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Observation of an Anomalous Angular Distribution in the Single Nucleon Transfer Reaction $^{12}C(^{14}N,^{13}N)^{13}C$ at 100 MeV*

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The reaction $^{12}C(^{14}N,^{13}N)^{13}C$ has been studied at a bombarding energy of 100 MeV. The measured differential cross sections have been compared with exact finite range DWBA calculations including recoil. The angular distribution of the reaction populating the $2s_{1/2}$ state in ^{13}C at 3.09 MeV shows pronounced oscillations which are out of phase with those of the predicted angular distribution. The measured spectroscopic factor for this state is such that it is unlikely that an unexpected reaction process is dominating the expected direct transfer process.

Recently it has been shown that the inclusion of "recoil effects" in numerical DWBA calculations of heavy ion transfer cross sections strongly affects the predicted differential cross sections in both shape and magnitude (particularly at higher energies), and explains many observations which are not

previously understood,[1,2] In particular, the inclusion of recoil increases the number of ℓ-transfers which contribute to the cross section. This can be seen from considering the selection rules. The angular momentum selection rules for a reaction A(a,b)B are:

$$|\ell_1 - \ell_2| \leq \ell \leq \ell_1 + \ell_2$$

and

$$|j_1 - j_2| \leq \ell \leq j_1 + j_2$$

where $a = b + x]^{j_1}_{\ell_1}$ and $B = A + x]^{j_2}_{\ell_2}$, i.e., b and A are the cores between which x is transferred.

If recoil effects are not included, there is an additional "rule" which is an artifact of the "no-recoil" approximation. It is: $(-1)^{\ell} = \Delta\pi$ where $\Delta\pi$ is the change in parity from the initial to the final system. The ℓ-values which satisfy this pseudo rule are called "normal" ℓ's and those which do not are called "non-normal" ℓ's. The contributions of these non-normal ℓ-transfers to the cross section have been found to be quite important in many heavy ion reactions.

One example of this was the successful analysis of single nucleon transfer reactions induced by ^{14}N on ^{12}C and ^{11}B at higher energies.[1] The relative lack of structure in some of the angular distributions for these reactions was explained by the complementary contribution of a "normal" $\ell = 0$ transfer and a "non-normal" $\ell = 1$ transfer, both of which were highly structured but out of phase with each other. In particular, the $^{12}C(^{14}N,^{13}N)^{13}C_{g.s.}$ reaction at 78 MeV was well fit with the incoherent sum of these rapidly oscillating components, producing a smooth angular distribution in reasonable agreement with the data.

This explanation of the relatively structureless angular distribution is quite plausible, but it would be preferable to fit an angular distribution with structure to test the correctness of the theoretical treatment. Such a test can be achieved by measuring the angular distribution of the reaction $^{12}C(^{14}N,^{13}N)^{13}C(3.09\ MeV, 2s_{1/2})$ which, according to the first of the above selection rules, will have only an $\ell = 1$ contribution to the cross section. If this contribution has the same rapidly oscillating angular dependence found in the $\ell = 1$ contribution to the ^{13}C ground state cross section, then the experimental $2s_{1/2}$ angular distribution would be expected to have pronounced oscillations.

To test this prediction, we have measured the $^{14}N + ^{12}C$ elastic scattering and single nucleon transfer differential cross sections at a bombarding energy of 100 MeV using an ^{14}N beam from the Berkeley 88" cyclotron. The reaction products were analyzed with magnetic spectrometer system.[3] A momentum spectrum for the transfer reaction is shown in Fig. 1, with the ground state and 3.09 MeV state indicated. Since ^{13}N is bound by only 1.94 MeV, no excited states of ^{13}N are expected in the spectrum.

Figure 2 shows the angular distributions of the ^{13}C states. Also shown for comparison is the measured elastic scattering angular distribution and its optical model fit. It can be seen clearly from Fig. 2 that the ^{13}C ground state ($1p_{1/2}$) does not oscillate while the angular distribution for the 3.09 MeV ($2s_{1/2}$) state has pronounced oscillations, in qualitative agreement with the prediction given above. However, a serious discrepancy appears when the oscillations of the 3.09 MeV ($2s_{1/2}$) angular distribution are compared with those of the elastic scattering angular distribution in Fig. 2. We see that the two distributions oscillate <u>out of phase</u>. The diffraction model for heavy ion

transfer reactions[5] indicates that this phasing is characteristic of an even ℓ transfer and, as has been previously mentioned, the transfer reaction is expected to populate the $2s_{1/2}$ state with $\ell = 1$ only. It is possible that the diffraction model is too crude to give reliable predictions of such phasing. To investigate this question we must employ a more accurate theoretical treatment.

Exact finite range DWBA calculations including recoil were made using the program LOLA.[2] These are shown in Fig. 3. The ground state ($1p_{1/2}$) angular distribution is reasonably well fit with the DWBA prediction which is an incoherent sum of $\ell = 0$ and $\ell = 1$ components and gives a product spectroscopic factor of 0.51. This number is in good agreement with the value determined in the 78 MeV analysis[2] (0.53) and with the theoretical value of Cohen and Kurath[6] (0.42). On the other hand, the $\ell = 1$ prediction for the $2s_{1/2}$ angular distribution is clearly out of phase with the data, as anticipated by the consideration of the diffraction model above. Curiously, the data bear an amazing resemblance in phase and shape to the $\ell = 0$ contribution to the ground state angular distribution.

We have investigated the dependence of these predictions on the optical model parameters used. Other parameter sets which fit the $^{14}N + ^{12}C$ elastic scattering in this energy region[7] were tried in the DWBA calculations. Also investigated were the effects of small changes in the bound state parameters (those used in the fits shown are $r_0 = 1.25$ F and $a = 0.65$ F. None of these changes produced any discernable change in the phase of the angular distributions.

Since the finite range DWBA program LOLA has given good agreement with other oscillating angular distributions in this mass and energy region[2] (no

$2s_{1/2}$ states were studied, however) and has also correctly predicted the angular distribution of a $2s_{1/2}$ state in the $^{30}Si(^{16}O,^{15}N)^{31}P$ reaction at 42 MeV,[8] we must conclude that the fault does not lie with the code, and that the reaction process responsible for the population of the $2s_{1/2}$ state is somehow not being correctly described.

At high excitation energy there appears (Fig. 1) a weakly excited group at 7.3 ± 0.3 MeV. The angular distribution of this group is shown in Fig. 2. Based on a comparison with other single-nucleon transfer data,[8] this group may correspond to the $5/2^+$ and $3/2^+$ states (at 6.86 and 7.68 MeV) which are known[9] to be mainly a $[^{12}C(2^+) \otimes 2s_{1/2}]$ configuration. The similarity of the angular distributions for the 7.3 MeV and 3.09 MeV states (Fig. 2) might then suggest that a multistep reaction mechanism is contributing in these cases. However, it should be noted that the spectroscopic factor for the $2s_{1/2}$ state obtained by matching the envelope of the $\ell = 1$ calculation to the envelope of the data is less than unity, i.e., the DWBA prediction is greater, on the average, than the data. Thus it is unlikely that some unanticipated reaction process is dominating the direct transfer to the $2s_{1/2}$ state and inverting the phase of the angular distribution.

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FIGURE CAPTIONS

Fig. 1 Position spectrum for the $^{12}C(^{14}N, ^{13}N)^{13}C$ reaction.

Fig. 2 Experimentally observed angular distributions. The elastic scattering optical model fit was obtained with the parameter set: V_0 = 145 MeV, r_0 = 0.925 F, a_0 = 0.816 F, W_{vol} = 35.3 MeV, r_I = 1.30 F, a_I = 0.178 F, where $R = r_0 (12^{1/3} + 14^{1/3})$.

Fig. 3 DWBA calculations (using the optical parameters of Fig. 2) for the ^{13}C ground state and 3.09 MeV excited states. As discussed in the text, the 3.09 MeV excited state should be an $\ell = 1$ transfer but seems to more closely resemble an $\ell = 0$ transfer.

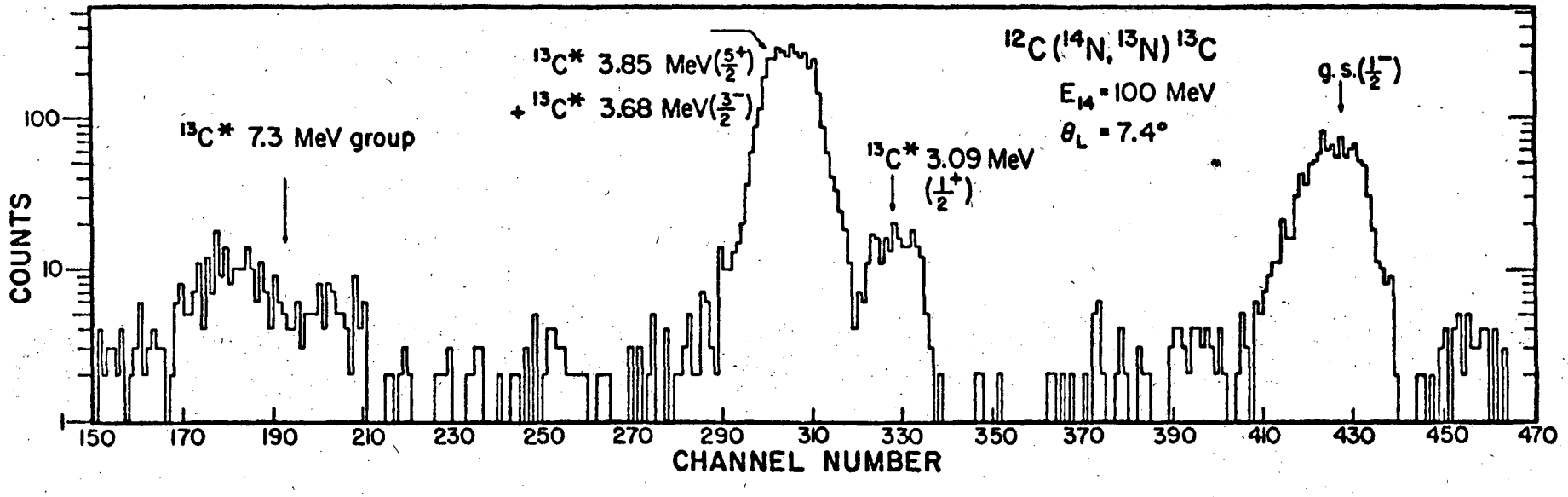
$^{12}C(^{14}N,^{13}N)^{13}C$
E_{14} = 100 MeV
θ_L = 7.4°
$^{13}C^*$ 7.3 MeV group
$^{13}C^*$ 3.85 MeV($\frac{5^+}{2}$)
+ $^{13}C^*$ 3.68 MeV($\frac{3^-}{2}$)
$^{13}C^*$ 3.09 MeV ($\frac{1^+}{2}$)
g.s.($\frac{1^-}{2}$)
COUNTS
100
10
1
150 170 190 210 230 250 270 290 310 330 350 370 390 410 430 450 470
CHANNEL NUMBER

Fig. 1

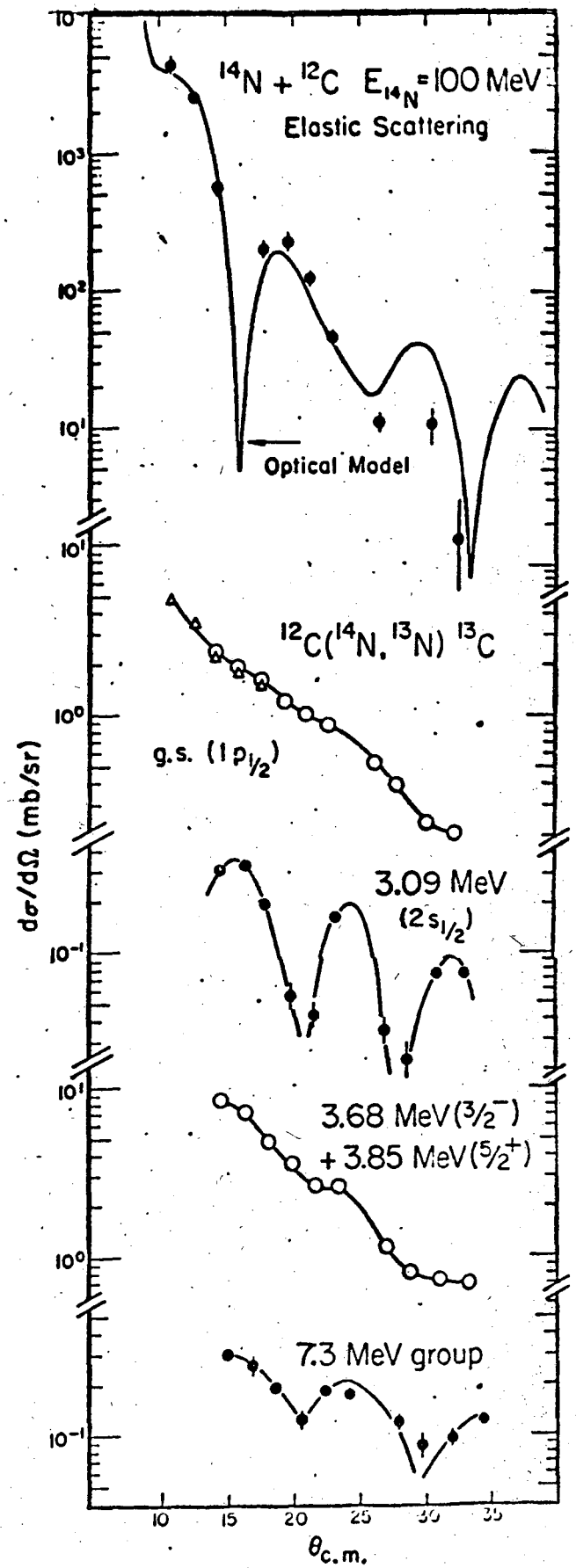
$^{14}N + ^{12}C$ $E_{^{14}N}$ = 100 MeV
Elastic Scattering
Optical Model
$^{12}C(^{14}N, ^{13}N)\ ^{13}C$
g.s. ($1p_{1/2}$)
3.09 MeV
($2s_{1/2}$)
3.68 MeV($3/2^-$)
+ 3.85 MeV($5/2^+$)
7.3 MeV group
$d\sigma/d\Omega$ (mb/sr)
$\theta_{c.m.}$

Fig. 2.

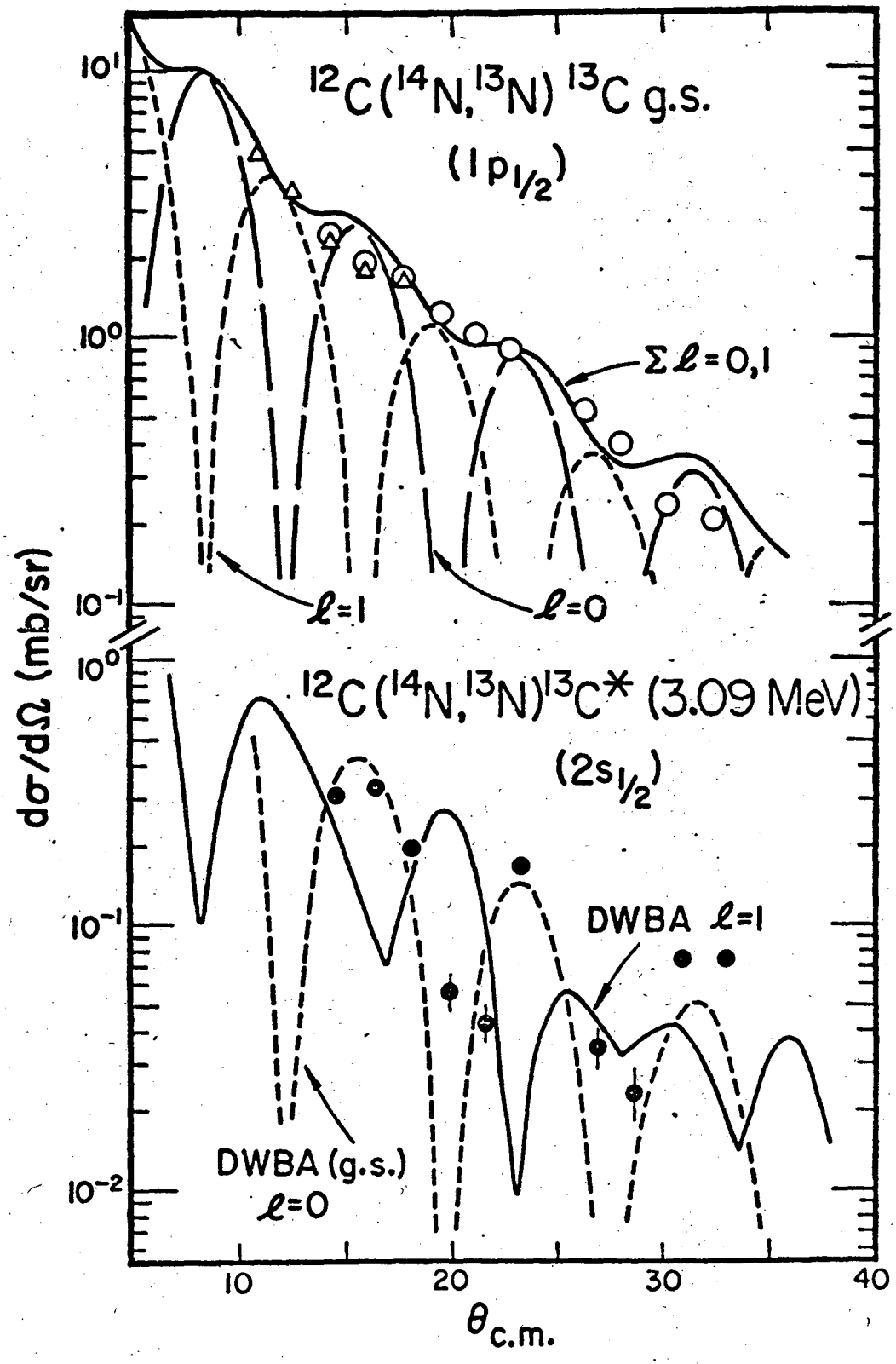
$^{12}C(^{14}N,^{13}N)\,^{13}C$ g.s.
$(1p_{1/2})$
$\Sigma\ell=0,1$
$\ell=1$
$\ell=0$
$^{12}C(^{14}N,^{13}N)^{13}C^*$ (3.09 MeV)
$(2s_{1/2})$
DWBA $\ell=1$
DWBA (g.s.)
$\ell=0$
$d\sigma/d\Omega$ (mb/sr)
$\theta_{c.m.}$
10^1
10^0
10^{-1}
10^0
10^{-1}
10^{-2}
10
20
30
40

Fig. 3.

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