^{11}B(^{15}N, ^{14}C)^{12}C REACTION MECHANISMS AND ANC FOR THE $^{15}\mathrm{N} \to {}^{14}\mathrm{C} + p$ CONFIGURATION*

Maulen Nassurlla, N. Burtebayev, S.B. Sakuta
Marzhan Nassurlla, A. Sabidolda

Institute of Nuclear Physics, 050032 Almaty, Kazakhstan

S.V. Artemov, E.T. Ruziev, F.Kh. Ergashev, O.R. Tojiboev

Institute of Nuclear Physics, 100214 Tashkent, Uzbekistan

K. Rusek, A. Trzcińska, M. Wolińska-Cichocka

Heavy Ion Laboratory University of Warsaw, 02-093 Warsaw, Poland

I. Boztosun

Department of Physics, Akdeniz University, 07058, Antalya, Turkey

A. Amar

Faculty of Science, Tanta University, Tanta, Egypt

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New differential cross sections of $^{11}\mathrm{B}+{}^{15}\mathrm{N}$ scattering and ^{11}B(^{15}N, ^{14}C) ^{12}C reaction were obtained at measurements on the U-200P cyclotron of the University of Warsaw at an energy of $E_{^{15}\mathrm{N}} = 43$ MeV. The contribution of the different mechanisms of the reaction was evaluated and the ANC squared value of 46 ± 9 fm^{-1} for the $^{15}\mathrm{N} \to {}^{14}\mathrm{C} + p$ configuration of the ^{15}N ground state has been extracted from these data by the MDWBA analysis.

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1. Introduction

The study of the proton transfer process during the interaction of accelerated nuclei with light nuclei near the Coulomb barrier is of great interest

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for astrophysics, since the information (spectroscopic factors (SF), asymptotic normalization coefficients (ANC)), obtained from the analysis of such reactions, makes it possible to estimate the contribution of direct processes to the astrophysical S-factors at very low energies.

When the exchange of a charged particle occurs at the periphery of nuclei, the Modified Distorted Waves Born Approximation (MDWBA) method [1, 2] becomes convenient, which makes it possible to extract the ANC values.

For example, from the analysis of the ^{11}B(^{15}N, ^{14}C)^{12}C reaction, one can obtain the ANC $^{15}\mathrm{N} \to \left\{^{14}\mathrm{C} + p\right\}$ for the proton-bound state in the ^{15}N nucleus, information about which is currently missing. A feature of this reaction is that the ^{15}N and ^{12}C nuclei have tightly bound proton configurations in the ground state, and the proton transfer process is not obviously peripheral. In addition to new data of the structure of the ^{15}N nucleus and the reaction mechanism, some knowledge of the ANCs is necessary for calculating the cross section for the proton radiative capture $^{14}\mathrm{C}(p,\gamma)^{15}\mathrm{N}$, which competes with the neutron capture $^{14}\mathrm{C}(n,\gamma)^{15}\mathrm{C}$ considered in the inhomogeneous Big Bang models [3].

The product of ANC squared values, $C^2_{B\to A+a} \times C^2_{x\to y+a}$ can be extracted from the differential cross section (DC) of peripheral particle a transfer reactions: $A(x,y)B$, where $B = A + a$ and $x = y + a$ using the MDWBA approach. Usually, one of the ANC values is assumed to be known (for definiteness let it be $C^2_{x\to y+a}$). Then the DC for a proton transfer has the form of

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}^{\mathrm{MDW}} = C^2_{B\to A+p} \times R\left(E, \theta; b_{x\to y+p}, b_{B\to A+p}\right) , \tag{1}$$

where

$$R\left(E, \theta; b_{x\to y+p}, b_{B\to A+p}\right) = C^2_{x\to y+p} \frac{\sigma^{\mathrm{DW}}\left(E, \theta; b_{x\to y+p}, b_{B\to A+p}\right)}{b^2_{x\to y+p} \times b^2_{B\to A+p}} \, . \tag{2}$$

Here, $b_{x\to y+p}$ and $b_{B\to A+p}$ are the model single-particle ANCs at the wave functions of the proton bind in the Woods–Saxon (WS) potentials of the nuclei x and B, $\sigma^{\mathrm{DW}}(\ldots)$ is the single-particle DC calculated within the DWBA framework, E and θ are the relative energy in the entrance channel and emission angle of the outgoing particle y. The function $R(\ldots)$ in the case of peripheral transfer must remain constant when changing the b values, and this is a criterion for the peripheral transfer of particle a in the reaction (see, for example, [3]).

The value of $b_{B\to A+p}$ is varied, changing the values of the geometric parameters r_0 and a of the nuclear part of the potential WS of the proton bound state in the nucleus B within physically reasonable limits (keeping the value of a proton binding energy equal to the experimental one — the so-called "well-depth" procedure). The value of θ is chosen within the main maximum of the diffraction structure of the DC angular distribution.

2. Experiment

Measurements of the DCs of ^{11}B + ^{15}N scattering and ^{11}B(^{15}N, ^{14}C)^{12}C reaction were carried out on the U-200P cyclotron of the Heavy Ion Laboratory of the University of Warsaw at an energy of $E_{^{15}\mathrm{N}} = 43$ MeV. The multi-detector system ICARE [4] was used, equipped with movable detector telescopes, a multi-position target device, a monitoring system, beam collection, and its current measuring systems.

The targets with an enrichment of 97% in the ^{11}B isotope ~ 0.25 mg/cm^2 thick, fabricated by vacuum evaporation at the VUP-5 facility of the Institute of Nuclear Physics of the Republic of Kazakhstan were used [5]. The target thicknesses were measured by the energy losses of α-particles from the Ra-226 alpha source with an accuracy of 6–7%. The system for the reaction products detecting was assembled of four ΔE–E telescopes consisting of silicon detectors (E) and ionization chambers (ΔE) filled with isobutylene. The telescopes were arranged in pairs on two platforms rotating in the reaction plane. To monitor the beam and measure its energy, three silicon detectors were used located at an angle of 15° to the beam trajectory outside the reaction plane. The standard CAMAC electronics and data acquisition systems MIDAS and SMAN [6] were utilized in measurement.

The measured two-dimensional ΔE–E spectra were analyzed using the ROOT program [7]. The angular distributions of the ^{15}N + ^{11}B interaction products were measured in the range of angles 5°–40° in the laboratory coordinate system. To illustrate the quality of particle-type identification and energy resolution, the two-dimensional ΔE–E and energy spectra of the detected carbon nuclei are shown in Fig. 1. Separation of loci by charges in two-dimensional ΔE–E spectra (see Fig. 1) allows us to confidently identify groups of reaction products with $Z < 10$. The right panel shows the energy spectrum of detected ^{14}C nuclei, where the peaks corresponding to

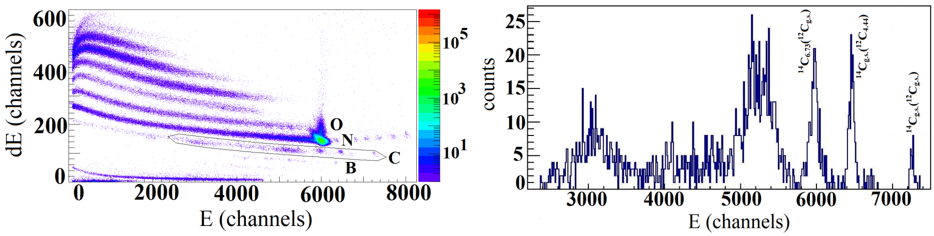

Fig. 1. ΔE–E spectrum of products of ^{15}N ions interaction with ^{11}B target (left) and the energy spectrum of formed carbon nuclei ($\theta_{\mathrm{lab}} = 7°$).

the ground (0^+) and first excited ($E^* = 4.44$ MeV, 2^+) states of the resulting ^{12}C nucleus, as well as the ground state (0^+) of the ^{14}C nucleus are indicated.

3. Analysis of experimental data

The obtained experimental DCs of the $^{11}\mathrm{B}(^{15}\mathrm{N},{}^{14}\mathrm{C})^{12}\mathrm{C}$ reactions with formation of the ^{12}C and ^{14}C nuclei in their ground (0^+) states, as well as the ^{12}C nucleus in the $E^* = 4.44$ MeV (2^+) state were analyzed in the same sequence as in [8].

The parameters of optical potentials (OP) for the entrance reaction channel were found from the analysis of $^{11}\mathrm{B} + {}^{15}\mathrm{N}$ elastic scattering, taking into account the effect of α-particle exchange [9], and also sets of OPs found in the literature were used. The OPs describing the $^{14}\mathrm{C} + {}^{12}\mathrm{C}$ scattering in the exit reaction channel, where ^{14}C is the radioactive nucleus, were selected according to the literature OPs for the mutual scattering of neighboring stable nuclei ($^{12-13}$C and ^{14}N) at the close relative energies. The selected OP parameters used in the calculations are given in Table 1. The imaginary part of the OP was taken only in the form of a volume term. The radii for all terms are taken as $R_i = r_i\left(A_{\mathrm{proj}}^{1/3} + A_{\mathrm{targ}}^{1/3}\right)$, where A_{proj} and A_{targ} are the mass numbers of projectile and target nuclei, respectively.

Table 1. OP parameters for entrance and exit channels of the $^{11}\mathrm{B}(^{15}\mathrm{N},{}^{14}\mathrm{C})^{12}\mathrm{C}$ reaction.

OP	Channel	V_v [MeV]	r_v [fm]	a_v [fm]	W [MeV]	r_w [fm]	a_w [fm]	r_C [fm]	Ref.
Entrance channel									
N1	$^{15}\mathrm{N} + {}^{11}\mathrm{B}$	200	0.790	0.750	11	1.250	0.750	1.250	[9]
N2	$^{14}\mathrm{N} + {}^{11}\mathrm{B}$	100	0.800	0.985	8.3	1.460	0.620	1.400	[10]
N3	$^{14}\mathrm{N} + {}^{11}\mathrm{B}$	50	1.010	0.950	25	1.320	0.600	1.400	[10]
Exit channel									
C1	$^{14}\mathrm{N} + {}^{12}\mathrm{C}$	55	1.214	0.484	15	1.350	0.250	0.734	[11]
C2	$^{14}\mathrm{N} + {}^{12}\mathrm{C}$	118	0.920	0.770	49	1.290	0.280	1.300	[12]
C3	$^{14}\mathrm{N} + {}^{12}\mathrm{C}$	100	0.920	0.770	38.5	1.290	0.260	1.400	[13]
Core–core interaction									
	$^{12}\mathrm{C} + {}^{11}\mathrm{B}$	241.6	0.788	0.670	9.0	1.250	0.670	1.250	[14]
	$^{14}\mathrm{C} + {}^{11}\mathrm{B}$	266.6	0.750	0.740	7.5	1.345	0.740	1.250	[14]

For evaluation of the peripherality of the reactions under consideration, we used a variant of the test function, which allows one to make an accumulative estimate for several experimental points θ_i, which lie in the region of the main maximum of the DS, in the form of

$$\rho\left(b_{^{15}\mathrm{N}\to{}^{14}\mathrm{C}+p}\right) = R\left(\theta_i, b_{B\to A+p}\right)/R_0\left(\theta_i, b_{\mathrm{B}\to A+p}\right) , \quad (3)$$

where the geometric parameters varied in the range of $1.10 < r_0 < 1.40$ fm and $0.5 < a < 0.8$ fm, and $R_0\left(b_{\mathrm{B}\to\mathrm{A}+p}\right)$ was calculated at the "standard" values $r_0 = 1.25$ fm^{-1}, $a = 0.65$ fm^{-1}. The single-particle DC $\sigma^{\mathrm{DW}}(E, \theta; b_{^{12}\mathrm{C}\to{}^{11}\mathrm{B}+p}, b_{^{15}\mathrm{N}\to{}^{14}\mathrm{C}+p})$ in all cases was calculated using the program NRV [15]. The values of the orbital and total moments of the transferred proton in the ground $(1/2^-)$ state of the nucleus $^{15}\mathrm{N} \to \left\{^{14}\mathrm{C} + p\right\}$ were taken equal to 1 and 0.5; in the ground (0^+) state of the nucleus $^{12}\mathrm{C} \to \left\{^{11}\mathrm{B} + p\right\}$ equal to 1 and 1.5; and in the state of the nucleus $^{12}\mathrm{C}_{4.44\ \mathrm{MeV}} \to \left\{^{11}\mathrm{B} + p\right\}$ equal to 1 and 0.5, respectively.

Analysis of the function $\rho\left(b_{^{15}\mathrm{N}\to{}^{14}\mathrm{C}+p}\right)$ range for the $^{11}\mathrm{B}(^{15}\mathrm{N}, ^{14}\mathrm{C}_{\mathrm{gs}})^{12}\mathrm{C}_{\mathrm{gs}}$ reaction (see Fig. 2) showed that its deviation from the average value lies within $\sim 8\%$, which does not exceed the experimental errors. Thus, the process of proton transfer can be considered peripheral despite the tight binding of the proton to both cores in this reaction. A similarly performed analysis also indicates the peripheral nature of the $^{11}\mathrm{B}(^{15}\mathrm{N}, ^{14}\mathrm{C}_{\mathrm{gs}})^{12}\mathrm{C}_{4.44\ \mathrm{MeV}}$ reactions, where the deviations of the function ρ from its mean value are $\sim 7.5\%$.

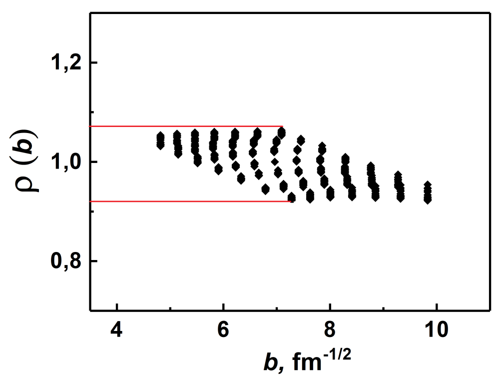

Fig. 2. View of the range of the function $\rho\left(b_{^{15}\mathrm{N}\to{}^{14}\mathrm{C}+p}\right)$ for the reaction channel $^{11}\mathrm{B}(^{15}\mathrm{N}, ^{14}\mathrm{C}_{\mathrm{gs}})^{12}\mathrm{C}_{\mathrm{gs}}$.

Since the analysis using the MDWBA assumes that only a single-step proton transfer mechanism takes place in the region of the main maximum (see Fig. 3, upper panel), we have estimated the contribution of the triton exchange mechanism (Fig. 3, lower panel) competing with proton transfer in

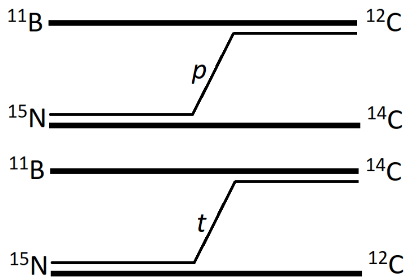

Fig. 3. Diagrams of proton transfer (upper) and triton exchange in the reaction ^{11}B(^{15}N,^{14} C)^{12}C.

the ^{11}B(^{15}N, ^{14}C$_{\rm gs}$)^{12}C$_{\rm gs}$ reaction, as well as the role of channel coupling in all mentioned above reactions using the Fresco program [16]. The following transitions and their spectroscopic amplitudes (SA) were taken into account: ^{15}N($1/2^-$) $\to$ ^{14}C(0^+), SA $= -0.900$; ^{12}C(0^+) $\to$ ^{11}B($3/2^-$), SA $= -1.706$; ^{15}N($1/2^-$) $\to$ ^{12}C(0^+), SA $= +1.0$; ^{14}C(0^+) $\to$ ^{11}B($3/2^-$), SA $= -0.368$. At that, the deformation parameters $\beta_2 = 0.43$ (^{11}B) and $\beta_2 = 0.5$ (^{12}C) were used. The calculation showed that the probability of a triton exchange (see Fig. 4, red/light gray curve) is almost three orders of magnitude lower than the simple proton stripping (black curve). The contribution of channel coupling in all cases turned out to be insignificant (not more than 1–2%) at the region of the main maximum of the DC angular distribution and rather more at the backward angles (see Fig. 5).

Also the probability of detecting ^{12}C and ^{14}C nuclei together instead of only ^{14}C nucleus in the region of forward angles was estimated (blue/gray curve in Fig. 4) due to the overlap of the corresponding peaks (the ^{12}C and ^{14}C loci were not separated), and its insignificance was shown.

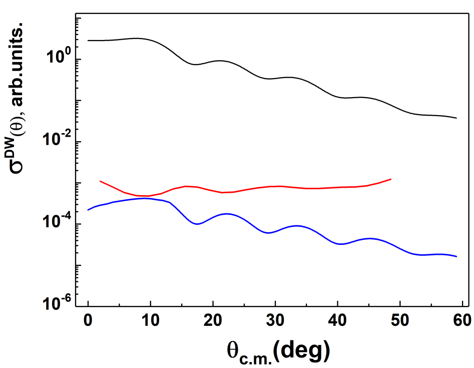

Fig. 4. (Color online) Calculated angular distributions of ^{14}C nuclei (single-particle DC) at proton stripping (black curve), triton exchange (red/light gray curve), and angular distribution of ^{12}C nuclei at proton stripping (blue/gray curve).

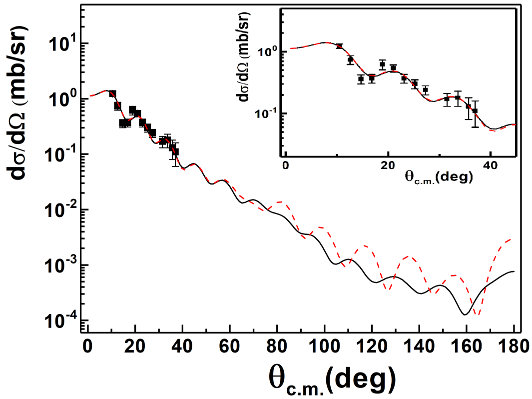

Fig. 5. (Color online) CRC calculation of DC of the $^{11}\mathrm{B}(^{15}\mathrm{N},{}^{14}\mathrm{C}_{\mathrm{gs}})^{12}\mathrm{C}_{\mathrm{gs}}$ reaction. Points — our experiment, red dashed curve — calculation without channels coupling; solid black curve — the same with channels coupling.

The angular distributions of the DCs of the above reactions were calculated according to relations (1) and (2) for all combinations of the OPs from Table 1. The products of the ANC squares of the proton binding in the $^{12}\mathrm{C} \to {}^{11}\mathrm{B} + p$ and $^{15}\mathrm{N} \to {}^{14}\mathrm{C} + p$ were extracted by normalizing the calculated DCs to the experimental ones in the region of the main maximum.

The experimental DC and calculated within MDWBA angular distributions for the $^{11}\mathrm{B}(^{15}\mathrm{N},{}^{14}\mathrm{C}_{\mathrm{gs}})^{12}\mathrm{C}_{\mathrm{gs}}$ and $^{11}\mathrm{B}(^{15}\mathrm{N},{}^{14}\mathrm{C}_{\mathrm{gs}})^{12}\mathrm{C}_{4.44\,\mathrm{MeV}}$ reactions are shown in figures 6 and 7. It can be seen that they describe the experiment rather well in both cases.

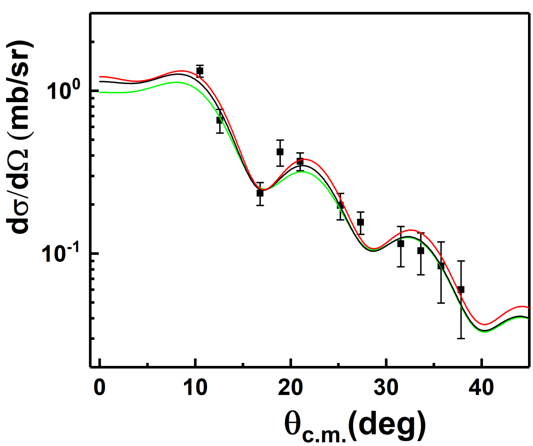

Fig. 6. (Color online) The experimental (points) and calculated DC of the $^{11}\mathrm{B}(^{15}\mathrm{N},{}^{14}\mathrm{C}_{\mathrm{gs}})^{12}\mathrm{C}_{\mathrm{gs}}$ reaction using different OP sets: green/light gray curve — set N1+C1, black — set N2+C2, red/gray — set N3+C3.

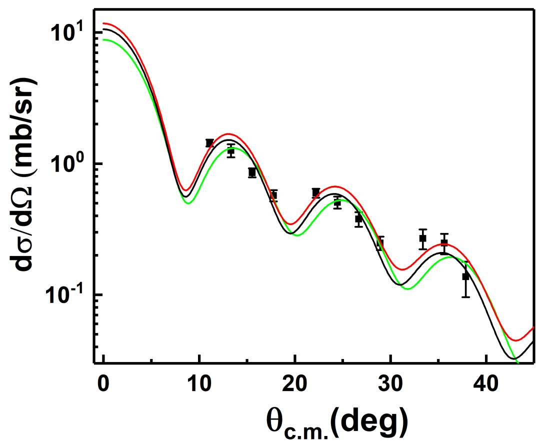

Fig. 7. (Color online) The experimental and calculated DC of the reaction ^{11}B(^{15}N, ^{14}C$_{gs}$)^{12}C$_{4.44\ \mathrm{MeV}}$. Designations are the same as in Fig. 6.

The squared ANC values of the ^{15}N nucleus in the $^{14}\mathrm{C}+p$ configuration were determined from normalization of the calculated DC to experimental ones at three smallest measurement angles θ for all combinations of the OP parameters from Table 1. At that, the known ANCs $C^2_{11\ 1} = 223 \pm 51$ fm^{-1} for the ground state and $C^2_{11\ 1^*} = 15.8 \pm 3.5$ fm^{-1} for the excited state ($E^* = 4.44$ MeV, 2^+) of the ^{12}C nucleus in the $^{11}\mathrm{B}+p$ configuration [17] were used. Next, the weighted average values were determined, which are found to be 43 ± 8 fm^{-1} and 49 ± 9 fm^{-1} through the reaction channels ^{11}B(^{15}N, ^{14}C$_{gs}$)^{12}C$_{gs}$ and ^{11}B(^{15}N, ^{14}C$_{gs}$)^{12}C$_{4.44\ \mathrm{MeV}}$, respectively. It can be seen that these values coincide within the error limits.

To confirm the correctness of the found ANC value in the ground state of the ^{15}N nucleus, an analysis of the reaction ^{15}N(d, ^{3}He)^{14}C$_{gs}$ from [18] was also performed within the framework of the MDWBA. Using the OP for this reaction given in [18] and found in the literature, its peripherality was established and the weighted mean value of the ANC square for the ground state of the ^{15}N nucleus, $C^2_{14\ 1} = 52 \pm 7$ fm^{-1}, was found which coincides within errors with these found from the reaction ^{11}B(^{15}N, ^{14}C)^{12}C. The ANC value $C^2_{2\ 1} = 4.28 \pm 0.50$ fm^{-1} for $^3\mathrm{He} \to d + p$ from [19] was used in these calculations.

Thus, the ANC squared values for the ground state of the ^{15}N nucleus, found by three methods, are in good agreement with each other, and their weight-averaged value recommended by us is 46 ± 9 fm^{-1}.

4. Conclusion

The new experimental DCs of the ^{11}B(^{15}N, ^{14}C)^{12}C reaction with formation of ^{12}C and ^{14}C nuclei in the ground and lower excited states at an energy near the Coulomb barrier have been obtained. The contributions of various mechanisms to the differential cross section for this reaction were estimated. The peripheral nature of the proton transfer process in the region of the main maximum is established. For the first time, the value of the squared ANC of the proton binding in the ground state of the ^{15}N nucleus has been obtained.

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