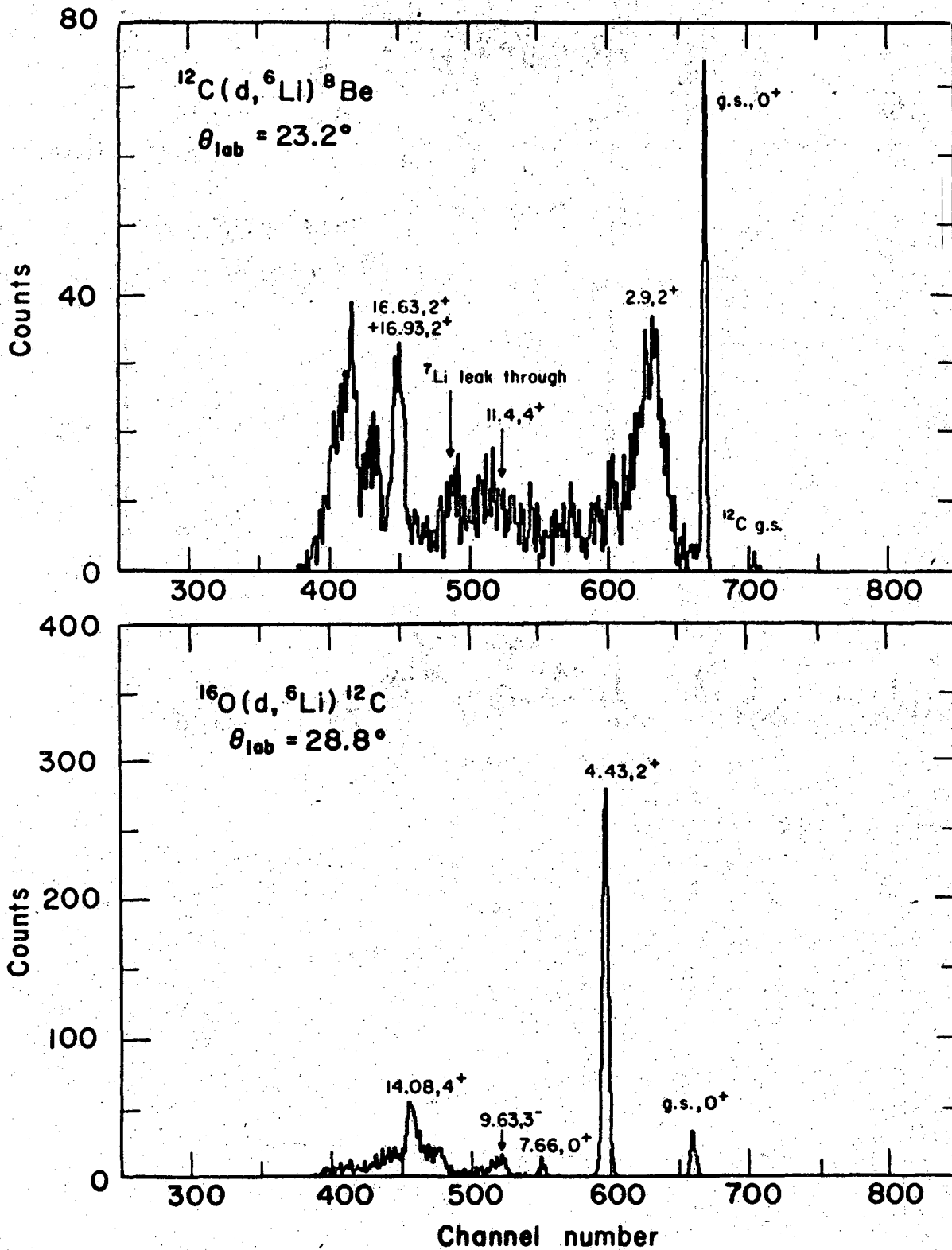
^d Integrated from 15° to 70° cm.

^e $(\lambda\mu)$ quantum numbers of SU_3 [7].

Figure Captions

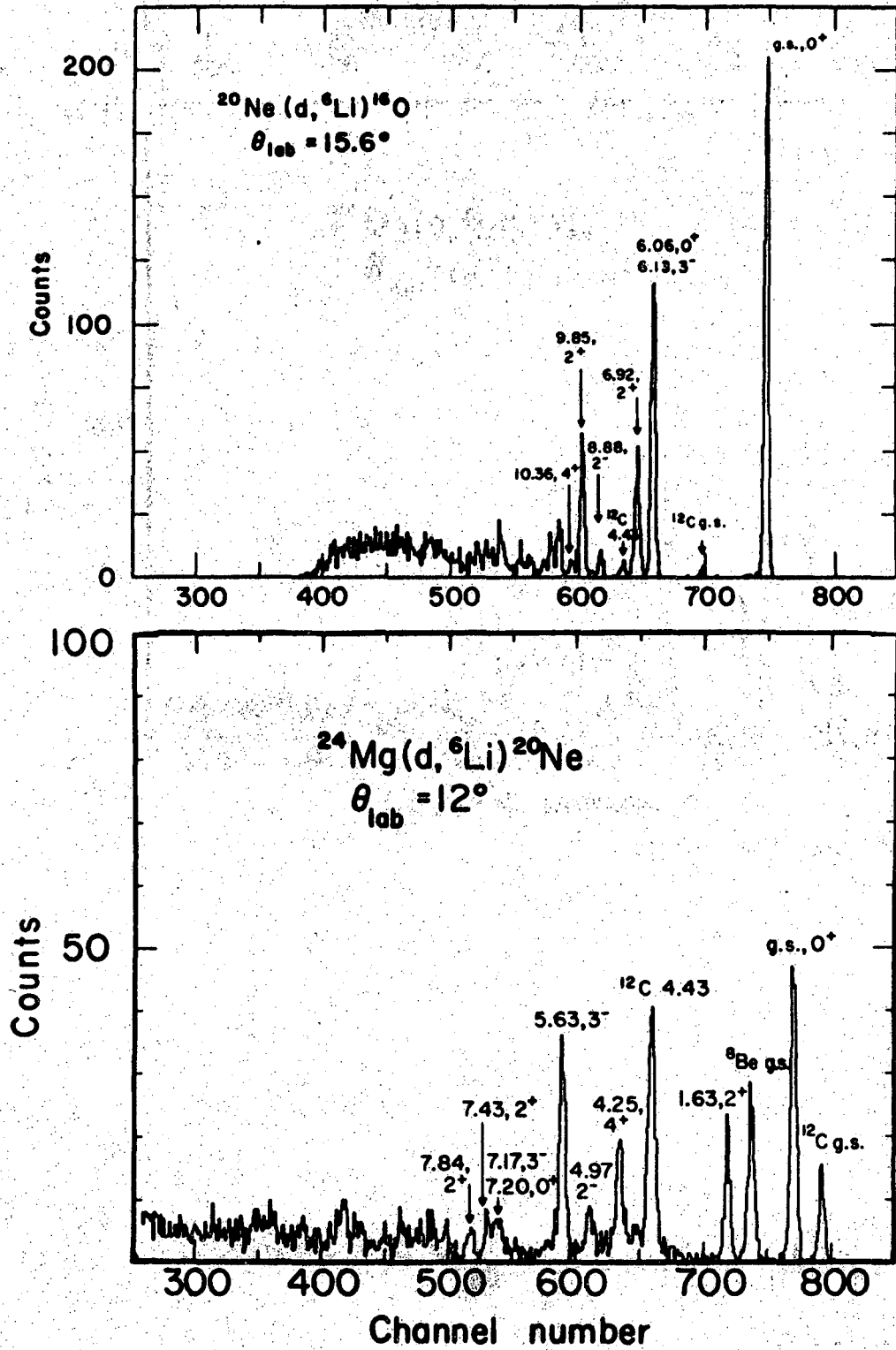
Fig. 1. ${}^6\text{Li}$ Energy Spectra from $(d, {}^6\text{Li})$ Reactions on ${}^{12}\text{C}$ and ${}^{16}\text{O}$.

Fig. 2. ${}^6\text{Li}$ Energy Spectra from $(d, {}^6\text{Li})$ Reactions on ${}^{20}\text{Ne}$ and ${}^{24}\text{Mg}$.



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Fig. 1



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Fig. 2

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