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Direct and Compound Processes in Nuclear Reactions

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1. Introduction

Nuclear reactions are intrinsically very complicated and yet in some circumstances they show features of relative simplicity that enable them to be treated quite successfully by appropriate models, and it is through studies of such reactions that most of our knowledge of nuclear structure is derived. Among these models the most familiar refer to the two extreme situations, namely when the reaction passes from the initial to the final state either in a single step or by a very large number of intermediate stages. The former type of reaction, called direct, may be very well understood in most cases by the optical model for elastic scattering and by the various distorted wave Bom approximation theories for other reactions. The calculation of the reaction amplitude requires a mechanism to be postulated together with a prescription for the initial and final nuclear states, and comparison of the calculated cross-section with the experimental data allows the validity of these models to be assessed.

The other extreme type of reaction, proceeding through a large number of intermediate states of the compound nucleus, can be treated very well by statistical theories, of which the most successful is that due to Hauser and Feshbach, with several later refinements.

We know, of course, that reactions are not so simple as this and, indeed, it is surprising that such simple theories work as well as they do. If we consider the nuclear excitation process in detail, we find that it proceeds by a series of stages in which successively more and more nucleons are excited. At each stage, there is a definite probability that the reaction will proceed at once to the final state, and such processes give rise to the phenomena of intermediate structure. Reactions can thus take place in a few steps and, to them, the theories developed for the extreme cases are inapplicable. In many types of reaction such processes contribute significantly and so they must be considered in detail if we are to understand the observed cross-sections.

In this lecture, I would like to review some recent work on reactions that cannot be treated by the direct or by the compound nucleus theories alone. The simplest of these is the situation when both direct and compound processes contribute and my reason for mentioning this case is that the method of tackling such reactions was developed in a fruitful collaboration between São Paulo and Oxford (Sec. 2).

Many reactions passing through a few intermediate states have been studied in recent years and this work has led to an understanding of the function of doorway and hallway states, of which the most conspicuous examples are the isobaric analogue states. A more recent example is provided by the studies of alpha-particle transfer reactions made with heavy ions, and this will be discussed because it seems to be a relatively simple reaction that can be used to study some highly excited nuclear states (Sec. 3).

Another example of an intermediate reaction is provided by the semi-direct capture theory of photonuclear reactions. This theory, initially developed in another Oxford collaboration, has recently received confirmation through the work of Bergqvist and his colleagues, and is discussed in Sec. 4.

An important class of reactions is that proceeding by a small number of direct processes, each of which can be calculated in a familiar way. The necessary formalism for the case of two-step reactions has been developed by Glendenning and his colleagues and has already been successfully applied to understand reactions that are not dominated by the one-step process. Such reactions, discussed in Sec. 5, are now being studied in Oxford and are likely to prove a useful spectroscopic tool.

2. Direct and Compound Processes

If it proves impossible to interpret a reaction as proceeding wholly by a direct or wholly by a compound nucleus process, the next simplest situation is when they both contribute, but the contribution of intermediate processes still remains negligible. Such situations can easily be identified by measuring the excitation function at a particular angle with high energy resolution. These functions vary smoothly with energy for direct reactions and fluctuate violently even down to zero cross-section for compound nucleus processes. If both processes contribute, the cross-sections still fluctuate but less violently and about a mean that varies smoothly with

energy. Intermediate processes give cross-sections that fluctuate about local energy average that itself shows energy variations of width much greater than that of the underlying compound nucleus resonance. nd the absence of such behaviour indicates that such processes are negligible.

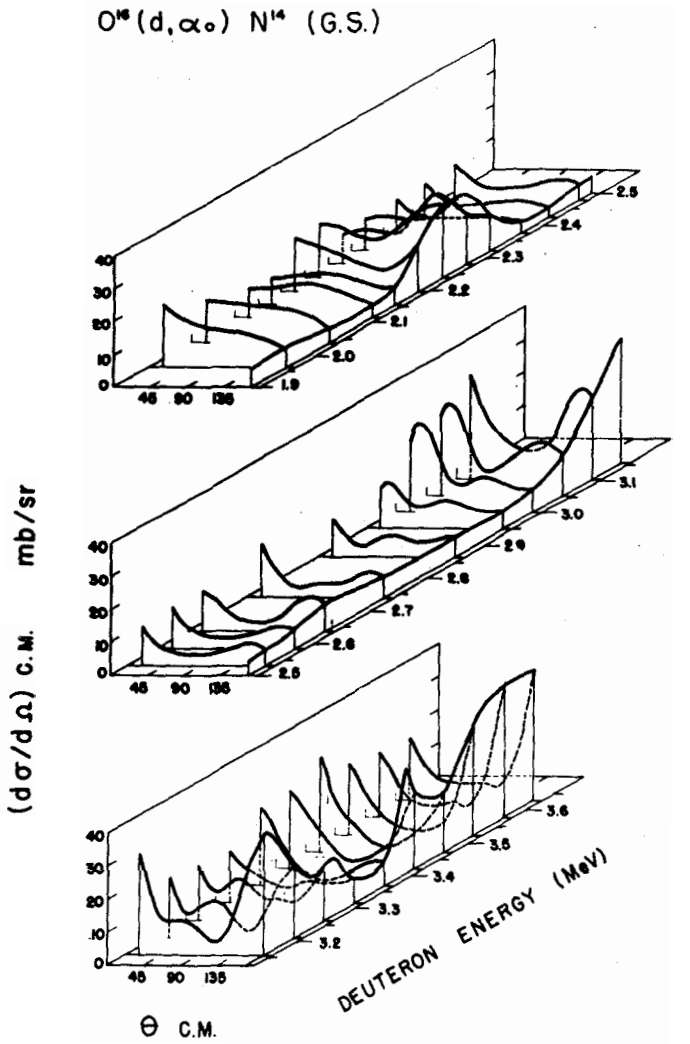

Fig. 1 - Angular distributions for the $O^{16}(d, \alpha)N^{14}$ ground state reaction as a function of energy (Dietzsch *et* al., 1968).

Examination of the excitation function thus suffices to identify reactions with substantial direct and compound nucleus components. The method of analysis will be illustrated by reference to the São Paulo data on deuteron reactions on light nuclei at low energies. These data are quite complicated and at first sight would appear difficult to understand. For example, Fig. 1 shows the cross section for the $O^{16}(d,\alpha)N^{14}$ reaction from 1.9 to 3.6 MeV. These cross sections show considerable variation both with angle and energy together with some overall trends, which indicate the presence of both compound nucleus and direct interaction components. The rapid energy variations can be understood as due to the superposition of large numbers of Breit-Wigner resonances in the compound system and the uniform background as due to the direct process. The scattering amplitude in these circumstances may be written

$$f = \sum_j \frac{a_j}{E - E_j + \frac{1}{2}i\Gamma_j} + f_{DI}\,, \tag{2-1}$$

where a_j, E_j and Γ_j are the amplitudes, energies and widths of the levels and f_{DI} the direct interaction amplitude. If one had extremely accurate measurements over the whole angular and energy range, perhaps with polarisation data as well, it might be possible to disentangle all these resonances and to determine their parameters individually. However, a short reflectionon the nature of Ericson fluctuations and on the exponential increase of level density with energy is enough to make clear that this is rather a hopeless task and in any case it is not certain that this information would be of great importance even if it wuld be obtained. So we do the next best thing, familiar in many other contexts and analyse, first, the energy-averaged cross sections and, second, the fluctuations of the cross sections about this average.

If we write the differential cross-section at a particular energy and angle as the sum of compound nucleus and direct interaction amplitudes

$$\sigma = |f_{CN} + f_{DI}|^2, \tag{2-2}$$

then the energy-averaged cross section is

$$\langle\sigma\rangle = \langle|f_{CN} + f_{DI}|^2\rangle = \langle|f_{CN}|^2\rangle + |f_{DI}|^2 \tag{2-3}$$

since the cross terms vanish because $\langle f_{CN}\rangle$ is zero. Thus

$$\langle\sigma\rangle = \sigma_{CN} + \sigma_{DI} \tag{2-4}$$

so that if we calculate the two components individually we can simply sum them to compare with the observed energy-averaged cross sections.

The coumpound nucleus cross sections may be calculated by the Hauser-Feshbach theory modified by the width fluctuation wrrection. For many reactions on light nuclei, the number of channels is so small that it is possible to take them all into account explicitly with the appropriate penetration factors calculated from the optical potentials in the channels concerned. This was done wherever possible and the usual expressions, involving an integral over the continuum and making use of level density functions, were only used for the closely-packed or unresolved levels. In the elastic channel, the direct or shape elastic contribution was calculated by the optical model and the (d, *p*) and (d, n) stripping cross sections by the distorted wave Bom approximation (DWBA). The formalism and numerical methods used in these calculations have been extensively described in previous publications.

There is a special difficulty in the analysis of these reactions that has not received much attention in the literature. The assumption made in the Hauser-Feshbach calculation is that some of the incident flux immediately passes into the outgoing elastic channel (shape elastic scattering) and the remainder forms the compound nucleus that subsequently decays into all the open channels including the elastic channel (compound elastic scattering). No acwunt is taken of the presence of direct interaction contributions to the reaction channels other than the elastic channel These direct interaction contributions are frequently prominent in deuteron reactions on light nuclei and have the effect of taking flux immediately from the incident channel so that it never reaches the compound nucleus. Thus, if such direct processes occur, all the compound nuclear cross sections are reduced and, if this is not taken into account, all the cross sections obtained from the Hauser-Feshbach theory are too high (Hodgson and Wilmore, 1967).

In principle it is not difficult to allow for this effect. If we knew the direct-interaction cross sections in all the reaction channels, we could simply subtract the corresponding flux from that previously assumed to enter the compound nucleus and repeat the Hauser-Feshbach calculation as before. This would, of course, have to be done for each partial wave individually since the direct interaction process usually takes more flux from the higher partial waves. In practice, however, this cannot easily be done as the direct interaction contributions to all the reaction channels are not known.

Until this accurate calculation can be made the effect may be allowed for approximately, by assuming that the compound nucleus cross sections

in all the reaction channels are reduced by the same factor, called the reduction factor R. If there are one or more channels with negligible direct interaction component, this reduction factor may then be determined as the ratio of the measured to the calculated cross section. If there are no such channels, it can be found by the requirement that the sum of the direct interaction and the reduced compound-nucleus cross sections gives the optimum fit to the data.

The assumption that the reduction factor is the same in all channels is unlikely to be exactly true, but a series of calculations in which the flux entering the compound nucleus in the various partial waves was varied showed that it is unlikely to change from channel to channel by more than about 10%, so the approximation of equal reduction factors is a useful one.

The differential cross sections for deuteron elastic scattering by light nuclei show the characteristic Coulomb-dominated peak in the forward direction and fáll rapidly as the scattering angle increases with superposed oscillations due to the nuclear interaction. The excitation functions of the cross sections at large angles show fluctuations characteristic of the compound nuclear process, so the data must be averaged over energy before they can be compared with optical model and Hauser-Feshbach calculations. It is not easy to determine the interval over which this averaging must be carried out: the relevant cnteria are that the averaging interval must be much greater than the mean width Γ of the underlying compound nucleus resonances and also much less than the energy over which the average cross sections change appreciably. Since Γ is usually several hundred KeV for light nuclei and the incident deuteron energies are only a few MeV, it is not clear that these conditions can be simultaneously satisfied. However, some calculations of Dallimore (1966) indicated that $AE \geq 2\Gamma$ is usually sufficient, so it is usual to average the data over intervals of around 200-500 KeV.

In view of the ambiguities in the deuteron optical potential, it is preferable to start the analyis with a potential known to give a good account of cross sections of similar reactions. The parameters of this potential may then be iterated to optimise the fit to the energy-averaged data using the appropriate reduction factor determined in the way described in the previous section. Some typical results of such a calculation are shown in Fig. 2

The (d, p) and (d, *n*) stripping cross-sections are calculated by the **DWBA** and the spectroscopic factors for each reaction are given by the requirement that the normalised **DWBA** cross-section when added to the com-

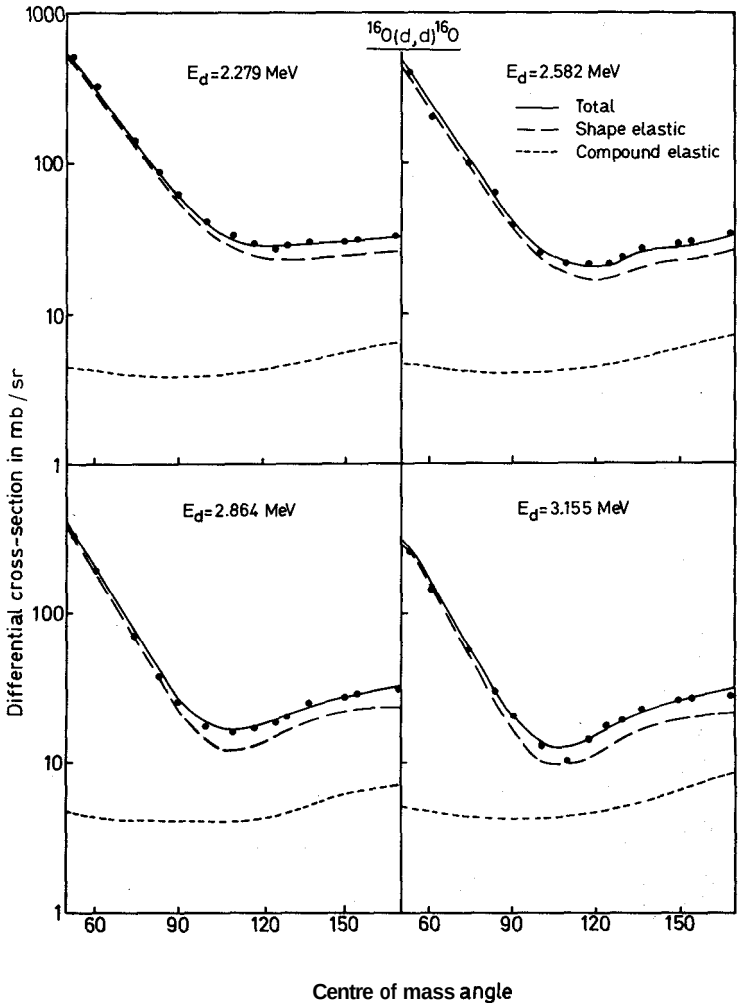

Fig. 2 - Energy-averaged differential cross-sections for the elastic scattering of deuterons by O^{16} compared with optical model and Hauser-Feshbach calculations (Dietzsch *et al.*, 1968).

pound nucleus component gives the best fit to the measured cross section in the region of the main peak. Some typical results of such a calculation are shown in Figures 3 and 4 and indicate that most of the cross section can be accounted for in this way. A further test of the correctness of the analysis is the independence of the extracted spectroscopic factors of the

incident deuteron energy. Some typical results for analyses at different energies are shown in Table 1 and it is seen that this independence is found within the statistical uncertainties.

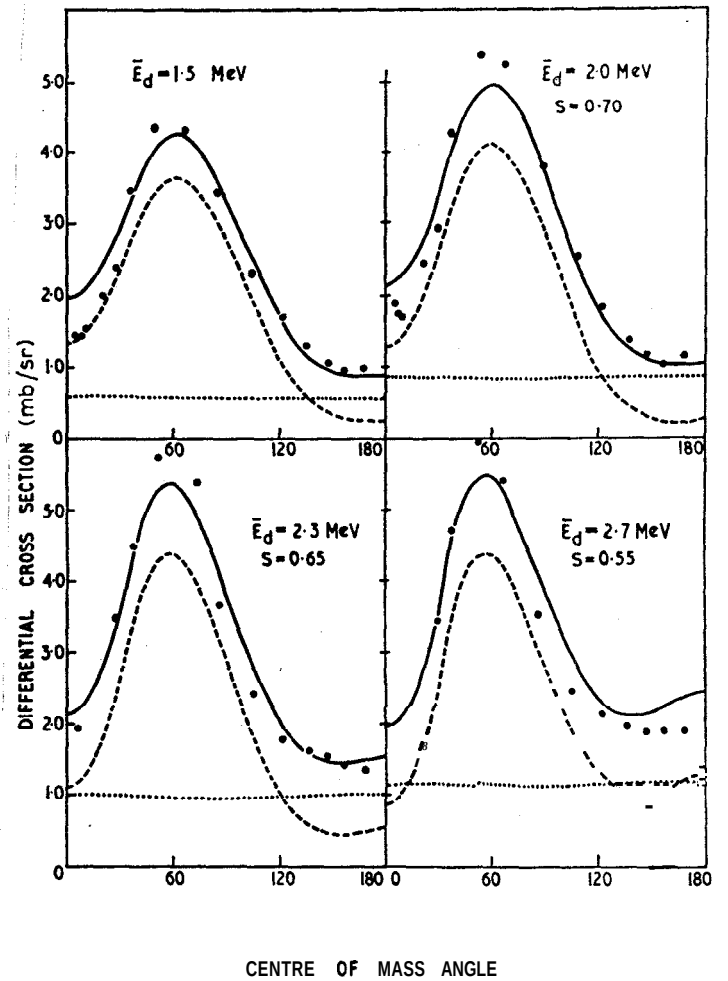

Fig. 3 - Energy-averaged differential cross-sections for the $N^{14}(d, p_4)N^{15}$ (7.16 MeV) reaction compared with distorted wave and Hauser-Feshbach calculations. (Gomes Porto et *al.*, 1968).

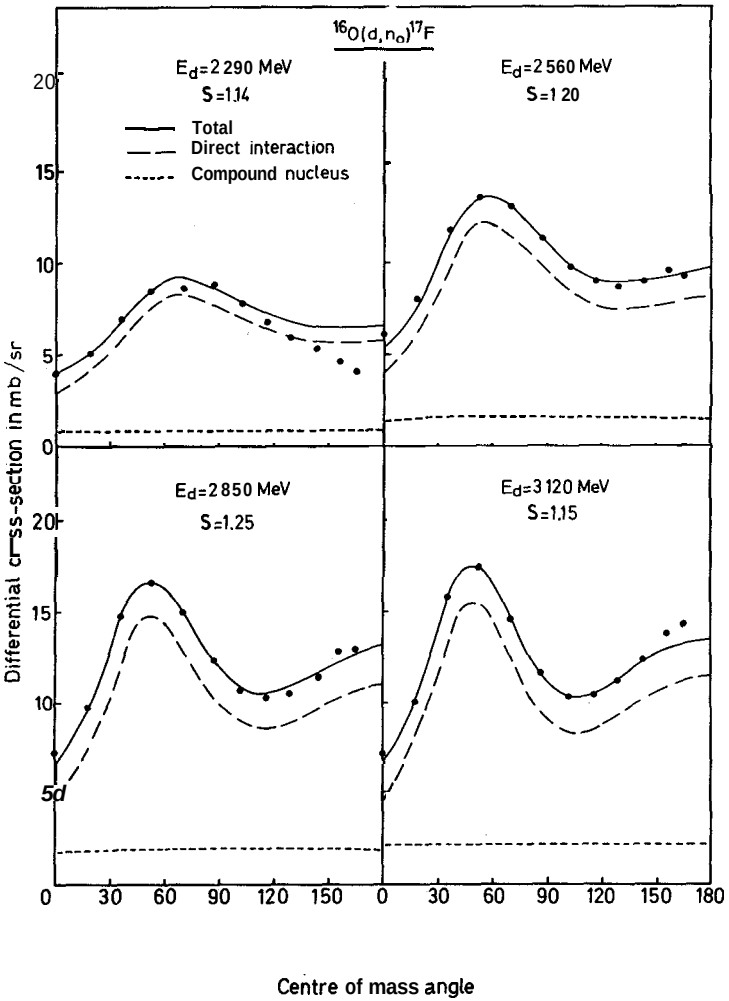

Fig. 4 - Energy-averaged differential cross-sections for the $O^{16}(d, n_0)F^{17}$ reaction compared with distorted wave and Hauser-Feshbach calculations. (Dietzsch *et* al., 1968).

Most of the useful information can be extracted from the energy-averaged cross section in this way but it is also interesting to examine the fluctuations about the average to see if they are consistent with what we already know about the reactions. This may be done using the theory of Ericson.

Reaction	(d, p_4) (7.16 MeV)		(d, p_5) (7.31 MeV)		(d, p_6) (7.57 MeV)	
$J^\pi(l_n)$	$5/2^+(2)$		$3/2^+(0)$		$7/2^+(2)$	
Potentials	1	2	1	2	1	2
Mean Energy (MeV)						
1.520	0.78	0.92	0.75	0.83	0.90	1.00
1.990	0.59	0.70	0.81	0.74	0.84	0.91
2.324	0.55	0.65	0.72	0.67	0.77	0.90
2.733	0.50	0.55	0.62	0.56	0.80	0.85
Average	0.60	0.70	0.72	0.70	0.82	0.91
Normalised	0.62	0.62	0.74	0.62	0.85	0.80
Theory*	0.62		0.64		0.73	

* Halbert, 1956.

Table 1 - Spectroscopic factors for the reaction $N^{14}(d, p)N^{15}$ using potentials 1 and 2 (Gomes Porto et al., 1969).

The fiuctuation of the measured cross sections about their average values is an indication of the presence of compound nucleus contributions and, in principle, it is possible to estimate the proportion of compound nucleus component from the magnitude of the measured fiuctuations. The inherently low statistical accuracy of any measure of fluctuations, together with the difficulties connected with the finite range of the experimental data, impose insuperable limits to the accuracy of these estimates so that the value obtained is less precise than that found from the energy-averaged cross sections.

A convenient measure of the magnitude of the fiuctuations is provided by the autocorrelation function

$$C_0(0) = \frac{1}{N}(1 - y^2) = \frac{\langle \sigma^2(E) \rangle - \langle \sigma(E) \rangle^2}{\langle \sigma(E) \rangle^2}, \qquad (2\text{-}5)$$

where $y = \sigma_D/(\sigma_D + \langle \sigma_C(E) \rangle)$, $\langle\ \rangle$ denotes an energy average, N the number of contributing channels and a, and σ_E the direct and compound nucleus contributions to the cross-sections σ_E. The value of the number of computing channels, N, may be calculated by the formalism of Brink, Stephen and Tanner (1964) or, alternatively, an upper limit for its value is given by the relation

$$N = \tfrac{1}{2}[(2I_A + 1)(2I_B + 1)(2i_A + 1)(2i_B + 1) + k], \qquad (2\text{-}6)$$

where I_A and I, are spins of the target and the residual nucleus respectively i, and i, are spins of the incident and emitted particles and k a constant which takes on the values 0 or 1 in order that N be integral.

The relation *(2-5)* for the autocorrelation requires that σ_D be independent of energy and that σ_C has a constant local mean throughout the energy interval used. In light nuclei with wide compound states, the averaging must be carried out over intervals of several MeV in order that the analysis be statistically meaningful. Over these intervals, the mean cross-section may vary considerably and it is thus necessary to extend the theory of fluctuating cross-sections to allow for these changes. This has been done for the cases where eíther the direct or the compound nucleus contribution predominates. For the *(d,d)* and *(d,*p,) reactions the reaction is predominantly direct and assuming that the energy dependence is of the form $(AE^2 + BE + C)$ relative to an energy origin at the centre of the experimental range gives a corrected autocorrelation function $C_1(0)$ given by

$$C_1(0) = \frac{1}{N}(1 - y_M^2) = \frac{\langle\sigma^2(E)\rangle - \langle\sigma(E)\rangle^2}{\langle\sigma(E)\rangle^2} - \frac{\Delta^2\{\frac{1}{15}A^2\Delta^2 + B^2\}}{12\langle\sigma(E)\rangle^2} \qquad (2\text{-}7)$$

where A is the energy interval under consideration and y_M the average fractional direct contribution. A further correction called the bias may be applied to take account of the finiteness of the energy interval A. The autocorrelation then becomes (Dallimore, 1966)

$$C_2(0) = C_1(0) + \frac{a(1 - y_M^2)(N + 1 - y_M^2)}{N\{N + a(1 - y_M^2)\}}, \qquad (2\text{-}8)$$

where $a = (2/n)\mathrm{tg}^{-1} n - (1/n)^2 \log_e(1 + n^2)$ and $n = \Delta/\Gamma$.

The calculated values of $C_0(0)$, $C_1(0)$ and $C_2(0)$ for the reactions $O^{16}(d,d)O^{16}$ and $O^{16}(d,p_1)O^{17*}$ are compared in Table 2 as a function of angle and this shows the importance of taking these corrections into account.

$^{16}O(d,d)^{16}O$				$^{16}O(d,p_1)^{17}O^*$			
θ	$C_0(O)$	$C_1(O)$	$C_2(O)$	θ	$C_0(O)$	$C_1(O)$	$C_2(O)$
73.7	0.228	0.048	0.063	70.7	0.068	0.027	0.035
83.1	0.296	0.035	0.046	79.8	0.057	0.020	0.026
90.0	0.323	0.040	0.052	86.7	0.073	0.026	0.034
99.7	0.331	0.047	0.062	96.4	0.131	0.040	0.053
109.5	0.277	0.057	0.075	106.3	0.215	0.065	0.085
116.7	0.191	0.065	0.085	113.6	0.267	0.087	0.116

Table 2 - Values of the autocorrelation functions for $^{16}O(d,d)^{16}O$ and $^{16}O(d,p_1)^{17}O^*$ showing the effect of correcting for the energy-dependent direct contribution ($C_1(O)$) and for the bias (C, *(O)*); Dietzsch *et al.*, 1968.

The compound-nucleus cross sections calculated from the autocorrelation coefficients are shown in Table 3 as a function of angle compared with the corresponding compound-nucleus cross sections calculated from the energy-averaged cross sections. On the whole, the agreement is satisfactory, even though an estimate of the ratio between the mean level spacing and the mean level width shows that the statistical theory is barely applicable to these particular reactions.

$^{16}O(d, d)^{16}O$				$^{16}O(d, p_1)^{17}O^*$			
θ	$\langle\sigma_T\rangle$	$\langle\sigma_c\rangle$HF	$\langle\sigma_c\rangle$FL	θ	$\langle\sigma_T\rangle$	$\langle\sigma_c\rangle$HF	$\langle\sigma_c\rangle$FL
73.7	99.6	4.2	14.7 ± 3.9	70.7	23.5	1.5	2.2 ± 0.6
83.1	59.6	4.0	6.4 ± 1.6	79.8	23.8	1.4	1.6 ± 0.4
90.0	41.5	4.0	5.1 ± 1.3	86.7	22.2	1.4	2.1 ± 0.5
99.7	27.6	4.0	4.0 ± 1.1	96.4	19.6	1.4	2.9 ± 0.8
109.5	22.5	4.2	4.0 ± 1.1	106.3	16.5	1.5	4.0 ± 1.2
116.7	21.5	4.3	4.3 ± 1.3	113.6	14.6	1.5	5.0 ± 1.8

Table 3 - Average total cross sections (mb/sr) for the reactions $^{16}O(d, d)^{16}O$ and $^{16}O(d, p_1)^{17}O^*$ from 1.96-3.64MeV and averaged compound nucleus contributions obtained from the Hauser-Feshbach (HF) and from the fluctuation analysis (FL) (Dietzsch *et al.*, 1968).

The distribution of the measured cross section about the mean value may also be used to estimate both the equivalent number of contributing channels and the proportion of direct interaction. Once again the comparison cannot be made sufficiently accurate to give reliable values of these quantities but it is, nevertheless, interesting to compare the measured distributions of cross sections with the calculated curves, using the known values of the relative proportions of the direct-interaction and compound-nucleus components in the interaction concerned. This distribution is given by the expression

$$P_N(y, y_d) = \frac{N}{1-y_d}\left(\frac{y}{y_d}\right)^{\frac{1}{2}(N-1)} \exp\left\{-\frac{N(y+y_d)}{1-y_d}\right\} I_{N-1}\left(\frac{2N\sqrt{yy_d}}{1-y_d}\right), \quad (2\text{-}9)$$

where I_n is a Bessel function of imaginary argument. Such a comparison is shown in Fig. 5 for the reaction $^{24}Mg(d, p)^{25}Mg$ and shows overall agreement within the statistical uncertainties.

It is thus possible to conclude that an analysis of the fluctuations in the reaction cross-section gives values of the compound nucleus contribution and of the equivalent number of contributing channels that are consistent with those found from analyses of the energy-averaged cross sections.

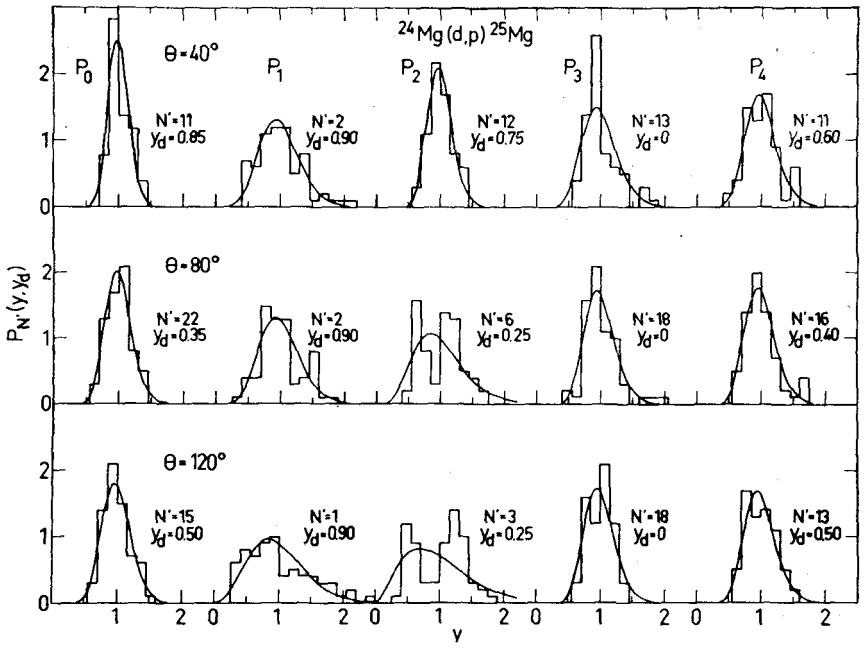

Fig. 5 - Distribution of the differential cross-sections for the reaction $Mg^{24}(d,p)Mg^{25}$ about their mean value and the distribution of the probability $P_N(y, y_d)$ at 40, 80 and 120°. (Gallmann *et al.*, 1966c).

These calculations show that the general features of the cross sections of many deuteron reactions on light nuclei at low energies can be accounted for quite well by standard reaction theories. The analysis of the (d, p) and (d, n) stripping cross-sections by the DWBA gives spectroscopic factors containing useful information on the structure of the residual nuclei and the analyses of compound nucleus components in the various reaction channels provides a method of determining the spin of the final states. The fluctuation analysis confirms, in general to somewhat lower accuracy, the results obtained by the analysis of average cross-sections and in addition gives an estimate of the mean width of the compound nucleus resonances.

The same type of analysis can be made for reactions on light nuclei initiated by protons and by other particles, with similar results. (Berinde et *al.*, 1971; Frickey et al., 1971).

These analyses constitute a unified treatment of the reactions in that the cross sections in all the open channels are calculateú from the same set of optical potentials. These potentials are determined from the appropriate elastic scattering and apart from the spectroscopic factors determineú from the normalisation conditions there are no other adjustable parameters in the model. Such analyses give a basic understanding of the reaction processes taking place so that it is possible to plan future experiments to answer specific questions in the most efficient way.

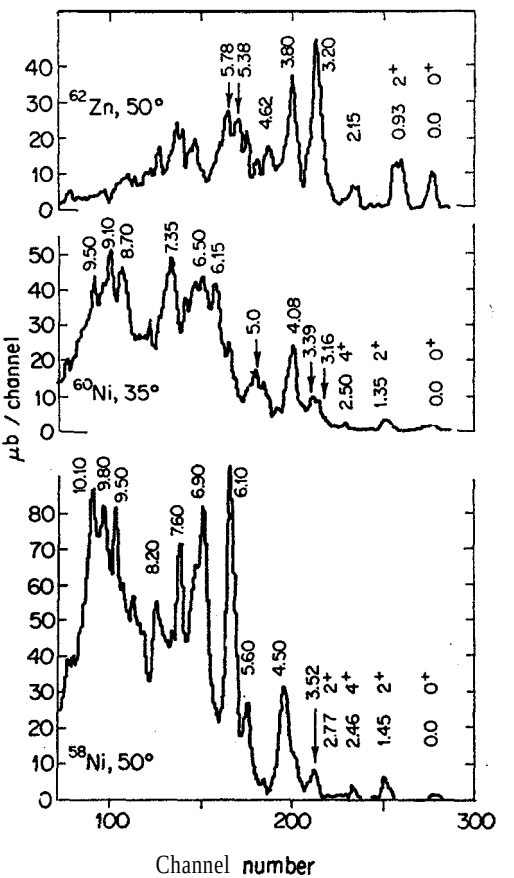

Fig. 6 - Spectra of outgoing Cf^2 ions from the reactions $Fe^{54,56}(O^{16}, C^{12})Ni^{58,60}$ and $Ni^{58}(O^{16}, C^{12})Zn^{62}$ at 48 MeV incident energy (Faraggi et al., 1971).

3. Intermediate States in Alpha-Transfer Reactions

Some recent studies, by Faraggi and collaborators (1971), of the (O^{16}, C^{12}) alpha-transfer reactions on isotopes of iron, nickel and zinc show strong groups of outgoing particles at energies corresponding to excitations of the compound nucleus where the level density is so high that a continuous distribution is expected. Some typical spectra are shown in Fig. 6, and the unexpected groups of particles are indicated. These groups correspond to short-lived states excited during the process of nuclear excitation and they may be considered as doorway states in alpha-particle excitation.

These states have been interpreted by Gillet and collaborators as two neutron – two proton or quartet states, and they have made some calculations of their structure. Lane (1971) has suggested that they may also

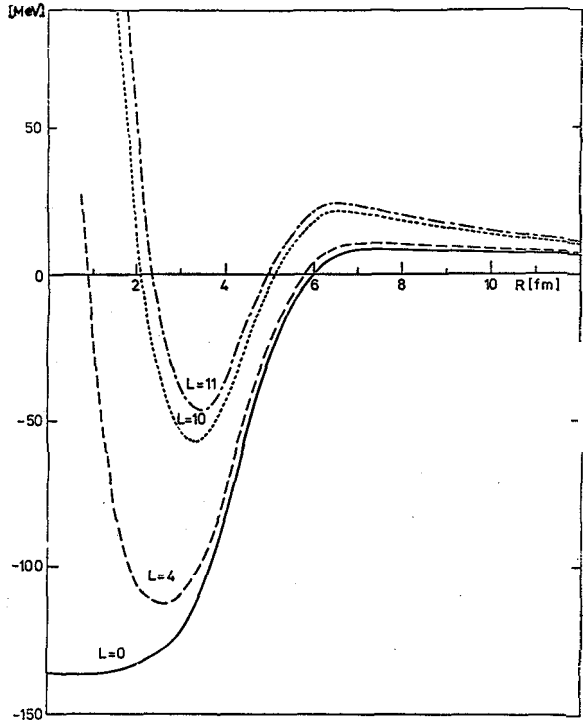

Fig. 7 - Total optical potentiai for alpha-particles as a function of radial distance for different partial waves (Dudek and Hodgson, 1971).

be considered, very simply, as alpha-particle resonant states in standard optical potentials, and preliminary calculations using this model have been made by Dudek and Hodgson (1971).

The possibility of such resonant states follows from the form of the optical potential. Gruhn and Wall (1966) have shown that the total potential for alpha-particles, obtained by adding the optical, angular momentum and Coulomb terms, shows minima for particular values of the orbital angular momentum, as illustrated in Fig. 7. For most partial waves, the absorbing poteniial quenches the incoming wave and so no resonance can occur in in these minima, but if the absorption in a particular partial wave is very small this restriction no longer applies. It has been shown that such reductions do occur in alpha-particle interactions because the outgoing channels cannot accept the high momenta brought in by the incident beam (Chatwin *et* al., 1970).

A theory able to account for these resonant states in detail depends on the detailed structure of the nuclei and can be studied by the quartet model. The resonant state model is able to give those systematic features that remain similar for all the nuclei and can be represented by a simple potential. We do not, therefore, expect to predict the exact energies and other characteristics of the states but only to see if some overall features such as their density and widths can be reproduced.

The energies of the unbound states in the optical potential were calculated with a standard Saxon-Woods form factor (r, $= 1.15f$, a $= 0.65f$) and the results for Ni^{58} are shown in Fig. 8. Severa1 features are immediately apparent:

1. The states group into bands and each band corresponds to the states of a particular number of oscillator quanta;
2. The orbital angular momenta of the states in each band are either all even or all odd. The band of N quanta contains states with L $= 0, 2, 4, \ldots,$ N for L even and L $= 1, 3, 5 \ldots$ N for L odd;
3. The density of states is very similar to that of the observed states. This is shown in Fig. 8 by the superposition of the observed energy spectrum on the calculated one, at a position corresponding to a potential of depth $U \sim 132$ MeV, which is physically very reasonable;
4. There is a tendency for one state to be rather separated from the remainder and this is found experimentally;
5. The variation of the energies of the states with the depth of the potential is almost linear but the rates of variation are slightly different, so that the lines on Fig. 8 are not quite parallel. Subsidiary calculations showed

that the ordering of the states within a band is very sensitive to the form factor chosen, particularly to the diffuseness parameter;
6. The gaps between the bands are approximately as broad as the bands themselves. This is in accord with the experimental data for the $^{54}Fe(^{16}O, ^{12}C)^{58}Ni$ reaction; the states are no longer found at excitation energies above 12 MeV.

This comparison shows that the calculations are entirely successful in giving the overali features of the observed resonant states. To confirm the interpretation, it is of course necessary to make distorted wave calculations in which the wavefunction of the captured particle is that of an alpha-particle in a potential well. The resonant structure will then appear automatically as the wavefunction is greater at the resonant energies.

Comparison of the calculated and measured differential cross-sections may give the orbital angular momentum transfer, although the preliminary results give rather featureless angular distributions and the situation may be similar in this respect to those found for the sub-Coulomb stripping of deuterons. It is an important test of the model to determine the angular momentum transfers because the model makes very definite predictions of the spins of these states (see 2. above).

It may prove possible to determine the orbits of the nucleons contributing to the alpha-particle states by calculating the appropriate overlap integral

If this interpretation of the quartet states is correct, it should be possible to detect them in alpha-particle elastic scattering, just as unbound nucleon single particle states appear as resonances superposed on the Coulomb plus nuclear background in the excitation functions for elastic scattering at backward angles. The states observed by Faraggi et al. correspond to incident alpha-particles of less than about 4 MeV, which is probably too far below the barrier to be detected in this way, but it may be possible to detect states at higher energies and experiments are already under way in Oxford to investigate this possibility (Grace and Ayres de Campos, 1971).

It is unlikely that the model will be able to give reliable absolute cross-sections, particularly when the alpha-particle is capture. into the lower states, as the presence of other nucleons is likely to block the available states and such detailed nuclear structure effects are beyond the scope of the model. It might, however, prove practicable to represent such effects by a single parameter for each state and to calculate the value of this parameter by a detailed nuclear model.

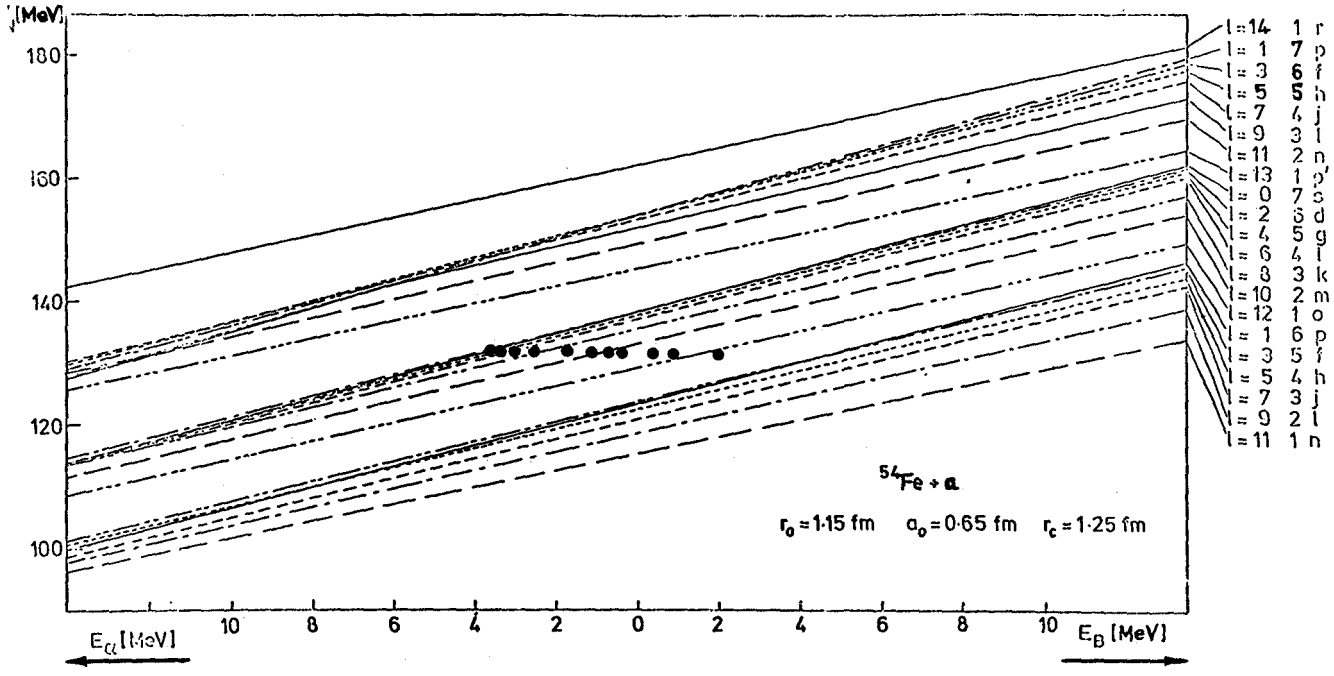

Fig. 8 - Calculated energies of alpha-particle states in an optical potential with typical experimental data superposed (Dudek and Hodgson, 1971).

4. Semi-Direct Processes in Photonuclear Reactions

The theories of photonuclear capture have developed over the years as data of higher precision have demanded more sophisticated models. The simplest model is the familiar compound nucleus theory which assumes that the incident neutron is captured to form an excited compound nucleus that persists for a long time (on the nuclear scale) before decaying to its ground state by cascade emission of gamma rays. According to this model, the energy brought in by the incident nucleon is shared and reshared among all the nucleons of the compound nucleus so that statistical equilibrium is established. The model predicts that the gamma rays are emitted symmetrically in the forward and backward directions and use of the statistical theory of nuclear level densities also allows their energy distributions to be calculated.

This compound nucleus theory accounts very well for the spectra of particles emitted from some low energy nuclear reactions and is also satisfactory for photonuclear reactions in the same energy region. As the energy increases beyond about 4 MeV, however, the measured cross-sections become progressively greater than those given by the compound-nucleus theory and at 14 MeV, for example, the theory is low by one to two orders of magnitude for light nuclei and four to five orders of magnitude for heavy nuclei (Lane and Lynn, 1959).

Clearly, another mechanism is operating at higher energies and several authors have proposed that the incident particle makes a direct radiative transition to the lower single-particle states of the compound system. Calculations by Daly, Rook and Hodgson (1964) showed that this model can account for the chief features of the measured cross-sections at higher energies, though the absolute magnitudes are still about an order of magnitude too low. Some additional process that enhances the cross-sections above their direct capture values must be taking place.

A possible mechanism for this enhancement was found by taking collective effects into account. This semi-direct model, as it is called, assumes that the incident particle is first captured into a lower single-particle orbit with simultaneous excitation of the giant dipole resonance of the target. This intermediate state then decays with gamma emission and the intensity of the gamma rays is enhanced by the collective nature of the excitation. Calculations by Clement, Lane and Rook (1965) showed that the enhan-

cement is of the correct order of magnitude to give the measured cross-sections.

The recent measurements of Bergqvist et al. (1971) have provided an accurate test of this theory. They chose the nucleus ^{208}Pb whose doubly magic nature ensured that good single-particle wavefunctions are available for the low-lying compound nuclear states. Measurements were made over the whole giant dipole resonance and one of their gamma ray spectra is shown in Fig. 9 together with the results of calculations using the compound-nucleus theory (dashed line) and the semi-direct capture theory (full line). The compound-nucleus theory accounts very well for the low energy gamma rays, indicating that the last stages of the de-excitation of the compound nucleus proceed by a statistical process; but it is quite unable to account for the gamma rays of higher energy that are emitted in the initial stages of the capture process. The semi-direct theory succeds very well, however, and even describes some of the detailed structure of the experimental results.

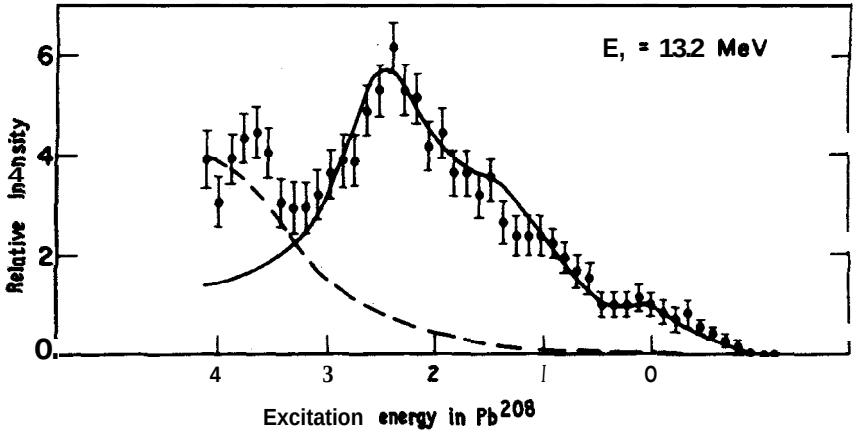

Fig. 9 - Spectrum of gamma ray from the reaction Pb^{208}(n, y) for 13.2 MeV neutrons. - - - Prediction of compound nucleus theory. — Prediction of semi-direct capture theory (Bergqvist et *al.*, 1971).

The calculations of the semi-direct cross-section made use of the energies of the single-particle states of ^{209}Pb and the position and width of the giant dipole resonance obtained in previous investigations. As there are

still some uncertainties remaining in the theory, the curves were normalised to the data over the 'upper portions of the spectra. It is unfortunate that the authors do not give their normalizing factor so that the magnitude of the remaining discrepancy is unknown In spite of this uncertainty about absolute cross-sections, these new experiments provide impressive evidente in support of the semi-direct theory of photonuclear capture. It will be necessary to perform further experiments and calculations to check that the absolute magnitudes agree, and it is also to be hoped that experiments on other nuclei will be undertaken so that the theory can be verified for a large number of nuclei. The more complicated phenomena associated with capture by nuclei with several nucleons outside the closed shells are particularly good candidates for study, for there are already some anomalous effects that await a detailed explanation.

5. Semi-Direct Processes in Nucleon Transfer Reactions

Many successful analyses of nucleon transfer reactions have been made by assuming that the dominant mechanism is a direct process from the initial to the final state and then evaluating the transition matrix element by the distorted wave Bom approximation. This approach is particularly successful when the reaction populates states of a strongly single-particle character, but becomes inadequate if the single-particle strength is small, or if the direct process is inhibited in some other way, for example by a selection rule. In such cases, the cross sections may be quite small and they are not given at all well by the simple distorted'wave theory.

For these reactions, it is useful to consider the contribution of processes in which the reaction proceeds by more than one step; these are referred to as *multistep* or semi-direct processes. Particularly important semi-direct processes occur when the target nucleus is first excited by the incoming particle, and then the nucleon transfer reaction takes place to this state, or when the residual nucleus is similarly excited by the emerging particle. These pre- and post-excitation processes can easily be computed by the coupled-channels formalism and the resulting amplitudes incorporated into the distorted-wave nucleon transfer formalism by the method developed by Ascuitto and Glendenning and used by them to study (d, p) and (*p*, t) reactions.

This model has been applied in Oxford by Dudek and Edens (1971) to calculate the cross-section of the (d, h) reaction on the strongly deformed

nucleus Ne^{20} to the 2.78, $9/7^+$ level, in F^{19}. This reaction cannot proceed by the direct transfer of an *s* or a d particle, and distorteú wave calculations assuming a $1g\ 9/2$ transfer require an improbably large spectroscopic factor and give rather a poor fit to the observed differential cross-section (Kaschel et al., 1970). Dudek and Edens included the effect of pre- and post-excitation in their calculations, as indicated schematically in Fig. 10.

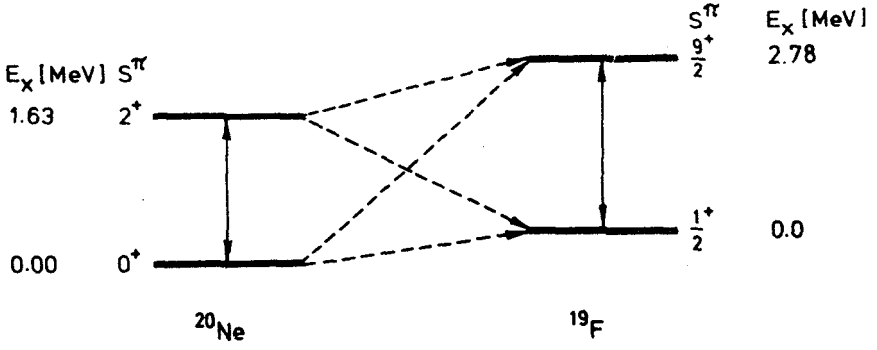

Fig. 10 - Schematicrepresentation of the semi-direct pick-up process on ^{20}Ne. The continuous lines represent inelastic scattenng reactions in both deuteron and helium channels which are taken into acwunt, while the dashed lines represent pick-up reactions (Dudek and Edens, 1971).

The calculations were made in two stages. Firstly the usual system of coupled equations for deuteron inelastic scattering were solved and the source term for the outgoing helions constructed. The deuteron system was solved subject to the boundary conditions that only the ground state channel has an incoming wave while all other channels may have outgoing waves. Secondly, the S-matrix elements for the (d, h) reaction were obtained by applying the physical boundary condition that there are only outgoing waves in the solution of the inhomogeneous system of equations describing the scattering in the residual system. The parameters of the deuteron and helion potentials were chosen to fit the appropriate elastic and inelastic scattering data.

The effects of including the various possible multistep processes in the calculation of the cross-section are shown separately in Fig. 11 and together in Fig. 12 and it is clear that the coupling between the 0^+ ground state and 2^+ excited state is appreciable and that íts inclusion substantially

improves the fit to the data. The two curves in Fig. 12 correspond to calculations using the Nilsson and shell model spectroscopic amplitudes.

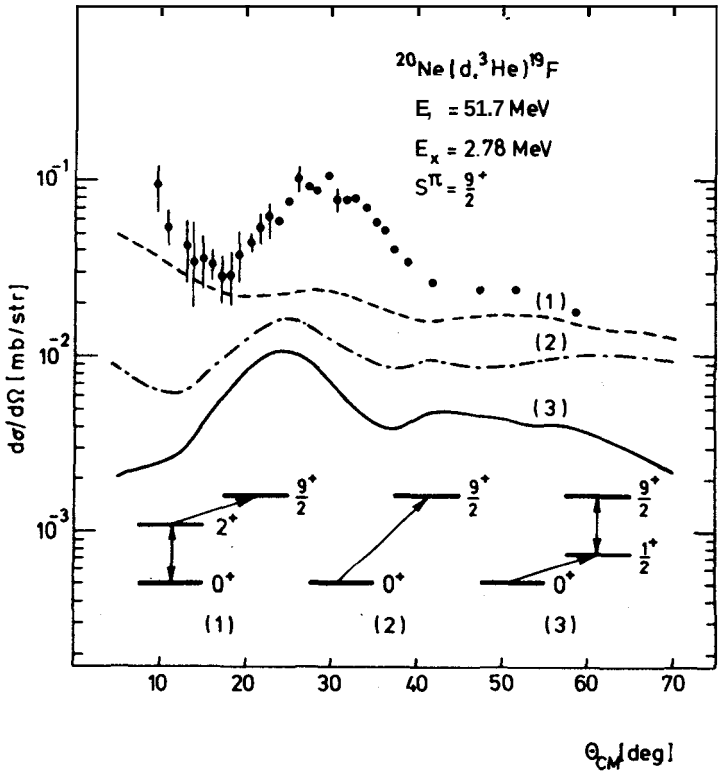

Fig. 11 - Comparison between the experimental data and various calculations for the $^{20}Ne(d, {}^{3}He)^{19}F$ reaction leading to the 2.78 MeV, $9/2^+$ state. The calculations labelled 1, 2 and 3 consider inelastic effects in the incoming channel, a direct $g_{9/2}$ pick-up and inelastic effects in the outgoing channel respectively (Dudek and Edens, 1971).

This formalism thus enables many reactions to be analysed that cannot be adequately understood as a single-step reaction, and the detailed comparison with experimental data enables the validity of the model used to describe the structure of the interacting nuclei to be assessed.

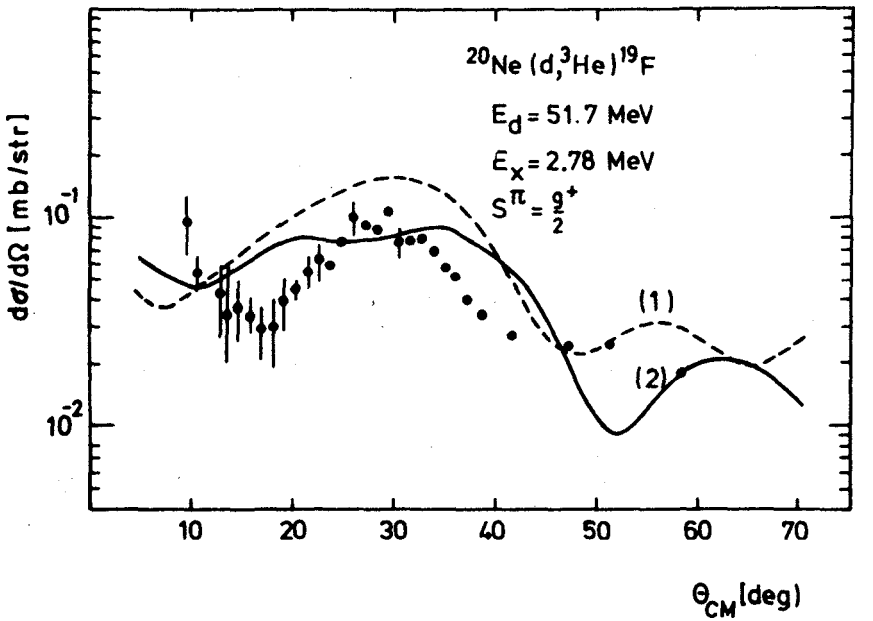

Fig. 12 - Companson between the differential cross section for the $^{20}Ne(d, {}^{3}He)^{19}F$ reaction leading to the 2.78 MeV, $9/2^{+}$ state and calculations which include all the possible reaction processes depicted in Fig. 10. The spectroswpic amplitudes calculated from the Nilsson model and the shell model yield cumes (2) and (1) respectively (Dudek and Edens, 1971).

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