Theory

Study of the Mechanism of the $^{13}$C($d,p)^{14}$C Reaction at $E_d = 15.3$ MeV


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Abstract—The angular dependences of the differential cross sections of the $^{13}$C($d,p)^{14}$C reaction at the deuteron energy of 15.3 MeV are presented according to measurements for the cases where the final nucleus is produced in the ground state ($0^+$) and in the $1^-$ excited state at 6.094 MeV. The angular distribution of protons corresponding to the sum $0^+ (6.589 \text{ MeV}) + 3^- (6.728 \text{ MeV}) + 0^- (6.903 \text{ MeV})$ of states of the $^{14}$C nucleus that were not separated experimentally is also obtained. These experimental results are compared with their counterparts calculated by means of the FRESCO code for the mechanisms of neutron stripping and sequential neutron and dineutron transfer. The neutron and dineutron spectroscopic amplitudes are calculated for pure and mixed shell configurations. The best set of optical-potential parameters is determined for the entrance and exit reaction channels. It is shown that the neutron-stripping mechanism permits describing the measured angular distributions for all states of the $^{14}$C nucleus that were investigated here.

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1. INTRODUCTION

The structure of the neutron-rich $^{14}$C nucleus has been studied both experimentally and theoretically for several decades, but interest in microscopically describing it in detail has not weakened to date [1–6]. The mixing of shell configurations in this nucleus is studied in various nuclear reactions including those that involve heavy ions. Its deformation parameters and its clustering in various states are determined.

Within the shell model, the $^{14}$C nucleus in the ground state is treated as a $^{12}$C core featuring $|1s^4\rangle$ and $|(1p_3/2)^8\rangle$ filled shells with a probability of 60 to 70% and two extra neutrons in the $|(1p_1/2)^2\rangle$ subshell with a probability of about 27% [6]. In the ground state of the $^{14}$C nucleus, the admixture of the $1d–2s$-shell configuration is negligible.

The properties of the excited states of the $^{14}$C nucleus are known up to the energy of $E^* = 24.3$ MeV [7]. Even at moderately low excitation energies, the $1p^{-n}(1d–2s)^n$ particle–hole neutron states ($n$ may change from 0 to 3) underlie their configuration [8]. The lowest excited states of the $^{14}$C nucleus correspond to the $1p^{-1}(1d–2s)$ configuration in the case of negative-parity states and to the $1p^{-2}(1d–2s)^2$ configuration in the case of positive-parity states.

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The angular distributions of protons from the $^{13}$C($d,p)^{14}$C reaction at deuteron energy between 13 and 18 MeV were studied earlier in [9–11]. The experimental angular distributions for the $0^+_1$, $1^-_1$, and $2^-_1$ states at $E_d = 13$ MeV were presented in [9] along with respective theoretical results calculated for the neutron-stripping mechanism. For the transition to the ground state, the calculations performed for the neutron-stripping mechanism by the method of the distorted-wave Born approximation (DWBA) with normalization factors used for spectroscopic factors led to good agreement with the experimental angular distributions only for scattering angles not larger than $\theta_p = 70^\circ$ (in the c.m. frame). For the transitions to the $1^-_1$ and $3^-_1$ levels, this resulted in similar agreement over the whole angular region under study, which extended to the c.m. angle of $\theta_p = 130^\circ$. At $E_d = 14.8$ MeV, transitions to six states of the final nucleus were studied in [10]. However, the measurements were performed there only up to $\theta_p = 90^\circ$, the absolute cross-section values were determined with an error of ±50%, and the calculations were performed in the plane-wave approximation. The most detailed measurements of the angular distribution of protons for the transitions to the $1^-_1$ and $3^-_1$ states were performed in [11] at $E_d = 17.7$ MeV. Their results were in satisfactory agreement with the results of DWBA calculations.
but the transition to the ground state of the $^{14}$C nucleus escaped the attention of the authors of [11].

The present study is devoted to measurements and a theoretical analysis of the angular distribution of protons from the $^{13}$C($d$, $p$)$^{14}$C reaction occurring at $E_d = 15.3$ MeV and leading to the production of the final $^{14}$C nucleus in the ground state ($0^+_1$) and in low-lying negative-parity excited states—specifically, $1^-$ and $3^-$. In our experiment, the angular distribution of protons for the transitions to the $0^+_2$ (6.589 MeV), $3^-_1$ (6.728 MeV), and $0^-_1$ (6.903 MeV) states of the $^{14}$C nucleus are not separated because of an insufficient energy resolution. From [9–11], we know, however, that, in this reaction (at similar values of the deuteron-beam energy), the proton yield for the $3^-_1$ state is nearly one order of magnitude higher than the proton yield for the $0^+_2$ and $0^-_1$ states over the whole range of $\theta_p$. In view of this, it is natural to assume that the cross section measured for the reaction leading to the excitation of these three states of the $^{14}$C nucleus receives a dominant contribution from the transition to the $3^-_1$ state.

In view of the predominantly direct mechanism of the $(d, p)$ reaction that we study here, it is natural to expect a weak and nonresonance energy dependence of its cross section at least in the range of $E_d = 13$–18 MeV. However, a comparison of the angular distributions obtained in [9–11] revealed a noticeable discrepancy of absolute cross-section values. For this reason, we refine here the absolute values of the differential cross sections obtained by different authors for the reaction being studied.

The theoretical analysis of experimental angular distributions in [12, 13] relied on the coupled-reaction channel (CRC) method and took into account the intermediate ($t$, $^{12}$C) state. In addition to the neutron-stripping mechanism, this approach involves the mechanism of sequential neutron and dineutron stripping. The respective calculations were performed by means of the FRESCO code [14] with allowance for a finite range of interaction in particle transfer.

The spectroscopic amplitudes in the decay vertices were calculated on the basis of the shell model with allowance for both $1p$–shell and mixed $1p^{-1}$–$(1d–2s)$ configurations [15, 16].

2. EXPERIMENTAL PROCEDURE

Our experiment was performed at the cyclotron at the Skobeltsyn Institute of Nuclear Physics (Moscow State University) by employing deuterons accelerated to an energy of 15.3 MeV. The energy spread of the beam was about 160 keV. The self-supporting carbon film 0.55 mg cm$^{-2}$ thick and enriched in the isotope $^{13}$C to 80% was used as a target. We determined the thickness of the target by measuring the energy loss of $\alpha$ particles from a $^{226}$Ra source, and the error in determining it did not exceed 5%. The error in the absolute values of the differential cross section was about 20% and was due primarily to the inaccuracy in the calibration of the deuteron-beam-current integrator.

The charged particles from the reaction under study were extracted from the chamber 23 cm in diameter through a horizontal slit with a thin (20 $\mu$m) Mylar window and were detected by silicon semiconductor detectors whose sensitive area had a thickness of about 2 mm. The measurements were performed for laboratory proton emission angles in the range of $\theta_p = 21^\circ$–161$^\circ$. The detector angular resolution was about $\pm 1^\circ$; the error in determining zero angle did not exceed $\pm 1^\circ$ either.

The spectra of charged particles were accumulated in an amplitude analyzer and were transferred to a computer for a digital processing. The contribution of the $^{12}$C($d$, $p$)$^{13}$C reaction on the $^{13}$C admixture was taken into account in processing the spectrum. In order to subtract this contribution we used the differential cross sections obtained in [17] at $E_d = 15$ MeV. An aluminium absorber slowed down deuterons from elastic scattering on $^{12}$C and $^{13}$C nuclei, thereby shifting them to the low-energy section of the spectrum.

Part of a typical proton spectrum is given in Figs. 1a and 1b. The calculated positions of proton groups indicated in Fig. 1 correspond to the following states of the final $^{15}$C and $^{14}$C nuclei: (1) ground state ($0^+_0$) of the $^{14}$C nucleus ($p_0$ group); (2) ground state of the $^{15}$C nucleus [$^{12}$C($d$, $p$)$^{13}$C reaction on the $^{12}$C admixture in the target]; (3) first excited state ($1^-$, 6.09 MeV) of the $^{14}$C nucleus ($p_1$ group); (4) sum of the $0^+_2$, $3^-_1$, and $0^-_1$ states of the $^{14}$C nucleus at, respectively, 6.589, 6.728, and 6.903 MeV ($p_{2–4}$ groups); and (5) sum of the $2^+$ and $2^-$ states of the $^{14}$C nucleus at, respectively, 7.01 and 7.34 MeV ($p_{5,6}$ groups). Protons corresponding to excited states of the $^{13}$C nucleus are within the same region of spectra. The separation of the $p_{2–4}$ mixed proton group from the $p_1$ and $p_{5,6}$ groups in the spectra was performed by means of the code for resolving overlapping peaks. Figure 1b shows a section of this spectrum upon processing it by means of the KATOK code [18]. One can see that the $p_1$ and $p_{2–4}$ groups were separated quite satisfactorily.

The differential cross sections $d\sigma/d\Omega(\theta_p)$ measured for the $^{13}$C($d$, $p$)$^{14}$C reaction versus the laboratory proton emission angle $\theta_p$ between $21^\circ$ and $161^\circ$ are given in Fig. 2 along with respective results.