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Reaction Mechanisms in (p,p') Reactions Exciting the High-Energy Continuum*

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The reaction mechanism in (p,p') reactions exciting states above about 3-MeV excitation energy has been studied in several nuclei in which ordinary compound-nucleus contributions have been shown to be unimportant. Up to 7 MeV in ^{64}Ni and ^{124}Sn, there is strong structure in the energy spectra of emitted protons which is closely correlated with the structure in (d,d') reactions; this indicates that direct reactions exciting collective states are the dominant mechanism here. Distorted-wave Born-approximation calculations are used to show that there is an additional mechanism contributing low-energy protons. This mechanism is believed to be isospin-conserving reactions via $T_>$ states, but it is shown that the decay of these states cannot be treated with statistical theory in the Sn region. A reason for this is proposed, and supporting evidence is presented. The applicability of pre-equilibrium calculations to (p,p') reactions is discussed.

I. INTRODUCTION

The energy spectra of protons from (p,p') reactions induced by 17-MeV protons on various isotopes of Sn are shown in Fig. 1. It is taken from the work of Cohen *et al.*[1] after removal of contributions from (p,np) reactions[2] and corrections for background. Similar results have been found[3] in various other mass regions. It has been shown[1,3] that the excess cross section in the light isotopes is due to contributions from ordinary compound-nucleus reactions in which the variation of $Q(p,n)$ causes rapid changes in the relative probabilities for proton and neutron emission, and that the spectra in the heavier isotopes are entirely due to processes in which competition with neutron emission is not a factor. It is the purpose of this paper to investigate what these latter processes are.

Three processes satisfying the above criterion have been widely discussed in the literature: (1) direct reactions; (2) pre-equilibrium reactions; (3) isospin-conserving reactions (ICR) via $T_>$ states. Direct reactions are usually defined as ones in which the time of interaction is of the order of the transit time of the incident particle across the nucleus. However, a combination of experimental and theoretical developments on the process[4] allow us to recognize them as reactions exciting collective states in a manner which is largely independent of whether the inelastically scattered particle is a proton, a deuteron, or a more complex particle. "Pre-equilibrium" processes in principle include direct reactions, but we operationally define them to be processes which can be treated by pre-equilibrium theories.[5] These theories are semiclassical and statistical in nature and do not include effects of collective excitation, but they have proven useful in explaining energy spectra of neutrons from (p,n) reactions.[6] The third process, ICR, was first introduced by Miller *et al.*[7] and is illustrated for ^{124}Sn(p,p') in Fig. 2. When the incident particle strikes a nucleus, states of $T_>$ (in this case, $T=\frac{25}{2}$) are formed with a probability $1/(2T+1)$, and for these states, decay by neutron emission is forbidden by isospin conservation; hence this is another case in which competition with neutron emission is not a factor in determining the probability of proton emission. The cross section for this process cannot be more than $1/(2T+1)$ times the total reaction cross section, but can be less, or even very much less, because isospin mixing can occur in the compound nucleus before the proton is emitted. In this situation the compound nucleus goes into $T_<$ states from which neutron emission occurs very rapidly, about 10^5 times more rapidly than proton emission for the ^{124}Sn case.

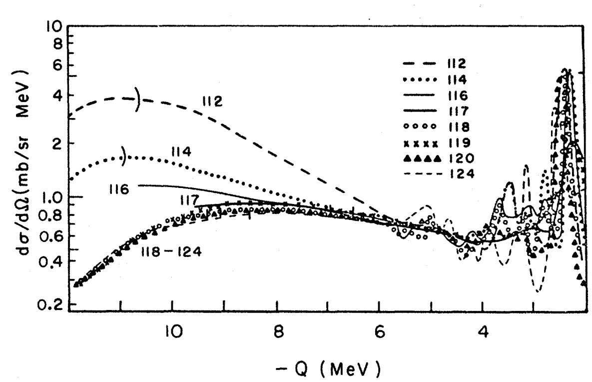

FIG. 1. Energy spectra of protons emitted at 75° from (p,p') reactions induced by 17-MeV protons on various isotopes of Sn. Data are from Ref. 1, with corrections applied. Portions of the upper two curves to the left of the parentheses are obtained by the method of Ref. 2.

Of the three processes listed above, we expect direct and pre-equilibrium reactions to be most important for the highest-energy emitted protons, and the ICR to give their biggest contribution at low energies. The relative importance of these three processes is, at the outset, almost completely unknown and any of them might be either completely dominant or completely negligible except for the well established fact that the 2^+ and 3^- collective states are strongly excited by direct reactions.[4]

The first aim of this paper is to assess the importance of direct reactions by making a comparison between (p, p') and (d, d') reactions. The latter are presumably understood to be direct reactions since, by any calculational techniques, one finds the probability for deuteron emission in pre-equilibrium or equilibrium processes to be very small. For example, statistical theory of nuclear reactions predicts a favoring of proton over deuteron emission by 2 orders of magnitude due to the difference in Q value; and in pre-equilibrium processes, one expects a deuteron to break up before undergoing very many collisions inside the nucleus.

We make the comparison between (p, p') and (d, d') primarily by studying the detailed structure of the spectra. We then introduce distorted-wave Born-approximation (DWBA) calculations and show how they fail in several ways to account for the data. They nevertheless do lead us to the conclusion that another process is needed to explain the low-energy protons. The ICR via $T_>$ states are investigated in this connection, and problems with them are pointed out. A solution to these problems is introduced and supported, leading to the conclusion that this process is present and important. Finally, the role of pre-equilibrium reactions is assessed.

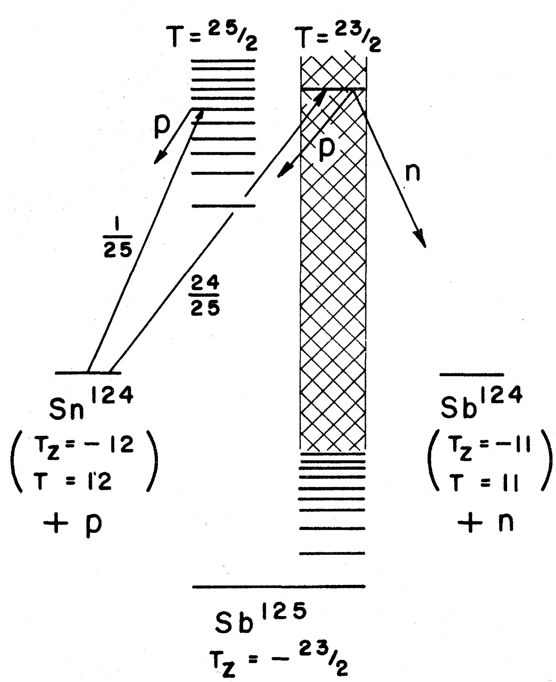

FIG. 2. Energy level diagram for $A = 125$. See discussion in text.

II. EXPERIMENTAL

Protons and deuterons of various energies from the University of Pittsburgh three stage Van de Graaff accelerator were used to bombard targets of about 2-mg/cm^2 thickness in a 24-in. scattering chamber. Scattered particles were detected with a ΔE-E telescope of semiconductor detectors in which "ΔE" was a 50-μ-thick planar surface-barrier detector and "E" was a 2000-μ-thick surface barrier or 2000-μ-thick lithium-drifted silicon detector. Beam monitoring was done by standard current-collection techniques and by measuring elastic scattering with two scintillation detectors at +25° and -25°. Target thicknesses were determined by weighing, by measuring the energy loss of ^{241}Am α particles in passing through them using a surface-barrier detector, and by measuring elastic scattering of 5-MeV protons at 35, 40, and 45°; in general, the various determinations agreed within about 5%. Two different targets of each isotope were used in most cases. Particle identification was done by use of the multiplier technique, although in some of the (d, d') measurements, the Goulding method[8] was used.

The most difficult experimental problem was the subtraction of background. This is due to:
(1) Slit scattering of the incident beam. This introduces into the beam a low-energy component which is elastically scattered by the target.
(2) Slit scattering of elastically scattered particles (and of higher-energy inelastically scattered particles) in the detector slit, giving lower-energy protons.
To minimize the first effect, only a single slit was used between the last bending magnet and the target; it was located a few inches in front of the target and the focusing system was tuned so that no detectable beam strikes this slit. In some of the later runs, a large-area ΔE detector was used with the detector slit between the ΔE and E detectors; this reduced the background by about one third, but it caused count-rate problems which just about offset this advantage. Background problems were studied by making measurements at forward angles where, due to the large cross section for elastic scattering, background over-

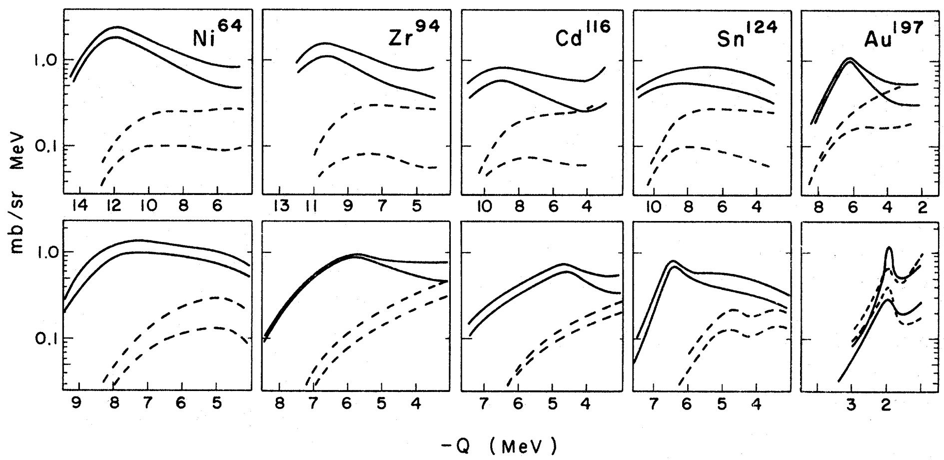

FIG. 3. Energy spectra from inelastic scattering on various nuclei. Bombarding energies are 17 MeV in upper diagrams and 12 MeV in lower diagrams. Solid curves are (p,p') and dashed curves are (d,d'). In each set of two curves, the upper is at 75° and the lower is at 135°. Fine structure in these curves has been smoothed out.

whelms inelastic scattering over the entire spectrum. In addition, for Au targets and in favorable situations for Sn targets, the contribution from inelastic scattering becomes negligible at low proton energies due to Coulomb barrier effects, whence background can be studied in that region. This was not possible in the lighter nuclei or in most cases in the Sn region because the continuum from inelastic scattering in carbon and oxygen, important impurities in all targets, is present at energies where inelastic scattering from the nucleus under study falls off. As an approximation to a very complicated situation, it was found suitable to assume that the background at any energy is proportional to the total number of counts with higher energy in the spectrum. The proportionality constant decreases by about a factor of 2 from forward to backward angles, is about 40% larger for protons than for deuterons, and decreases by about 20% between 17 and 12 MeV. But it was found to be remarkably constant over the many months when data were taken.

The principal difficulty from uncertainties in background subtraction are in causing errors in angular distributions since the total background increases rapidly with decreasing angle. An independent method has therefore been used for measuring angular distributions, and it will be reported separately.[9] That method gives good agreement with the method used here for angles greater than 70°.

Measurements in this work were largely restricted to 75 and 135°; the former is about as far forward as one can go without introducing serious background difficulties and interference from the broad peak due to the hydrogen impurity, and the latter should be fairly typical of angles in the backward hemisphere.

Due to the wide energy range being studied and the necessity for accepting very low-energy particles which requires the use of a thin ΔE detector,

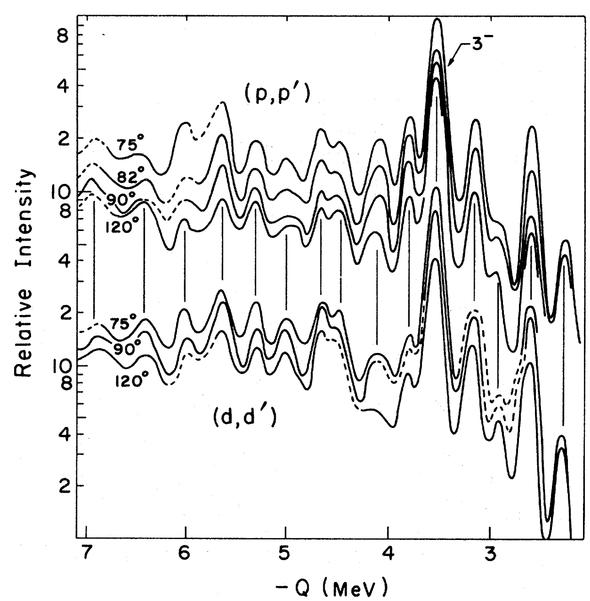

FIG. 4. Comparison of fine structure in energy spectra from (p, p') upper curves and (d, d') lower curves. Dashed portions are "blacked-out" by peaks from impurities, but there are data from every part of the spectra at some angles. Vertical lines indicate peaks that are similar in (p, p') and (d, d'). The various curves are normalized arbitrarily. Target is ^{64}Ni and bombarding energy is 17 MeV.

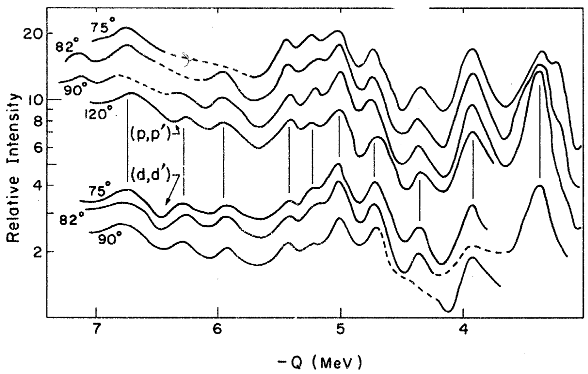

FIG. 5. Same caption as Fig. 4 except the target is ^{124}Sn.

particle identification was not perfect. Difficulties were most severe in (d, d') where the ratio of protons to deuterons is sometimes very large. The uncertainties in (d, d') absolute cross sections are therefore especially large, perhaps about 30%. In runs where fine structure in the energy spectrum was the primary concern, the windows on particle identification were made especially small so as to eliminate peaks due to other particles; these runs were not used for cross-section determinations.

Measurements were made with ^{64}Ni, ^{94}Zr, ^{116}Cd, ^{124}Sn, and ^{197}Au plus a few other targets for special purposes. In all of these cases, previous work[3] has shown that ordinary compound-nucleus processes are not present, except perhaps to a small extent in ^{64}Ni. A gross picture of some of the results, with fine structure smoothed out, is shown in Fig. 3.

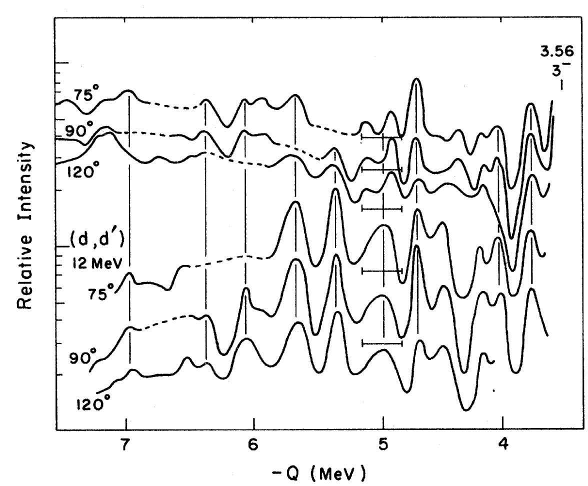

FIG. 6. Same caption as Fig. 4 except the bombarding energy is 12 MeV.

III. DETAILED STRUCTURE OF SPECTRA

The fine structure in the energy spectra was most marked in ^{64}Ni and ^{124}Sn, perhaps because they are closed-shell nuclei. The energy spectra from (p,p') and (d, d') on these nuclei at 17- and 12-MeV bombarding energies are shown in Figs. 4–7. Parts of the spectra that are "blacked out" by carbon and oxygen impurity peaks are shown by dashed lines; runs were made at several angles so that all parts of the energy spectra are observable at some angle. It is apparent from these figures that there is a great deal of similarity between the spectra from (d, d') and (p, p') in that peaks occur at the same energies and have similar relative intensities. It seems fairly certain from the spacings of these peaks that they are not closely related to the occurrence of individual energy levels–the number of levels is far larger and increases rapidly with increasing excitation energy. The peaks in (d, d') are then very probably due to variations in strengths for reaching various collective excitations, and the similarity of the peaks in (p, p') to those in (d, d') indicates that the former are also due to this. We must therefore conclude that direct reaction plays an important role in (p, p') reactions at least up to 7 MeV excitation in both the Ni and Sn regions. From the fact that the structure is just as sharp in (p, p') as in (d, d'), at least for 17-MeV bombarding energy, we may conclude that direct reaction is the *dominant* process in this region.

It should be emphasized that this region is far from completely dominated by the well-known collective 2^+ and 3^- states. These two states combined contribute only about 18% of the total (d, d') spectrum in ^{124}Sn, and about 25% in ^{64}Ni. We clearly have a great deal to learn about these other collective excitations that contribute the majority of the cross section for (d, d'), and whose

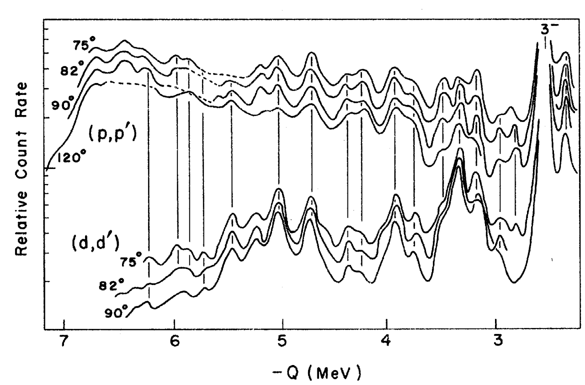

FIG. 7. Same caption as Fig. 4 except the target is ^{124}Sn and bombarding energy is 12 MeV.

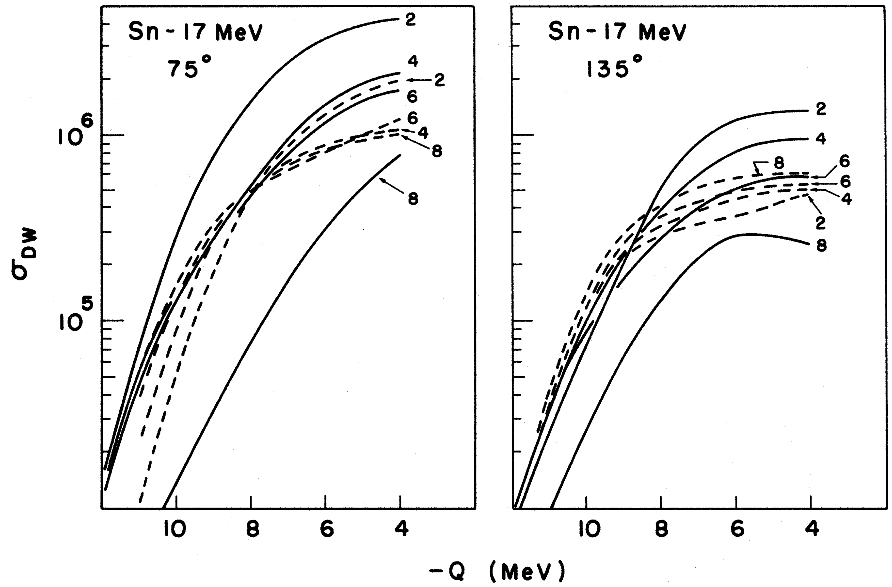

FIG. 8. Some results of DWBA calculations on ^{124}Sn at 17-MeV incident energy. Solid curves are for (p, p') and dashed curves are for (d, d'). Numbers attached to curves are l-transfer values.

excitation dominates much of the spectrum from (p, p').

IV. APPLICATIONS OF DWBA

Since the theory of direct-reaction cross sections is believed to be reasonably well understood through the DWBA, it seems natural to attempt to apply it here. In that theory, the cross section for exciting a region of excitation energy E^* is

$$\frac{d^2\sigma}{d\Omega\, dE^*} = \sum_l \sigma_{DW}(l, E^*, \theta) S_l(E^*), \tag{1}$$

where σ_{DW} is the cross section obtained from a DWBA calculation as a function of the angular mo-

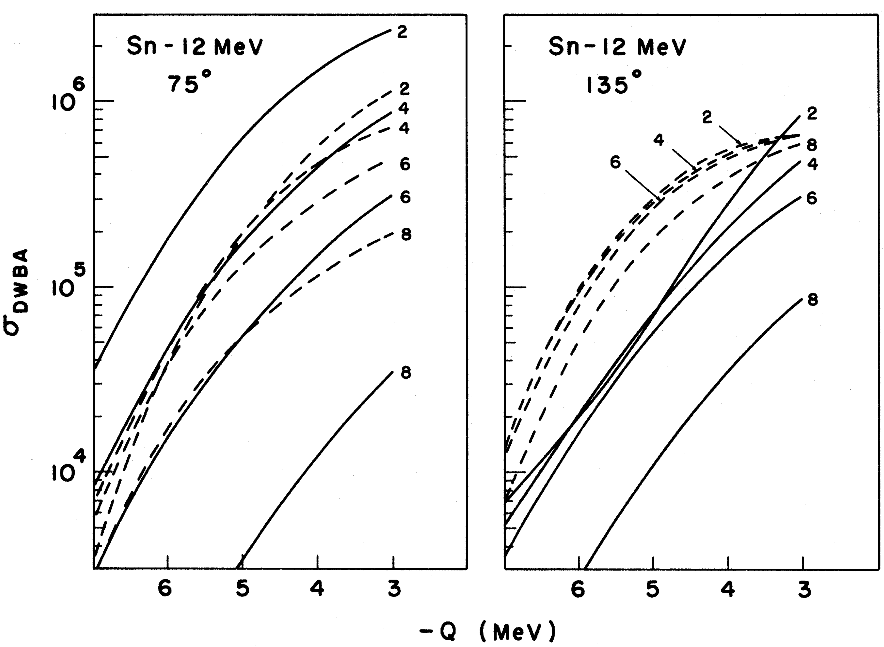

FIG. 9. Same caption as Fig. 8 except at 12-MeV incident energy.

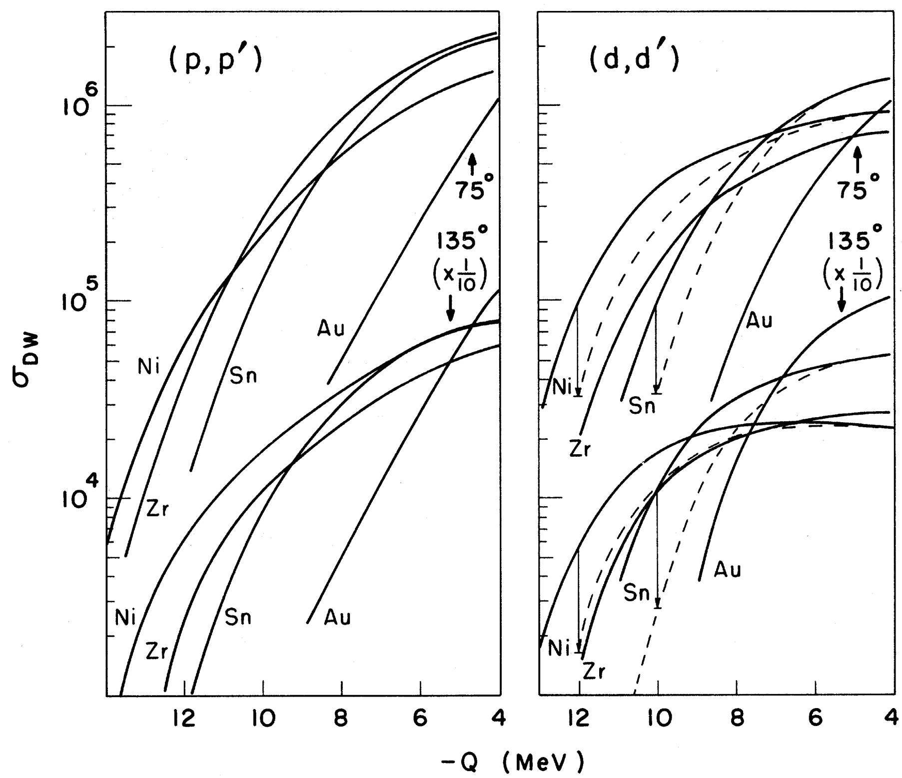

FIG. 10. Results of DWBA calculations on various nuclei at 17-MeV bombarding energy. Curves are averaged logarithmically over calculations for $l = 2, 4, 6,$ and 8. Upper sets of curves are at 75° and lower sets are at 135°. Dashed curves are the effect of changing optical-model parameter W' by letting it go smoothly to zero at $Q = -12$ MeV.

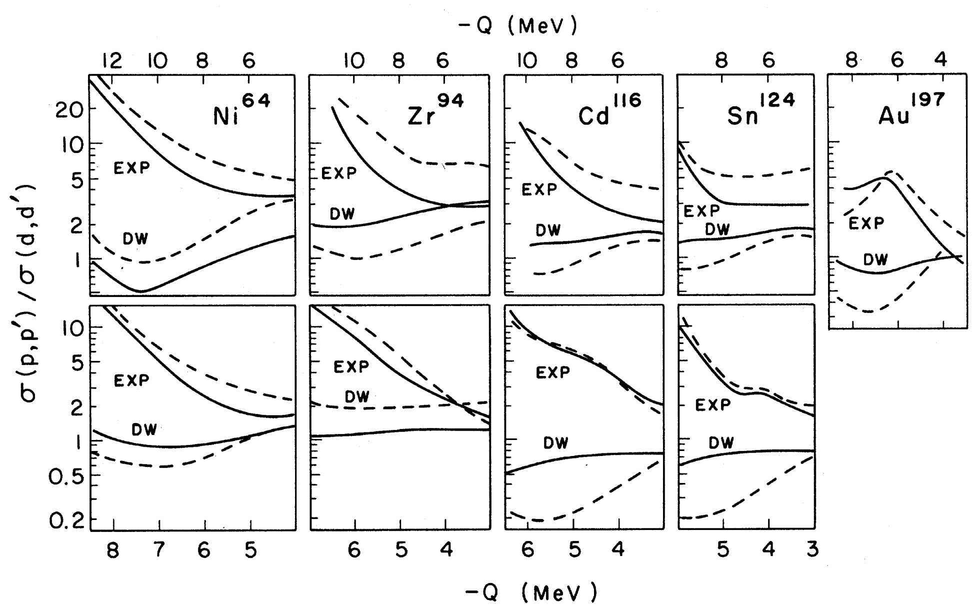

FIG. 11. The ratio $\sigma(p,p')/\sigma(d,d')$ in various nuclei. Upper diagrams are for 17-MeV bombarding energy and lower diagrams are for 12-MeV bombarding energy. In each diagram, the upper set of curves labeled EXP are the experimental ratio while the lower set of curves labeled DW are the ratio calculated from DWBA curves of the type shown in Fig. 10. Solid curves are results at 75° and dashed curves are results at 135°.

mentum transfer l and the scattering angle θ, and S_l is the strength distribution for l transfers defined by

$$S_l = \frac{d}{dE^*}\left[\sum_i (\beta_l{}^2)_i\right] .$$

Here β_l is the familiar amplitude for 2^l-pole oscillation in the nuclear state i, and the sum is assumed to be smoothed out as a function of energy before differentiating. It may be noted that E^* is just equal to $-Q$, where Q has its usual meaning of energy release in the reaction.

Since the S_l are essentially completely unknown and (1) is not factorable, one might think that no use can be made of DWBA calculations. However, the situation is not that unfavorable, largely because σ_{DW} is a smoothly varying function in the energy region of interest. Examples of this are shown in Figs. 8 and 9, which are calculations of σ_{DW} made with computer code JULIE[10] using collective form factors and Perey-Set B optical-model parameters.[11] We see there that the oscillatory behavior so well known at low excitation energies is almost completely smoothed out at the energies of interest here, presumably because of poorer momentum matching. The behavior of σ_{DW} as a function of target mass is illustrated in Fig. 10 which shows a logarithmic average of the l = 2, 4, 6, and 8 curves for various nuclei; they correspond to curves for an average l, $\bar{l}$, of about 4. Once again the smooth behavior is evident.

The ratios of $\sigma(p, p')$ to $\sigma(d, d')$ are shown in Fig. 11. The experimental ratios are from Fig. 3, and the ratios labeled "DW" are from curves of average σ_{DW} like those in Fig. 10. In comparing the experimental and theoretical curves in Fig. 11, one finds large discrepancies:

(1) The absolute values of the ratio are always higher experimentally than in DWBA. This discrepancy could be eliminated if we took $\bar{l}$ for the DW curves to be about 2 instead of about 4. This is not impossible, but it is not what one would ordinarily expect.

(2) In Sn and in several other cases, the 135° curve is above the 75° curve in the experimental results, but below it in the DWBA calculations; that is, experimentally (d, d') has a steeper angular distribution than (p, p') whereas DWBA predicts the opposite. This discrepancy is not very sensitive to $\bar{l}$. It has been shown previously[12] that the angular distribution in Sn(d, d') falls off more rapidly with increasing angle (i.e. is steeper) than can be explained by DWBA regardless of the behavior of S_l.

(3) The experimental curves rise with increasing $E^*(= -Q)$, whereas the DWBA curves fall. From Figs. 8 and 9 we see that in the energy regions of interest, the (p, p') curves fall off more rapidly than the (d, d'), so the latter behavior would be valid independently of $\bar{l}$. Moreover, the (p, p') curves decrease more rapidly with increasing l than do the (d, d'), so if $\bar{l}$ increases with increasing E^* as one would ordinarily expect, the DWBA curves in Fig. 11 would fall even more rapidly with increasing E^*, thus increasing the discrepancy.

There are two alternative interpretations for these discrepancies, either DWBA does not work well, or the (p, p') reactions are not predominantly direct reactions. In explaining the first two

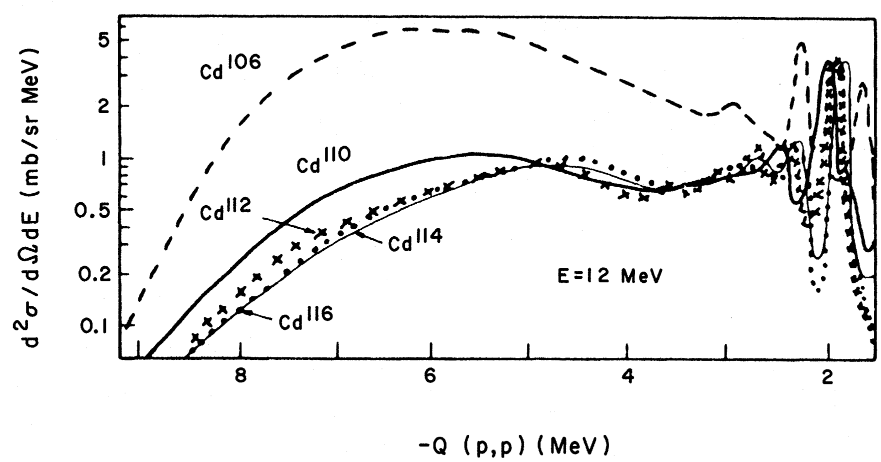

FIG. 12. Energy distribution of protons emitted at 75° from (p, p') reactions on various isotopes of cadmium with 12-MeV bombarding energy. Data are from Ref. 3.

discrepancies, we favor the first of these alternatives because:

(a) There is independent evidence that DWBA does not correctly predict the angular distributions.[12] If angular distributions are not correct, absolute cross sections can at most be correct at one angle, and there is no reason to believe that either of the angles we have chosen is the correct one.

(b) There are other failures in DWBA for (d, d'). For example, we see from Figs. 9 and 10 that σ_{DW} for all l decreases much more rapidly between $E^*=3$ and 5 MeV in Sn at 12- than at 17-MeV bombarding energy; this behavior is not evident in the experimental results of Fig. 3.

(c) Much of the direct-reaction cross section may lead to two phonon states, and it is well known that simple DWBA calculations of the type done here are not valid for two-phonon states.[13]

(d) Much effort was expended in optimizing DWBA techniques to reproduce correctly the oscillations in the angular distributions for transitions to the 2^+ and 3^- states, and to give correct cross sections for these. Since these are the DWBA techniques we are using, there is no reason to believe that they were simultaneously optimized for the high excitation region.

(e) The evidence in Sec. III that direct reactions are predominant in the region $E^* \lesssim 7$ MeV seems too overwhelming to consider the second alternative.

Since the first two discrepancies are typically of the order of a factor of 2, it is not hard to believe that a DWBA calculation that does not work very well can be their cause. However, the third discrepancy – the fact that the experimental curves in Fig. 11 rise rapidly with increasing E^* whereas theory predicts that they should fall even more rapidly than the curves labeled DW in Fig. 11 – is more than a factor of 10 discrepancy and depends only on the ability of DWBA to correctly calculate the Coulomb barrier penetrability. Stated in another way, the experimental curves in Fig. 3 indicate that (p, p') yields far more low-energy particles than does (d, d') and DWBA gives us no reason to expect such behavior. We therefore conclude that another process is present in (p, p') contributing heavily to the low-energy portion of the spectrum. From the candidates listed in the Sec. I, only isospin-conserving reactions via $T_>$ states are expected to have this property.

V. ISOSPIN-CONSERVING REACTIONS VIA $T_>$ STATES

In previous treatments of ICR via $T_>$ states the decay has been treated by statistical theory.[7] If this is done here, serious difficulties are immediately encountered in understanding the shape of the energy spectrum. One evidence for this may be seen in Fig. 1. The low-energy part of the curve for ^{112}Sn has been shown to be dominated by ordinary compound-nucleus reactions, and if one uses statistical theory to treat ICR, one expects a similar spectrum. However, the curve for ^{124}Sn in Fig. 1, whose low-energy part we attribute to ICR, is seen to be very different, peaked about 3 MeV higher in energy. Another example of this type is shown in Fig. 12 which is taken from Ref. 3. The curve for ^{106}Cd, dominated by ordinary

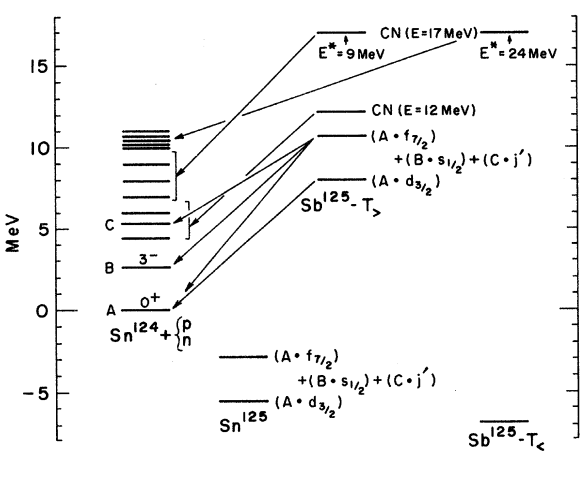

FIG. 13. Energy level diagram for $A=125$. See explanation in text.

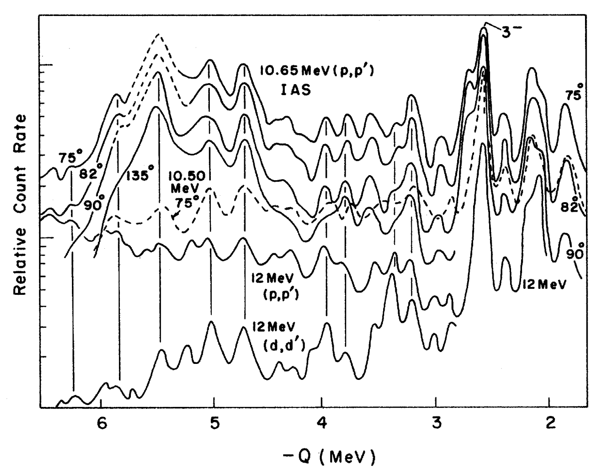

FIG. 14. Comparison of fine structure in energy spectra from (p, p') reactions via the 10.65-MeV isobaric-analog-state resonance, and (p, p') and (d, d') reactions at 12 MeV. See caption for Fig. 4. The 12-MeV curves are composites of the curves in Fig. 7. The dashed curve labeled "10.50 MeV-75°" is normalized to the uppermost curve in the figure, indicating that the intensity is very much larger at 10.65 than at 10.50 MeV.

compound-nucleus reactions, is peaked at a much lower energy than the curves for the heavy isotopes whose low-energy part we are explaining by ICR.

Cline, Huizenga, and Vonach[14] have observed smaller energy shifts between their ^{112}Sn(p, p') evaporation peak and their ^{116}Sn, ^{118}Sn, and ^{124}Sn data. They have found their results to be consistent with the possibility that ICR decay is predominantly pre-equilibrium, with much of the decay occuring close to the equilibrium limit. Our purpose here is not to quarrel with the proposal of Ref. 14, but to show that even if equilibrium is reached, one does not expect the decay to be governed by statistical theory.

At lower energies, ICR reduces simply to inelastic scattering via isobaric analog states, a subject that has been widely studied for many years. These reactions are well known to give strong excitation of the 2^+ and 3^- collective states, presumably because those states contain wide mixtures of configurations and wave functions with a coherent relationship to the ground state. For similar reasons we might expect ICR to strongly excite collective states in the residual nucleus.

To be more specific to the cases under consideration here, the highest-energy known isobaric analog state in ^{124}Sn(p, p') is one excited by 10.65-MeV protons[15]; it is the analog of a state at 2.78 MeV in ^{125}Sn which is strongly excited by ^{124}Sn(d,p) with transfer of an $f_{7/2}$ neutron.[16] An energy diagram is shown in Fig. 13. From the (d, p) data we know that its wave function has a strong component of $(A \cdot f_{7/2})$ where A is the ground-state wave function for ^{124}Sn. Since this state is near in energy to the $\frac{7}{2}^-$ component of the octupole vibrational state, it might well have a strong component of $(B \cdot s_{1/2})$ where B is the wave function for the 3^- collective state in ^{124}Sn and $s_{1/2}$ is a typical single particle in the ground-state shell (it could also be $d_{3/2}$ and still be at about the same energy). This component would be evidenced by a strong decay of the isobaric analog state to state B. This is an example of the "window effect" first proposed by Allan *et al*[17]: There is a strong probability for an isobaric analog state to decay to collective states in a region of excitation energy which is about equal to the energy by which it is above the lowest-energy isobaric analog state. These transitions are expected to have large reduced widths for emission of particles in the shell that is filling.

The window effect leads to the emission of protons with about the same energy as those needed to excite the lowest-energy isobaric analog state, which in ^{124}Sn is 7.9 MeV. One therefore expects the peak of the energy spectrum to be at a proton energy of about 7.9 MeV, which corresponds to $-Q = 9$ and 4 MeV at 17- and 12-MeV bombarding energies, respectively, in reasonable agreement with Figs. 1 and 12.

The window effect should not, of course, be taken so literally as to give a precise determination of the energy of the emitted protons. The point is that nuclear structure effects are important because there are large reduced widths for decay by emission of particles in the shell that is filling, and these are concentrated in a relatively narrow energy region. A statistical treatment completely ignores this point.

The energy spectrum of protons emitted from ^{124}Sn(p, p') reactions on the 10.65-MeV isobaric-analog-state resonance is shown in Fig. 14. This is a very strong resonance as can be seen by comparing the intensities at 75° with that from 10.50-MeV bombarding energy, just below the resonance (those two curves have been normalized to the same cross-section scale). Even though the resonant state clearly decays by a compound-nucleus process in which equilibrium has been reached, the decay is anything but statistical. In fact, there is a very strong tendency for its decay to populate the same states as are populated by (d, d'), which are presumably the collective states.

In the energy region we are primarily concerned with in this paper, 12–17-MeV bombarding energy, there are no known isobaric analog resonances. However, there is considerable evidence for effects of the details of nuclear structure in the region where ICR are believe to be dominant. Figures 15 and 16 show spectra from the various heavy Sn and Cd isotopes. We see that there is a considerable variation among the various isotopes. At 12-MeV bombarding energy, for which the ICR region begins at $E^* \approx 5.5$ MeV according to Fig. 11, the heavier isotopes seem to have a strong peak in the low-energy region, a peak that is completely missing in the lighter isotopes. A similar situation still seems to be in evidence at 14 MeV, although the peak is at a rather different excitation energy and also at a somewhat higher emitted-proton energy. There is even some evidence for this shifting of the peak at 16-MeV bombarding energy, for which data are shown in Fig. 17, although the effect is somewhat smaller. The fact that the spectra become smoother at the higher bombarding energies is expected from the fact that we are dealing with higher excitation energies.

It is interesting to note from Fig. 17 that the cross sections at the peak increase with decreasing A approximately in proportion to $1/(2T+1)$ as might be expected from the fact that this is proportional to the probability for the system to be in a $T_>$ state.

Since it has been shown that ICR can explain the

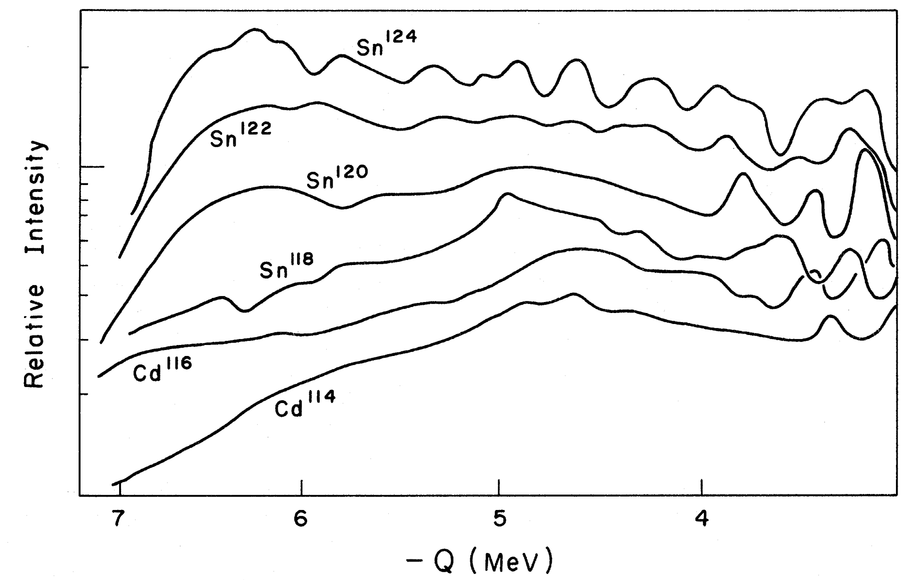

FIG. 15. Energy spectra from (p,p') reactions on various Sn and Cd isotopes with 12-MeV bombarding energy. Detection angle is 135°.

excitation of collective states, it might be asked whether this could account for the region we have been ascribing to direct reactions. There are two strong arguments against this:
(1) It is clear from Fig. 3 that angular distributions are not isotropic or symmetric about 90°, but are somewhat forward peaked. Special techniques are required to measure angular distributions forward of 70°, and these measurements will be reported separately when completed.[9] But it is clear from the preliminary results that the intensity continues to increase as one goes to more forward angles.
(2) The maximum cross section for ICR is $1/(2T+1)$ times the reaction cross section, which for ^{124}Sn, is about 40 mb. One expects this to be reduced by an appreciable factor due to isospin mixing. However, the total cross section for ^{124}Sn(p, p') leaving the final nucleus with >3-MeV excitation energy is about 70 mb.
It is thus apparent that at least half of the cross

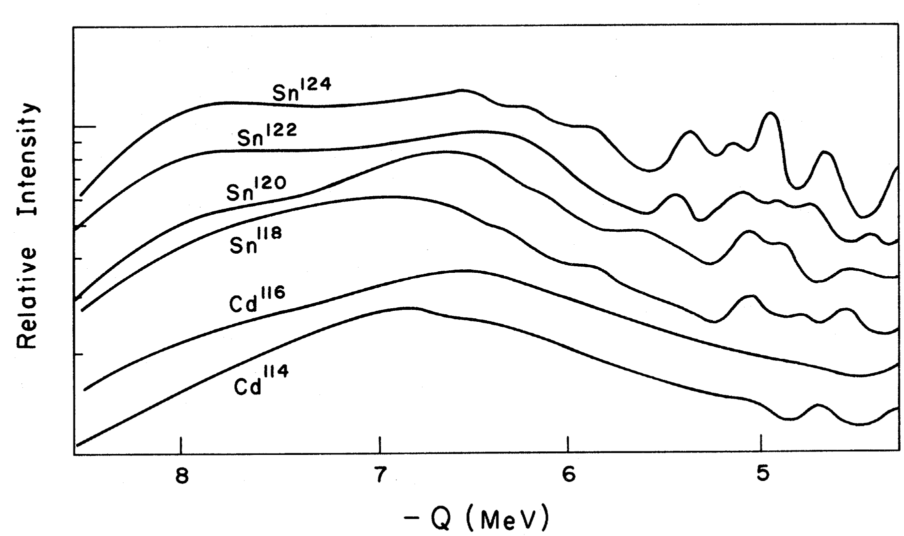

FIG. 16. Energy spectra from (p,p') reactions on various Sn and Cd isotopes with 14-MeV bombarding energy. Detection angle is 135°.

section is due to direct reactions, and not more than half is due to ICR. This does not include the lower excitation energy region (2^+, 3^-, and two-phonon 2^+ collective states) which has long been conceded to be dominated by direct reactions.

VI. PRE-EQUILIBRIUM MODEL

The question of the role of pre-equilibrium reactions put forth in Sec. I boils down to the question of whether the usual type of pre-equilibrium calculations are useful in explaining the gross features of the spectrum whose fine structure is explained by direct reactions. These calculations are basically non-quantum mechanical and include the unrealistic requirement of energy conservation following each of the many interactions (i.e., they ignore off-energy-shell effects), but they have been useful in interpreting the high-energy portion of the neutron energy spectrum from (p, n) reactions.[5,6] The question of whether they can be useful for (p, p') reactions remains to be answered. They cannot reproduce collective effects, but they could be useful if one interprets (p, p') spectra like those in Figs. 4–7 as peaks from collective excitations adding up to a smoothly varying envelope. This would then imply that these collective states are excited with a strength determined by their location on the envelope, which seems to be contrary to usual ideas. An alternative explanation would be that the (p, p') spectra consist of sharp peaks from collective excitations superimposed on a smoothly varying "background"; this would then seem to require a similar explanation for (d, d'), and one would then have to find an explanation for the smoothly varying background in (d, d'). These questions could be settled by high-resolution measurements which are in progress.

A second problem to overcome before demonstrating the usefulness of pre-equilibrium calculations for (p, p') would be to explain the rather considerable differences between the high-energy end of the spectra from (p, p') and (p, n). This problem was discussed by Cohen.[18] There has been much new data since that evaluation, but the data at

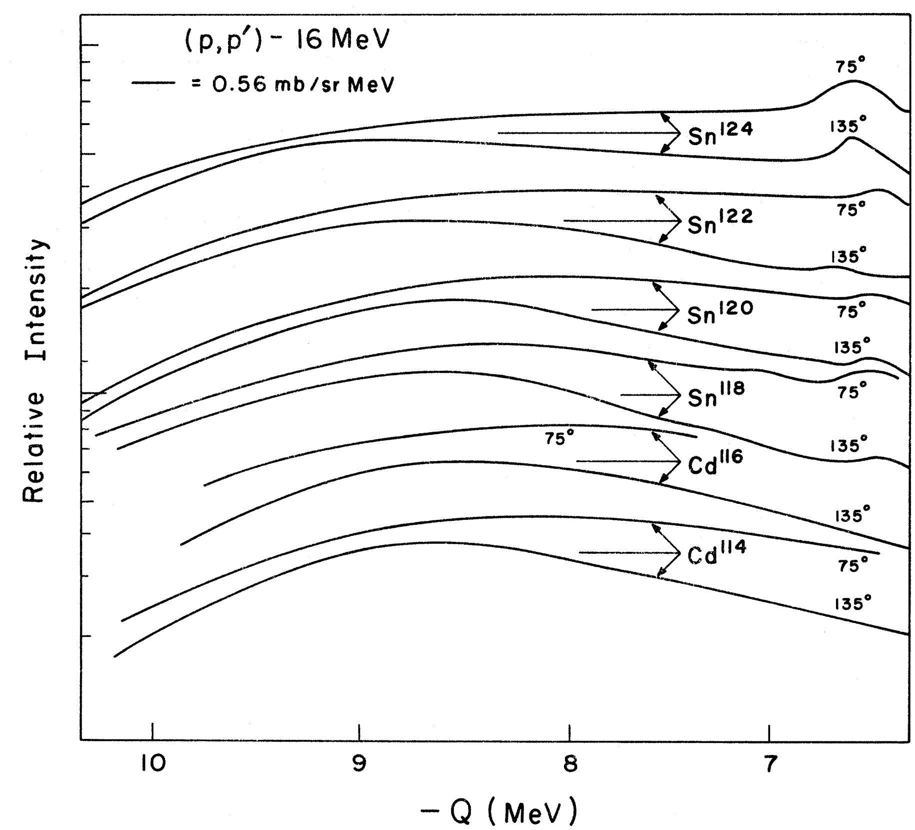

FIG. 17. Energy spectra from (p, p') reactions on various Sn and Cd isotopes with 16-MeV bombarding energy. Upper and lower curves of each pair are at 75 and 135°, respectively, and absolute cross sections are indicated by the horizontal lines indicating 0.56 mb/sr MeV.

higher energies ($E > 30$ MeV)[19] seems to confirm its conclusions – the activation cross sections for (p, n) reactions, which are indicative of neutron emission within ~8 MeV of the maximum available energy, are much lower than directly measured cross sections for (p, p') reactions in which the proton energy is within 8 MeV of its maximum. The new data in the lower-energy region under consideration here ($E < 20$ MeV) are mostly from direct measurements of neutron spectra[6] and seem to indicate that the $(p, p')/(p,n)$ cross-section ratio for E^* less than about 7 MeV is only about a factor of 1.5. Such a factor could be explainable within the framework of pre-equilibrium calculations,[20] but before this matter is settled, there should be measurements at higher bombarding energies to ease the process of separating equilibrium and pre-equilibrium neutrons.

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