ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ
ДУБНА

E7-83-440

C.Borcea, E.Gierlik, R.Kalpakchieva,
Nguyen Hoai Chau, Yu.Ts.Oganessian,
T.Pawlat, Yu.E.Penionzhkevich

ANGULAR AND ENERGY DEPENDENCES OF EMISSION PROBABILITY FOR LIGHT PARTICLES IN ^{22}Ne-INDUCED REACTIONS AT 8 MeV/NUCLEON

Submitted to "Nuclear Physics"

1983

1. INTRODUCTION

The mechanism of α particle emission in the interaction of complex nuclei is at present one of the most intensively studied aspects of heavy ion physics. There are some review articles dealing with the experimental data in this field and various theoretical models proposed to explain them /1-5/. Here we shall consider only one, but very interesting, from our point of view, effect which for first time has been observed in our studies of heavy-ion reactions at bombarding energies of 7-10 MeV/nucleon /6/. At these heavy-ion energies α particles with energies of 30 MeV/nucleon and even more /6-8/ were observed in the exit channel at 0° with respect to the beam direction. It has been found that the experimentally measured maximum α particle energy almost amounts to the maximum possible value calculated from the reaction energy balance for a two-body exit channel, i.e., that some kind of a cumulative process is involved in the formation of high energy α particles. The subsequent energy spectra measurements at 0° showed that in all the reactions we have investigated, other light charged particles and nuclei are also emitted with relatively large cross sections ($^{1,2,3}H$, $^{3,4,6,8}He$, $^{6,7,8}Li$, $^{7,9}Be$, etc.) and with velocities several times exceeding that of the bombarding ions. As in the case of α particles, the end-point energy of the spectra of these light charged particles (except ^{8}He) is only a few MeV lower than the maximum possible energy available for a given particle according to the laws of conservation. Thus it is likely that these other particles are produced as a result of some cumulative mechanism of fast particle formation.

An important information on the mechanism of reaction products formation can be obtained on the basis of their angular distributions, as well as from the dependence of their yield on the bombarding energy (excitation functions). The aim of this work is to investigate the angular distributions and excitation functions of light charged particles in the reaction $^{181}Ta + ^{22}Ne$.

2. EXPERIMENTAL SET-UP

Experiments were carried out on an external beam from the 300 cm heavy ion cyclotron of the JINR Laboratory of Nuclear

Reactions. The ^{22}Ne -beam of a maximum energy of 178 MeV bombarded a metallic ^{181}Ta target after passing a collimator system. The target thickness was chosen to be 2.8 mg/cm^2 so as to ensure an energy resolution of the ions, after passing it, not worse than that of the primary beam. The measurement of the energy spectra of light charged particles was performed with the help of a MSP-144-type magnetic spectrometer and a special detecting system placed in its focal plane. The resolution of the spectrometer was $\Delta p/p = 2\cdot10^{-9}$ and the magnetic rigidity $1.0 \le B\rho \le 1.6$ (ref./9/). The magnetic field was measured by means of a Hall-effect detector. The field stability was better than 0.1%.

In the spectrometer focal plane, which is about 1500 mm long, a detector system was placed consisting of 8 pairs of silicon detectors - a ΔE-detector 80 μm thick, and an E-detector 2 mm thick. The position of the telescopes in the focal plane was chosen so as to ensure equal energy intervals between them, determined by the square-law dependence of the particle energy on the radius of its trajectory in the magnet. The given detector system covered 600 mm of the focal plane. This allowed one to measure only a part of the energy spectra at a time, thus ensuring almost equal counting rates of the telescopes. The different parts of the energy spectra were measured simply by varying the magnetic rigidity of the spectrometer. The energy calibration was carried out by measuring the same α particle energy alternately by the different telescopes, this energy being varied with the magnetic rigidity. The absolute detection efficiency of the system was estimated as the ratio of the intensity of all the charge states of the ion beam detected by the telescopes to that registered by the detector serving to monitor the beam and placed at 20° with respect to it. The thus determined inlet solid angle of the spectrometer amounted to $5\cdot10^{-4}$ ar. The magnetic spectrometer could be rotated to stand at different angles with respect to the beam direction, and its position could be determined with an accuracy of 1°. The energy resolution of each ΔE-E telescope was determined by the relation $\Delta E = 2E\Delta R/R$. Here E is the energy of the detected particle, ΔR is the projection of the telescope diameter on the focal plane, and R is the radius corresponding to the telescope position in the focal plane. The energy resolution of the detection system evaluated in this manner was $\Delta E/E \lesssim 2\%$. The value of ΔE was calculated for each telescope separately and was subsequently used to determine the absolute differential cross sections.

Pulses from the ΔE-E telescopes were fed into an electronic circuit consisting of analog and digital devices/10/. After amplification, each pair of pulses from the different telescopes arrived in a multiplexer, which was triggered by a coincidence system in turn triggered by the simultaneous arrival of pulses from the ΔE and E detectors. From the multiplexer, the information having the form of three-digit words (the energy channel numbers of the ΔE and E detectors, and the number of the corresponding telescope) was fed, via a controller, into a SM-3 computer. This registration system provided a counting rate of 10^3 events per second.

In order to study the angular distributions of the most intense parts of the energy spectra measurements were carried out in a reaction chamber in the angular range of 15° to 165°. The light particle energy spectra were measured with a ΔE-E semiconductor telescope consisting of a 40 μm ΔE detector and a 2 mm thick E-detector. The solid angle subtended by the telescope was 10^{-3} sr. The beam was monitored by means of a surface-barrier Si(Au) detector placed at 20° with respect to the incident beam.

The technique used to measure the energy spectra at forward angles allowed one to determine the formation differential cross sections with a sensitivity of up to 10^{-6} mb/MeV sr. This permitted the accurate determination of the cross sections in the region of the end-point energies.

At such cross section values it is rather important to estimate the contribution of light element admixtures in the target, especially the ^{12}C contamination. The determination of light element contaminants in our case was done by studying the scattering of 3 MeV ^{3}H nuclei at an angle of 135° on the Van de Graaf generator EG-5 of the JINR Laboratory of Neutron Physics. The contamination could be estimated up to 10^{-2} at/at. Within the experimental error light element contaminants in the ^{181}Ta -target were not observed. Hence, taking into account the previous data on the yield of α particles from reactions on a ^{12}C-target/8/, a conclusion can be drawn that the contribution of light element contamination of the Ta target to the high energy part of the α particle spectra ($E_\alpha \gtrsim 100$ MeV) does not exceed 10% of the cross section.

3. EXPERIMENTAL RESULTS

Figures 1,2 show the laboratory energy spectra of light particles with $Z = 1$-4, measured with the help of the magnetic spectrometer at different angles. These data show that the intensity of the high energy tails of the spectra increases as the angle of observation is decreased. Moreover, at small angles relatively large cross sections are seen for the particles whose velocities significantly exceed the beam velocity. For example, for the α particles this velocity is twice while for protons even 4 times greater than the velocity of the ^{22}Ne

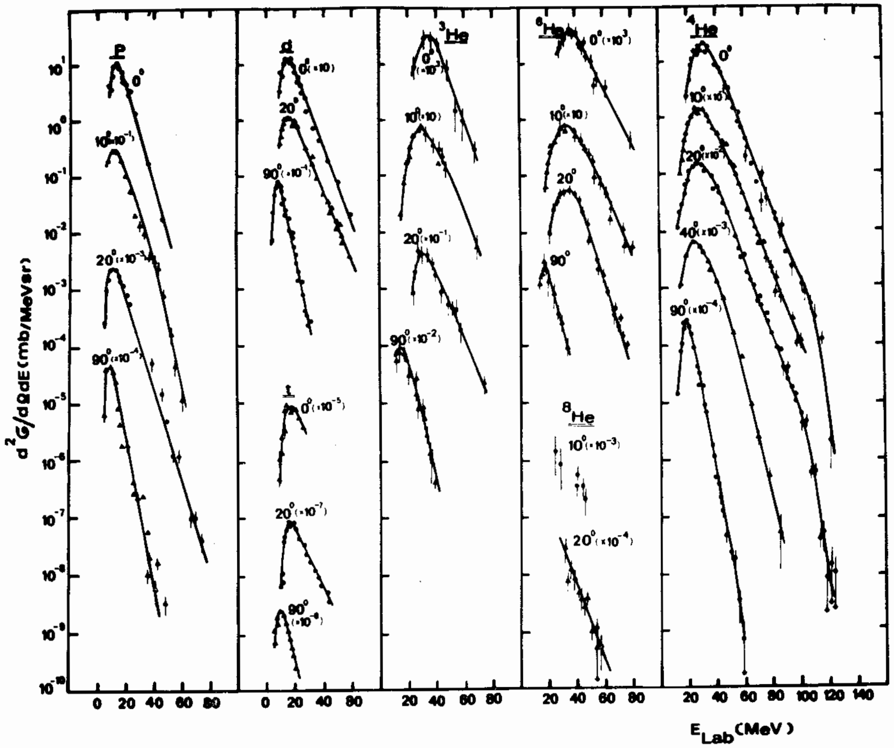

Fig.1. Laboratory energy spectra of p, d, t and He isotopes measured at different angles in the reaction $^{181}Ta + ^{22}Ne$ (178 MeV). The curves are drawn to guide the eye.

beam. The high sensitivity of the experiments described allowed us to measure cross sections which are about seven orders of magnitude lower than the cross section corresponding to the most probable energy. Consequently, it was possible to investigate some features of the spectra close to the respective kinematic limits. In fig.3 one can see the angular dependence of the *a* particle energy spectra, these spectra fairly sharply deviating from the exponential fall at energies of about 80-90 MeV. In addition, in the energy spectra there is a gap between the so-called kinematic limit calculated on the basis of the laws of conservation by assuming a two-body exit channel/8/ (in fig. 3 the kinematic limit is indicated by an arrow on the E_{cm} axis) and the experimentally measured end-point energies. It is noteworthy that at forward angles (0°, 10°, 20°) the measured end-point energy comes nearest to the kinematic limit. However, as the observation angle is increased

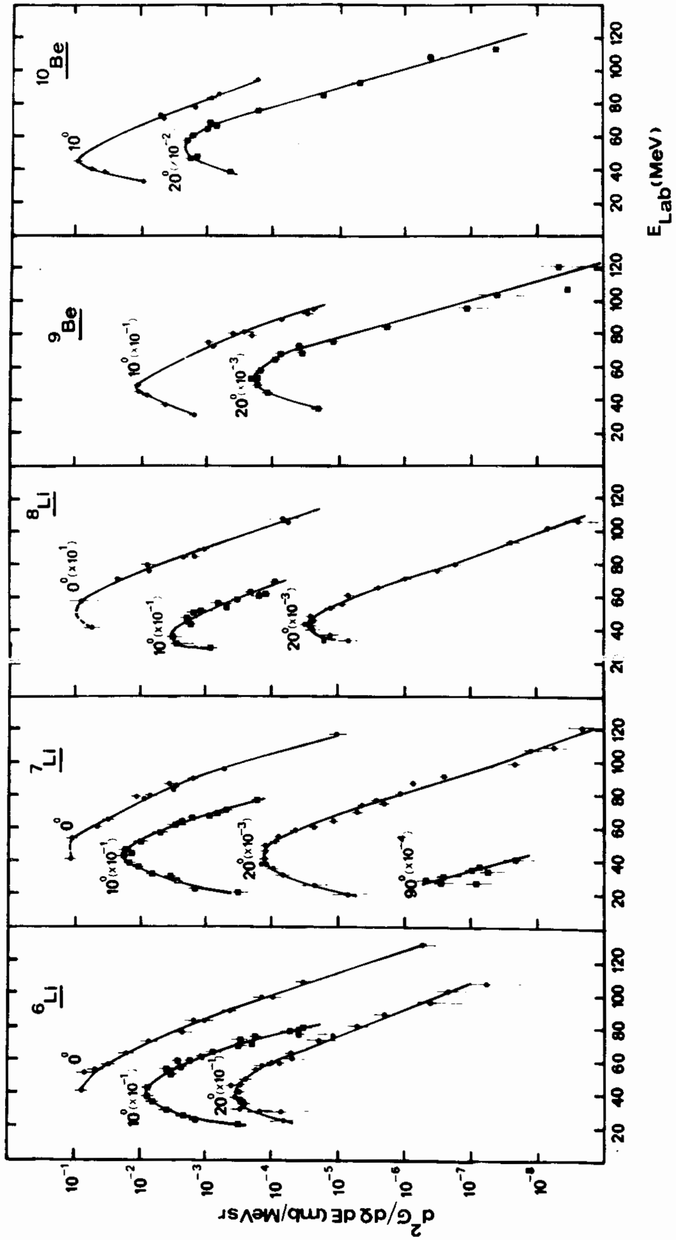

Fig.2. Laboratory energy spectra of Li and Be isotopes, measured at different angles in the reaction $^{181}Ta + ^{22}Ne$ (178 MeV). The curves are drawn to guide the eye.

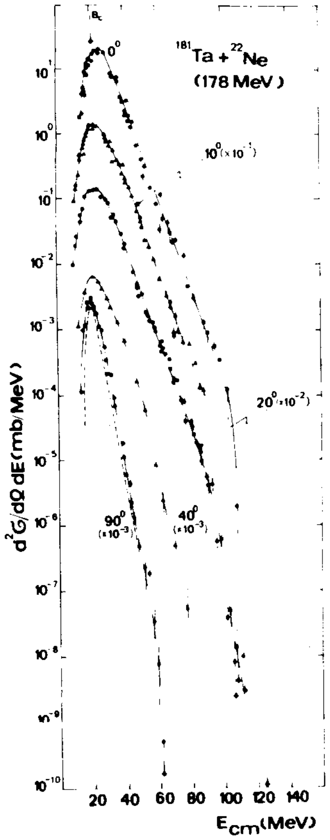

Fig.3. Centre-of-mass α particle energy spectra measured at different angles. The full curves are drawn to guide the eye. The broken line shows the spectrum calculated for an angle of 90° within the model of evaporation from the compound nucleus. The arrow in the upper part of the figure is the exit channel Coulomb barrier B_c. The arrow on the E_{cm}-axis indicates the two-body kinematic limit.

the difference between them significantly increases, too. For example, in the α particle energy spectra at 40° this difference amounts to about 40 MeV, while at 90° it is greater than 60 MeV, (see fig.3). The light particle energy spectrum measured at 90° practically coincides with the evaporation spectrum. As far as the most probable particle energies are concerned, at small angles they are close to the values corresponding to the ion beam energy. However, as the angle is increased, they approach the value of the exit Coulomb barrier. The most probable proton energy measured at forward angles is somewhat lower than the exit Coulomb barrier, as in this case the beam energy (8.1 MeV/nucleon) is below the exit Coulomb barrier (12 MeV).

From comparing the total yields of different isotopes of a given element at the same angle it can be deduced that the isotopes closest to the line of β-stability are formed with the largest cross section. As one goes away from β-stability, the cross section decreases. This fact follows from energy considerations (the Q_{gg} dependence) affecting the probability of a given process.

The angular differential distributions of α particles and protons are shown in figs.4 and 5. As is seen from the figures, the angular distributions for different energy bins behave differently - they are strongly forward peaked for the high-energy part of the spectra.

Figure 6 shows the angular distribution of α particles emitted in the reaction ^{181}Ta(^{22}Ne, α) at 178 MeV beam energy. Using this distribution, the cross section of the

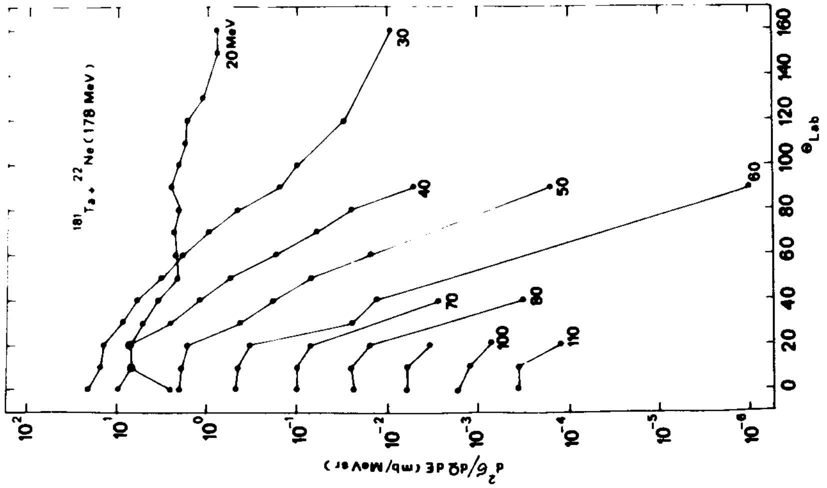

Fig.4. Differential angular distributions for different α particle energy bins.

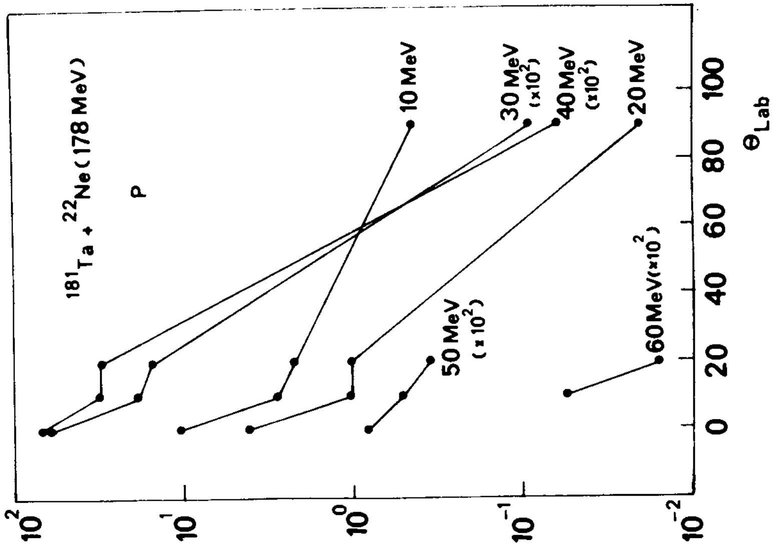

Fig.5. The same as fig.4, for protons.

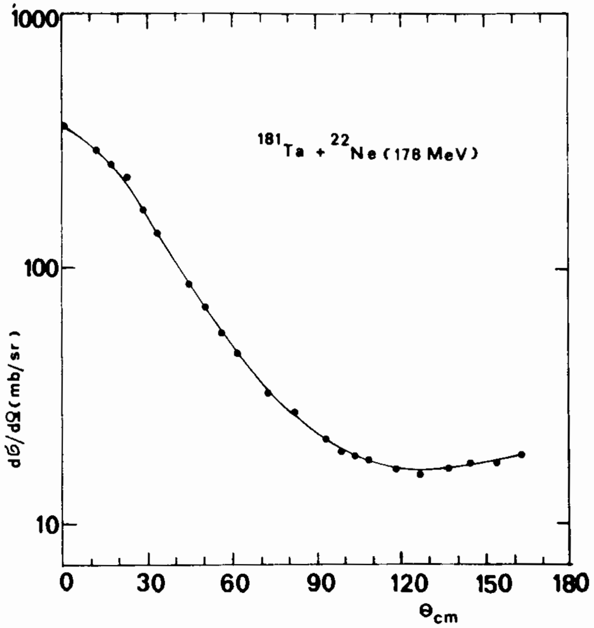

Fig.6. The angular distribution of α particles.

α particles evaporated can be determined. This cross section was estimated to be $\sigma_{\alpha CN} \approx 200$ mb. The total cross section of α particle formation obtained by integrating over the curve of fig.6 amounts to $\sigma_\alpha = 595 \pm 50$ mb. Keeping in mind that the geometrical cross section of the reaction is $\sigma_R = 2000$ mb, it can be concluded that the cross section for the formation of α particles not connected with evapolation from the compound nucleus is about 20% of the total reaction cross section. The angular dependence of the energy spectra can be given in a three-dimensional presentation (N, E_α, θ) using the so-called Wilczynski diagrams /11/. In fig.7, where such a diagram is presented, one can follow the evolution of the α particle energy spectra measured in the reaction ^{181}Ta + ^{22}Ne as a function of the angle. It is seen that the yield of α particles has a maximum value at 0° and, besides, at forward angles their spectrum is the hardest one. The diagram significantly differs from what one could expect for a transfer reaction /12/.

Figure 8 shows the energy spectra of α particles measured at 20° with respect to the beam direction at incident energies of 116, 141 and 178 MeV. As is seen from these data, the α particle yield diminishes with lowering the energy of incident ions. The slope of the high-energy part of the spectrum changes significantly, too. The most probable α particle energy as the

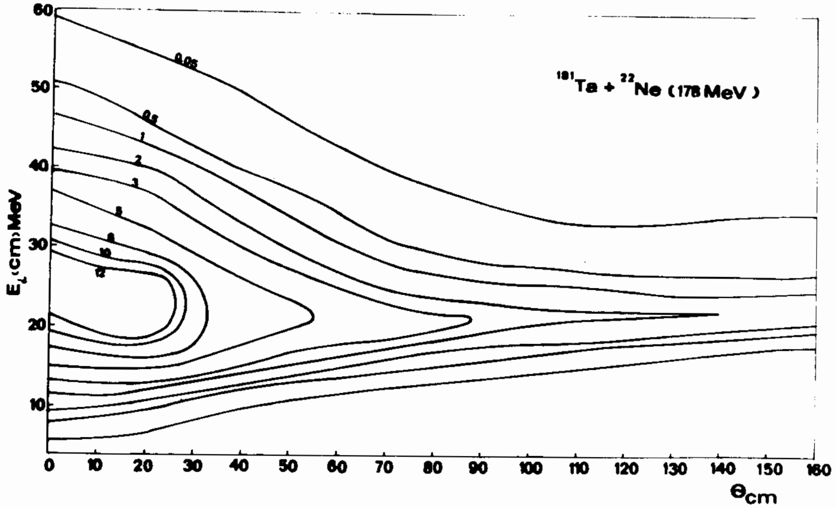

Fig.7. The Wilczynski diagram for the α particle energy spectra measured at different angles. The contours are drawn through equal cross section values.

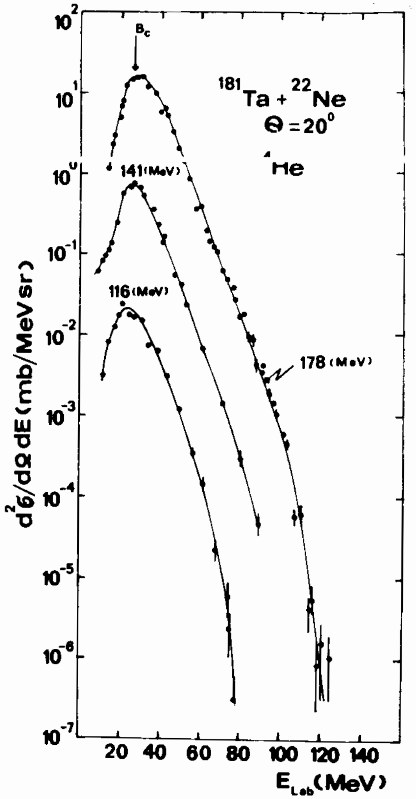

Fig.8. The α particle energy spectra for the reaction ^{181}Ta + + ^{22}Ne measured at 20° with respect to the beam direction at three different ^{22}Ne bombarding energies of 116, 141 and 178 MeV.

bombarding energy decreases approaches the value of the exit channel Coulomb barrier. It is also necessary to note that the particle kinematic limit is approached at the same cross section level irrespective of the bombarding energy.

4. DISCUSSION

A comparison of the experimental light particle energy spectra with the ones calculated in the framework of the evaporation model shows that in all the spectra, measured at forward angles, a significant contribution due to preequilibrium emission can be observed for the bombarding energies used. Even in the case of α particles detected at 90° where the observed spectrum is close to the calculated one (fig.3), the intensity of the high-energy component exceeds the calcullated value. The cross sections of the heavier particles (the isotopes of Li and Be) fall faster with increasing angle than in the case of protons and α particles. Thus at angles greater than 40° particles with $Z > 3$ were not observed in the range of experimental sensitivity of 10^{-33} cm^2/MeV.sr. This implies that these particles are formed solely in a direct process.

As till now there is no unified theoretical description of the light-charged-particle emission mechanism in heavy-ion reactions, we shall try to interpret our data on the basis of the existing models. In our opinion, the most important aspects of the problem of light-charged-particle emission which need a theoretical explanation are the following ones: the determination of the number of the components contributing to the energy spectra (i.e., the number of emission sources), the relative intensity of the emitted particles, their most probable energy, and the behaviour of the cross section in the vicinity of the maximum energy of the ejectiles.

Several theoretical models exist, which are based on the concept of a "particle source" and are used to describe the inclusive spectra/13-17/. In all these models it is assumed that the energy imparted to the composite nuclear system is localized in some region consisting of nucleons belonging to both the projectile and the target. Such a formalism was developed in ref. /15/ where the time dependence of the so-called temperature and that of the "hot spot" velocity was calculated. It seems to us that averaging these quantities over time and taking into account the Coulomb repulsion in the exit channel lead to results which can be obtained in the framework of a model describing particle emission from a single source/16,17/.

In order to elucidate the existence of such a source we drew the velocity diagram by transforming the experimentally measured cross sections $(d^2\sigma/dEs\omega)_{lab}$ into the Lorentz-invariant form $d^2\sigma/pdEd\Omega$. Here $E = p^2/2m$. For simplicity these cross sections are presented as a function of the velocity components parallel and perpendicular to the beam direction, $v_\parallel$ and $v_\perp$ respectively. This kind of presentation of the experimental spectra is shown in fig.9. The analysis of the data of fig.9 shows that the existence of two sources is possible. The velocity of one of them coincides with the centre-of-mass velocity ($v_{CN} =$ 0-0143 c) and refers to the emission of particles at backward angles. The distribution of particles in the forward hemisphere allows one to determine the velocity of the second source equal to $v =$ $=$ 0.053 c. This value is close to half of the projectile velocity after slowing down in the Coulomb field ($v_p \sim$ 0.089c). Thus simple kinematical considerations show that in principle, in the interaction of two complex nuclei, several particle emission sources can exist.

On the other hand, within the framework of the moving source model/17/ the energy spectra at all observation angles can be described by means of an equation including the velocity of the particle source, its temperature, the mass of the particle and the emission angle. Using this formalism we tried to describe our experimental α particle energy spectra. However, in contrast to the results of ref./17/, we have not succeeded in obtaining a satisfactory agreement with the experiment merely assuming a single source. Bearing in mind that at bombarding energies below 10 MeV/nucleon the process of particle evaporation from the composite system plays a significant role, in order to describe the energy spectra we used two emission sources.

The parameters of the first source, describing evaporation from the composite system, were determined in our case by fitting the calculated spectra at backward angles to the experimental ones. The velocity of this source ($v =$ 0.0143c) was taken from the velocity diagram (fig.9). For the same source a temperature was obtained equal to 3 MeV which exceeds by 1 MeV the one expected for the compound nucleus. Taking into account the contribution to the cross section from the second source, whose velocity determined from the Lorentz-invariant cross-section diagram is 0.053c, while the temperature is 4.53 MeV, it can be shown that this contribution decreases with increasing emission angle. This fact is in contradiction to the initial assumptions of the given model about the isotropical emission of particles in the rest frame of the source. The observed decrease of the contribution to the cross section when increasing the angle may indicate the comparatively short lifetime of this source in comparison with the rotational time of the system formed.

An attempt was also made to analyse our data within the framework of the rotating hot spot model /17/. The latter dif-

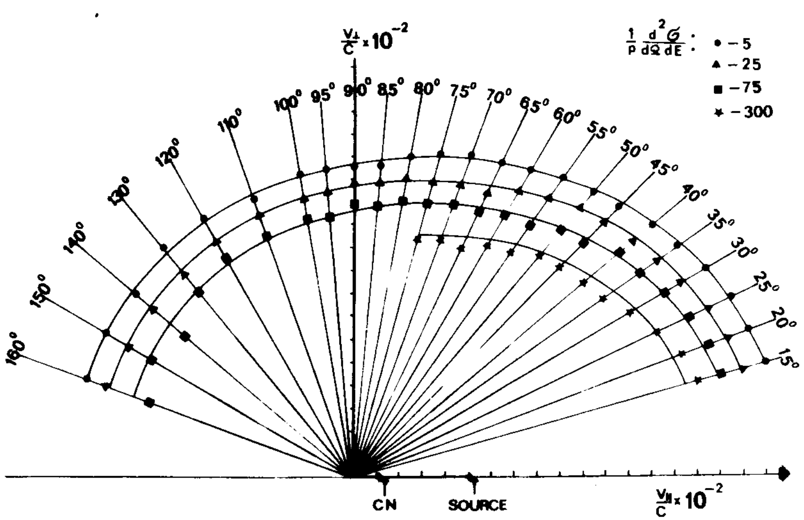

Fig.9. Contour plot of the Lorentz invariant α particle cross section for the reaction ^{181}Ta + ^{22}Ne. $v_\parallel$ and $v_\perp$ are the velocity components parallel and prependicular to the beam direction, respectively. The contours are drawn through equal $\frac{1}{p}\cdot\frac{d^2\sigma}{d\Omega dE}$ values. The velocities of the composite system (v_{CN}) and the source (V_{source}) contributing to the emission of α particles at forward angles are shown on the $v_\parallel$-axis.

fers from the moving source model in that it assumes the temperature to increase as the angle decreases while the source is moving with the velocity of the composite system (0.0143c). However, in order to describe, in this model, the light particle energy spectra quantitatively at different angles it was necessary to assume the "source" velocity to be 0.039c. This high value may imply a summation of the rotational velocity of the system with the recoil velocity. From the angular dependence of the temperature (fig.10) for the emission of α particles the time interval necessary to achieve the equilibrium temperature can be estimated. As is seen from fig.10, the decrease of the "spot" temperature as a function of angle can be fitted by an exponent. In this case, the average value of the rotation angle of the system can be evaluated equal to 40°. On the assumption of a grazing collision the velocity of the heated spot was estimated to be 10^{-21} rad/s. Hence, the lifetime of the heated spot was calculated equal to $7\cdot10^{-22}$ s.

The estimate of the interaction time, or the lifetime of the "source", carried out on the basis of the rotating hot spot model gives quite an approximate, but nevertheless, a sufficient value which allows one to interpret the process of emission of high-energy particles as a fast one. The strong forward peaking of the angular distribution of fast charged particles (figs.4,5) and also the information about the independence of the fast particle emission channels from the subsequent decay of the residual nucleus, obtained in our earlier paper[18] dealing with correlation experiments, also confirm this interpretation of the process taking place in the early stage of the reaction ($t_{int} \sim 10^{-22}$ s). In this case, the process of the formation and emission of high-energy light particles seems to be a direct process which can be interpreted making use of the basic concepts of direct reaction models.

Unfortunately up to now, a strictly quantitative theory of direct reactions, within the framework of distorted waves, has been developed only for the simplest projectiles. However, the existing, mainly qualitative models of direct reactions with heavy ions allow one to make some basic predictions about the characteristics of these nuclear reactions. Models of direct reactions with heavy ions, for the explanation of the formation mechanism of fast charged particles, are presently being developed[4,19,20]. The concept of "massive transfer"[21] has formed the basis for one of these models. In accordance with this model a portion of the projectile is transferred to the target while the rest of it flies on. The development of this approach in ref.[22] was called the "sum-rule" model and showed that the fraction of the projectile is captured by the target nucleus on the condition that the imparted angular momentum does not exceed the critical value of angular momentum for the combination target + the fragment transferred.

Within the framework of this model we calculated the absolute values of the emission cross section of different particles and nuclei. The calculated ratios of these cross sections are equal to the experimental ones. An exception are the values for protons and α particles. The cross section for α particle formation in the reaction ^{181}Ta + ^{22}Ne at 178 MeV bombarding energy was calculated to be 245 mb, taking into account the contribution from the ^{8}Be-breakup. This result is ~150 mb less than the experimental cross section. It seems to us that the observed difference can be explained in the following way. From energy balance considerations it follows that after an α particle is emitted with the most probable energy the residual nucleus has an excitation energy equal to 95 MeV. At this excitation energy the evaporation of α particles from the residual nucleus takes place with high probability. If these α particles evaporated are taken into account it is possible to obtain a better agreement between the calculated and experimental cross section values.

From the calculations done in terms of the "sum-rule" model it also follows that the formation of α particles takes place in a narrow angular momentum window from 65h to 85h with the highest probability at 75h. This means that the given reaction is localized on the surface of the nucleus. Using the estimated values of the angular momentum, and assuming the rigid-body moment of inertia of the composite system, its velocity can be obtained. It is equal to 0.050c, and is in good agreement with the source velocity determined by the diagram of Lorentz-invariant cross sections in fig.9.

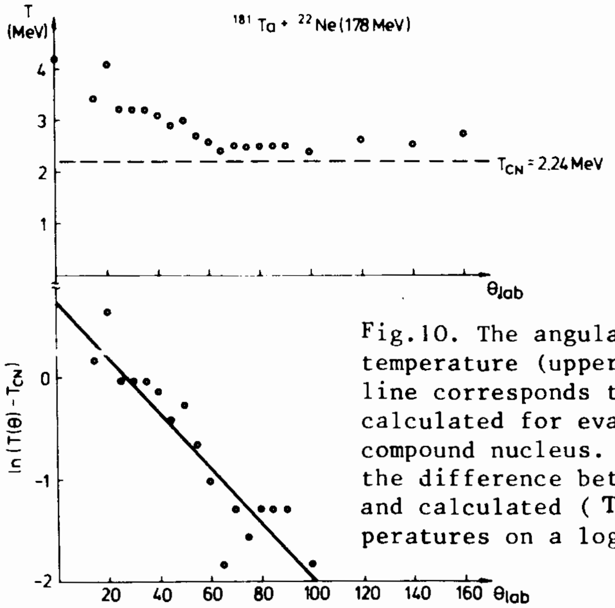

Fig.10. The angular dependence of the temperature (upper part). The broken line corresponds to the temperature calculated for evaporation from the compound nucleus. The lower part shows the difference between the experimental and calculated (T_{CN}= 2.24 MeV) temperatures on a log scale.

In the given approach of the "massive transfer" model it is supposed that the imparted angular momentum is divided between the ejectile and the fragment transferred proportionally to their masses. The same assumption was made by us with respect to the kinetic energy of the bombarding ion. Under this assumption one can define the most probable energy of the ejectile as follows:

$$E_{mp} = E_c(R) + [E_p - V_c(R) - E_s - E_D] \cdot \frac{A_X}{A_p} \cos^2\theta , \qquad (1)$$

where $E_c(R)$ is the Coulomb repulsive energy of the ejectile X at a distance $R = 1.5(A_p^{1/3} + A_t^{1/3})$,
E_p - the centre-of-mass energy of the projectile,
E_s - the separation energy of the ejectile X,
$V_c(R)$ - the energy corresponding to the Coulomb deceleration of the projectile at a distance R,
A_X - the mass of the ejectile
A_p - the mass of projectile,
E_D - the dissipation energy,
θ - the ejectile centre-of-mass emission angle.

Table

A comparison between the experimental most probable energies of the particles emitted in the reaction ^{181}Ta + ^{22}Ne and the calculated ones at a laboratory angle of 20°

Particle	E_{mp} (MeV) Experiment	E_{mp} (MeV) Calculation
p	11±2	12.71
d	16±2	14.65
t	17±2	16.7
^{3}He	32±4	26.0
^{4}He	29±2	30.5
^{6}He	35±4	32.8
^{8}He	33	32
^{6}Li	40±4	40.7
^{7}Li	45±2	43.8
^{8}Li	44±2	42.5
^{9}Li	47	41.2
^{9}Be	54±2	56.8

The values of the most probable energies of the particles emitted in the reaction ^{181}Ta + ^{22}Ne are presented in the Table. It seems to us that in the framework of the model under consideration it is possible to understand the increase in E_{mp} with the isotope mass (see fig.2) and also the decrease in E_{mp} in going from ^{6}He to ^{8}He as being due to increasing separation energy E_s.

The approach being developed at present [4,23], on the basis of the breakup-fusion model, allows one to explain the behaviour of the energy spectra in the vicinity of the kinematic limit. On our part, using the energy and angular momentum balance for a given reaction, we tried to find some qualitative presentations capable of explaining the shape of the spectrum high-energy tail. In fig.11 we present the relation between the energy of the α particles emitted and the angular momentum of the residual nucleus for the reaction ^{181}Ta + ^{22}Ne at the two values of the ^{22}Ne-energy 178 MeV and 116 MeV, on the assumption of a two-body process occurring in a peripheral collision. The region of the emitted α particles is limited, on the one hand, by the yrast band of the residual nucleus (^{199}Tl) and by the curve showing the energy dependence of the maximum angular momentum carried away by the α particle (the so-called in-

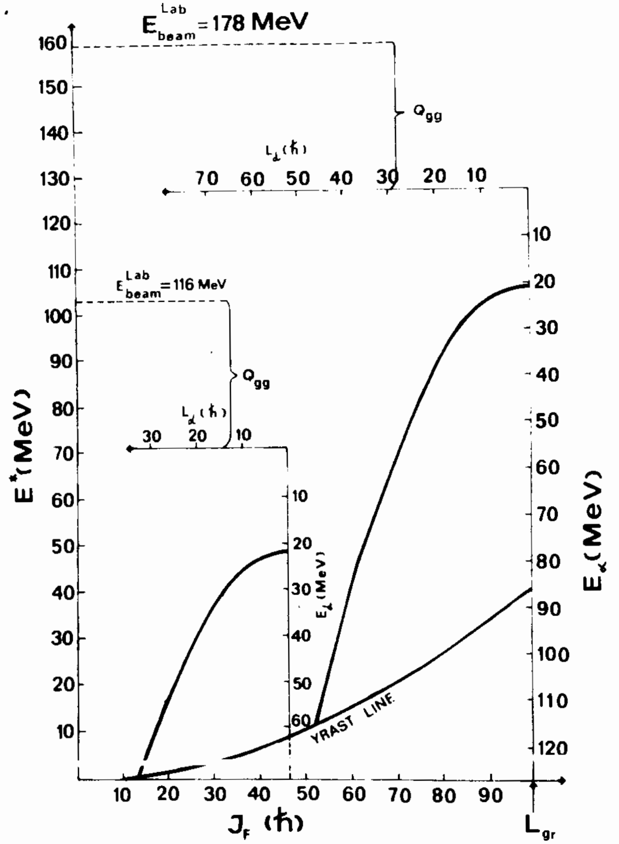

Fig.11. The residual nucleus angular momentum as a function of the energy of the emitted α particle in the reaction $^{181}Ta + ^{22}Ne$ at two energies of the incident beam, 116 and 178 MeV. The calculations are performed for a binary process on the assumption of a peripheral collision. E* is the excitation energy of the residual nucleus ^{199}Tl, l_α is the angular momentum carried away by the α particle, and $Q_{gg} = -31$ MeV. The maximum value of l_α as a function of the α particle energy E_α is presented by the full curve. Shown in the figure is also the yrast line of the nucleus ^{199}Tl.

verse grazing curve), on the other. This dependence is determined by the relation usually used for calculating

As is seen from fig.11, at the ^{22}Ne energy of 178 MeV the curve of inverse grazing crosses the yrast-band one at 115 MeV α particle energy. For this value of the α particle energy,

as was mentioned earlier, a change in the slope of the energy spectrum (see fig.3) has been observed, even though, according to conservation laws, the emission of an α particle having an energy of 125 MeV is possible /7/. A similar analysis for 116 MeV bombarding energy shows that in this case the emission of particle takes place at energies up to the kinematic limit. It is noteworthy that the authors of ref./4/ obtain the same result when using the mathematical recipe of the direct reaction model.

The microscopical approach to the description of α particle spectra, which is presently developed /4,19,20/, is based on the application of the distorted-wave method to the inclusive processes of the projectile break-up and stripping of the heavy fragment, which are studied as direct processes. The quantitative estimates /23/ supported the qualitative explanation of the particle energy spectra given in ref./4/, including the behaviour of these spectra near the kinematic limit.

Using a quasiclassical approximation and simplifying the initial formulae, the authors of ref./4/ obtained, for the cross section of the heavy fragment transfer, a relation containing an additional exponent: $\exp(C_\lambda^2(\theta)/\gamma R)$, where $C_\lambda = L_i - L_f \cos\theta - \lambda$, λ being the angular momentum of the residual nucleus, L_i is the angular momentum brought in by the projectile, and L_f is the angular momentum carried away by the ejectile emitted at an angle θ. This factor reflects, in principle, the angular momentum conservation law. As the total cross section includes the sum over λ, for high excitation energies of the residual nucleus (small E_α's) one can always find such values of λ for which $C_\lambda = 0$ and the corresponding exponent becomes equal to 1. The residual nucleus is formed with greater probability exactly at these values of λ. When E_α increases, however, the residual nucleus excitation energy falls resulting in a decrease in the maximum possible, for this nucleus, angular momentum, which corresponds to the given excitation energy (L_{yrast}). When the values of λ for which C_λ becomes equal to 0 exceed L_{yrast}, $\exp(C_\lambda^2/\gamma R)$ becomes less than 1 (for all possible values of λ) and abruptly decreases with the further increase in E_α. This leads to a change in the slope near the kinematic limit.

It is not difficult to calculate the value of E_α at which this change takes place. This value corresponds to the rotational excitation energy of the residual nucleus

$$E^* = E_{rot} = \frac{h(L_i - L_f\cos\theta)^2}{2J}, \qquad (2)$$

where J is the moment of inertia of this nucleus. The experimental data confirm this behaviour of the calculated spectra (see fig.3). It should be noted that as the observation angle increases, the residual rotational energy, as it follows from eq.2, increases, thus leading to a decrease in the end-point energy of the emitted particle. This also is confirmed by the experiment.

CONCLUSIONS

On the basis of the experimental data obtained and their analysis the following conclusions can be drawn:

1. The interaction between two complex nuclei at bombarding energies of 6-8 MeV/nucleon involves the emission of light charged particles (isotopes of H, He, Li, Be), whose spectrum end-point energies correlate with the kinematic limits calculated for a two-body reaction mechanism.
2. The angular distribution of the light charged particles strongly depends on their energy. The angular distribution of the high-energy particles is strongly forward peaked.
3. In the case of the heavier ejectiles the kinematic limit is reached for higher values of the cross section. A decrease in the bombarding energy does not lead to a decrease in the particle formation cross section at energies close to the kinematic limit.
4. The most probable energies of the particles at forward angles have values close to the energies corresponding to the recoil velocity, and approach the values of the exit Coulomb barriers as the emission angle is increased.
5. The experimental data on the relative formation cross section of the different isotopes and also the values of the most probable energies are described by the massive transfer model[22].
6. The experimental data on the emission of particles with energies close to the maximum possible ones can be qualitatively explained within the framework of the break-up model with the sequential capture of the massive fragment[4,20].

We would like to thank Academician G.N.Flerov for his stimulating interest in the present investigations. We are also indebted to V.E.Bunakov, V.I.Zagrebaev, V.V.Kartavenko, B.I.Pustylnik and Yu.A.Muzychka for fruitful discussions on the experimental data and their analysis. Thanks are also due to Yu.P.Kharitonov and A.V.Rykhlyuk for manufacturing the semiconductor detectors, and to Z.D.Pokrovskaya for her help in data handling.

REFERENCES

1. Betak E., Toneev V.D. Particles and Nuclei v.12, 1981, part 6, p. 1432.
2. Wurm J.P. Proc. Int.Conf. on Nuclear Behaviour at High Angular Momentum, Strasbourg, 1980: in Journ.Phys., 1980, C10, p. 200.
3. Gerschel C. Proc. Int.Conf. on Selected Aspects of Heavy Ion Reactions, Saclay, 3-7 May, 1982, ed. M.Martinot, C.Ngo and P.Gugenberger (North-Holland, Amsterdam 1982), p. 297c.
4. Bunakov V.E., V.I.Zagrebaev V.I. Z.Physik, 1982, A304, p. 231; Bunakov V.E., Zagrebaev V.I. Preprint Leningrad Inst. of Nuclear Physics, 1981, No. 650.
5. Schrödinger W.V. Proc. Int. Symposium on Continuum Spectra of Heavy Ion Reactions, San Antonio, Texas, 1979, ed. T.Tamura (Harwood Academic Publishers, GMbH), p. 19.
6. Gierlik E. et al. Z.Physik, 1980, A295, p. 295.
7. Borcea C. et al. Nucl.Phys., 1981, A351, p. 312.
8. Borcea C. et. al. Nucl.Phys., 1982, A391, p. 520.
9. Maidikov V.Z. et al. Pribory i Tekhnika Eksperimenta, 1979, No. 4, p. 68.
10. Kuinetsov A.N. JINR, 13-81-713, Dubna, 1981.
11. Wilczynski J. Phys.Lett., 1973, 47B, p. 484.
12. Gobbi A., Norenberg W. In: Heavy Ion Collisions, ed. R.Bock (North-Holland, Amsterdam 1980), p. 128.
13. Gottschalk P.A., Westrom M. Nucl.Phys., 1979, A314, p.232.
14. Weiner R., Westrom M. Nucl.Phys., 1977, A286, p. 282.
15. Jolos R.V., Kartavenko V.G. JINR, P4-80-37, Dubna, 1980.
16. Awes T.C. et al. Phys.Rev.Lett., 1980, 45, p. 513.
17. Awes T.C. et al. Phys.Rev., 1982, C25, p. 2361.
18. Gierlik E. et al. Yad.Fiz., 1980, 32, p. 45.
19. Udagawa T., Price D., Tamura T. Phys.Lett., 1982, 116B, p. 311.
20. Christov Chr.V., Petkov I.J., Delchev I.I. Internal Report IC/82/211, Miramare-Trieste, October 1982.
21. Inamura T. et al. Phys.Lett., 1977, 68B, p. 51; Zolnowski D.R. et al. Phys.Rev.Lett., 1978, 41, p. 92;
Yamada H. et al. Phys.Rev.Lett., 1979, 43, p. 605.
22. Wilczynski J. et al. Phys.Rev.Lett., 1980, 54, p. 606.
23. Bunakov V.E., Zagrebaev V.I. In: Abstracts, 33rd Conf. on Nuclear Spectroscopy and Structure of the Nucleus, Moscow, 1983 (Nauka, Leningrad, 1983).
24. Norenberg W., Weidenmuller H.A. Lecture Notes in Physics (Springer Verlag, 1976).

Received by Publishing Department
on June 23, 1983.

WILL YOU FILL BLANK SPACES IN YOUR LIBRARY?

You can receive by post the books listed below. Prices - in US $, including the packing and registered postage

D-12965	The Proceedings of the International School on the Problems of Charged Particle Accelerators for Young Scientists. Minsk, 1979.	8.00
D11-80-13	The Proceedings of the International Conference on Systems and Techniques of Analytical Computing and Their Applications in Theoretical Physics. Dubna, 1979.	8.00
D4-80-271	The Proceedings of the International Symposium on Few Particle Problems in Nuclear Physics. Dubna, 1979.	8.50
D4-80-385	The Proceedings of the International School on Nuclear Structure. Alushta, 1980.	10.00
	Proceedings of the VII All-Union Conference on Charged Particle Accelerators. Dubna, 1980. 2 volumes.	25.00
D4-80-572	N.N.Kolesnikov et al. "The Energies and Half-Lives for the α - and β-Decays of Transfermium Elements"	10.00
D2-81-543	Proceedings of the VI International Conference on the Problems of Quantum Field Theory. Alushta, 1981	9.50
D10,11-81-622	Proceedings of the International Meeting on Problems of Mathematical Simulation in Nuclear Physics Researches. Dubna, 1980	9.00
D1,2-81-728	Proceedings of the VI International Seminar on High Energy Physics Problems. Dubna, 1981.	9.50
D17-81-758	Proceedings of the II International Symposium on Selected Problems in Statistical Mechanics. Dubna, 1981.	15.50
D1,2-82-27	Proceedings of the International Symposium on Polarization Phenomena in High Energy Physics. Dubna, 1981.	9.00
D2-82-568	Proceedings of the Meeting on Investigations in the Field of Relativistic Nuclear Physics. Dubna, 1982	7.50
D9-82-664	Proceedings of the Symposium on the Problems of Collective Methods of Acceleration. Dubna, 1982	9.20
D3,4-82-704	Proceedings of the IV International School on Neutron Physics. Dubna, 1982	12.00

Orders for the above-mentioned books can be sent at the address:
Publishing Department, JINR
Head Post Office, P.O.Box 79 101000 Moscow, USSR

Борча К. и др. E7-83-440
Угловые и энергетические зависимости вероятности испускания легких ядер в реакциях с ионами ^{22}Ne при энергии ≤ 8 МэВ/нуклон

Измерялись энергетические и угловые распределения легких заряженных частиц с $Z = 1-4$ при взаимодействии ионов ^{22}Ne с ядром ^{181}Ta. Продукты реакции анализировались магнитным спектрометром и регистрировались системой из $\Delta E-E$ телескопов. Энергетические спектры легких частиц достигают кинематических пределов для двухтельных реакций с учетом ротационной энергии остаточного ядра. Угловое распределение высокоэнергетических частиц имеет резкую направленность вперед. Полученные данные анализируются с использованием различных моделей: движущегося источника, вращающегося нагретого пятна, массивной передачи, развала с последующим захватом массивного фрагмента. Относительные выходы разных изотопов, а также наиболее вероятные энергии описываются моделью массивной передачи. Качественное поведение спектров вблизи максимально возможных энергий находит объяснение в рамках модели развала с захватом массивного фрагмента.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1983

Borcea C. et al. E7-83-440
Angular and Energy Dependences of Emission Probability for Light Particles in ^{22}Ne-Induced Reactions at 8 MeV/Nucleon

Inclusive energy spectra and angular distributions have been measured for light charged particles with $Z = 1-4$ emitted in the interaction of ^{22}Ne ions with a ^{181}Ta target. The reaction products were analysed and detected by means of a system of $\Delta E-E$ telescopes placed in the focal plane of a magnetic spectrometer. The end-point energies of the light particles correspond to the calculated kinematic limits taking into account the rotational energy of the residual nucleus. The angular distributions of the high-energy particles are strongly forward peaked. The data obtained are analysed on the basis of the moving source, rotating hot spot, massive transfer and breakup-fusion models. The relative yields of the different isotopes and their most probable energies are described by the massive transfer model. The qualitative behaviour of the spectra in the vicinity of the kinematic limits can be explained in terms of the breakup-fusion model.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1983