CORRELATION BETWEEN (^{6}Li, ^{8}B) TWO-PROTON PICKUP AND (d, ^{6}Li) α-PARTICLE PICKUP IN THE ZIRCONIUM REGION

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Spectra have been measured for the ^{94,98}Mo(^{6}Li, ^{8}B)^{92,96}Zr reactions at 90 MeV. Differences in transition strengths for the first excited 0$^+$ states, first noted in some recent (d, ^{6}Li) work, are quantitatively accounted for by the changing proton configurations with neutron number.

It has been shown by Kurath and Towner [1] that many properties of α-transfer reactions can be related to the behavior of two-nucleon transfer reactions. In particular, they have demonstrated that α-particle spectroscopic amplitudes can be expressed as a sum of coupled two-proton and two-neutron spectroscopic amplitudes. If, in addition, the proton amplitude may be factored and considered constant for α-pickup from a chain of isotopes, one might in this case expect the relative strengths to correlate with those of two-neutron pickup to the same final states, with the protons acting as "spectators".

An interesting exception to this naive expectation has been observed recently in a study of the ^{94,96,98,100}Mo(d, ^{6}Li)^{90,92,94,96}Zr reactions by Saha et al. [2]. In α-pickup leading to ^{96}Zr, there is an exceptionally strong excitation of the 1.59 MeV 0$^+$ state, which has a cross section more than twice that of the ground state. This behavior is in sharp contrast, however, with that observed in transitions to ^{90,92,94}Zr, where strengths for the first excited 0$^+$ states are much weaker than strengths for the ground states. Noting that the α-pickup strengths do not correlate with those from the Zr(p, t) reactions, Saha et al. conclude that this apparent discrepancy can be explained by the known variation with mass number of the proton configuration in zirconium. We verify this conclusion by presenting in this letter our results from a study of the ^{94,98}Mo(^{6}Li, ^{8}B)^{92,96}Zr two-proton pickup reactions.

Energy analyzed beams of 90 MeV ^{6}Li ions from the Indiana University Cyclotron Facility were used to bombard isotopically enriched (> 94%) self-supporting targets of ^{94,98}Mo having thicknesses of 1.03 and 0.42 mg/cm^2, respectively. The ^{8}B ejectiles were momentum analyzed in a QDDM magnetic spectrograph and detected in a position-sensing gridded ionization chamber placed at the focal plane of the spectrograph. For each event, the energy, differential energy loss, and position signals from the ionization chamber were recorded on magnetic tape in event mode and simultaneously sorted on line. In two-dimensional displays of E versus ΔE, the ^{8}B events were clearly separated from those of other ion species.

Spectra for the (^{6}Li, ^{8}B) reaction on ^{94,98}Mo targets recorded at $\theta_{\text{lab}} = 8°$ are shown in fig. 1. The g.s. peak widths are about 325 and 200 keV respectively, reflecting the thicknesses of the two targets. The g.s. laboratory differential cross sections (8°) are

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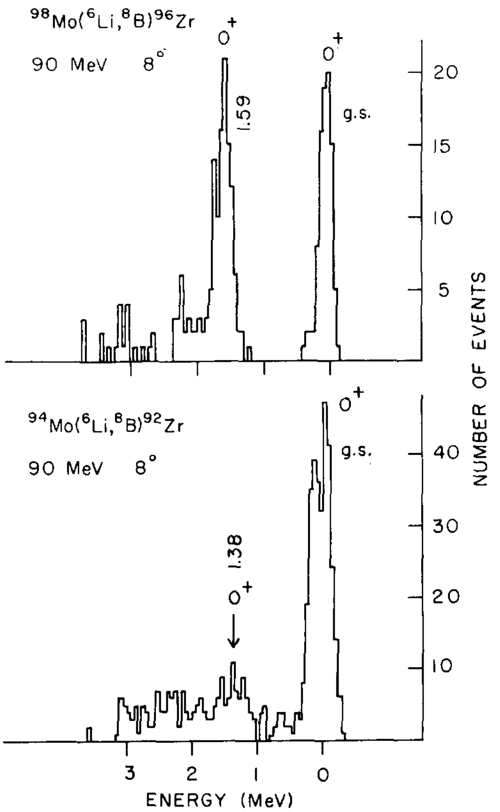

Fig. 1. Spectra at 8° lab from the ^{94,98}Mo(^{6}Li, ^{8}B)^{92,96}Zr reactions at 90 MeV. Note the lack of excited 0^+ strength in ^{92}Zr as compared to that in ^{96}Zr.

21.8 ± 3.5 and 6.5 ± 0.9 μb/sr for ^{92}Zr and ^{96}Zr, respectively. Although angular distributions were not measured here, it is believed they would be similar to those we have observed, for comparable Q-values and bombarding energy, in the ^{90}Zr(^{6}Li, ^{8}B)^{88}Sr reaction. In that case the angular distributions for the g.s. and 2_1^+ state are featureless and fall off rapidly with increasing angle. Of interest here are the $0^+ \rightarrow 0^+$ g.s. and lowest excited 0^+ state transitions. It is immediately apparent that insofar as these transitions are concerned, the two spectra are quite dissimilar; in ^{96}Zr the transition to the first excited 0^+ state at 1.59 MeV is as strong as the transition to the g.s., whereas in ^{92}Zr the transition to the 0^+ state at 1.38 MeV is much weaker than the g.s. transition.

Next to the (n, ^{3}He) reaction, which is burdened with obvious experimental problems, the (^{6}Li, ^{8}B) reaction is the lightest of the many possible two-proton pickup reactions. However, there have been but a few reports [3] in the literature concerning the (^{6}Li, ^{8}B) reaction and only one investigation [4] of its spectroscopic utility, this on four 1p-shell targets. Although a distorted wave analysis was not attempted in ref. [4], the reaction at 80 MeV was found to be selective, with the observed pattern of transition strengths in qualitative agreement with shell model expectations, as well as with the strengths observed in the analogous (p, t) reaction on the same $T_Z = 0$ targets. Thus the available evidence suggests that the reaction may proceed predominantly by direct transfer of a proton pair.

To provide a theoretical prediction of the $0^+ \rightarrow 0^+$ transition strengths observed for the two Mo targets, we have carried out exact finite-range distorted-wave Born approximation (EFR DWBA) calculations using the code DWUCK5 [5]. The form factors were calculated in the cluster approximation, following the adaptation of the theory presented in ref. [1] by Becchetti [6]. In ref. [4] it was determined experimentally, at least for p-shell targets, that the two protons in the (^{6}Li, ^{8}B) reaction are picked up predominantly in a spatially-symmetric (and hence spin-singlet) state. Following this result, in our calculations we have considered only spin-singlet states for the transferred proton pair. The entrance channel optical parameters were obtained from an analysis of 99 MeV ^{6}Li ions elastically scattered from ^{90}Zr [7]. Data from ^{8}B elastic scattering are not available as ^{8}B is unstable, hence parameters from the elastic scattering of ^{11}B from ^{208}Pb at 72 MeV [8] were substituted.

The EFR DWBA code was used to calculate the ratio of the cross section for the first excited 0^+ state to that of the ground state in both ^{92}Zr and ^{96}Zr. These calculated cross section ratios depend sensitively on the choice of spectroscopic amplitudes for the (Mo, Zr) pair, but should be relatively less sensitive to uncertainties in the potential parameters used in the analysis. The proton configuration of the zirconium ground states was assumed to be of the form $\alpha(p_{1/2})^2 + \beta(g_{9/2})^2$. The first excited 0^+ state is the orthogonal state $\beta(p_{1/2})^2 - \alpha(g_{9/2})^2$. The neutrons were assumed to be inert. The amplitudes α and β can be obtained from proton pickup [9] and stripping [10] data and are based on averages of the experimentally obtained values given in table 13 of ref. [10].

Table 1
Cross-section ratios comparing the four $0^+ \rightarrow 0^+$ transitions observed in this study (see text).

	Experimental ratio	Calculated ratio
$[\sigma(0_2^+)/\sigma(gs)]\,^{92}Zr$	0.21	0.17
$[\sigma(0_2^+)/\sigma(gs)]\,^{96}Zr$	1.1	1.2
$[\sigma(^{92}Zr)/\sigma(^{96}Zr)]_{gs}$	3.3	2.6

We used $(\alpha,\beta) = (0.71, 0.71)$ and $(0.95, 0.32)$ for $^{92,96}Zr$, respectively. A pure $(p_{1/2})^2\,(g_{9/2})^2$ proton configuration was assumed for the Mo ground states.

A comparison of the calculated and experimental ratios is given in table 1, where it can be seen that the agreement is quite good. Also shown is the ratio $[\sigma(^{92}Zr)/\sigma(^{96}Zr)]$ gs, which compares g.s. cross sections for the two isotopes. The very good agreement ($\approx$ 10–25%) between calculation and experiment for all three of the relevant $0^+ \rightarrow 0^+$ transition ratios suggests that the simple model we have employed is basically correct.

It is easy to understand in a qualitative way how the interplay between the phases and amplitudes of the proton configurations in Zr is instrumental in determining the cross-section ratios. The sensitivity of these ratios to the assumed configurations is partly due to the "hot orbit" effect, since the predicted cross section at 8° is approximately five times larger for pickup of the proton pair from the $p_{1/2}$ as compared to the $g_{9/2}$ orbital. Following ref. [2] and neglecting any Q-dependence, the relative cross sections for populating the g.s. and first excited 0^+ state are given by the expressions $(d\sigma/d\Omega)_{gs} \propto |R\alpha + \beta|^2$ and $(d\sigma/d\Omega)_{exc} \propto |R\beta - \alpha|^2$, where α and β, respectively, are the $(p_{1/2})^2$ and $(g_{9/2})^2$ amplitudes in Zr, and R^2 is the ratio of cross sections for pickup of a $(g_{9/2})^2$ versus a $(p_{1/2})^2$ proton pair. Taking $R^2 = 0.2$, as determined from the EFR DWBA calculations, and using the amplitudes given above, we obtain the following estimates for the relevant cross section ratios: $(\sigma_{exc}/\sigma_{gs})^{92}Zr = 0.15$, $(\sigma_{exc}/\sigma_{gs})^{96}Zr = 1.2$, and $[\sigma(^{92}Zr)/\sigma(^{96}Zr)]_{gs} = 1.9$. The first two ratios are essentially the same as those given in table 1, while the third, which compares g.s. cross sections, is somewhat smaller than the experimental value of 3.3

Although the question of the importance of multistep transfer amplitudes in heavy-ion induced reactions is still not completely answered, in a recent study [11] significant cross-section contributions from sequential transfer in $(^{16}O, ^{14}C)$ and $(^{12}C, ^{10}Be)$ reactions have been observed. Such contributions, when present, greatly complicate the analysis. The $(^6Li, ^8B)$ reaction, at least in the present case, seems to be adequately described by assuming the reaction consists of a direct, one-step cluster transfer of a $T = 1, S = 0$ proton pair, which can be easily calculated with existing finite-range codes.

In summary, our results have demonstrated the great similarity in strengths of the $(^6Li, ^8B)$ and $(d, ^6Li)$ $0^+ \rightarrow 0^+$ transitions leading to the same final states in ^{92}Zr and ^{96}Zr. In particular, we have established that the rather dramatic difference in the excited 0^+ state transitions, which is evident in fig. 1, can be attributed to changing proton configurations in zirconium, where the g.s. occupation probability of the $2p_{1/2}$ orbital increases with increasing neutron number. As predicted in ref. [2], and verified here, it is these changing proton configurations which are responsible for the unusually strong excitation of the 1.59 MeV 0^+ state in the $^{100}Mo(d, ^6Li)^{96}Zr$ reaction.

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