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High-resolution comparison of (p,p') and (d,d') reactions*

B. L. Cohen, J. E. Holden, and G. R. Rao
University of Pittsburgh, Pittsburgh, Pennsylvania 15260
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A comparison is made between the strengths with which each nuclear state up to 5.3 MeV excitation in ^{124}Sn, 7.3 MeV in ^{64}Ni, and 7.6 MeV in ^{58}Ni is excited in (p,p') and (d,d') reactions. A very strong correlation is found, indicating that direct-reaction processes are dominant in both reactions. The fraction of these direct reactions resulting in excitation of the lowest energy 2^+ and 3^- collective states is determined and in each case is less than 20%.

[NUCLEAR REACTIONS ^{58}Ni, ^{64}Ni, ^{124}Sn(d,d'), (p,p'); $E=17, 12$ MeV; compared cross sections for exciting same levels in the two reactions.]

INTRODUCTION

There are essentially two different theories for noncompound nucleus inelastic proton scattering, preequilibrium emission,[1] and direct reaction.[2] The first pictures a succession of nucleon-nucleon collisions in the course of which a proton gets into an unbound orbit and is emitted before the collision process reaches thermodynamic equilibrium as characterized by the compound-nucleus concept. This process has been discussed since the 1940's, and in the later 1950's it was treated by Monte Carlo calculations, but its most quantitative successes came with the theoretical work of Griffin[1] treating it as a succession of transitions

$$1\text{p} \rightleftharpoons 2\text{p-1h} \rightleftharpoons 3\text{p-2h} \rightleftharpoons \cdots \rightleftharpoons \text{equilibrium},$$

where the figures preceding p and h are the numbers of particles and holes. When the incident proton enters the nucleus we have a 1p configuration, after its first collision with another nucleon (exciting it to a higher-energy orbit) we have a 2p-1h configuration, etc.; all transition probabilities are taken to be proportional to the number of configurations available, and an expression for these numbers is parametrized in the theory. Griffin found that most preequilibrium emissions occur after 1, 2, or 3 such transitions, so, for example, his theory predicts strong excitation of 1p-1h states in the residual nucleus, the result of a proton emission from the 2p-1h stage of the process. In an odd-A nucleus one would then expect strong excitation of states in which the odd nucleon is raised to a higher-energy orbit.

Experimentally such 1p-1h states are weakly excited in (p,p') reactions, and by far the most strongly excited levels (in spherical nuclei) are the 2^+ and 3^- collective vibrational states.[3,2] This process, which is called "direct reaction," may be thought of as a perturbation on the very predominant process of elastic scattering.[2] As particles are bounced off the nucleus there is some probability that it will "ring" as in the classical analogy of bouncing things off a bell. Ringing in quantum mechanics means that the various vibrational normal modes of the system may be excited with 0, 1, 2, or more phonons of energy, and the strong excitation of the 2^+ and 3^- collective states is expected from the fact that these are the one phonon excitations of the two lowest-energy normal modes, $l=2$ and $l=3$. The two-phonon $l=2$ vibrational states are also well known and are rather strongly excited in direct reactions,[2] but few other vibrational states have been established and there has been a tendency among some nuclear physicists and chemists to assume that they do not exist.

Excitation of the above named collective states accounts for less than 20% of the noncompound nucleus (p,p') cross section at 17-MeV bombarding energy,[4] whence the question has arisen as to which of the two processes, preequilibrium or direct reaction, is responsible for the remainder. In principle the two theories are not mutually exclusive and in any microscopic treatment both processes are made up principally of one, two, or three nucleon-nucleon collisions; but operationally a preequilibrium process is conventionally taken to be one well described by Griffin theory which ignores coherence effects, requires strict energy conservation in each "collision," and assumes all available configurations to have equal probability of being reached in a collision; direct reactions are operationally considered to be ones in which coherence properties are of dominant importance.

One area in which the two theories give very different predictions is in comparisons of different

inelastic scattering reactions, as with (p,p') and (d,d'). The direct-reaction mechanism predicts a very similar behavior for these as well as for (α,α'), $(^{12}C,^{12}C')$, etc., —the manner in which a bell rings is rather independent of what is bounced off it—and indeed this property is well established experimentally for the one-phonon 2^+ and 3^- states. In the preequilibrium picture, however, it is most difficult to imagine a deuteron surviving a succession of collisions inside the nucleus and eventually being emitted as a lower-energy deuteron, whereas such a picture is most acceptable for a proton. We therefore adopt the point of view that the extent to which (p,p') and (d,d') exhibit *similar* properties is a measure of the extent to which they both go by direct reactions. This point of view was accepted in advance of the experiments by leading proponents of both theories. Moreover, it is not much dependent on the details of the two theories as layed out in Refs. 1 and 2 but only on the simple idea that a deuteron is much less capable of surviving multiple collisions than is a proton. On the other hand, if a reader is not willing to accept or at least consider this point of view, he is wasting his time reading further.

The similarity of (d,d') and (p,p') noncompound-nucleus reactions was investigated in a previous paper[4] with about 100-keV energy resolution. Figures 1 and 2 show results for ^{64}Ni and ^{124}Sn from that work. They reveal a considerable amount of fine structure which is very similar for the two reactions, indicating that direct reactions are probably important in (p,p'). However, this structure could be explained as a few peaks from direct reactions superimposed on an otherwise smooth background from preequilibrium reactions, in which case the latter would still be the dominant mechanism. Another possibility is that the fine structure in Figs. 1 and 2 is due simply to groupings of levels, in which case peaks would occur at the same energy regardless of the reaction mechanism. It was partly to answer these questions that the high-energy resolution study reported here was undertaken.

Beyond this, however, is the question of how strong are the correlations between excitation cross sections for various levels by different inelastic scattering direct reactions. If they are very strong we have a technique for determining "ringing patterns," the natural manner in which a nucleus is excited if the mode of excitation is nonspecific. This ringing would seem to be a very fundamental piece of knowledge from which much can be learned about the nucleus.

EXPERIMENTAL

Thin targets of ^{64}Ni (1.0 mg/cm^2), ^{58}Ni (0.4mg /cm^2), and ^{124}Sn (0.3 mg/cm^2) were bombarded in separate experiments with protons and deuterons from the University of Pittsburgh three-stage Van de Graaff accelerator. Reaction products were analyzed with the Enge split-pole spectrograph and detected with photographic plates covered with aluminum absorbers of thickness calculated to reduce the energies of detected particles to 4–7 MeV. For (p,p') reactions the absorbers stopped all particles other than protons, but in the (d,d') experiments both deuterons and protons [from (d,p)] registered tracks, so short separate runs with absorbers thick enough to stop all deuterons were made to identify peaks due to protons. These peaks are generally quite large, and their pres-

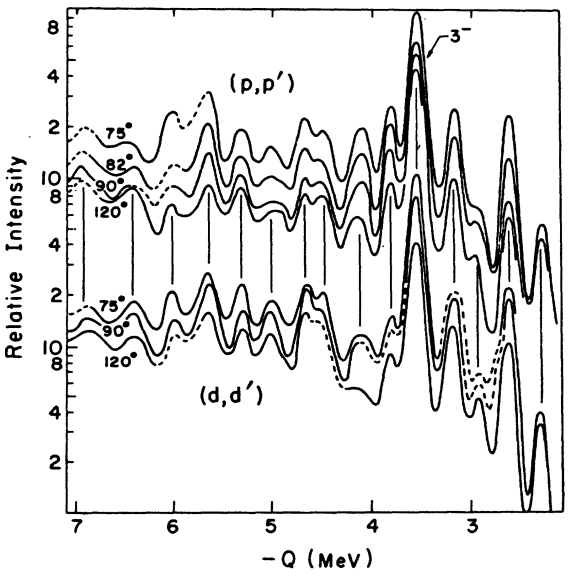

FIG. 1. Energy spectra obtained at various angles from (p,p') and (d,d') reactions on ^{64}Ni. Vertical lines indicate similarities in fine structure between the two reactions.

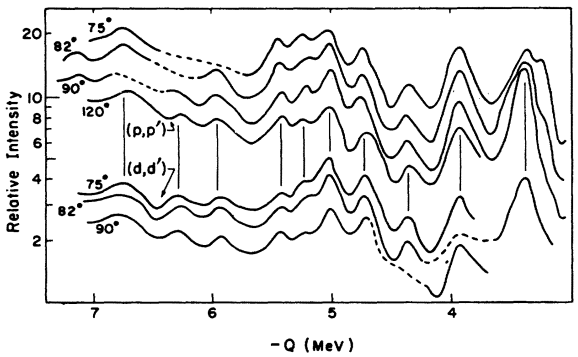

FIG. 2. Energy spectra obtained at various angles from (p,p') and (d,d') reactions on ^{124}Sn. Vertical lines indicate similarities in fine structure between the two reactions.

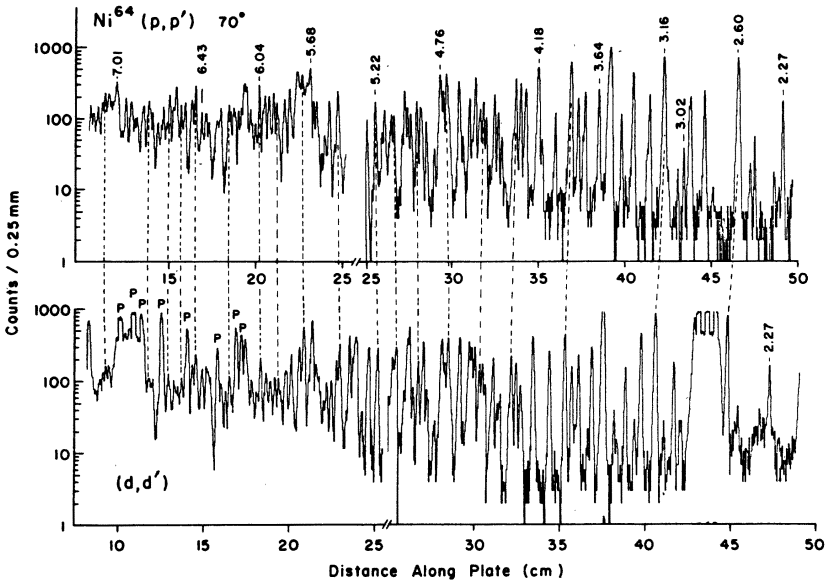

FIG. 3. Typical data. These are readings of track density vs position on plates. Upper data are from (p,p') and lower from (d,d') on ^{64}Ni at $\theta = 70°$ with 17-MeV bombarding energy. Dashed lines connect corresponding peaks. Figures above a few peaks are excitation energies in MeV of states excited. Energies of other peaks may be interpolated, except that many of these peaks are due to impurities as can be determined from measurements at other angles.

ence even when identified was a major limitation on the (d,d') studies on ^{58}Ni and ^{64}Ni, especially at higher excitation energies. Measurements were made at 60, 70, 80, and 90° deflection angles (60, 75, and 90° in the 12-MeV data) to identify peaks due to impurities, to give coverage to energy regions blanked out by impurity peaks or proton peaks in deuteron spectra at some angles, and to allow a reasonable degree of angle averaging in the results. The over-all energy resolution was about 8 keV for ^{58}Ni and ^{124}Sn and about 15 keV for ^{64}Ni (due to its target thickness). Typical spectra are shown in Fig. 3.

Tracks were counted with the Argonne National Laboratory automatic plate scanner.[5] In analyzing the results peaks were accepted as real if there was evidence for them at all angles not blanked out by impurity peaks in either (p,p') or (d,d'). Peak heights were estimated with due regard to the known energy resolution and to statistical variations in single datum points, and an estimated background was subtracted. While there is considerable room for subjective error in this process, perhaps as much as 30% for some weakly excited peaks, much of this should be removed in the angular averaging. Using areas would not have helped the situation since the principal errors are in background estimation. The angular averaging was weighted so as to give each angle an approximately equal influence on the average. Tables of energies and average intensities of peaks may be obtained by writing to the first author.

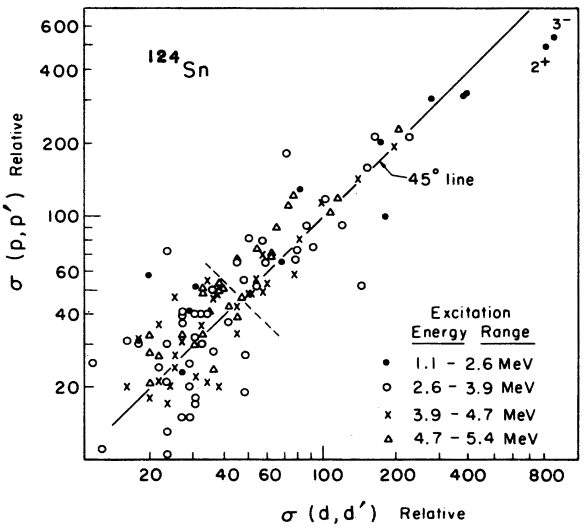

FIG. 4. $\sigma(p,p')$ vs $\sigma(d,d')$ for ^{124}Sn for exciting various states. Excitation energy range is indicated by different symbols. The significance of the 45° line and of the dashed line are explained in the text. Points due to the lowest-energy collective 2^+ and 3^- states are so indicated.

RESULTS AND DISCUSSION

The data for ^{124}Sn are plotted in Fig. 4 as $\sigma(p,p')$ vs $\sigma(d,d')$ for each state, and it is immediately clear from this plot that there is a very strong correlation between the two. Moreover, this correlation is clearly evident in each excitation energy region independently. This strongly indicates that direct reaction is the dominant reaction mechanism throughout.

In simple direct-reaction theory[6] the cross section for exciting a given state σ_i is given by

$$\sigma_i = \sigma_{DW}(l, E^*, \theta)\beta_i^2(i), \tag{1}$$

where l is the angular momentum transfer, σ_{DW} is derived from reaction dynamics usually by use of the distorted-wave Born approximation (DWBA), and β_i^2 is a characteristic of the state i given in the simplest model by the well-known shape deformation parameter β. It is convenient to define the ratio R of σ_{DW} for (p,p') and (d,d') reactions, and from (1) we see that

$$R(l, E^*, \theta) \equiv \frac{\sigma_{DW}(p,p')}{\sigma_{DW}(d,d')} = \frac{\sigma_i(p,p')}{\sigma_i(d,d')}. \tag{2}$$

If we make the not unreasonable assumption that after our angle averaging R is independent of l and E^* and hence the same for all states, the points in the log-log plot of Fig. 4 should lie on a straight line of 45° slope; and if we make the weaker assumption that R is uncorrelated with the σ_i, the points should be correlated with this line.

A line through the data with 45° slope is shown in Fig. 4 and there is indeed a strong tendency for the points to follow it, although the deviations are wide. The extent to which these deviations are due to the E^* dependence of R may be discerned by comparing the different types of points with the line; points from the highest E^* range do mostly lie above the line, but in general E^* dependence does not seem to be responsible for much of the variation. Another explanation may be the l dependence of R, but probably more important is the fact that σ_{DW} in (1) is also dependent in a very complex way on the number of phonons in the excitation, and this could be $1, 2, 3, \cdots$, or any combination of these. This complication should be especially severe in the small cross-section reactions, and it is among these that the deviations from the 45° line are seen to be greatest.

An interesting aspect of Fig. 4 is that the points for the strongest collective states, the lowest energy 2^+ and 3^-, lie well to the right of the line; i.e., they are relatively more strongly excited in (d,d') than in (p,p') than are most other states by a factor of about 1.5. This is what would be expected if the preequilibrium mechanism were an important contributor to excitation of the other states, but that mechanism could not explain the strong over-all correlation between (p,p') and (d,d'). A more plausible explanation for the deviation of the 2^+ and 3^- points is that most of the other states include multiphonon excitation and that process has a higher R than does single-phonon excitation. There is some evidence for this in the fact that the other strongly excited states in the lowest excitation energy region are known to be two-phonon excitations, and they lie close to the line.

The results for ^{64}Ni are shown in Fig. 5. Again we see a strong correlation between (p,p') and (d,d') both over all and in each excitation energy region independently, which indicates that direct reaction is here again the dominant process. There is also a reasonable degree of correlation with a

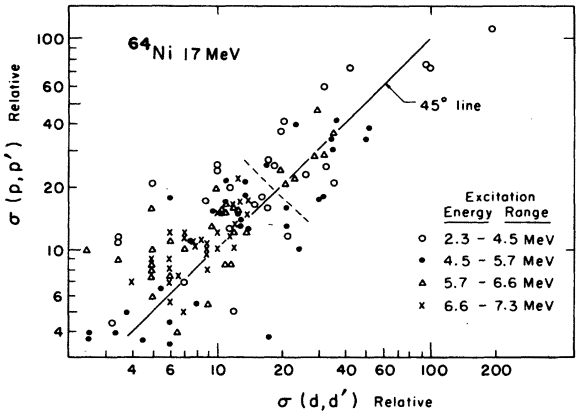

FIG. 5. $\sigma(p,p')$ vs $\sigma(d,d')$ for ^{64}Ni at 17-MeV bombarding energy. For other explanations see caption for Fig. 4.

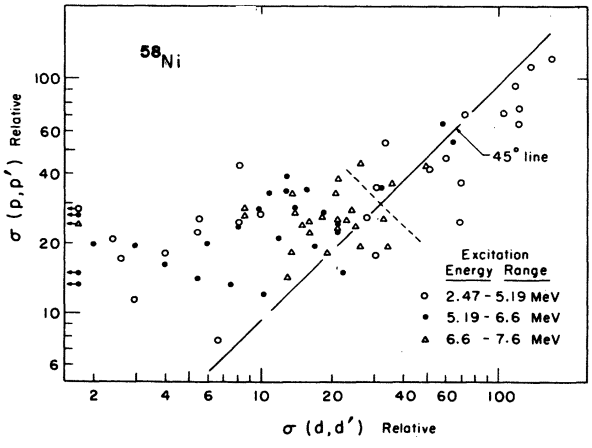

FIG. 6. $\sigma(p,p')$ vs $\sigma(d,d')$ for ^{58}Ni at 17-MeV bombarding energy. For other explanations see caption for Fig. 4.

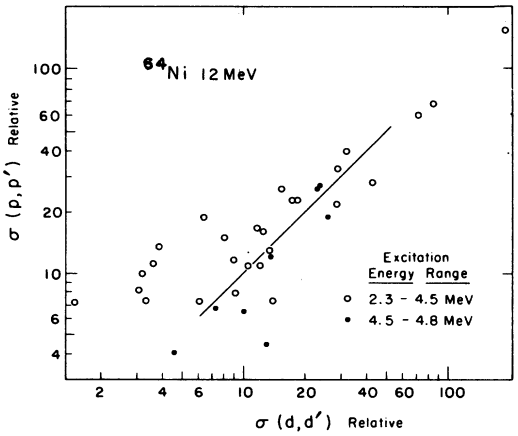

FIG. 7. $\sigma(p,p')$ vs $\sigma(d,d')$ for ^{64}Ni at 12-MeV bombarding energy.

45° line, although we see a new feature—a preponderance of points in the low-cross-section region above the line. This means that (p,p') cross sections are frequently larger than expected among weakly excited states. This could indicate that preequilibrium processes are important, but it could also be due to compound-nucleus (p,p') reactions which are not entirely absent here[7] as they are in ^{124}Sn.

A test of this explanation is a comparison with

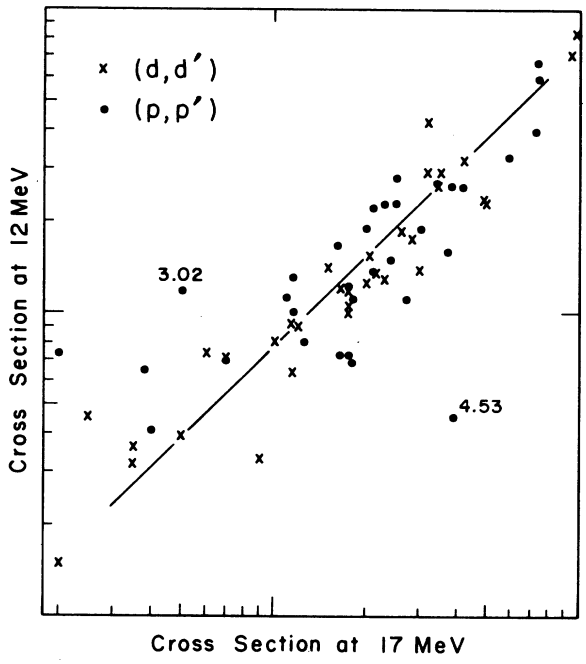

FIG. 8. Cross sections for excitation of same states in ^{64}Ni by the same reaction at 12 vs 17 MeV. Points labeled 3.02 and 4.53 are for states at those excitation energies in MeV. The line is drawn with a 45° slope.

^{58}Ni in which the compound-nucleus process is known to be much more important.[7] The data for this are shown in Fig. 6 where we see that the excess of low-cross-section points above the 45° line is very much larger in ^{58}Ni than in ^{64}Ni. It therefore seems reasonable to conclude that the effect is due to the compound nucleus. Even in ^{58}Ni, however, the dozen or so most strongly excited states are from direct reactions.

It is interesting to see to what extent the effects under study are dependent on bombarding energy. The low-resolution work[4] indicated that the effects are essentially unchanged between 17 and 12 MeV, and a high-resolution study of ^{64}Ni at 12 MeV is shown in Fig. 7. The energy region covered here is smaller than in the 17-MeV data because interferences of (d,p) with (d,d') were encountered at a lower excitation energy, but otherwise Fig. 7 has all the same features as the 17-MeV data of Fig. 5 including the 45° correlation and the low-cross-section excess above the line attributed to compound-nucleus reactions.

A more detailed indication of the extent to which a study of this type is independent of bombarding energy may be seen in Fig. 8 which is a plot of cross sections for exciting the same state with the same reaction at 12 vs 17 MeV. In general the correlation is quite strong for both (p,p') and (d,d') reactions which corroborates our procedure and some of our underlying assumptions.

One feature of Fig. 8 that is difficult to ignore is the point for the 4.53-MeV state which deviates from the line by more than twice the distance of any other large cross-section point. More detail on this situation is shown in Fig. 9 which shows the data for the pertinent region of the spectrum.

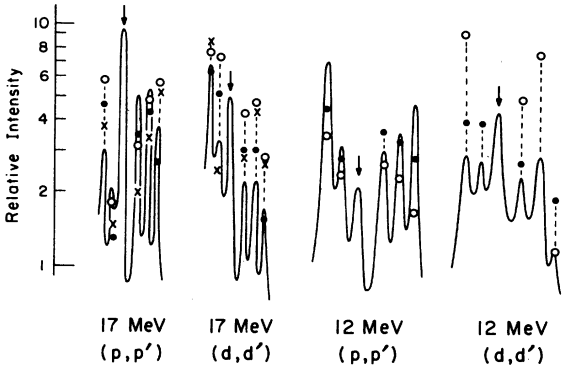

FIG. 9. Data for the 4.53-MeV state in ^{64}Ni. Curves are data at 60° for 17-MeV measurements and at 90° for the 12-MeV measurements. Other symbols show heights of the other peaks at the other angles when data are normalized for the 4.53-MeV peak (↓). The six peaks shown are due to excitation of states (right to left) at 4.45, 4.47, 4.50, 4.53(↓), 4.54, and 4.57 MeV.

TABLE I. Parameters from least-squares analysis of the data. The table shows the linear correlation coefficients and slopes for the best straight-line fit of the *logs* of the (p,p') cross sections versus the *logs* of the (d,d') cross sections.

Isotopes	Beam energy (MeV)	Linear correlation coefficient	Slope
^{124}Sn	17.	0.88	0.86
^{58}Ni	17.	0.70	0.38
^{64}Ni	17.	0.81	0.71
^{64}Ni	12.	0.82	0.64

We see that the 4.53-MeV state is excited with reasonable and similar strength by (d,d') at both energies, but in (p,p') it is excited very strongly at 17 MeV and very weakly at 12 MeV. A possible explanation might be that it is a high-l state for which $l<qR$ for 12-MeV protons.[8]

The data shown in Figs. 4–7 were compared further by least-squares analysis. The best straight-line fits of the logs of the (p,p') cross sections versus the logs of the (d,d') cross sections were calculated in all four cases. The fitting of the logs of the data helped avoid undue weighting of the strongest cross sections. The results are shown in Table I. It can be seen that the cases where the direct reaction dominates are characterized by linear correlation coefficients and slopes close to the value 1.0. The case for which the compound-nucleus contribution is known to be most important, ^{58}Ni, has, on the other hand, the smallest values for these quantities.

In considering the ringing pattern of a nucleus it is perhaps best to confine one's attention to the more strongly excited states, since this simplifies the problem and these states are more certainly due to direct reactions. For ^{124}Sn we place in this category states contributing points upward and to the right of the dashed line in Fig. 4. The cross sections averaged between (p,p') and (d,d') for these are plotted vs their energy in Fig. 10. From that plot each peak in Fig. 1 up to 5.3 MeV can be accounted for and its fine structure can be understood. The levels included in Fig. 10 contribute 76% of the total cross section up to 5.35 MeV, whereas the lowest energy 2^+ and 3^- states contribute only 16% of that total. Clearly then, the latter are by no means the principal contribution to the direct-reaction process as has sometimes been alleged. It should be noted that there is no reason to believe that the remaining 24% of the cross section contributed by more weakly excited states is not also due to direct reactions as the points below and to the left of the dashed line in Fig. 4 are also correlated with the 45° line.

The results of a similar analysis for ^{64}Ni are shown in Fig. 11 which includes all points above and to the right of the dashed line in Fig. 5. Since no points with $E^*>6.6$ MeV (crosses in Fig. 5) are included in that region, the strongest states from that energy range are also shown in Fig. 11 (open circles). Again all the peaks in Fig. 2 are explained by the levels represented in Fig. 11 and their fine structure is clarified. The levels included in Fig. 11 account for 66% of the cross section up to 6.6 MeV, and 11% is made up of more weakly excited levels lying below and to the right of the 45° line in Fig. 5 which it seems natural to assume are also direct reactions. It also seems natural to assume that an equal contribution, 11%, comes

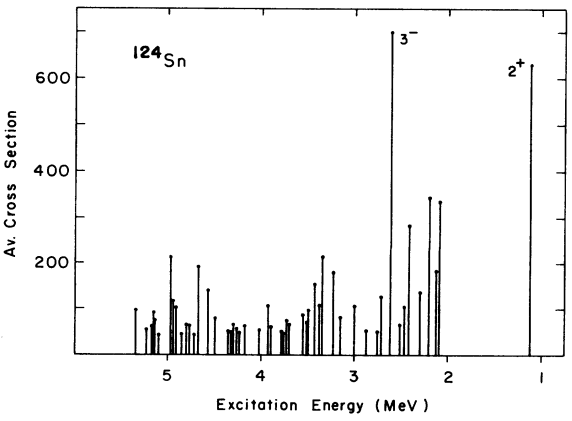

FIG. 10. Energies and intensities of strongly excited peaks in ^{124}Sn. Heights of lines are average of (p,p') and (d,d') cross sections. Peaks included are those above and to the right of the dashed line in Fig. 4.

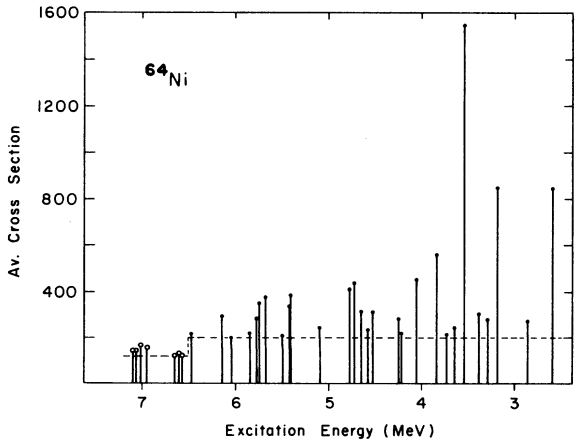

FIG. 11. Energies and intensities of strongly excited peaks in ^{64}Ni at 17-MeV bombarding energy. Heights of lines are average of (p,p') and (d,d') cross sections. Peaks included are those above and to the right of the dashed line in Fig. 5. Dashed lines here are minimum average cross section for states included in this plot.

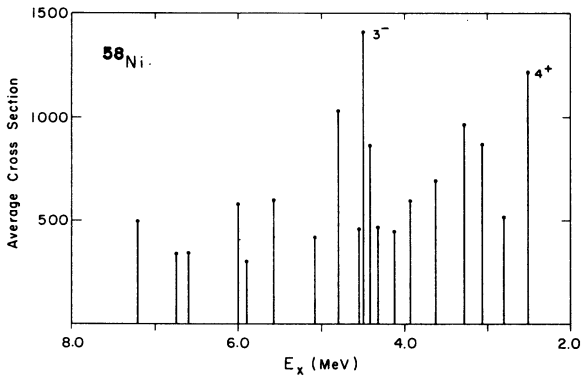

FIG. 12. Energies and excitation energies of strongly excited peaks in ^{58}Ni. Heights of lines are average of (p,p') and (d,d') cross sections. Peaks included are those above and to the right of the dashed line in Fig. 6.

from points above and to the left of the 45° line, making the total contribution of direct reactions about 88%. We thus conclude that only 12% of the total cross section to below 6.6 MeV excitation is other than direct reaction, and we have previously concluded that much if not all of this 12% is due to compound nucleus.

In the region between 6.6- and 7.3-MeV excitation energy in ^{64}Ni there is still quite a strong correlation with a 45° line in Fig. 5 although it is displaced from the solid line shown. Such a displacement is not unexpected from (2), since R is a function of E^*. The deviations from this correlation give no indication that this region is not also dominated by direct reactions.

Finally, the results of such an analysis for ^{58}Ni are shown in Fig. 12. All points above and to the right of the dashed line in Fig. 6 are included. The levels included in Fig. 12 represent 55% of the cross section up to 7.6 MeV. While the distribution of points below the dashed line in Fig. 6 makes it difficult to judge the likelihood of a direct-reaction mechanism for any given state, for the sake of completeness we include the cross sections of those states whose points lie to the right of the solid line in Fig. 6, an additional 8.5%. Adding a similar contribution for points above the line yields a total of 72%, consistent with previous comments about the importance of compound mechanisms for this nucleus. It must be noted that these totals do not include the direct cross section for the 2^+ first excited state which could raise this quoted fraction by a few percent.

The fact that essentially all noncompound nucleus (p,p') reactions are found here to be direct leaves us with the need for explaining what happened to the preequilibrium reactions. The process seems to work well for (p,n), so why should it be absent in (p,p')? One answer is that direct reactions *are* preequilibrium processes, so there is no difficulty in explaining missing cross section; the only question involves the *operational* definition of preequilibrium given in the Introduction. The point at issue here is whether a Griffin theory calculation is applicable in explaining the energy spectrum. It has been successfully used for this purpose,[9] but the calculations include adjustable parameters and the results are rather featureless so this may not be a convincing affirmative argument.

The fact that the same spectrum is obtained from (d,d') reactions would seem to be a convincing negative argument, although there is perhaps room for more subtle considerations here. In any case, direct-reaction theory seems definitely to be applicable, and since it is a much deeper and more powerful theory it should be diligently pursued.

ACKNOWLEDGMENT

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