DEUTERON AND ALPHA PARTICLE PICKUP IN THE INTERACTION BETWEEN B^{10} AND O^{16}

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The reaction $O^{16} + B^{10} \rightarrow N^{14} + 3\alpha - 2.8$ MeV between 100-MeV B^{10} ions and O^{16} nuclei in nuclear emulsion is studied. The excitation function of the reaction has a maximum at 60-MeV B^{10} energy. The c.m.s. N^{14} angular distribution has both a small-angle and a large-angle maximum, due to α-particle and deuteron pickup from O^{16}, respectively. The reaction proceeds via formation of a C^{12} nucleus, whose excitation and decay into three α particles are considered.

AMONG the many types of reactions between heavy ions and nuclei we can distinguish a broad class of transfer reactions whereby one or more nucleons are transferred between nuclei, mainly without involving the formation of a compound system. The transfer of protons, neutrons, α particles, and larger fragments has been treated in many publications.[1-11] The angular distribution of the reaction products of single-nucleon transfer is characterized by a maximum at nearly the Rutherford angle for grazing elastic collisions and by an upturn near 0°.

The angular distributions of multinucleon-transfer products obtained by Kaufmann and Wolfgang[8] have a prominent peak in the beam direction and no maximum at any other angle. In the angular distributions of the reaction products when 5–8 nucleons were transferred Kumpf and Donets[9] observed peaks at both 0° and other angles.

In the investigation of transfer reactions β- or α-active products are usually registered. In the present work we have studied the interaction between B^{10} ions and O^{16} nuclei in nuclear emulsion. In contrast with earlier work on transfer reactions we here registered simultaneously all the reactions products and their characteristic energies and momenta.

EXPERIMENTAL METHOD

We irradiated 400-μ NIKFI-D nuclear emulsions with B^{10} ions that had been accelerated to 100 MeV in the linear accelerator of multiply-charged ions at the Physico-technical Institute of the Ukrainian Academy of Sciences, and that entered the emulsions at an angle of 25° to the surface. Reliable visual discrimination was possible for the tracks of singly-charged and doubly-charged particles as well as heavier nuclei. We selected four-prong stars with three prongs representing α tracks. By determining the nature of the fourth prong we learned the type of reaction represented by each star; this was achieved by means of kinematic analysis. To determine the type of reaction, for all possible interpretations of each star we calculated the functions

$$\chi^2 = \frac{[E_f - E_f(R)]^2}{\overline{\Delta E^2}} + \frac{[p_x - p_x(R,\theta)]^2}{\overline{\Delta p_x^2}} + \frac{[p_y - p_y(R,\theta,\varphi)]^2}{\overline{\Delta p_y^2}} + \frac{[p_z - p_z(R,\theta,\varphi)]^2}{\overline{\Delta p_z^2}},$$

where E_f is the kinetic energy of the desired nucleus, calculated from energy balance; $E_f(R)$ is the kinetic energy of the same nucleus based on its range; p_x, p_y, p_z are the momentum projections of the nucleus calculated from vector momentum balance (with the x axis in the ion beam direction); $p_x(R,\theta)$, $p_y(R,\theta,\varphi)$, $p_z(R,\theta,\varphi)$ are the same momentum projections based on range and on angle measurements in the emulsion; $\overline{\Delta E^2}$, $\overline{\Delta p_x^2}$, $\overline{\Delta p_y^2}$, $\overline{\Delta p_z^2}$ are the total mean square uncertainties of the respective quantities resulting from nonmonochromaticity of the initial beam and from inaccuracy of the range and angle measurements.

We were able to identify 252 stars representing the reaction

$$O^{16} + B^{10} \rightarrow N^{14} + 3\alpha - 2.8 \text{ MeV}. \quad (1)$$

The Ural-2 computer was used for the kinematic analysis and for all subsequent calculations.

EXCITATION FUNCTIONS AND ANGULAR DISTRIBUTIONS

The excitation function of the reaction $O^{16} + B^{10} \rightarrow N^{14} + 3\alpha$ is represented in Fig. 1. (Since the initial energy is known the B^{10} range measurement can be used to determine the reaction energy.) Statistical errors are indicated. Not a single instance of this reaction was observed at less than 25 MeV bombarding energy. With 60-MeV ions (lab system) the cross section reaches 110 mb, but falls off somewhat at higher B^{10} energies.

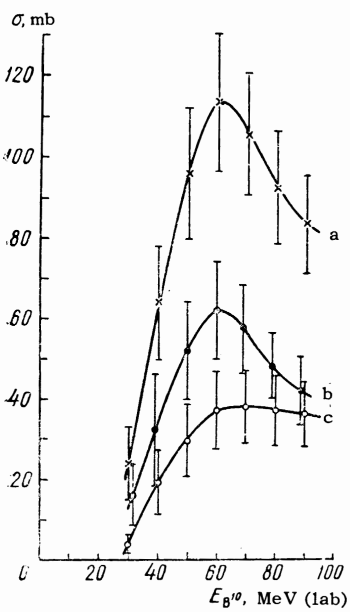

FIG. 1. Excitation functions. a – reaction (1), b – deuteron pickup by B^{10}, c – α-particle pickup by B^{10}.

In Fig. 2a the angular distribution of N^{14} nuclei formed in the reaction is seen to have two prominent c.m.s. peaks, at 20 mb/sr for small angles and 14 mb/sr for large angles. The N^{14} angular distributions for different bombarding energies are shown in Fig. 2, b and c. With decreasing incident energy the small-angle peak is shifted towards larger angles, while the large-angle peak is shifted towards smaller angles. At the same time the peaks become lower, especially the right-hand peak. The angular distribution of α particles from this reaction is shown in Fig. 3a.

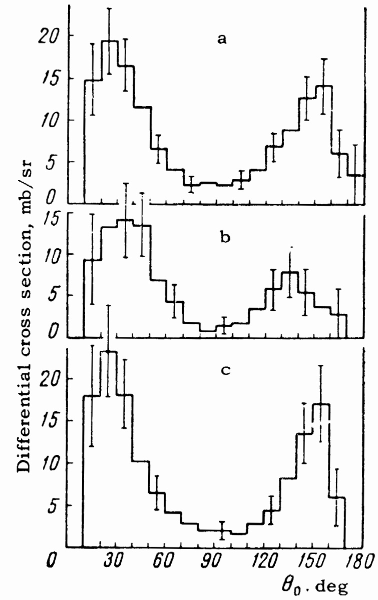

FIG. 2. C.m.s. angular distributions of N^{14} from reaction (1) averaged over the B^{10} energies: a – 25–95 MeV, b – 25–60 MeV, c – 60–95 MeV (lab system).

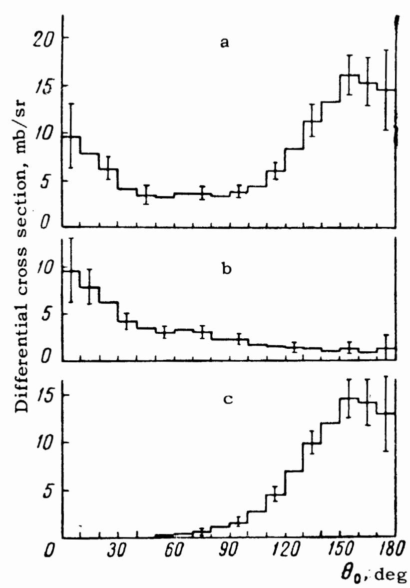

FIG. 3. C.m.s. angular distributions of α particles from reaction (1), averaged over bombarding-ion energies from 25 to 95 MeV (lab system). a – for all stars, b – for stars formed in deuteron pickup by B^{10}, c – for stars formed in α-particle pickup by B^{10}.

Figure 4 shows the range distribution of N^{14} formed in the reaction. A sharp peak is observed for ranges under 10 μ and a long tail for greater ranges, which for some N^{14} nuclei can exceed 40 μ. It is striking that almost all N^{14} having ranges under 10 μ belong to stars contributing to the large-angle peak of the N^{14} angular distribution, while all N^{14} having ranges exceeding 10 μ belong to stars contributing to the small-angle peak. In other words, the large-angle peak corresponds to stars where the lab-system kinetic energy of N^{14} is under 15 MeV, while the small-angle peak corresponds to stars where N^{14} has a lab-system energy that is mainly greater than 15 MeV. The energy of individual nuclei can exceed 50 MeV.

The foregoing results indicate that the given re-

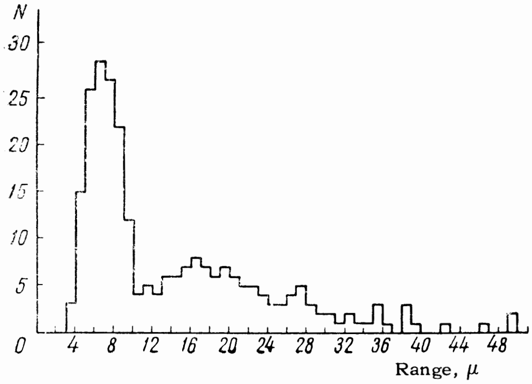

FIG. 4. N^{14} range distribution in reaction (1).

action can follow more than one path. The observed N^{14} angular distribution can result from at least three different reactions mechanisms.

DEUTERON STRIPPING BY O^{16}

The large-angle peak of the N^{14} angular distribution can be attributed to two mechanisms, deuteron stripping by O^{16} (Fig. 5) and deuteron pickup by B^{10} (Fig. 5b). We shall now discuss the first of these mechanisms.

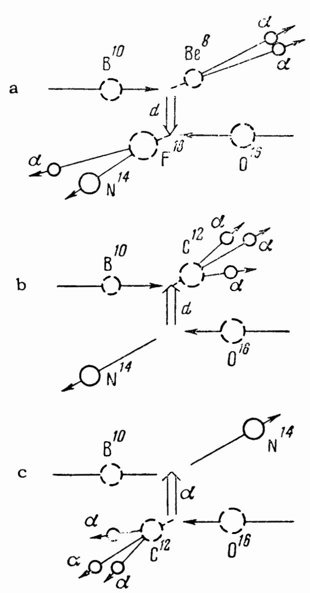

FIG. 5. Reaction mechanisms. a – deuteron capture by O^{16}, b – deuteron pickup by B^{10}, c – α-particle pickup by B^{10}.

At the closest approach of the interacting nuclei O^{16} can capture a deuteron cluster from the incident B^{10} ion and form an F^{18} nucleus in a state of excitation energy that is higher than the energy for dissociation into N^{14} and an α particle. The F^{18} excitation can then be completely removed through α emission. The O^{16} nucleus moves backward in the c.m. system. Because of the large initial momentum, the F^{18} nucleus and the N^{14} nucleus resulting from the dissociation of the former will also move dominantly backward.

The present mechanism is distinguished by the presence of an α pair from the decay of Be^8, which is formed when B^{10} loses a deuteron. The energies E_1 and E_2 of these a particles and the angle θ_{12} between them are related by

$$E_1 + E_2 - 2\sqrt{E_1 E_2} \cos \theta_{12} = 2\mathscr{E}, \tag{2}$$

where $\mathscr{E}$ is the Be^8 decay energy. Moreover, when Be^8 possesses large momentum and decays from its ground state or from its first excited state, the α particles form a characteristic two-pronged fork in the emulsion. Using these properties in conjunction with the N^{14} laboratory energy and c.m. momentum direction, we discriminated 28 stars resulting from this reaction. The N^{14} angular distribution from these stars has no peak. When they are subtracted from the total number the large-angle peak is only slightly lowered, and the overall character of the N^{14} angular distribution is practically unaffected. We shall henceforth disregard these stars because of their small number; they are omitted from the angular distributions in Fig. 2, b and c.

In the course of analyzing these stars for α pairs from Be^8 decay it was also determined that the remaining stars corresponding to the large-angle peak of the N^{14} distribution have no α pairs resulting from Be^8 decay out of states with less than 20-MeV excitation, whereas all stars corresponding to the small-angle peak have an α pair from the decay of Be^8 with small excitation energy. This circumstance enabled clearer discrimination of the reaction mechanisms.

DEUTERON PICKUP BY B^{10}

The second reaction mechanism responsible for the large-angle peak of the N^{14} angular distribution is that in which an incoming B^{10} picks up a deuteron cluster from O^{16} (Fig. 5b). The N^{14} nucleus that is the residue of O^{16} can remain in an unexcited state. Like O^{16}, it will recoil backward in the c.m. system, but because of the deuteron recoil momentum and interaction with B^{10} it can be deflected to the angular region where the peak is observed.

The B^{10} ion that picks up a deuteron cluster from O^{16} can form a resonant threshold state[12] of C^{12} corresponding to the preservation of the initial cluster structure B^{10} + d, which after nucleon rearrangement can be dissociated into three α particles. Since the deuteron binding energy in C^{12} is large, we expect a high probability that C^{12} will be formed in states of excitation energies that are fully sufficient for dissociation into three α particles.

The excitation function of this process, based on 91 stars, is shown in Fig. 1b. The cross section for the process reaches its peak at 35–40 mb for 65–70-MeV (lab system) bombarding energy. There is no further increase of the cross section with energy.

Because of the small total number of stars we do not have sufficient statistics to plot the N^{14} energy distribution for any fixed ion energy. The relative velocity distribution in Fig. 6a thus becomes the best available characteristic; here the c.m.s velocity of each N^{14} nucleus is divided by the velocity of the corresponding parent O^{16}. This distribution cannot be plotted in the lab system, where O^{16} is at rest. The distribution shows that most of the N^{14} nuclei formed after O^{16} loses a deuteron retain 70–90% of the parent-nucleus velocity.

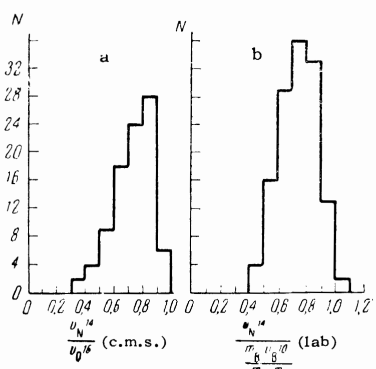

FIG. 6. N^{14} relative velocity distribution. a – in stars resulting from deuteron pickup by B^{10} (c.m.s.), b – in stars resulting from α pickup by B^{10} (lab system).

The α angular distribution for stars resulting from this mechanism (Fig. 3b) is peaked forward. However, we could have expected a more prominent peak on the basis of the N^{14} angular distribution.

ALPHA-PARTICLE PICKUP BY B^{10}

The small-angle peak of the angular distribution (Fig. 2) can result from this mechanism, in which an incident B^{10} ion picks up an α cluster from O^{16} (Fig. 5c), leaving a ground-state N^{14} nucleus. In the c.m. system the N^{14} nucleus, like the B^{10} nucleus, will move mainly forward. The C^{12} nucleus formed when O^{16} loses an α particle can be left in this case with sufficient excitation for dissociation into three α particles.

A good argument favoring this mechanism is found in the N^{14} lab-system energy distribution. It has already been pointed out that the small-angle peak corresponds to the stars where N^{14} has a relatively long range and therefore high kinetic energy. As in the preceding case, the energy distribution will be more easily interpretable when represented in the form of relative velocities. This eliminates the smudging of the energy distribution associated with the broad range of bombarding energies. In this case, however, for greater clarity the N^{14} velocity is not divided by the velocity v_B of the B^{10} ion, but by the somewhat reduced velocity $m_B v_B/(m_B + m_\alpha)$, where m_B and m_α are the B^{10} and α-particle masses. This distribution, shown in Fig. 6b, indicates that very little of the initial kinetic energy is lost in the interaction, and is thus consistent with α pickup in a grazing interaction.

The same reaction mechanism is also consistent with the angular distribution of α particles in these stars that is shown in Fig. 3c. Here a broad but prominent peak is observed at large angles, i.e., in a direction opposite to that of N^{14} emission. The excitation function of this mechanism is shown in Fig. 1c, which is based on 133 stars. The cross section for α pickup by B^{10} from O^{16} reaches 60 mb for 60-MeV (lab-system) B^{10} ions, and diminishes somewhat at higher energies.

EXCITATION OF C^{12}

It is assumed that each of the aforementioned two mechanisms begins with the formation of an excited C^{12} nucleus which then dissociates into three α particles. The excitation energy must, of course, exceed the dissociation energy.

From an invariant-mass analysis of the kinetic energies of the α particles we confirmed their actual origin in C^{12} decay and also determined the excitation of the latter. If we have a quasi-stationary state of three α particles (an excited state of C^{12}), the distribution of events as a function of the invariant mass M should have a more or less prominent peak for some $M = M_0$, where

$$M_0 = m_{C^{12}} + E^*_{C^{12}} \qquad (3)$$

($m_{C^{12}}$ is the mass of ground-state C^{12} and $E_{C^{12}*}$ is the energy of the considered quasi-stationary state of C^{12}). It is thus seen that knowledge of the invariant mass enables us to determine the excitation energy of the intermediate C^{12} nucleus that dissociates into three α particles. In our case the invariant mass M is given by

$$M^2 = (p_1 + p_2 + p_3)^2, \quad (4)$$

where p_1, p_2, p_3 are the four-dimensional momenta of the α particles.

The invariant mass distribution can be transformed into a more perspicuous distribution over the C^{12} excitation energies. In the distribution of the stars shown in Fig. 7, the excitation energy peaks at 10–15 MeV and 25–30 MeV can be regarded as corresponding to excited C^{12} states from which C^{12} actually decays into α particles.

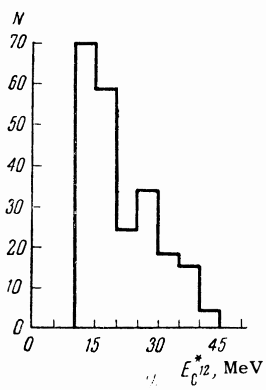

FIG. 7. Distribution of stars with respect to C^{12} excitation energies.

Figure 8 shows a number of N^{14} angular distributions, each of which pertains to stars where C^{12} having excitation energy in a given range dissociates into three α particles. These angular distributions show that C^{12} excitation in the range 10–20 MeV results from the mechanisms of α cluster pickup by B^{10} from O^{16} (C^{12} is the residue of O^{16}), while excitation in the range 20–40 MeV results from deuteron pickup by B^{10}. The most probable excited states of C^{12} are in the range 10–15 MeV for the first case, and 25–30 MeV for the second case. In both cases we find the smallest deviation of N^{14} from the direction of the parent nucleus. There appears to exist the greatest pickup probability for deuterons and α particles having zero or very small momentum. With increasing energy of the transferred cluster there is an increase in the C^{12} excitation energy and its deviation from the primary direction, while the transfer probability is seen to diminish. Of course, the smaller number of observed C^{12} decays from excitation above 30 MeV can result not only from a reduced transfer probability for deuterons having large momentum, but also through C^{12} decay

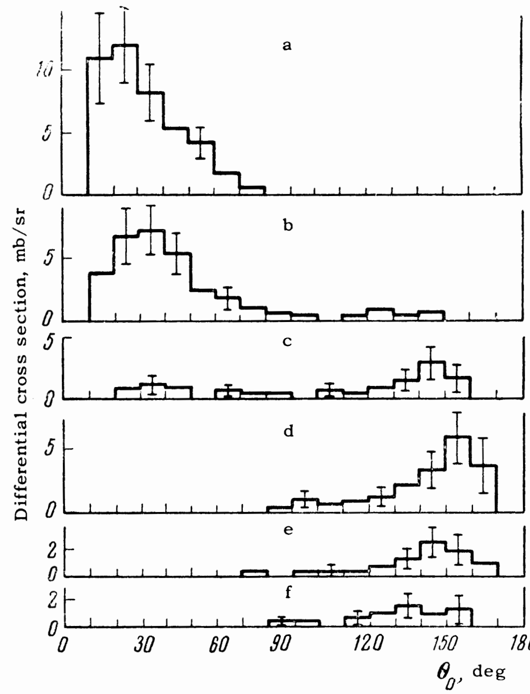

FIG. 8. N^{14} c.m.s. angular distributions averaged over bombarding energies from 25 to 95 MeV, for stars with the following C^{12} excitation energies: a – 10–15 MeV, b – 15–20 MeV, c – 20–25 MeV, d – 25–30 MeV, e – 30–35 MeV, f – 35–40 MeV.

channels other than $C^{12} \to 3\alpha$ from the same states. We shall not consider the latter cases.

$C^{12} \to 3\alpha$ DECAY

As already mentioned, all stars corresponding to the left-hand peak of the N^{14} angular distribution (Fig. 2) include an α-particle pair from Be^8 decay. This means that the intermediate C^{12} nucleus with 10–20 MeV excitation decays into three α particles in two stages: $C^{12} \to Be^8 + \alpha \to 3\alpha$ (decay into an α particle and Be^8, which then decays into two additional α particles).

From a knowledge of all the star parameters we determined that the C^{12} nuclei with 10–15 MeV excitation decay through the Be^8 ground state in 37% of the events, and through the first excited state in 63%. C^{12} with 15–20 MeV excitation decays through the Be^8 ground state in 26% of the events, and through the first and second excited states in 57% and 17%, respectively.

In stars corresponding to the right-hand maximum of the N^{14} angular distribution (Fig. 2) no α pair was observed from the decay of Be^8 with under 20 MeV excitation. This means that in these events, i.e., for excitations above 25 MeV, we find mainly the direct decay of C^{12} into three noninteracting α particles.

DISCUSSION OF RESULTS

In the mechanism that has been proposed to account for the right-hand maximum of the N^{14} angular distribution (Fig. 2) it is predicated that B^{10} picks up a deuteron cluster from O^{16}. At first glance this mechanism seems unlikely, with a probability considerably smaller than the probability of α pickup corresponding to the left-hand maximum of the N^{14} angular distribution.

In actuality, there is considerable probability for the operation of this mechanism if the O^{16} nucleus has the configuration N^{14} + d for an appreciable length of time, although a 4α configuration is commonly assumed for O^{16}. We cannot exclude the possibility that a considerable admixture of the N^{14} + d configuration exists. If our conception of the given mechanism is correct, our results favor this admixture. To be sure, the ratio between these two configurations which might be deduced from our data can be increased in favor of the 4α configuration for the following reason. In the deuteron pickup mechanism N^{14} is the residual nucleus of O^{16}, while C^{12} results from deuteron pickup by B^{10}. Therefore it appears that N^{14} will most probably be formed in its ground state, while C^{12} will be formed in a highly excited state.

On the other hand, in α pickup the residue of O^{16} is C^{12}, while N^{14} results from α pickup by B^{10}. We can therefore expect that in this case C^{12} will most probably be formed in its ground state and N^{14} in an excited state. The formation of ground-state N^{14} and of C^{12} with sufficient excitation for breakup into three α particles is evidently much less probable. In the given reaction we consider only events in which ground-state N^{14} is formed but C^{12} is highly excited. This leads to an apparent equalization of deuteron and α pickup probabilities from O^{16}.

The probability of the N^{14} + d configuration does not appear, however, to differ very strongly from the probability of the 4α configuration. This is confirmed by the work of Anderson et al.,[10] who bombarded Al with 160-MeV O^{16} ions and observed an approximately equal yield of nitrogen and carbon isotopes resulting from transfer reactions. They obtained the cross-section 170 mb for nitrogen isotope formation, and 210 mb for carbon isotopes. A comparison of these results with radiochemical and other data[11] showed that 80–90% of these cross-sections represent the formation of N^{14} and C^{12}. These data therefore indicate that there is no very marked difference between the probabilities of the 4α and N^{14} + d configurations for O^{16}.

The relative narrowness of the N^{14} angular distribution peaks in Fig. 2, and the character of the energy distributions of these nuclei in Fig. 6 favor the arguments that α and deuteron transfer from O^{16} to B^{10} occurs in grazing interactions. Both peaks correspond to angles different from zero. (The right-hand peak must be measured from 180°.) Their energy dependences have the form that characterizes the products of single-nucleon transfer.[4] In the postulated mechanisms we have the transfer of a deuteron, which is a bound two-nucleon group, or of a tightly bound particle. It is entirely possible that processes resembling single-nucleon transfer occur at the instant of transfer.

The tail of backward angles in the angular distribution of α particles produced through deuteron pickup by B^{10} (Fig. 3b) is evidently accounted for by the decay of highly excited C^{12} into α particles. Some of the α particles, ejected in a direction opposite to that of C^{12}, can have velocities greater than that of the parent C^{12} nucleus.

The smallness of the cross-section for deuteron stripping by O^{16} (Fig. 5a) results more probably from the small likelihood that the resultant F^{18} will decay into N^{14} and an α particle, than from the small probability that O^{16} will strip a deuteron from B^{10}.

In conclusion the authors wish to express their deep appreciation to E. V. Inopin and V. G. Neudachin for valuable discussions, and to acknowledge the large amount of work done in scanning the emulsions by E. V. Cherkavskaya, V. N. Emlyaninova, E. K. Panteleeva, K. P. Skibenko, and T. N. Startseva.

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