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UNIVERSITY of CALIFORNIA BERKELEY

DISCLAIMER

ASSESMENT OF TWO-STEP PROCESSES IN (p,t) REACTIONS[*]

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ABSTRACT

Multiple step processes (core excitation) are evaluated for the (p,t) reaction at a typical energy (30 MeV) and for a typical moderately collective spherical nucleus (nickel). Our model nucleus has three kinds of states; the ground and collective 2^+, which have a strong direct transition, other typical non-collective states which also can be produced in a single step, and a two-phonon triplet, which can be produced only through multiple-step processes. We find that these later are produced as strongly as the other non-collective states and that the angular distributions and polarizations are characterized by the multipolarity of the overall transition and not by the multiplicity of the reaction mechanism. Comparison is made with the DWBA. We find that it underestimates the (p,t) cross sections to all three types of states, and that even relative cross sections are in error by up to a factor 2, and absolute cross sections by as much as a factor 5.

1. INTRODUCTION

Particle transfer reactions have been treated customarily as proceeding
directly from the target ground state to the final state by a simple deposit
or pickup of the transferred particle (simple or composite) which leaves the
other nucleons undisturbed.[1] Undoubtedly this is the dominant mechanism
by which most low-lying levels are produced. However some nuclear levels,
even at low excitation, will have a parentage that is based more on an
excited state of the target rather than on the ground state. If this excited
state is produced with appreciable cross section in inelastic collisions,
then alternate modes of producing the final state in the transfer reaction
are possible. These are the two-step modes that proceed through the inter-
mediate state produced by inelastic collisions with the incoming or outgoing
particle. In Fig. 1, two extreme cases of pure parentage are illustrated
for the (t,p) reaction. One state of (A+2) is assumed to have a structure
in which A nucleons (which we shall refer to as the core) are in a state
of motion corresponding to the ground state of nucleus (A). In the other,
the state of these A nucleons corresponds to an excited state of nucleus
(A). The former can be reached by a direct transition which deposits a pair
of neutrons onto the target ground state. The latter can be reached only
through the higher order processes that involve the inelastic production of
the parent state. Of course in real nuclei, the parentage of any state will
not be pure. Instead each state of (A+2) will have many parents. In principle
therefore the final state can be reached both directly through that component
of its wave function that has the ground state of (A) as parent, and indirectly
through the other components. Whether in fact the indirect modes compete with

$$\Phi_1(A) \phi(n_1\, n_2)$$

$$\Phi_1(A)$$

$$\Phi_0(A) \phi(n_1\, n_2)$$

$$\Phi_0(A)$$

$$t + (A) \longrightarrow p + (A+2)$$
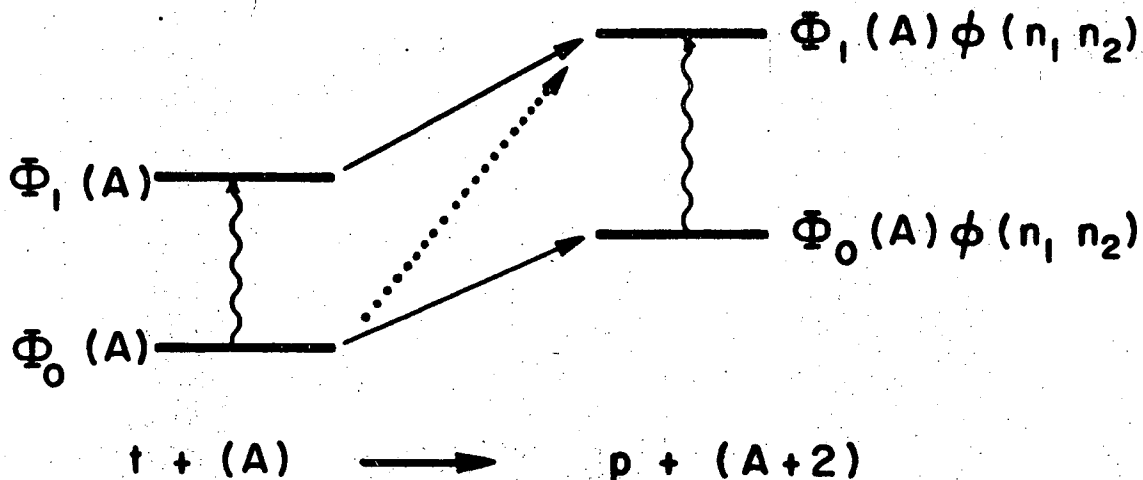
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Fig. 1. An idealized example of two states in the nucleus (A+2), the lower
one having a pure parentage based on the ground state of nucleus (A) and the
other on an excited state. The higher state in (A+2) is sometimes said to
be "core excited". It clearly can be reached only by multiple-step processes
that involve the inelastic excitation of the core by either the triton or
proton.

the direct will depend both on the fraction of parentage that is based on
excited states of the core, and on the strength with which these states
are produced in inelastic collisions.

The primary purpose of this investigation is to assess whether higher
order processes are likely to be significant in two-nucleon transfer reactions,
and if so, whether there are any special characteristics by which they can be
distinguished from direct transitions. While this question would seem
largely academic as long as attention was focused on the lowest-lying states,
it acquires ever more importance as improving experimental techniques allow
detailed investigations of higher-lying levels whose parentage is expected
to be more complicated. It is already evident that a number of interesting
new phenomena involving second order processes will be uncovered.[2]

It has been customary to compute the cross section for those states
that can be produced directly, by use of the distorted wave Born approximation.[1,3]
In this approximation, the wave function for the relative motion between the
nucleus and free particle in the entrance and exit channels are generated by
a one-channel optical potential. However when inelastic processes are very
strong, the usual optical potential may not provide a sufficiently accurate
representation for these wave functions within the nuclear interior, just
where they have their largest overlap with the nuclear wave functions appearing
in the DWBA integrals. Since the optical parameters are chosen so as to
reproduce the observed elastic cross section, this assures that the wave function
is correct in the external region. However if a particular inelastic transition
is very strong, the population of the excited state becomes large enough that
de-excitation back to the ground state becomes significant. This process

cannot be described by a one-channel optical potential, and it produces

changes in the wave function in the nuclear interior, just where it is

needed in the reaction calculation. In this circumstance the inelastic

processes play a role even for states that are produced directly in the

transfer reaction. Therefore as a secondary purpose of this investigation

we examine at what point the strength of inelastic transitions leads to

significant errors in the usual distorted wave Born approximation for direct

single-step transitions.

The method that we use to include the multiple-step processes (some-

times referred to as core excitation) that proceed through excited states of

either target or residual nucleus, has been described in previous publications.[4,5]

If the inelastic processes are neglected, the results correspond precisely to

the usual DWBA. In other words, we treat the particle transfer reaction in the

usual way,[6] and in first order only. The inelastic transitions are treated

to all orders among the states considered. We refer to it as the source

term method, and it is equivalent in its results to the procedure described

by Penny and Satchler,[7] though apparently it is more amenable to numerical

calculation.

2. NUCLEAR MODEL

To carry out the investigation described above, we adopt a model for

a nucleus having a collectivity typical of spherical nuclei, which we refer

to nominally as Ni. The ground state is taken to be a BCS vacuum. There

are excited states of two-quasiparticle configurations, the lowest of which

is the collective 2_1^+ state.[8] In addition we construct a triplet of two-

phonon states by using the operator that creates the collective 2^+ state.

This state, which we sometimes call the one-phonon state has the structure,

$$|2_1^+\rangle = B_2^+ |BCS\rangle \tag{1}$$

$$B_{2,M}^+ = \frac{1}{2} \sum_{a,b} \eta_{ab} [\alpha_a^+ \alpha_b^+]_{2,M} \tag{2}$$

where $a \equiv n\ell j$, and α_a^+ creates a quasiparticle in the state a. The η_{ab}

are the configuration mixing amplitudes, and the square bracket denotes vector

coupling. The two-phonon states are

$$|J\rangle = \frac{1}{\sqrt{2}} [B_2^+ B_2^+]_J |BCS\rangle \quad , \quad J = 0, 2, 4 \quad . \tag{3}$$

They have the special significance that they cannot be produced directly

by the two-nucleon transfer reaction. This follows because they are four

quasiparticle states and therefore cannot be connected to the ground state

vacuum by a two-particle process. Presumably in real nuclei ideal two-phonon

states do not exist. In terms of quasiparticles, they would also have two

qp components (and others). We shall comment on this again later after

presenting our results for the idealized model described here. The main

parent of the two-phonon states is, <u>in any case</u>, the collective 2^+, and the

two-nucleon transfer reaction connecting them to this state is enhanced in the

same sense as the transition from the ground to the one-phonon state is en-

hanced. (The parentage amplitudes in the two cases are equal within a statis-

tical factor.)

Our model therefore possesses three kinds of states, the ground and

2_1^+ which have a strong direct transition, the remaining two-<u>quasiparticle</u>

states $(0^+,2^+,4^+)$ which have weaker direct transitions; however the ground

state is their main parent, and finally the two-<u>phonon</u> states which have a

strong transition from the collective 2_1^+ but which are not fed directly at all.
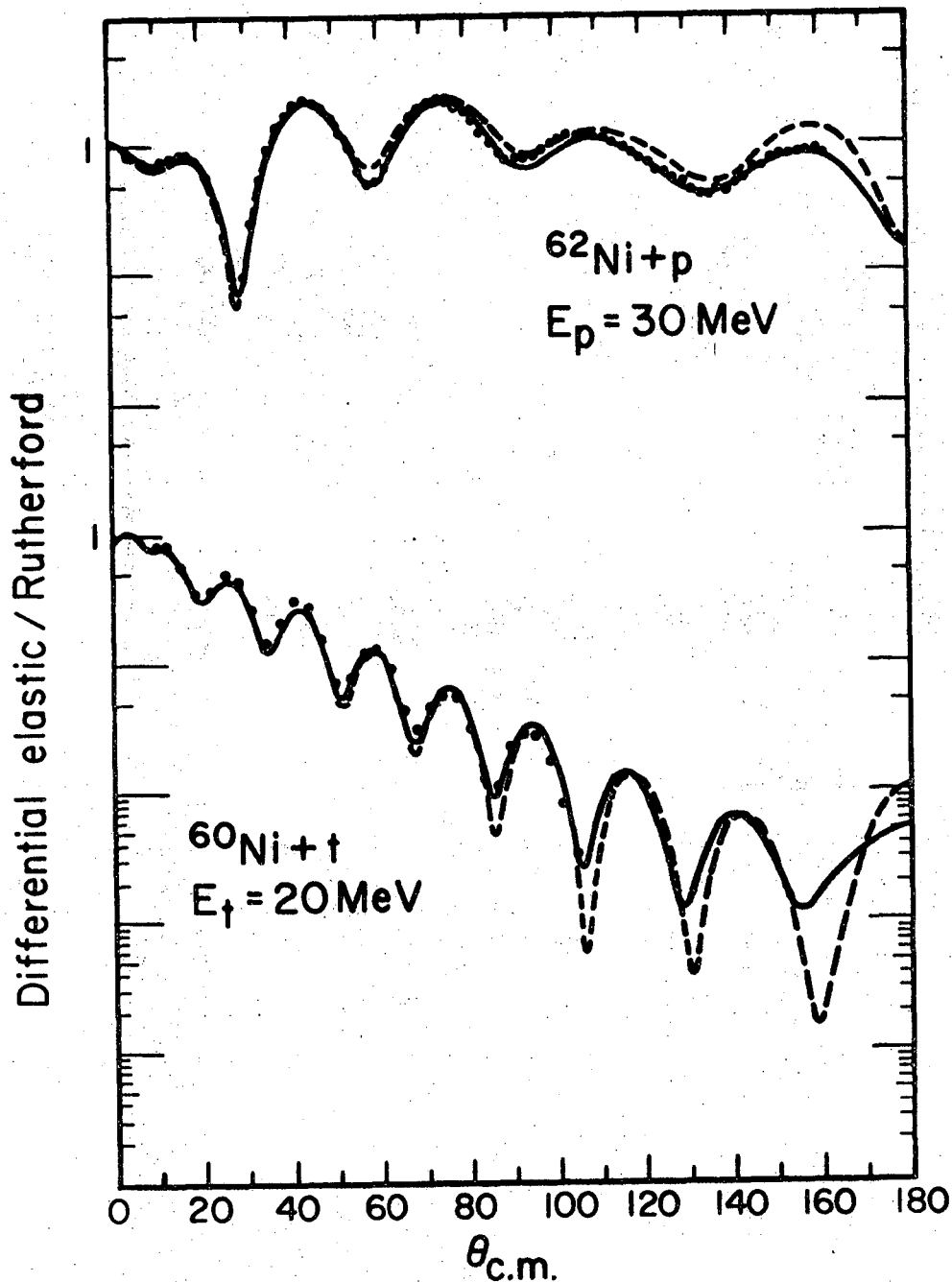
3. PARAMETERS

To assess the effect of inelastic processes on the two-nucleon transfer reaction, we consider the (p,t) reaction on a moderately collective nucleus, nickel, at a typical bombarding energy of E_p = 30 MeV. A complete body of data would consist of the elastic and inelastic cross sections of the 2^+ collective state (since it is the most important intermediate state for those included in our model) in both the initial and final nuclei, at the appropriate energies of the (p,t) reaction. This body of data does not exist, but fortunately there is data on neighboring nuclei which is sufficient to define the parameters realistically for our model calculations.

The reaction we consider is

$$^{62}\text{Ni(p,t)}^{60}\text{Ni}   ,   E_p = 30 \text{ MeV} . \tag{4}$$
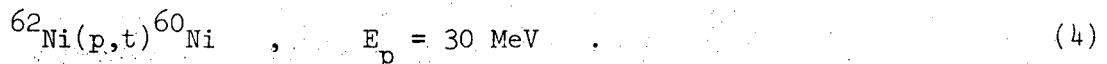
The Q of the reaction is - 10 MeV. There exist proton data[9] at 30 MeV on ^{60}Ni and triton data[10] at 20 MeV on ^{62}Ni. This data we use to define the optical model parameters for protons and tritons in Eq. (4), and it is shown in Fig. 2. The elastic cross sections were computed by solving the coupled equations for the set of states described in Section 2. The corresponding optical model parameters are labelled C.C. in Table 1. (The parametrization of the Oak Ridge Group is employed.[11]) We also used an optical model search routine to obtain parameters of the one-channel optical potential that reproduce the _same_ elastic cross section as obtained in the coupled-channel calculation. These are needed for comparison of our results for the (p,t) reaction with those predicted by the usual DWBA. The solid line in the figure represents _both_ these calculations. The dashed line corresponds to the usual one-channel

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Fig. 2. Elastic cross sections are shown. Solid line represents two calcula-
tions 1) a coupled channel one involving all the states described in Section
2 and using the optic parameters labelled "C.C." in Table 1, and 2) a usual
one-channel optic model calculation using adjusted parameters labelled "elastic"
in Table 1 which reproduce the same elastic cross section as the coupled channel
calculation. The dashed lines are also one-channel optical model calculations
but use the same parameters as the coupled channel calculation. The differences
show the effect of coupling to other states. Data is from refs. 9 and 10.

optical potential using the same parameters as in the coupled channel calculation. The difference shows the effect of the coupling of other channels of which the collective 2^+ is the most important. The figure illustrates the importance of back-angle scattering for determining the effect of the coupling on the optical model parameters.

In the calculations reported here, we did not include a spin-orbit term in the triton optical potential. The strength of this term is expected, on theoretical grounds, to be about one third that of the nucleon spin-orbit strength. We did include it in several calculations but its effect on the (p,t) reaction was very small.

The strength of the inelastic transition to the 2^+ collective state in both target and final nucleus is vital in our analysis because it is the parent of the two-phonon states. Again we have to rely on an extrapolation from other situations but this is quite adequate for our purposes. For tritons[12] the cross section to the 2^+ state has been measured in ^{64}Ni at 20 MeV. For protons,[13] we do not have data at the appropriate energy, but the reaction has been studied at 18 and 40 MeV and we use the strength of the direct interaction obtained there. We are able to handle a direct interaction of the form

$$V(r) = [V_0 + V_1 (\sigma_1 \cdot \sigma_2)] e^{-(r/r_0)^2} . \tag{5}$$

However since the V_1 part is so unimportant for the excitation of the collective state, we have set it equal to zero in these calculations. The remaining two parameters V_0 and r_0 for protons and tritons are shown in Table 2. The range parameter for tritons bears the kind of relationship to that for protons as described for other composite particles elsewhere.[14] It is larger because of the finite extension of the triton.

The strength of the interaction causing the (p,t) reaction is unimpor-

tant in our calculations because we treat the reaction in first order. Thus

all our calculated (p,t) cross sections scale as the square of this strength.

However we believe our arbitrary units are approximately millibarns.

Finally the single-particle bound state wave functions in terms of which

the nuclear wave functions are expressed are harmonic oscillator functions

having a constant $\nu = 0.25 \ F^{-2}$ $[\psi \sim \exp(-\frac{1}{2}\nu r^2)]$. We confirmed (see later)

that as concerns an evaluation of the role of inelastic processes, correction

of the asymptotic behavior of the oscillator functions is not necessary.

4. RESULTS

The complete calculation for the ^{62}Ni(p,t)^{60}Ni reaction at 30 MeV, is

shown in Fig. 3. All the inelastic couplings between the eight states in each

nucleus that are implied by their microscopic structure are included to all

orders.[15] All the particle transfer couplings leading from all target states

to all final states are included with the strengths prescribed by their struc-

ture.[5,6] The features that determine the strength of this coupling between a

pair of states are the fraction of parentage of the state in the heavier nucleus

that is based on the other, and on the degree to which the extra pair of neu-

trons are correlated in the way they are in the triton. As expected, the

ground and collective 2^+ states have the largest cross sections. Two very

surprising facts can be learned from the figure. First, the two-phonon states,

which, as discussed in Section 2, can be excited only through higher order

processes, nonetheless have cross sections just as strong as the other non-

collective states, running about one tenth that of the collective 2^+ state.

Second, the angular distributions are largely characterized by the multi-

polarity of the transition, independent of whether the state was produced directly,

or through an intermediate state. The polarizations of outgoing tritons from

this reaction are shown in Fig. 4 and, like the angular distributions, are

characterized by the multipolarity of the overall transition. Thus we find

that under the typical circumstances of this calculation there is nothing about

the angular distributions nor polarizations that can be used to distinguish

multiple processes from direct ones, and the probability of the higher order

transitions is as large as typical non-collective ones.
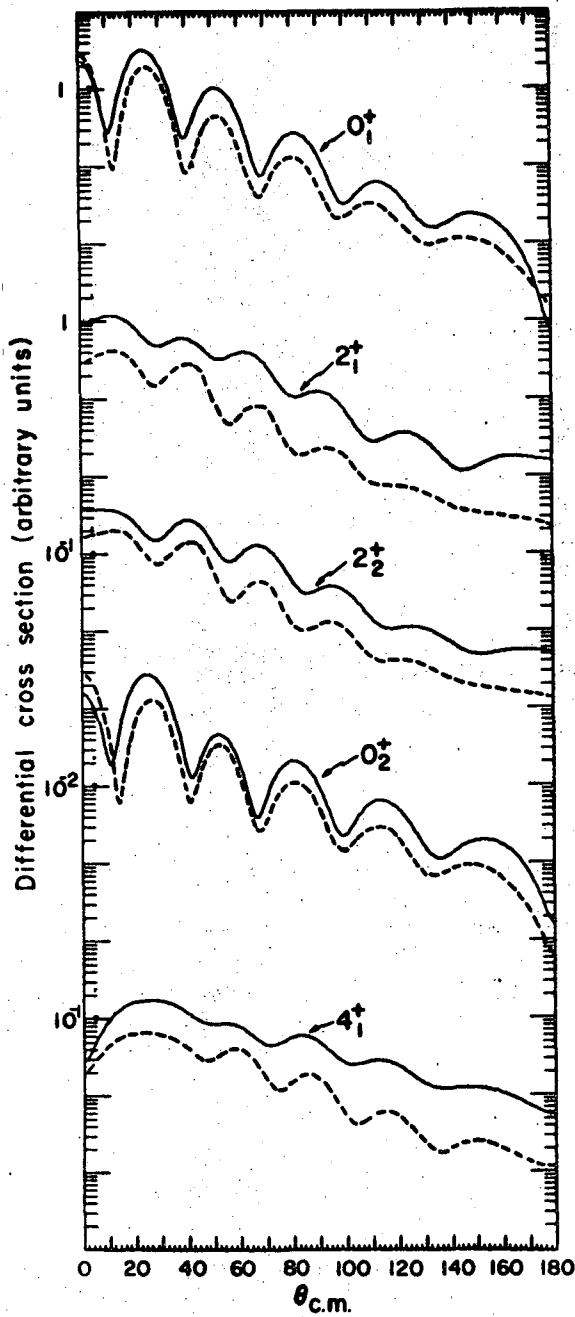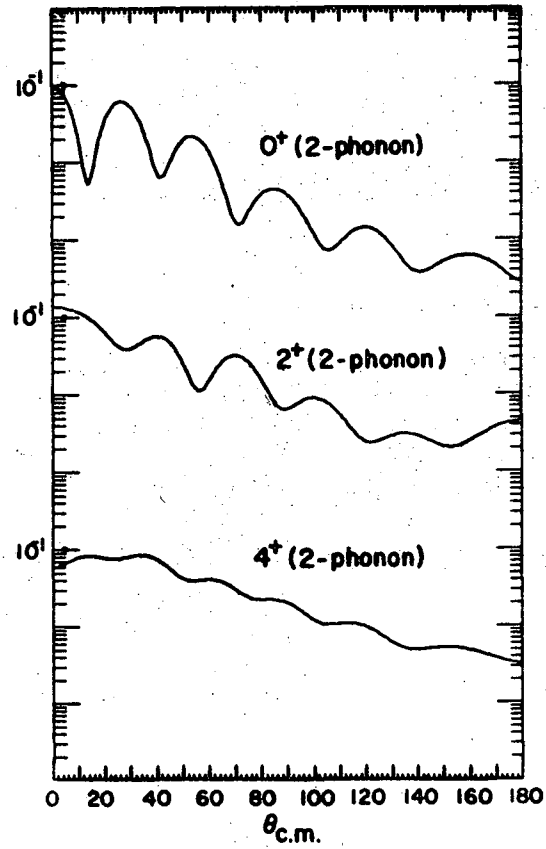
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Fig. 3. Calculated cross sections of ^{62}Ni(p,t) reaction to ground and two-quasiparticle states are shown on left, and "microscopic" two-phonon states on the right. Solid lines include multiple step processes. Optical parameters are labelled "C.C." in Table 1. Microscopic structure of the states is described in Section 2. Dashed lines show DWBA calculations, using optical parameters labelled "elastic" in Table 1 which reproduce the same triton and proton elastic cross sections as the coupled channel calculation.
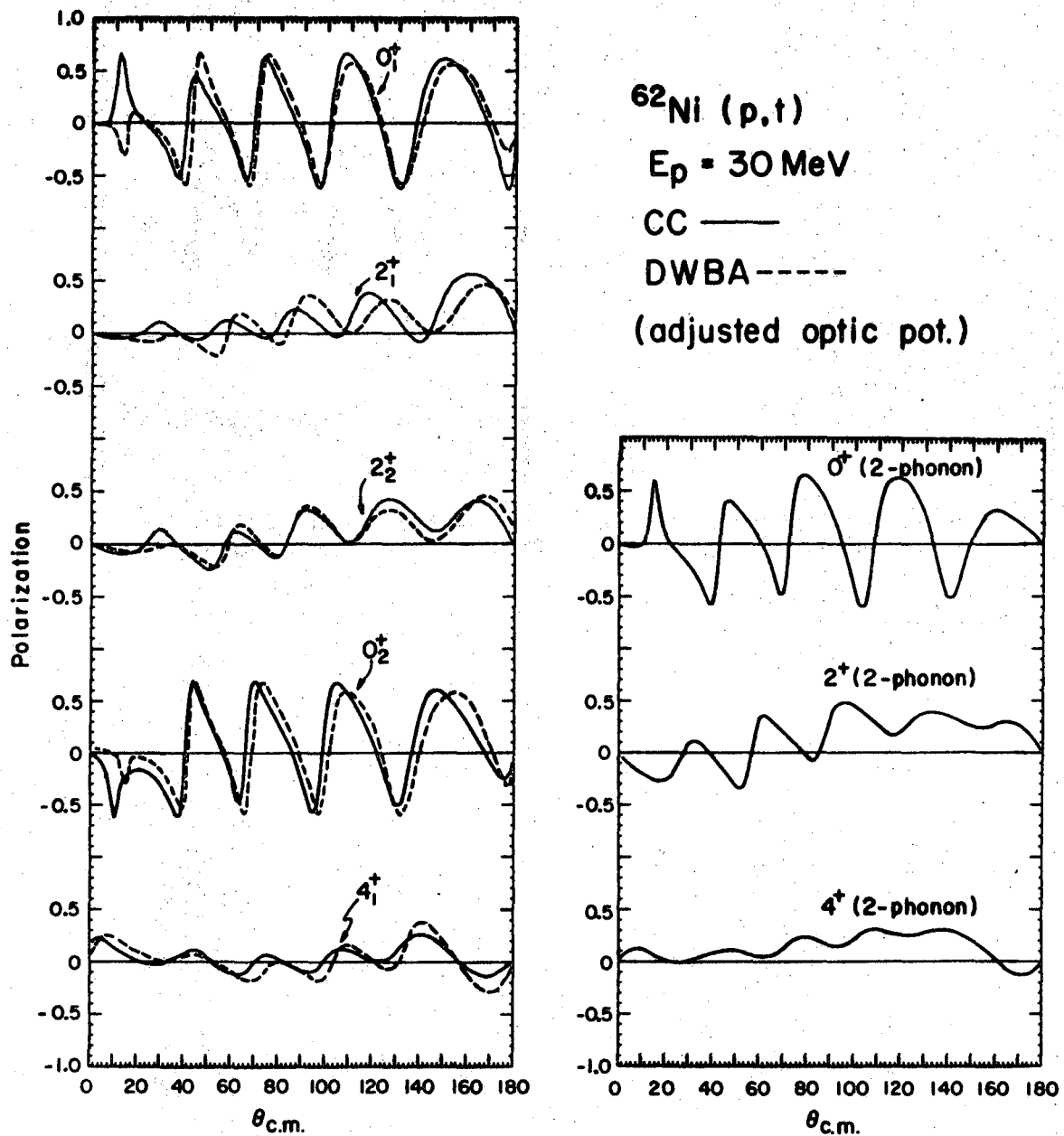
Fig. 4. Polarization of outgoing tritons of ^{62}Ni(p,t) reaction corresponding
to cross sections of Fig. 3.   •
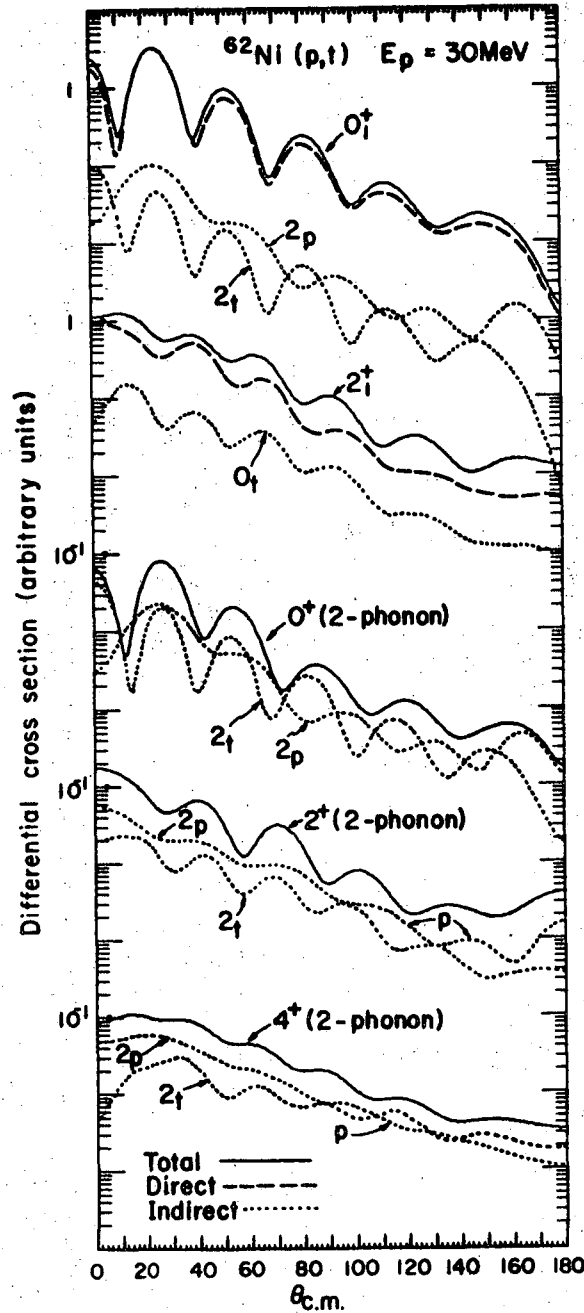
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Fig. 5. Dashed lines represent cross sections for ground and collective 2^+ corresponding to the direct (p,t) transition from ground to final state, if it alone were possible, while dotted lines represent two-step processes going through the collective 2^+ state in either proton or triton system or through the ground state of the triton system as marked by subscripts. The idealized two-phonon states do not have a direct transition as explained in Section 2. Solid lines represent cross sections in which all inelastic and transfer processes allowed by the structure of the states take place. Amplitudes of the individual processes add.

In Fig. 3 we also compare a DWBA calculation of those states that <u>can</u>
be produced in a single step with the full calculation. The DWBA cross
sections were computed according to the usual prescription. For this com-
parison that means that the optical parameters were chosen to reproduce the
<u>same</u> proton and triton elastic cross-sections as emerged from the coupled-channel
calculation as shown in Fig. 2. One sees in Fig. 3 discrepancies of up to a
<u>factor</u> 5 in absolute cross sections and up to nearly 2 in relative cross sections.
The DWBA in every case underestimates cross sections. Thus even for a nucleus
no more strongly collective than nickel, application of the usual DWBA leads
to large errors in relative cross sections. The higher order processes do in
fact play a very important role. This is shown in more detail in Fig. 5 where
the cross sections of individual paths leading to the final states are shown.
One sees that the direct route, if it alone were present, accounts for about
half the cross section of the collective 2^+ state. The other major contributions
are the transition through the collective 2^+ state on the target (not shown),
and through the ground state of the final nucleus. Although the <u>cross section</u>
of this latter process is only about 1/6 that of the direct, its <u>amplitude</u> is
about 40% of the direct. Of course the cross section for exciting a state
which can be reached in several distinct ways is obtained by squaring the sum
of the amplitudes for the individual ways. In our model, the two-phonon states
are not produced directly. The two main paths go through the collective 2^+
states of the target and final nucleus. The corresponding cross sections are
shown and it is seen that the one involving the inelastic transition in the
triton channel, as compared to the proton channel, differs in two ways: 1)
the frequency of oscillation is slightly faster which probably corresponds to
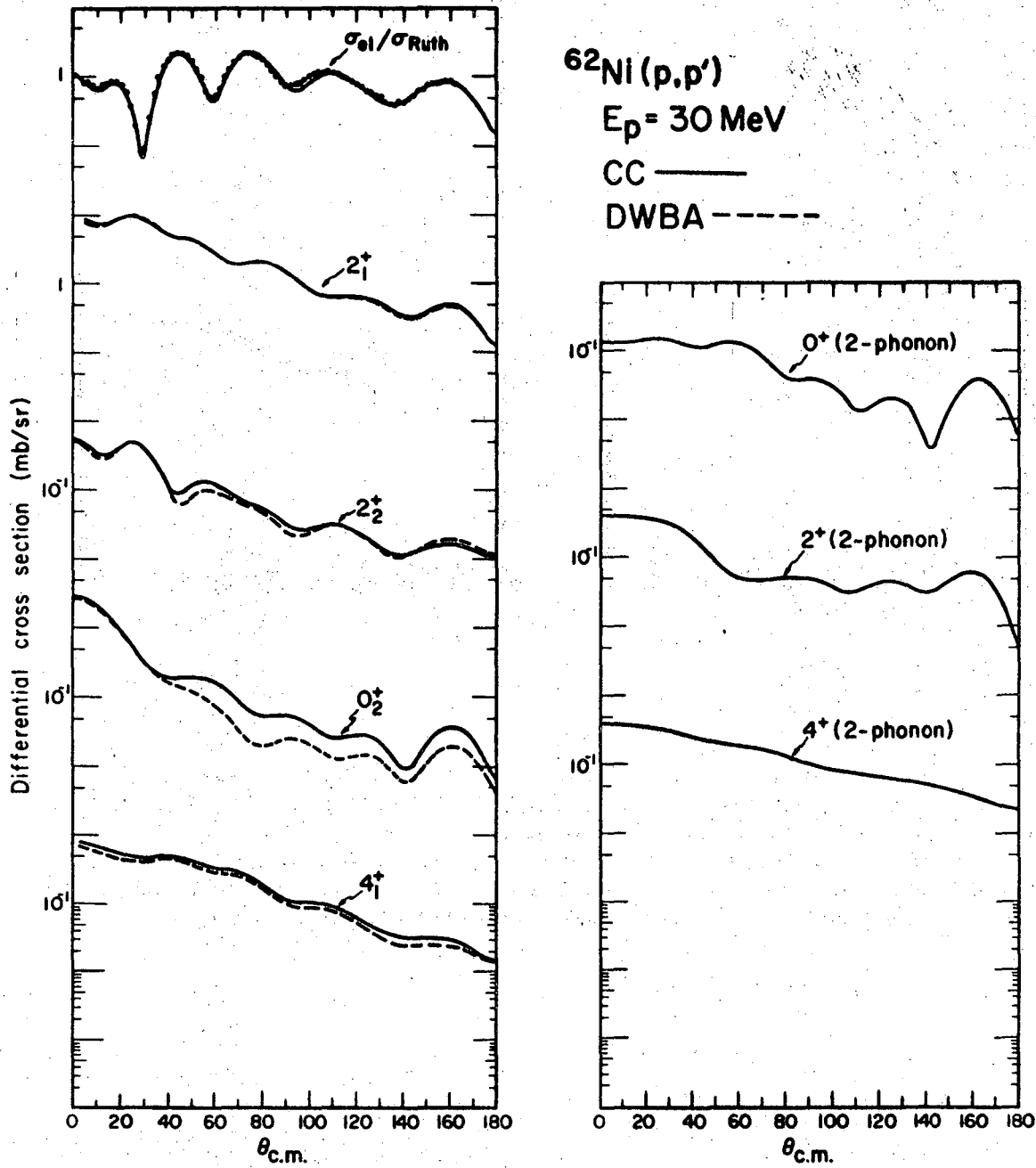
Fig. 6. Corresponding to the reaction of Fig. 3, the proton scattering from the ^{62}Ni calculated by the coupled channel method using the microscopic description of Section 2 is compared with the DWBA. The optic parameters of the former are labelled "C.C." in Table 1 while those of the latter, which have been adjusted to yield the same elastic cross sections are labelled "elastic". The experimental elastic data (Ref. 9) is for ^{60}Ni.

a more surface dominated reaction, and 2) that the oscillations are deeper.
The second point can be understood in terms of the much stronger forward
peaking in the triton inelastic scattering compared to the proton, as can
be seen by comparing Figs. 6 and 7. Thus the structure of the reaction itself
(see the direct processes) is preserved.

Concerning the non-collective two-quasiparticle states $(0_2, 2_2, 4_1)$
shown in Fig. 3, their main parent is the ground state, and they are produced
almost exclusively through the direct transition from the ground. Even so we
see that the DWBA underestimates their cross sections. The cause for this,
as discussed in the introduction, is the modification of the wave function in
the elastic channel due to coupling to the 2^+ collective state. This is an
important effect even in such moderately collective nuclei as these.

In contrast to the above DWBA calculations, we did another in which
the same optic parameters were used as for the coupled channel calculation.
In this case the elastic cross section (see Fig. 2) is not well reproduced
especially at large angles. However the DWBA now agrees better with the com-
plete calculation at forward angles, for those states that can be produced in
a single step, as seen in Fig. 8. One can understand why these DWBA cross-
sections are larger than those of Fig. 3 since the optic parameters here do
not contain absorption corresponding to the low-lying levels. In particular
the imaginary part is smaller. However it is hard to see how this would be a
reliable prescription in general.

If it is true that in a nucleus as mildly collective as nickel, the
DWBA underestimates cross sections by as much as a factor of five, and fails
in relative cross sections by a factor of two or so, one may ask how weak must
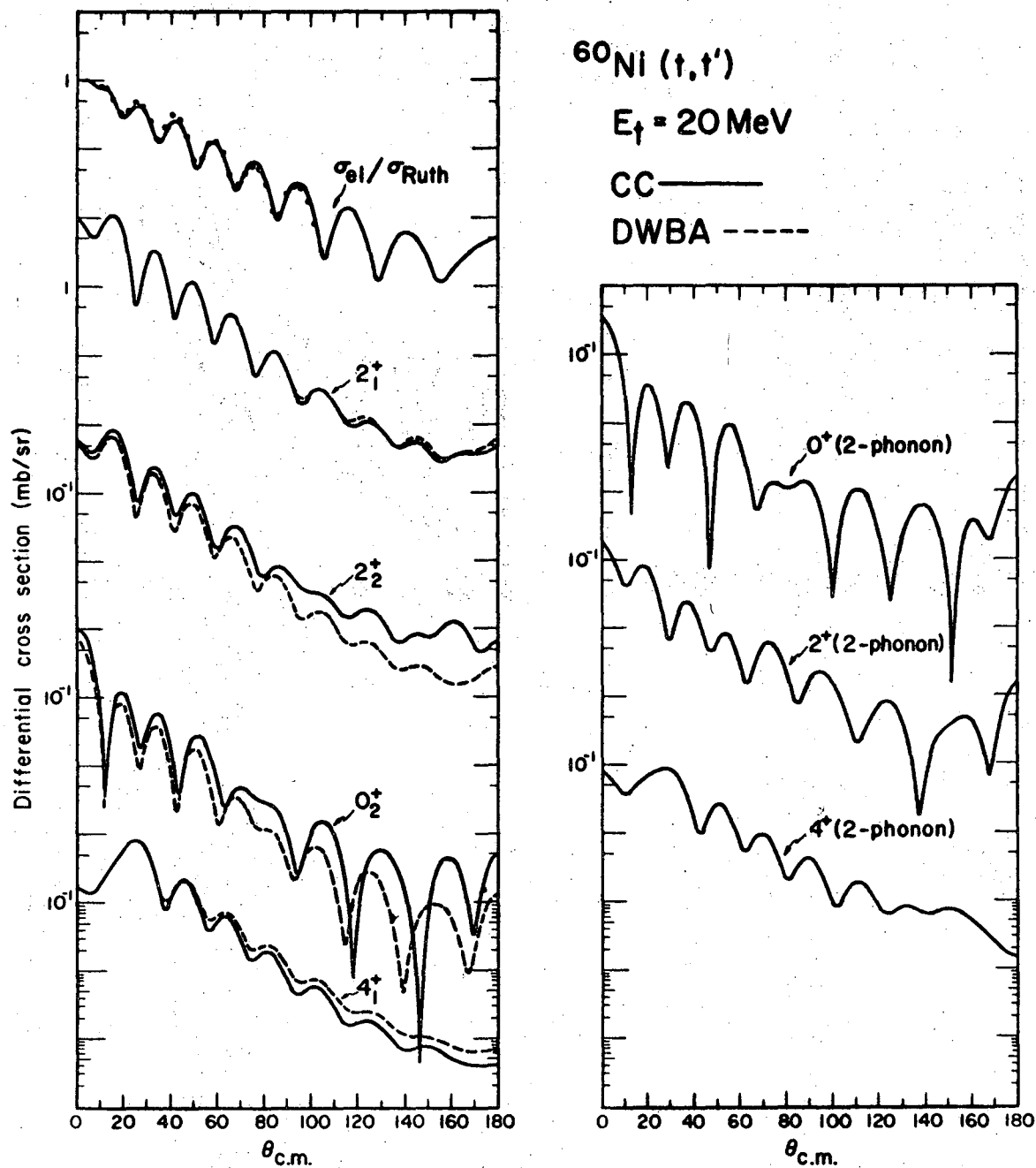
Fig. 7. Triton scattering from ^{60}Ni at the energy of the outgoing tritons in the reaction shown in Fig. 3. Description is same as Fig. 6. Triton data is for ^{62}Ni (Ref. 10).
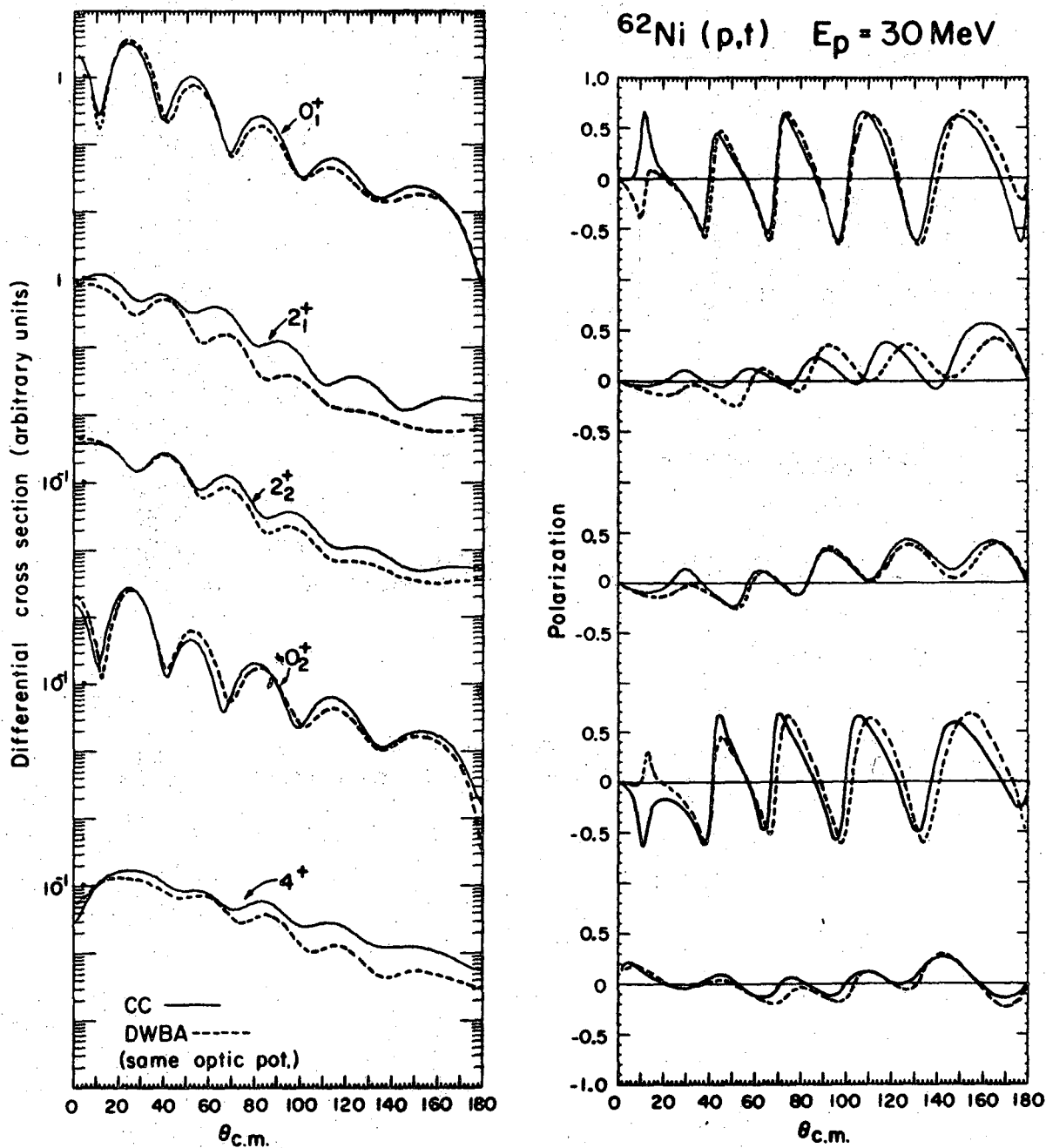
Fig. 8.   Coupled channel and DWBA calculation using same optic parameters in both calculations.   Elastic cross sections therefore do not agree (see Fig. 2).   Two-phonon states not shown because they cannot be reached directly (therefore zero DWBA cross section).

be the collectivity of the intermediate state in the two-step process before

the errors are suitably reduced. In Fig. 9 we show a calculation analogous

to that of Fig. 3 except that the strength of the direct reaction causing

inelastic transitions has been reduced by $\sqrt{2}$. This cuts the inelastic cross

section to the collective state by about 2, so that two-step processes are

correspondingly weaker. The DWBA calculation was again carried out by adjusting

the optic parameters so that the elastic cross sections of the coupled channel

calculations for both protons and tritons were reproduced. The DWBA still

underestimates the (p,t) cross sections but does considerably better than for

the case of stronger collectively in Fig. 3. The relative cross sections are

however in very good agreement with the full calculation, so that we may con-

clude that if the collectivity of an intermediate state in a two-step (p,t)

reaction is about half as strong as it is in nickel, then the DWBA works very

well for those states that have the target ground state as their main parent.

The cross sections to the two-phonon states, which can be produced only by

multiple processes are reduced by almost a factor of 2. In other words they

scale, as expected, with the collectivity of the parent intermediate state.

Although the DWBA understimates the (p,t) reaction calculation, it

does better, especially at forward angles, for inelastic scattering as seen in

Fig. 6 and 7. There the inelastic cross sections corresponding to the reaction

calculation of Fig. 3 are shown. The optic parameters of the DWBA were adjusted

to yield the same elastic cross section as the coupled channel calculation.

It was noted in connection with the (p,t) reaction that the multipolarity of

the transition determined to a larger degree the angular distribution. This is

still true for tritons but less so for the protons which are more sensitive to
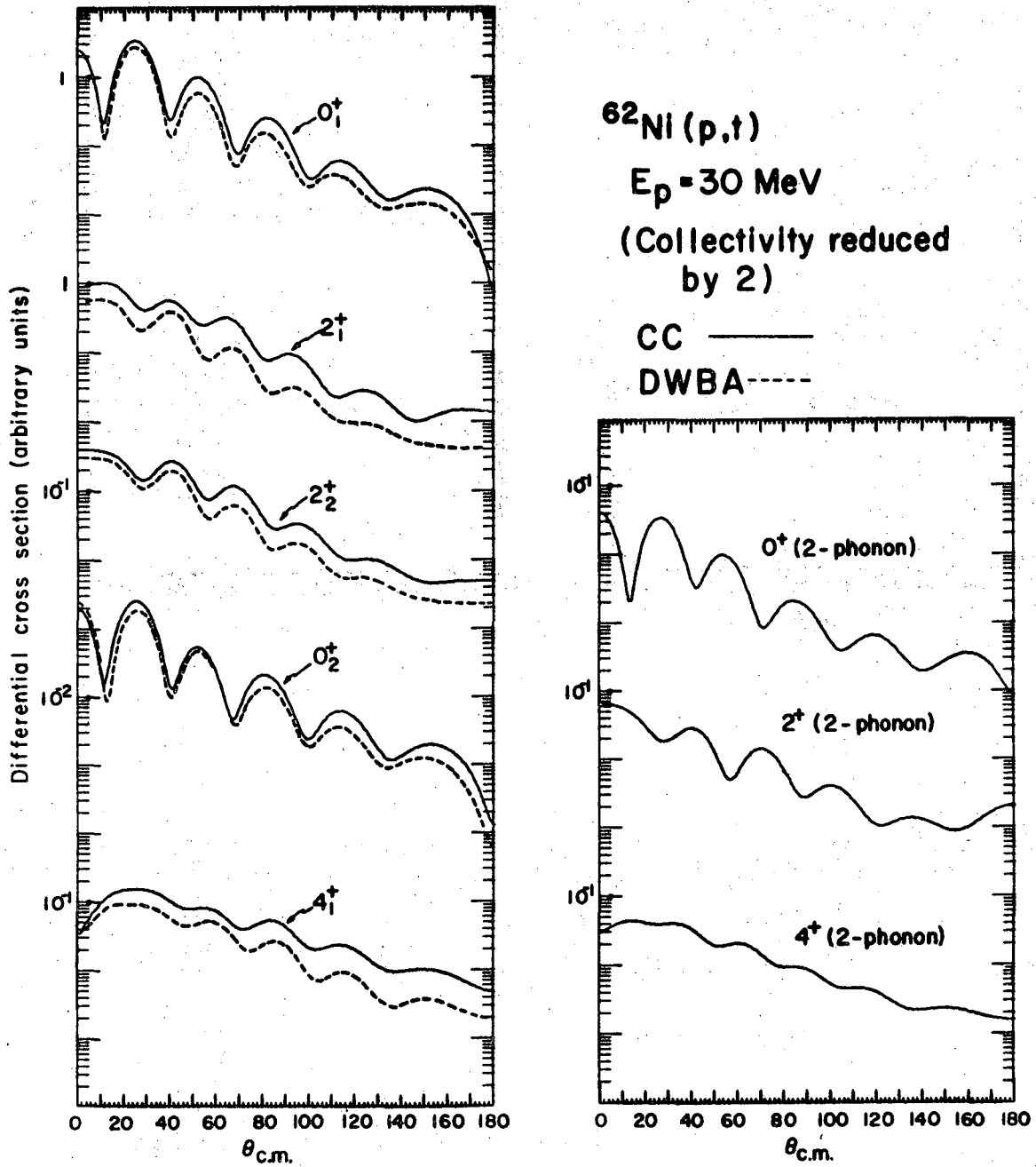
Fig. 9. Same calculation as Fig. 3 except that the strength of the interaction causing inelastic transitions is reduced by $\sqrt{2}$. For our purposes this corresponds to a collectivity of the 2_1^+ state of about 1/2 that of Fig. 3.

the interior conditions. This can be understood easily in terms of a discussion given elsewhere.[16]

All our reaction calculations discussed so far used the same (harmonic oscillator) single-particle wave functions as were employed in the original structure calculation. It has been recognized for a long time that as concerns reactions, it is important to correct the tail of these functions since they decay too rapidly at large radius.[6,17] To confirm that our conclusions concerning the strength with which the two-phonon states are produced is not materially effected by the treatment of the tails, Fig. 10 compares two calculations in one of which the harmonic oscillator function describing the center-of-mass of the transferred neutron pair is truncated and matched to a Hankel function of the appropriate separation energy.
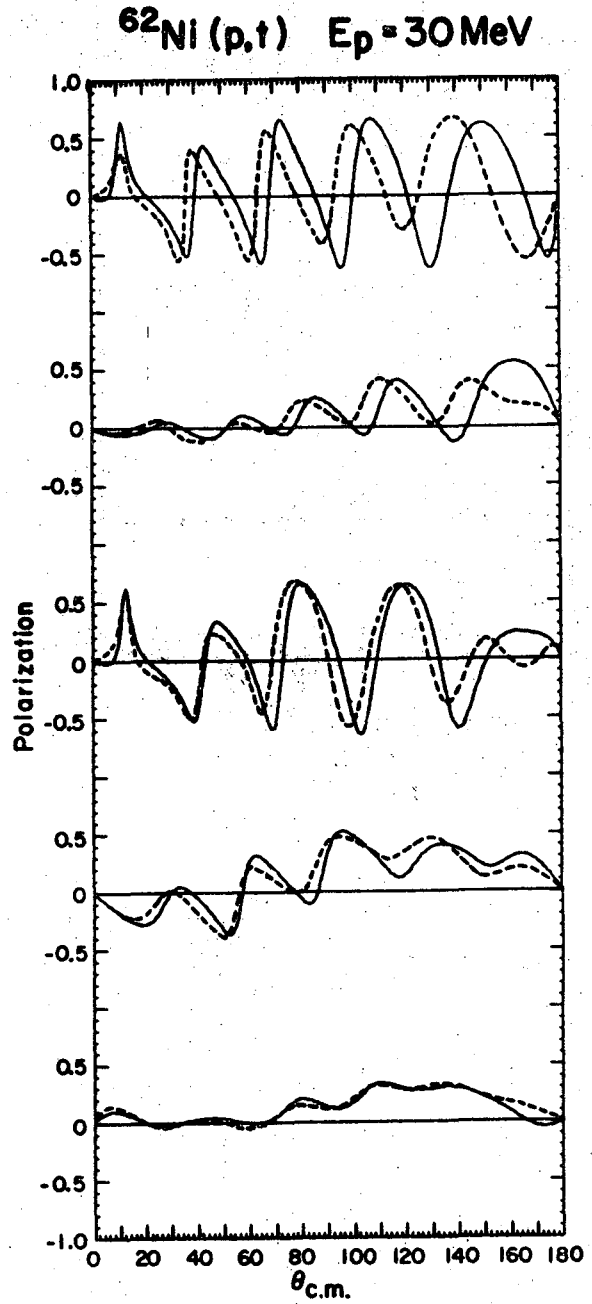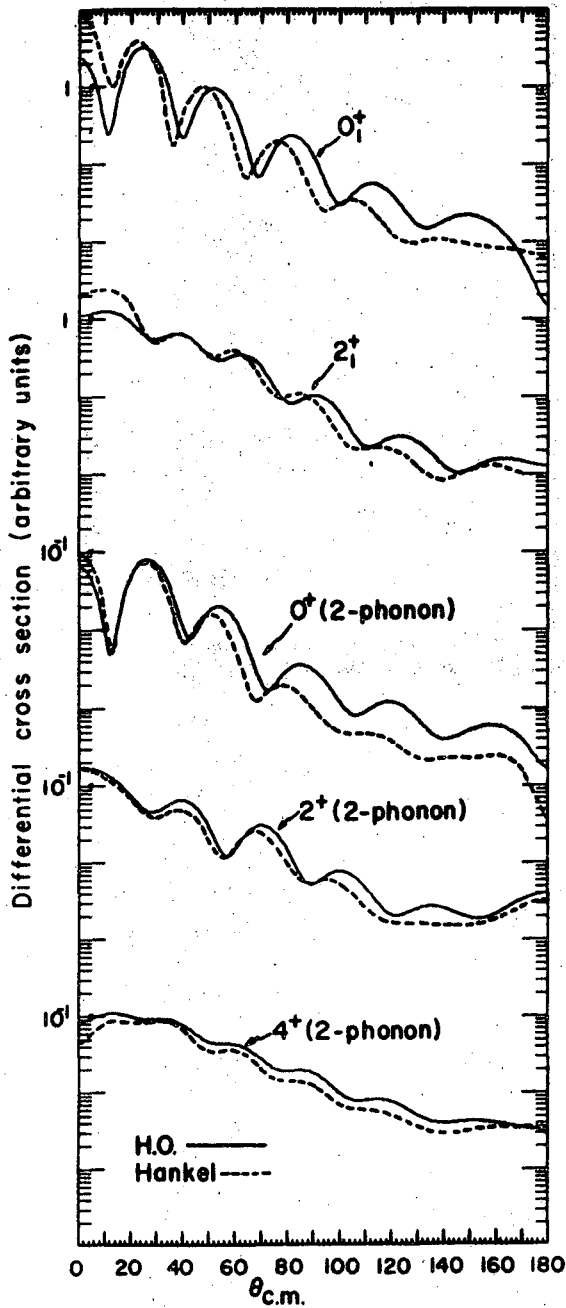
Fig. 10. Cross-sections for the ^{62}Ni(p,t) reaction computed using oscillator bound state wave functions compared to matching these to Hankel function tail.

5.   SUMMARY AND CONCLUSIONS

We have studied two-step processes in (p,t) reactions in a model which contains some states (a triplet) which have as their parent a state which has an enhanced inelastic transition from the ground, namely the collective 2^+ state. We found that although these states can be produced only indirectly by two-step transitions through the parent state, their cross sections are comparable in magnitude to other non-collective states which can be produced directly. This finding holds for a nucleus, namely nickel, in which the collectivity of the intermediate state is only moderate. The two-step processes scale as the strength of the inelastic transition from the ground to the intermediate parent state. Therefore, since most nuclei are more collective than nickel, our result probably indicates a widespread phenomenon. Moreover both angular distributions and polarizations are characterized mainly by the multipolarity of the overall transition and not by the multiplicity of the reaction process. The two-step processes therefore do not have a special fingerprint, at least not under the typical conditions of our calculation.

Presumably in real nuclei, ideal two-phonon states such as we studied, do not exist. Some of their character persists since the radiative selection rules hold approximately, but they most likely possess admixtures in their wave function other than the two-phonon component of Eq. (3). Conversely other near-lying states share the two-phonon character. Suppose that a non-collective state has a 10% admixture of two-phonon character. Previously one would have ignored this component and calculated the cross section to this state on the basis of those components that can be produced directly. Let us denote by F the amplitude that can be produced directly. Then in this approximation

the cross section is F^2. However since we now know that the two-phonon state is excited as strongly as a typical non-collective state and that its angular distribution is nearly the same, then corresponding to the 10% admixture we should add to the above amplitude, $F/\sqrt{10}$. The phase could vary anywhere from - 1 to + 1 with the result that the cross-section for the admixed state could be anywhere from 0.4 to 1.6 times the result based on the neglect of the 10% two-phonon admixture.

Concerning those states which are produced dominantly by the direct transition from the ground, the DWBA does underestimate their cross sections also, and seriously. This is due to changes in the wave function in the elastic channel induced by inelastic coupling to the collective 2^+ state. We see no reason to believe that this effect is exclusive to the (p,t) reaction and suggest therefore that the DWBA also underestimates (d,p) cross sections more or less, depending on the degree of collectivity. Thus it appears that single-particle spectroscopic factors may be overestimated in the usual DWBA analysis.

Although our findings give cause for pessimism we do point out that the so-called source term method that we have used to include higher order processes in particle transfer reactions does provide a feasible means of incorporating these previously neglected processes. Moreover if one suspects that special parentage relations exist among certain states, one can now explicitly compute the results of such relations. Two interesting examples have already been studied at this laboratory.[2]

Table 1. Optical model parameters. The "elastic" ones yield the same elastic cross-section as obtained in the coupled channel calculation which uses the "C.C." parameters.

triton

	V	W	W_D	r_v	r_w	r_c	a_v	a_w
C.C.	-158.35	-22.9	1.094	1.22	1.506	1.25	0.695	0.8
elastic	-149.04	-27.	4.313	1.274	1.576	1.25	0.6559	0.8828

proton

	V	W	W_D	r_v	r_w	r_c	a_v	a_w
C.C.	-54.	-2.	-5.2	1.09	1.3	1.2	0.772	0.64
elastic	-54.087	-3.239	-5.367	1.099	1.295	1.2	0.772	0.601

V_{SO}	r_{SO}	a_{SO}
-5.74	1.022	0.688

Table 2. Parameters of the direct interaction
causing inelastic transitions (see Eq. (5)).

	V_0	r_0
Proton	-55	1.85
Triton	-70	2.3

FOOTNOTES AND REFERENCES

*This work performed under the auspices of the U. S. Atomic Energy Commission.

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New Haven, Connecticut 06520.

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16. See the Introduction of Ref. 13.

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