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Direct component in the $^{12}C(^{7}Li,p)^{18}O$ reaction

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For the $^{12}C(^{7}Li,p)^{18}O$ reaction previously observed deviations of cross sections from statistical $(2J+1)$ dependence can be accounted for in a simple model of direct six-nucleon transfer.

In an earlier investigation[1] of the reaction $^{12}C(^{7}Li,p)^{18}O$, at bombarding energies of 16.0 and 18.0 MeV, angular distributions for some states were forward peaked. Deviations of angle-integrated cross sections from a $(2J+1)$ proportionality were observed at both energies. These deviations were virtually identical at the two energies and appeared to be correlated with known aspects of nuclear structure. We attempt herein to ascertain whether the deviations imply the presence of a direct reaction component.

A direct component might involve six-nucleon transfer, or possibly a two-step reaction of the type (^{7}Li,t) followed by (t,p). We illustrate the two-step route schematically in Fig. 1. To a large extent, the only 0^+ states populated[2] in the reaction $^{12}C(^{7}Li,t)^{16}O$ are the ground state and the 0^+ [dominantly four-particle—four-hole (4p-4h)] state at 6.06 MeV. The reaction also selectively excites the 2^+ and 4^+ 4p-4h levels at 6.92 and 10.35 MeV, respectively.

Thus, in the present analysis, we consider a two-step reaction, if it exists, to proceed only through ^{16}O(g.s.) and these 4p-4h states. Alternately, for direct six-nucleon transfer to low-lying positive-parity states of ^{18}O, we consider the six-nucleon transfer amplitudes to be sums of products of four- and two-nucleon amplitudes involving the same ^{16}O states. This hypothesis is consistent with what is known[3] about the ^{18}O levels.

Thus, consider a 0^+ state of ^{18}O, whose structure is

$$\psi(0_i^+)=A_i(sd)_i^2+C_i(sd)^4(1p)^{-2} .$$

The amplitude for making such a 0^+ state from ^{12}C will involve a product of amplitudes for

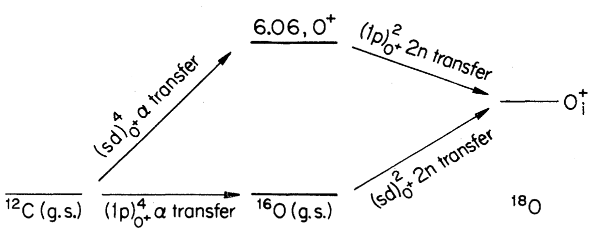

FIG. 1. Schematic representation of the model assumed for the direct component in $^{12}C\rightarrow^{18}O$. In the 2n transfer, the lower route populates only the $(sd)^2$ component in ^{18}O, while the upper route excites only the 4p-2h component.

$$^{12}C\rightarrow^{16}O(\text{closed core})$$

and

$$^{16}O(\text{closed core})\rightarrow^{18}O(A_i(sd)_i^2)$$

as well as the product

$$^{12}C\rightarrow^{16}O(\text{4p-4h})$$

and

$$^{16}O(\text{4p-4h})\rightarrow^{18}O(C_i(\text{4p-2h})) .$$

In fact, as the 4p are coupled to 0^+ in the 4p-2h components of ^{18}O 0^+ states, only the 0^+ 4p-4h ^{16}O state can be involved in transfer to a 0^+ state in ^{18}O.

Amplitudes (see Fig. 2) for 2^+ states of ^{18}O involve products of amplitudes for

$$^{12}C\rightarrow^{16}O(\text{closed core})$$

and

$$^{16}O(\text{closed core})\rightarrow^{18}O(B_i(sd)_i^2)$$

and amplitudes

$$^{12}C\rightarrow^{16}O(\text{4p-4h};\ J^\pi=2^+)$$

times

$$^{16}O(\text{4p-4h},\ 2^+)\rightarrow^{18}O(\gamma_i\text{4p-2h},\ 2^+) .$$

In zeroth order the 4p in the 4p-2h states of ^{18}O have identical structure to the 4p in the 4p-4h states of ^{16}O, viz., ^{20}Ne(0^+,2^+,4^+). Thus, two-nucleon transfer 4p-4h→4p-2h should be roughly equal to that for 4h→2h, i.e., $^{12}C\rightarrow^{14}C$(g.s.). Then, if we take the closed core to be the ^{16}O(g.s.) and the 4p-4h 0^+ states to be those mentioned above, we find that all the amplitudes needed to describe $^{12}C\rightarrow^{18}O$ can be determined from experimental data, up to possible ambiguities in phases.

We thus have

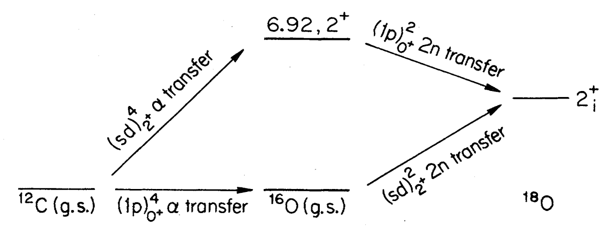

FIG. 2. Same as Fig. 1, but for 2^+ states of ^{18}O.

TABLE I. Estimated angle-integrated (0°–90°) cross sections for direct transfer $^{12}C\to{}^{18}O$.

E_x (MeV)	σ_{calc} (μb)
0.0	20.2
3.63	15.0
5.33	0.066
1.98	1.76
3.92	6.05
5.25	119
3.55	12.0
7.11	394

TABLE II. Results of $^{12}C(^7Li,p)^{18}O$, at 16.0 MeV, for the weakest state of each J^π.

E_x (MeV)	J^π	σ_{tot} (0°–90°) (μb)	$\frac{\sigma_{tot}}{2J+1}$ (μb)
5.33	0^+	30	30
6.86	0^-	19	19
4.45	1^-	111	37
6.34	2^-	132	26
3.92	2^+	176	35
5.37	3^+	102	15
6.39	3^-	176	35
3.55	4^+	285	32
		Average	28.6

$$A(^{12}C\to{}^{18}O(0_i^+)) = A(^{12}C\to{}^{16}O(g.s.))A(^{16}O(g.s.)\to{}^{18}O(0_i^+) \text{ via } (sd)_0^2) + A(^{12}C\to{}^{16}O(6.06))A(^{16}O(6.06)\to{}^{18}O(0_i^+) \text{ via } (1p)_0^2)$$

and

$$A(^{12}C\to{}^{18}O(2_i^+)) = A(^{12}C\to{}^{16}O(g.s.))A(^{16}O(g.s.)\to{}^{18}O(2_i^+) \text{ via } (sd)_2^2) + A(^{12}C\to{}^{16}O(6.92))A(^{16}O(6.92)\to{}^{18}O(2_i^+) \text{ via } (1p)_0^2) ,$$

and similarly for 4^+ states.

The first factor in each term can be determined from α transfer[2] on ^{12}C. The second factor in the first term comes from $^{16}O(t,p)$ (Refs. 4 and 5), and we assume the second factor of the second term is equivalent to the amplitude for $^{12}C\to{}^{14}C(g.s.)$ (Ref. 6) times the coefficient[3] of the 4p-2h component in the ^{18}O state of interest.

We deal only with angle-integrated cross sections in what follows, and we establish the overall cross section scale by assuming

$$\sigma_{2\ step} = \frac{\sigma_{step\ 1}\sigma_{step\ 2}}{\sigma_{tot\ reac}} ,$$

where the denominator is approximated by πR^2, R being the strong absorption radius appropriate to $^{12}C+{}^7Li$. Thus

$$\sigma(^{12}C(^7Li,p)^{18}O(0_i^+)) = \frac{\sigma(^{12}C(^7Li,t)^{16}O(g.s.))\sigma(^{16}O(t,p)^{18}O(g.s.))}{\pi R^2}\left[\frac{a_{2n}(0_i^+)}{a_{2n}(g.s.)} + \frac{a_\alpha(6.06)}{a_\alpha(g.s.)}\frac{a(^{12}C\to{}^{14}C)}{a(^{16}O\to{}^{18}O)}C_i\right]^2 .$$

For 2^+ states, the terms in square brackets are replaced by

$$\left[\frac{a_{2n}(2_i^+)}{a_{2n}(g.s.)} + \frac{a_\alpha(6.92)}{a_\alpha(g.s.)}R\gamma_i\right]^2 ,$$

where

$$R \equiv \frac{a(^{12}C\to{}^{14}C)}{a(^{16}O\to{}^{18}O)} .$$

The C_i's and γ_i's are the 4p-2h coefficients from Ref. 3. Similar expressions hold for the 4^+ states. The factor in front, using angle-integrated cross sections,[2,4] and $R=3.3$ fm, is 11 μb.

For the 0^+ states, the restriction to $J=0$ coupling everywhere makes the phases trivial—they are such as to cause constructive interference for the ^{18}O(g.s.). For the 2^+ and 4^+ states, there is one overall relative phase whose determination is beyond the ability of the present author. We pick it so as to give destructive interference for the

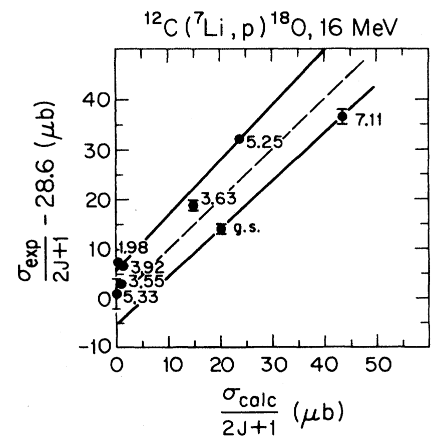

FIG. 3. Plot of measured angle-integrated cross sections divided by $2J+1$ minus 28.6 μb vs calculated direct angle-integrated cross sections divided by $2J+1$ for the reaction $^{12}C(^7Li,p)^{18}O$ at $E(^7Li)=16.0$ MeV.

lowest 2^+ state. Results of the calculations are listed in Table I for the lowest three 0^+, three 2^+, and two 4^+ states of ^{18}O.

Table II lists the results of Ref. 1 for the weakest state of each $J^\pi = 0^\pm \rightarrow 4^+$. These include the states previously discussed, but several additional J^π's as well. We note that the average value of $\sigma_{tot}/(2J+1)$ for these weak states is 28.6 μb. Thus in what follows we subtract this quantity before comparing with calculations.

In Fig. 3, we plot the measured $\sigma_{tot}/(2J+1)$ *minus* 28.6 μb vs the calculated "direct" cross sections as described above, for the eight states of Table I. All the points lie near a straight line having roughly unit slope and passing through the origin.

In summary, for the reaction $^{12}C(^7Li,p)^{18}O$, we have rough agreement between simple estimates of direct six-nucleon transfer cross sections and experimentally-observed deviations from statistical compound-nucleus expectations. It would be interesting to make a similar comparison for data at higher energies, where the relative importance of the direct component should be larger.

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