JOINT INSTITUTE FOR NUCLEAR RESEARCH, DUBNA

Report No. P7 - 3041

SPECTRA AND ANGULAR DISTRIBUTIONS OF α-PARTICLES FROM THE INTERACTION OF ACCELERATED ^{22}Ne AND ^{40}Ar IONS WITH Au AND Th NUCLEI

by

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Translated at CERN by J. Rice
and revised by N. Mouravieff
(Original : Russian)

(CERN Trans. 68-10)

Geneva
September, 1968

JR/GG
5.3.1968

1. INTRODUCTION

Study of the interaction products of accelerated heavy ions and complex nuclei gives useful information about nuclear systems with high angular momentum, the competition between light particle emission and fission, and boundary interactions occuring without production of a compound nucleus.

So far a number of papers have been published dealing with the study of spectra and angular distributions of α-particles and protons produced in reactions between complex nuclei[1-7], and also the study of spectra and angular distributions of neutrons[8]. As is shown in these papers the most essential role in such reactions is played by two types of processes.

First, processes occuring with production of a compound nucleus due to the total fusion of two nuclei. Such processes predominate at small impact parameters and the behaviour of the compound nucleus can be satisfactorily described in terms of statistical theory. Secondly, direct processes occuring with slightly larger impact parameters. Such processes are characterised by the strong interaction of the surface of the colliding nuclei, both the incident nucleus and the target nucleus apparently being excited. However, the excitation energy of the target nucleus is considerably lower than that of the compound nucleus. The incident nucleus which can obtain an excitation energy of 10 - 100 MeV then emits light charged particles mainly in the forward semi-sphere, since it retains a considerable part of the initial momentum. At such energies, relatively light C^{12} and O^{16} incident nuclei in the majority of cases disintegrate completely, into α-particles[9].

Therefore, there is a definite interest in studying such processes with heavier bombarding nuclei, e.g. Ne^{22} and Ar^{40} which cannot be considered as a combination of weakly connected α-particles.

Analysis of the experimental data obtained shows that the contribution of direct processes is increased in the region of the heaviest target nuclei, where the competing fission of the compound nucleus and the high Coulomb barrier lead to reduction of the probability of evaporation of the charged particles.

Experiments to study the spectra and angular distributions of light charged particles in reactions between the heaviest nuclei are of particular interest also in connection with the problem of obtaining new transuranium elements, since they give information about the behaviour of compound nuclei with $Z > 100$.

2. EXPERIMENTAL TECHNIQUE

The experiments to study spectra and angular distributions of light charged particles ($Z < 2$) from the interaction of accelerated Ne^{22} ions with Au and Th nuclei and Ar^{40} ions with Th nuclei, were carried out on the internal beam of the JINR U-300 cyclotron. The experimental layout used is shown in figure 1.

The accelerated ions pass through a 3-6 mu aluminium foil which screens the ion collector from the effects of the RF field.

The ion collector directly behind the foil was used for adjustment and reference measurements of the ion flux. Internally, this set-up is in free communication with the cyclotron vacuum.

In the centre of the collector, there was a gap with a diameter of 3 mm through which the ions passed into the collimating system and then hit the target of experimental material, mounted at an angle of 45° to the beam. The Th target was 1-2 mu thick and the Au 4.5.mu.

200 and 400 mu, type Ya-2 nuclear emulsions were used as charged particle detectors.

Since the angular distributions of light charged particles in this type of reaction have a sharp maximum at small angles, the photosensitive layers in the forward semi-sphere were placed at distances of up to 65 mm and at an angle of 10° to the direction of the centre of the target (figure 1). In the rear semi-sphere the detectors were placed at an angle of 15° to the direction of the centre of the target. Such a lay-out of the nuclear emulsions guaranteed that sufficiently detailed information was obtained about the spectra of light charged particles at angles between 10 and 150° in each individual experiment.

To decrease the background formed by X-rays and γ-rays the nuclear emulsion holder was protected by a 2 mu layer of lead.

Normal exposure of the target was carried out at an ion current of 0.02-0.03 micro-ampere and the exposure time was five minutes.

After irradiation in the U-300 cyclotron the type Ya-2 nuclear emulsions were developed in amidol developer using the under-development technique. The composition of the developer used was : anhydrous sulphate - 12 g., amidol - 3 g., citric acid - 2 g., distilled water - up to 1 litre. The 400 mu nuclear emulsions were first placed for one hour in distilled water at 5°C, then they were soaked for an hour in amidol developer at 2-3°C diluted with water in the proportion 1:2.

Warm developing in a 1:5 dilution of developer at 20°C lasted for thirty minutes. After fixing and rinsing, the emulsions were dried in a solution of alcohol and glycerine. The emulsion layers were reduced to the original size and stuck on glass backing plates.

The development processes used guaranteed visual discrimination of α-particle and proton tracks, for lengths between 50 and 1000 μ. Elastic and inelastic heavy ion scattering was also recorded in the nuclear emulsions. The ion tracks had a typical conical shape narrowing at the end of the mean free path and were easily distinguished from the α-particle tracks.

For scanning 630-1350 x magnification was used. Tracks were chosen which began at the surface, coincided with the direction of the particles scattered elastically within the limits $\pm 5^{\circ}$, and finished in the emulsion layer.

The length of the horizontal projection and the penetration depths of the track were measured, and the range and the angle at which the particles entered the emulsion were determined by means of a nomograph.

Since it was in practice difficult to guarantee the exact arrangement of the nuclear emulsions at angles of 10° or 15° to the direction of the centre of the target, the distributions of the measured angles at which the particles entered were plotted at intervals of 2°. By such a process it was possible to determine the real angles at which the photo-emulsions were arranged and consequently the geometrical efficiency for each individual photographic plate.

The stopping power of type Ya-2 emulsion was calibrated according to the mean free path of ThC and ThC' α-particles and also according to the recoil protons from 14.1 MeV neutrons. These experiments showed that the stopping power of type Ya-2 emulsion and of Ilford emulsion coincided to within 3%.

In the present experiments the energy of the accelerated ions and the cross-section of the reactions with emission of light charged particles were determined according to the elastically scattered heavy ions. For this purpose the spectra of the elastically scattered ions were measured and their number determined in units of area for several emulsions placed at angles of $10\text{-}50^{\circ}$ to the beam.

Figure 2 shows the spectrum of Ne^{22} ions elastically scattered in a Th target at an angle of 30°.

As can be seen from this figure the spectrum of Ne^{22} ions has a sharp maximum and its half-width does not exceed 8 MeV. Measurements of ion energy carried out earlier[10)] with the aid of nuclear emulsions showed a good agreement with the data obtained from semi-conducting detectors.

3. RESULTS OF MEASUREMENTS

In the present experiments the spectra of light particles from the interaction of Ne^{22} ions with Au at 110 and 120 MeV, with Th at 115 and 140 MeV and of Ar^{40} ions with Th nuclei at 240 MeV, were studied. The energy of the bombarding ions was changed by moving the arrangement inside the cyclotron along the radius. The number of a-particles measured at each angle was 100-300. The particle spectra were converted for the centre of mass system of the compound nucleus, and corrections were made for geometry and the passage of short-range particles.

The differential cross-section of reactions with α-particle emission was determined in the following way:

After finding the number of elastically scattered ions in the photographic plates arranged at small angles ranging from 20 to 50°, the elastic scattering cross-section of the ions was calculated according to the Rutherford formula. The cross section of reactions with α-particle emission was calculated from the relationship $\sigma_\alpha = \sigma_R \cdot N_\alpha / N_R$ where N_α and N_R are the number of α-particles and elastically scattered ions per unit of area in the centre-of-mass system. As pointed out in (6) the accuracy of measurement of the cross-section by this method is 10%, however, since the geometrical precision of the arrangement of our cameras was not more than ±3° with relation to the ion beam, the error in the determination of the cross-section is ±30%.

Figure 3 shows the angular distribution of α-particles measured in experiments exposing gold targets to Ne^{22} ions at 110 and 120 MeV.

As shown in Fig. 3 the angular distributions of α-particles have a shape similar to that obtained by Britt and Quinton$^{6)}$ by exposing gold to carbon, nitrogen and oxygen ions.

In the angular distributions components can be distinguished which correspond to direct processes and to α-particle emission from the compound nucleus.

Figure 4 gives the results of experiments to determine the angular distribution of α particle in the Ne^{22} + Th reaction at 115 and 140 MeV and also in the Ar^{40} + Th reaction at 240 MeV.

As follows from Fig. 4 the angular distributions of α-particles at small angles are similar for all reactions and have a much sharper forward direction than in the case of the Ne^{22} + Au interaction.

At angles above 100° in the centre of mass system α-particles emitted from the compound nucleus predominated.

The energy spectra of α-particles in the cms for the reactions Ne^{22} + Au Ne^{22} + Th Ar^{40} + Th at various angles are given in figures 5 - 8. In these spectra components can be distinguished which correspond to direct processes and to decay of the compound nucleus. At angles below 100° shifting of the maxima of the α-spectra with increasing angles is characteristic. In practice this effect is missing in the Ne^{22} + Au reaction but in the Ne^{22} + Th and especially the Ar^{40} + Th interaction it is clearly expressed and has a regular character. At angles above 100° the α-particle spectra in the Ne^{22} + Au, Ne^{22} + Th and Ar^{40} + Th reactions have maxima at energies of 20, 22 - 23 and 24 MeV respectively. It was not possible to measure with a sufficient degree of reliability but indications were obtained that the angular distributions of protons for the reactions Ne^{22} + Au and Ne^{22} + Th are similar to those of α-particles.

The proton spectra obtained for these reactions have a considerably lower energy at the maxima at all angles than the proton spectra from the Ar^{40} + Ag reaction (Fig. 9).

As can be seen from figure 9 the α-particle and proton spectra in the Ar^{40} + Ag reaction have maxima at energies of 16-17 and 8.5 MeV, which is in good agreement with the calculation of the Coulomb barriers in terms of the optical model 11).

However, since in the experiments on the internal beam there is a large background of fast neutrons leading to the appearance of recoil protons in the nuclear emulsions, additional checking of the experiments is necessary in order to obtain reliable measurements of these spectra.

In conclusion, we would point out that none of the published papers give proton spectra for compound nuclei with $Z > 80$.

4. CONSIDERATION OF RESULTS

A. α-particle emission from the compound nucleus.

In the spectra and angular distributions of α-particles from the interaction of accelerated Ne^{22} ions with Au and Th, and of Ar^{40} with Th, components can be clearly distinguished which correspond to direct processes and the decay of the compound nucleus. Evidence for the production of compound nuclei (Ac^{219}, Fm^{254} and 108^{252}) in these reactions is provided by the α-particle spectra at large angles, which have maxima at energies of $\approx$ 20, 22-23 and 24 MeV respectively.

These results satisfactorily agree with the barriers calculated from the optical model 11) which are equal to 21.5, 23.4 and 24.7 MeV respectively.

For these compound nuclei, the main type of decay is fission, evaporation of charged particles being prevented by the large Coulomb barrier.

However, as follows from Fig. 4, evaporation of α-particles from the compound nucleus corresponds to cross-sections exceeding 10 mb for all nuclei considered when the energy range of the particles bombarding the nucleon is 5-6.5 MeV. The decrease in the evaporation cross-section of α-particles from Fm^{254} nucleus when the Ne^{22} energy is changed by

25 MeV is much sharper than that resulting from calculations 12) for the production cross-section of the compound nucleus. A similar calculation was carried out for the C^{12} + Bi reaction 6) for which the evaporation cross-sections of α-particles at carbon ion energies of 126, 105 and 85 MeV are known. For this reaction a much sharper decrease of σ_a is also noticed compared with the production cross-section of the compound nucleus. These results indicate that the evaporation of α-particles apparently occurs mainly at the initial stage of the de-excitation process. According to calculations mentioned out in ref. (12) the mean angular momentum of the 108^{272} nucleus is 110 - 115 h, but anisotropy in the angular distribution of α-particles at large angles could not be detected.

The large evaporation cross-section of α-particles from the compound nucleus 108^{272} which has an excitation energy of around 75 MeV is in contradiction with known systematics, which predict a sharp decrease in the probability of particle evaporation for Z and N nuclei in this region 13).

The extra number of α-particles at large angles, obtained in the reaction may be due to the contribution from ternary fission provided that it exceeds 5 - 6% of σ . However, it would also be necessary to assume that the energy spectrum from the compound nucleus, and that their angular distribution is almost isotropic.

The temperature of the residual nucleus was calculated in a way similar to that given in ref. (6) according to the formula $(N(E_\alpha) \approx E_\alpha \sigma_c (E_\alpha) e^{-E_\alpha/T}$, where E_α is the energy of the emitted α-particle in the cms of the compound nucleus. The temperature of the residual nucleus in this expression is represented in the form $T=[(E^*_\alpha - B_\alpha)/a]^{1/2}$ where a is the density level, E^*_α is the largest energy of the α-particle emission and B_α is the barrier preventing it from penetrating into the residual nucleus.

For the nucleus produced in the Ne^{22} + Au reaction at a neon energy 110 MeV, the temperature T = 1.45 MeV and the density level a = 19 MeV^{-1}.

In the Ne^{22} + Th reaction with 115 and 140 MeV incident particles the two temperatures obtained were 1.5 and 2.1 MeV respectively.

For the nucleus producted in the Ar^{40} + Th reaction the temperature was 2.3 MeV.

It should be noted that the density level obtained for the final nuclei Cf^{250} and 106^{258} is considerably less than that derived from the relationship $a = A/\mathcal{E}$, where $\mathcal{E} \approx 10$ MeV⁶).

B. <u>α-particle emission in direct processes.</u>

The angular distributions of α-particles at angles of 10^o-100^o (figures 3-8) indicate that the contribution from direct process predominates.

According to calculations carried out in ref. 14, purely Coulomb interaction may account for not more than a few percent of the effect at small angles.

Apparently the main contribution is caused by α-particle emission in pick-up, knock-on and disintegration reactions of the incident particle which occur in long-range and grazing interactions.

In ref. 6 a direct reaction mechanism was suggested as a basis for the assumption of α-particle emission with energy roughly equal to the mean energy of the α-particle in the incident nucleus.

Experimental results and theoretical calculations15) support this assumption for light bombarding particles, for example, carbon C^{12}.

However, in our case this assumption is not confirmed. In fact for the Ne^{22} + Th reaction at 115 MeV the maximum of the α-particle spectrum ($\theta_{lab}= 30^o$) is at 26 MeV instead of $\approx$ 21 MeV and for the Ar^{40} + Th reaction at 240 MeV the α-particle energy maximum ($\theta_{lab} = 20^o$) is at 38 MeV instead of 24 MeV.

An important singularity of the α-particle spectra at small angles is the smooth shift of the maximum of their energy distributions in the Ne^{22} + Au reaction (figure 5).

In the case of the Ne^{22} + Th reaction the effect is clearly distinguishable and has a regular character, the energy decreases from 24 MeV (cms of the Fm^{254} nucleus) to about 14 MeV at an angle of 80° (Figs. 6 and 7).

Further decreases in energy at large angles cannot be traced, since the α-particle energy is lower than their detection threshold in the present experiments, which is equal to 8-10 MeV. It should be noted that in spite of great differences in ion energies and reaction cross-sections, in two experiments with Ne^{22} α-particle spectra have maxima at the same energies.

The effect of decrease in energy with increase in angle Θ is most clearly expressed in the Ar^{40} + Th reaction (figure 8). In spite of the fact that the angular distributions of α-particles in Ne^{22} and Ar^{40} interactions with Th are in good agreement (figure 4), when the energies of these ions are 140 and 240 MeV (6.3 and 6 MeV per nucleon), the energy distributions of the α-particles differ sharply.

To obtain additional information about processes not connected with the production of a compound nucleus, calculations were made on the dependence of the probability of α-particle production in direct processes on the classical parameter of the greatest approximation r_{min}.

Such calculations are correct if the α-particles have an energy much greater than the binding energy in the incident nucleus and if they do not interact strongly with the target nucleus 6,16).

Figure 10 shows the results of these calculations for the Ne^{22} + Th, Ar^{40} + Th and N^{14} + Th reactions 7).

As can be seen from the figure, the radii of the greatest approximation, at which maxima of $d\sigma/r_{min}dr_{min}$ for Ne^{22} + Th, and Ar^{40} + Th reactions are observed are 15.0×10^{-13} cm and 15.5×10^{-13} cm respectively, i.e. they slightly exceed the sum of the radii of the interacting nuclei ($r_0 = 1.5 \times 10^{-13}$ cm) which are equal to 13.4×10^{-13} and 14.4×10^{-13} cm respectively.

A similar result was obtained for the Ne^{22} + Au reaction. It should be noted that for the N^{14} + Th reaction the value $r_{min} = 11.5 \times 10^{-13}$ cm is slightly less than the sum of the radii of nitrogen and thorium.

In ref. 6 values of $r_{min} < r_0 (A_1^{1/3} + A_2^{1/3})$ were also obtained for the interaction of N^{14} and O^{16} ions with Au and Bi nuclei. In C + Au, Bi reactions the radius of the greatest approximation was equal to the sum of the radii of the interacting nuclei.

In this way the following results obtained are in contradiction to the hypothesis of Britt and Quinton$^{6)}$ concerning the emission of an α-particle from the incident nucleus with mean energy and momentum matching its contribution.

1. The energy spectra at small angles have maxima at energies higher than the mean kinetic energy of the α-particle in the incident nucleus.

2. There is no shifting of the maxima of the α-particle spectra when the energy of the Ne^{22} ion is altered by 25 MeV in the experiment with thorium.

3. In experiments with Ne^{22} and Ar^{40} at 140 and 240 MeV (corresponding to 25 and 24 MeV per α-particle) the α-particle spectra at small angles are shifted by almost 10 MeV.

4. According to calculations carried out as in refs. 6, 16, the probability of α-particle production in direct processes in the interaction of Ne^{22} and Ar^{40} ions with heavy nuclei reaches a maximum at distances r_{min} which exceed the sum of the radii of the interacting

nuclei, unlike the reactions N^{14} + Th, C^{12}, N^{14}, O^{16}, + Au, Bi, where the calculated r_{min} is less than or equal to the sum of the radii of the nuclei.

To explain the emission mechanism of high energy light particles in direct processes, the following hypothesis for the reaction procedure was put forward in reference 17. The incident particle (for example the O^{16} nucleus) undergoes inelastic interaction with the target nucleus and is excited up to an energy of 20-30 MeV. Since the O^{16} nucleus even at such excitation energies has a sufficiently long life 18) it has time to withdraw from the target nucleus to a distance where the Coulomb field is $\approx$ 0.1 E_B, i.e. it obtains the energy $\approx E_B$. If the charged particle is them emitted in the direction of motion, then its energy will increase considerably owing to the kinetic energy of the ion.

This hypothesis explains the appearance of 50 MeV protons in the O^{16} + Au reaction at an ion energy of 167 MeV 19).

However, in our case, the energy distributions of α-particles cannot be fitted to this hypothesis.

In fact, if it is assumed that the argon nucleus excited as a result of interaction with Th attains an energy of 150 MeV owing to Coulomb repulsion, then the energy spectra of α-particles at small angles must have a maximum in the region of $\approx$ 60 MeV. With increase of the angle Θ this maximum must be shifted very quickly into the region of lower α-particle energies.

In our case, the spectra of α-particles at small angles (figure 6-8) have maxima at energies considerably lower than in that model and they are characterised by a gradual shifting of the energy E_{max} with increase of the angle Θ. With regard to the aforementioned, it can be assumed that α-particle emission occurs immediately after interaction when the bombarding nucleus is in the region of the Coulomb field of the target nucleus and its kinetic energy is much less than E_B.

In conclusion, we wish to thank G. N. Flerov corresponding Member of the USSR Academy of Science for his constant attention to this work, and S. M. Polikanov, V. A. Karnaukhov, Yu Ts Oganesyan, V. K. Luk'yanov, and B. N. Kalinkin for their useful discussions.

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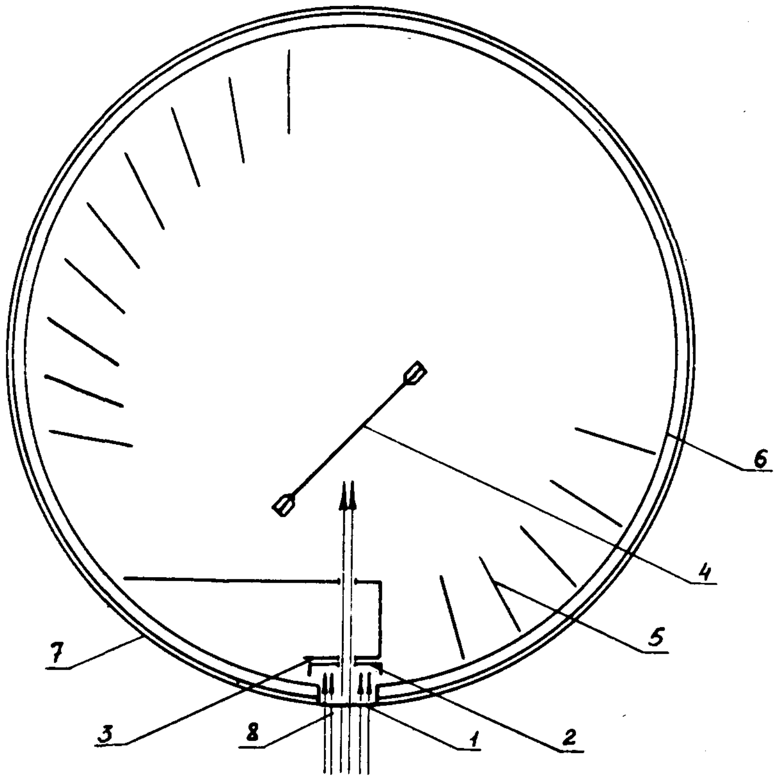

Fig. 1

Diagram of the experimental set-up in the internal beam of the U-300 cyclotron.

1. Aluminium foil across the entrance
2. Tantalum ion collector
3. Collimator
4. Target
5. Nuclear emulsions
6. Lead shielding
7. Copper body
8. Ion beam

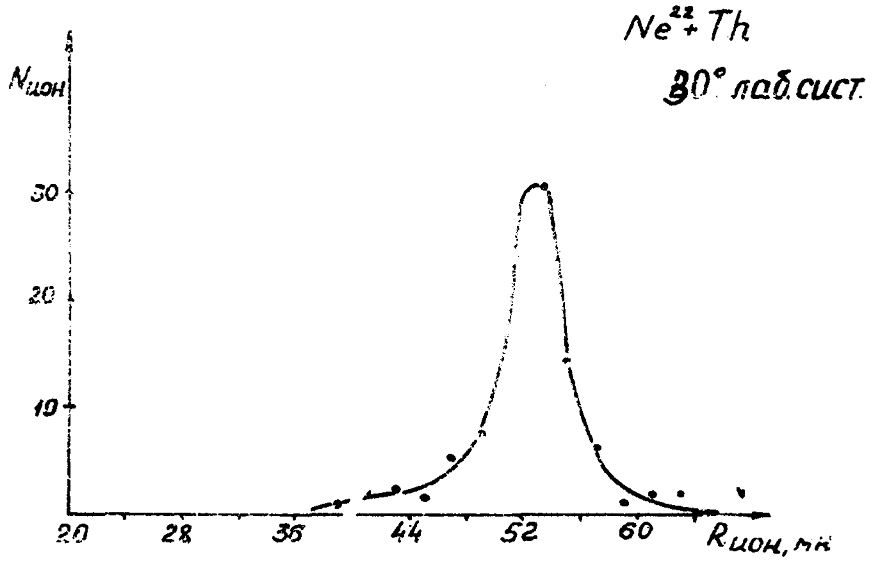

Fig. 2

Spectrum of Ne^{22} ions, elastically scattered by a Th target at an angle of 30°.

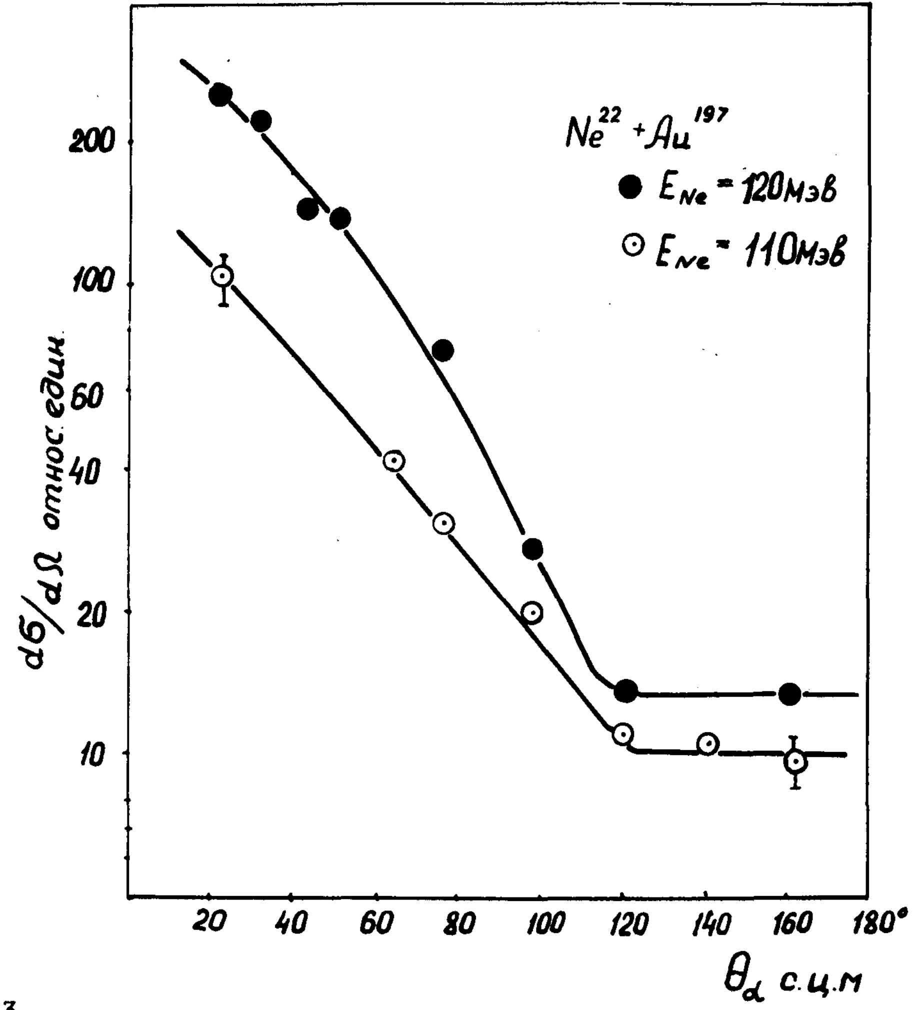

Fig. 3

Angular distributions of α-particles, measured in the Ne^{22} + Au reaction.

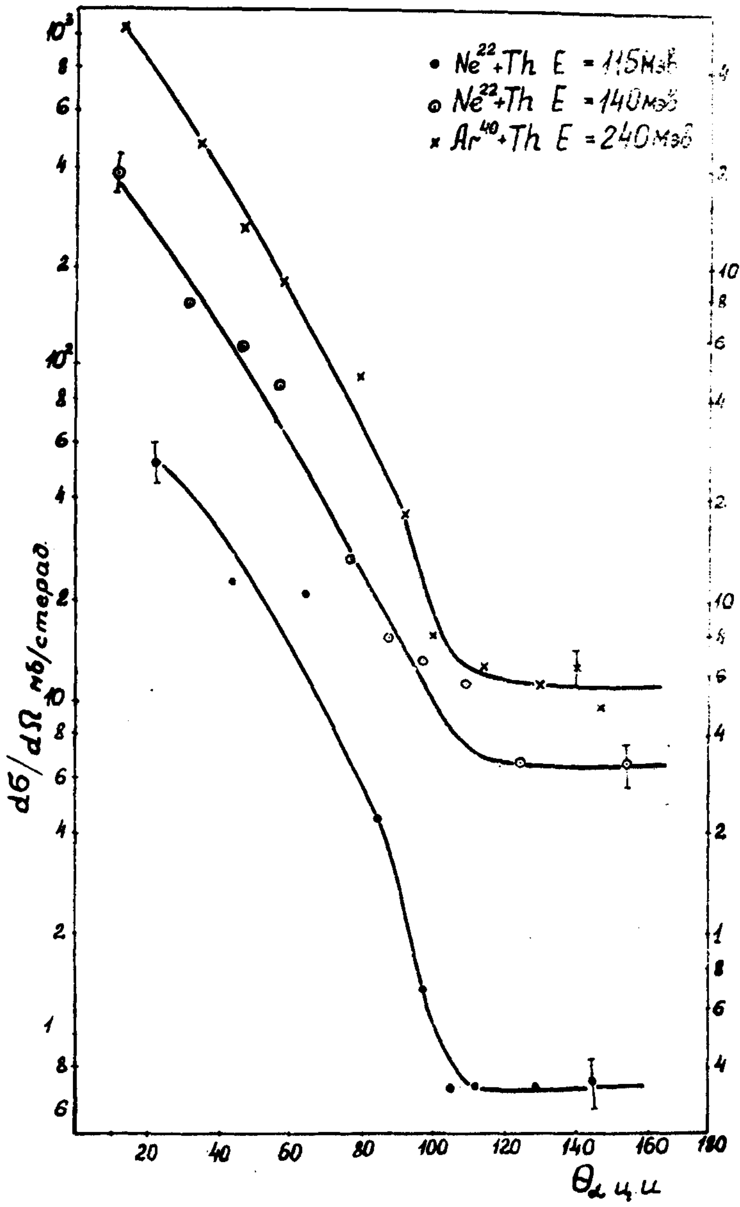

Fig. 4

Angular distributions of α-particles, measured in the Ne^{22} + Th (scale on left) and the Ar^{40} + Th (scale on right) reactions.

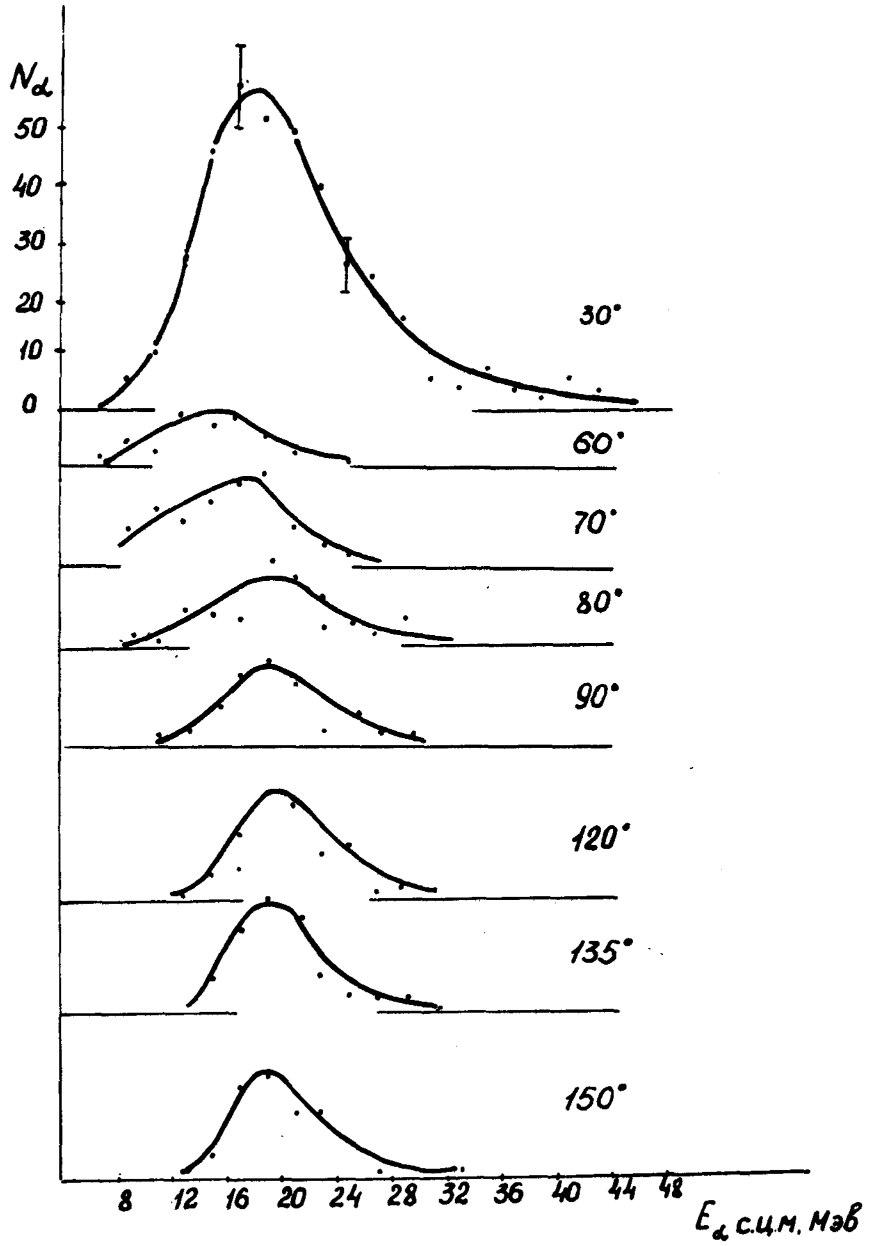

Fig. 5

Energy spectra of α-particles, measured in the Ne^{22} + Au reaction when the energy of the neon ions is 110 MeV.

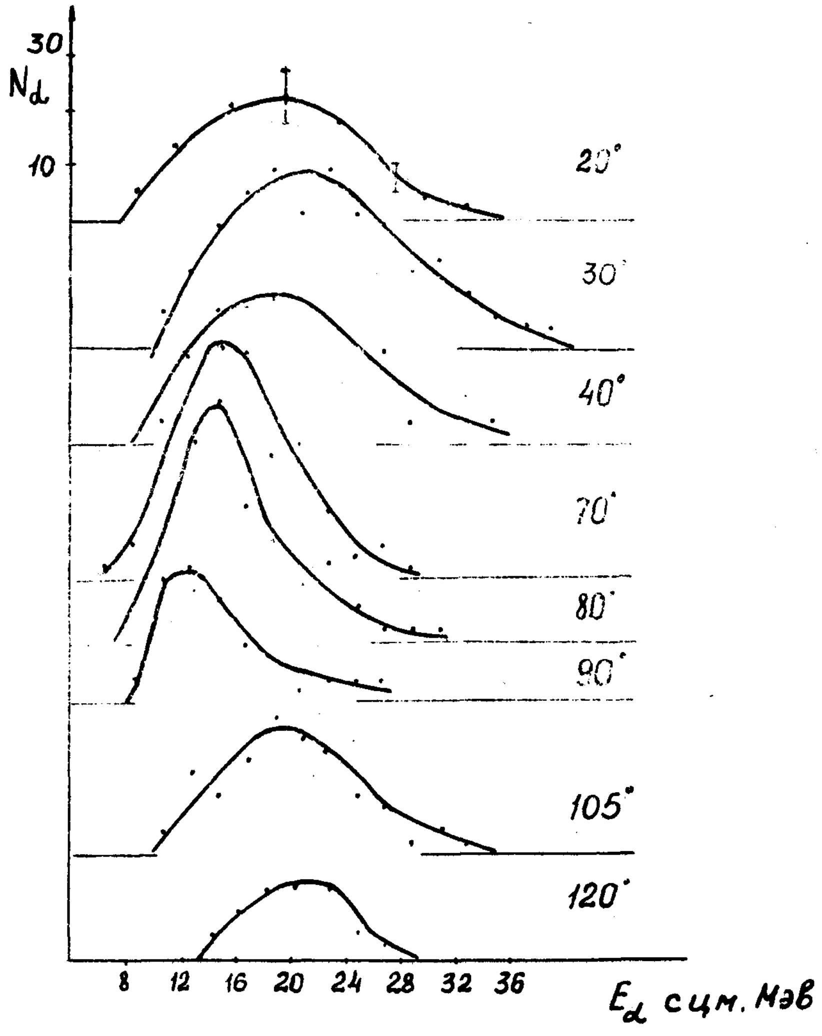

Fig. 6

Energy spectra of α-particles, measured in the Ne^{22} + Th reaction when the energy of the neon ions is 115 MeV.

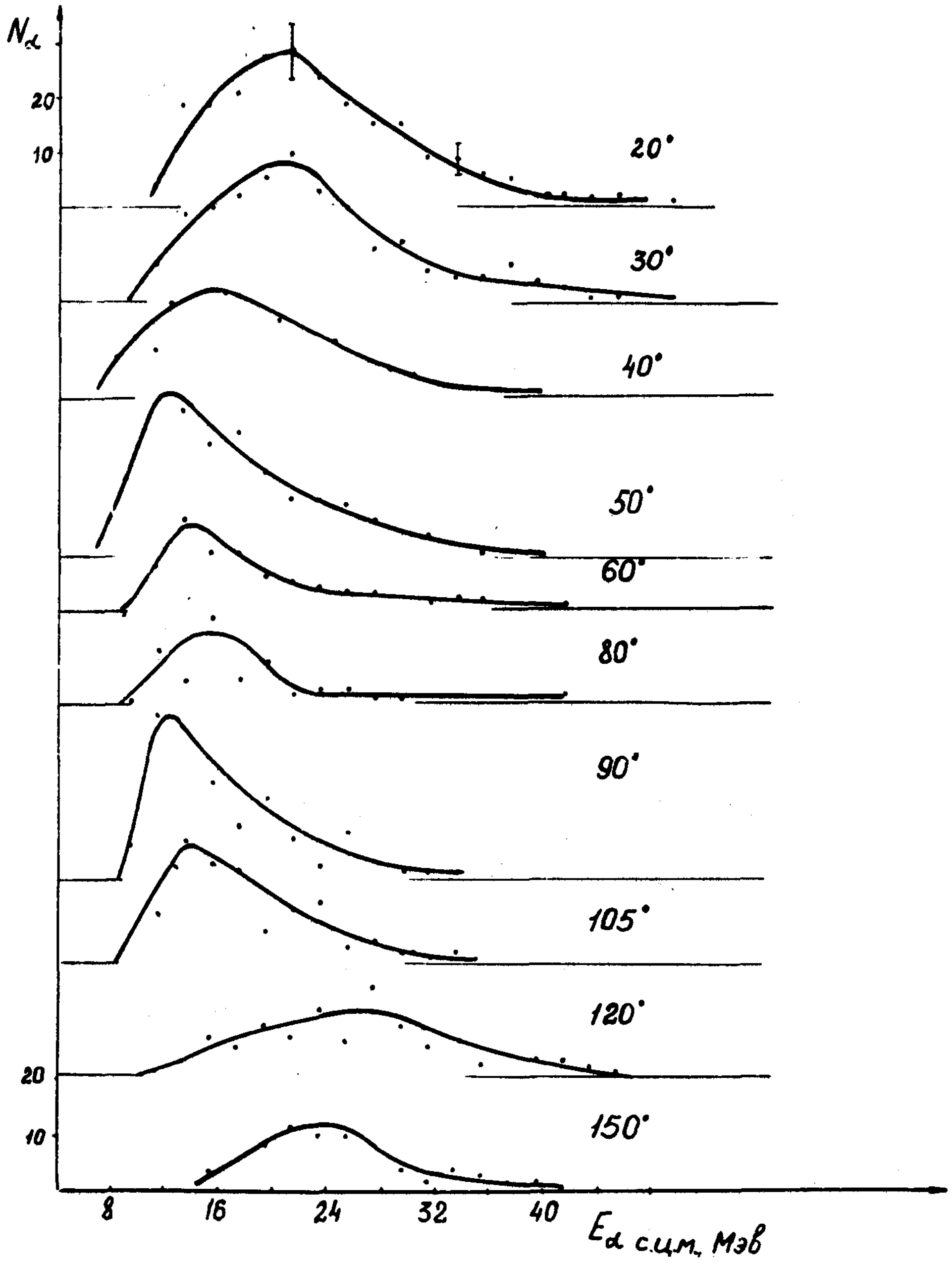

Fig. 7

Energy spectra of α-particles, measured in the Ne^{22} + Th reaction when the energy of the neon ions is 140 MeV.

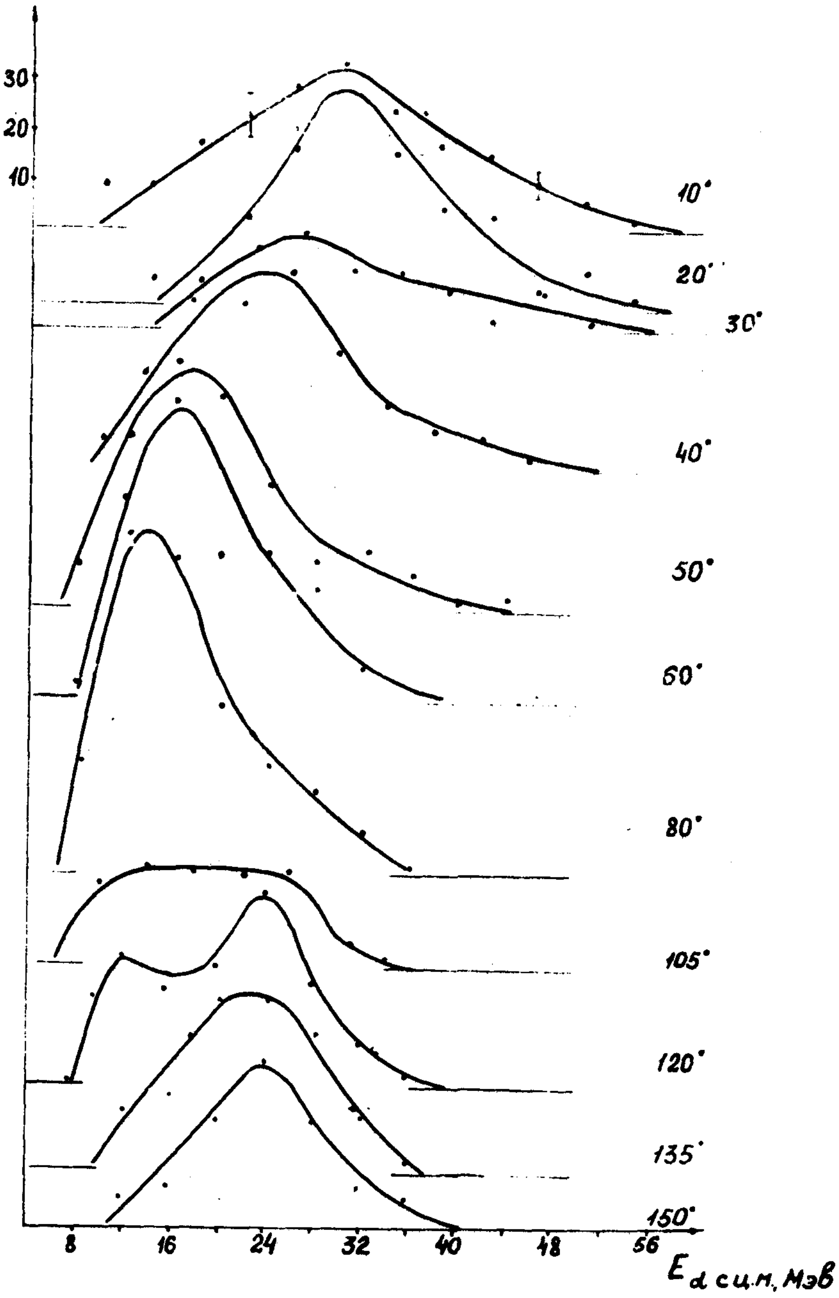

Fig. 8
Energy spectra of α-particles, obtained in the Ar^{40} + Th reaction when the energy of the argon ions is 240 MeV.

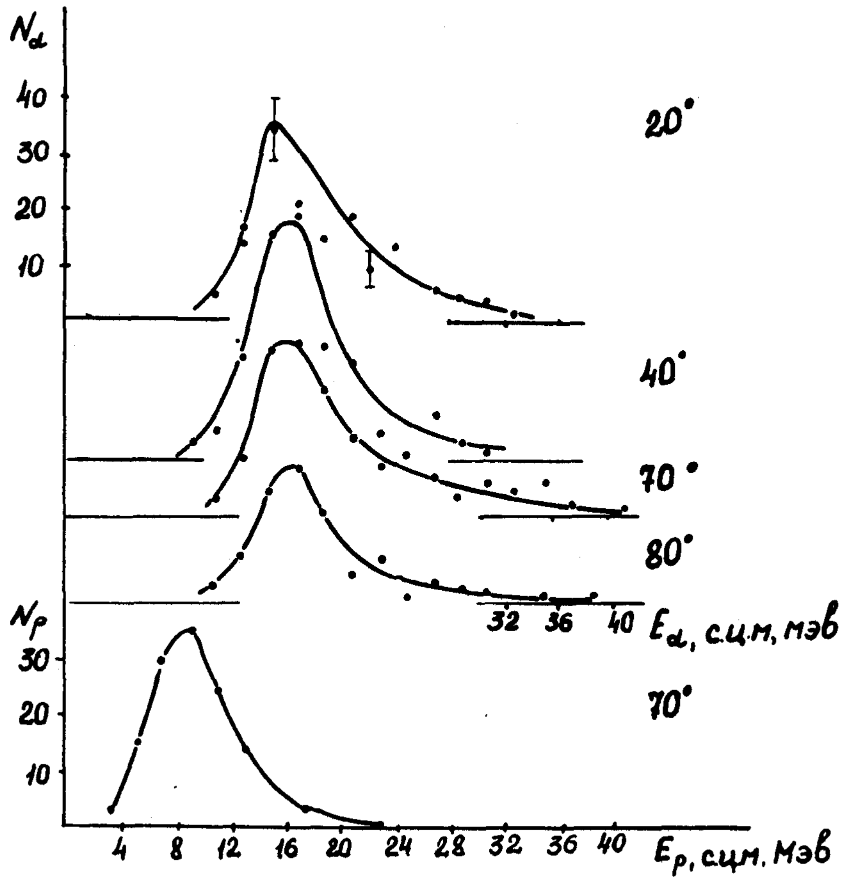

Fig. 9

Energy spectra of α-particles and protons, obtained in the Ar^{40} + Ag reaction when the energy of the argon ions is 165 MeV.

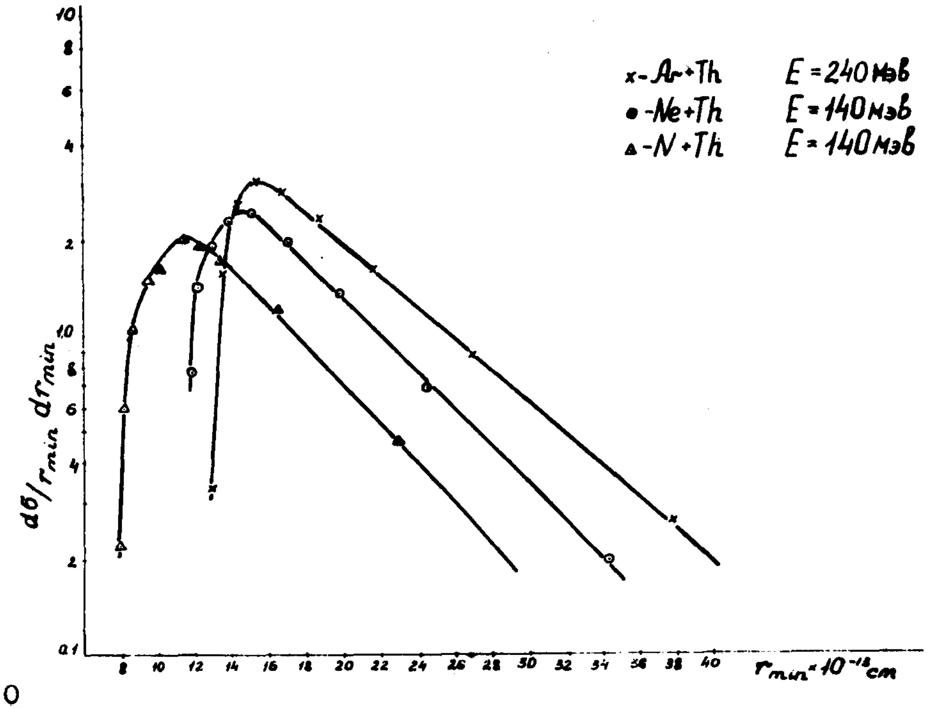

Fig. 10

The probability of α-particle production in direct processes as a function of the classic radius of the greatest approximation during interaction. The value of r_0 is assumed to be 1.5 x 10^{-13}cm.