possibly could be explained by invoking a prompt mechanism, we feel that one should not ignore the well-known evaporation process, which is certain to be present. In fact, we have shown that evaporation in the presence of thermal fluctuations in the division of the excitation energy could reproduce the high-energy protons associated with the deep-inelastic channel.

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Properties of the (α, α^*) Reaction at Very Forward Angles: Coupled-Channels Effects in Single and Mutual Excitation

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(Received 1 May 1980)

Use was made of a special feature in the detection of unbound ejectiles, to extend previous measurements of the (α,α^*) reaction on ^{24}Mg and ^{28}Si to very forward angles. The characteristic differential cross sections obtained for mutual as well as for single excitation are well reproduced in a full coupled-channels calculation in which the strong couplings to the first excited 2^+ states of the target nuclei are taken into account.

PACS numbers: 25.60.Cy, 24.10.Dp, 27.30.+t

Nuclear reactions in which the projectile is excited via inelastic scattering from the target nucleus into a bound state have already been studied[1,2] for a number of heavy-ion systems. More recently, there has been much interest[3] in studies of nuclear reactions resulting in unbound ejectiles. This type of studies, including projectile excitation into an unbound state, opens[4] many new possibilities in nuclear reaction investigations. It also necessitates extending our theoretical understanding of direct nuclear reactions into a new domain in which very little work has been done. Recently for instance, Kunz, Saha, and Fortune[5] developed a new method of finite-range distorted-wave Born approximation (DWBA) to treat pickup reactions to unbound ejectiles.

In order to understand the reaction mechanism involved in the (α, α^*) reaction, exciting the α particle to its first excited state ($J^\pi=0^+$, $E_x=20.1$ MeV), Kamermans *et al.*[6] studied this reaction at $E_\alpha=65$ MeV on a wide range of nuclei. Surprisingly, strong mutual excitation of both target and projectile have also been observed. In an attempt to understand this unexpected result, folding-model DWBA calculations were performed[6] for single and mutual excitation. The differential cross section for single excitation was overestimated by almost an order of magnitude but reproduced[6] in shape with use of a transition density for α^* deduced[7] from inelastic electron scattering. For the mutual excitations, however, the calculated cross sections were in disagreement with the experimental ones. At the very forward angles where the data could present a severe test of the folding-model DWBA calculations, no such data were available.

In this Letter we report on a measurement of the (α, α^*) reaction at very forward angles (0°, 4°, and 7°) made possible because of the breakup properties of unbound ejectiles. Moreover, we report on a coupled-channels (CC) calculation in which we were able to describe both single and mutual excitations in the same framework with parameters that were obtained from or found to be in agreement with other experiments. CC effects were found to be important and rather unexpectedly at very forward angles. Such a CC calculation is, to our knowledge, the first in which mutual excitation of target and projectile are considered simultaneously. Similar calculations could be very useful in understanding inelastic heavy-ion scattering.

The detection system (see Fig. 1) consisted of two telescopes each of which had two solid state ΔE and E counters of 0.3 and 5 mm thickness, respectively. A slit between the telescopes allowed the beam to pass through at very forward angles. The outgoing α^* was detected by requiring a fast coincidence between a proton and a triton with relative energies between 0.2 and 0.8 MeV. Because of the unequal masses, the detector position at, e.g., $\theta_{\text{det}} = 0°$ corresponds to $\theta_{\text{lab}} = 2°$ for the α^*. Self-supporting foils of isotopically enriched ^{24}Mg and ^{28}Si of 1.4 and 1.3 mg/cm^2 thickness, respectively, were used as targets. All measurements were performed with a momentum analyzed beam of 65-MeV α particles from the Kernfysisch Versnellar Instituut cyclotron. The data were written event by event on magnetic tape, allowing off-line data analysis. Absolute cross sections have been calculated from the target thickness, integrated charges, and the calculated[6] effective solid angle.

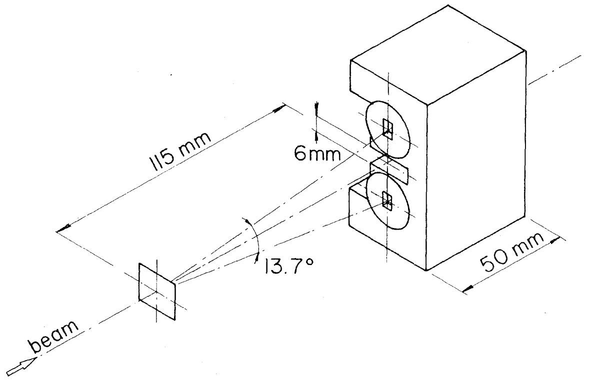

FIG. 1. A schematic view of the detection system positioned at $\theta_{\text{det}} = 0°$.

The observed differential cross sections for both the single and mutual excitations are displayed in Fig. 2. The data from the present investigation are displayed as open circles. In order to make the monopole strength observed in our (α, α^*) measurements compatible with the strength obtained from direct measurements such as the ^{4}He$(\alpha, \alpha')^4$He* measurement of Gross *et al.*,[8] our (α, α^*) cross sections should be corrected for the limited relative energy range be-

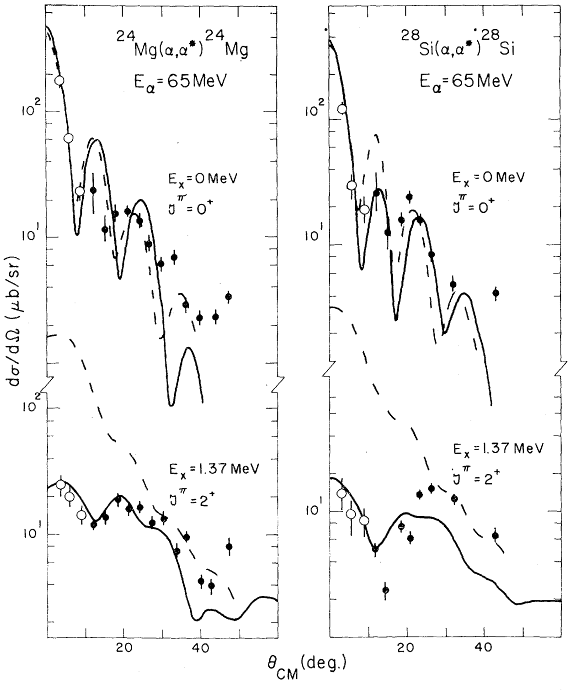

FIG. 2. Angular distributions for single and mutual excitation cross sections for the (α, α^*) reaction on ^{24}Mg and ^{28}Si. The dashed lines represent the DWBA calculations as described in Ref. 6. Open circles indicate the results obtained in this work, the other data have been taken from Ref. 6. The solid lines are results of CC calculations, reduced by a factor of 2.6 (see text).

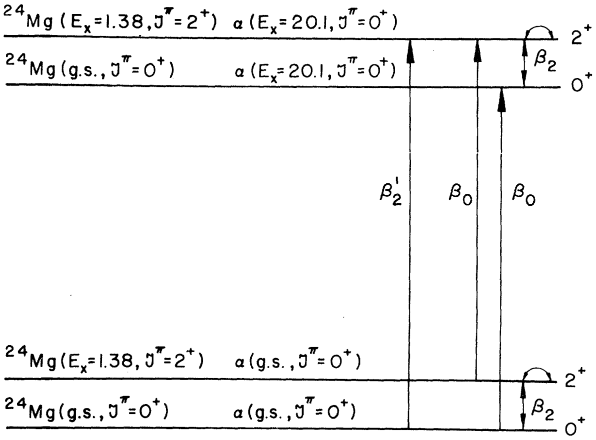

FIG. 3. Coupling scheme used in the CC calculation, if we assume all excitations in one system.

cause of the detector arrangement and the unobserved $n+{}^3$He channel. With use of the Breit-Wigner parameter set[9] $a=3.3$ fm, $E_0=0.6$ MeV, $\gamma_p{}^2=3.53$ MeV, and $\gamma_n{}^2=1.74$ MeV to describe the α^* state, the correction factor is calculated to be 2.6. In Fig. 2, all theoretical calculations were scaled down by this factor. The dashed curves through the data are the results of the DWBA calculations as obtained by Kamermans *et al.*, Ref. 6. The mutual excitation could not be reproduced for $\theta < 25°$, if the same normalization is used[6] for the theoretical mutual and single excitation cross sections. This discrepancy is due to CC effects as we will show in the following.

With the existing CC codes it is not possible to treat a reaction process that involves simultaneous excitations in both final nuclei. If one, however, can assume that the excitation of the projectile can be considered as a loss of kinetic energy into the excitation of the total system without any dramatic modifications of the optical-model geometrical parameters generating the outgoing waves, then one can incorporate the influence of CC effects on the mutual excitation cross section by considering that mutual exciation occurs in a total system which is schematically drawn in Fig. 3. The CC calculations were performed with the code CHUCK[10] with the indicated scheme which involves three strength parameters:

(i) β_2; the coupling between the 0^+ ground state (g.s.) and the 2^+ first excited state of the target nucleus. These were obtained for ^{24}Mg and ^{28}Si[11,12] from Refs. 11 and 12, respectively, by scaling the deformation lengths $\beta_2 R$, where R is the radius of the optical potential used.

(ii) β_0; the coupling between the 0^+ g.s. and the 0^+ state at $E_x=20.1$ MeV of ^{4}He. This value determines the strength of the single excitation process in the absence of mutual excitation.

(iii) β_2'; the coupling between the g.s. $J^\pi=0^+$ in ^{24}Mg (^{28}Si) and ^{4}He and the mutual excitation $J^\pi=2^+$ in ^{24}Mg (^{28}Si) and $J^\pi=0^+$ at $E_x=20.1$ MeV in ^{4}He, i.e., 2^+ hypothetical state at $E_x=21.48$ (21.89) MeV in the schematic system for ^{24}Mg (^{28}Si).

The couplings between the ground state and first excited states of ^{24}Mg (^{28}Si) as well as between the hypothetical states 0^+ at 20.1 MeV and 2^+ at 21.48 (21.89) MeV for ^{24}Mg (^{28}Si) have been considered in the limit of the symmetric rotational model. Reorientation terms were included[11] but Coulomb excitation was neglected. The form factor used for the monopole excitation was that proposed by Satchler[13]; $f(r)=-3U_0-r\,dU_0/dr$. The mutual excitation form factor was taken of the usual collective type for $L \geqslant 2$: $R\,dU_0/dr$.

For ^{24}Mg, optical potentials were deduced[14] from α scattering at $E_\alpha=65.7$ MeV and $E_\alpha=50.1$ MeV. The strength of the imaginary potentials were further reduced by 20% to account[11] for explicitly coupling the 2^+ state. The resulting potentials are listed in Table I. With use of a deformation parameter $\beta_2=0.32$ taken from Ref. 11, excellent fits were obtained both for the single and mutual excitation cross sections. These are drawn as solid lines in Fig. 2. The resulting parameters β_0 and β_2' are listed in Table II.

For ^{28}Si the same potentials were used as for

TABLE I. Optical-model parameters used in the various calculations.

Reaction	V (MeV)	r_r (fm)	a_r (fm)	W (MeV)	r_i (fm)	a_i (fm)	r_C (fm)
$\alpha+{}^{24}$Mg	-100.0	1.44	0.66	-32.0^{a}, -16.0^{b}	1.6	0.48	1.3
$\alpha+{}^{28}$Si	-100.0	1.44	0.66	-28.0^{a}, -14.0^{b}	1.6	0.48	1.3
$\alpha+{}^{4}$He	-107.0	1.14	0.70	-16.0	1.14	0.7	1.14

[a] Entrance channel.
[b] Exit channel.

TABLE II. Deformation and strength parameters needed to fit the experimental data.

Reaction	β_2	β_0	β_2'	$\beta_0 R$ (fm)
$\alpha + {}^{24}\mathrm{Mg}$	0.32[a]	0.040	0.027	0.16
$\alpha + {}^{28}\mathrm{Si}$	0.24[b]	0.034	0.016	0.15
$\alpha + {}^{4}\mathrm{He}$	···	0.1	···	0.18

[a] Obtained from Ref. 11, when βR is assumed to be constant.

[b] Obtained from Ref. 12, when βR is assumed to be constant.

^{24}Mg and the deformation parameter $\beta_2 = 0.24$ was taken from Ref. 12. Again, good fits for both the single and mutual excitation cross sections were obtained (drawn as solid lines in Fig. 2) if the imaginary depths were slightly varied as listed in Table I. The strength parameters β_0 and β_2' obtained from this analysis are listed in Table II.

To be able to attach any significance to the strength parameters β_0 and β_2' and hence get an overall consistent picture of single and mutual excitation in (α, α^*) reactions, these strength parameters β_0 and β_2' should satisfy certain criteria. Firstly, $\beta_0 R$ should be constant for all reactions as well as equal to the strength parameter for the direct excitation of this monopole state by an isoscalar probe. We undertook the DWBA analysis of the inelastic ^{4}He$(\alpha, \alpha')^4$He* data[8] with the monopole form factor of Satchler.[13] The total wave function of the incoming α-α channel was symmetrized.[10] An α-α optical potential obtained[14] at $E_\alpha = 47.1$ MeV, was used; however, here the imaginary depth had to be changed drastically (see Table I) to obtain a reasonable fit to the elastic and inelastic scattering data of Gross *et al.*,[8] (not shown) obtained at $E_\alpha = 64$ MeV. The uncertainties in β_0 obtained from this analysis are estimated around 50% because of optical-model potential ambiguities. The resulting β_0 and $\beta_0 R$ values obtained from this analysis are listed in Table II. It is quite remarkable that the $\beta_0 R$ values obtained for the excitation of the monopole state in ^{4}He from the various experiments are in very good agreement.

Secondly, the β_2' values should be of the order of $\beta_0 \beta_2$, since in the folding model β_2' would correspond to the folding of the transition densities for the excitation of the 2^+ state in ^{24}Mg or ^{28}Si and the monopole state in ^{4}He. A cursory look at Table II confirms this criterion.

To conclude an overall consistent picture of single and mutual excitations in (α, α^*) reactions emerges in which CC effects play an important role. CC calculations with parameters obtained from or in agreement with other experimental evidence, although *a priori* not necessarily expected, give excellent fits to the single and mutual excitation cross sections. Such strong CC effects can play a significant role in single and mutual excitation of target and projectile in heavy-ion scattering.

The authors would like to thank R. H. Siemssen for many useful discussions.

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