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Channel-Coupling Effects in Analog Charge-Exchange Reactions*

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We present data and coupled-channel calculations on charge-exchange reactions in ^{56}Fe and ^{26}Mg to 0^+ and 2^+ analog states. For the (p,n) reaction in the neighborhood of 20 MeV the two-step processes dominate the excited 2^+ analog transitions, thus explaining the large strength of these states in the (p,n) spectrum. The two-step mechanism is relatively weaker but still important in the corresponding $(^3\mathrm{He},t)$ reaction.

In the experimental studies of charge-exchange reactions, analogs of collective excited states are a prominent feature of the spectra. The first attempt to explain the mechanism was made by Satchler, Drisko, and Bassel[1] on the basis of the collective model. They calculated the cross section in the distorted-wave Born approximation (DWBA) for the 2^+ analog state seen in the data of Anderson *et al.*[2] on ^{56}Fe(p,n) using as an interaction a deformed Lane potential V_1. Taking deformation parameter $\beta = 0.24$ from the literature, they calculated a cross section at least an order of magnitude too small.

Following a suggestion by Blair,[3] several workers[4-6] have subsequently attempted to explain the strength of the $(^3\mathrm{He},t)$ reaction by including the two-step processes proceeding through the 2^+ inelastic and 0^+ analog states. The conclusion one can make on the basis of recent work[5,6] is that the two-step mechanism, while important for angular distributions, does not lead to large cross sections for the 2^+ analog state in $(^3\mathrm{He},t)$. However, we present evidence in this Letter that the two-step processes actually dominate this transition in the (p,n) reaction; in fact, the previously unexplained large excited-analog cross section

is now accounted for with no adjustment of the deformation parameter β_1 of the Lane optical potential and is indeed fairly insensitive to its value.

The protons and ^{3}He ions were accelerated by the Livermore 90-in. cyclotron. The (p,n) 0^+ analog and 2^+ excited-analog transitions on ^{56}Fe and ^{26}Mg were measured using standard time-of-flight techniques.[2] The target thicknesses were 6.85 mg/cm^2 for ^{56}Fe and 3.0 mg/cm^2 for ^{26}Mg. The $(^3\text{He},t)$ 0^+ and 2^+ transitions on ^{26}Mg were measured using standard charged-particle techniques.[7] The ^{26}Mg target thickness was 1.0 mg/cm^2.

In our calculations we have adopted the following procedure: We use the collective model[1,8,9] with a deformed Lane potential V_1 taking its deformation parameter $\beta_1 = \beta$ from the literature[10,11] and the optical parameters from the analysis of Becchetti and Greenlees[12] (BG). Although the BG parameters are not recommended for $A < 40$ or $E < 20$, they are nevertheless expected[13] to give reasonable systematics of N, Z, and E dependence. We have left out the spin-orbit optical potential because of the large saving in time which the use of spin-zero projectiles permits. Test calculations including it have angular distributions slightly different beyond 90° but there is no substantial change in total cross sections. If necessary, we permit ourselves to adjust the imaginary potential strengths to fit the 2^+ inelastic cross section (p,p') and the V_1 parameter in the interaction to fit the 0^+ analog transition. Thus for the 2^+ analog transition we have a no-parameter calculation.

The Schrödinger equation was solved using the coupled-channel method,[8] including the 0^+ ground state and the 2^+ excited state of the target and their analogs as four coupled states. The calculations were done with the Oregon State University coupled-channel code, which has been checked by comparison with the code LOKI[14] for $0^+ \rightarrow 0^+$ analog transitions and by comparison with Buck's work[8] on 2^+ inelastic excitations. Figure 1 shows the analog and excited-analog differential cross sections for ^{56}Fe(p,n) at 18 MeV and ^{26}Mg(p,n) at 17 MeV. The coupled-channel calculations require a scaling factor of about 1.1 in ^{56}Fe and 1.6 in ^{26}Mg for the Lane potential V_1 compared to that for the BG parameters. For ^{56}Fe all imaginary optical potentials were scaled down by 17% to fit inelastic data[11]; no adjustment was needed[15] for ^{26}Mg. The latter result and the large scaling of V_1 probably reflect inadequacies in the nuclear model[9] and optical potential for ^{26}Mg. However,

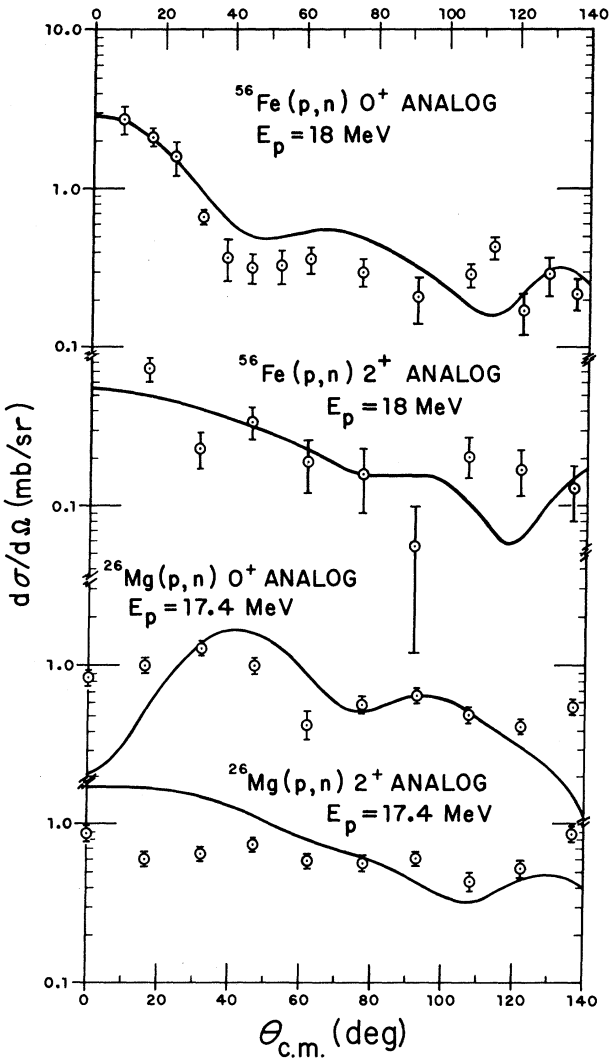

FIG. 1. The differential cross sections for ^{56}Fe(p,n) and ^{26}Mg(p,n). The curves are the result of coupled-channel calculations including the ground and first 2^+ states of the target and their analogs. Optical parameters are from Ref. 12.

these defects are not likely to affect our conclusions concerning the reaction mechanism. The magnitude of the excited-analog cross section is satisfactorily accounted for in both cases. The 2^+ analog group in ^{26}Mg actually consists of three states.[16] Our results indicate, therefore, that the (p,n) cross section to the $T = 0$ members of the triplet cannot be very large. Although the angular distribution is rather poor for ^{26}Mg, the calculation for the 0^+ state is sensitive to the real-imaginary mixture of the Lane potential; it peaks at 0° for a purely real interaction and can be made to fit fairly well with a choice of

TABLE I. Total cross sections from proton bombardment of ^{26}Mg and ^{56}Fe. The Lane potential V_1 is scaled so that it fits roughly the strength of the 0^+ analog transition in the coupled-channel calculation. Factors of 1.1 and 1.6 times the symmetry potential of Ref. 12 are used for ^{56}Fe and ^{26}Mg, respectively, except for the numbers in parentheses, which use the values from Ref. 12.

Target	Energy	Source	Cross section (mb) (p,p') 2^+	(p,n) 0^+	(p,n) 2^+
^{56}Fe	18 MeV	Experiment	43.[a]	5.13±0.8	2.7±0.9
		Full coupling	41.3	5.72	2.40
		Two step[b]	41.9	5.68	2.43
		Weak coupling[c]	49.5	8.56(6.82)	0.132(0.105)
^{26}Mg	17 MeV	Experiment	61.2±1.[d]	8.2±1.2	8.4±1.3
		Full coupling	59.3	8.32	8.34
		Two step[b]	62.1	7.59	9.46
		Weak coupling[c]	83.7	18.3(7.15)	1.08(0.043)

[a]See Ref. 11; the table entry is an average of 17- and 19.1-MeV cross sections.
[b]Coupled-channel calculation with $0^+ \rightarrow 2^+$ charge-exchange coupling set to zero.
[c]These cross sections are equivalent to a DWBA.
[d]See Ref. 15.

ImV_1 about half the BG value of 48 MeV. However, the 2^+ angular distribution is not strongly affected by this change.

Table I compares the experimental total cross sections with the results of various calculations for the two nuclei. When the code is run in weak coupling so it is equivalent to the DWBA, the 2^+ analog cross section is an order of magnitude too small, in agreement with Satchler, Drisko, and Bassel.[1] From a comparison of the pure two-step cross section with the full-coupling cross section, we see that the interference between one- and two-step amplitudes is slightly destructive but makes little difference in the cross section. Thus, the explanation for the previously unaccountably large excited-analog cross section is the two-step mechanism.

Microscopic coupled-channel calculations using simple nuclear models were also carried out, scaling inelastic and isospin strengths to fit the data. The results were very similar to the corresponding collective-model calculations.

It seems contradictory to the work on $(^3\mathrm{He},t)$ referred to in the introductory paragraph that the two-step mechanism should dominate the (p,n) excited-analog reaction. Table II shows our experimental analog cross sections for $^{26}\mathrm{Mg}(^3\mathrm{He},t)$ along with various coupled-channel calculations. The optical parameters were supplied by Becchetti,[17] and the parameter $\beta = 0.35$ was obtained by fitting the 2^+ inelastic data of Barengoltz.[18] In this reaction the two-step mechanism is much weaker than in (p,n) but still stronger than the one-step process (weak coupling). In the full coupling calculation the one- and two-step amplitudes almost exactly cancel for the 2^+ analog. Since the strength of the two-step amplitude is determined from the experimental inelastic and 0^+ analog cross sections, we have no freedom to adjust it. On the other hand, the deformation parameter β_1 of the Lane potential is not necessarily the same as the β determined from inelastic scattering. In order to obtain a 2^+ analog cross section in agreement with experiment we have had to use $\beta_1 = 2.9\beta$. Because of the contamination of the 2^+ state, this is an upper limit on β_1; however, on the basis of the (p,n) results one would not expect a large contribution from the other states. In DWBA we would have needed $\beta_1 = 2.3\beta$. A much smaller value of β_1 would also be consistent with the data if it were negative.[19]

TABLE II. $^{26}\mathrm{Mg}(^3\mathrm{He},t)$ cross sections. The deformation parameter β is the value from inelastic scattering, and β_1 is the deformation parameter for the Lane isospin term.

Source	Cross section (mb) $(^3\mathrm{He},t)$ 0^+	$(^3\mathrm{He},t)$ 2^+
Experiment, 18.3 MeV ^{3}He	0.255±0.050	0.399±0.080
$\beta_1 = \beta = 0.35$, full coupling	0.440	0.025
$\beta_1 = \beta = 0.35$, two step	0.599	0.113
$\beta_1 = \beta = 0.35$, weak coupling	0.479	0.0665
$\beta_1 = 2.92\beta$, full coupling	0.255	0.348

In summary, we have shown that in the (p,n) reaction the excited 2^+ analog states are excited primarily by the two-step mechanism proceeding through the inelastic 2^+ and 0^+ analog states. The direct transition is an order of magnitude too small and adds roughly incoherently with the two-step amplitude. The two-step mechanism is also very important in $(^3\mathrm{He},t)$ but it has a relatively much smaller effect than in the (p,n) reaction. This is probably due to the overall weakness of $(^3\mathrm{He},t)$ compared to (p,n) cross sections, resulting in a more rapid convergence of a perturbation-series expansion. To explain the strength of the 2^+ cross section in $(^3\mathrm{He},t)$, we have had to scale our deformation parameter to values several times β as have previous workers.[4] Because the relative phase of the one- and two-step (p,n) amplitudes is a little greater than 90°, the scaling of β_1 by a factor of 2 or 3 would also be compatible with the (p,n) experiment.

It is unfortunate that the (p,n) experiment is so insensitive to β_1 since this parameter contains important nuclear-structure information. It is roughly proportional to the isovector effective charge and also affects the ratio of (p,p') and (n,n') inelastic scattering cross sections. One might conclude from the fact that interference is present to a much greater extent in $(^3\mathrm{He},t)$ than in (p,n) that the former reaction is the way to determine the isovector effective charge. This may in fact be true; however, we feel that there are good reasons[20] to doubt that the $(^3\mathrm{He},t)$ mechanism is really well understood. Our results on the importance of the two-step mechanism in (p,n) reactions remove an apparent contradiction between the large strength of the $0^+ \rightarrow 2^+$ excited-analog transitions and effective-charge calculations,[21] which indicate that the isovector $E2$ effective charge is lowered by collective effects rather than enhanced.

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