THE CORRELATION CHARACTERISTICS OF ^{14}C(3$^-$; 6.73 MeV) NUCLEUS IN THE ^{13}C(*d*, *pγ*)^{14}C REACTION

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The double-differential cross sections of the $C^{13}(d, p\gamma)^{14}C$ (3$^-$; 6.73 MeV) reaction at E_d = 15.3 MeV were measured for six proton emission angles on the SINP MSU 120-cm cyclotron. The angular correlation functions $W(\theta_p;\ \theta_\gamma,\ \varphi_\gamma)$ were measured at four planes of gamma-rays registration. It allowed to restore sixteen even $A_{k\kappa}(\vartheta_p)$ components of density matrix spin-tensor of the final nucleus $^{14}C(3^-)$. The obtained $A_{k\kappa}(\theta_p)$ were used to determine other $^{14}C(3^-)$ orientation characteristics: the populations $P_{\pm M}(\theta_p)$ of sublevels with the M projection of the 3^- spin, orientation tensors $t_{k\kappa}(\theta_p)$ and polarization tensors $T_{k\kappa}(\theta_p)$ ($2 \le k \le 6$). Experimental data were compared with theoretical ones, obtained within the neutron stripping mechanism by the coupled-channel method and for the compound nucleus statistical mechanism.

INTRODUCTION

In the last time a detailed description of the neutron-excess nucleus ^{14}C structure at the microscopic level remains the current task [1-6]. Mixing of shell configurations, the parameters of nucleus deformation and its clustering in various states are determined in various nuclear reactions.

A significant number of both experimental and theoretical works [7] is devoted to the study of mechanism of the ^{13}C(*d*, *p*)^{14}C reaction. Studies have been carried out in a wide energy range from several hundred keV to 56 MeV. The angular distributions (AD) of ^{13}C(*d*, *p*)^{14}C reaction at 13-18 MeV deuterons energies were previously measured in the works [8–10], as well as in our recent work [11]. The angular *pγ*-correlations in the ^{13}C(*d*, $p\gamma_{6.73}$)^{14}C reaction were previously examined only in [12] at low energy E_d = 3.7 MeV. Correlation measurements were made in the reaction plane at the only angle θ_p = 35°. Within the framework of direct neutron stripping model at the plane wave approximation the authors determined the spin and parity of studied state of the final nucleus. It should be noted that the stripping mechanism was successfully involved for the analysis of this reaction by other authors quite at the deuteron energy of several hundred keV [13], which is obviously associated with both the low deuteron binding energy and the relatively large Q value of the reaction.

In presented work the results of measurement of angular correlation functions (ACF) of protons with the gamma-rays which are formed in ^{13}C(d, p)^{14}C (3^-, 6.73 MeV) reaction upon transition of ^{14}C from the excited state (3^-) to the ground state (0^+) with emission of gamma-rays of $E3$ multipolarity are presented. From ACF all even components of density matrix spin-tensors of ^{14}C (3^-, 6.73 MeV) are restored. Based on these, a set of orientation characteristics of this nucleus were determined.

Experimental data were compared with theoretical ones performed under the assumption of neutron stripping mechanism (FRESCO code [14]) and under the assumption of compound nucleus (CN) statistical mechanism (CNCOR code [15]). Spectroscopic amplitudes of neutrons for ^{14}C nucleus required for calculations were defined earlier in shell model with configurations mixing [11].

1. EXPERIMENTAL PROCEDURE

The experiment was performed on SINP Moscow State University 120-cm cyclotron with deuterons accelerated to an energy of 15.3 MeV. The energy spread of the beam was about 160 keV. As a target, a self-supporting carbon film with a thickness of 0.55 mg sm^{-2} with an enriched (up to 80%) isotope ^{13}C was used.

The ACFs of ^{13}C(d, $p_3\gamma_{6.73}$)^{14}C reaction are measured for the emitted protons angles 20°, 30°, 50°, 60°, 120° and 140° (lab.). Protons from the reaction were recorded by three silicon semiconductor detectors with a sensitive region thickness of about 1800 μm. They were located inside the scattering chamber at distance of 75 mm from the target on the turntable and had an angular resolution of 2.5°. In order to measure the ACF outside the reaction plane, the inclination of the table was changed with respect to the horizontal plane.

γ -rays were registered in the range of emitted angles θ_γ from 20 to 150° at 5-9 values of θ_γ angle in each plane φ_γ by four scintillation detectors BDEG-23 with crystals of NaI(Tl) with length and a diameter of 63 mm which were established with the fixed interval $\Delta\theta_\gamma$ = 32.5° on the rotary horizontal ring platform out of the dispersion camera. The angular resolution of the γ-detectors was 13° and corrections for it were taken into account when processing experimental data.

The method of restoring density matrix spin-tensors from ACF $W(\theta_p;\ \theta_\gamma,\ \varphi_\gamma)$ consists in solving of a linear equations system relative to the spin-tensors components $A_{k\kappa}(\theta_p)$ [16]:

$$W(\theta_\gamma,\ \varphi_\gamma;\ \theta_p) = \frac{1}{\sqrt{4\pi}} \sum_{k\kappa} \frac{1+(-1)^k}{\sqrt{2k+1}} A_{k\kappa}(\theta_p) \mathrm{Y}^*_{k\kappa}(\theta_\gamma,\ \varphi_\gamma), \tag{1}$$

$A_{k\kappa}(\theta_p)$ in case of pure electromagnetic transitions are connected with density matrix spin-tensors $\rho_{k\kappa}(\theta_p)$ by simple relation

$$A_{k\kappa}(\theta_p) = \sqrt{2L+1}(-1)^{L+1} \left\langle L1L-1 \middle| k0 \right\rangle \rho_{k\kappa}(\theta_p)\,. \tag{2}$$

The components $A_{k\kappa}(\theta_p)$ in the used coordinate system (CS) are real and $A_{k\kappa}(\theta_p)$ = $(-1)^\kappa A_{k-\kappa}(\theta_p)$, and the normalization is selected such that $A_{00}(\theta_p) \equiv d\sigma/d\Omega(\theta_p)$. The tensor rank k is determined by the nucleus state spin value and multiplicity of γ-transition L: $\boldsymbol{k} = \boldsymbol{J}_f + \boldsymbol{J}_f = \boldsymbol{L} + \boldsymbol{L}$, its projection values κ vary from -k to k. In (1) $Y^*_{k\kappa}\left(\theta_\gamma, \varphi_\gamma\right)$ is conjugate spherical functions of θ_γ and φ_γ angles of γ-rays emitted in spherical CS with Z axis directed along momentum of incident particles and (X, Z) plane coinciding with reaction plane ("experimental" CS).

The maximum rank of the density matrix spin tensor is limited to k = 6, so the multiplicity L of the corresponding transition is 3. The number of independent components of even rank spin tensors $A_{k\kappa}(\theta_p)$ for the state with spin $J_f = 3^-$ is 16, and, accordingly, the number of independent measurements of ACF $W(\theta_p;\ \theta_\gamma,\ \varphi_\gamma)$ should not be less, and these measurements should be made in at least four planes relative to the reaction plane [17]. Therefore, the measurement ACF were made for four values of the φ_γ angle and five –nine values of the θ_γ angle.

The spin-tensors components found on the basis of experimental ACF made it possible to determine a set of correlation characteristics of $^{14}C(3^-)$ nucleus, such as:

1. population $P_{\pm M}(\theta_p)$ – diagonal elements of the density matrix in a CS whose Z axis is perpendicular to the reaction plane.
2. orientation tensors of multipole moments $t_{k\kappa}(\theta_p)$ of even rank k in CS, whose Z axis coincides with the axis of nucleus symmetry and is directed by the recoil nucleus momentum.
3. tensor polarization $T_{k\kappa}(\theta_p)$ of the oriented nucleus [17, 18], characterizing asymmetric orientation of its spin relative to axis perpendicular to reaction plane. $T_{k\kappa}(\theta_p)$ are defined in CS with Z axis perpendicular to reaction plane and X axis directed along incident beam.

Note that in most polarization experiments, only $T_{k\kappa}(\theta_p)$ components with zero projection on the quantization axis are determined.

2. RESULTS OF THE EXPERIMENT

The AD of the differential cross section $d\sigma/d\Omega(\theta_p)$ of the $^{13}C(d, p_3)^{14}C(3^-$, 6.73 MeV) reaction, measured at proton emitted angles θ_p = 21–161°, is given in Fig. 1.

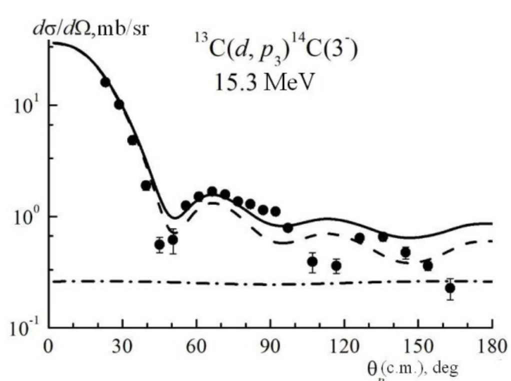

Fig. 1. AD of protons from $^{13}C(d, p_3)^{14}C(3^-$, 6.73 MeV) reaction. Points - experiment, dashed - FRESCO calculation, dashed - CNCOR calculation, solid curve - sum of calculations.

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The shape of the AD is oscillating form with a decline when the emitted protons angle increases that is characteristic of a direct reaction mechanism

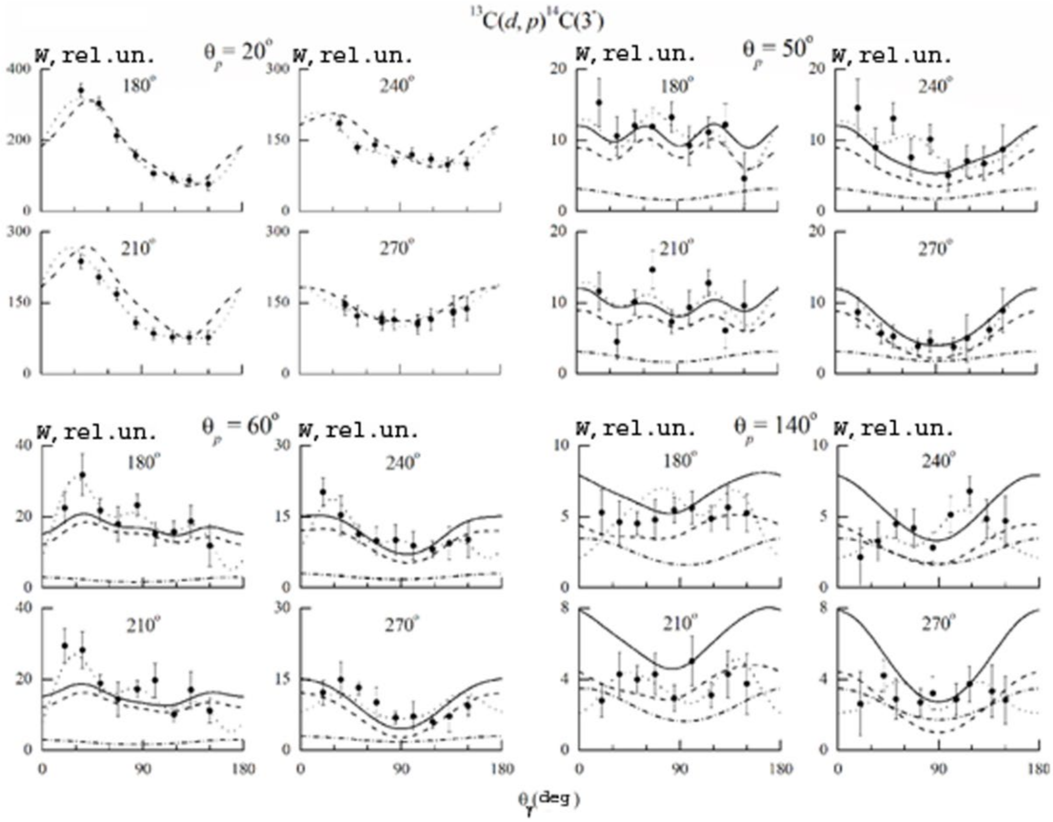

Fig. 2. ACF in $^{13}C(d, p\gamma_{6.73})^{14}C$ reaction for θ_p = 20 °, 50 °, 60 ° and 140 ° in four planes φ_γ of γ-rays registration. Point curves - 16 parametric fitting, symbols of other curves are the same as in fig. 1.

Fig. 2 shows the part of the measured ACF $W(\theta_p,; \theta_\gamma, \varphi_\gamma;)$. The 16-parametric least squares fit (1) is shown by point curves. The average χ^2 value was 30 with the number of degrees of freedom 35, and the average value of the confidence level –0.7. Statistical error of ACF amounted to an average of 23%. It is worth noting that the errors were significant at high angles due to a strong drop in the differential cross section. The form of the $W(\theta_p; \theta_\gamma, \varphi_\gamma;)$ generally shows anisotropy and oscillations, while in the plane at φ_γ = 270° it becomes almost symmetric with respect to θ_γ = 90˚.

Fig. 3 shows the AD of the populations of $^{14}C(3^-$, 6.73 MeV) sublevels for various spin projections *M*. These dependencies are non-isotropic and oscillate.

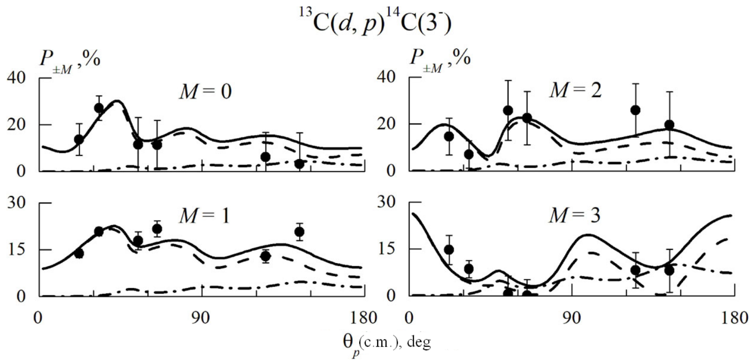

Fig. 3. AD of population of ^{14}C (3^-, 6.73 MeV) magnetic sublevels. The curve symbols are the same as in Fig.1.

AD of orientation tensors of multipole moments $t_{k\kappa}(\theta_p)$ of ^{14}C (3^-6.73 MeV) experimentally restored are given in fig. 4. It can be seen that $t_{k\kappa}(\theta_p)$ have a irregular alternating form, and the components $t_{2\kappa}(\theta_p)$ take mainly negative values.

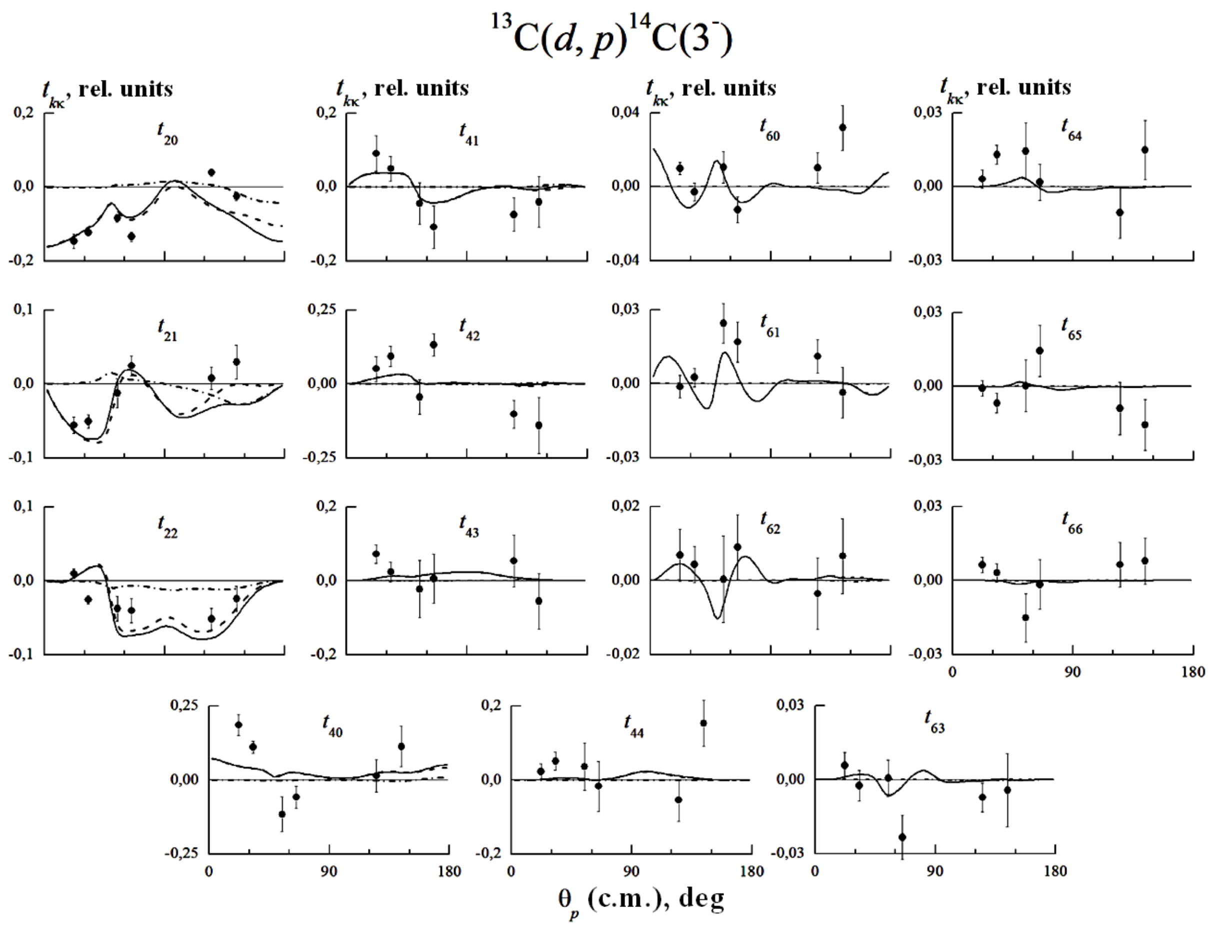

Fig. 4. Angular dependencies of multipole moments orientation tensors $t_{k\kappa}(\theta_p)$. The curve symbols are the same as in fig.1

Tensors of both quadrupole and hexadecapole polarization also have irregular alternating oscillations depending on θ_α (fig. 5). Note that the component $T_{20}(\theta_p)$ takes strictly negative values.

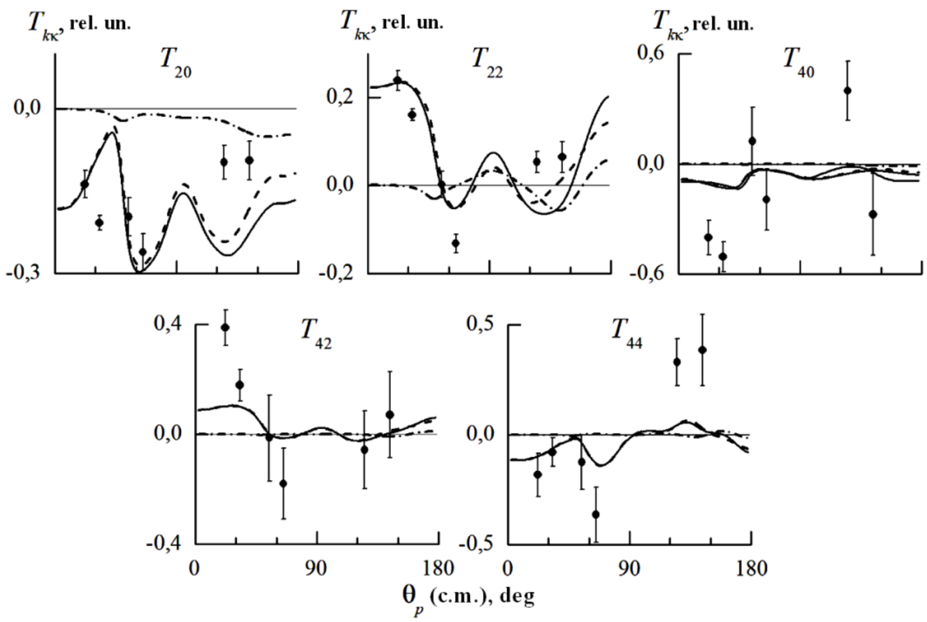

Fig. 5. Angular dependencies of the quadrupole and hexadecapole components of the nucleus $^{14}C(3^-)$ polarization. The curve symbols are the same as in fig.1.

3. DISCUSSION OF RESULTS

We analyzed the experimental characteristics under the assumption of the neutron stripping mechanism (FRESCO code) within the coupled channel method and the CN model in its statistical limit (CNCOR code).

Spectroscopic amplitudes of neutrons for ^{14}C nucleus required for calculations were defined earlier in shell model with configurations mixing [11]. Optical potential parameters (OP) for the input and output channels were obtained using slightly corrected global potential [19, 20]. Since the excitation energy of the considered ^{14}C levels is large enough, it was taken into account in the output channel OP. The specific OP parameter values used in calculations are shown in table.

In calculations according to the CN model, channels with *p*, *n*, *d*, *t* and α emission were taken into account. Values of OP parameters for competing channels were taken from [21]. The state density of the residual nuclei was described within the fermi-gas model.

Table. OP parameters for Woods-Saxon form

channel	V, MeV	r_V, Fm	a_V, Fm	W, MeV	r_W, Fm	a_W, Fm	WD^*, MeV	r_{WD}, Fm	a_{WD}, Fm	V_{so}, MeV	r_{so}, Fm	a_{so}, Фм	r_C, Фм
$d + {}^{13}C$	80.15	1.17	0.81	–	–	–	16.41	1.56	0.57	3.70	1.23	0.81	1.70
$p + {}^{14}C(0^+)$	51.85	1.17	0.75	1.82	1.17	0.75	8.4	1.32	0.61	6.25	1.01	0.75	1.4
$p + {}^{14}C(1^-)$	53.93	1.17	0.75	0.39	1.17	0.75	10.0	1.32	0.61	6.25	1.01	0.75	1.4
$p + {}^{14}C(3^-)$	54.15	1.17	0.75	0.24	1.17	0.75	10.2	1.32	0.61	6.25	1.01	0.75	1.4

Comparison experimental and calculated AD of protons in ${}^{13}C(d, p){}^{14}C(3^-)$ reaction is shown in fig. 1. The calculation from the CN model is tied to the experiment with a coefficient of 0.25. As can be seen from the figure, the neutron stripping mechanism makes the main contribution to the protons AD. There is a certain discrepancy between experimental and calculated sections at $\theta_p > 115°$, which could not be eliminated by choosing calculation parameters (OP).

The calculated and experimental ACF of the ${}^{13}C(d, p\gamma_{6.73}){}^{14}C$ reaction (fig. 2) are satisfactorily consistent with all θ_p, except $\theta_p = 140°$.

The calculated ${}^{14}C$ nucleus populations $P_{\pm M}$ for various projections of M are quite well consistent with the experimental ones for all projection values (fig. 4) and are determined by the direct mechanism of neutron stripping, although at large angles of proton emission the contribution of CN formation mechanism is comparable to the contribution of the direct process.

The agreement of the calculated and experimental components of the multipole moment orientation tensors (fig. 5) and the tensor polarization (fig. 6) of the $^{14}C(3^-)$ nucleus can be assessed as being of high quality, while it is noticeable that the components of rank $k = 2$ are described by the calculation better than the rest.

CONCLUSION

The used analysis method of $^{13}C(d, p\gamma)^{14}C$ reaction allowed to restore for the first time completely all even components of a matrix of density of a final ^{14}C at state 3^-(6.73 MeV). On their basis, for the first time, a set of orientation characteristics of this nucleus were obtained, which significantly expands the amount of experimental information to be analyzed.

The used model approach allowed to receive in satisfactory consent with an experiment as differential cross sections of $^{13}C(d, p_3)^{14}C(3^-)$ reaction in a front hemisphere of protons emission, and the most part of orientation characteristics of $^{14}C(3^-)$. On the other hand, the presence of differences in the experiment and the calculation at large angles for the individual components of the correlation characteristics seems to indicate the presence of reaction mechanisms more complex than those used here.

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