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Further Evidence for Anomalous Angular Distributions for Transitions to the $2s_{1/2}$ States in the Mass-13 System*

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(Received 21 October 1974)

The reaction $^{12}C(^{10}B,^{9}Be)^{13}N$ is investigated at 100 MeV with special emphasis on the transition to the first excited state in ^{13}N at 2.37 MeV. An anomaly in the angular distribution for the latter transition is observed similar to the one reported earlier by DeVries *et al.* in a study of the reaction $^{12}C(^{14}N,^{13}N)^{13}C(3.09,\frac{1}{2}^+)$.

Recently, an anomalous angular distribution populating the first excited state at 3.09 MeV ($J^\pi=\frac{1}{2}^+$) in ^{13}C has been reported by DeVries *et al.*[1] in a study of the reaction $^{12}C(^{14}N,^{13}N)^{13}C$ at 100 MeV. Since this transition is expected to occur between a $1p_{1/2}$ orbit and a $2s_{1/2}$ orbit, the angular momentum transfer ($l=1$) is unique. Thus the experimental angular distribution should show a characteristic oscillatory pattern, if one assumes a direct one-step reaction mechanism. One then hopes that an exact distorted-wave Born-approximation (DWBA) calculation should fit the results well. However, it was found[1] that even though there were oscillations in the data, the $l=1$ theoretical fit was completely out of phase with the observed experimental angular distribution. Curiously, the latter had a strong resemblance to an $l=0$ angular distribution.

One reaction which could provide additional information in this connection is the proton transfer reaction $^{12}C(^{10}B,^{9}Be)^{13}N$ populating the corresponding analog state in ^{13}N. Consequently, we performed such an experiment at an incident energy of 100 MeV. Since ^{9}B is unstable, the analog reaction $^{12}C(^{10}B,^{9}B)^{13}C$ populating the states in ^{13}C could not be investigated. Here we present the experimental angular distributions of the reaction $^{12}C(^{10}B,^{9}Be)^{13}N$ leading to the various states of ^{13}N and the corresponding exact finite-range DWBA fits with special emphasis on the results pertaining to the first excited state.

Natural carbon targets of thickness 600 $\mu g/cm^2$ were bombarded by 100-MeV ^{10}B beams from the Texas A& M variable-energy cyclotron. All outgoing heavy ions were detected by using a three-detector telescope and particle-identification technique. The details of the experimental setup and data-collection methods will be published elsewhere.[2] A typical energy spectrum of the detected ^{9}Be nuclei at $\theta_{lab}=10°$ is shown in Fig. 1. The energy resolution is approximately 600 keV,

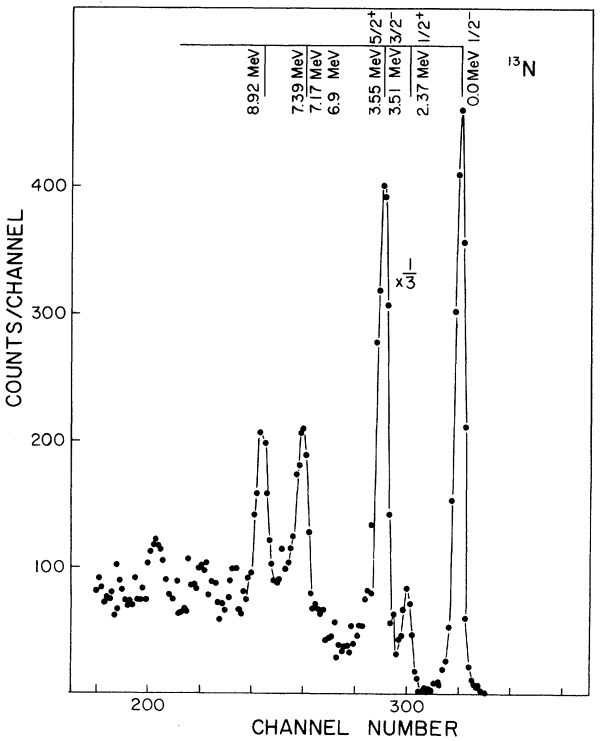

FIG. 1. Energy spectra of the detected ^{9}Be nuclei at $\theta_{lab}=10°$. The low-lying levels of ^{13}N are shown in the inset.

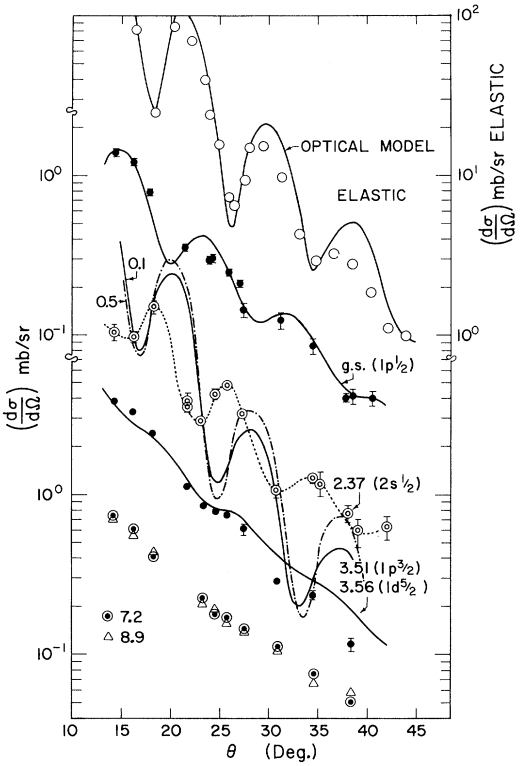

FIG. 2. Experimental elastic and transfer angular distributions. The continuous lines signify exact finite-range DWBA calculations. The dotted line connecting the experimental points for the state ^{13}N(2.37, $J^\pi = \frac{1}{2}^+$) is intended only to guide the eye. The continuous and dash-dotted lines correspond to theoretical calculations with 0.1 MeV and 0.5 MeV binding, respectively, for this state.

mainly because of kinematic broadening. The states clearly identifiable from this energy spectrum are ^{13}N(g.s., $J^\pi = \frac{1}{2}^-$), ^{13}N(2.37, $J^\pi = \frac{1}{2}^-$), and the unresolved states ^{13}N(3.51, $J^\pi = \frac{3}{2}^-$) and ^{13}N(3.56, $J^\pi = \frac{5}{2}^+$). The two prominent peaks at higher excitation are tentatively identified as the 7.2-MeV and 8.9-MeV states in ^{13}N. The corresponding experimental angular distributions as well as the elastic angular distribution are shown in Fig. 2.

Calculations were performed on these transfer angular distributions using the exact finite-range (EFR) DWBA theory including recoil as described by Tamura.[3] We have used the program SATURN-MARS,[4] suitably adapted to fit an IBM-7094 computer with the relatively small word length (36 bits) and memory size (32K) in our laboratory, for this purpose. Test calculations and comparisons with the original version, which is primarily written for a CDC 6600 computer, showed agreement to within 0.1%.

Optical-model fits to the elastic data yielded several six-parameter sets. We have used the set $V = 30.57$ MeV, $W = 17.18$ MeV, $r_{0v} = 1.129$ fm, $r_{0w} = 1.181$ fm, $a_v = 0.651$ fm, $a_w = 0.520$ fm, and $r_{0c} = 1.03$ fm (the continuous line for the elastic data in Fig. 2 corresponds to this set) for all of the transfer calculations with the specific assumption that the entrance- and exit-channel optical parameters are the same. The bound-state geometry was $r_0 = 1.26$ fm, $a_0 = 0.6$ fm, and $v_{s.o.} = 6.0$ MeV. The central depth of the binding Woods-Saxon potential was searched for in the usual manner by assuming the physical binding energy for the ground state of ^{13}N. Since all the excited states of ^{13}N are unbound, we made the assumption that they are bound by the small binding energy of 0.1 MeV. This assumption is expected to be quite reasonable (the first excited state at 2.37 MeV, for example, is unbound by only 430 keV; further arguments in favor of similar recipes are given by Fortune *et al.*[5]). In fact, we did investigate the effects of this artificial binding energy on the cross sections; for example, in Fig. 2, the continuous and dash-dotted lines correspond to calculations with $E_b = 0.1$ MeV and 0.5 MeV, respectively, for the first excited state. It is clear that the phase of the oscillations did not change noticeably even for such a relatively large change in binding energies, while the magnitude of the cross section was affected only slightly.

The ground-state calculation assuming the angular momentum transfers $l = 1$ and 2 fits the data very well. However, the corresponding product spectroscopic factor $C_1^2S_1C_2^2S_2$ (where C_1 and C_2 are the appropriate isospin Clebsch-Gordan coefficients) is 0.15, which is considerably smaller than the value 0.37 predicted by Cohen and Kurath,[6] but is closer to the value 0.21 predicted by Varma and Goldhammer.[7] For the second excited group, the contribution from the $1p_{3/2}$ hole state at 3.51 MeV is expected to be very small.[5] Hence the DWBA calculation indicated by the continuous line for this group in Fig. 2 corresponds to the assumption that it is purely the 3.56 MeV ($J^\pi = \frac{5}{2}^+$) state in ^{13}N. The angular momentum transfers here are $l = 1$, 2, and 3. Again the fit is quite good and the product spectroscopic factor extracted is $C_1^2S_1C_2^2S_2 = 0.14$. Assuming the values 0.6 or 0.38 for the value of $C_1^2S_1$ for $^{10}\mathrm{B} = {}^9\mathrm{Be} + p$ predicted by Cohen and Kurath or Varma and Goldhammer, respectively, we get values of $C_2^2S_2$ for the $1d_{5/2}$ state of 0.23

TABLE I. Spectroscopic factors. The columns a and b signify the values based on the predictions of values of $C_1^2S_1$ for $^{10}B=^9Be+p$ by Cohen and Kurath (Ref. 6) and Varma and Goldhammer (Ref. 7), respectively. The value quoted for the $2s_{1/2}$ state is obviously not derived from a fit and clearly depends on the rather arbitrary normalization as shown in Fig. 2.

State	Orbit	$C_1^2S_1C_2^2S_2$ Absolute	$C_1^2S_1C_2^2S_2$ Relative[a]	$C_2^2S_2$ (Absolute) a	b
^{13}N(g.s.)	$1p_{1/2}$	0.15	0.42	0.25	0.40
^{13}N(2.37)	$2s_{1/2}$	0.23	0.64	0.38	0.61
^{13}N(3.56)	$1d_{5/2}$	0.14	0.39	0.23	0.37

[a]The relative product spectroscopic factors with the normalization assuming the Cohen-Kurath value for the ground state.

or 0.37. The higher excited states show experimental angular distributions with progressively washed-out structures, a feature noted by Fortune *et al.*[5] in their study of the reaction $^{12}C(^3He, d)^{13}N$. We have made no attempt to fit these data with theory.

In contrast to the other fits, the EFR DWBA calculation for the first excited state in ^{13}N at 2.37 MeV ($J^\pi=\frac{1}{2}^+$) shows the same puzzling discrepancy as noted by DeVries *et al.*[1] in their study of the transition to the analog state in ^{13}C at 3.09 MeV ($J^\pi=\frac{1}{2}^+$). The continuous line is the EFR DWBA calculation corresponding to $l=1$ (the dotted line through the experimental points is drawn only to guide the eye) in Fig. 2. The experimental angular distribution is clearly out of phase with the theoretical calculations as well as with the elastic angular distribution. The extracted product spectroscopic factor with the assumption of the normalization shown in the figure is $C_1^2S_1C_2^2S_2=0.23$. Again $C_2^2S_2=0.38$ or 0.61 depending on the value of $C_1^2S_1$ as noted before. This result has to be compared with the full single-particle strength reported by Rolfs and Azuma[8] who report a value $C^2S=1.02\pm0.15$ extracted from a study of the reaction $^{12}C(p,\gamma)$. For the first excited analog state in ^{13}C, DeVries *et al.*[1] report a value of 0.25. A summary of the extracted spectroscopic factors for the present case is given in Table I. For comparison, the relative product spectroscopic factors normalized to the ground-state calculation with the Cohen-Kurath value of 0.42 for $C_1^2S_1C_2^2S_2$ are also given in Table I. Although there is scope for improvement in our extracted absolute spectroscopic factors, our major conclusion regarding the lack of fit of the $2s_{1/2}$ angular distribution is not affected by this as was verified by calculations with different values for the various parameters.

Preliminary measurements of the reaction $^{12}C(^{14}N, ^{13}C)^{13}N(2.37, J^\pi=\frac{1}{2}^+)$ were performed at this laboratory at 155 MeV and the measured cross section was found to be about 0.6 mb/sr at forward angles ($\theta_{lab}=4°$). An EFR DWBA calculation yielded the rough estimate for the spectroscopic factor for this state of 0.28, consistent with the results of DeVries *et al.* for its analog state.

The present results clearly support the belief that a single-step direction-reaction theory, even with the inclusion of finite range and recoil, is not capable of satisfactorily explaining heavy-ion–induced one-nucleon transfer to the first excited $2s_{1/2}$ states in the mass-13 system. This fully corroborates the point of view of DeVries *et al.*[1] It would be instructive to perform additional experiments and make extensive calculations including multistep processes for the $2s_{1/2}$ states in this mass and energy region.

We wish to thank Professor T. Udagawa for many helpful discussions. We are indebted to Dr. K. S. Low and Professor T. Tamura for making the EFR DWBA program SATURN-MARS available to us as well as for many valuable suggestions.

*Research supported in part by the National Science Foundation.

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