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Reaction Mechanism in Direct Interaction Inelastic Scattering*

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It is pointed out that experimental results indicate very striking similarities between (p,p') and (d,d') reactions, and very striking differences between (p,p') and (p,n) reactions. It is shown that this is in strong disagreement with the nucleon-nucleon collision model commonly used in interpreting (p,p') reactions, but in agreement with the recent inelastic diffraction scattering model of Blair.

IT has recently been found[1,2] that there are very striking similarities between medium energy (p,p') and (d,d') reactions on heavy elements in the direct-interaction region[3]; it is the purpose of this paper to point out that, in contrast to this situation, (p,p') reactions give results very different from (p,n) reactions in this region, and to show that these experimental results indicate that the nucleon-nucleon collision model so widely used in theoretical studies of (p,p') reactions[4–9] is not the correct one. The similarities between (p,p') and (d,d') reactions include the following: both reactions strongly excite the well-known low-lying collective levels with the same relative strength[2]; both reactions strongly excite the "anomalous" peak[10] at ~2.5-Mev excitation with the same relative strength; the energy spectra of both have minima at about 3.5 Mev, followed by a rise up to about 5 Mev; and both reactions have roughly the same total cross sections for an energy loss less than 6 Mev.[1]

The comparison of energy spectrum shapes between (p,p') and (p,n) reactions cannot be made directly because of lack of data on the latter; however, there is data on the inverse to that reaction, namely (n,p) reactions induced by 14-Mev neutrons. In the energy spectra of protons from these reactions,[11,12] the low-lying collective levels and the "anomalous" peak are not strongly excited, and there is no other resemblance between these spectra and those from (p,p') reactions.

One very pertinent direct comparison between (p,p') and (p,n) reactions comes from measurements of activation cross sections for (p,n) reactions.[13–19] These are essentially determinations of the cross sections for (p,n) reactions in which the energy of the emitted neutron is within about 8 Mev of the incident proton energy ($\Delta E<8$ Mev), for if the neutron were emitted with lower energy, a $(p,2n)$ or (p,np) reaction would result and there would be no contribution to the (p,n) activation cross section. A compilation of known (p,n) activation cross sections is given in Table I. While the data are somewhat limited in quantity, there is no reason to suspect that they are not typical of all (p,n) cross sections.

In order to compare these with cross sections for (p,p') reactions in which the emitted proton energy is within 8 Mev of the incident proton energy ($\Delta E<8$ Mev), it is necessary to integrate over the last 8 Mev of the measured energy spectra of inelastically scattered protons[20–22] and integrate over angles. Pertinent data are shown in Tables II and III for incident proton energies of 23 Mev and 31 Mev. In Table II, unpublished angular distribution measurements were used to estimate the total cross sections.

In comparing Table I with Tables II and III, it is clear that (p,p') cross sections are about an order of magnitude larger than (p,n) cross sections; the latter are decreasing with increasing bombarding energy,

TABLE I. (p,n) cross sections by activation.

Target nuclide	(p,n) cross section (mb) 23 Mev	31 Mev	Ref.
Al^{27}		2	19
S^{34}	20	10	13
Cu^{63}	40	20	14, 15
Bi^{209}	~17	~21	16
Th^{232}	8		17
U^{238}	4		18

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while the former are about constant[23]; the latter are decreasing with increasing nuclear mass while the former are constant or even increasing; and the latter vary widely from nucleus to nucleus, while the former are in all cases the same for neighboring nuclei and vary by only ±20% for all heavy elements. These represent vast differences.

In the model most commonly used to explain (p,p') reactions[4–9,21,24] one considers the incident proton to have nucleon-nucleon collisions with the neutrons and protons in the nucleus, with either the incident or struck nucleon being emitted. In this model, the emitted particle has roughly equal probability of being a neutron or a proton. (Actually, proton emission would be about twice as probable neglecting reflection effects; these make proton emission relatively less probable[6]); the energy spectra of the two should be very similar, and their variations with mass and with energy should be the same. All of these expectations are in very serious disagreement with the experimental results. It might be thought that the difference in cross sections may be caused by lack of overlap between initial and final state wave functions in (p,n) reactions. However, it should be noted that the energy distributions are relatively flat over the 8-Mev interval, so that a very large number of states contribute to these cross sections. It seems very unlikely that there could be a regular order of magnitude difference in average overlap integrals when such a large number of states is included in the average.

TABLE II. (p,p') cross sections ($\Delta E<8$ Mev) at 23 Mev. Data are from Cohen and Mosko.[a]

Target elements	(p,p') (mb)
Fe-Co-Ni-Cu-Zn	110
Pd-Ag	100
Au-Pt	90
Pb-Bi	120
Th	80

[a] See reference 20.

In addition to the above discrepancies, the comparison between (p,p') and (d,d') reactions represents a serious discrepancy with the nucleon-nucleon collision theory. The latter is clearly inapplicable to (d,d') reactions since it would be very improbable for deuterons to have high-energy collisions with nucleons without breaking up. (There is also direct evidence for this from optical model studies.[25]) Thus, the striking similarities between (p,p') and (d,d') reactions would have to be considered a pure coincidence in this model. Even if it were so, some other process would be necessary to explain (d,d') reactions, and it would be very difficult to understand why this other process should not be important in (p,p') reactions.

TABLE III. (p,p') cross sections ($\Delta E<8$ Mev) at 31 Mev. Data are from Eisberg and Igo[a] and Levinthal *et al.*[b]

Target element	(p,p') (mb)
Al	80
Sn	100
Ta	100
Au	120
Pb	120

[a] See reference 21.
[b] See reference 22.

It thus seems safe to conclude that the nucleon-nucleon collision process can play only a small role in (p,p') reactions. The predominant process must be one which depends on the fact that the incident and outgoing particles are identical, and which can explain the facts that deuterons are not broken up in the process, and that collective levels are strongly excited.[2]

The recent diffraction inelastic scattering model of Blair[26,27] fits these criteria, as would any other theory in which the interaction is between the incident particle and the nucleus as a whole, leading to excitation of collective motions. It should be noted that only about 30% of the (p,p') and (d,d') cross sections lead to known or suspected collective states. There would thus seem to be many as yet unknown collective states up to excitation energies of 5 Mev or higher.

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[23] This is explained by the fact that in the sulfur and copper regions, compound nucleus contributions to (p,n) reactions are still important at 23 Mev as evidenced by the excitation functions (see references 13, 14, and 15); whereas in (p,p') reactions, the cross sections are so large that compound nucleus contributions are negligible. An alternative to considering this as a difference between the two reactions would be to reduce the 23 Mev (p,n) cross sections to the values at 32 Mev in Table I; this would then accentuate the first difference cited.

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