dependence of α on T in alkali halides through the use of only a single parameter whose value may be checked through use of data on the thermal expansion coefficient. Quite recently, Sparks and Sham[8] have extended their earlier work[2] to account for the variation of α with T. Their starting Hamiltonian is more complete than ours since it includes phonon dispersion, but they calculate α by a perturbation method which introduces higher-order anharmonic effects phenomenologically only through a temperature dependence of the phonon frequencies. The two theories agree in the one important regard that in the multiphonon regime large deviations from the T^{n-1} law come from large anharmonic corrections to the perturbation-theory result for α.

We are indebted to Dr. J. A. Harrington for sending us his data in advance of publication, and for useful discussions. We are also grateful to Dr. M. Sparks for many useful conversations.

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*Research supported by The Advanced Research Projects Agency of the Department of Defense and monitored by the Defense Supply Service, Washington, D.C., under Contract No. DAHC 15-72-C-0129.

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Observation of Nuclear Structure Dependence of the Phase of the (d, d') Form Factor*

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(Received 19 July 1973)

Interference between Coulomb and nuclear excitations for inelastic deuteron scattering has been observed for a number of nuclei. Most data are in qualitative, although not quantitative, agreement with collective-model distorted-wave Born-approximation predictions of constructive Coulomb-nuclear interference; excitation functions for the first 2^+ states of $N = 82$ nuclei, however, show destructive interference not predicted by the collective model.

There has recently been considerable interest[1-13] in the study of interference between Coulomb and nuclear processes for inelastic scattering. The most striking result of these studies has been the remarkable success of the collective model[14] in the distorted-wave Born-approximation (DWBA) description of the data; Coulomb-nuclear interference for α particles,[1-4] ^{3}He,[5-8] and more recently for heavy ions[10-12] is well described provided that an adequate number of partial waves is included.

In order to examine the validity of the collective model for deuterons, excitation functions at back angles have been measured for inelastic deuteron scattering from ^{54,56}Fe, ^{60}Ni, ^{114}Cd, ^{138}Ba, ^{144,150,152}Sm, and ^{192}Os. Data were obtained at back angles so that the maximum Coulomb-nuclear interference will occur near the middle of the energy range of the FN tandem accelerator. Scattered deuterons were observed using a position-sensitive proportional counter[15] on the image surface of an Enge split-pole spectrograph. Results for low-lying 2^+ and 3^- states of ^{138}Ba and ^{144,150}Sm are presented here; the other results will be published elsewhere.

Optical-model parameters used in the analysis

TABLE I. Optical-model parameters.

Target	V (MeV)	r_0 (fm)	a (fm)	W (MeV)	r_0' (fm)	a' (fm)
^{138}Ba	98.76	1.15	0.828	17.5	1.327	0.644
^{144}Sm	99.72	1.15	0.85	20.76	1.379	0.535
^{150}Sm [a]	94.0	1.15	0.912	24.0	1.364	0.583

[a] Obtained by interpolating ^{148}Sm and ^{152}Sm parameters.

TABLE II. Spectroscopic results.

Target	E (MeV)	J^π	$\delta_L{}^{C}$ [a] (fm)	$\delta_L{}^{N}$ [a] (fm)
^{138}Ba	1.44	2^+	0.56	0.42
^{144}Sm	1.67	2^+	0.56	0.45
	1.82	3^-	0.64	0.64
^{150}Sm	0.33	2^+	1.00	1.00
	1.1	3^-	0.74	0.74

[a] Estimated uncertainty ± 10%.

are shown in Table I. The Sm parameters are from Barker and Hiebert[16]; the ^{138}Ba parameters were obtained by fitting a 15-MeV elastic-scattering angular distribution using the search code MAGALI.[17] The form assumed for the optical potential was the usual surface-absorption form,

$$V(r) = V_C(r) - Vf(x) + 4iW\, df(x')/dx',$$

where $V_C(r)$ is the Coulomb potential of a uniformly charged sphere of radius $1.25A^{1/3}$ fm and where $f(x) = (1+e^x)^{-1}$ and $x = (r - r_0A^{1/3})/a$. The use of optical potentials with volume absorption and with spin-orbit potentials was investigated and found to give results similar to those described here. It should be pointed out that energy dependence of the deuteron optical potential has been studied by Dickens and Perey[18] for ^{114}Cd and ^{60}Ni; the energy variation of the optical-model parameters is too small to explain the discrepancies described in this Letter.

DWBA calculations were done using the code DWUCK.[19] Careful investigation of the convergence of the calculations revealed that fifty partial waves and a maximum integration radius of 60 fm ($E_d > 5$ MeV) or 80 fm ($E_d \leq 5$ MeV) were adequate. Collective-model form factors were calculated assuming equal deformation lengths, $\delta_L = \beta_L R$, for real and imaginary parts. For ^{138}Ba and ^{144}Sm the relative Coulomb ($\delta_L{}^C$) and nuclear ($\delta_L{}^N$) deformations used were those implied by the (α, α') results of Barker and Hiebert,[16,20] but use of equal values of δ_L gives quite similar results; equal values of δ_L were used for ^{150}Sm and for both $L = 3$ calculations. Values of $\delta_L{}^N$ were obtained by normalizing DWBA predictions to the data at high energies. Spectroscopic results for the normalizations shown in the figures are shown in Table II.

The experimental results and DWBA predictions are shown in Figs. 1–3. It should be noted that the DWBA calculations predict, using a collective-model form factor, constructive interference between Coulomb and nuclear excitation; this is in contrast to α-particle and heavy-ion results, where destructive interference is observed as a result of the dominance of the real parts of the collective-model form factors. For deuterons (and ^{3}He), however, the imaginary part of the form factor dominates because of the larger radial extent of the imaginary part of the optical potential. The results for ^{150}Sm, shown in Fig. 1, are representative of all nuclei studied except ^{138}Ba and ^{144}Sm, i.e., the data display constructive interference, in qualitative agreement with the collective-model predictions, but are

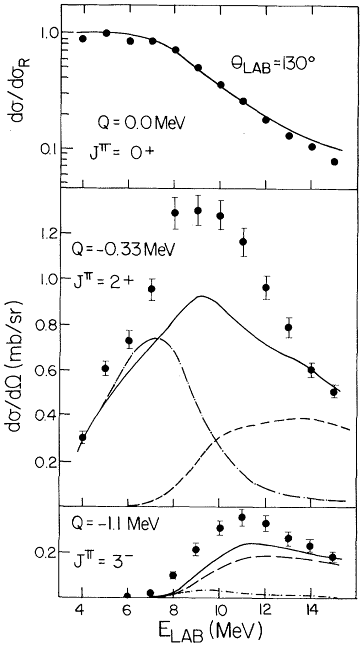

FIG. 1. Results for ^{150}Sm(d,d'). For elastic scattering: solid line, optical-model prediction using the parameters of Table I. For inelastic scattering: solid lines, DWBA collective-model predictions including Coulomb excitation; dashed lines, predictions for collective nuclear excitation only; dot-dashed lines, predictions for Coulomb excitation only.

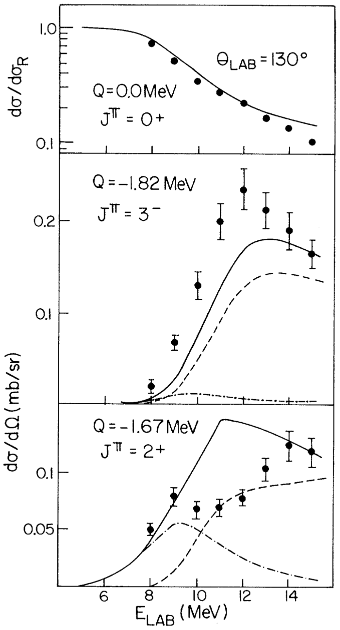

FIG. 2. Results for ^{144}Sm(d,d'), presented as in Fig. 1.

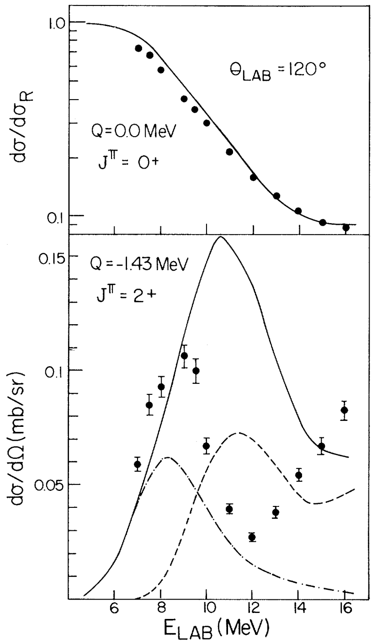

FIG. 3. Results for ^{138}Ba(d,d'), presented as in Fig. 1.

significantly larger than the DWBA calculations in the region of maximum interference. The results for excitation of the first 2^+ states of the $N=82$ nuclei ^{144}Sm and ^{138}Ba are strikingly different from all other results—the observed interference is destructive over part of the energy range, revealing a sudden change in the relative phase of the Coulomb and nuclear transition amplitudes not accounted for by the collective model. This failure of the collective model supports previous investigations[16,20,21] of $N=82$ nuclei which have indicated that the lowest 2^+ levels are not well described as vibrational states. The present results are of particular importance in the formulation of a microscopic model of the (d, d') reaction: The collective model clearly cannot, at least for $N=82$ nuclei, serve as a guide to the size and shape of the imaginary part of the form factor as is done in the best current microscopic model.[22,23] It is interesting to note that a recently published microscopic analysis[24] of the ^{39}K(d, d') experiment is in much better agreement with data for noncollective levels if the imaginary part of the form factor[22,23] is left out altogether.

Finally, the behavior of the "normal" (i.e., $N\neq 82$) cases warrants some further discussion. The failure of the collective model to be in quantitative agreement with the data is probably not a result of the large experimental scattering angles since several angular distributions have been measured, both near maximum interference and at higher energies, and the *shapes* of the predicted angular distributions are in good agreement with the data. One possible explanation is that the optical-model parameters are incorrect. For instance, if Coulomb breakup were an important process, the optical potential should have a very long-range imaginary tail; the collective-model form factor would thus similarly have a long-range imaginary part which would likely improve the agreement between experiment and collective-model predictions. Soper and Johnson[25] have developed a very successful formalism to include implicitly nuclear breakup of the deuteron for stripping and pickup reactions; unfortunately, their technique does not appear to be applicable to inelastic channels and does not include Coulomb breakup which is likely to be an important process at low energies. Investigation of the effects of breakup on inelastic scattering may provide insight into the apparent failure of the collective model observed here.

Resolution of the discrepancy observed here between experiment and theory is of interest for two reasons: First, the fact that the $N=82$ data are so different from other data might indicate sufficient sensitivity of the form factor to nuclear structure for the (d, d') reaction to be a useful spectroscopic probe in a microscopic sense; secondly, if the source of the discrepancies is the deuteron optical potential, changes may affect the spectroscopic results of deuteron-induced reactions, many of which have been done in the same energy range as the present experiment.

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*Work supported in part by the National Science Foundation.

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Supermultiplet Symmetry in the Reaction ^{3}H + ^{9}Be → ^{6}Li + ^{6}He, ^{6}Li* + ^{6}He

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(Received 25 June 1973)

The reactions ^{9}Be$(t, {}^6$Li$)^6$He and ^{9}Be$(t, {}^6$Li$^*)^6$He have been measured at a bombarding energy of 23.5 MeV. The reaction products ^{6}He(ground state), ^{6}Li(ground state), and ^{6}Li(3.56 MeV) are members of a spin-isospin supermultiplet, and the observed differential cross sections are dominated by a symmetry expected from such considerations. Significant deviations from symmetry are, however, seen, especially in the isospin-multiplet channel.

In light nuclei the nucleons are coupled in the *L-S* coupling scheme—the result of a weak spin-orbit interaction. If it is then assumed that the nucleon forces in these cases are independent of both spin and isospin (charge independence), supermultiplets of the type proposed by Wigner[1] should be observed. The lightest bound nuclear system which should be described by such assumptions is the mass-six system: ^{6}He, ^{6}Li, and ^{6}Be. The nuclei ^{6}He, ^{6}Li* $(T=1)$, and ^{6}Be form the spin singlet, isospin triplet, with $T=1$ and $S=0$, whereas the ^{6}Li $(T=0)$ ground state is the degenerate isospin-singlet, spin-triplet multiplet member. Together these states form the supermultiplet, and they would be degenerate in energy if the nuclear forces were completely spin and isospin independent. Actually the masses (energies) of the three states of the isospin triplet differ by ~2.0 MeV, which is ~0.05% of the total mass, and the isospin triplet and spin triplet differ by 3.56 MeV, the observed energy of the excited state of ^{6}Li $(T=1,\ S=0)$.

This Letter reports an experiment in which different combinations of two members of the mass-