объединенный
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дубна

E4-82-894

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ANALYSIS OF ALPHA-PARTICLE EMISSION MECHANISMS IN HEAVY-ION INDUCED REACTIONS

Submitted to "ЯФ"

1982

INTRODUCTION

The recent progress in experimental investigation of the heavy ion (HI) induced reactions has stimulated extensive theoretical studies. One of the rapidly growing fields is the study of spectra and angular distributions of light particles (from nucleons to, say, alphas) produced by collisions of HI (up to ^{40}Ar) with medium and heavy nuclei ($A > 100$) at incident energies of about 10 MeV/A (see, e.g., the reviews [1-3]). The most complete data have been acquired for the alpha-particle emission. In these reactions, irrespective of the target-projectile combination, the following common features have been observed: i) The spectra are much harder than those predicted by the compound-nucleus mechanism, and the high-energy edge of the observed alpha-particle spectra practically reaches the two-body kinematical limit, exceeding thus considerably the incident energy per nucleon; ii) The alpha-particles are dominantly emitted in the forward direction; iii) The alpha-particle yield exhausts the considerable part (up to about 50 per cent) of the total reaction cross section.

A considerable theoretical effort has been made to explain the experimental data, and a variety of approaches has been developed and tested (see [3] for an introductory review). Nevertheless, we are still missing a comparative study of different processes and their relative role. We try to fill up this gap in the present work. To do this, we have calculated (often under simplifying assumptions) the alpha-particle inclusive spectra at different angles which come out from the deep-inelastic collisions (DIC), including the emission from the DIC fragments, and also the direct reaction contribution, the pre-equilibrium decay of a composite system as well as the compound nucleus emission.

SCALES OF THE PROCESS

In order to get some insight into the course of a reaction, we have estimated the duration of the phase of the HI approach and that of the HI interaction. The calculations have been done within the frame of the linear response theory [4] adapted by Schmidt et al. [5] and realized in the computer code TRAJEC [6]. The code is written mainly in order to produce various multi-differential cross sections of the HI reactions, and as an op-

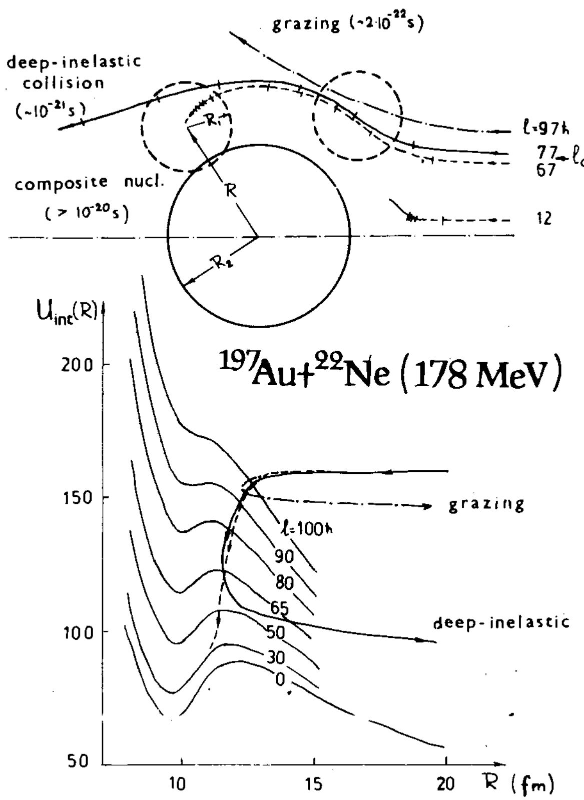


Fig. 1. The trajectory calculations for the $^{22}Ne+^{197}Au$ reaction at 178 MeV. Trajectories with different ℓ values are shown, the dashes on each trajectory denote time intervals of 2×10^{-22} s.

tional output the trajectory as a function of time can be obtained. The program uses the proximity potential in the entrance channel, allows for the fragment deformation in the exit channel, and can supply all required parameters (like friction constants, etc.) when necessary. We have used that program option, because we aimed not to fit some specific feature of a specific reaction, but rather to study a general behaviour of reactions. As an example, we have done the calculations (Fig. 1) for the $^{22}Ne+^{197}Au$ reaction at 178 MeV incident laboratory energy, where probably the most complete experimental information on outgoing alphas and other light ejectiles is available/7,8/. The collisions with

$\ell_{cr} \lesssim \ell \lesssim \ell_{gr}$ proceed rather fast, their time varying from 2×10^{-22} s (at $\ell \simeq \ell_{gr}$) to 10^{-21} s ($\ell \simeq \ell_{cr}$). For smaller impact parameters, a composite system is being formed. The approach phase is rather short (about 5×10^{-22} s), and it is followed by a relatively long existence of a composite nuclear system. Here, the penetration of nuclei is extremely small, and assuming the Fermi distribution of nuclear matter, the overlap volume is of 1.5 nucleons only, nearly independently of the impact parameter. In spite of using the global set of parameters only, as well as of possible fluctuations of trajectory, one cannot rely too much on this number; nevertheless, one can conclude that the overlap of nuclei at energies of about 5 MeV/nucleon above the Coulomb barrier is very small and corresponds only to a few nucleons.This rather a surprising point sharply distinguishes the process from that at slightly higher energies, where nearly complete penetration of nuclei is supposed. As a test between two models of friction the overlap of nuclei at the HI reactions has been studied by Brosa and Gross/9/. From the analysis of the neutron-to-proton ratio they concluded very little overlaps of interacting nuclei, that is in strong support of the validity of our trajectory calculations.

DEEP-INELASTIC COLLISIONS

The mechanism of deep-inelastic collisions (DIC) is probably the most widely used one for the description of HI reactions at not too high energies. It is therefore natural to start our considerations with this type of processes. A pretty spread set of approaches and methods has been developed and is frequently used for calculating the emission of fragments, which are not too far from the initial ion combination (see reviews/10-12/). We benefitted from the use of the TRAJEC code/6/, which is able to produce cross sections $\frac{d^3\sigma}{dE\, d\Theta\, dZ}$, just we need for a comparison with the experimental data. Nevertheless, two changes of the original version of TRAJEC we felt necessary to be included. Firstly, the usual way of statistically independent treating of the energy and mass collective variables leads to the energy conservation law violation for light ejectiles (and we are interested just in the light-particle emission). Secondly, the potential of the system as a function of Z is not well approximated by a second-order polynomial (in the vicinity of the injection point), especially if one tries to go from the projectile (^{22}Ne in our case) as far as to the alphas. This will influence at least the calculated outcome of the isotopes. We assumed that the influence of the real potential on the shape of the differential cross section is of minor significance.

Both the problems can be approximately taken into account by some kind of renormalization[13] : the peak energy in the spectrum is shifted in accord with the ejectile mass and the spectra calculated within the TRAJEC code are normalized to the element yields obtained from the use of the master equations. To see, how good these modifications are, we have calculated the element yields for the $^{22}Ne+{}^{232}Th$ reaction, which is very close to the reaction studied (to our knowledge, there are no data for the $^{22}Ne+{}^{197}Au$ reaction). According to Moretto and co-workers[14], the shell effects are depressed at higher excitations. We have approximately simulated this effect by introducing a factor, which reduces the shell effects in the ground state energies. A reasonable agreement with the experiment was obtained if this factor was put equal to 0.1 (see Fig. 2). The prediction of the element yields based on the master-equation description agrees with the experiment typically within a factor of 2. This is much better than the results obtained from the code TRAJEC itself, where for significant deviation from the input point the predicted yield can easily differ by 3 to 5 orders of magnitude.

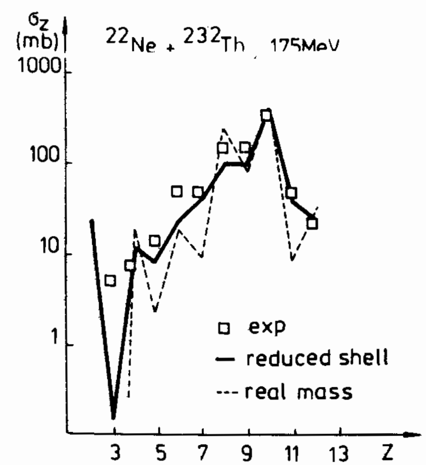


Fig. 2. Experimental (points) and calculated element yields for $^{22}Ne+{}^{232}Th$ at 175 MeV with real masses (dashed) and with reduced shell effects (full line) in the ground-state energies.

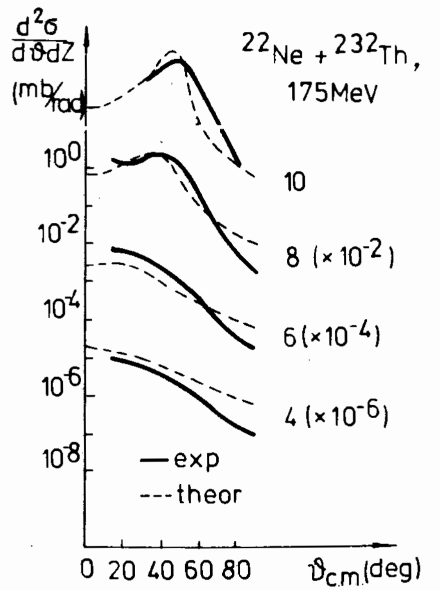


Fig. 3. Calculated (dashed) and experimental (full line) angular distributions of elements (atomic number given at each curve) from the $^{22}Ne+{}^{232}Th$ reaction at 175 MeV.

As a second test, how much one can rely on our DIC calculations, we present in Fig. 3 the angular distributions. Again, as in the previous case, the agreement is quite reasonable.

The fragments resulting from the DIC are generally excited enough to undergo the Fermi break-up (the light fragment) and the de-excitation by a particle evaporation (the heavy one). Both these processes contribute to the production of light particles in HI induced reactions. From the DIC calculations one obtains masses, charges and momenta of the fragments. Subtracting the rotational energy from the maximum energy available, one gets the total excitation energy (the sum of energies of the two fragments). In accord with[15] we assumed the thermal distribution of energy, $E^*_{i,eq} \propto A$, spread by statistical fluctuations

$$P(E^*_i) \sim \exp\left[-\frac{(E^*_i - E^*_{i,eq})^2}{2\sigma^2}\right] \tag{1}$$

with

$$\sigma^2 = 2T^3 a_1 a_2/(a_1+a_2). \tag{2}$$

Here, T is the nuclear temperature and the a's are the level density parameters. These assumptions close the set of parameters which are necessary to start the statistical break-up and/or the evaporation calculations.

ALPHAS FROM DIC AND FROM THE FRAGMENTS

In principle, the mass transfer during DIC can be so great that the incoming ion can become an alpha-particle. The double differential cross section resulting from DIC is given as the sum of such extreme-DIC alphas and those emitted from the DIC excited fragments. The alpha-spectra calculated at three different angles, together with the experimental data[7] are given in Fig. 4. As expected, the evaporation from the DIC fragments contributes only to the lower energy part of the spectrum. The contribution from extreme DIC including the break-up of the light fragments vanishes at higher emission angles ($\Theta \gtrsim 90^o$), leaving only the evaporation component. Fig. 5 presents the element yields as calculated from the (primary) DIC as well as after the emission from DIC products. The shell structure is somewhat smeared out, but for $Z \geq 5$ the element yields are practically uninfluenced by the secondary particle emission.

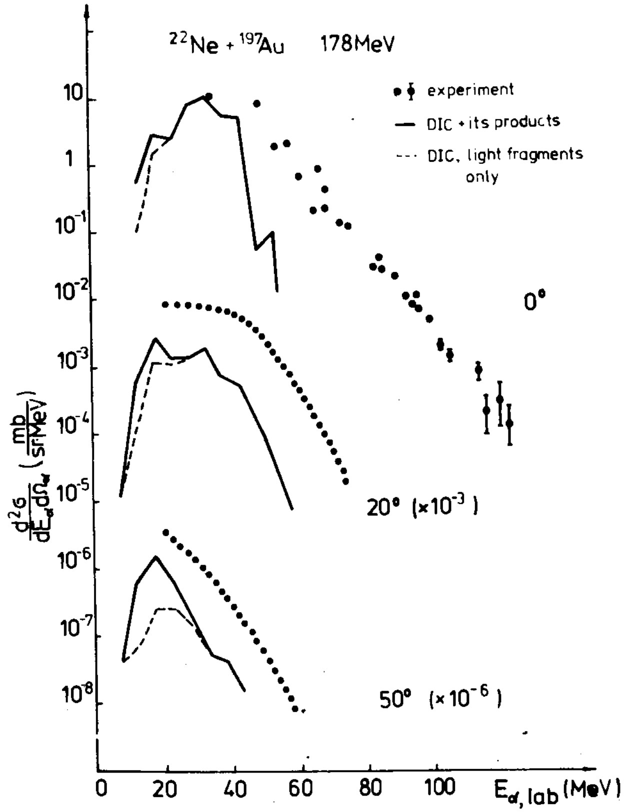


Fig.4. Experimental (dots) and calculated spectra (lines) of alpha-particles from $^{22}Ne+{}^{197}Au$ reaction at 178 MeV at three different angles. The calculation refers to the results of DIC including the alpha-emission from the fragments. The sum of primary alphas and the contribution from light fragments break-up is given by the dashed line, the sum of primary alphas plus the emission both from the light as well as from the heavy fragments is presented in the full line.

COMPOUND NUCLEUS DECAY

The compound nucleus evaporation resulting from HI fusion can be calculated straightforwardly. Obviously, the spectra are extremely soft (see Fig.6), and some harder mechanism is expected to be present, too. A natural generalization of the compound nucleus concept is the pre-equilibrium decay.

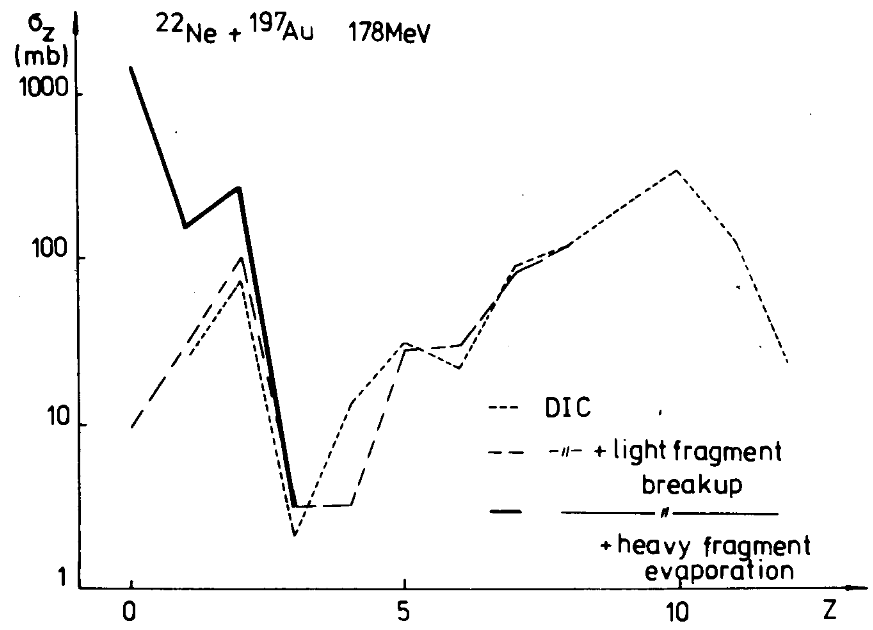


Fig.5. Element yields as calculated for the $^{22}Ne+{}^{197}Au$ reaction at 178 MeV. The primary DIC yields are given by the dotted line, after break-up of light fragments by a dashed one and the resulting yields (including evaporation from heavy fragments) by the full line.

PRE-EQUILIBRIUM EMISSION

In the course of time, many approaches (sometimes called as models) to the pre-equilibrium nuclear reactions have been developed. If we select those applicable to the same excitation energy region, they all speak different languages about the same phenomena. The common feature of these models is the assumption that the initial excitation is shared only by a part of the composite nucleus. The system then evolves towards equilibrium, the particle emission is in principle possible at each step of this development.

Now we shall choose the so-called exciton model, the most transparent one among all of its relatives, for a description of our type of reactions (see, e.g., refs./3,16/ for a review). In the simplest case, the spectrum of emitted particles can be written as

$$\frac{d\sigma}{dE} = \sigma_R \sum_{n=n_0} \tau_n \lambda_c(n,E), \qquad (3)$$

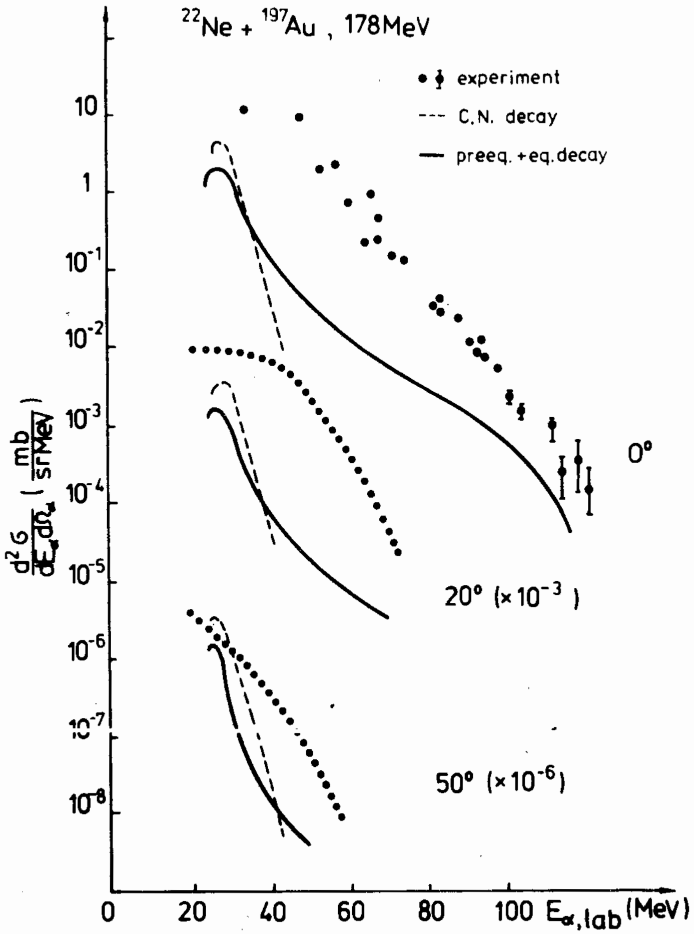


Fig.6. Experimental (dots) and calculated alpha-particle spectra from $^{22}Ne + ^{197}Au$ reaction at 178 MeV. The compound nucleus evaporation is drawn by the dashed line; the pre-equilibrium plus equilibrium emission, by the full line.

where σ_R is the capture cross section; τ_n, the lifetime of the n-exciton state (n being the number of excitons, i.e., the particles above plus the holes below the Fermi level); $\lambda_c(n,E)$, the emission rate of a particle of energy E from the n-exciton state; the summation proceeds from the initial exciton number n_0 in steps of $\Delta n = 2$. With some modifications, the exciton model is capable to describe also the angular distributions, even that for the complex particles[17].

From the trajectory calculations we have seen that the approach phase of two interacting nuclei is rather short. After that, a relatively long period of existence of a composite nuclear system with rather a small overlap occurs. It can be treated as the initial configuration for the pre-equilibrium (exciton) model calculations. The calculated overlap of the two nuclei is only few nucleons, practically independent of ℓ for $0 \leq \ell \leq \ell_{cr}$.

The initial configuration can be estimated from the slope analysis of the high-energy edge of the particle spectrum. Keeping in (3) only the energy-dependent terms and assuming the equidistant-spacing model for the state densities contained in the emission rate (this is without any loss of generality, but it helps to obtain the results in an illustrative form), one has

$$\frac{d\sigma}{dE} \propto E\,\sigma_{inv}(E) \sum_{m=m_0} \left(\frac{U_R}{E^*}\right)^m \qquad (4)$$

with $U_R = E^* - E - B$ being the residual nucleus excitation energy; B, the binding energy of the emitted particle; and σ_{inv}, the cross section for the inverse process. At the high-energy edge only the term with the lowest exciton number is maintained. The value of m is uniquely connected with the exciton number n, $m = n - \Delta_n$. Here, $\Delta_n = 2$ for the nucleons and varies from 2 to 5 for the alphas depending on the model for their emission[18]. The most widely used model for the emission of complex particles[19] is in its spirit able of generalization, and it is implemented within the cascade-exciton model with angular distributions[17] and is used in our calculations. This version gives $\Delta_n = 5$. From the slope analysis we have concluded $m_0 = 3$, i.e., $n_0 = 8$ for our reaction. This is far less than the value stated by Blann[20] or obtained by Billerey et al.[21], who both put approximately equal the initial exciton number with the mass number of the projectile. But the mentioned papers deal with higher energies above the Coulomb barrier, where also the slope analysis produces initial exciton number close to the projectile mass[3,22]. The contribution of the pre-equilibrium plus equilibrium decay to the analyzed reaction is seen from Fig.6. At larger emission angles ($\Theta \gtrsim 90°$) only evaporation plus the pre-equilibrium component (if any) is maintained, so that this region of angles is especially suitable for the test of presence of the pre-equilibrium mechanism.

DIRECT REACTIONS

Though the direct reaction theories applicable to the emission of light particles in the HI reactions can be traced to the end of forties [23], these approaches marked remarkable success only within the last 3 years. Recent papers of Bunakov et al. analyse these reactions within the DWBA description of stripping [24] and knock-out [25] mechanisms, and are able to explain many features of the alpha-particle inclusive spectra. Nevertheless, one cannot extract from these works how important the direct reaction mechanism is, because the results refer only to the shapes of the double differential cross section, and nothing is said about the absolute value. Similarly, the multistep direct reaction theory of Tamura et al. [26] when applied to the HI reactions [27] also leaves a space for other mechanisms as well.

Having in mind the problems of finding the absolute value of cross sections within the direct reaction theories applied to the HI reactions, we dare to simplify the problem and use the PWBA description. Therein, the double-differential break-up cross section may be written (in the laboratory system) in the form [28-30]

$$\frac{d\sigma}{d\Omega\, dE} \sim |\Phi(\vec{p})|^2 m_x \sqrt{2m_x E}\,, \qquad (5)$$

where $\Phi(\vec{p})$ is the cluster wave function, often taken in the form of a Gaussian,

$$|\Phi(\vec{p})|^2 \sim \exp(-\frac{p^2}{2p_c^2}) \qquad (6)$$

with $p = |\vec{p}|$

$$p^2 = p_0^2 + 2m_x E - 2p_0\sqrt{2m_x E}\ \cos\Theta \qquad (7)$$

being the momentum of the emitted particle. Here, p_0 is the introduced momentum and p_c is the width of the cluster impulse distribution. The PWBA was modified so that we have included the real Coulomb trajectory of the incoming HI up to its breaking point. If it occurs at the minimal distance of the interacting nuclei, this angle is $\Theta'_{gr}/2$. The angle Θ'_{gr} was treated as a parameter and we have performed three calculations, namely for $\Theta'_{gr} = 0°$, 20° and 40°. Here, $\Theta'_{gr} = 40°$ coincides with the values of grazing angle for the ^{22}Ne on ^{197}Au reaction as obtained from the trajectory calculations. The formulae (5)-(7) do not predict the absolute value either. In principle, it can be introduced into them and expressed via the spectroscopic factor, or its equivalent, the effective number of clusters; but it is just the problem of normalization of the direct reaction theories, as discussed above. Therefore, we preferred to use the normalization to the "missing part" of the spectrum (after the subtraction of all known processes from the experimental spectra, namely DIC and emission from its products and the pre-equilibrium and compound nucleus decay) and required this "experimental normalization factor" to be independent of angle. Obviously, our procedure may overestimate the importance of the direct reaction mechanism, and therefore the cross sections deduced in this way can serve only as an upper limit. Fitting the observed shapes of the alpha-particle spectra we found $p_c \simeq$ 80-90 MeV/c. This value can be directly compared with the prediction of the abrasion model [31,32], to connect it to the value of Fermi momentum p_F

$$p_c^2 = \frac{A_\alpha (A_p - A_\alpha)}{5(A_p - 1)}\, p_F^2 \ .$$

Here, A_p (A_α) are the mass numbers of the projectile (observed alpha-particle fragment). This procedure gives a value $p_F \simeq$ 90-115 MeV/c. Similarly, assuming a thermal-like excitation of the projectile [32] one has

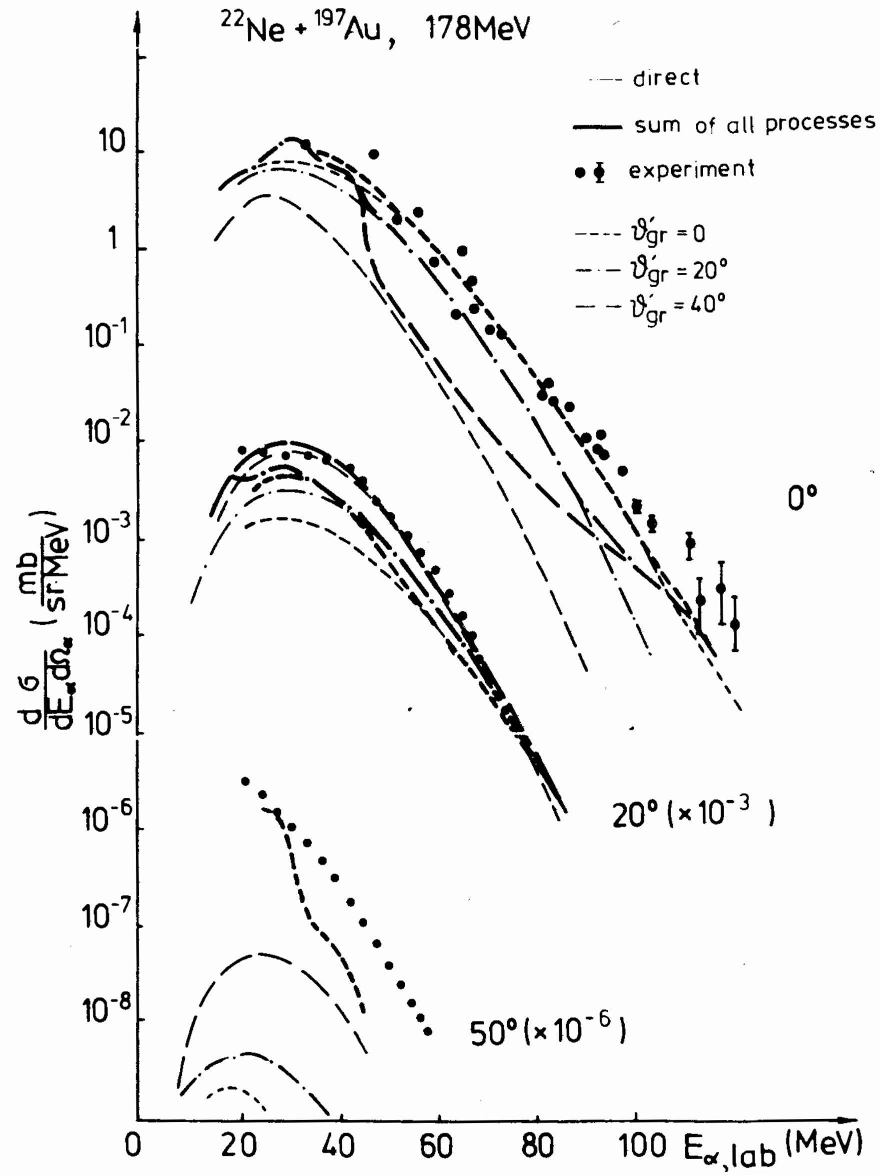
$$T = \frac{A_p}{A_\alpha (A_p - A_\alpha)}\, \frac{p_c^2}{m}$$

(m is the nucleon mass), yielding $T \simeq$ 2-3 MeV. In the limit of low transferred momentum and assuming the oscillator wave function [28,33] an estimate of binding energy B_α of the α-particle within the projectile can be found as $B_\alpha \simeq$ 2.0-2.8 MeV (the real value of $B_\alpha \simeq$ 7 MeV should result in $p_c \simeq 140$ MeV/c). It is interesting to note that our width of the momenta distribution is in surprisingly good agreement with the width of the alpha cluster momentum distribution of Hogan [34] as well as with the radii of the momentum coalescence spheres for different nuclei [35,36].

The importance of the direct mechanism decreases strongly with increasing emission angle (see Fig.7); it might be a dominant process at low angles ($\Theta \lesssim \Theta'_{gr}/2$) and it is negligible at $\Theta \gtrsim 50°$.

DISCUSSION AND CONCLUSIONS

From our analysis one can conclude that the sum of known possible processes of the alpha-particle emission from the HI collisions as tested in the case of the $^{22}Ne + {}^{197}Au$ reaction at 178 MeV does not describe completely the set of experimental data. The character of disagreements indicates the presence of a nonequilibrium or direct-type process, characterized by its contribution to higher energies ($E \simeq$ 50-120 MeV) at the forward



angles, or an importance to include some modification of the existing processes (as is the inclusion of angular momentum into the statistical decay theory /37/ etc.).

Anyway, the majority of features of observed alpha-particle spectra is reproduced (c.f. Fig.7) within the unique approach of calculating the cluster emission of HI reactions. It should

Fig.7. Experimental and calculated alpha-particle spectra from the $^{22}Ne+^{197}Au$ reaction. The experiment is given by dots; the thin lines denote the contribution of direct reactions, and the heavy ones the sum of all calculated processes (i.e., pre-equilibrium plus equilibrium emission, DIC including the emission from the products, and the direct reaction contribution). The dotted line presents pure DWBA calculation ($\Theta'_{gr} = 0$), the dashed one is for $\Theta'_{gr} = \Theta_{gr}$ and the dotted-dashed line stands for the intermediate value of $\Theta'_{gr} = 20°$. At the emission at 50°, the sum of all processes is uninfluenced by the details of the direct reaction estimate (within the precision of the figure).

be emphasized that we did not aim to fit only the data on alpha emission, but rather attempted to reach a reasonable result for other types of clusters as well. The corresponding values of the alpha-particle production cross section (integrated over the angle and the energy), as obtained within our present analysis, are given in the Table. Many processes contribute especially in forward direction ($\Theta \lesssim 20°$) and low energies ($E \lesssim 50$-80MeV), so that in this region it is practically impossible to separate different mechanisms.

Table

Alpha-particle cross sections calculated for $^{22}Ne+^{197}Au$ reaction at 178 MeV (in mb)

Type of decay		Cross section
C.N. decay		12
Pre-eq. decay		54
DIC	primary	73
	light fragm.breakup	34
	heavy fragm. evap.	164
Direct ($\Theta'_{gr} = 20°$)		80

A further investigation of the problem is needed for a better understanding the role of various mechanisms. The following aspects would be especially desirable:

i) Precise measurements in the vicinity of the peak cross section at low angles ($\Theta \simeq 5$-10°) for better determination of the break-up point of the incoming ion.

ii) Measurements of the high-energy part of spectra ($E \gtrsim 50$-80 MeV) for large angles ($\Theta \gtrsim 90°$) can clarify the importance of the pre-equilibrium mechanism, as well as the possible manifestation of friction mechanism of α-particle emission, suggested by Gross and Wilczynski /38/, which is predicted to produce a peak near $\Theta_m \simeq 70°$ ($\Theta_m \approx 90° - \Theta'_{gr}/2$) for our reaction.

iii) Simultaneous analysis of various channels (say, n,p ,...) of the same reaction needs no new assumptions or parameters, as the relative weights of various channels have been fixed within our phenomenological model.

iv) The same is the situation with HI-light particle correlations: here again we do not need any more parameters for such an analysis.

v) For better understanding of the problem also analyses at higher energies (say, to 20 or 50 MeV/A) might be desirable, as they can demonstrate the energetic dependence of the processes involved.

The authors acknowledge the kind help of O.N.Karpov, who generously supplied the code for statistical break-up. We thank Prof. J.Bondorf for the discussions and valuable comments. The contacts with Yu.E.Penionzhkevich and his collaborators helped us with the better understanding of experimental situation.

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Received by Publishing Department
on December 22,1982.

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Анализ механизмов эмиссии α-частиц в реакциях с тяжелыми ионами

На примере реакции $^{22}Ne + ^{197}Au$ при энергии 178 МэВ исследуется роль различных механизмов испускания альфа-частиц в столкновении тяжелых ионов. Дана оценка соответствующих сечений для возможных механизмов эмиссии. Результаты вычислений находятся в разумном согласии с экспериментом, тем не менее небольшое систематическое расхождение указывает на присутствие некоторого нового механизма неравновесного или прямого типа или, возможно, на необходимость модификации уже учтенных процессов. Обсуждаются эксперименты, которые могут облегчить идентификацию вклада основных механизмов реакции.

Работа выполнена в Лаборатории теоретической физики ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1982

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Analysis of Alpha-Particle Emission Mechanisms in Heavy-Ion Induced Reactions

Role of different mechanisms of the alpha-particle emission from heavy-ion induced reactions is studied for the $^{22}Ne + ^{197}Au$ reaction at 178 MeV. The corresponding cross section for possible mechanisms is estimated. The agreement of the calculations and the experiment is reasonable; nevertheless, a slight systematic deviation indicates the presence of some new nonequilibrium or direct-type mechanism, or, possibly, the necessity of modifications of already included processes. Experiments, which can enlighten the undergoing mechanisms, are suggested.

The investigation has been performed at the Laboratory of Theoretical Physics, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1982