Coupled channel effects in the Ru(d,^{6}Li)Mo reaction

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Strong and systematic anomalies in the angular distributions for transitions to the first 2^+ levels in ^{96,98,100}Mo via the (d,^{6}Li) reaction are reproduced by coupled channels calculations. Disturbingly large effects of the coupled channels calculations on the strength of the ground-state transitions can be explained by assuming modified distorted waves in the exit channel.

[NUCLEAR REACTIONS ^{100,102,104}Ru(d,^{6}Li) $E=45$ MeV. ^{96,98,100}Mo measured $\sigma(\theta)$. DWBA, CCBA analysis, enriched targets, magnetic spectrograph.]

The (d,^{6}Li) and (^{6}Li, d) reactions in recent years have enjoyed much interest for the study of four-nucleon correlations in nuclei. Although cross sections to excited states are typically very small (<1 μb) the analysis of the data with one-step distorted-wave Born approximation (DWBA) calculations has met with reasonable success at least in as much as the shapes of the angular distributions are concerned. For the relative strengths of excited states no reliable benchmark exists. Very little is known up to now about the importance of coupled channel effects on four-nucleon transfer reactions. Possibly such effects have been observed in a study of the (d,^{6}Li) reaction on sd-shell nuclei[1] in the excitation of unnatural parity states and the lowest 2^+ state in ^{20}Ne, but these observations have not been followed up as yet.

We report in this paper on a study of the Ru(d,^{6}Li) reaction in which we observe strong and systematic anomalies in the angular distributions of the first 2^+ states. We find that these anomalous angular distributions can be reproduced by coupled channels (CCBA) calculations. These calculations, however, lead to an unexpected and disturbingly large effect on the strength of the ground-state transition. This effect can be attributed to the modification of the distorted waves in the exit channel.

Highly enriched ($>92\%$) ^{104,102,100}Ru targets were produced via electroplating and bombarded with a 45 MeV momentum analyzed deuteron beam from the KVI cyclotron. The thickness of the targets was about 100–200 μg/cm^2 Ru metal on a Mylar backing. To avoid damage to the targets from heating by the incoming beam a thin layer (about 30 μg/cm^2) of Al was evaporated on the Ru metal. Reaction products were momentum analyzed with a QMG/2 spectrograph[2] and detected with the accompanying focal plane detection system.[3] The energy resolution was mainly limited by the target thickness to about 50 keV for the two lightest and to 80 keV for the heaviest target. Differential cross sections were measured in the angular range from $\theta_{lab}=6°$ to 26°, and absolute cross sections were determined by normalizing the data to elastically scattered deuterons at the same incident energy. The absolute error in the cross sections is believed to be smaller than 15%.

In Fig. 1 angular distributions are shown for the transitions to the ground state and to the two lowest 2^+ states together with the results of zero-range DWBA calculations performed with the code DWUCK4 (Ref. 4) (full curves). Since for the transition to the 2_2^+ state of ^{100}Mo very low statistics were accumulated, an angular distribution for this state could not be obtained. The optical model parameter sets A, B, and C listed in Table I were taken from Refs. 5–7, respectively. They have been used extensively before in the analysis of other (d,^{6}Li) reactions.[1,7–8] All calculations were performed with an α-cluster form factor with the number of oscillator quanta $Q=16$. As is seen from Fig. 1 the shapes of the angular distributions of the 2_1^+ states are only poorly reproduced by the DWBA calculations. Particularly, the minimum at 13° predicted by the DWBA calculations appears to be a maximum in the experimental angular distributions. This is in contrast to the angular distributions of the 2_2^+ states which are well fitted. The systematic behavior of the observed effect, i.e., the good fits obtained for the 2_2^+ states and the failure to fit the first excited 2^+ states excludes an explanation in terms of inadequate (^{6}Li) optical model parameters. Neither can Q value or finite-range effects account for this observation. The observed behavior is very similar to effects seen in (p,t) reactions[9] and is most likely due to strong channel coupling between the ground state and the first 2^+ state.

To explore these coupled channel effects we have performed CCBA calculations with the code CHUCK3 (Ref. 4) using the same optical model parameter sets A, B, and C from Table I. In these calculations it was assumed that the 2^+ state is reached by a direct transition as well as by a ground-state to ground-state transition followed by inelastic excitation of the 2_1^+

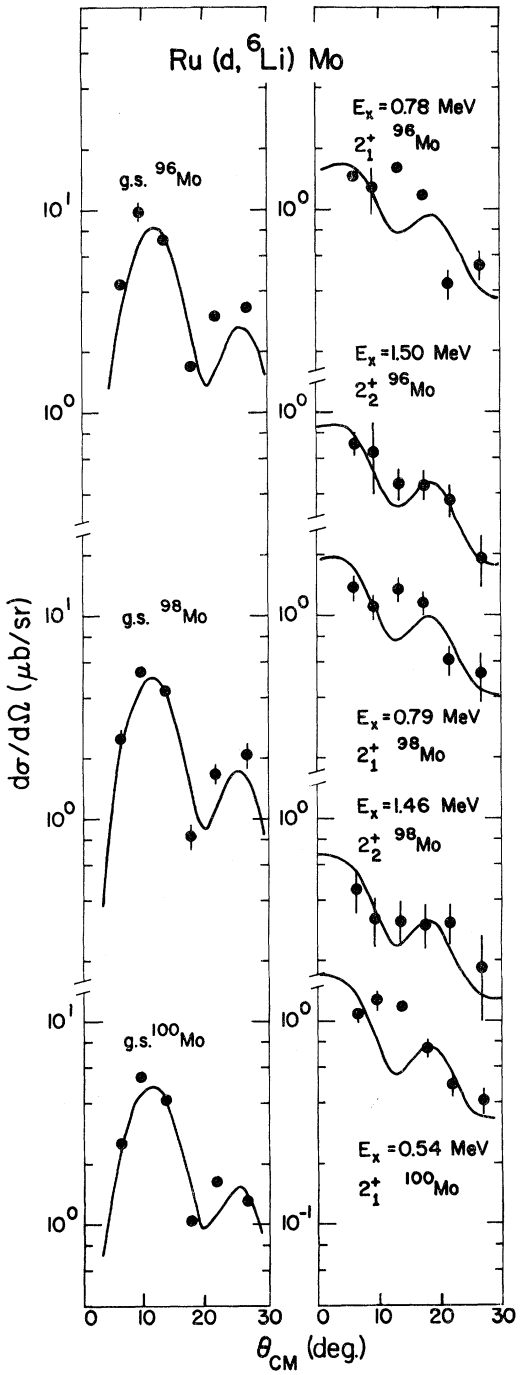

FIG. 1. Angular distributions of the ground state and the $2^+_{1,2}$ states together with zero-range DWBA calculations (curves).

level, using a collective form factor for rotational coupling. Except for the deformation parameter β the only free parameters are the transition amplitudes for the direct excitation of the ground state and the 2^+_1 state, respectively. For β, the averaged value of β_2 is taken from Table 3 of Ref. 10. Since the 2^+_1 state of ^{96}Mo is assumed to be representative for all investigated isotopes the results of the CCBA calculations will be shown for this state only [see Fig. 2(a)]. The shape of the ground-state angular distribution is not affected at all by switching on the channel coupling. It is therefore not shown.

The angular distribution for the 2^+_1 state computed with the CCBA is seen to be in better agreement with the data than that obtained with the DWBA. In order to compare coupling strengths S (squares of the spectroscopic amplitudes for direct transitions) obtained via the CCBA with those from the DWBA calculations ($S=\sigma_{\rm exp}/\sigma_{\rm DWBA}$) we also performed a CCBA calculation with the deformation parameter set to $\beta=0.001$, resulting in an angular distribution that is virtually identical to the DWBA angular distribution [see Fig. 2(b)]. In Figs. 2(a) and 2(b) the direct strengths S_0 and S_2 from the CCBA calculations [all normalized to the ground-state strength in Fig. 2(a)] are presented as well. Large reductions in the strengths S_0 and S_2 occur when the coupling is switched on. The reduction of the direct strength S_2 for exciting the 2^+_1 state is not surprising. The CCBA calculation with $S_2=0$ indicates that the 2^+_1 state obtains most of its cross section ($>80\%$) from coupling to the ground state. The shape of the angular distribution for the transition to the 2^+_1 state is only little affected by setting S_2 equal to zero [see Fig. 2(c)].

The reduction in the strength S_0 of the ground-state to ground-state transition, on the other hand, is very disturbing. Similar effects were found before in an analysis of the ^{176}Yb$(p,t)^{174}$Yb reaction by Tamura *et al.*[11] The ground-state transitions typically are the strongest transitions in the $(d,^6\text{Li})$ reaction. Their reduction in strength by a factor of 2 thus cannot be attributed to feeding from other states, as also has

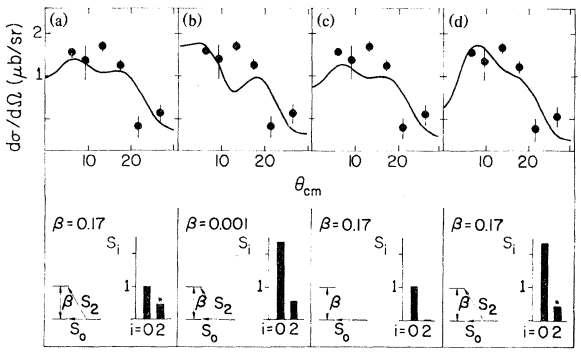

FIG. 2. Results of CCBA calculations using different coupled channel parameters (see text). All strengths (S_i, $i=0,2$) are normalized to the ground-state strength shown in Fig. 2(a). An asterisk on top of a bar indicates that this strength is multiplied by a factor of 10.

TABLE I. Optical model parameters.

Set		V_0	r_0	a_0	W	W_D	r_I	a_I	V_{so}	r_{so}	a_{so}	r_C
A	*d*	−77.47	1.25	0.71		12.0	1.25	0.86	−6.0	1.25	0.7	1.3
B	^{6}Li	−240.0	1.30	0.65	−17.0		1.70	0.90				1.3
BC	^{6}Li	−245.2	1.34	0.63	−11.5		1.88	0.69				1.3
C	"α"	a	1.30	0.73								1.3

[a]Adjusted to fit the binding energy of the α particle.

been verified by the CCBA calculation with $S_2=0$ discussed in the previous paragraph. The extreme sensitivity to CCBA effects as observed in the present investigation would cast serious doubts on all strengths, absolute or relative, obtained from $(d,^6\text{Li})$ data. The inclusion of channel coupling for some transitions and not for others will obviously affect even for strong transitions the *relative strengths* with which they are populated apart from trivial feeding effects. A complete CCBA analysis including all final states, on the other hand, is highly impractical.

Since feeding of the ground state via the 2_1^+ state can be excluded as cause for the reduction in the direct strength S_0, the sensitivity to the CCBA must be sought in the modification of the distorted waves in the exit channel due to channel coupling. The calculations show a very large sensitivity of the computed $(d,^6\text{Li})$ cross section on small changes in the ^{6}Li optical model parameters. For instance, an increase of the parameters r_0 and V_0 from set *B* of Table I by 0.3% and by 3%, respectively, results in an increase of the ground-state transition strength by typically 10%. To investigate therefore the effects of the channel coupling on the distorted waves we created synthetic ^{6}Li elastic scattering data in the angular range $\theta < 80°$ with potential set *B* and have then used these synthetic data as input for an optical model search in a coupled channel calculation. With the inclusion of channel coupling the modified optical model parameter set *BC* was obtained by this method. This potential was then used for a CCBA analysis of the $(d,^6\text{Li})$ reaction [see Fig. 2(d)]. It is seen from this figure that it is possible to obtain a strength S_0 in good agreement with that from DWBA (or CCBA) calculations with $\beta=0.0$ and using the original optical model parameters [see Fig. 2(b)]. From these results we conclude that CCBA and DWBA will yield the same spectroscopic factors for the strong transitions if the CCBA optical model parameters are modified in a consistent way, taking into account the effects of the channel coupling. Thus for the strong transitions the DWBA can be employed to extract relative spectroscopic factors in contrast to what would have seemed on the basis of the initial CCBA calculations.

For the transitions to the 2_1^+ states the CCBA calculations with the modified optical model parameter set *BC* still yield a strength S_2 that is smaller by a factor of 10 than that obtained from the DWBA calculation [see Fig. 2(b)]. Because of the weakness of the direct transition to the 2_1^+ state this reduction in S_2 is as expected, as was already discussed above.

In summary, we observe strong and systematic coupled channel effects on the angular distribution and strength of the transition to the 2_1^+ states in the $\text{Ru}(d,^6\text{Li})\text{Mo}$ reaction that can be reproduced by CCBA calculations. The effects observed are very similar to those seen in two-nucleon transfer reactions to the same final states.[12] The inclusion of the channel coupling via CCBA calculations has an unexpectedly large effect on the magnitude of the direct strength even of strong transitions. These effects were found to be due to variations in the distorted waves of the exit channel due to channel coupling. Similar effects have been found in the analysis of the $^9\text{Be}(\alpha,t)^{10}\text{B}$ reaction[13] and of the $^{16}\text{O}+^{40}\text{Ca}$ elastic and inelastic scattering data.[14] The use of properly adjusted ^{6}Li optical model parameters that make allowance for the channel coupling does yield the original ground-state transition strength.

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