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Isospin Mixing in ^{14}N and the Reaction Mechanism

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1. Introduction

I have thus far reported extensively on our study at Wisconsin of the isospin-forbidden $^{16}O(d, \alpha_1)^{14}N(T = 1)$ and the $^{14}N(\alpha, \alpha_1)^{14}N(T = 1)$ reactions. The evidence we have presented I hope persuades everyone that the isospin-violation occurs through relatively long lived wmpound nuclear states, (^{18}F). Further, we see no background that could come from a direct sort of reaction.

However, in 1966, Meyer-Schutzmeister, Von Ehrenstein, and Allas[1] looked at the isospin-forbidden reaction $^{14}C(d, \alpha_2)^{10}B(T = 1)$ and concluded that for deuteron energy above 11.5 MeV direct reactions predominated The evidence on which the conclusion rested consisted of only two angular distributions, one at $E_d = 12.1$ MeV and one at E, = 12.5 MeV. Both were strongly forward peaked at $\theta_{cm} \approx 25°$. This direct reaction claim ignited many theoretical attempts to understand the large cross sections. They were uniformly unsuccessful. Then Jänecke and collaborators[2] at Michigan extended $\theta_{cm} \approx 20°$ data to higher deuteron energies (up to 21 MeV) and found the results shown in Fig. 1. Clearly, Meyer-Schutzmeister et al's. direct reaction shows strong resonances, but instead of abandoning the direct reaction point of view, Jänecke's group remained convinced of the need for direct reaction because of some partial angular distributions which they took at energies indicated by arrows. The partial angular distributions included only about 15° on either side of $\theta_{cm} = 25°$. These all showed a drop at the small and at large angles. Because of this forward peaking, Jänecke et al. believed they confirmed the earlier claim of direct reaction taking over at the higher energies. They apparently were unaware that the simple spin-parity combination $0^+ \; 1^+ \rightarrow 0^+ \; 0^+$ for $^{12}C(d,$ a) $^{10}B(T = 1)$ reaction requires the cross section go to zero at 0° independent of the reaction mechanism and that any partial with $l > 1$ will give a forward peak. So, really all their data demonstrated was that, at these high deuteron energies, partial waves with $l \geq 3$ were important.

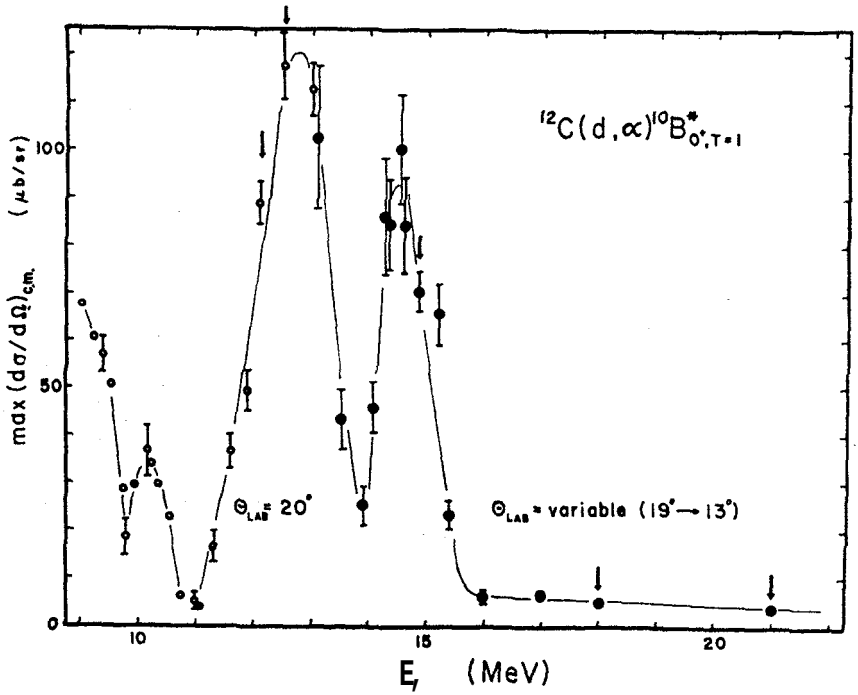

Fig. 1 - Excitation function of the reaction $^{12}C(d, \alpha_2)^{10}B^*$, according to Ref. 2.

Jänecke et *al.* however did emphasize the paradox of the resonant behavior and speculated about semidirect mechanisms involving Noble's suggestion[3] of a spin-flip in the deuteron at energies which correspond to particular cluster-like states. They also pointed out that the previously proposed direct reaction mechanisms simply cannot account for cross sections in excess of a few μb/sr (certainly less than 10).

Quite recently, Jänecke's group published[4] eight more data points again at $\theta_{cm} \approx 19°$ but for E_d = 26 to 29.6 MeV. Not surprisingly, they once more find a forward peaking in the one very limited angular distribution at E_d = 29.1 MeV. However, the maximum cross section they observe is about 8 μb/sr. They conclude that the results favor a direct or semidirect mechanism. In my opinion, the data is not extensive enough in this energy range to draw any conclusions concerning reaction mechanism. The low cross sections could also yet show structure characteristic of compound nuclear formation.

Meanwhile, at Wisconsin, H. V. Smith, Jr. undertook for his Ph. D. thesis project an extensive study of this reaction for the deuteron energies available

on our tandem. This task was formidable because 1) the cross sections were lower than those we encountered in the ^{18}F case, 2) the isospin forbidden state of ^{10}B lies within 400 keV of an allowed state so resolution and background problems become severe. Precisely for this reason the earlier groups relied heavily on magnetic spectrographs and scanning photographic emulsions. Also attempts to use solid state detectors with a solid carbon target often ran into contamination from the strong alpha groups from oxygen contamination in the solid targets. Smith overcame some of these problems by use of a continuously pumped methane gas target and therebv achieved the resolution shown[5] in Fig. 2 which is adequate. The low yield still left him with a background problem which required a computer fit of both the peak and the background to extract reliable cross sections.

Another experimental difficulty is the negative Q of the reaction. The resultant low a energies limited us to E, > 7 MeV. Furthermore, the corresponding excitation energy in the compound nucleus (^{14}N) starts out some 6 MeV higher than our ^{18}F case. These factors conspired to limit us to $16.5 < E_x(^{14}N) < 22$ MeV.

2. Results

Figure 3 displays the forward angle excitation curve[5] for the isospin forbidden reaction. The low cross section plus background subtraction result in the large statistical errors, but the general resonant character of the reaction is apparent. The sharp levels at $E_r = 7.8$ and 9.6 MeV are 5^- and two of the high energy resonances are also 5^-. Elsewhere $l_{max} \leq 4$.

Fig. 4 includes the $\theta_{cm} \sim 90°$ data[5] where only odd l contributes. On the bottom excitation curve the broad peak around $E_r = 11.4$ MeV comes mainly from a 1^- level in ^{14}N which by the top scale is at $E_x(^{14}N) \approx 20$ MeV. We believe this is associated with an anomalous ratio of $\gamma n/\gamma p$ cross sections in the ^{14}N giant dipole resonance at this energy[6].

Fig. 5 shows part of the back angle cross sections[5]. Angular distributions, Fig. 6 and Fig. 7, show both pronounced forward and backward peaking. The theoretical curves[5] illustrate the quality of the fit with our simple partial wave expansion discussed earlier in connection with the ^{18}F data Again, while the fit is excellent, there remain ambiguities in the combinations of partial waves to give identical fits and there is the perennial question of whether one can stay on the same solution as a function of energy.

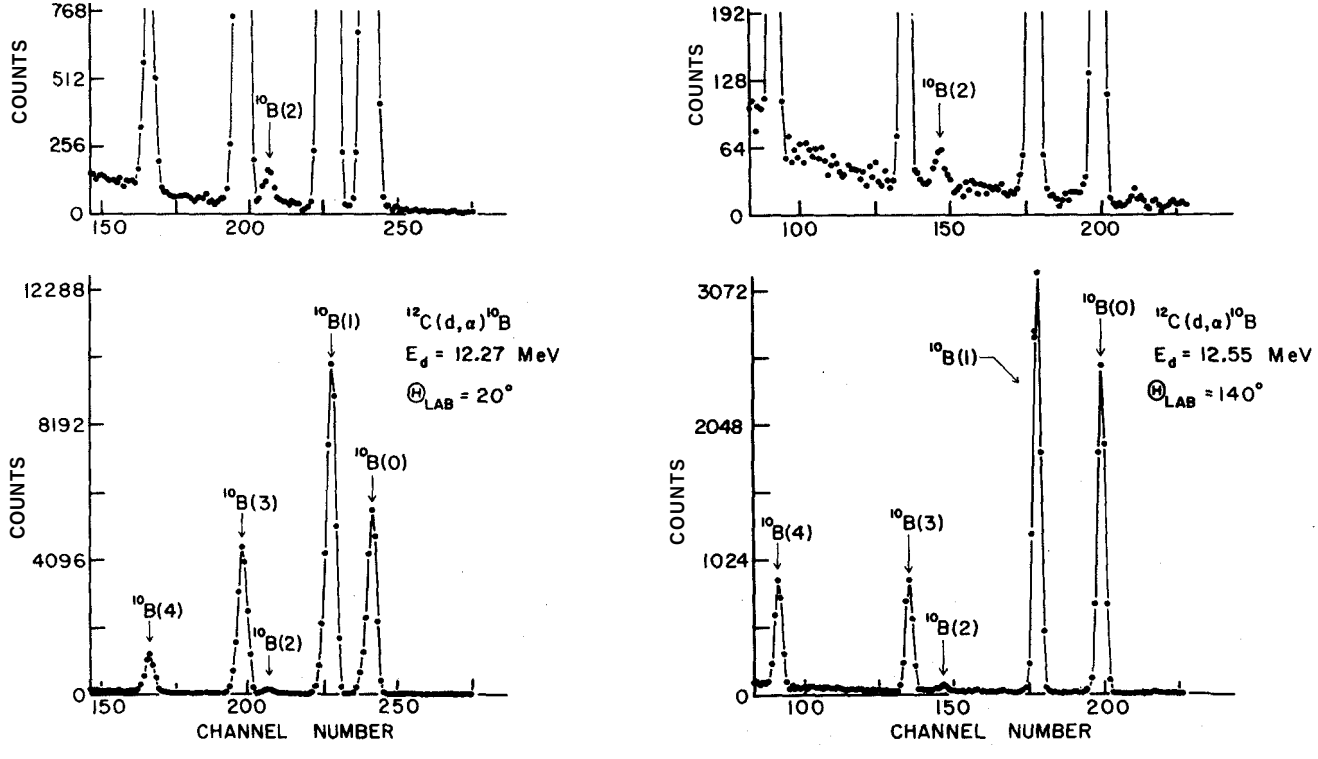

Fig. 2 - Pulse height spectra from the $^{12}C(d, \alpha)^{10}B$ reactions.

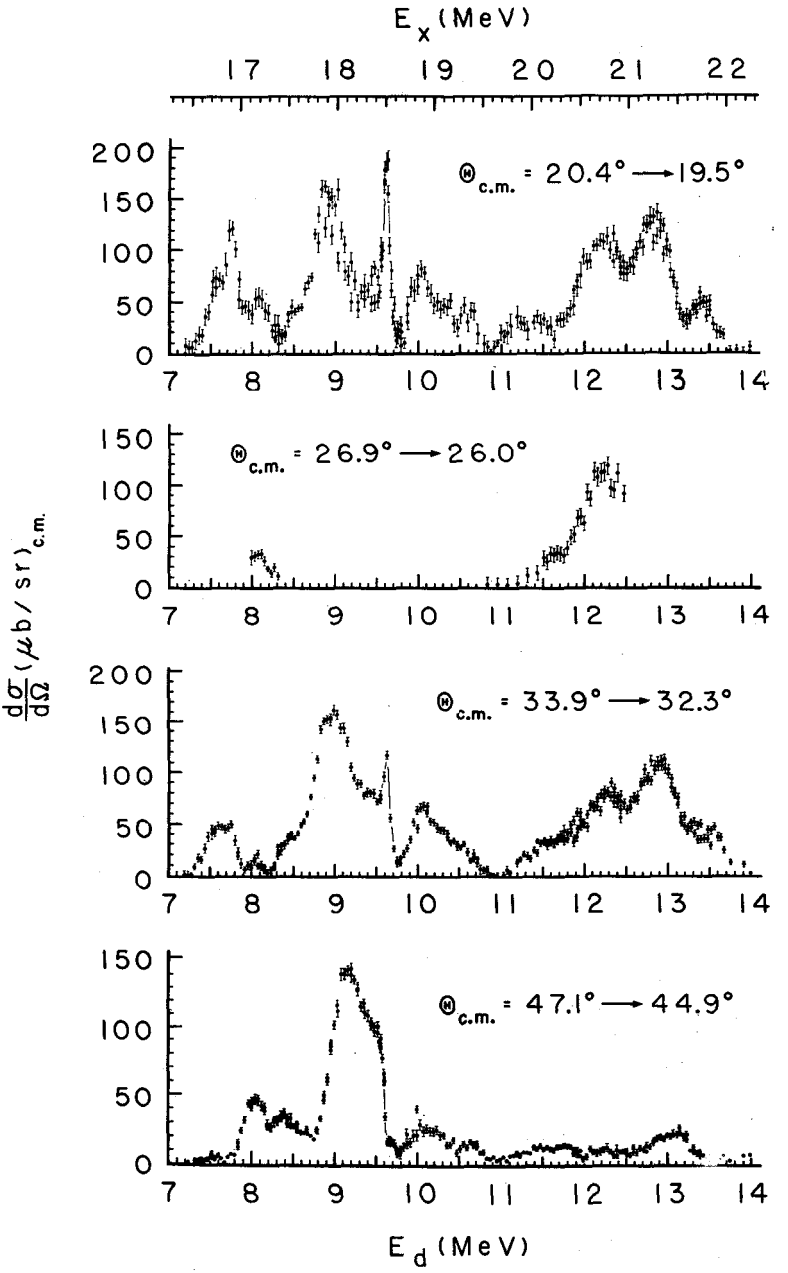

Fig. 3 - Forward angle excitation functions for the reaction $^{12}C(d, \alpha_2)^{10}B^*$

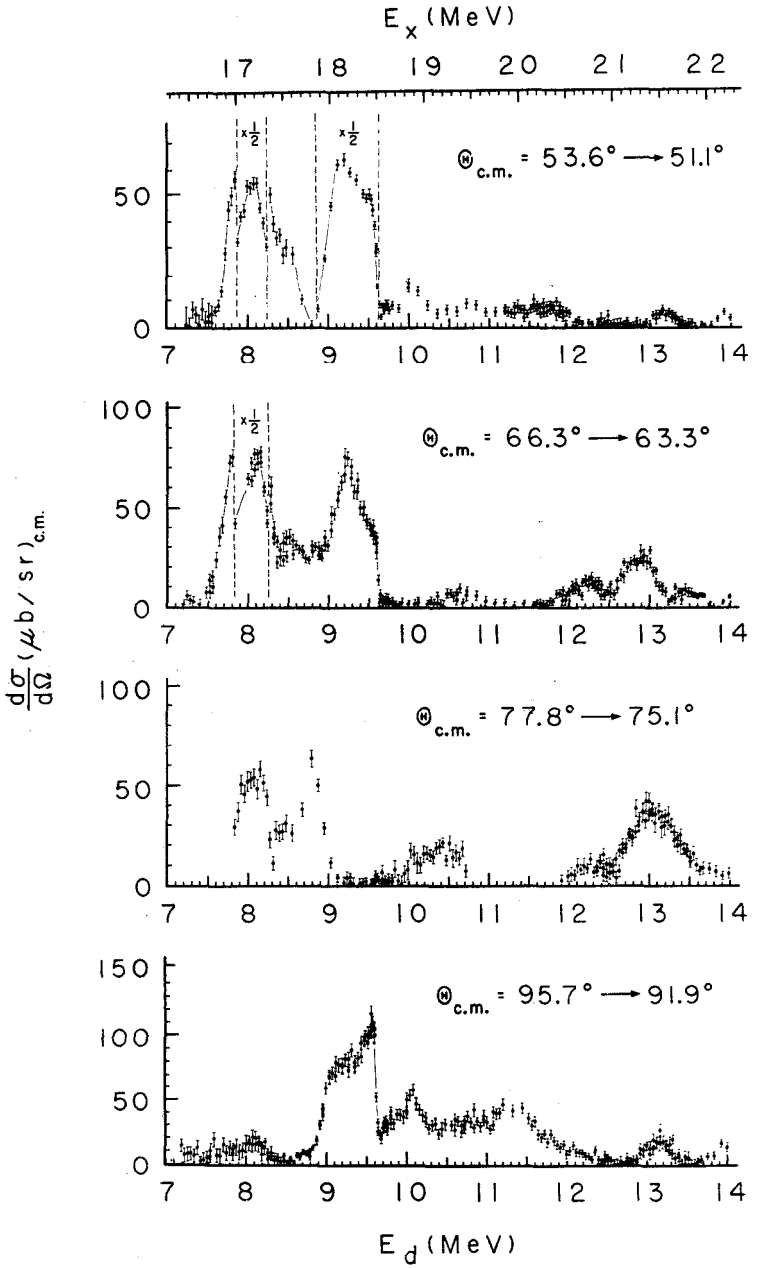

Fig. 4 - Excitation functions for the reaction $^{12}C(d, \alpha_2)^{10}B^*$ for the middle angles.

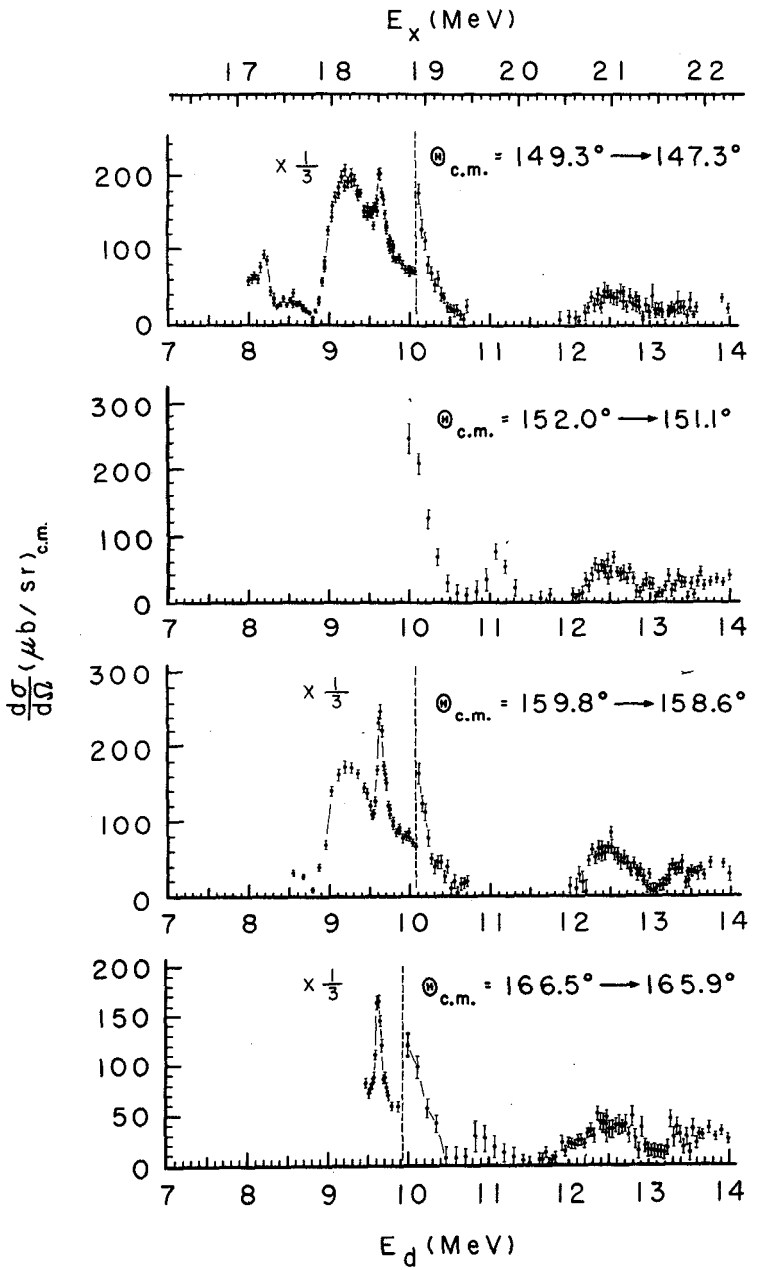

Fig. 5 - Back angle excitation functions for the reaction $^{12}C(d, \alpha_2)^{10}B^*$.

Smith's original analysis of this data occurred before Jolivette[7] had worked out our current techniques for picking and following a solution, so it is with this warning that I present and discuss one of Smith's[5] eight possible solution sets shown in Fig. 8. Here he has plotted $\sigma_l = (2l+1)|S_l|^2$ rather than the $|S_l|$ we showed for the $^{16}O + d$ data.

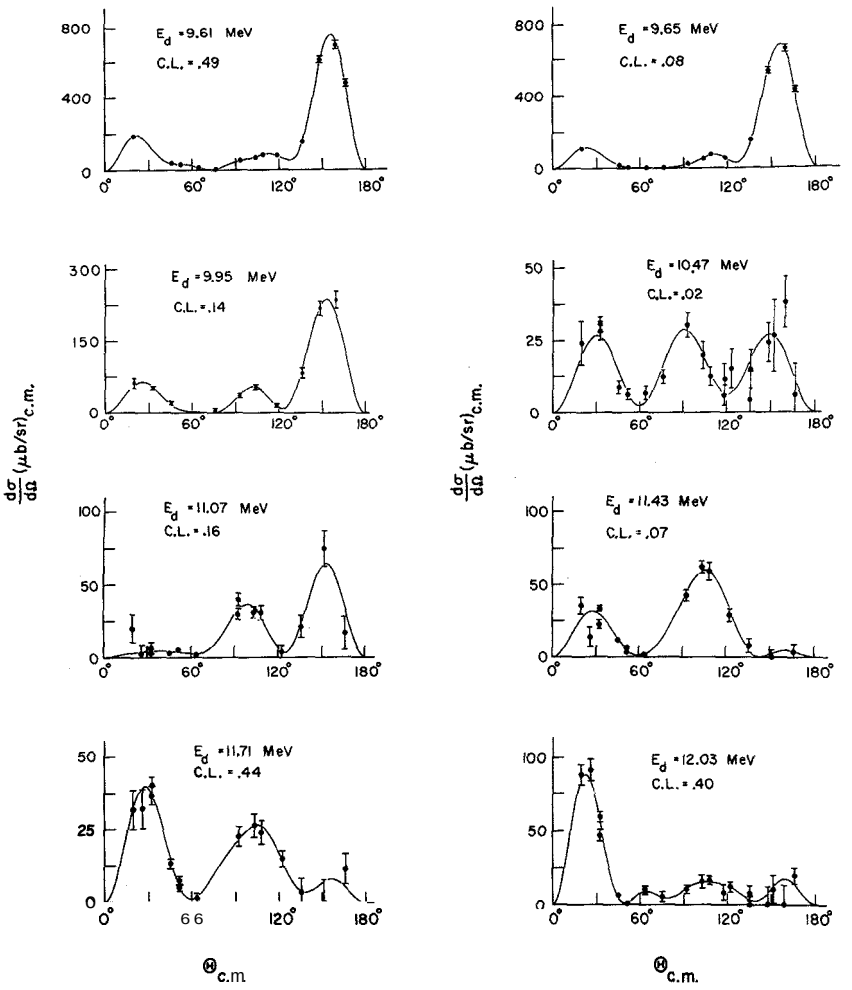

Fig. 6 - Angular distrbutions for the reaction $^{12}C(d, \alpha_2)^{10}B^*$.

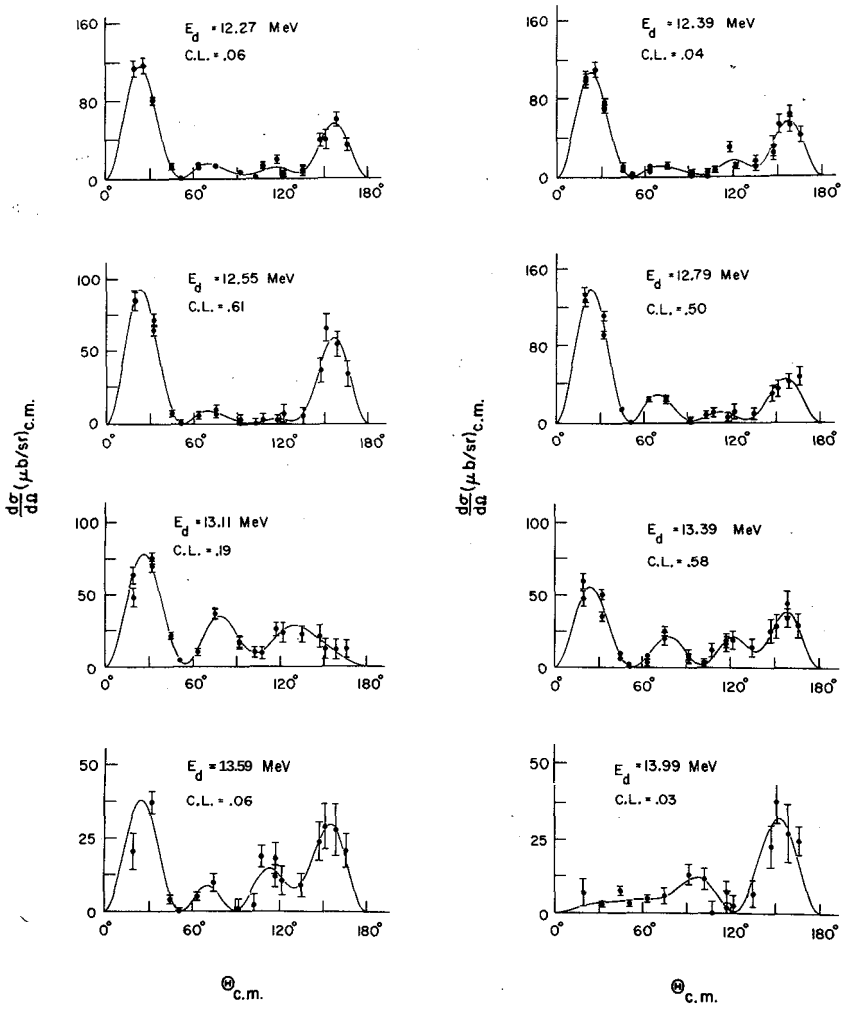

Fig. 7 - Angular distributions for the reaction $^{12}C(d, \alpha_2)^{10}B^*$.

For $l_{\max} = 5$ there are, of course, no ambiguities, and the 5^- levels which I pointed out on the excitation functions here reveal themselves clearly. For the energies where $l_{max} = 4$, the solution is again unique. We are now testing whether we stay with this same solution at high energies where $1 = 5$ enters. For the $1 = 3$ partial wave there is an energy region

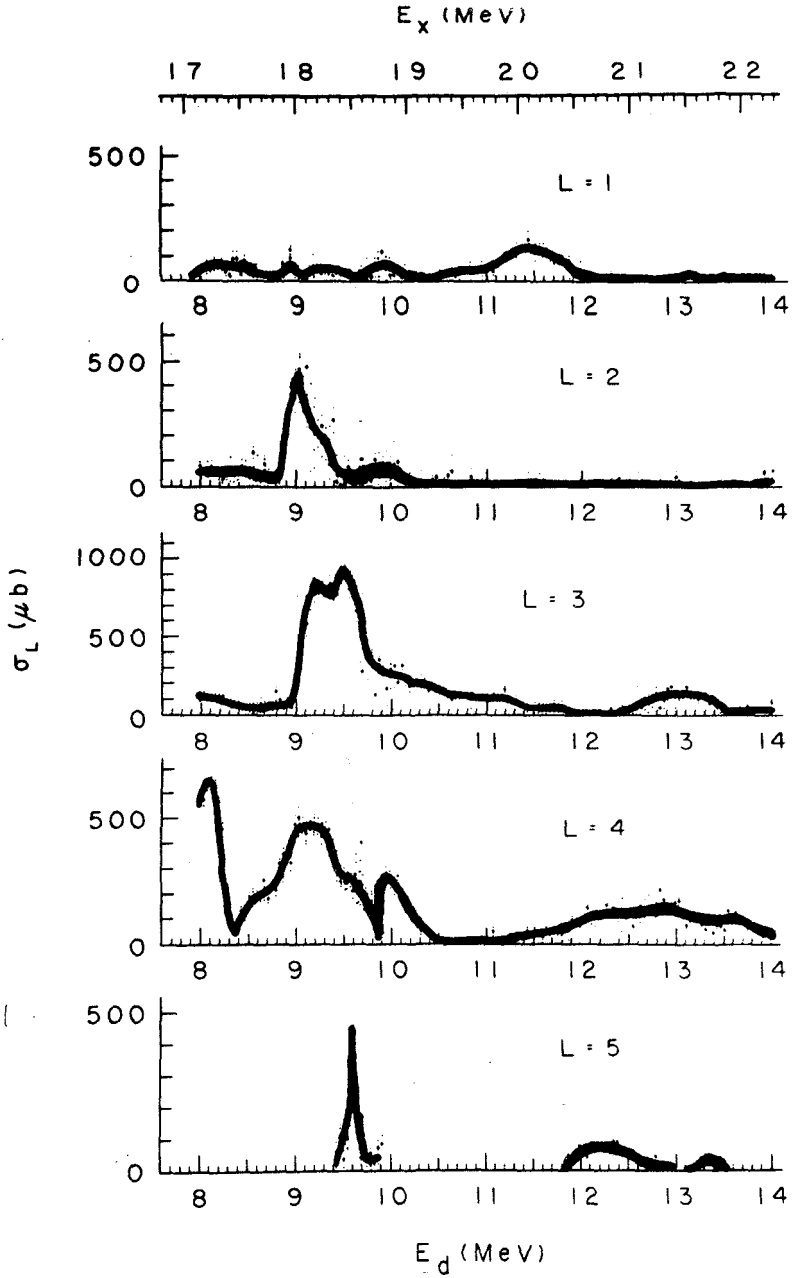

Fig. 8 - Plots of $\sigma_l = (2l + 1)\,|S_l|^2$ from calculations by Smith

$10.5 < E_x < 11$ MeV where $l = 4$ is negligible and hence the ambiguities disappear for $l = 3$. If we have stayed with the same solution set elsewhere, the general features of the $1 = 3$ curve must be correct. However, the only feature of the $l = 1$ and $1 = 2$ curves currently believable is the broad resonance in $l = 1$ at $E_x = 11.5$ MeV to which I referred earlier. This corresponds to a 1^- state in ^{14}N and was present in all solution sets.

In the interesting next step another graduate student, Dan Steck, has a preliminary parametrization of these partial wave curves in terms of ^{14}N level parrimeters. He finds reasonable fits with ≤ 4 states for any one of the partial waves. At first glance, the small number of states seems surprising for fitting such odd shapes, but the interference effects from a coherent sum of their Breit-Wigner resonances can indeed reproduce these shapes. However, until we have reanalyzed the data to be sure we've stayed with the same solution set and have picked the right physical solution, we prefer not to quote specific level parameters. Nevertheless, if application of Jolivette's criterion picks a different solution set, by Occam's razor it must be a simpler set so we feel fairly confident that thc bulk of Smith's isospin forbidden cross sections will require fewer than 20 levels in ^{14}N for a reasonable description over a six MeV deuteron range. To us this constitutes a remarkably simple descnption.

I would end the story here except last July the group collaborating with Meyer-Schutzmeister and Von Ehrenstein[8] used their new FN tandem to extend their old data to somewhat higher energies. Most of their new data appears in Fig. 9. They conclude that these new data do not permit a simple compound nucleus description, but they have made no attempt at a quantitative level fitting. Apparently, the evidence persuasive to this conclusinn was the fact that, over a severa1 MeV energy interval, the cross sections do not average to symmetry ribout 90° c.m..

In fact, such symmetry about 90" will exist only if there is an isolated resonance or if the number of levels involved is sufficiently large that the interference effects will average to zero. Since Smith's analysis shows that only a few ^{14}N states contribute, we should therefore expect large departures from symmetry even when data is averaged over large energy intervals. Another effect, peculiar to the isospin forbidden reaction, may extend the energy region where the asymmetry is of one sign. I refer to the fact that though the observed leve1 density is low, the selection mechanism for the forbidden final states requires isospin mixing in the intermediate state. Such mixing implies close spacing of states of different isospin but same J^n. The result is a tendency for the observable compound states

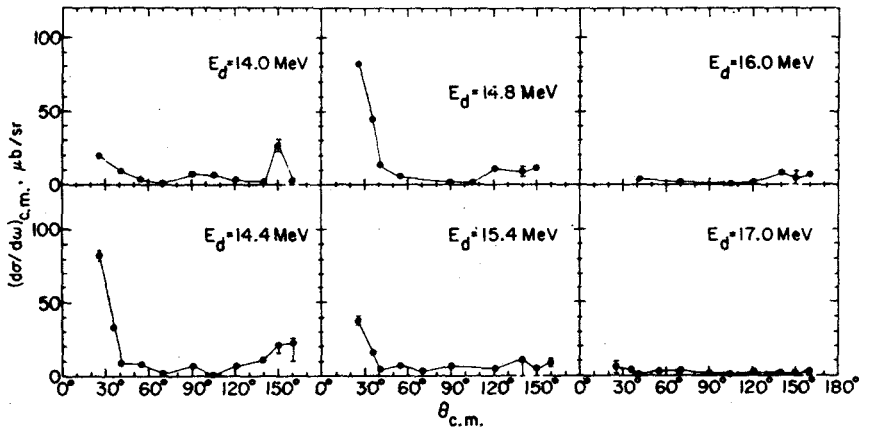

Fig. 9 - Angular distributions of the reaction $^{12}C(d, \alpha_2)^{10}B^*$ reported in Ref. 8.

of the same spin and parity to clump in doublets or multiplets. As a consequence, interference between states of the same J^n is important for many half widths beyond a strong doublet location.

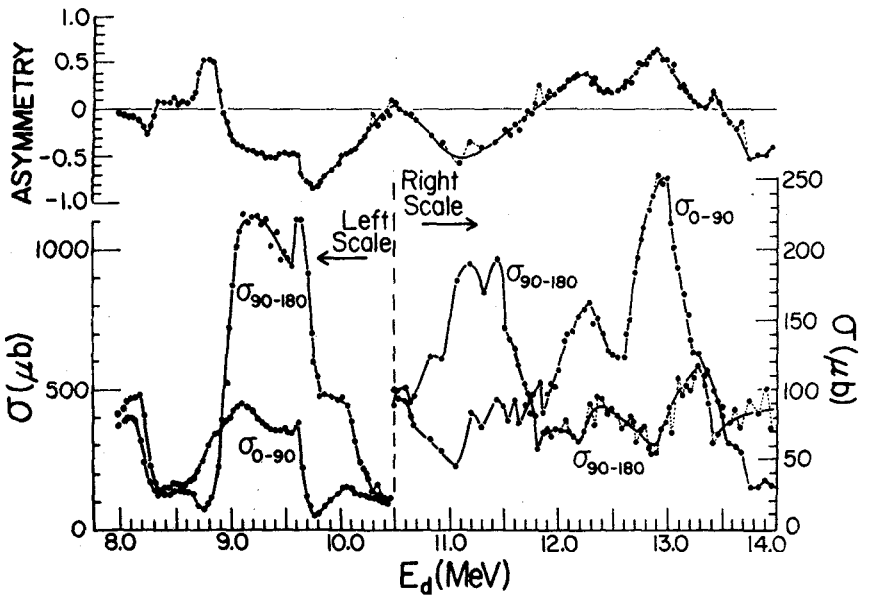

Fig. 10 - Fitted angular distributions integrated from 0 to 90° and from 90" to 180". The upper curve, gives the difference between the integrated cross sections in the forward and backward hemispheres divided by the total cross section.

We have therefore found it of interest to look at the symmetry of Smith's data[4] which indeed parametrizes in terms of a few compound nuclear levels to see over what energy intervals the asymmetry is of one sign.

Fig. 10 displays the results[g]. Plotted are the fitted angular distributions integrated from 0-90" and from 90"-180" to give cross sections in the forward and in the backward hemispheres. In the upper curve we plot an asymmetry parameter defined as the difference in the cross section between the two hemispheres divided by the total cross section. Note the quite extensive energy regions where there is a net forward or a net backward asymmetry.

We therefore conclude that the simple compound nucleus viewpoint is, for our data, consistent with extended regions of departures from symmetry about 90". Since the data of Von Ehrenstein *et al.*[8] are not qualitatively different from ours, we question their conclusion concerning the inadequacy of the simple compound nucleus viewpoint.

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