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Neutron Transfer to the Ground State of ^{14}C in the $^{13}C(^{14}N, ^{13}N)^{14}C$ Reaction*

R. M. Gaedke†
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
and Physics Department, Trinity University, San Antonio, Texas 78212

and

W. Tobocman
Physics Department, Case Western Reserve University, Cleveland, Ohio 44106

and

K. S. Toth
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830
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Thick targets of ^{13}C (91.7%) were bombarded with ^{14}N ions accelerated in the Oak Ridge tandem Van de Graaff, and the cross section for the neutron-transfer reaction $^{13}C(^{14}N, ^{13}N)^{14}C$ was measured from 12.5 to 20.5 MeV. The cross section measured in this energy range is due predominantly to transfer that proceed to the ^{14}C ground state, since the threshold for the reaction to populate the 6.09-MeV first excited state is 17.6 MeV. The measured excitation function was then compared with cross sections calculated from the recent distorted-wave Born-approximation (DWBA) treatment of Schmittroth, Tobocman, and Golestaneh. It was possible to find an optical potential for which the DWBA matched the observed excitation function above 14-MeV (lab) incident energy. From this fit the spectroscopic factor for the ^{14}C ground state was determined. The excitation function for the compound-nucleus reaction $^{13}C(^{14}N, 2p)^{25}Na$ was also measured for ^{14}N incident energies from 13.5 to 20.5 MeV.

I. INTRODUCTION

The main motivation for the study of heavy-ion-induced transfer reactions has been the possibility that such investigations could be used to determine single-particle reduced widths and nuclear spectroscopic factors. A quantitative description of the transfer of neutrons between heavy ions for energies below the Coulomb barrier has been formulated by Breit and Ebel[1] specifically for the reaction $^{14}N(^{14}N, ^{13}N)^{15}N$. Investigators[2,3] have used the theory to derive neutron reduced widths by measuring the total cross section for the reaction $^{14}N(^{14}N, ^{13}N)^{15}N$ as a function of energy, and by assuming that the reduced widths in ^{14}N and ^{15}N are equal. Good agreement was found[2,3] between the reduced widths extracted in this manner and values derived from shell-model calculations, and from (d,p) and (p,d) experiments on ^{14}N. Surprising success has also been attained in the extraction of the neutron reduced width in ^{11}B when the theory was applied[3] to cross-section measurements for the reaction $^{10}B(^{14}N, ^{13}N)^{11}B$. The derived reduced width for ^{11}B agreed well with a shell-model calculation that assumed the ^{11}B ground state to be $^{10}B + 1p_{3/2}$ neutron. This agreement may have been largely coincidental or may have been observed because the neutron states involved in the ^{14}N and ^{10}B reactions are fairly similar.

The Coulomb-wave Born-approximation (CWBA) treatment has been proposed as an alternative to the tunneling theory.[4,5] When the CWBA treatment was applied to the $^{14}N(^{14}N, ^{13}N)^{15}N$ reaction, it was found to give results in agreement with those of the tunneling theory. The validity of the CWBA treatment, however, is not restricted to

low (or zero) Q values as is the case for tunneling. [The Q value for the $^{14}N(^{14}N, ^{13}N)^{15}N$ reaction is 0.29 MeV.]

The treatments mentioned above are valid only for incident energies sufficiently small so that the interaction between the ions can be regarded as being purely Coulombic. The restriction to such cases has the advantage that the determination of spectroscopic factors will not be complicated by uncertainties in the optical potentials. Distorted-wave Born-approximation (DWBA) treatments have been formulated[6-8] which are restricted neither to low Q value nor to very low incident energies.

The present study was undertaken in the hope of determining the ^{14}C neutron spectroscopic factor by measuring the excitation function for the $^{13}C-(^{14}N, ^{13}N)^{14}C$ reaction whose Q value (−2.38 MeV) is quite different from zero. The analysis of the excitation function should yield the ^{14}C neutron spectroscopic factor, since the value for ^{14}N is known. The reaction has the advantage that the ^{14}C first excited state is 6.09 MeV above ground. Therefore, at ^{14}N incident energies below 17.6 MeV one is concerned only with transfers to the ^{14}C ground state. The $^{13}C(^{14}N, ^{13}N)^{14}C$ reaction had the following additional advantage. Since the reaction had to be investigated at energies far below the Coulomb barrier, the Q value could not be too negative. Otherwise the cross section would be too small to measure.

The cross section for the reaction was measured for ^{14}N energies from 12.5 to 20.5 MeV. The excitation function was then compared with cross sections calculated by means of the DWBA theory reported in Ref. 8. It was possible to find an optical potential for which the DWBA calculation matched the experimental excitation function for energies above 14 MeV. From this fit a spectroscopic factor for ^{14}C was determined. Below 14 MeV there appears a discrepancy between the energy dependence predicted by theory and the shape of the observed excitation function. This discrepancy is absent in the $(^{14}N, ^{13}N)$ reactions on ^{10}B and ^{14}N targets.[4-8] It is perhaps an indication of the existence of some competing mechanism for nucleon transfer between ^{14}N and ^{13}C which does not fall off with energy as rapidly as the direct reaction.

II. EXPERIMENTAL TECHNIQUE AND RESULTS

Finely powdered carbon, enriched in ^{13}C to 91.7% was used as the target material in this investigation. Targets were prepared by compressing the powdered material into brass molds $\frac{1}{2}$ in. in diameter. These targets were thicker than the range of the nitrogen ions and presented a hard and uniform surface to the incident particles. Bombardments were made in a Faraday-cup assembly, and beam currents up to 150 nA were recorded. The energy of the ^{14}N ions, accelerated in the Oak Ridge tandem Van de Graaff, was varied from 12.0 to 21.0 MeV.

After bombardment the targets were counted in a fixed geometry in a low-level gas-flow β detector with a background of ~0.25 counts/min. Decay curves were resolved into their components and the presence of ^{13}N in each target was established by the identification of its 10-min half-life. Two other activities were observed: ^{25}Na(60 sec), produced in the reaction $^{13}C(^{14}N, 2p)^{25}Na$, and a small amount of ^{24}Na(15.0 h), produced primarily in the corresponding reaction on ^{12}C present in the target material. A computer program was used to give least-squares fits to the decay curves and to determine the magnitudes of the various decay curve components extrapolated to time zero, i.e., to the end of bombardment. The program also supplied the standard deviations for the time-zero magnitudes. The absolute counting efficiency of the low-level counter was 22%. Counting rates at time

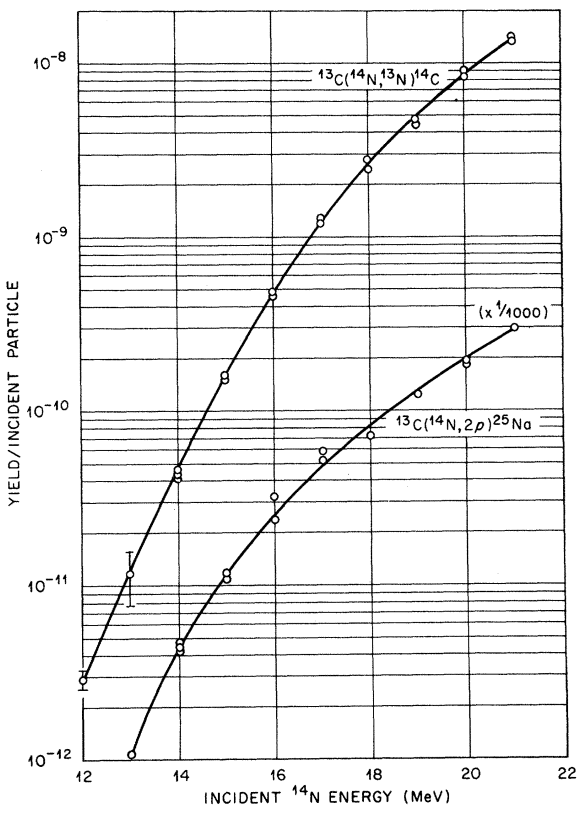

FIG. 1. Yields per incident particle as a function of bombarding energy. Note that the data points for the $^{13}C-(^{14}N, 2p)^{25}Na$ reaction have been decreased by a factor of 1000.

zero as obtained from the computer fit were then corrected by the efficiency to obtain the absolute yields per incident particle. The probable error in these yields results mainly from the uncertainty in the counter efficiency determination and is estimated to be ±15%.

The thick-target yields measured for the production of ^{13}N and ^{25}Na are shown in Fig. 1. Smooth curves were drawn through the thick-target yield points and these curves were then differentiated to obtain the excitation functions (see Fig. 2). For this determination the stopping power of the target material for ^{14}N ions had to be known. It was calculated by using the known stopping power of nickel for nitrogen ions[9] and by assuming that the relative stopping power for protons and ^{14}N ions of the same velocity in a given material is the same. Proton stopping powers for carbon and nickel were taken from Allison and Warshaw.[10] Probable errors in the absolute cross sections are estimated to be ±30% and are attributed to errors arising from uncertainties in the counter efficiency, the slope of the yield curves, and the stopping power.

Since the Q value for the reaction ^{12}C(^{14}N, ^{13}N)^{13}C is −5.61 MeV, the contribution of ^{13}N activity from ^{12}C present in the target material was not expected to be appreciable. As a precautionary measure, however, carbon powder with natural isotopic content was also bombarded. A small amount of short-lived activity was observed at incident energies above 17 MeV. The half-life was difficult to determine because of the low counting rates. If all of the short-lived activity were ascribed to ^{13}N, then, for a given energy, the yields from these natural-carbon targets were less than 10% of those from the enriched ^{13}C targets. This information coupled with the fact that ^{12}C made up only 8.3% of the targets enriched in ^{13}C indicated that the production of ^{13}N from ^{12}C in these targets could be neglected.

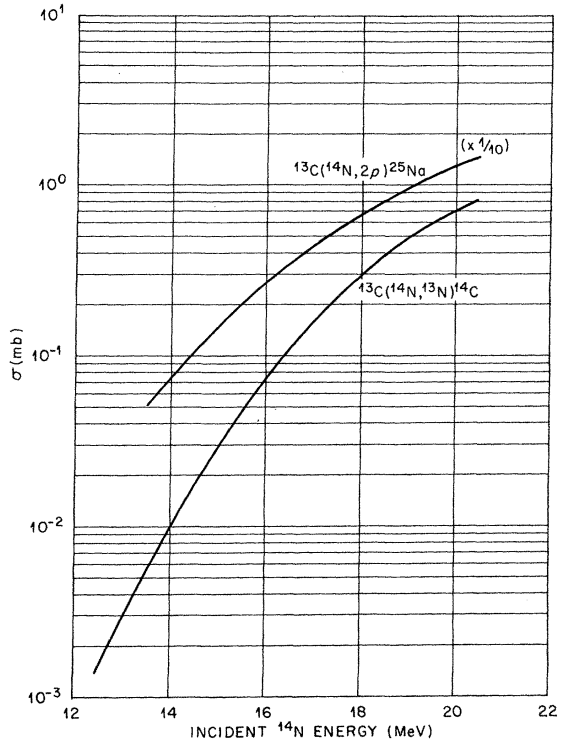

FIG. 2. Excitation functions for the reactions ^{13}C-(^{14}N, ^{13}N)^{14}C and ^{13}C(^{14}N, 2p)^{25}Na. Note that the cross sections for the latter reaction have been decreased by a factor of 10.

III. DISCUSSION

The formal details of the DWBA program used here to calculate the neutron-transfer cross sections are given in Ref. 8. The DWBA expression for the $I(A,B)F$ reaction, where

$$A+I=(B+N)+I\rightarrow B+(N+I)=B+F\,, \tag{1}$$

is

$$\frac{d\sigma_{AB}}{d\Omega}=\frac{M_{AI}M_{BF}}{(2\pi\hbar^2)^2}\,\frac{k_B}{k_A}\,\frac{(2J_F+1)}{(2J_I+1)}\,B \times\sum_{LM}\frac{|\langle\Psi_{BF}^{(-)}|Y_{LM}F_{LM}|\Psi_{AI}^{(+)}\rangle|}{2L+1}\,. \tag{2}$$

In Eq. (2), B is given by the following relationship:

$$B=N_AN_F\left\{\theta_{j_1l_1}^{(A)}\theta_{j_2l_2}^{(F)}\frac{4}{\pi}[(2l_1+1)(2l_2+1)]^{1/2} \times W(l_2j_2l_1j_1;\tfrac{1}{2}L)(l_2l_100|L0)\right\}^2\,, \tag{3}$$

where N_A and N_F are the number of neutrons in the incident projectile and residual target, respectively, that may be transferred. The spectroscopic factors are defined by

$$S_A=N_A[\theta_{j_1l_1}^{(A)}]^2$$

and

$$S_F=N_F[\theta_{j_2l_2}^{(F)}]^2\,.$$

$\Psi_{AI}^{(+)}$ and $\Psi_{BF}^{(-)}$ are the distorted wave functions for the initial and final channels, respectively, Y_{LM} is the spherical harmonic, and F_{LM} is the finite-range form factor constructed from the initial and final neutron bound-state radial wave functions calculated for real Woods-Saxon potential wells.

The calculated cross sections are compared with the experimental data in Fig. 3. Various choices for the real and imaginary part of the Woods-Saxon optical potential were tried. The Woods-Saxon potential was assigned a radius of 5.47 F and a diffuseness of 0.55 F. The choice of $V\approx 50$ MeV for the depth of the real potential and

$W = 10$ MeV for the depth of the imaginary potential seems to give a good fit to experiment above 14-MeV incident energy. The calculation used $S_A S_F = 2.0$. On the assumption of a pure single-particle configuration for the outer-shell neutron in ^{14}N, a value of $S_A = S_{^{14}\mathrm{N}} = 1$ has been used[5,6,8] to fit experimental cross sections measured for the reactions ^{14}N(^{14}N, ^{13}N)^{15}N and ^{10}B(^{14}N, ^{13}N)^{11}B. If S_A is taken to be 1, then the ^{14}C spectroscopic factor must be $S_F = S_{^{14}\mathrm{C}} = 2.0$. This value is in agreement with that of 2.05 determined by Schiffer *et al.*[11] in their study of the (d,p) reaction on ^{13}C. We should also add that the shell-model predictions of Cohen and Kurath[12] give values of $S_{^{14}\mathrm{N}} = 1.43$ and $S_{^{14}\mathrm{C}} = 1.73$.

Note that below 14-MeV incident energy, where the optical potential has no effect on the calculation, the calculated cross section falls below the observed value. This would seem to indicate the presence of some competing process contributing to the neutron-transfer reaction.

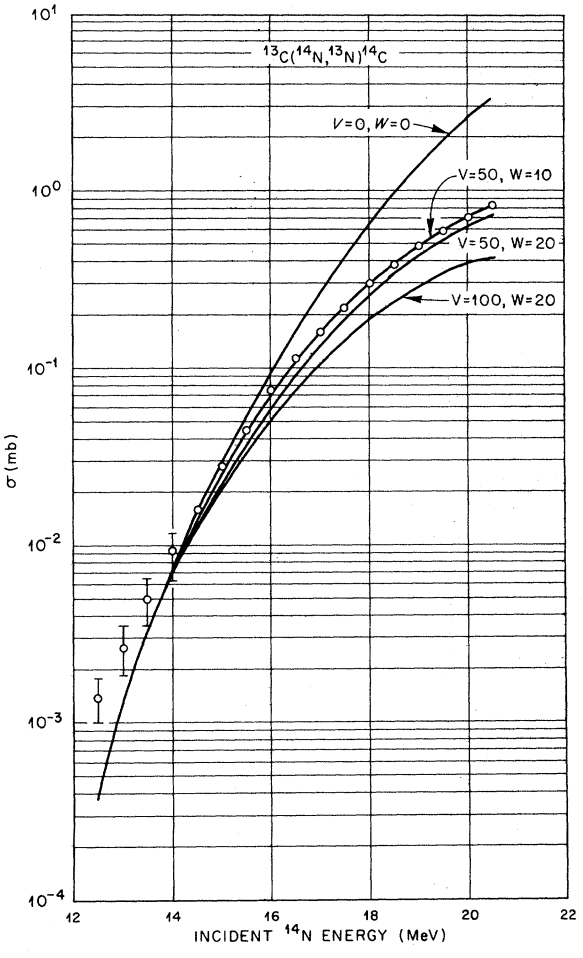

FIG. 3. Comparison of the experimental cross-section data (indicated by points) with the various predictions (solid curves) of the DWBA calculation for the reaction ^{13}C(^{14}N, ^{13}N)^{14}C.

One mechanism that might account for the shallow slope of the excitation function could be virtual Coulomb excitation preceded or followed by neutron transfer. Virtual Coulomb excitation as a contributing process to nucleon transfer was first proposed by Breit and Ebel[1] in an effort to explain the cross-section data obtained by Reynolds and Zucker[13] for the ^{14}N(^{14}N, ^{13}N)^{15}N reaction. Subsequent measurements[3,14] showed that the earlier data[13] were incorrect for incident ^{14}N energies below ~13 MeV. Nevertheless, Hiebert, McIntyre, and Couch[14] still invoked virtual Coulomb excitation to account for a small deviation between their results and the tunneling theory[1] for energies below ~11 MeV. Gaedke, Toth, and Williams[3] were able to show that there was no disagreement between tunneling theory and experiment even at the lowest energy measured, i.e., ~9 MeV. Similarly, they found[3] no disagreement between theory and the experimental excitation function measured for the ^{10}B(^{14}N, ^{13}N)^{11}B reaction.

Transitions to the giant dipole resonance were regarded[1] as the most important contributors to the virtual Coulomb-excitation effect. Breit[15] in 1967 concluded that these effects would be very small due to the high excitation energy of the giant dipole resonance.

In the case of the ^{13}C(^{14}N, ^{13}N)^{14}C reaction, however, there could conceivably be an effect due to the low-lying one-phonon quadrupole excitations[16] in ^{13}C and ^{13}N.

Alternatively, it may be that the giant-dipole virtual Coulomb-excitation effects have become noticeable below 14 MeV because the simple neutron-transfer process has become so weak. For the ^{13}C(^{14}N, ^{13}N)^{14}C reaction the cross section at low bombarding energies is severely decreased by the negative Q value so that it is not unreasonable that an effect such as virtual Coulomb excitation could show up. [The Q values for the (^{14}N, ^{13}N) reactions on ^{10}B and ^{14}N are 0.91 and 0.29 MeV, respectively.] At 13.0 MeV, where the DWBA calculation and experiment deviate appreciably (see Fig. 3) the cross section for the ^{13}C reaction is 0.0027 mb. This laboratory energy corresponds to a value of −2.15 MeV for the difference between $E_{\mathrm{c.m.}}$ and $E_{\mathrm{Coulomb\ barrier}}$ (calculated with $r_0 = 1.5$ F). At that value, i.e., −2.15 MeV, of $E_{\mathrm{c.m.}} - E_B$ the cross sections for the ^{10}B and ^{14}N reactions are ~0.7 − 1.0 mb.[3] Thus, while the effect due to virtual Coulomb excitation for the ^{14}N and ^{10}B reactions may indeed be negligible, it would not necessarily be masked in the ^{13}C reaction. Additional data with other targets and projectiles are needed before any definite conclusions can be made.

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†Present address: Trinity University, San Antonio, Texas 78212.

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Quasielastic Electron Scattering and Pion Electroproduction from C^{12}†

K. C. Stanfield,* C. R. Canizares,‡ W. L. Faissler,§ and F. M. Pipkin
Cyclotron Laboratory, Harvard University, Cambridge, Massachusetts 02138
(Received 27 October 1970)

This paper reports measurements made at the Cambridge Electron Accelerator of the electron-carbon scattering cross section at incident energies of 1, 1.5, 2.25, 3, and 4 GeV and at lab angles of 8.5, 12, and 18°. The measurements included quasielastic scattering and inelastic scattering through the region of the first pion-nucleon resonance. The data are compared with a spectrum generated by summing the known elastic cross section, the known cross sections for excitation of nuclear levels, and a theoretical expression for quasielastic scattering based on the Fermi model for the nucleus. The agreement is satisfactory. The meson electroproduction cross section was derived by subtracting the above calculated spectrum from the data. The total equivalent photoabsorption cross section is consistent with the cross section expected for 12 independent nucleons; the existing Fermi-model calculation does not, however, correctly predict the shape of the electron momentum spectrum. The data are also used to test the Drell-Schwartz sum rule.

I. INTRODUCTION

Many experimental and theoretical studies have been made of electron scattering from carbon.[1,2] There are several reasons for this attention. The carbon nucleus is quite interesting from the standpoint of nuclear physics; thus, much of the experimental work has emphasized the elastic and nuclear level regions of the momentum spectrum.[3,4] Because of its accessibility and simplicity the car-