$2J+1$ DEPENDENCE OF TOTAL CROSS SECTIONS IN LITHIUM + BORON REACTIONS*

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The statistical compound-nucleus theory predicts[1] that the total cross section for production of a residual nucleus with spin J in a specific nuclear reaction is proportional to $2J+1$ and independent of other properties of the state, provided (a) an appreciable number of orbital angular momenta contribute to the reaction, and (b) the exit-channel energy is much larger than the Coulomb-barrier energy. Previous results with (d,α)[2] and (n,α)[3] reactions have shown this dependence. Experimental evidence is presented here which indicates that this rule is applicable to lithium-induced nuclear reactions on the boron isotopes. These reactions were studied with bombarding energies equal to the Coulomb barrier giving excitations ranging from 27 to 34 MeV in the compound nucleus. Such excitations are characteristic of lithium reactions and are in the region where statistical theory should be applicable. Lithium nuclei, with their relatively large size and great mass for bombarding particles, can impart large orbital angular momenta (up to $5\hbar$ in the present case).

The lithium-plus-boron reactions provide a number of residual nuclei whose excited states have been extensively studied.[4] Measurements were made on the p, d, t, He^3, and He^4 groups resulting from Li^6+B^{10}, Li^7+B^{10}, Li^6+B^{11}, and Li^7+B^{11}. Thus data were obtained corresponding to states of C^{12}, C^{13}, C^{14}, N^{13}, N^{14}, N^{15}, N^{16}, and N^{17}, and the data show the same characteristics as do those presented here. A more detailed account including these other data will be published elsewhere.

Measurements were made with a Li^6 or Li^7 beam accelerated by a Van de Graaff generator to about 5 MeV. Self-supported B^{10} and B^{11} targets were prepared by vacuum evaporation. The beam lost about 80 keV in the boron targets. This energy loss serves to integrate over a number of states in the compound nucleus. It is estimated with the level-density formula of Newton[5] that this energy spread corresponds to a minimum of about 50 levels.

Charged particles coming from the target were detected by a lithium-drifted solid-state detector for E, and by a proportional counter for dE/dx measurements. The E and dE/dx signals were analyzed by two 1024-channel pulse-height analyzers, and the 20 bits of information were handled by a general-purpose computer (CDC 160A). A condensed display of the accumulated two-parameter data showing dE/dx vs E was put out on an oscilloscope screen for continuous monitoring. The full detail of the data was recorded on magnetic tape for later analysis. The same computer was later used to extract the number of counts observed in the various particle groups. The particle type was identified by the ionization curve on which the group fell. The important point here is that all particle groups were measured simultaneously and, therefore, were not subject to errors arising from normalizing runs on different particle groups. Relative errors for runs on the same targets are estimated to be less than 7%. Absolute errors are 20%.

Differential cross sections were measured at 15 angles in the laboratory. Unless otherwise indicated, the total cross section was obtained by integrating differential–cross-section data from 0° to about 150° in the center-of-mass system and adding a contribution equal to the average differential cross section integrated over unobserved angles.

The angular distributions are not symmetric about 90°; however, the asymmetries are not very large. Strong forward peaking occurs in only a few cases. The asymmetry may indicate a certain amount of direct-reaction contribution to the cross section but, apparently, this contribution is usually too small to dominate the angular distribution.

The data from Li^6+B^{10}, Li^7+B^{10}, and Li^6+B^{11} reactions are shown in Fig. 1, corresponding to residual states of N^{14} and C^{13}, since the spins of these nuclei are well known. Various outgoing particles are included: deuterons, tritons, He^3, and He^4. The integrated cross sections show a marked tendency to be proportional to $2J+1$. The outstanding deviation is the 6.44-MeV state in the reaction $B^{10}(Li^7,t)N^{14}$. A possible explanation for this case is that it has a relatively large direct-reaction contribution. The angular distribution is consistent with this explanation since it shows strong for-

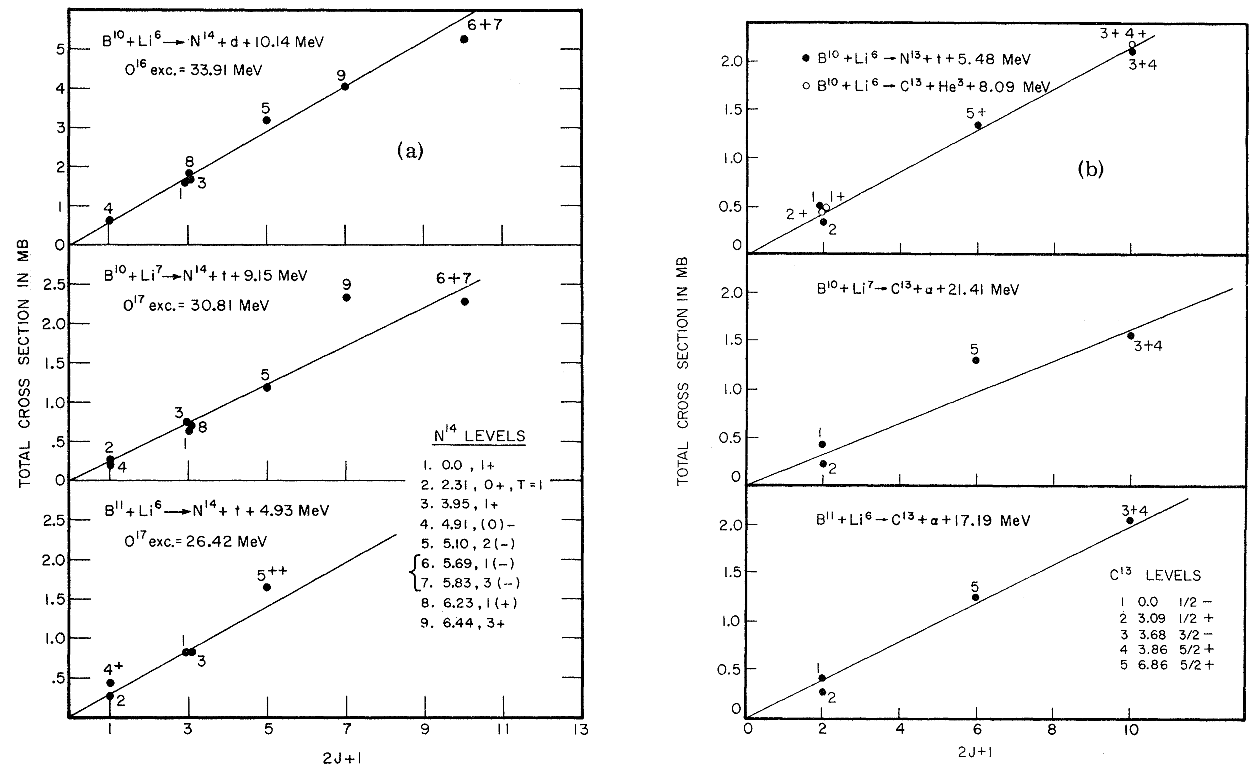

FIG. 1. Total cross section in mb versus value of $2J+1$. All points obtained from measurements of differential cross sections over angular range from 0° to 150° (c.m.) unless noted. Level excitations are given in MeV. (a) N^{14} residual states; (+) and (++) points are observed from 0° to 40° and 0° to 53°, respectively. (b) C^{13} residual states; (+) points are observed from 0° to 70°.

ward peaking for this group. The group in the reaction $B^{10}(Li^6, d)N^{14}$ corresponding to the same state does not have any strong forward peak in its angular distribution. It has the same general character as the other groups in this reaction and, as can be seen in Fig. 1(a), the total cross section does not show any significant deviation from the indicated proportionality to $2J+1$.

Figure 1 shows data for the same compound nucleus reached by way of two different reactions, Li^7+B^{10} and Li^6+B^{11}. Even though the compound nucleus differs in excitation by 4.39 MeV, the total cross section for corresponding states is the same within the experimental error. The similarity of the cross-section values argues for a statistical compound nucleus in itself.

In Fig. 1(a) there is no point plotted for the reaction $B^{10}(Li^6, d)N^{14}$ leading to the $T=1$-, 2.31-MeV state of N^{14} since there was no detectable yield to this state, in agreement with the prediction based on isotopic-spin conservation. Points are plotted for the reactions $B^{10}(Li^7, t)N^{14}$ and $B^{11}(Li^6, t)N^{14}$ leading to this state. The plotted cross sections are $2T+1$ times the measured values so that a proper comparison can be made with the other points. The initial systems have $T=\frac{1}{2}, T_3=\frac{1}{2}$, and the final system consists of N^{14} with $T=1, T_3=0$ and a triton with $T=\frac{1}{2}, T_3=\frac{1}{2}$ giving a factor, $(\frac{1}{2}1\frac{1}{2}0|\frac{1}{2}\frac{1}{2})^2=\frac{1}{3}$, in the cross section. Multiplication by $2T+1$ puts the cross sections on the same basis. The low cross sections for formation of the 2.31-MeV state in N^{14} in the reactions where it is not forbidden by isotopic spin is thus the result of the isotopic-spin factor $(2T+1)^{-1}$, and the low value of the spin factor, $2J+1$, and is not necessarily due to a direct-reaction mechanism which forbids the coupling of an alpha particle from Li^7 to the spin 3^+ B^{10} to form N^{14} with spin 0^+.[6]

The total cross section for the unresolved doublets lies on the continuation of the line through the points from states of lower spin in each case. On the basis of cross section alone, it would be concluded that the points labeled "6 + 7" and "3 + 4" are due to a single level of high spin or to unresolved levels of lower spins. The spins of these levels are known so the conclusion is that both levels are excited. Without being able to resolve two levels of known spin, therefore, it is possible to detect their formation from the magnitude of the total cross section. Conversely, a large cross section corresponding to a level of known small spin would indicate an unresolved doublet.

If a $2J+1$ rule can be firmly established, the utility for spin assignment is obvious. Although the range of validity of this rule needs to be more thoroughly investigated, it is perhaps of some interest to try to use it to make tentative spin assignments for the states of N^{17}. None of the excited states of this nuclide have been assigned spin values previously. It is produced in the reaction $B^{11}(Li^7,p)N^{17}$ with a Q value of 8.417 MeV. The energy levels are well known and particle-gamma coincidence studies[7] have given the gamma-ray branching ratios of the bound states. Figure 2 shows the measured values of total cross sections for formation of N^{17} states. The cross sections are plotted against values of $2J+1$ assigned so as to get the best agreement with proportionality to $2J+1$ and the gamma-ray data. There is a tendency for points to cluster about the least-mean-squares line which is what is expected on the basis of the $2J+1$ rule and is the justification for the assignments. The ground state is assigned spin $\frac{1}{2}$ as expected on the basis of the shell model. All assignments are consistent with observed gamma-ray data except that for the 2.54-MeV state, which implies a $\frac{7}{2}\rightarrow\frac{1}{2}$ transition. The 10.9% average deviation about the line drawn in Fig. 2 is somewhat larger than the estimated 7% upper limit of relative error.

The experimental evidence adduced here implies that the lithium-plus-boron nuclear reactions proceed to low-lying states primarily by a statistical compound-nucleus reaction mechanism when the lithium nuclei have an energy equal to the Coulomb barrier. In general, yields from states above 7-MeV excitation are larger than those from lower lying states of equal spin; perhaps at these excitations direct reactions supplement the yield from the statistical mechanism.

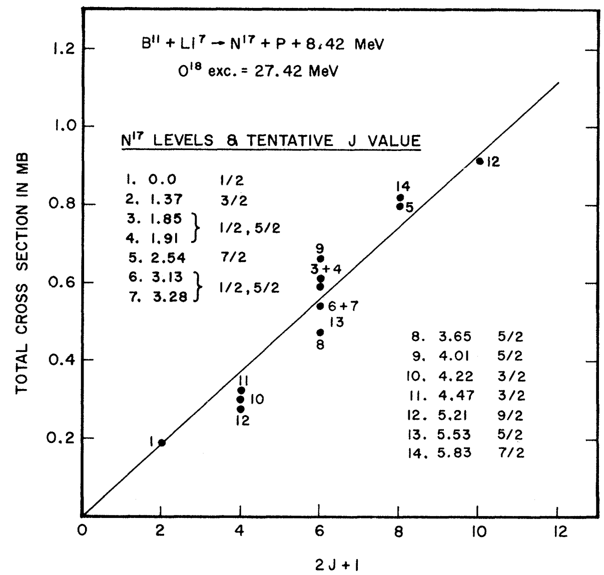

FIG. 2. Total cross section in mb versus tentative value of $2J+1$ for N^{17} residual nuclear state. In this case no spins were previously known and values are assigned on the basis of the $2J+1$ rule. Level excitations are given in MeV.

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