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DIRECT REACTIONS WITH LIGHT IONS*

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1. Introduction

First I must start with the usual disclaimers! Copies of some 170 contributed papers (about 1/4 of the total) were sent to me as probably relevant to my talk and this is only an indication of the great number of published papers on direct reactions. Clearly I cannot summarise this vast field in 30 minutes so I have chosen some highlights that appeal to me. The omissions reflect my personal interests rather than value judgments. In particular I will not discuss heavy ion transfer reactions, despite their current importance; undoubtedly they will receive attention elsewhere in this meeting. While they provide some exciting new points of view and exhibit their own idiosyncracies, they also share many features in common with light ion reactions, especially those involving the light heavy ions ^{3}He and ^{4}He.

There has been a revival of interest in studying a region of excitation in the nuclear spectrum which previously has been rather neglected, namely the lower part of the continuum with excitation energies of the order of 10 MeV or more. For example, (α,α') spectra in this region show an interesting plateau or "mesa"[1] which has been interpreted as due to the intermediate formation and decay of ^{5}He. In addition there is the possibility of learning about some gross (non-statistical) properties of nuclei. Giant resonances have been seen in inelastic scattering[2] which correspond not only to the well-known giant-dipole but also to a new giant quadrupole oscillation. These are discussed in other talks here. We may expect that other resonances of this type will be discovered. "Giant resonances" are also observed[3] in (p,d) and (^{3}He,α) spectra for the excitation of deep hole states, corresponding to pick-up of a nucleon from the target, not from the valence shell but the next deeper major shell. (Of course, some deep hole states have been seen previously in (p,2p) and (e,e'p) reactions[4].) One is tempted to speculate that other aspects of the underlying microstructure of nuclei may manifest themselves in this region of high excitation energies.

2. Beyond the DWBA

For almost two decades the description of direct reaction phenomena has been dominated by the distorted-wave Born approximation (DWBA), which is a first-order "theory" (although there is still considerable uncertainty as to what theoretical series, if any, it may be the first term of!). Indeed, "first order process" and "direct reaction" have been taken as almost synonymous. The coupled-equations approach[5] to inelastic scattering was the first serious departure from the DWBA. The last few years have seen other attempts to go beyond the first-order DWBA for transfer and charge-exchange reactions and these have had some remarkable results. Fig. 1 shows schematically some of the physical processes for a reaction $A(a,b)B^*$. Besides the direct, one-step process $A \rightarrow B^*$, which is the only one the DWBA can describe, there are various indirect routes.

We may have inelastic scattering before and after an (a,b) transfer reaction, e.g. $A(a,a')A^*(a',b)B^*$ or $A(a,b)B(b,b')B^*$, etc.; this is usually calculated using the coupled-channel Born approximation (CCBA) in which the elastic waves of the DWBA are replaced by solutions of the elastic-inelastic coupled equations[6,7], or

the equivalent source-term method[8]. The (a,b) transition is still treated in first order.

Another possibility is pick-up followed by stripping (or vice versa) such as (^{3}He,α) followed by (α,t) in (^{3}He,t) reactions. This process may be treated in second order[9] or it may be calculated from coupled equations[10]. Earlier, coupled equations for A+d and certain B+p channels have been solved[11]; these then treat the transfer (stripping) process to all orders and enable one to study its feedback on the elastic scattering. In these cases, inelastic scattering in the entrance and exit channels was neglected. In all these calculations, there remain some questions about lack of orthogonality between the rearranged channels[12].

Further, one may solve a set of coupled equations which include both inelastic and transfer reactions. I am only aware of one treatment[13] of this kind, which was applied to the ^{12}C(^{3}He,α) and (^{3}He,^{3}He') reactions where some of the inelastic and transfer processes are very strong (the cross section for exciting the 2^+ of ^{12}C is larger than the elastic for angles greater than 30° and the ground-state pick-up is comparable). This includes an example where the $p_{3/2}$ pick-up is so strong that it "saturates" (i.e. the cross section is almost independent of the coupling strength) and others ($f_{7/2}$ and $f_{5/2}$) where it is weak and mainly fed via inelastic scattering to the 2^+ state.

This case emphasises two obvious situations where these extended two- or multi-step calculations are needed: (i) where the first-order transition is forbidden or inhibited, or (ii) where some non-elastic transitions are comparable in magnitude to the elastic scattering. We then encounter a strong interplay between nuclear structure and reaction physics. No longer does the reaction analysis provide a simple tool as it did with the DWBA, where one calculated a cross section, divided it into the measured one and obtained a spectroscopic factor or deformation parameter. In principle one should now search for an optimum set of values for several such parameters by fitting simultaneously several sets of data. In practice there has to be a severe truncation of the number of channels coupled in order to make the computation feasible, and the amount of parameter searching one can afford to do is often limited.

2.1. Inelastic Effects

Fig. 2 illustrates the importance of inelastic effects for (p,t) reactions on collective nuclei. This is a nice example[8] because the same nuclear collective model can be used consistently for both the transfer and the inelastic events. The left side shows the cross sections for 3 routes to excite the 2^+ in ^{174}Yb. Note that direct (solid curve) and indirect (broken curves) are comparable and each appreciably larger than the measurements; indeed they interfere destructively to produce the fit shown on the right side. Note that the resulting angular distribution is strongly modified from that for the direct transfer. Even the distribution for the strong 0^+ is modified somewhat and its magnitude reduced by the inelastic effects. This is to be contrasted to the results[8] for (p,t) on the spherical nucleus ^{208}Pb where inelastic scattering is much weaker and the DWBA appears to be adequate.

Fig. 3 shows excitation of the 2^+ by (p,t) for a series of nuclei which can be grouped as "hard" or "soft" according to their quadrupole deformation parameters[14]. The former show distributions close to that for the DWBA while the latter require the CCBA.

The Yb($\vec{p}$,t) reaction with polarized protons has also been analyzed using the CCBA[15].

Single nucleon transfers are also susceptible to inelastic effects[6,8]. Fig.

4 shows this for the ^{172}Yb(p,d) reaction[8], where the effects are especially marked for the $3/2^-$ and $9/2^-$ levels. The magnitudes of the cross sections are significantly changed in nearly all cases. Good agreement has also been found for some weak (p,d) transitions with a spherical nucleus[16]. Fig. 5 shows another example of a weak pick-up transition, with the (d,^{3}He) reaction[17].

Experiments on charge exchange reactions often reveal strong transitions to the analogs of collective excited states in the target. Simply deforming the isovector term in the optical potential requires an unrealistic deformation parameter. However, coupled channel calculations[7] for (p,n) to the 2^+ excited analogue show that excitations including inelastic scattering dominate and are in good agreement with the measurements (Fig. 6), whereas the direct term alone is an order of magnitude too small. These calculations used the macroscopic (optical model) interaction. Similar studies[18] of 2^+ analogues excited in Ni(^{3}He,t) reactions were made with a microscopic interaction. Here again inelastic effects were important, although in this case the direct and indirect amplitudes were comparable. Further, evidence was adduced from their interference that the effective projectile-target nucleon interaction should be complex; indeed the best fit was obtained with it almost pure imaginary.

2.2. Pick-up/Stripping Effects

If two- and multi-step processes (i.e. couplings to other channels) are subsumed into the effective interaction, this becomes complex (and non-local and energy dependent!), in the same way that the optical potential has an imaginary part arising from the couplings to non-elastic channels. To second order, including these couplings is equivalent to replacing the interaction v by the effective interaction

$$v' = v + v\,G(E+i\varepsilon)v$$

where G is the propagator for the intermediate channel[9]. (We note however that the validity of this second-order approximation has been questioned[19].)

Thus the (^{3}He,t) case just discussed suggests that higher-order effects, other than the inelastic ones included explicitly, are important. One possibility is the pick-up/stripping process (Fig. 1) and it was shown[9] that (^{3}He,α;α,t) can dominate the reaction while (^{3}He,d;d,t) need not be negligible. Fig. 7 illustrates this for the ^{48}Ca(^{3}He,t) reaction exciting the 0^+ and 6^+ states[20]. Direct excitation of the 0^+, while small, has important interference effects, but the direct transition has become entirely negligible for the 6^+. This could explain the difficulties encountered in earlier microscopic analyses[21] where the effective interaction strength was found to depend strongly on the multipolarity. This same (^{3}He,α;α,t) process also explains the anomalous angular distributions seen when exciting anti-analogue 0^+ states[10] (see Fig. 8).

Corresponding analyses[22] of (p,n) transitions to 0^+ analogue states find the (p,d;d,n) process to be important. Although appreciably weaker than the direct term, it interferes destructively with it to produce markedly better fits to the measured angular distributions (Fig. 9). The strength of the effective nucleon-nucleon interaction required to reproduce the magnitudes now varies much less with energy or with target nucleus.

We have already mentioned the effects on weak transfer reactions of coupling to inelastic channels[13,16]; another possibility is the two-step transition via another transfer channel. A second-order calculation[23] of the (p,t;t,d) process in the ^{210}Pb(p,d) reaction to weak states indicated (Fig. 10) that it is very important and, when interfering destructively with the direct term, gives good agreement with the data. This may raise the question, yet to be studied, whether we

have a superabundance of two-step possibilities, since we see one case[16] of a spherical nucleus where inelastic scattering was sufficient and another[23] where intermediate 2-neutron pick-up fits the data. Certainly the structure factors and available intermediate states are different in the two cases, but more attention will have to be given to this problem.

Another case[24] where 2-neutron pick-up is important is the (p,t;t,p') process in the ^{40}Ca(p,p') reaction to the excited 0^+ state (Fig. 11). An interesting feature here is that this process can excite <u>two</u> target nucleons rather than just one like the direct (p,p') or two-step (p,d;d,p) processes. This is clearly important for excited 0^+ states which are largely of 2 particle - 2 hole character.

3. Adiabatic Model of Deuteron Stripping

A rather different kind of extension of the DWBA has been successfully applied to (d,p) and (p,d) reactions in recent years. This is the adiabatic model. The normal DWBA uses deuteron distorted waves which are obtained from the observed deuteron elastic scattering. However, it is recognised that the deuteron is loosely bound and hence easily broken up; these break-up components will still contribute to, say, a (d,p) reaction if the neutron is subsequently captured. The techniques just described could be applied if it were practicable to couple in all the (3-body) break-up channels. Fortunately Johnson and Soper[25] found a simple prescription which includes approximately in the distorted waves those break-up components in which the neutron and proton continue to move together in a ^{3}S state with little relative momentum. It is just these components which are most likely to contribute to the usual stripping reactions. The prescription is simply to use a modified optical potential to generate the deuteron distorted wave in an otherwise conventional DWBA, namely

$$\tilde{U}_d(r) = \langle\phi_o|V_{np}(U_n+U_p)|\phi_o\rangle/\langle\phi_o|V_{np}|\phi_o\rangle,$$

where ϕ_o is the deuteron ground state and $U_n(U_p)$ are the neutron (proton) optical potentials evaluated at one-half the deuteron bombarding energy. Note again that this potential $\tilde{U}_d$ will <u>not</u> reproduce the deuteron elastic scattering. This adiabatic model has been tested[26] for a number of (d,p) and (p,d) reactions on targets ranging from C to Pb; it has been particularly successful in those cases where a conventional treatment has required the use of a radial cut-off to eliminate the contributions from the nuclear interior (even though the effect of using the potential $\tilde{U}_d$ is <u>not</u> to suppress the deuteron wave in the interior). Fig. 12 shows an example[27] for ^{16}O where the conventional DWBA (labelled LZR) fails completely without considerable damping of the interior contributions (labelled DFRNL), whereas the adiabatic model immediately gives reasonable fits to the data. Fig. 13 shows results for ^{208}Pb at 52 MeV; the differences between using adiabatic (DB) and elastic (DE) deuteron waves are less dramatic than at lower energies[26] but the DB definitely improves the fit (note especially the $p_{3/2}$ pick-up). A more consistent set of spectroscopic factors has also been obtained for the Pb(d,p) reaction at various energies[29] by using the adiabatic model.

It is straightforward to include in this model the deuteron D-state and neutron-proton tensor force; amongst other things, this results in a tensor spin-orbit term. As far as I know, this extension has not yet been applied to polarization measurements of deuteron stripping, although including the D-state has definitely improved fits to Ni and Pb (p,d) angular distributions[30].

The analysis of the inelastic scattering of deuterons often has difficulties in obtaining good fits to the data. (The simple collective model, so successful for other projectiles, is often inadequate for deuterons.) Here again break-up

effects may be expected to be important and a treatment based upon the same philosophy as the adiabatic model is a possibility[30].

4. Polarized Beams, especially Deuterons

Another interesting feature of direct-reaction studies in recent years has been the number of experiments with polarized beams[31]. Their use provides a more sensitive check on reaction mechanisms and can yield more detailed knowledge of nuclear structure (for example, identification of the multipolarity of the giant quadrupole resonance by proton scattering[32] and determination of j-values in (d,p) reactions, etc.). I find particular interest in the work with polarized deuterons (both vector and tensor). This has mostly been limited to energies of 15 MeV and below. A few experiments have been done at higher energies, but it would be useful to have more extensive results. For example, they could help elucidate (i) the tensor spin-orbit coupling for elastic scattering, (ii) the role of the D-state in deuteron stripping and (iii) the validity of the adiabatic model.

A recent study[33] was made of the vector (VAP) and tensor (TAP) analyzing powers for 28.6 MeV deuterons elastically scattered from ^{120}Sn (Fig. 14). By studying the symmetry properties of the amplitudes and the low-order effects of the vector and tensor spin-orbit potentials, it can be shown[34] that the TAP $T_{21}(\theta)$ and $X(\theta) = T_{22}(\theta) - \sqrt{(3/2)}T_{20}(\theta)$ are particularly sensitive to the tensor spin-orbit potential. It is often harder to obtain polarized deuteron beams with a T_{21} moment, but the combination X usually is easy to achieve. Fig. 14 includes optical model predictions with (solid curves) and without (dashed curves) a tensor spin-orbit term. Without it, the TAP X is much smaller than the measured values, whereas T_{20} by itself, and the VAP T_{11}, are changed very little.

A very interesting investigation made recently[35] compared similar calculations with measured VAP and TAP for 5.5 MeV deuterons on ^{90}Zr (Fig. 14). The optical potential was obtained by folding the appropriate neutron and proton potentials into the deuteron density. If the deuteron D-state is included, this gives rise to a tensor spin-orbit term[36]. The solid curves are calculated with this term, the dashed ones without it. In the latter case, the predicted TAP are essentially zero, but with it the measurements are fitted very well. This is said to be the first case in which all five elastic observables have been well reproduced by an optical model calculation. Of course, the AP are all small and their distributions have little structure, so other studies at higher energies would be valuable.

There are, by now, a large number of measurements of VAP in transfer reactions induced by polarized beams[31], especially (d,p) reactions, but again most of these have been at relatively low energies. Several groups[37-39] have recently studied the single neutron states in ^{209}Pb populated by 12.3 MeV polarized deuterons. The standard DWBA provides satisfactory fits to the data[39]; even though the energy is near the Coulomb barrier, distortions due to the nuclear potentials are very important. The TAP have also been measured for this reaction[37,38] and others[40,41]. Of particular interest here is the effect of the deuteron D-state which can change the TAP substantially. In the sub-Coulomb barrier case, the TAP are essentially zero if the D-state is ignored but can become substantial if it is included. Fig. 15 illustrates this and shows that standard DWBA with the D-state[42] gives good agreement with the data. At these energies, the D-state effect is determined by essentially one number, the deuteron quadrupole moment. With higher energies one would probe the deuteron wavefunction more deeply. Further one would expect the break-up effects to become more noticeable so that TAP measurements could test the adiabatic model more sensitively. (It has already been noticed that the adiabatic model describes the VAP better[41].)

Other examples of the sensitivity of the TAP to the D-state are given in Fig. 16 for an energy (10 MeV) above the Coulomb barrier. We note here that T_{21} is essentially zero unless the D-state is included, and so is T_{20} at small angles.

5. The Phenomenological Optical Model

The phenomenological optical potential for protons with energies from 20 to 60 MeV is now quite well determined[43]; it would be valuable theoretically to see this confidence extended up to, say, several hundred MeV. Unfortunately the same knowledge cannot be claimed for neutrons[44], partly because much of the data is of poorer quality and partly because it is largely confined to energies below 15 MeV. Now, the Lane model relates neutron and proton scattering, as well as providing a description of the (p,n) transitions to analogue states, hence two recent applications of it are of interest. Both take the model seriously and apply it more consistently than has been the custom in the past.

Neither recently measured excitation functions[44,45] for (p,n) to the analogue state nor their angular distributions[46] at 23 MeV could be explained by using a symmetry potential obtained from the (N-Z) dependence of the proton optical potential[43]. The first problem seems to have been largely resolved for Pb and Bi by taking literally the prediction that the symmetry potential is proportional to the difference between the proton and neutron potentials obtained from elastic scattering. Fig. 17 shows the resulting symmetry potential whose shape is "unusual" because the neutron and proton potentials have different radii, etc. Nonetheless, Fig. 17 shows that it reproduces the excitation function much better than the previous prescription; it also fits the (p,n) angular distributions[45]. However this approach does have the weakness that in general the neutron potential is rather poorly determined.

The second problem was resolved[46] by taking a different approach, namely by assuming that good (p,n) data enable one to determine the symmetry potential which then, with knowledge of the proton potential, allows one to predict the neutron potential and hence scattering. Good fits to the 23 MeV (p,n) data were obtained[46] with the real part of the symmetry potential close to that predicted by the BG proton potential[43], however the imaginary part peaks at progressively smaller radii but with increasing width as A increases (Fig. 18). This is then found to result in simultaneously good fits to (p,p), (p,n) and (n,n) data (Fig. 19). It will be interesting to see whether the features of this phenomenological imaginary symmetry potential can be deduced from a microscopic calculation of the effective interaction from the coupling to, say, the pick-up channel[22] discussed earlier.

Another fairly recent development with the phenomenological optical potential is that some of the ambiguities associated with strongly absorbed particles are disappearing, especially for ^{3}He and ^{4}He. This has come about from the use of higher bombarding energies and also from measurements of angular distributions out to large angles[47,48]. (This would seem to have implications for the study of heavy-ion optical potentials!) It has also been suggested[49] that using aligned targets can help remove the ambiguities. We are also beginning to learn about the energy-dependence of these potentials[50], which is weaker than one might naively expect from the corresponding nucleon potentials. There is now some evidence for the effects of spin-orbit coupling on ^{3}He cross sections[51].

The optical potential is also involved whenever one uses the collective (deformed potential) model to describe inelastic scattering. Measurements with composite projectiles near the Coulomb barrier show marked interference between Coulomb and nuclear excitation which allows one to determine quite precisely the nuclear effective interaction near the strong absorption radius. It also determines the phase of that interaction; for ^{3}He for example it is largely imaginary[52] (Fig. 20). The simple collective model has been very successful in the

analysis of these measurements, except for deuteron scattering[53]. Presumably break-up is playing an important role in that case.

6. "Microscopic" Treatment of Scattering

By this I mean approaches ranging from simply a more sophisticated phenomenology to fundamental studies. There are two, not unrelated, objectives: (i) gaining a better understanding of the reaction, (ii) acquiring a more precise spectroscopic tool.

The first category consists of the folding models which go one step beyond the purely phenomenological optical potentials by attempting to relate the potential U to the matter density distribution ρ (about which some independent information can be obtained, e.g. by electron scattering) and consequently relating potentials for different projectiles to one another. They have been very successful and represent a useful step towards a fuller understanding. The starting point is the expression for the nucleon optical potential,

$$U(\vec{r}) = \int \rho(\vec{r}_i) v(\vec{r},\vec{r}_i) d\vec{r}_i + \text{exchange terms}$$

$$+ \text{ terms of order } v^2 \text{ and higher,}$$

where v is an effective interaction between the projectile nucleon and a target nucleon. A variety of choices have been made for v, from simple Gauss or Yukawa forms to the long-range parts of realistic interactions (intended as approximations to the Brueckner-Bethe G-matrix[54]), and including density- and energy-dependences[55]. Provided v is real, the first term (which is closely related to a Hartree-Fock potential) contributes to ReU only; it gives a good account of this part (for example[54], see Fig. 23; the good agreement with experiment is somewhat fortuitous!). The second and higher order terms give rise to the imaginary part of the potential (as well as contributing to the real part); so far only tentative calculations of these have been made[56].

These formulations are now being extended successfully to composite projectiles; we have mentioned deuterons[35,36] earlier and there are recent examples[57] of ^{3}He and ^{4}He. The results are very gratifying in view of the simplicity of the theory.

Parallel with these developments has been similar work on inelastic scattering interactions[54,58]. There have been various developments in the technology; e.g., inclusion of exchange effects, tensor and spin-orbit forces, density-dependent forces and core-polarization contributions.

When, as is usually the case, the nuclear wavefunctions available are inadequate to explain transition rates without the introduction of effective charges, corresponding factors are needed for inelastic scattering[59]. The renormalisation needed to fit data can be used to extract effective charges for high multipoles which are not normally available to electromagnetic measurements[60]. Alternatively, electric transition rates, if available, can be used to extract a proton enhancement factor. Then, since nuclear interactions excite both neutrons and protons, measurement of the nuclear excitations will yield a neutron enhancement factor[61]. The two approaches correspond to different assumptions about the radial dependence of the polarization effect.

Polarization of the core during an exchange process may reveal valuable information about any giant resonant states of the core. In this the incident nucleon excites the core and is captured, then the core deexcites by ejecting

another valence nucleon. This process resonates as the bombarding energy passes the energy of a core state and especially affects the cross section at large angles. The positions and widths of giant resonances with multipolarities L = 1, 2, 3 and 4 have been deduced[62] from the excitation of the 2^- state in the $^{16}O(p,p')$ reaction. It would be interesting to see a study of this kind on heavier nuclei, to throw further light on the giant resonances recently reported[2].

Microscopic analyses of inelastic scattering often indicate a need for an imaginary part to the interaction[18,58]. This would arise from coupling to other channels (e.g. the (p,d;d,p) and (p,t;t,p) processes discussed earlier) but no detailed study of this has yet been made.

Just as with elastic scattering, the microscopic description of inelastic scattering has been extended to composite projectiles. A self-consistent treatment of elastic and inelastic alpha scattering has been reported[63] and also an example[64] of the use of ^3He scattering to study the structure of excited 0^+ states.

Hopefully the microscopic point of view will also help us to understand better the relation between transition densities and transition potentials and in particular to understand better the role of the collective (deformed potential) model[65] (e.g. the relation between deformation parameters obtained from electric and nuclear excitations).

7. Sum Rules and Transfer Reactions

The use of sum rules in the analysis of spectroscopic factors from transfer reactions[66] is a somewhat neglected art. With them, single-nucleon S factors can be related to nuclear spins and electromagnetic moments, for example. Interest in them has revived recently in connection with an extended theory of overlap functions ("stripping form factors") as a representation for nuclear properties[67]. This theory gives exact versions of the earlier results[66] which include recoil corrections. Application to transfer reactions on ^{45}Sc led to spin assignments being deduced[67] and incidentally suggested a high absolute accuracy for the DWBA analyses. Similarly, values were deduced for the quadrupole and hexadecapole moments of ^{51}V; the quadrupole moment may be more accurate than values obtained by more conventional means, and the hexadecapole moment has not been measured directly.

Sum rules for two-nucleon transfers have also been discussed recently[68]. For example, the sum of stripping strengths to states of a given spin consisting of nucleons in a given major shell, minus the corresponding sum for pick-up strengths, is related to the single-particle occupancies in the spin-zero target. The latter, of course, are also observable in single-nucleon transfer reactions.

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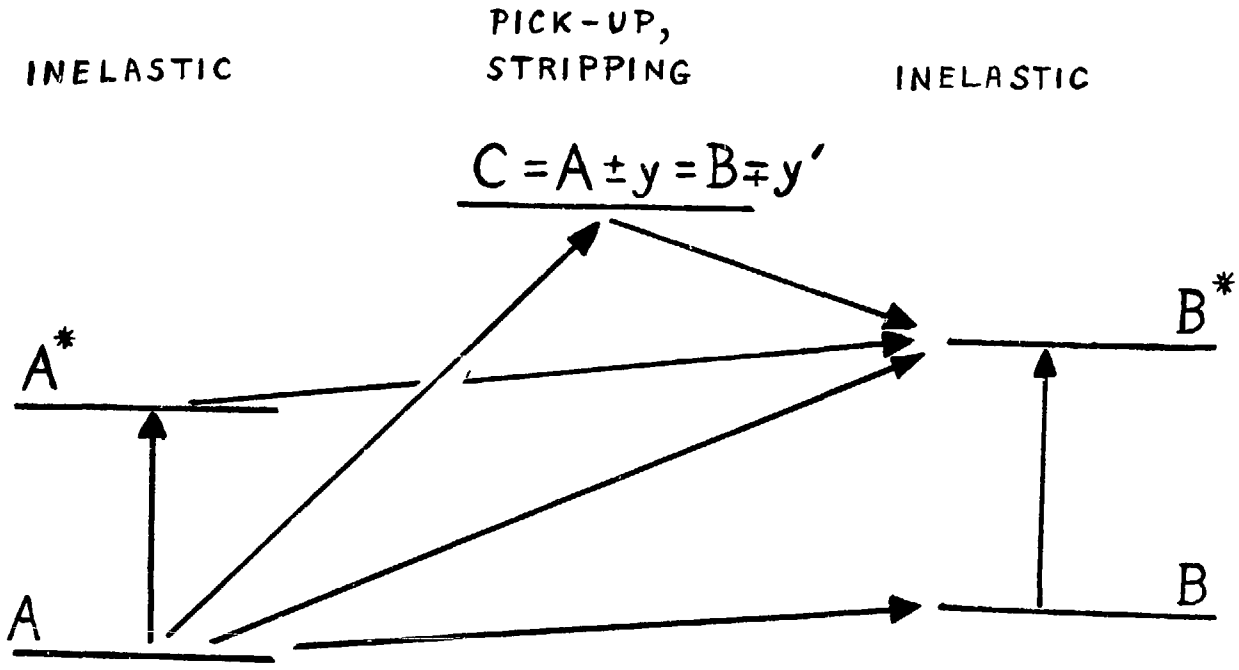
ORNL-DWG 73-7635



$$A\,(a,b)\,B^*$$

Fig. 1

ORNL-DWG 73-7654

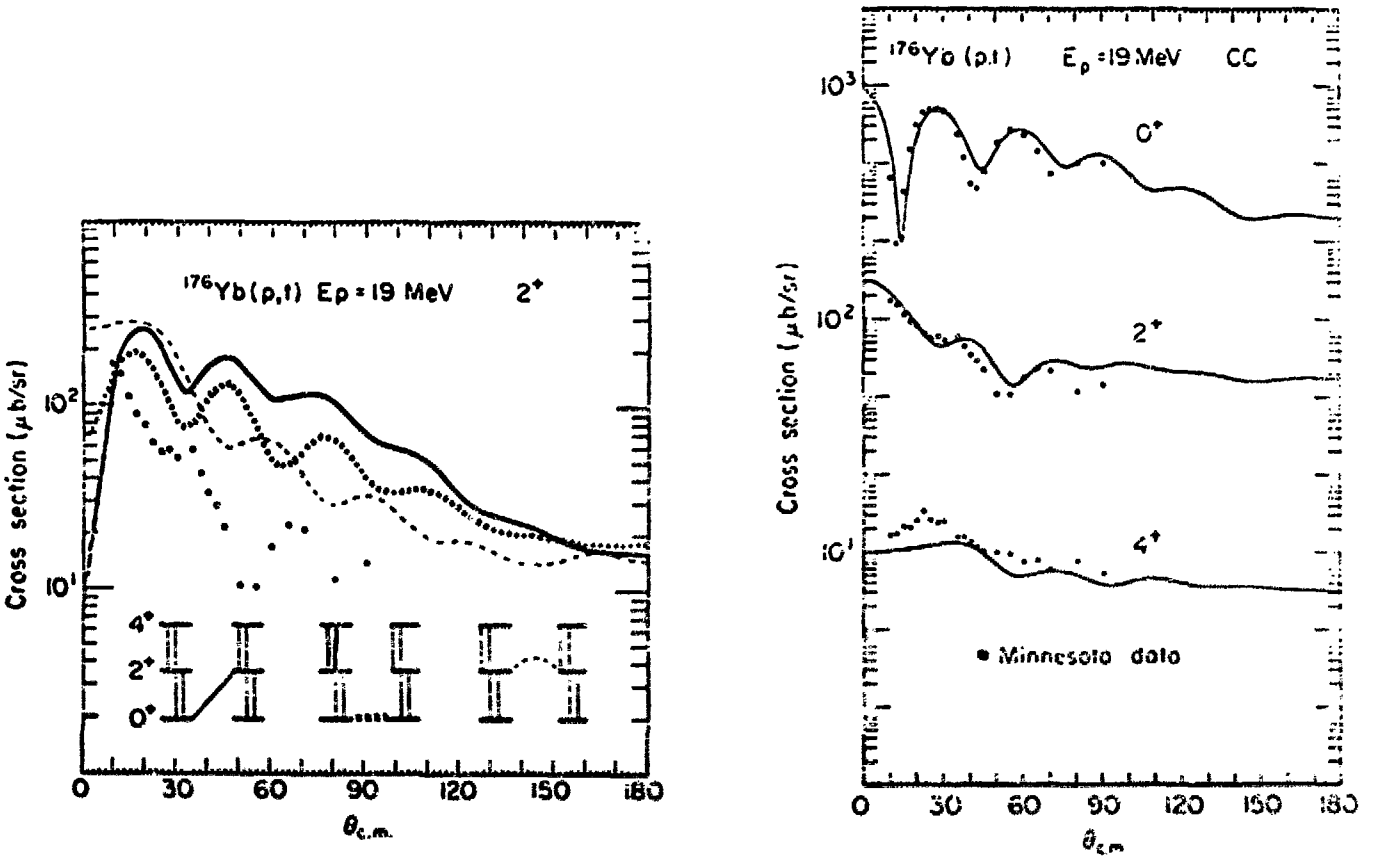


Fig. 2

ORNL-DWG 73-7650

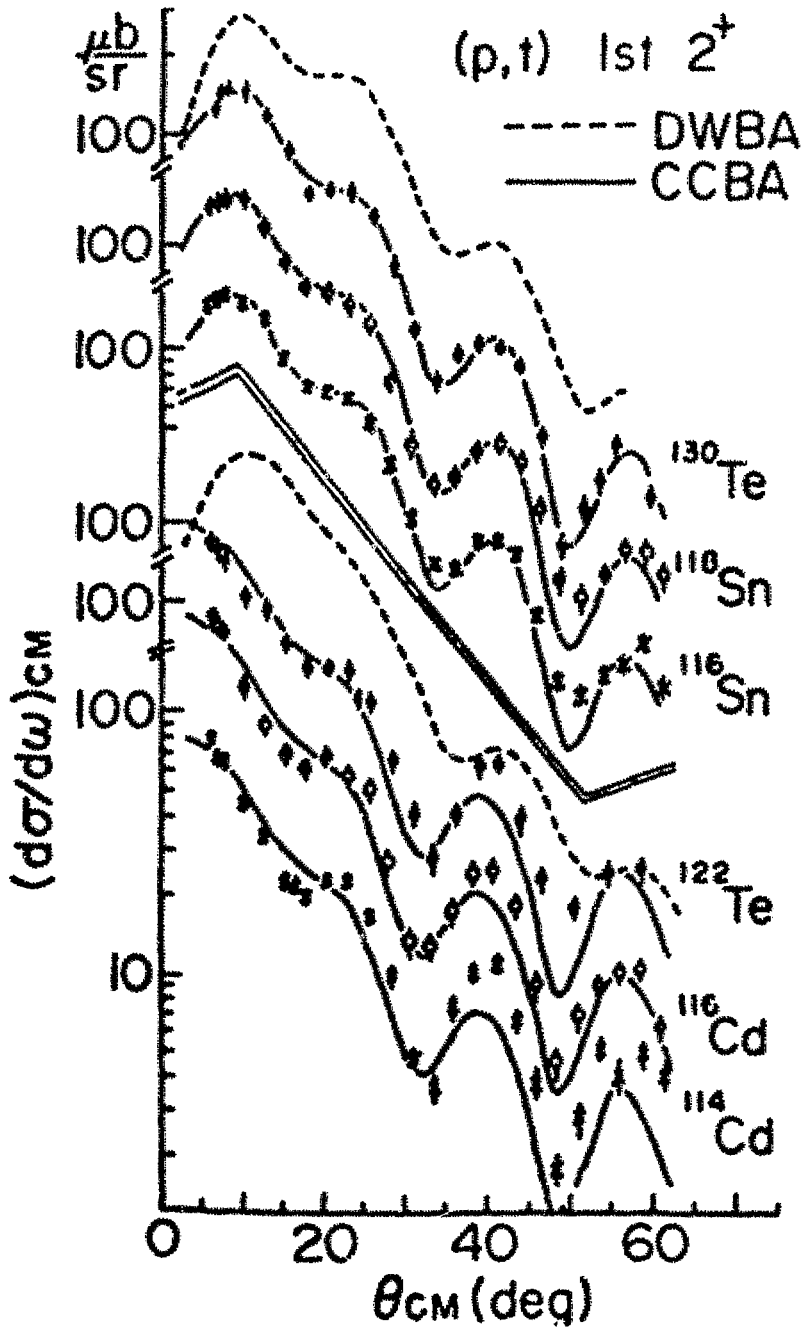


Fig. 3

ORNL-DWG 73-7651

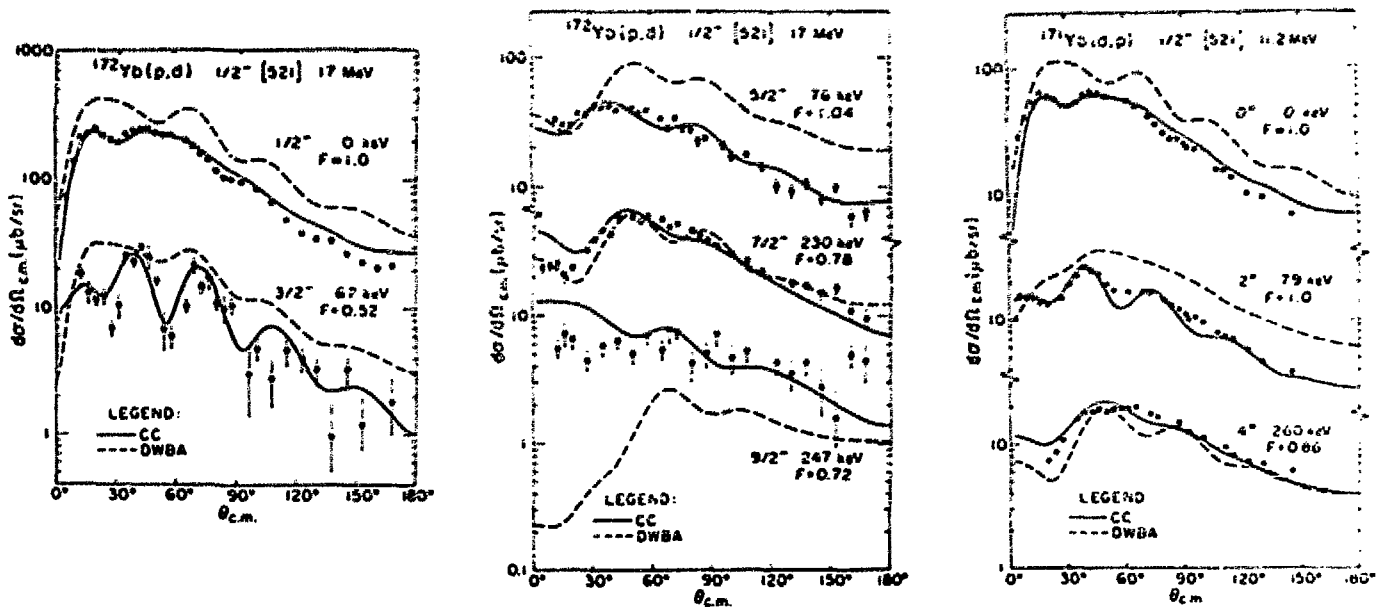


Fig. 4

ORNL-DWG 73-7649

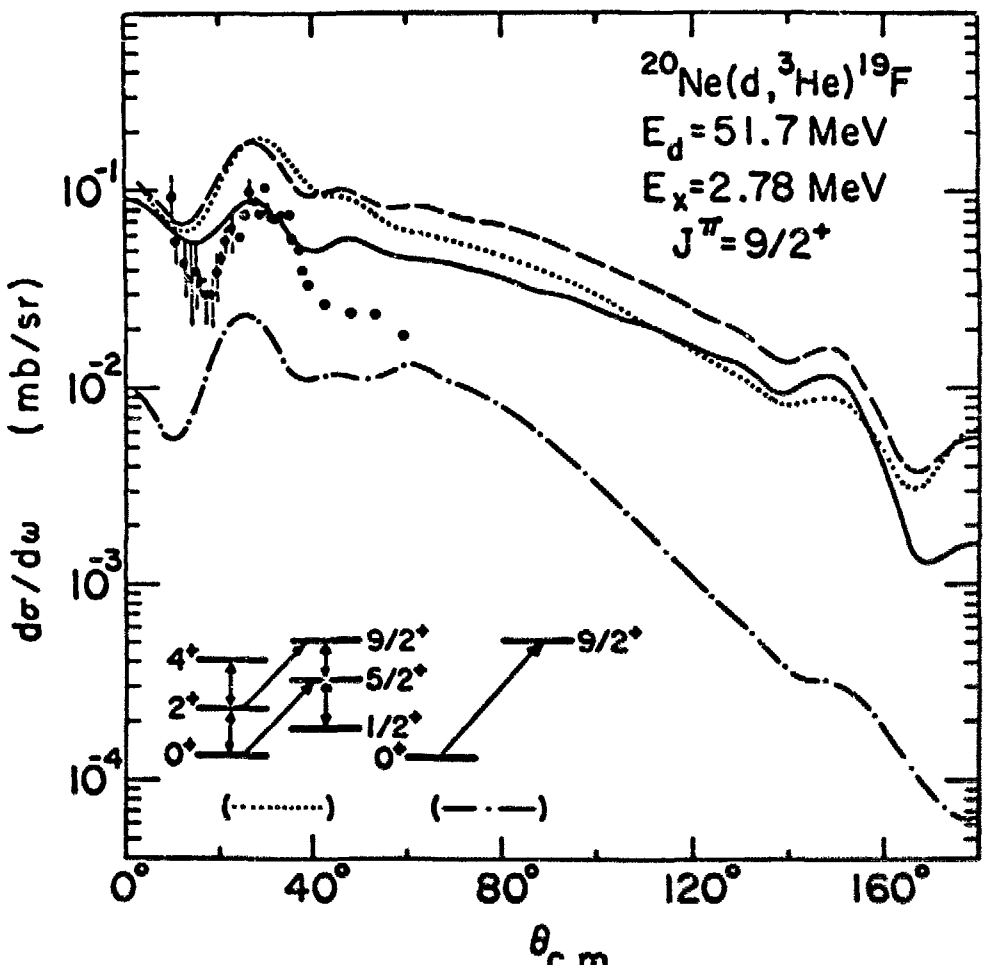
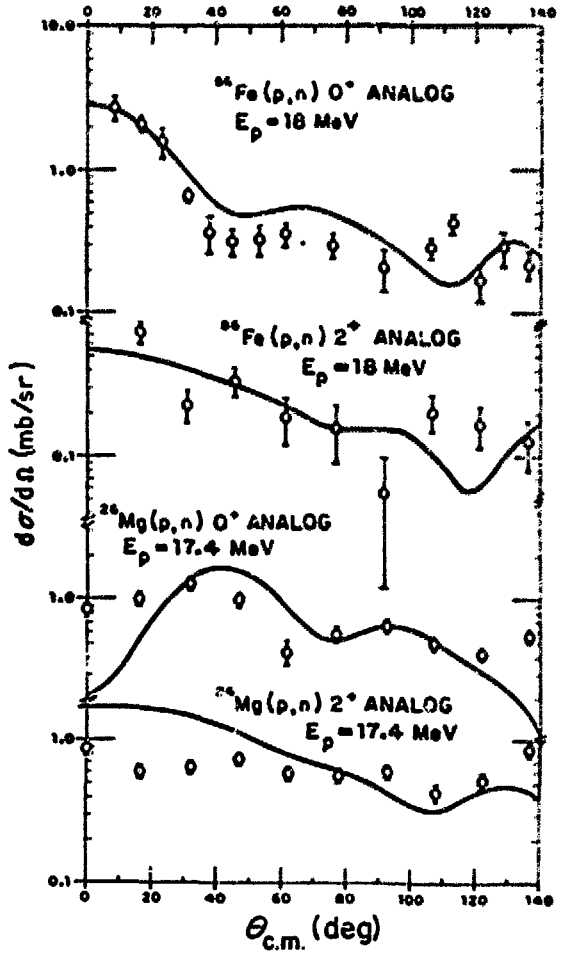


Fig. 5

ORNL-DWG 73-7652



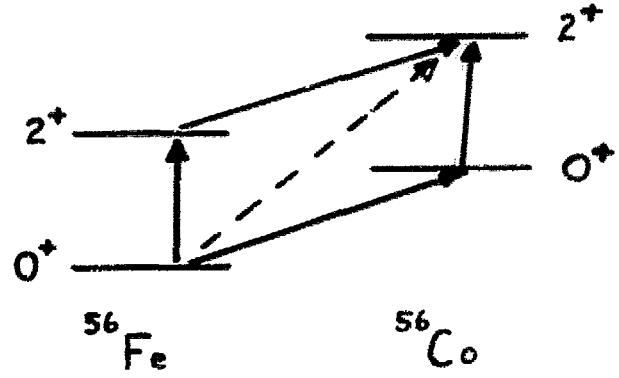


Fig. 6

ORNL-DWG 73-7644

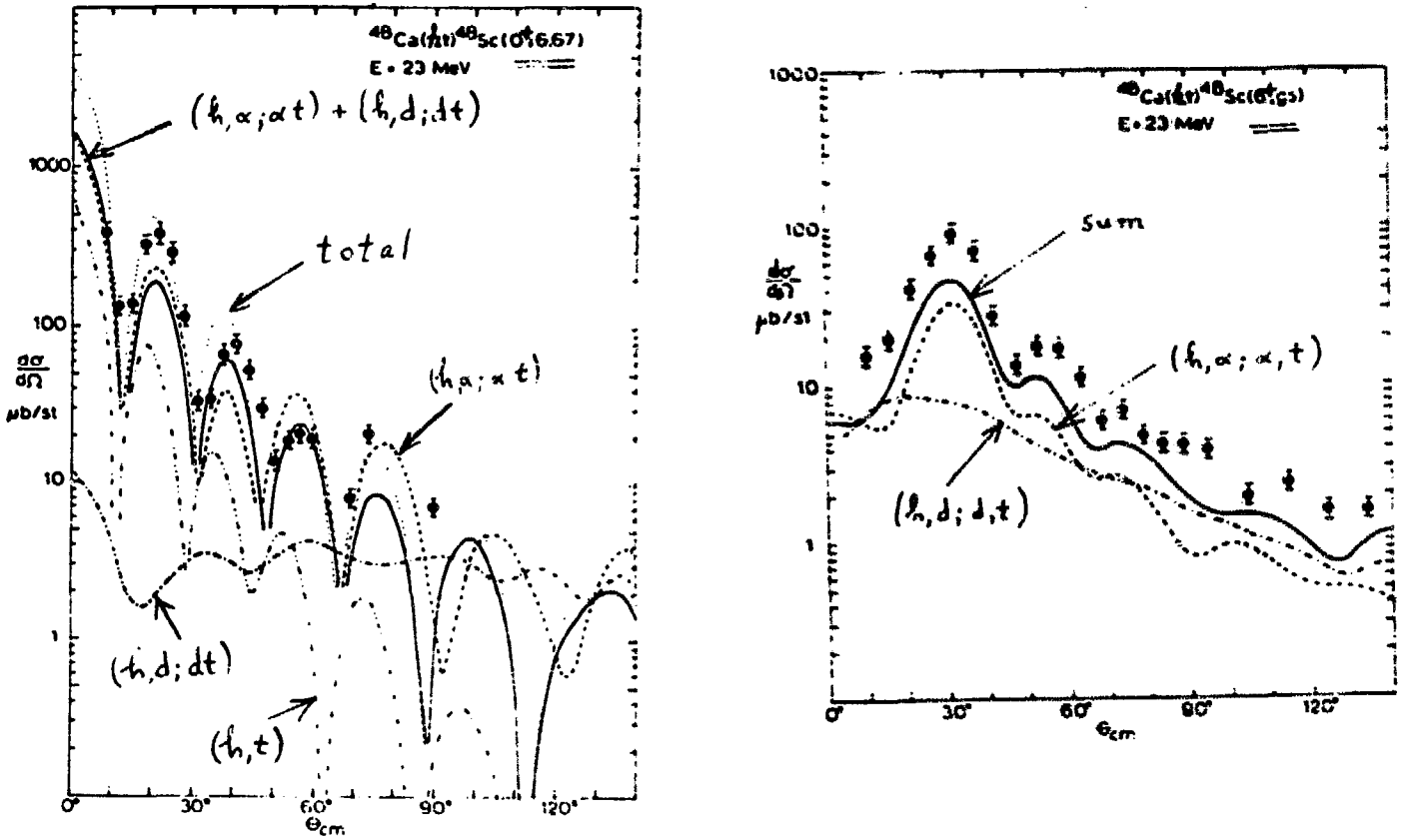


Fig. 7

ORNL-DWG 73-7646

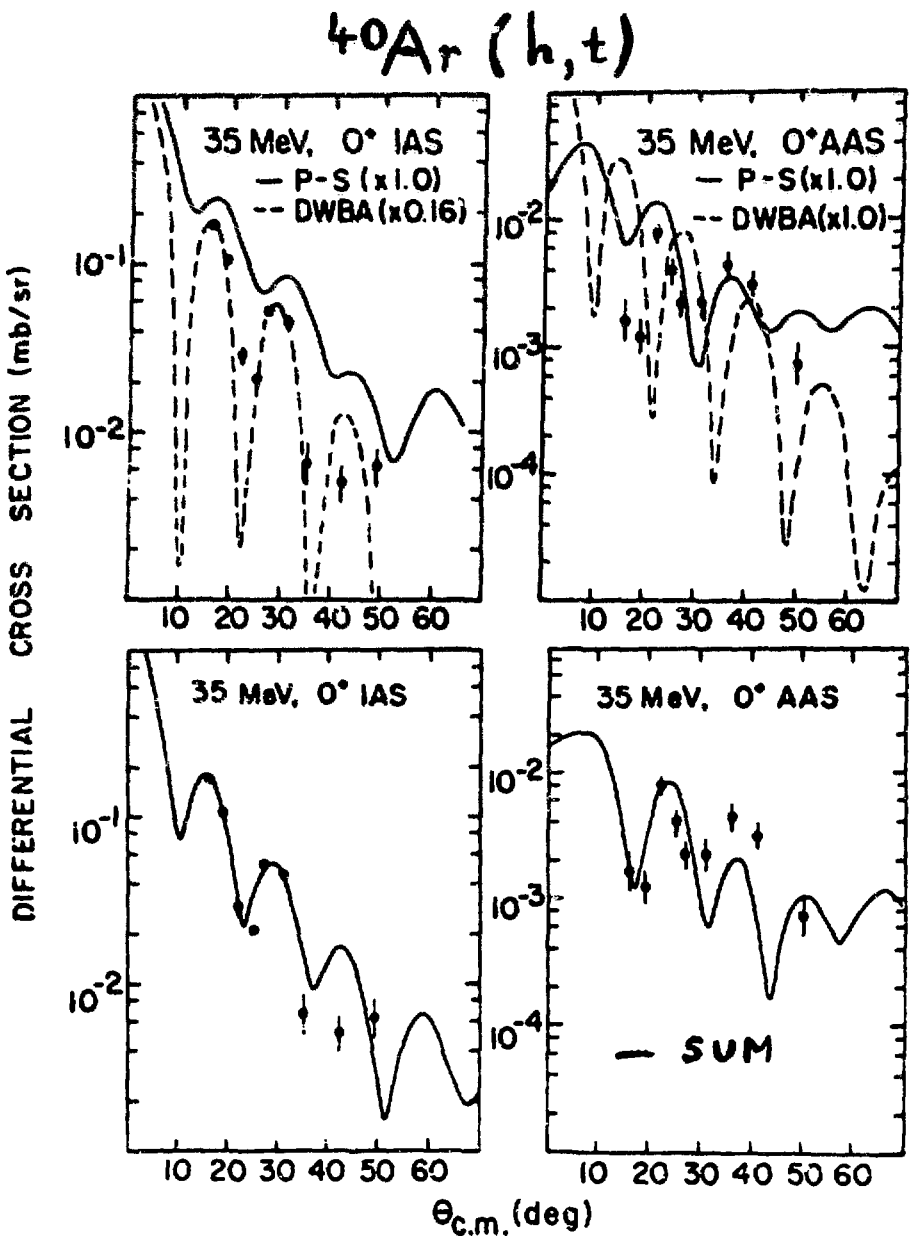


Fig. 8

ORNL-DWG 73-7648

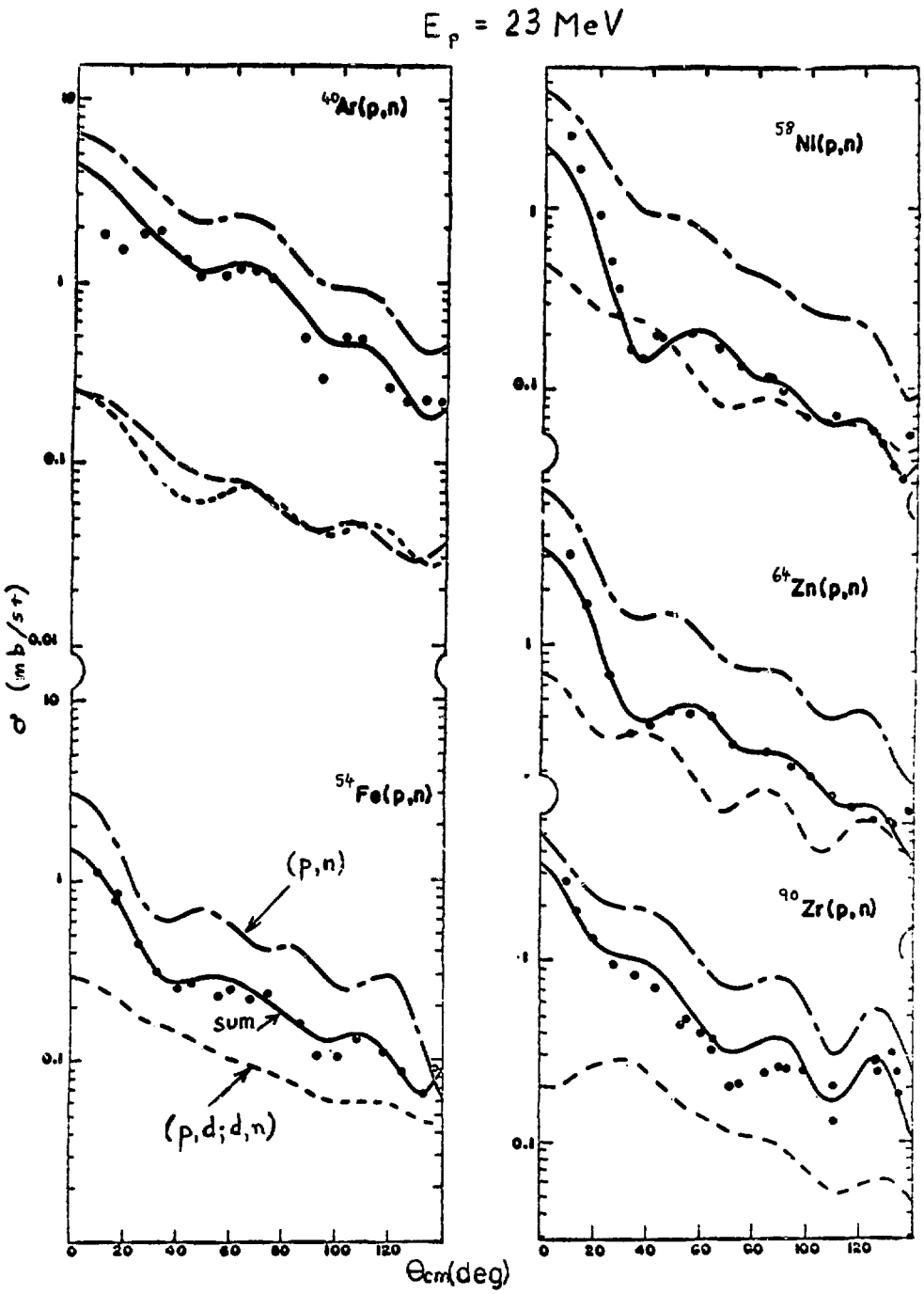


Fig. 9

ORNL-DWG 73-7645

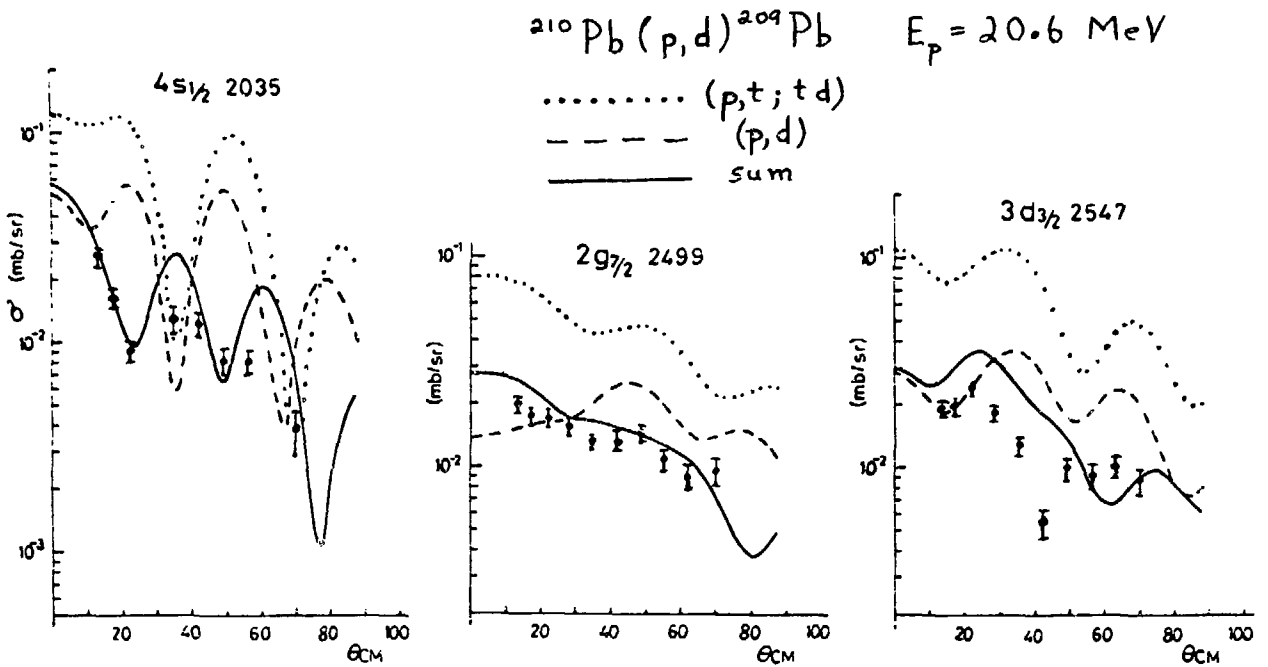
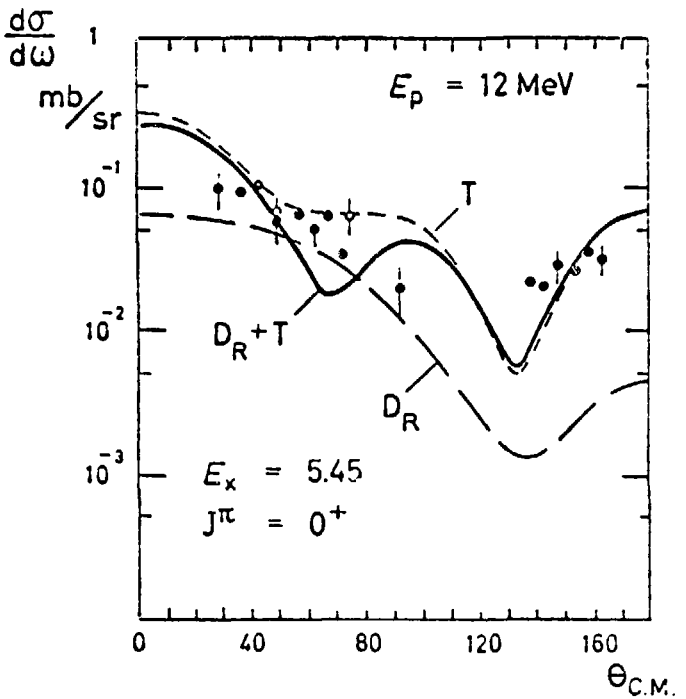


Fig. 10

ORNL-DWG 73-7653



$^{48}Ca\,(p,p')$

$D_R = 0_1^+\,(p,p')\,0_3^+$

$T = 0_1^+\,(p,t)\,0_1^+\,(t,p')\,0_3^+$

Fig. 11

ORNL-DWG 73-7638

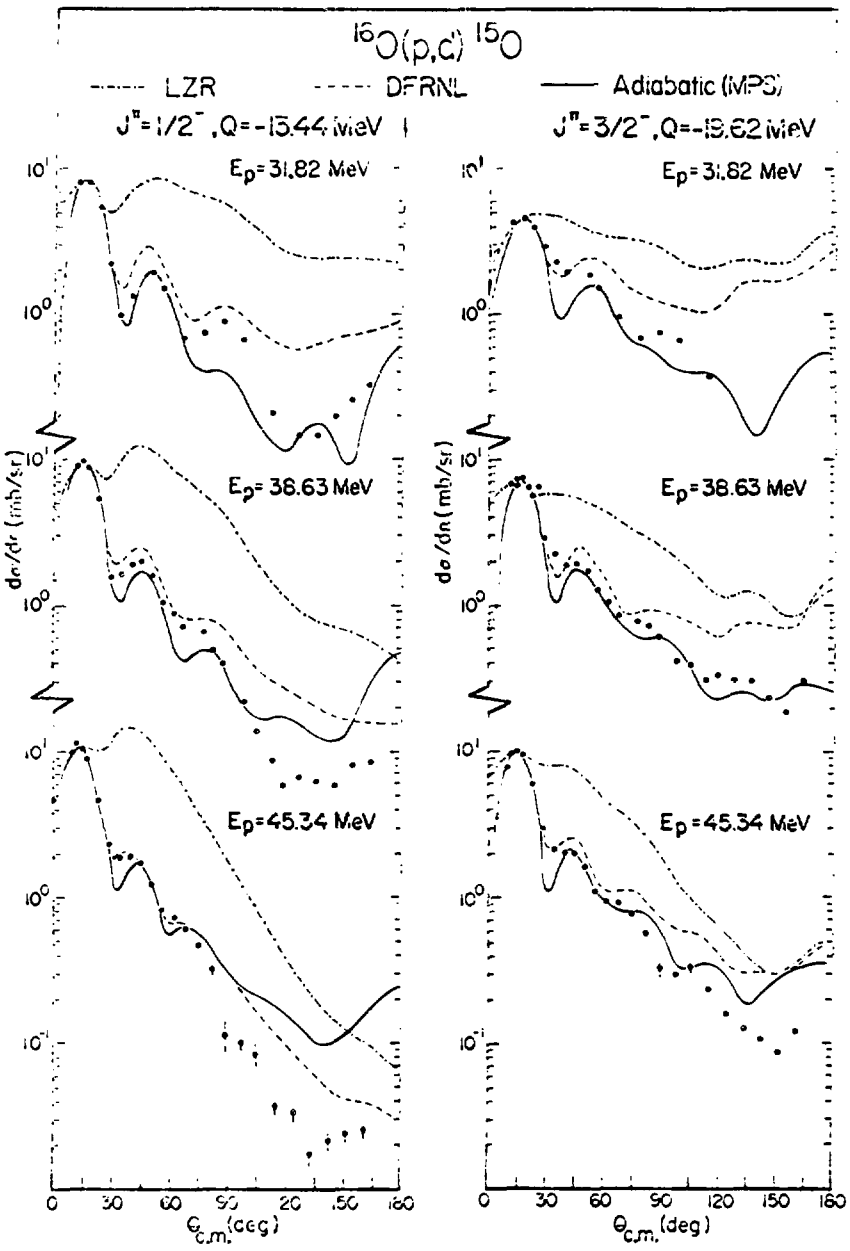


Fig. 12

ORNL-DWG 73-7639

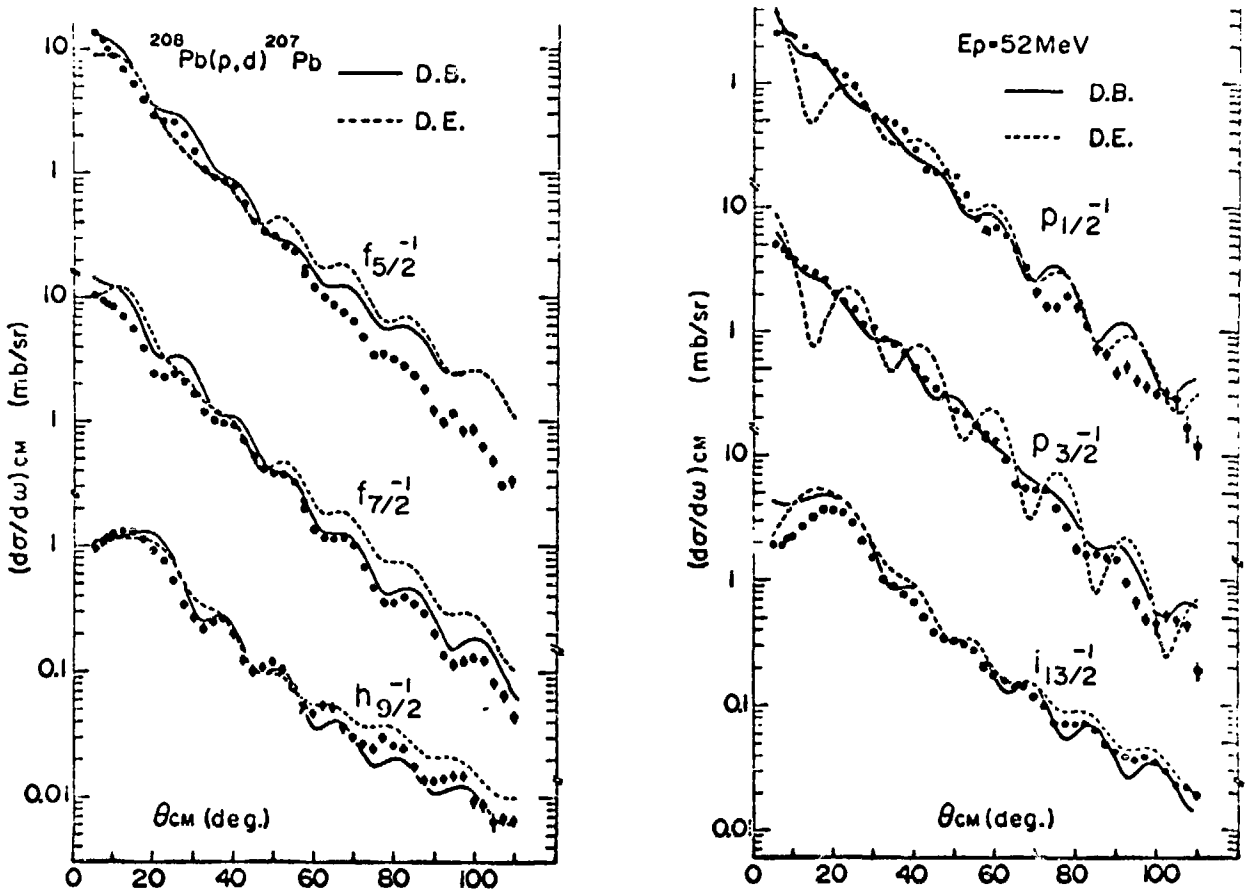
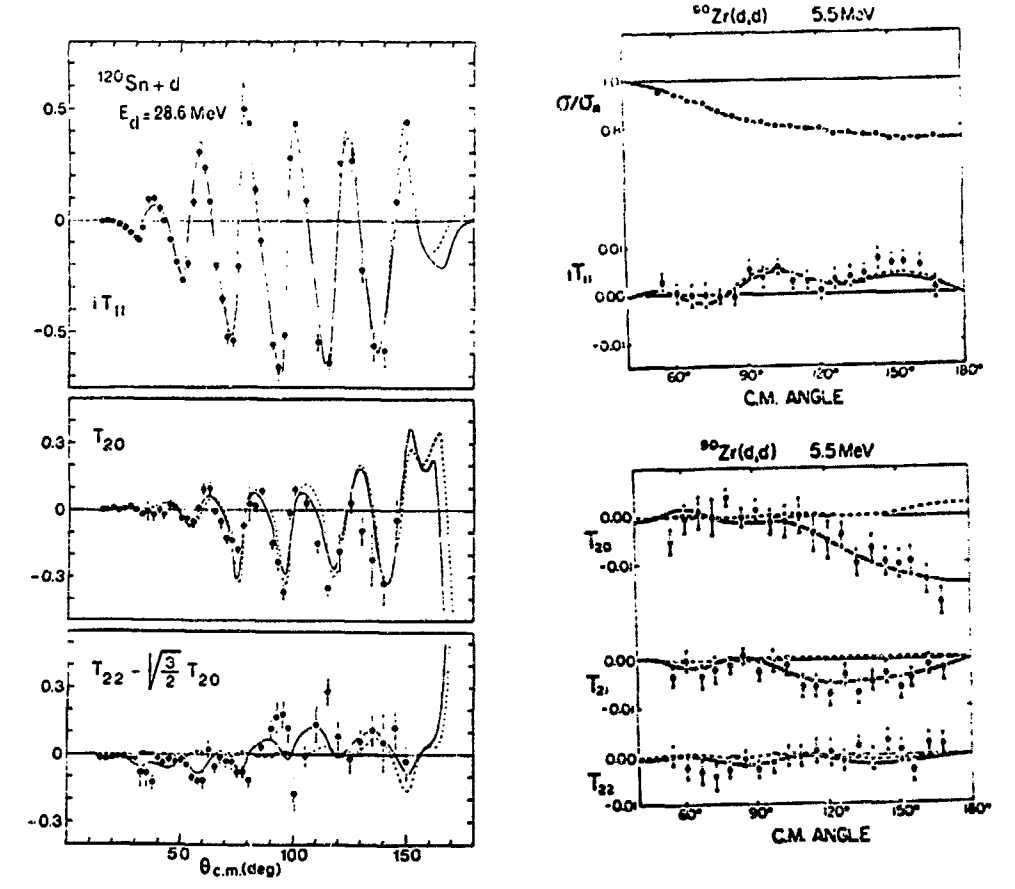


Fig. 13

ORNL-DWG 73-7640



OPTICAL MODEL: ——— WITH TENSOR S-O - - - - - - WITHOUT TENSOR S-O

Fig. 14

ORNL-DWG 73-7637

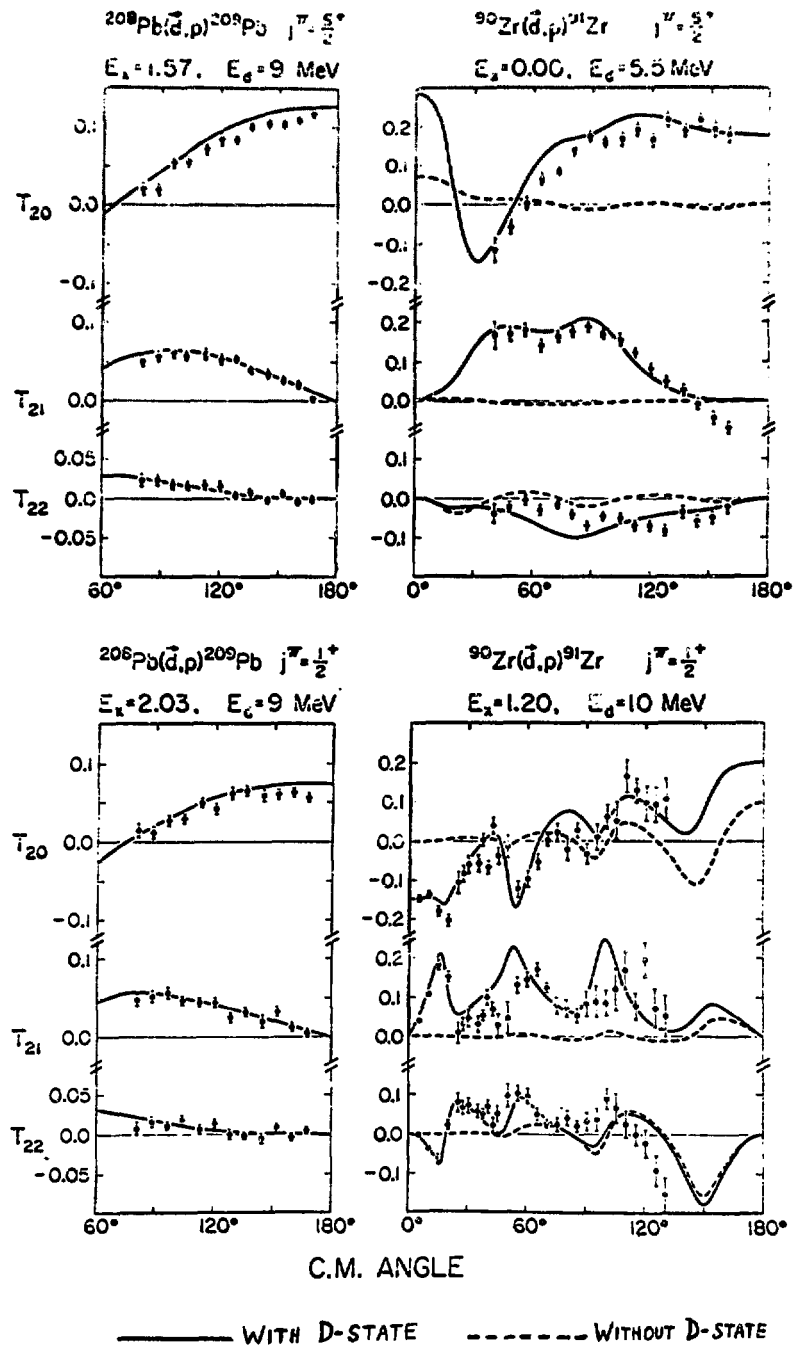


Fig. 15

ORNL-DWG 73-7643

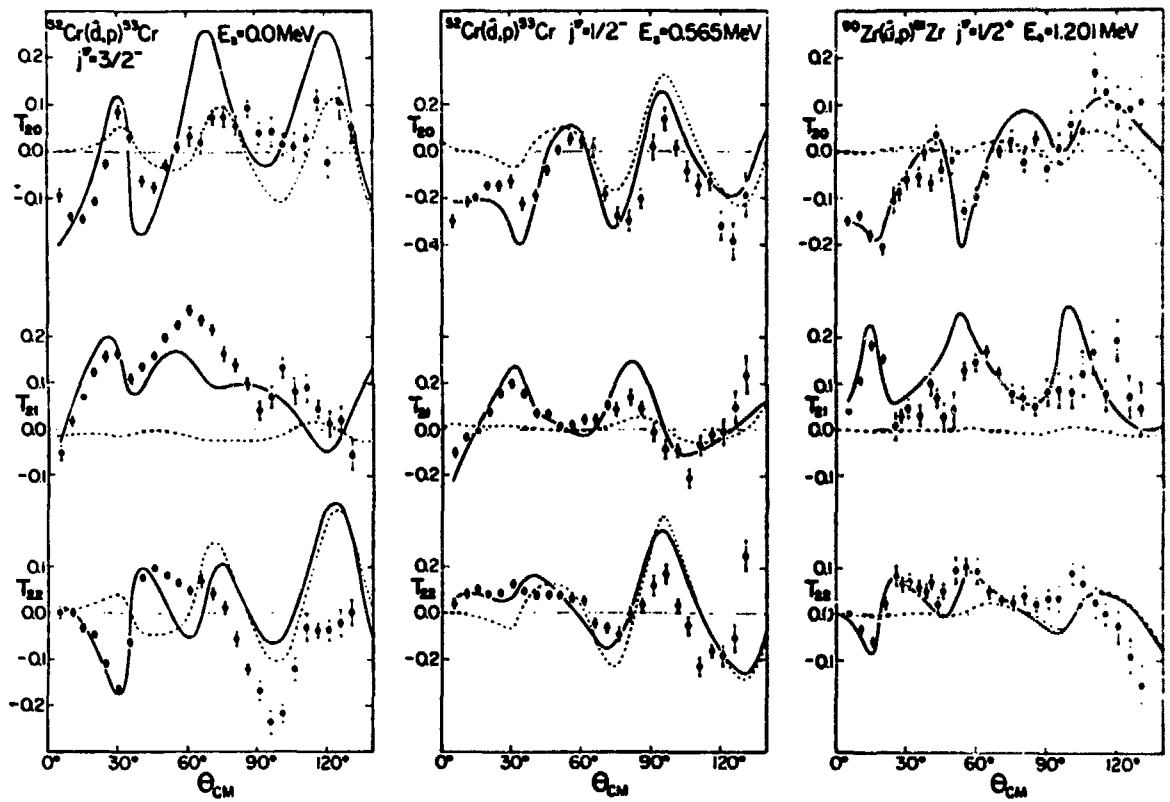
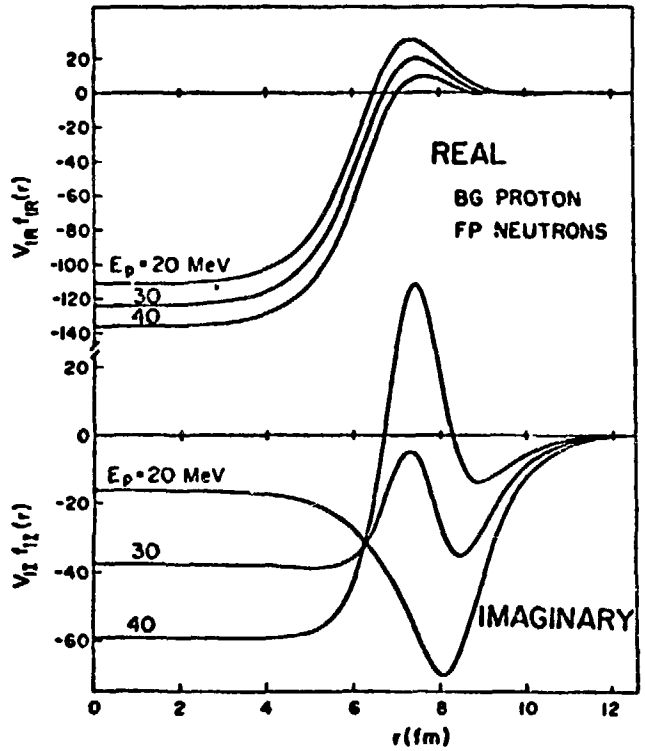


Fig. 16

ORNL-DWG 73-7642



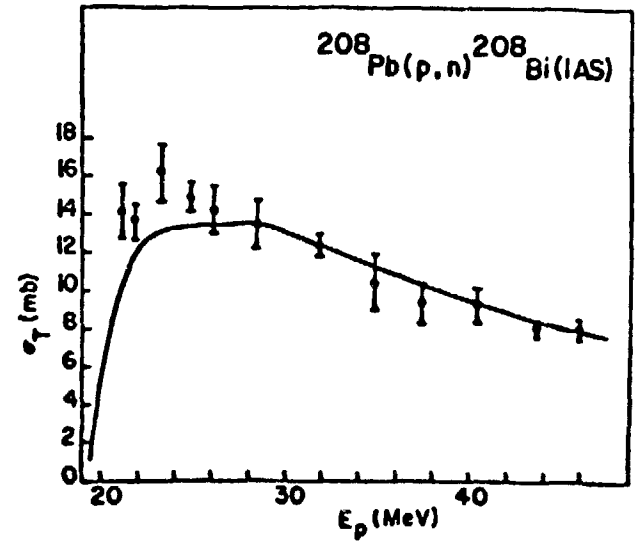


Fig. 17

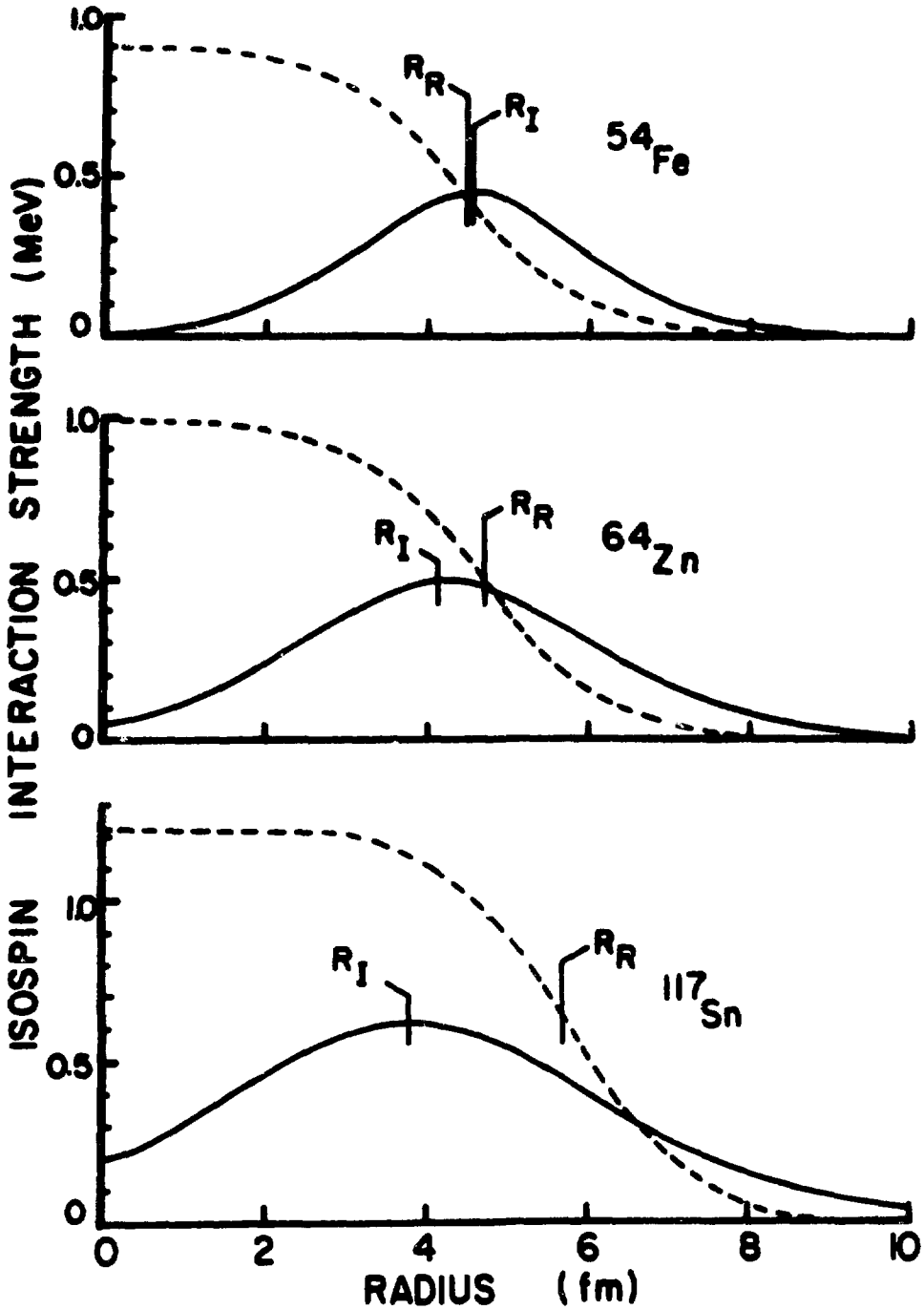

ISOSPIN INTERACTION STRENGTH (MeV)
1.0
0.5
0
R_R
R_I
^{54}Fe
^{64}Zn
^{117}Sn
0
2
4
6
8
10
RADIUS (fm)

Fig. 18

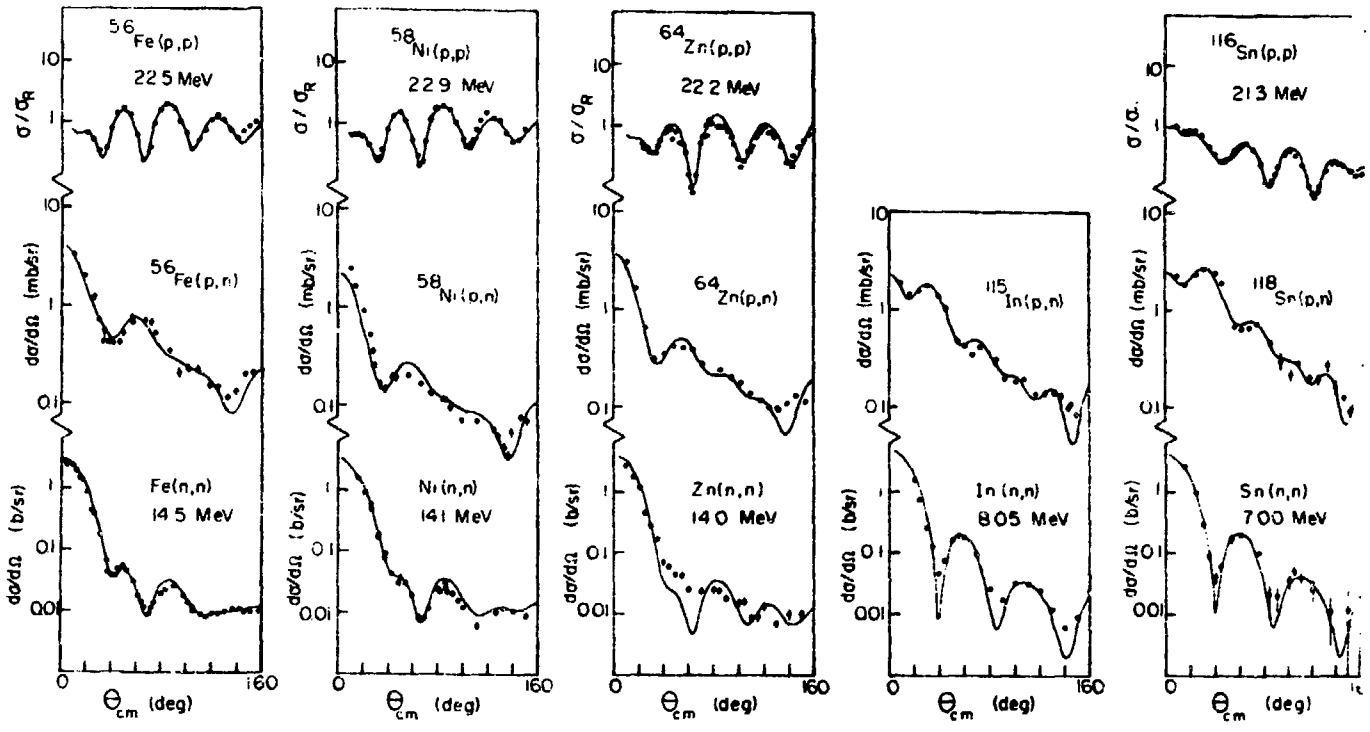

56Fe(p,p)
22.5 MeV
56Fe(p,n)
Fe(n,n)
14.5 MeV
58Ni(p,p)
22.9 MeV
58Ni(p,n)
Ni(n,n)
14.1 MeV
64Zn(p,p)
22.2 MeV
64Zn(p,n)
Zn(n,n)
14.0 MeV
115In(p,n)
In(n,n)
8.05 MeV
116Sn(p,p)
21.3 MeV
118Sn(p,n)
Sn(n,n)
7.00 MeV
σ/σR
dσ/dΩ (mb/sr)
dσ/dΩ (b/sr)
θcm (deg)
0
160

Fig. 19

ORNL-DWG 73-7636

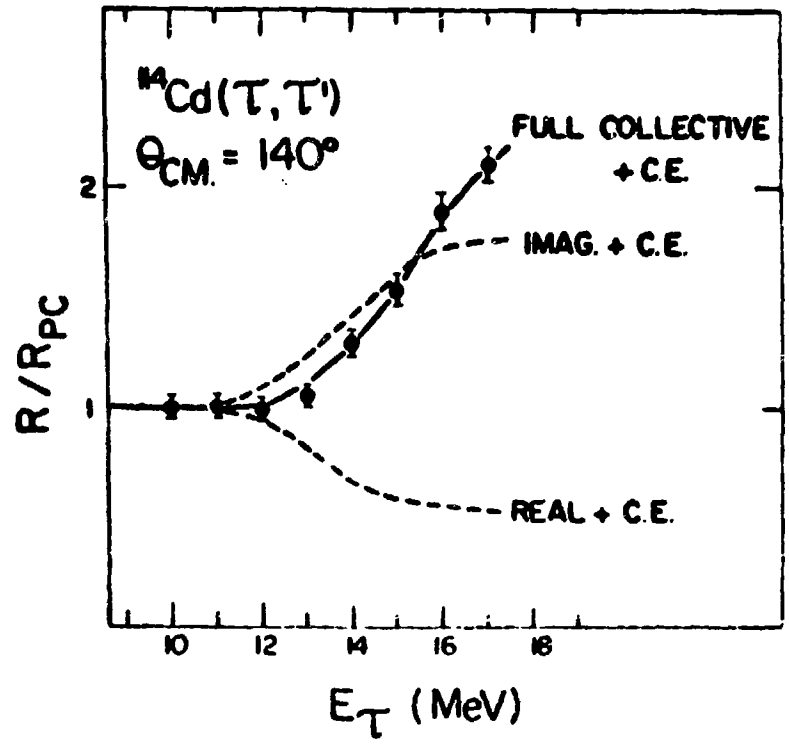


Fig. 20

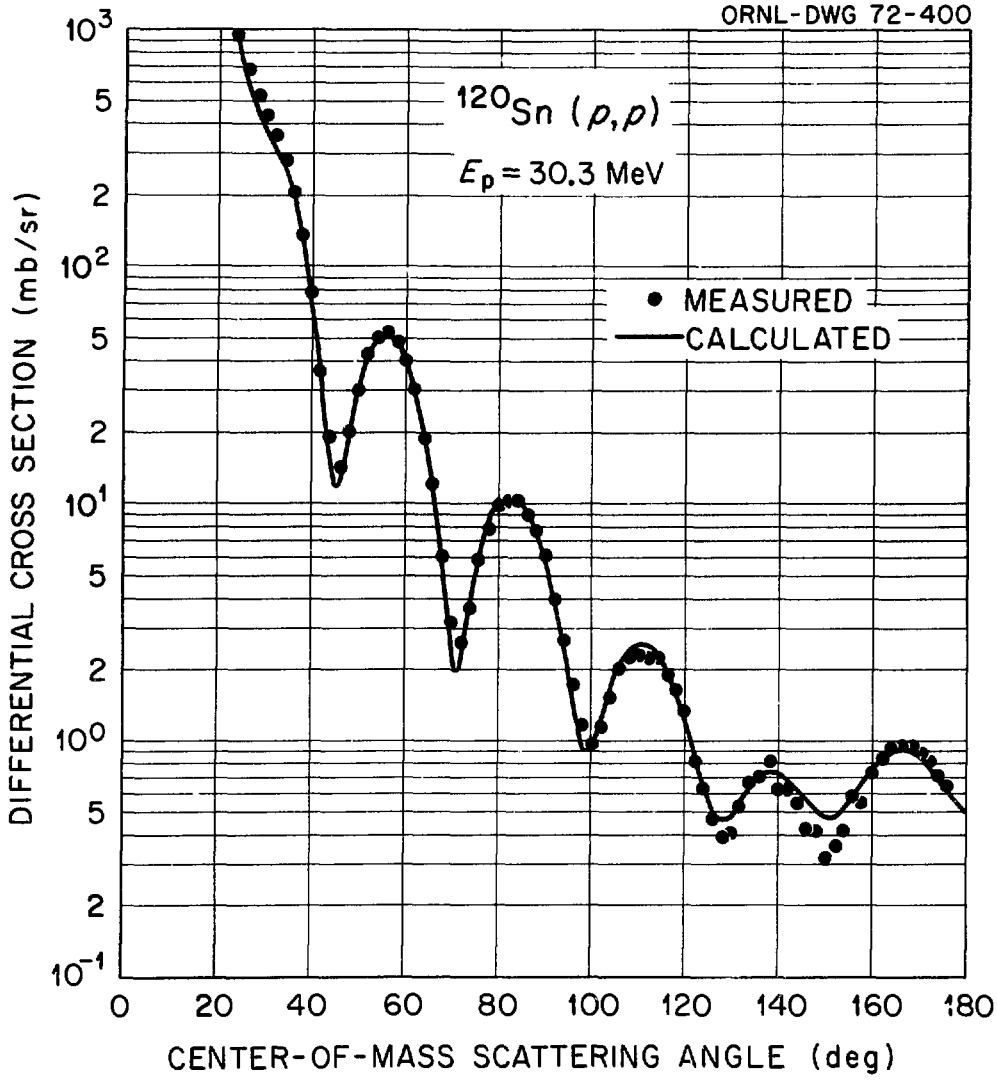

ORNL-DWG 72-400
^{120}Sn (p,p)
E_p = 30.3 MeV
MEASURED
CALCULATED
DIFFERENTIAL CROSS SECTION (mb/sr)
CENTER-OF-MASS SCATTERING ANGLE (deg)
10^3
5
2
10^2
5
2
10^1
5
2
10^0
5
2
10^{-1}
0
20
40
60
80
100
120
140
160
180

Fig. 21