sition the DCO ratios involving the composite (714.6 + 713.9)-keV peak can now be analyzed, together with the directional distribution data. All data are consistent with the 714.6-keV transition being an essentially pure ($|\delta| < 0.1$) $9 \rightarrow 8$ transition. The possibility of a mixed $8 \rightarrow 8$ transition with $\delta \approx +2.0$ (in the definition of Krane and Steffen[5]), cannot entirely be excluded from the DCO and directional distribution data. This assignment, however, is unlikely in view of the absence of crossover transitions to the 6^+ state.

All coincidence rates, DCO, and directional-distribution data are consistent with the level scheme of ^{102}Pd that is shown in Fig. 1. The fact that *all* possible DCO ratios involving the 714.6-keV γ transition are far from unity clearly demonstrates that the 1019–892–705–714.6-keV cascade in ^{102}Pd is not an extension of the ground-state band as previously proposed.[1] It is more likely that this cascade corresponds to another $\Delta I = 2$ band built upon a $J = 9$ state. A band of this type, built on a $J = 7$ state, has been observed in the neighbor nucleus ^{104}Pd.[6,7] It is also to be noted that the 1019–893–705–540–713.9-keV transitions form a $15 \rightarrow 13 \rightarrow 11 \rightarrow 9 \rightarrow 7 \rightarrow 5$ sequence of states. The parity of these states has not been determined experimentally and this spin sequence could possibly correspond to an odd-parity band with a strong accidental overlap of its 9^- state with the 8^+ state of the ground-state band.

The measurements described here show that DCO-ratio observations are practical and very useful for the determination of the multipole character of, and spin changes in, γ transitions that take place in the complex decay of nuclei produced in (HI, xn) reactions. A more detailed account of the DCO and directional-distribution measurements on the ^{102}Pd γ rays following the (^{13}C, xn) reaction will be published in the near future.[3]

[1]G. Scharff-Goldhaber, M. McKeown, A. H. Lumpkin, and W. F. Piel, Phys. Lett. 44B, 416 (1973).

[2]K. S. Krane, R. M. Steffen, and R. M. Wheeler, Nucl. Data, Sect. A 11, 351 (1973).

[3]J. A. Grau, F. A. Rickey, P. C. Simms, G. J. Smith, R. M. Steffen, and J. R. Tesmer, to be published.

[4]P. C. Simms, R. Anderson, F. A. Rickey, G. Smith, R. M. Steffen, and J. R. Tesmer, Phys. Rev. C 7, 1631 (1973).

[5]K. S. Krane and R. M. Steffen, Phys. Rev. C 2, 724 (1970).

[6]S. Cochavi, O. C. Kistner, M. McKeown, and G. Scharff-Goldhaber, J. Phys. (Paris) 33, No. 8-9, 103 (1972).

[7]G. J. Smith, J. A. Grau, F. A. Rickey, P. C. Simms, and J. R. Tesmer, to be published.

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

R. M. DeVries,† M. S. Zisman, J. G. Cramer, and K.-L. Liu
University of Washington, Seattle, Washington 98195

and

F. D. Becchetti,‡ B. G. Harvey, H. Homeyer,§ D. G. Kovar,‖ J. Mahoney, and W. von Oertzen§
Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 11 February 1974)

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 distorted-wave Born approximation 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.

Recently it has been shown that the inclusion of "recoil" in numerical distorted-wave Born-approximation 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 were not previously understood.[1,2] In particular, the inclusion of recoil increases the number of l transfers which can 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

$$|l_1 - l_2| \leq l \leq l_1 + l_2$$

and

$$|j_1 - j_2| \leq l \leq j_1 + j_2,$$

where $a = b + x|_{l_1}{}^{j_1}$ and $B = A + x|_{l_2}{}^{j_2}$, 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 $(-1)^l = \Delta\pi$, where $\Delta\pi$ is the change in parity from the initial to the final system. The l values which satisfy this pseudorule are called "normal" l's and those which do not are called "nonnormal" l's. The contributions of these nonnormal 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 high 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" $l = 0$ transfer and a "nonnormal" $l = 1$ transfer, both of which were highly structured but out of phase with each other. In particular, the reaction $^{12}C(^{14}N, ^{13}N)^{13}C$(g.s.) at 78 MeV was well fitted with the incoherent sum of these rapidly oscillating components, producing a smooth angular distribution in reasonable agreement with the data.

This explanation of a 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 $^{12}C(^{14}N, ^{13}N)^{13}C(3.09\text{ MeV}, 2s_{1/2})$ which, according to the first of the above selection rules, will have only an $l = 1$ contribution to the cross section. If this contribution has the same rapidly oscillating angular dependence found in the $l = 1$ 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-in. cyclotron. The reaction products were analyzed with a magnetic spectrometer system.[3] A momentum spectrum for the transfer reaction is shown in Fig. 1, with the ground, 3.09-MeV, and 3.85-MeV states 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 *out of phase*. The diffraction model for heavy-ion transfer reactions[4] indicates

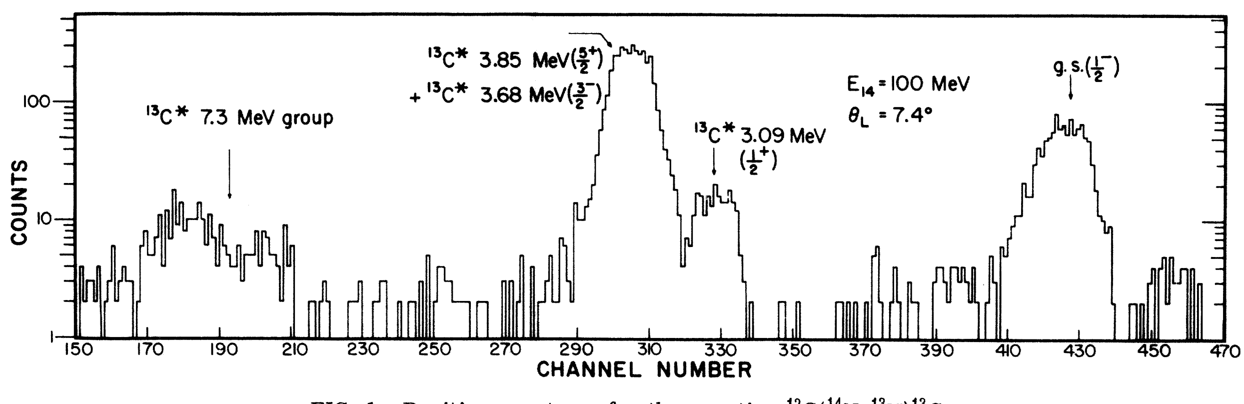

FIG. 1. Position spectrum for the reaction $^{12}C(^{14}N, ^{13}N)^{13}C$.

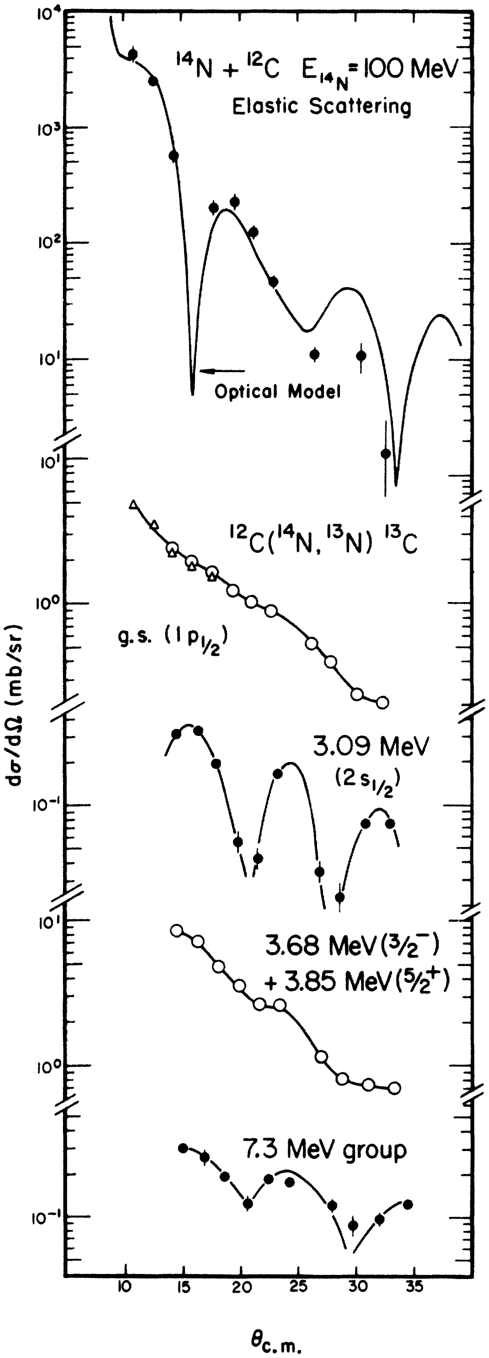

FIG. 2. Experimentally observed angular distributions. The elastic-scattering optical-model fit was obtained with the parameter set $V_0 = 145$ MeV, $r_0 = 0.925$ F, $a_0 = 0.816$ F, $W_{vol} = 35.3$ MeV, $r_I = 1.30$ F, $a_I = 0.178$ F, where $R = r_0(12^{1/3} + 14^{1/3})$. The triangular points in the ^{13}C ground-state angular distribution were obtained from measurements of the mirror reaction $^{12}C(^{14}N, ^{13}C)^{13}N$(g.s.). The solid curves through the transfer reaction angular distributions are only to guide the eye.

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 $l = 1$ 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

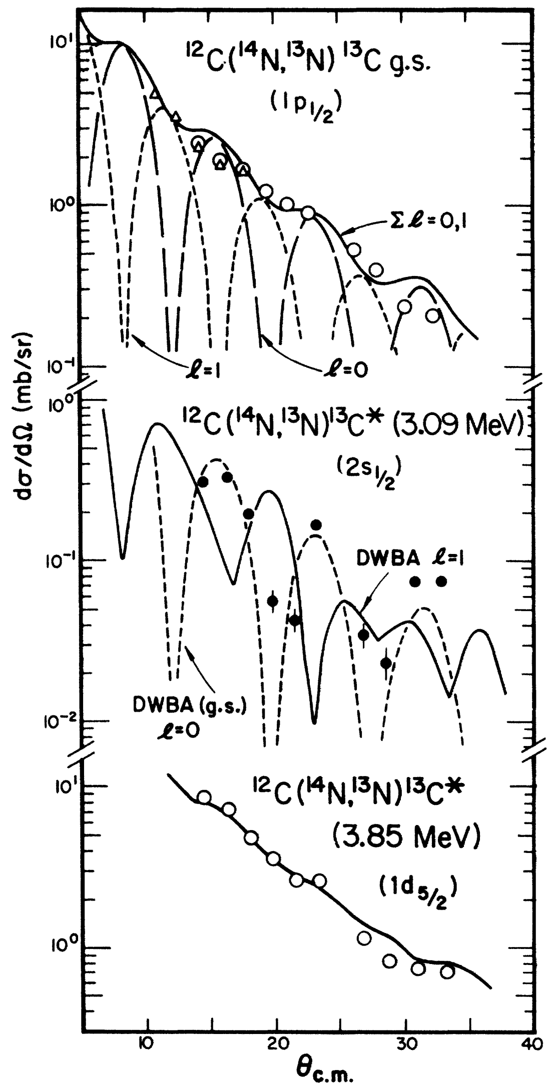

FIG. 3. DWBA calculations (using the optical parameters of Fig. 2) for the ^{13}C ground, 3.09-MeV, and 3.85-MeV states. As discussed in the text, the 3.09-MeV excited state should be an $l = 1$ transfer but seems to more closely resemble an $l = 0$ transfer.

fitted with the DWBA prediction which is an incoherent sum of $l = 0$ and $l = 1$ 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[5] (0.42). The 3.85-MeV ($1d_{5/2}$) angular distribution is also well reproduced by the DWBA calculation, although in this case the measured spectroscopic factor, 0.37, is less than the expected value of unity. [Based on a comparison with high-resolution $^{12}C(^{7}Li, ^{6}Li)$ data,[6] the contribution to the 3.85-MeV peak from the unresolved $1p_{3/2}^{-1}$ level at 3.68 MeV is expected to be very small.] However, the $l = 1$ 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, and the normalization shown in the figure yields a spectroscopic factor (0.25) considerably smaller than expected. Curiously, the data bear an amazing resemblance in phase and shape to the $l = 0$ 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 $r_0 = 1.25$ fm and $a = 0.65$ fm). None of these changes produced any discernible 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 reaction $^{30}Si(^{16}O, ^{15}N)^{31}P$ 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,[6,9] this group may correspond to the $\frac{5}{2}^+$ and $\frac{3}{2}^+$ states (at 6.85 and 7.68 MeV) which are known[10] to be mainly a $^{12}C(2^+) \otimes 2s_{1/2}$ configuration. The similarity of the angular distributions for the 7.3 and 3.09-MeV states (Fig. 2) might then suggest that a multistep reaction mechanism is contributing in these cases. However, since the spectroscopic factor obtained for the $2s_{1/2}$ state is too small, any multistep contribution to the reaction process presumably is such that it interferes destructively with the direct $2s_{1/2}$ transfer.

In summary, we find that the ground and 3.85-MeV state angular distributions are well reproduced by finite-range DWBA calculations but the 3.09-MeV state has a highly oscillatory angular distribution which is completely out of phase with the theoretical prediction. The explanation for this anomaly is presently unknown and further measurements should be undertaken to clarify the reaction mechanisms in this mass region.

We would like to thank J. S. Blair and D. L. Johnson for helpful discussions.

*Work supported in part by the U. S. Atomic Energy Commission.

†Present address: Nuclear Structure Laboratory, University of Rochester, Rochester, N. Y. 14627.

‡Present address: Cyclotron Laboratory, University of Michigan, Ann Arbor, Mich. 48105.

§Present address: Hahn-Meitner Institute, Berlin, Germany D1000.

||Present address: Physics Division, Argonne National Laboratory, Argonne, Ill. 60439.

[1]R. M. DeVries and K. I. Kubo, Phys. Rev. Lett. 30, 325 (1973).

[2]R. M. DeVries, Phys. Rev. C 8, 951 (1973).

[3]B. G. Harvey *et al.*, Nucl. Instrum. Methods 104, 21 (1972); M. S. Zisman, Ph.D thesis, Lawrence Berkeley Laboratory Report No. LBL-1247, 1972 (unpublished).

[4]K. R. Greider, *Nuclear Reactions Induced by Heavy Ions* (North-Holland, Amsterdam, 1970), p. 217; A. Dar, Phys. Lett. 7, 339 (1963).

[5]S. Cohen and D. Kurath, Nucl. Phys. A101, 1 (1967).

[6]P. Schumacher, N. Ueta, H. H. Duhm, K. I. Kubo, and W. J. Klages, Nucl. Phys. A212, 573 (1973).

[7]I. Kohno, S. Nakajima, T. Tonuma, and M. Odera, J. Phys. Soc. Jap. 30, 910 (1971); W. von Oertzen, M. Liu, C. Caverzasio, J. C. Jacmart, R. Pougheon, M. Riou, J. C. Roynette, and C. Stephan, Nucl. Phys. A143, 34 (1970).

[8]R. M. DeVries, Phys. Rev. C 8, 1542 (1973).

[9]H. T. Fortune, T. J. Gray, W. Trost, and N. R. Fletcher, Phys. Rev. 179, 1033 (1969); however, see, M. L. Munger and R. J. Peterson, Bull. Amer. Phys. Soc. 18, 1389 (1973).

[10]O. Mikoshiba, T. Terasawa, and M. Tanifuji, Nucl. Phys. A168, 417 (1971).