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NUCLEI
Experiment

Fast Charged Particles in the Interaction of ^{56}Fe with Be, Ta, and U Nuclei at an Energy of 400 MeV

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Abstract—The energy spectra of alpha particles emitted at an angle of 0° in the interaction of 400-MeV ^{56}Fe ions with ^{238}U, ^{181}Ta, and ^{9}Be targets were measured by means of a high-resolution magnetic analyzer (MAVR, which is the acronym of the Russian name of this setup). The energy spectra of charged particles ranging from Li to Ne were also measured. The experimental data obtained in this way indicate that the emission of alpha particles is a dominant process in the above reactions. Particles of high energy, up to those in the vicinity of the so-called kinematical limit for two-body reactions, were observed with a rather high yield. The sensitivity of the experimental procedure that employed the aforementioned magnetic analyzer made it possible to observe events characterized by cross-section values smaller by six to eight orders of magnitude than that at the maximum of the spectrum. The cross section for the production of light particles is shown to be dependent on their binding energy in the target. The experimental data obtained in this study were analyzed with aid of the moving-source model.

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1. INTRODUCTION

The interaction of two complex nuclei can be accompanied by the emission of alpha particles, with a relatively large cross section (up to 1 b), and other charged particles. Several components are observed in the energy spectra of these particles. One of them is formed by evaporated particles. Another is that of high energy particles whose angular distribution has a maximum at zero angle [1].

Measurements of the energy spectra of these particles at various angles reveal that the yield of high-energy alpha particles exceeds substantially the predictions of the evaporation model for compound-nucleus decay [2, 3], the angular distribution of alpha particles featuring a strong forward orientation [4]. In addition to alpha particles, heavier charged particles (lithium and beryllium isotopes) of energy different from those of evaporated particles can be emitted in such processes [5, 6]. Betak and Toneev [7] showed that the emission of fast particles occurred at the first reaction stage prior to statistical equilibration in the remaining nuclei. After the emission of nonequilibrium particles, the remaining compound nuclei have some distributions with respect to Z and A and with respect to the excitation energy. The deexcitation of compound nuclei formed at the first reaction stage occurs at the second, properly evaporation, stage.

The projectile remnant, together with the target nucleus, forms either a compound nucleus or a dinuclear system, which, after the redistribution of mass, energy, and angular momentum, decays to products characteristic of deep-inelastic collisions of heavy ions. The problem of sources of light-particle emission was discussed in detail elsewhere [7, 8], all experiments devoted to studying the emission of fast charged particles being performed for reactions involving heavy ions of ^{22}Ne and ^{40}Ar.

Measurement of the energy spectra of fast charged particles and their production cross sections for various targets and projectiles may furnish important information about the mechanism of production of such particles. The objective of the present study was to obtain information about the mechanism of emission of fast alpha particles and light nuclei in the interaction of ^{56}Fe ions with Be, Ta, and U target nuclei. A high-resolution magnetic analyzer (MAVR, which is the acronym of the Russian name of this setup) [9] was used to measure the energy spectra of light charged particles.

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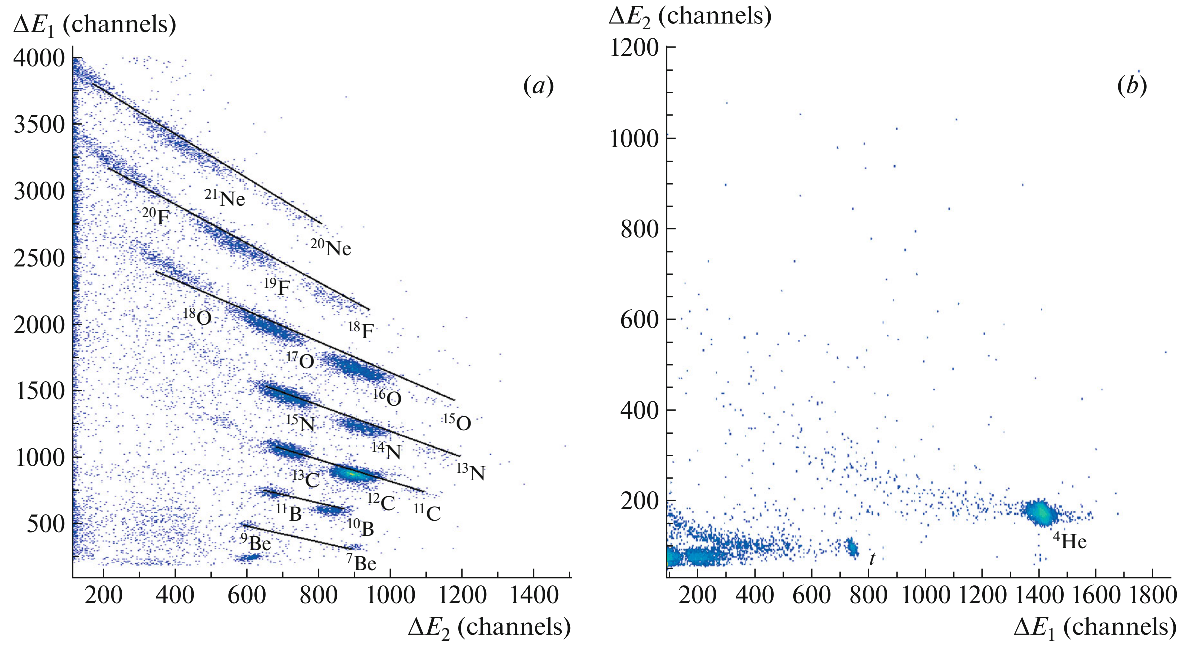

Fig. 1. Experimental matrices of (*a*) light nuclei from beryllium to neon and (*b*) alpha particles and tritons for the ^{56}Fe + ^{238}U reaction at 400 MeV.

2. IMPLEMENTATION OF THE EXPERIMENT

The experiment being discussed was performed in 400-MeV beams of ^{56}Fe ions at the U-400 cyclotron of Laboratory of Nuclear Reactions (LNR) at Joint Institute for Nuclear Research (JINR). The beam was shaped by means of the U-400 magnetic optics supplemented with a system of diaphragms, and the beam shape was monitored by employing two profilometers. The ^{56}Fe ion beam of intensity 100 nA was 5×5 mm in size at the target. A ^{238}U target 1 μm thick, a ^{181}Ta target 2 μm thick, and a ^{9}Be target 10 μm thick were used in the experiment. The angular resolution of the detectors used was $\pm 0.8°$ with allowance for the beam spread at the target. With the aim of separating reaction products and beam nuclei in the forward direction, we used the high-resolution magnetic analyzer MAVR, which had a focal plane as long as 1.5 m, and this made it possible to separate in position fast charged particles and beam nuclei. The energy range of the reaction products that could be detected by the analyzer was $E_{\max}/E_{\min} = 5.2$ at the energy resolution of $\Delta E/E = 5 \times 10^{-4}$. The analyzer had a good linear dependence of the dispersion and resolution over the whole focal-plane length of 1500 mm. The particle deflection angle in the analyzer was 110.7°. This system of analysis and particle detection permitted measuring energy spectra of light charged particles over the energy range between 30 and 110 MeV. The use of the MAVR setup for detecting light charged particles made it possible to perform experiments at forward angles with ^{56}Fe ion beams of high intensity (up to 5×10^{12} s^{-1}) and to measure thereby the energy spectra of particles up to energies at which the yield was 10^{-5} down to 10^{-6} of the maximum value.

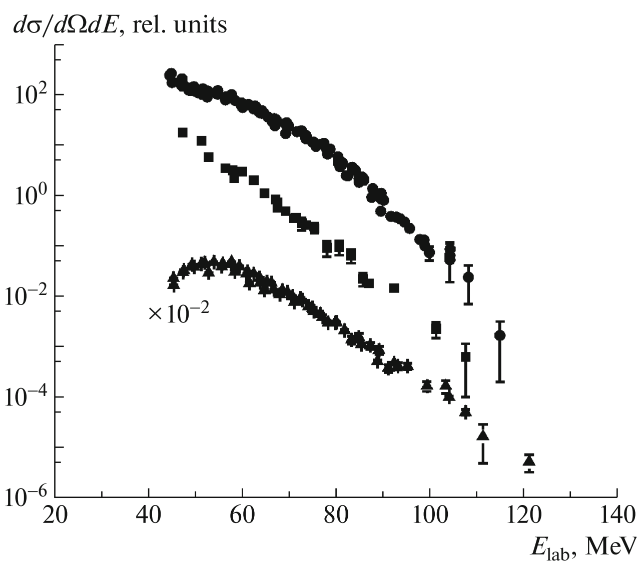

Fig. 2. Energy spectra of alpha particles according to measurements a zero angle in the reactions induced in (circles) ^{238}U, (squares) ^{181}Ta, and (triangles) ^{9}Be targets by ^{56}Fe ions of laboratory energy $E_{\rm lab} = 400$ MeV. The spectrum of alpha particles obtained by employing the ^{9}Be target was multiplied by 10^{-2}.

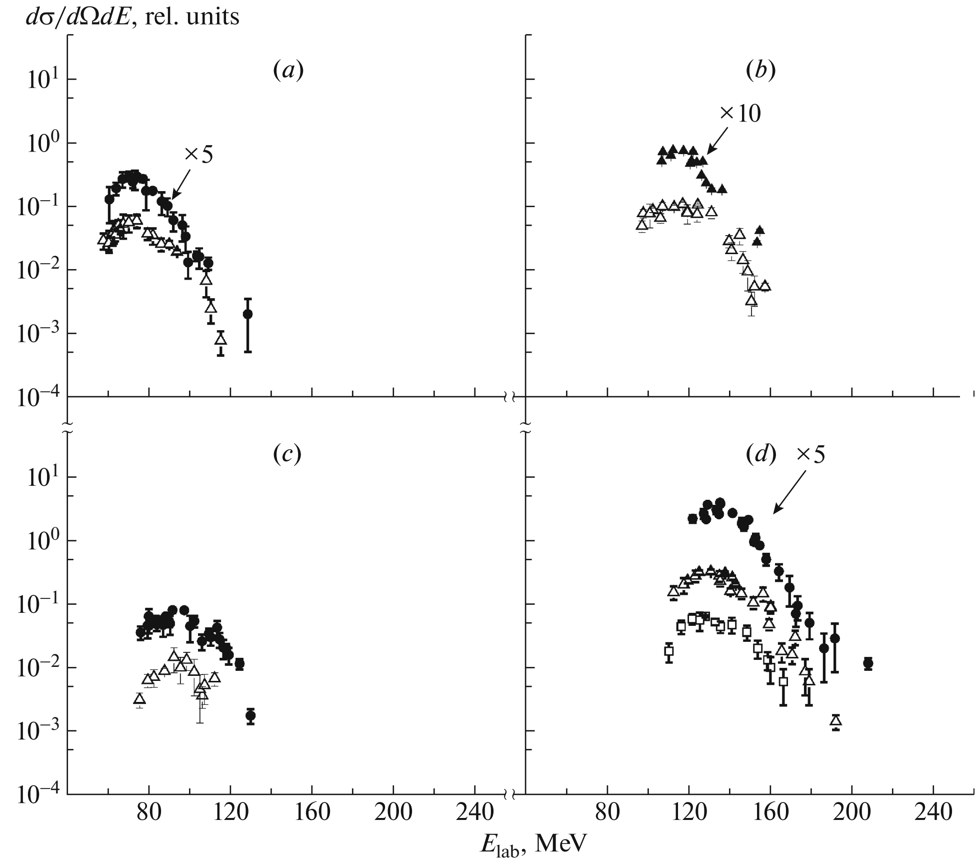

Fig. 3. Energy spectra of the following light nuclei according to measurements at zero angle in the reaction induced in a ^{238}U target by ^{56}Fe ions of laboratory energy $E_{\rm lab} = 400$ MeV: (*a*) ^{6}Li (circles) and ^{7}Li (triangles); (*b*) ^{10}B (circles) and ^{11}B (triangles); (*c*) ^{9}Be (circles) and ^{10}Be (triangles); and (*d*) ^{12}C (circles), ^{13}C (triangles), and ^{14}C (squares).

The detection of reaction products in the focal plane of the analyzer was accomplished by means of semiconductor strip detectors. The positions of the products in the focal plane and the ion charges (Q_i) corresponding to them were compared with the values calculated by employing the LISE code [10]. Light charged particles produced in the reaction being discussed were focused after their escape from the target by the doublet of quadrupole lenses at the inlet of the magnetic analyzer, whereby the solid angle covered by the analyzer was increased to 10 msr. After focusing, reaction products, traveled to the spectrometer magnet, where their separation from the primary beam occurred. Thereupon, the detector system situated in the focal plane and formed by four semiconductor telescopes made it possible record and identify reaction products by charge, Z, and mass, A, numbers; by energy loss, ΔE; and by total energy, E. Four semiconductor silicon telescopes in which the detector thicknesses ΔE_1, ΔE_2, and E were 100, 700, and 3200 μm, respectively, recorded high-energy light charged particles. The detector thicknesses were chosen in such a way as to ensure the identification of light charged particles in the energy range between 30 and 120 MeV.

Figure 1 shows examples of identification matrices of light nuclei. Ions of charge equal to the charge of the nucleus were detected in the experiment. From a simulation performed by means of the LISE++ code, it was found that such ions are produced for elements from lithium to nitrogen. For elements from oxygen to neon, there arise, in addition to them, not fully stripped ions—that is, ions of charge smaller than the charge of the nucleus. The contribution of these, not fully stripped, ions is as small as a few percent, and we took it into account in evaluating the yields of product nuclei.

In order to protect the detectors from scattered ions of the beam, an aluminum foil 80 μm thick was positioned in front of each telescope. The foil thickness was chosen in such a way that ^{56}Fe nuclei of energy 400 MeV were fully stopped in the aluminum foil before reaching the silicon detectors used. The experiment harnessed four telescope, and this permitted simultaneously detecting light charged particles of four energies. Only particles of specific magnetic

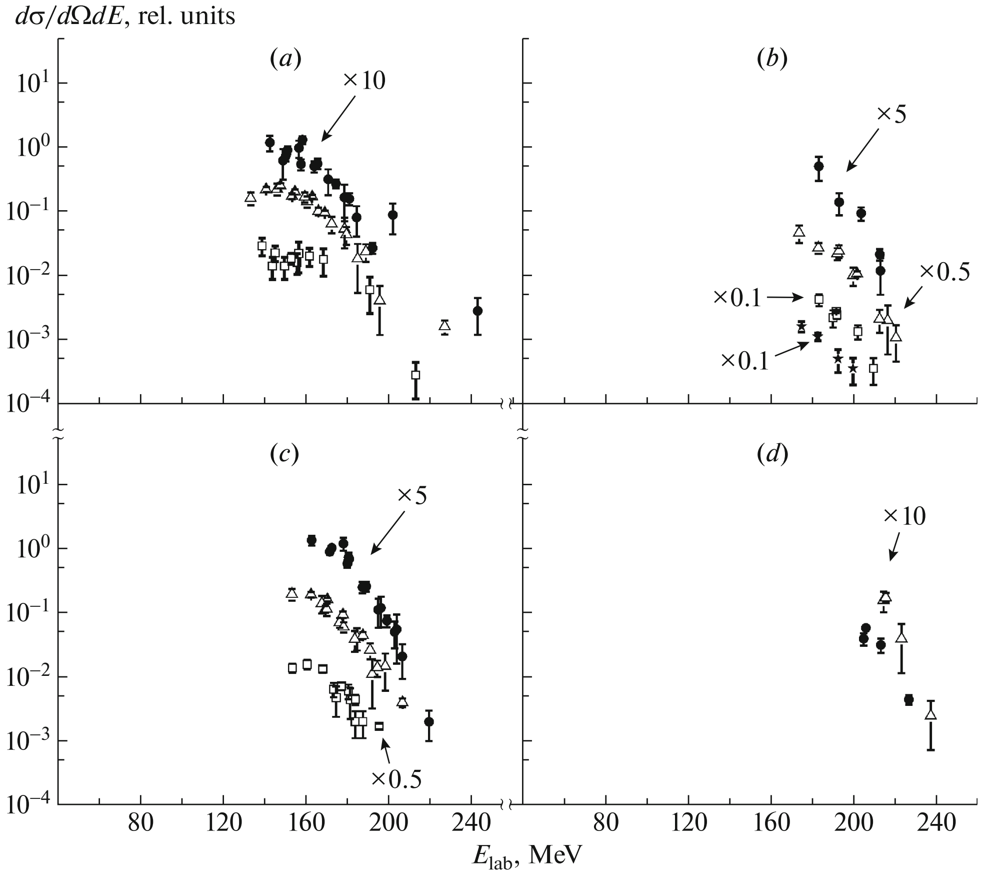

Fig. 4. Energy spectra of the following nuclei according to measurements at zero angle in the reaction induced in a ^{238}U target by ^{56}Fe ions of laboratory energy $E_{\rm lab} = 400$ MeV: (*a*) ^{14}N (circles), ^{15}N (triangles), and ^{16}N (squares); (*b*) ^{18}F (circles), ^{19}F (triangles), ^{20}F (squares), and ^{21}F (stars); (*c*) ^{16}O (circles), ^{17}O (triangles), and ^{18}O (squares); and (*d*) ^{21}Ne (circles) and ^{22}Ne (triangles).

rigidity determined by the telescope position in the focal plane of the analyzer hit each telescope. The intensity of the ion beam at the target was determined by measuring the current from an isolated target, this current being normalized to the readings of the Faraday cup placed in the reaction chamber.

3. EXPERIMENTAL RESULTS

For the reactions induced in ^{238}U, ^{181}Ta, and ^{9}Be targets by a ^{56}Fe ion beam of laboratory energy $E_{\rm lab} = 400$ MeV, the energy spectra of alpha particles were measured at zero emission angle (see Fig. 2). For ^{238}U, ^{181}Ta, and ^{9}Be targets, the endpoints of the spectra were 115, 107, and 121 MeV, respectively. As a result, reaction-product yields five orders of magnitude smaller than the maximum yield could be measures on the basis of cross sections. Alpha particles of energy below 40 MeV were not detected because of large detector thicknesses.

For the reaction on the ^{238}U target, the energy spectra of charged particles from lithium to neon nuclei were measured at zero angle (see Figs. 3 and 4). The results show that the number of lithium nuclei is nearly one-third as large as the number of alpha particles and that, as the atomic number grows, the yield of nuclei increases up to carbon (their yield is one order of magnitude larger is the yield of lithium nuclei) and then again decreases up to neon. Nuclei heavier than those of neon could not be measured because of the detector thicknesses, since heavier particles were stopped in the first detector of the ΔE_1 semiconductor telescope.

Thus, the following conclusions can be drawn from the experimental results reported above:

(i) The production cross sections for high-energy alpha particles may reach values one-half as large as the total reaction cross section, suggesting the dependence of their production mechanism on other reaction channels.

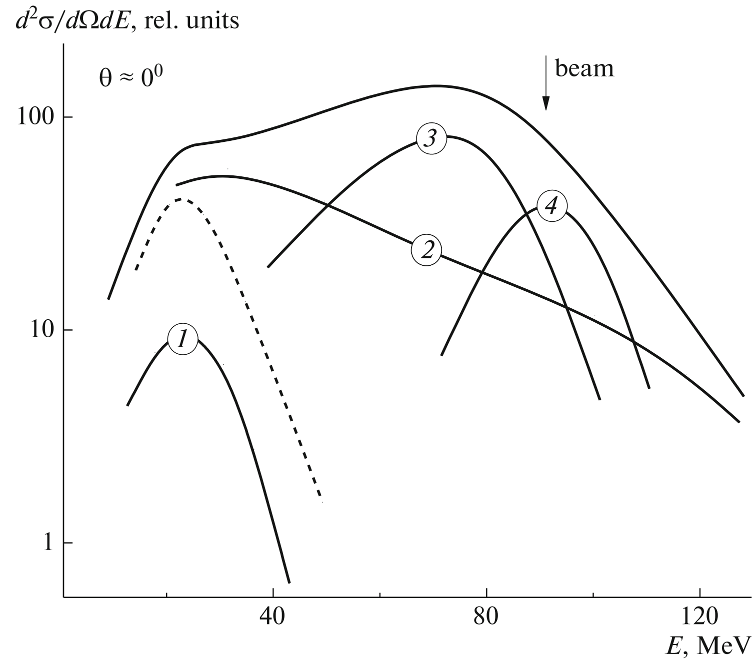

Fig. 5. Schematic representation of the energy spectrum of alpha particles and presumed contributions of four mechanism of their formation at a beam energy of about 20 MeV per nucleon: (*1*) evaporation from the compound nucleus, (*2*) incomplete fusion, (*3*) projectile breakup in inelastic processes, and (*4*) elastic breakup (fragmentation). The dashed curve represents the sum of all evaporated particles (from the compound nucleus and from the final nuclei produced in processes *2* and *3*) [11]. The arrow indicates the alpha particle energy corresponding to the beam speed.

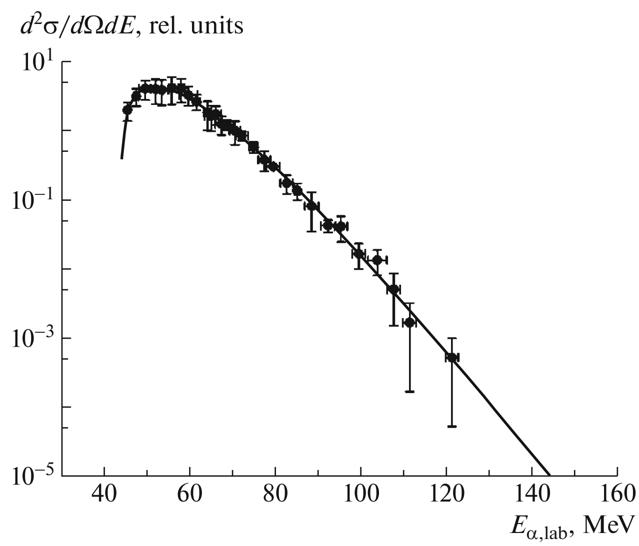

Fig. 6. Energy spectrum of alpha particles according to measurements at zero angle in the reaction induced in a ^{9}Be target by ^{56}Fe ions of laboratory energy 400 MeV. The solid curve represents its approximation by the spectrum of one moving source.

(ii) The position of the maximum in the energy distribution at forward angles moves toward the energy corresponding to the projectile-ion speed. The maximum yield of alpha particles corresponds to the projectile-ion speed. Alpha particles of speed several times as high as the projectile-ion speed are produced in the reaction with a relatively high probability. In reactions involving heavy ions, the production of heavier nuclei also proceeds with a sizable cross section.

(iii) The differential cross sections for alpha-particle production depend on the charge number (Z) of the target nucleus (the cross section in question is

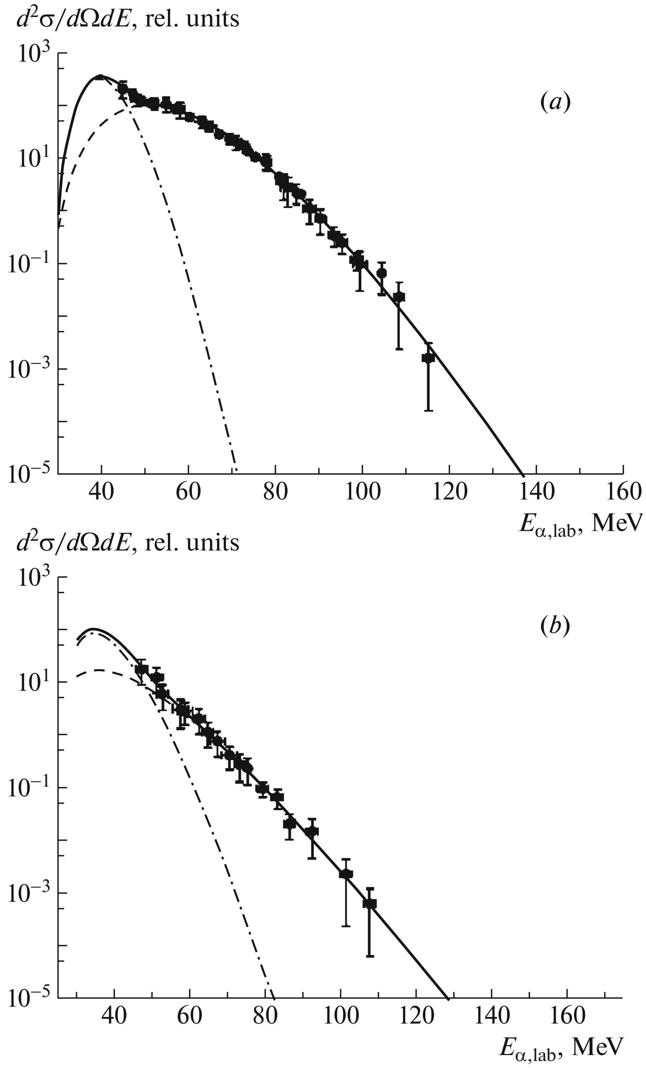

Fig. 7. Approximation (solid curves) of the experimental energy spectra of alpha particles (circles) on the basis of the model of two moving sources for the (*a*) ^{56}Fe + ^{238}U and (*b*) ^{56}Fe + ^{181}Ta reactions. The dashed and dash-dotted curves represent the contributions of, respectively, the first and second sources. The model parameters are given in Table 1.

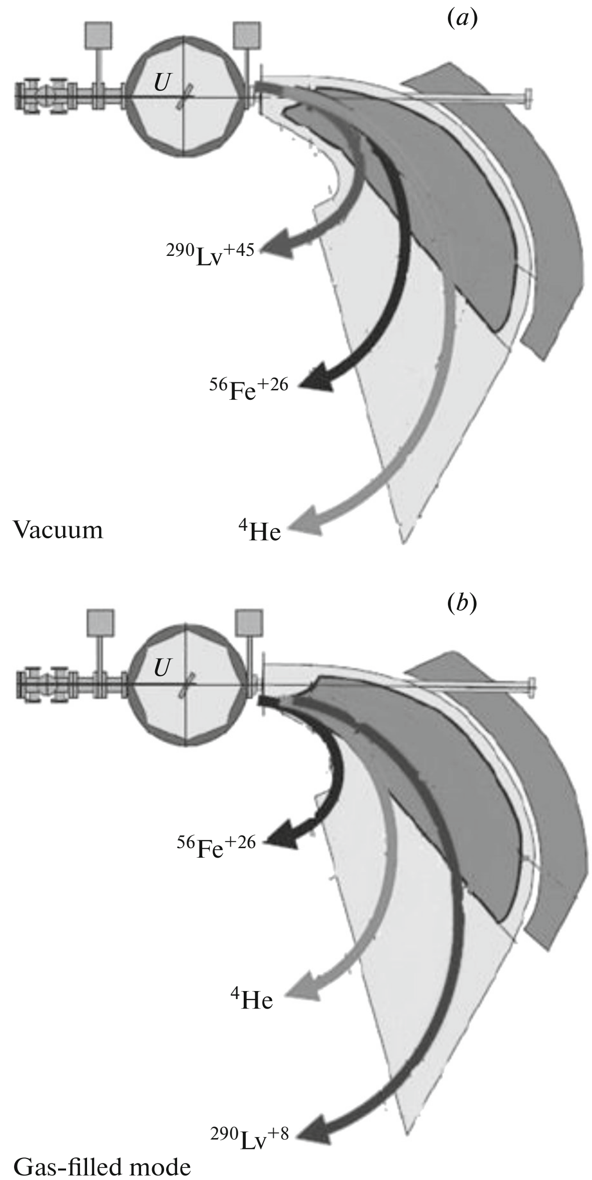

Fig. 8. Scheme of an experiment aimed at simultaneously detecting a fast alpha particle and the compound nucleus ^{290}Lv at the MAVR setup for the options of (*a*) reaction-product detection in a vacuum and (*b*) gas filling. The trajectories of alpha particles, beam ions, and heavy nuclei are indicated.

substantially larger in the case of the ^{238}U target than in the case of the ^{181}Ta target).

We have analyzed the experimental spectra of alpha particles with the aim of determining the sources of their formation.

4. ANALYSIS OF EXPERIMENTAL DATA ON THE BASIS OF THE MODEL OF MOVING SOURCES

It is of interest to analyze experimental data from the point of view of the mechanism of alpha-particle formation in the reactions that we studied here. In [11], it was shown that several processes are involved in the formation of the energy spectrum of alpha particles. These processes include (*1*) evaporation from the compound nucleus, (*2*) incomplete fusion, (*3*) projectile breakup in inelastic processes, and (*4*) elastic breakup (fragmentation). Figure 5 shows schematically the spectrum of alpha particles for the ^{22}Ne+^{181}Ta reaction from [11]. The possible relative contributions of various processes (*1*–*4*) are represented by respective curves.

We are interested in the high-energy section of the spectrum. Presumably, this section can be explained by three reaction channels.

In order to describe quantitatively the energy spectrum of alpha particles, we employed the empirical model of moving sources [11]. It relies on the assumption that there exist several sources of alpha-particle emission.

Within this empirical model, it is assumed that alpha particles are evaporated isotropically from the ith source moving toward the projectile beam at a speed v_i. Within the source, the alpha-particle kinetic energy $\varepsilon_\alpha = mv_\alpha^2/2$ (where v_α is the alpha-particle speed) obeys a Boltzmann distribution that corresponds to some temperature T_i. It is assumed that the kinetic energy of an alpha particle emitted from an immobile source is $E_\mathrm{C} + mv_\alpha^2/2$. Here, the parameter E_C is referred to as the Coulomb energy of this alpha particle. The differential cross section for alpha-particle emission was calculated by the formula

$$\frac{d\sigma}{d\Omega dE} = f(E) = \sum_i N_i \sqrt{E - E_\mathrm{C}} \quad (1)$$

$$\times \exp\left(-\frac{E - E_\mathrm{C} + E_i - 2\sqrt{E_i(E - E_\mathrm{C})}}{T_i}\right),$$

where N_i are normalization factors, E is the energy of the emitted alpha particle in the laboratory frame, $E_i = m_\alpha v_i^2/2$, and T_i stand for the temperatures of the moving sources (in MeV units). The values of the parameters E_i, T_i, N_i, and E_C can be determined by minimizing the mean-square deviation of the theoretical values $f_\mathrm{theor}(E_{\alpha,k})$ from their experimental counterparts $f_\mathrm{exp}(E_{\alpha,k})$; that is

$$\chi^2 = \sum_k \{\log[f_\mathrm{theor}(E_{\alpha,k})] - \log[f_\mathrm{exp}(E_{\alpha,k})]\}^2. \quad (2)$$

The spectrum obtained for the ^{56}Fe + ^{9}Be reaction could be described in terms of one source (see Fig. 6), the parameter values being given in Table 1.

For the ^{56}Fe + ^{238}U and ^{56}Fe + ^{181}Ta reactions, the positions of the maxima in the spectra were not determined in the experiments. This complicated an unambiguous determination of the alpha-particle kinetic energy E_C. Therefore, this energy was taken to be equal to the Coulomb barrier height B_α in the *heavy fragment* + ^{4}He system, $E_\mathrm{C} = B_\alpha$. The results of describing the spectrum of alpha particles in the ^{56}Fe + ^{238}U and ^{56}Fe + ^{181}Ta reactions are shown in Fig. 7. Two sources turned out to be sufficient for satisfactorily describing the whole spectrum measured experimentally. The resulting values of the temperatures and speed of two moving sources are given in Table 1. For the ^{56}Fe + ^{238}U and ^{56}Fe + ^{181}Ta reactions, the speeds of the sources are higher than speed of the compound nuclei but are lower than the speed of nuclei in the ^{56}Fe beam. For the ^{56}Fe + ^{9}Be reaction, the speed of the source is lower than the speed of the compound nucleus and the speed of nuclei in the ^{56}Fe beam. The different numbers of the sources and the different ratios of their speeds to the speed of nuclei in the ^{56}Fe beam are indicative of the difference in the mechanisms of alpha-particle formation in the ^{56}Fe + ^{238}U and ^{56}Fe + ^{181}Ta reactions, on one hand, proceeding on heavy targets and in the ^{56}Fe + ^{9}Be reaction, on the other hand, proceeding on a light target. For the ^{56}Fe + ^{9}Be reaction, the value of the parameter $E_\mathrm{C} =$ 44 MeV turned out to be substantially higher than the Coulomb barrier height of $B_\alpha = 8.8$ MeV for the ^{61}Ni + ^{4}He system. Therefore, the source of alpha particles cannot be associated with the compound nucleus. It would be more reasonable to associate it with ^{9}Be target breakup via the emission of two alpha particles.

5. PROSPECTS OF EMPLOYING REACTIONS THAT LEAD TO THE EMISSION OF FAST CHARGED PARTICLES

It is shown that reactions involving heavy ions and occurring at energies between 10 and 20 MeV per nucleon lead to the emission of alpha particles, with a rather large cross section, as well as to the emission of lithium and beryllium nuclei with an energy close to the maximum energy possible in the two-body process (that is, an energy in the vicinity of the so-called kinematical reaction barrier). If, after the emission of these particles, the fusion of the residual nuclei occurs, the remaining heavy nucleus has a rather low excitation energy, which is predominantly rotational [11]. This cumulative process can be used to synthesize “cold” exotic nuclei, including those of heavy elements. The excitation energy and the kinetic energy of the ^{290}Lv residual nucleus produced in the ^{56}Fe + ^{238}U = ^{290}Lv + ^{4}He reaction was calculated for various segments of the energy spectrum (see Table 2). As the alpha-particle energy grows, the excitation energy of the compound nucleus decreases down to small values, whereas its kinetic energy remains sufficient for detection.

The emission of fast charged particles proceeds with the highest probability at zero angle with respect to the bombarding-beam direction. In performing experiments devoted to detecting recoil nuclei and fast light particles accompanying these reactions, it is therefore necessary to separate reaction products and nuclei of the primary beam. In principle, this can be done by means of the MAVR magnetic analyzer.

Table 1. Features of sources in terms of which experimental energy spectra of alpha particles were described: Coulomb energy of alpha particles, E_C; kinetic energies of alpha particles from two sources, $E_1 = m_\alpha v_1^2/2$ and $E_2 = m_\alpha v_2^2/2$; temperatures of moving sources, T_1 and T_2; normalization factors, N_1 and N_2; speed of 400-MeV ^{56}Fe projectiles in the laboratory frame, $v_{\rm beam}$; and compound-nucleus speed in the laboratory frame, $v_{\rm comp}$

Reaction	$E_1 = m_\alpha v_1^2/2$, MeV	$E_2 = m_\alpha v_2^2/2$, MeV	T_1, MeV	T_2, MeV	E_C, MeV	N_1	N_2	$\frac{v_1}{v_{\rm beam}}$	$\frac{v_1}{v_{\rm comp}}$	$\frac{v_2}{v_{\rm beam}}$
^{56}Fe + ^{9}Be	3.90	–	4.50	–	44.0	1.78	–	0.37	0.43	–
^{56}Fe + ^{238}U	21.72	11.82	2.0	0.57	27.1	22.0	95.47	0.87	4.58	0.64
^{56}Fe + ^{181}Ta	9.37	10.04	3.32	1.11	23.7	5.0	27.52	0.57	3.0	0.59

The proposed scheme of an experiment aimed at producing ^{190}Lv nuclei is illustrated in Fig. 8 in two versions: that of reaction-product detection in a vacuum (a) and that of detection in the gas-filling mode (b). It is proposed to measure coincidences of recoil nuclei and alpha particles in the focal plane. Figure 8 shows the trajectories of alpha particles, beam ions, and heavy nuclei. In the future, the use of the MAVR magnetic spectrometer and beams from the U-400R cyclotron may become an efficient tool for performing such investigation. Upon supplementing the currently operating setup with two highly efficient detectors for fission fragments, experiments of this type can be used to study a different channel of the reaction involving the emission of fast particles—namely, the fission of a heavy residual nucleus.

Table 2. Kinetic energies of ^{290}Lv and ^{4}He versus the excitation energy of the ^{290}Lv nucleus produced in the ^{56}Fe + ^{238}U = ^{290}Lv + ^{4}He reaction at the ^{56}Fe projectile ion energy of 400 MeV

Excitation energy of ^{290}Lv	Kinetic energy of ^{290}Lv	Kinetic energy of ^{4}He
80	62.5	57.2
70	61.1	68.6
60	59.9	79.8
50	58.8	90.9
40	57.8	101.9
30	56.8	112.9
20	55.9	123.8
10	55.1	134.6
0	54.3	145.4

6. CONCLUSIONS

The energy spectra of alpha particles originating from the reactions induced by 400-MeV beams of ^{56}Fe ions incident to ^{238}U, ^{181}Ta, and ^{9}Be targets were measured at zero angle by means of the MAVR magnetic spectrometer. The energy spectra of charged particles from lithium to neon nuclei were also measured. The experimental data obtained in this way indicate that alpha-particle emission is a dominant process in these reactions. The sensitivity of the experimental procedure that made use of the magnetic analyzer permitted measuring yield of products whose cross sections were five orders of magnitude smaller than that at the maximum of the spectrum. The production cross section for light particles has been shown to be dependent on the target charge number Z. The experimental data have been analyzed on the basis of the moving-source model. This analysis has revealed the presence of different alpha-particle sources in reactions on heavy target nuclei (^{238}U and ^{181}Ta) as contrasted against the reaction on the light target nucleus of ^{9}Be. This suggest the difference in the mechanism of alpha-particle formation in the reactions on these targets.

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