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ALPHA-PARTICLE ENERGY SPECTRA MEASURED AT FORWARD ANGLES IN HEAVY-ION-INDUCED REACTIONS

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The experimental investigation of the energy spectra of protons and α-particles emitted in heavy-ion-induced reactions, carried out as early as in 1961 by Britt and Quinton [1], showed the presence in these spectra, besides the evaporation component, of a more intensive and energetic one. The formation of highly energetic α-particles ($E_\alpha \geq 40$ MeV) emitted predominantly in the direction of the incident beam and having the velocity spectrum of the type:

$$P(v) \sim v^2 \exp(-v^2/v_0^2),$$

was explained in terms of the separation of an α-particle from the projectile (in the case of ^{12}C-induced reactions, in terms of projectile breakup in the field of the target nucleus).

Further investigations of energetic light particles indicated the possible existence of other emission mechanisms. There being no necessity to review all the recent experimental and theoretical investigations in this field, which have already been briefly mentioned in ref. [2], here we shall refer solely to some interesting papers dealing with α-particle emission. Thus, Ho et al. [3] measured the α-particle spectrum in coincidence with transfer reaction products. An interpretation was proposed that the emission of highly energetic α-particles proceeded from a strongly heated spot at the point of contact of the incident ion with the target nucleus. This idea was considered theoretically in refs. [4,5]. A different approach to the problem was used by Yamada et al. [6], who suggested the mechanism of "massive transfer" during the interaction. This representation was developed by Siwek-Wilczynska et al. [7] who tried to connect such a process with the input angular momentum. In ref. [8], the results of angular distribution measurements of α-particles in coincidence with light transfer products have been reported and the conclusion was drawn that the processes of this type are fast ones. The sequential emission of α-particles was regarded to be unlikely and a supposition was made that the energetic α-particles are emitted in the early stage of the reaction. In our previous paper [2], such a conclusion was also drawn on the basis of α-particle spectra measured in coincidence with binary fission fragments. The lack of dependence of the α-particle spectrum shape and

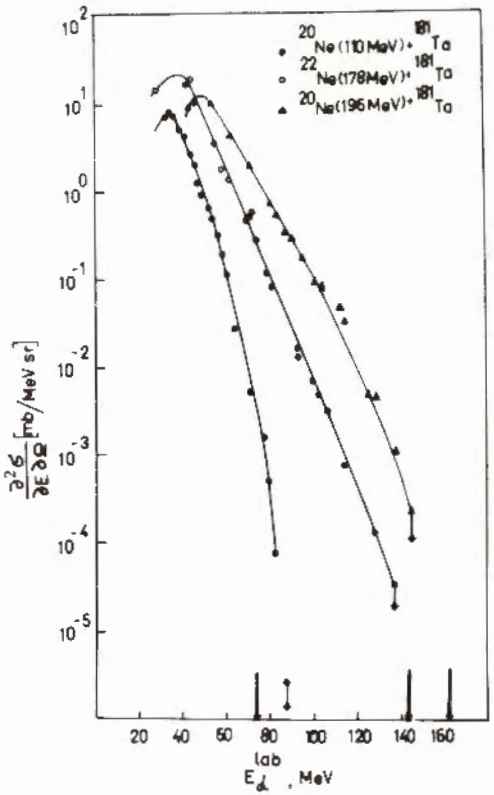

Fig.1. Laboratory energy spectra of α-particles observed at 0° in the ^{20}Ne and ^{22}Ne bombardments of ^{181}Ta. The thick arrows indicate the E_α^{max} values calculated as described in the text.

yield on the angle between the fission axis and the beam direction indicated the emission of α-particles before the fission of the residual nucleus. A similar result was obtained by Awes et al. /9/, who, in the bombardment of U with 300 MeV oxygen beam, showed that the light particle spectra measured in coincidence with different reaction products including fission fragments, slightly depended on the product detected.

Because of the strongly forward-peaked angular distributions of energetic α-particles, it is of great interest to measure their energy spectra at 0°. In ref. /10/ we reported on the measurements of the energy spectrum of α-particles emitted in the beam direction in the reaction ^{22}Ne + ^{197}Au. These measurements showed that in the given reaction α-particles were observed with an energy only slightly lower than the maximum possible value calculated on the basis of the conservation laws of a two-body process. It is of interest in this case to determine the end-point energy of the α-particle spectrum, which can be connected with the mechanism of this complex process.

In the present experiment measurements have been made of the energy spectra of light charged particles emitted in the beam direction in different heavy-ion-induced reactions. The experiments were carried out at ^{20}Ne, ^{22}Ne, and ^{40}Ar ion beams from the 300 cm cyclotron of the JINR Laboratory of Nuclear Reactions. Light charged particles entered a MSP-144

magnetic spectrometer located at an angle $\theta = 0°$ with respect to the ion beam and having an angular aperture $\Delta\theta = \pm 2°$. The focal plane of the spectrometer being ~1500 mm long corresponded to the charged-particle momentum range $1.0 \leq P \leq 1.6$ (for α-particles this corresponds to the energy range 20-130 MeV). In those experiments, in which charged particles of higher energy were detected, a thick target was used, which served as a beam absorber and a charged-particle degrader simultaneously. In the focal plane of the spectrometer, a telescope was placed consisting of two semiconductor detectors - a surface-barrier detector 300 μm thick and a drift Si(Au) detector 3.5 mm thick. Each detector had a 9 mm diameter corresponding to an energy range of 1%. Such a detector system, together with a suitable electronic setup including a fast-slow coincidence circuit, allowed us to carry out the unambiguous detection and identification of light charged particles. The beam was monitored by means of a surface-barrier Si (Au) detector placed at 30° with respect to the beam. The absolute α-particle formation cross section was determined with better than 15% accuracy taking into account the ion current, the target thickness and the efficiency of the magnetic spectrometer. The targets used were 2-7 mg/cm^2 Tb, Ta, Au, and Th foils.

Figure 1 shows the laboratory α-particle spectra measured using the described technique at 0° in the bombardment of targets by ^{20}Ne and ^{22}Ne projectiles at bombarding energies of 5.5, 8 and 9.8 MeV/nucleon. As is seen from the figure, the α-particle formation cross section in the maxima of the energy spectra slightly depends on the projectile energy, whereas the position of the maxima, as it follows from a simple calculation, is close to the exit Coulomb barrier for an α-particle. Figure 2 shows an α-particle spectrum obtained in the reaction ^{22}Ne + ^{197}Au in comparison with the calculated evaporation spectrum. It can be seen that the cross section in the maximum is predominantly due to evaporation. However, the high energy portion of the experimental spectrum, as was pointed out in ref. /10/, strongly differs from the one expected on the basis of the evaporation model. For this high energy part of the energy spectra a strong dependence on the projectile energy is observed. It should be pointed out that in the studied reactions α-particles can be emitted with velocities significantly greater than the velocity of the incident ions. All the experimental α-particle spectra are characterised by well pronounced end-point energies E_α^{max} (indicated by arrows in the figures). These energies are estimated on the basis of the conservation laws under the assumption of

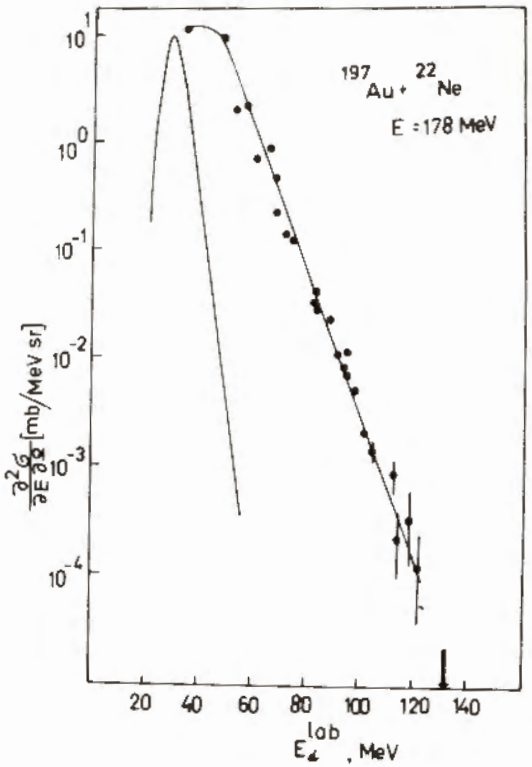

Fig.2. Laboratory energy spectrum of α-particles observed in the $^{197}Au + ^{22}Ne$ reaction at 178 MeV. The upper curve is drawn through experimental points to guide the eye; the lower curve is the calculated evaporation spectrum. The thick arrow is as in Fig.1.

a two-body exit channel, viz. α-particle emission accompanied by the fusion of the remaining nucleons. The maximum α-particle energy is determined by the simple expression:

$$E_{\alpha,c.m.}^{max} = E_0 + Q + V,$$

where E_0 is the projectile energy in the centre-of-mass system; Q, the total energy released in the reaction; V, the potential energy, which, in the case of a two-body process, is equal to 0. It can be shown that the maximum value of the α-particle energy corresponds to a two-body process. Thus, in the case of a three-body exit channel in the reaction ^{22}Ne (178 MeV) + ^{197}Au, e.g., the breakup of the projectile, the α-particle energy cannot exceed 70 MeV.

The values of E_α^{max} calculated in this way are in good agreement with the spectrum end-point energies obtained for α-particles emitted in a series of target-ion combinations. The presence in the α-particle energy spectra of energies close to the maximum possible ones in a two-body process shows that the second reaction product after the α-particle emission takes place is a composite system having a mass by 4 a.m.u. less than the sum of the masses of the interacting nuclei. The compound nucleus formed as a result of the complete fusion of the interacting nuclei would have an excitation

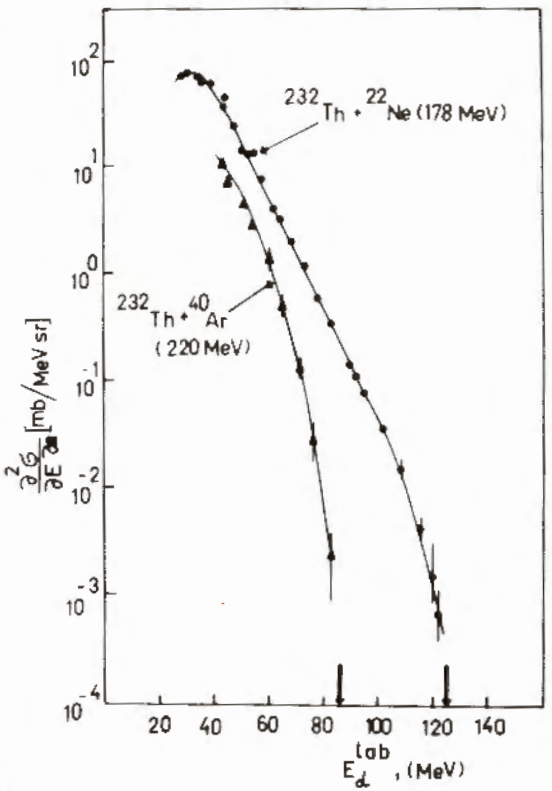

Fig.3. Laboratory α-particle energy spectra measured at 0° in the reactions $^{232}Th + ^{22}Ne$ at 178 MeV and $^{232}Th + ^{40}Ar$ at 220 MeV. The thick arrows are as in Fig.1.

energy $E^* = E_{c.m.} + Q_{CN}$. In contrast to the compound nucleus, the above-mentioned system can be found in states of different excitation energy depending on the emitted α-particle energy. In the extreme case, the system will be in a low excited state (cold nucleus). These nuclei either decay to the ground state by the emission of nucleons and γ-rays, or fission to two fragments. If the small difference between E_α^{max} and the α-particle spectrum end-point energy is presumably of rotational nature, then this may be an indication of the high angular momentum left in the residual nucleus or system.

The α-particle emission cross section at the end-point energy strongly depends on the target-ion combination. Fig.3 shows the α-particle energy spectra obtained in the bombardment of a ^{232}Th-target by ^{22}Ne and ^{40}Ar projectiles. The α-particle emission cross section is higher in the case of the ^{40}Ar ions than in the ^{22}Ne case. Nevertheless, the kinematic limit (E_α^{max}) is reached at several times higher cross section in the ^{40}Ar case. This fact can be of great importance if such processes are employed in the synthesis of heavy and superheavy nuclei in the ground state.

Figure 4 shows α-particle spectra measured in ^{22}Ne (178 MeV)-induced reactions on different target nuclei. As is seen from the figure, the shape of the spectra slightly changes

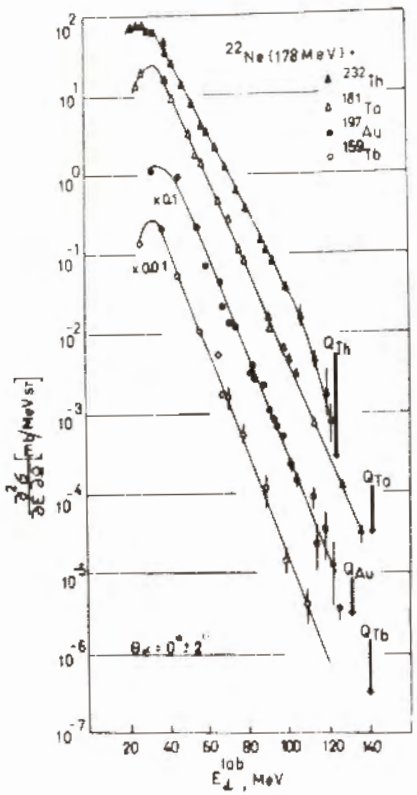

Fig.4. Laboratory α-particle energy spectra measured at 0° in the bombardment of ^{232}Th, ^{181}Ta, ^{197}Au, and ^{159}Tb targets with ^{22}Ne ions at 178 MeV. The thick arrows are as in Fig.1. (Q with different symbols for the target nuclei specifies E_{α}^{max} for different targets).

with the target nucleus, and this agrees with the conclusions of ref.[11], where ^{12}C projectiles were used. As was mentioned earlier, the maxima in our measured spectra are close to the exit Coulomb barrier for α-particles or to the velocity corresponding to the incident-ion velocity. All spectra shown in fig.4 practically reach their kinematic limits and the small difference between the measured end-point energy and the maximum possible one can be explained in terms of the residual nucleus angular momentum.

The analysis of the absolute α-particle cross section obtained in reactions with different targets allowed us to find a correlation between the α-particle-emission cross section at $E_{\alpha} \geq 60$ MeV and the α-particle binding energy in the target nucleus. This dependence is shown in fig.5, where the energy released at the emission of α-particles by the ^{159}Tb, ^{181}Ta, ^{197}Au, and ^{232}Th nuclei is indicated on the x-axis and the emission cross section for α-particles with energies of 60, 100 MeV and a value in the maxima is indicated on the y-axis. For the ^{40}Ar-induced reaction the dependence for 60 MeV α-particles is shown too. As is seen from this figure, the α-particle yield grows fast with an increase of the energy released at the separation of the α-particle from the target nucleus. The correlation mentioned is best pronounced for the high-energy α-particles. In the case of energies in the spectrum maxima the α-particle emission cross section for the Tb target does not obey the common correlation. This fact can

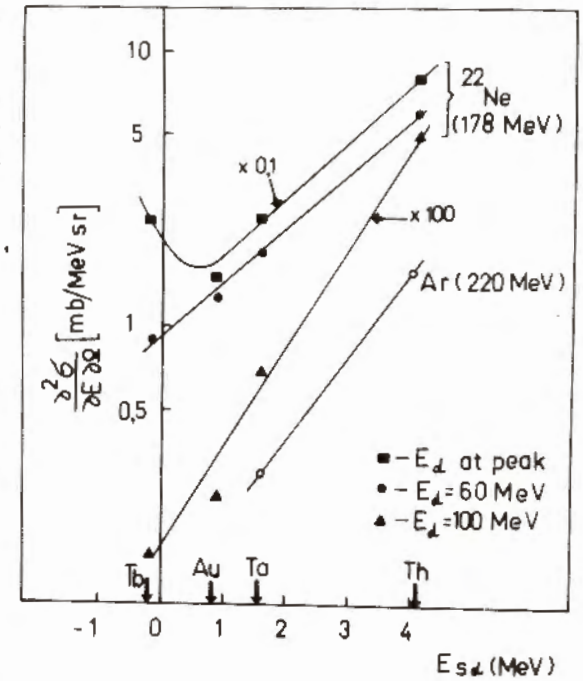

Fig.5. The differential cross section at different values of the α-particle energy as a function of the α-particle binding energy in the target nucleus in the case of ^{22}Ne- and ^{40}Ar-induced reactions.

be explained by the evaporation component contribution especially important in this case.

In order to determine the yield of other charded particles, the energy spectra of tritons and deuterons were measured at 0° in the reaction ^{40}Ar + ^{181}Ta. These spectra are shown in fig.6 together with the α-particle spectrum. It is seen that the emission cross section of other charged particles in all energy intervals is several orders of magnitude smaller than the α-particle emission cross section.

Thus, in the investigated process we see the predominant emission of α-particles as compared to other light charged particles. The observation of high α-particle energies close to E_{α}^{max} indicates the transfer of almost all the input incident-ion energy to the ^{4}He nucleus. This can lead to a non-equilibrium emission of α-particles in contrast to the low energy component, in which the dissipation of a significant part of the input energy to the internal degrees of freedom of the formed nucleus occurs. The observation of the energetic α-particles can indicate the existence of a two-body formation mechanism in which the α-particle carries away practically all the available energy. In addition, if the α-particle emission is followed by the fusion of the remaining nuclei, the newly formed nucleus will possess high angular momentum. With an increase of the α-particle energy the total excitation energy of the residual nucleus falls fast, while the relative contribution of the rotational energy increases. In particular, at $E_{\alpha} = E_{\alpha}^{max}$ the excitation of the nucleus is

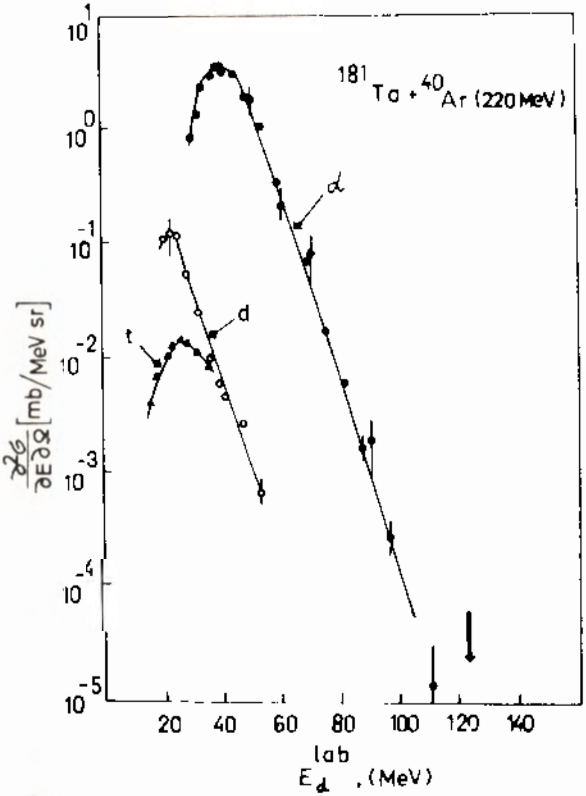

Fig.6. Laboratory energy spectra of tritons, deuterons, and α-particles observed at 0° in the ^{181}Ta + ^{40}Ar reaction at 220 MeV. The thick arrow is as in Fig.1.

determined basically by rotation and this can lead to the formation of fast rotating cold nuclei. We intend to continue our investigations in this direction.

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