DIRECT REACTIONS AND SYNTHESIS OF COLD HEAVY NUCLEI

V.E. Bunakov[1], Yu.E. Penionzhkevich[2]

[1] Petersburg Nuclear Physics Institute, National Research Center Kurchatov Institute, Gatchina, Russia;

[2] Joint Institute for Nuclear Research, Dubna, Russia

The cross-section of the superheavy element's yields produced in collision of heavy ions is extremely small (a few pb).

One of the main reasons for this smallness comes from the fact that the compound nucleus produced in this collision possesses the excitation energy which substantially exceeds its fission barrier and therefore practically immediately performs fission into the two fragments. Moreover, even the meager amount of the surviving superheavy elements immediately starts neutron evaporation and leaves the region of the most stable superheavy isotopes.

We shall consider direct reactions as a possible means to avoid this difficulty.

It was observed long ago that fast alpha-particles emerge in collisions of ^{12}C and ^{14}N ions with the ^{197}Au target which cannot be explained by evaporation from the compound nucleus.

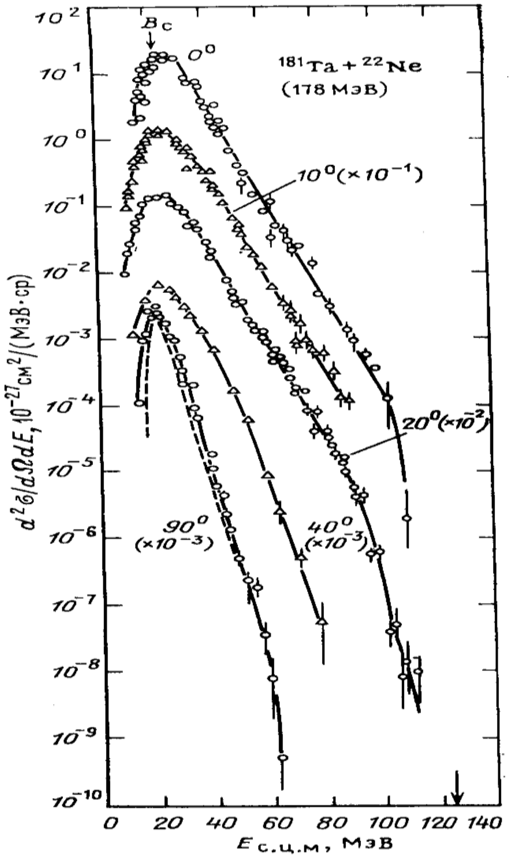
These particles in collisions of the incident ion I=α+t with the target T were shown to appear in coincidence with residual nuclei B=T+t. Those reactions were called "incomplete fusion" or "massive transfer" and described by the semi-empirical models using temperature parameter or by the two-step process of the target break-up with subsequent fusion. The name "fast" was used for any particle which could not be described by evaporation.

In contrast to these works the experimentalists of FLNR at JINR managed to measure the highest-energy part of alpha spectra in collisions of *Ne* and *Ar* projectiles with different targets.

It was a great surprise to find that the most energetic alphas were carrying away practically all the energy E_I of the incident ion and were emitted predominantly in the incident beam direction.

Their energy was closely reaching the two-body kinematical limit of the endothermal reaction

$$E_\alpha^{(2)} = E_I - E_R - Q$$



This also meant that the excitation energy of the final nucleus B was practically zero.

It is obvious that emission of alphas that carry away all the incoming energy and keep memory of the incident beam direction cannot be explained by any model which makes use of temperature (evaporation model, hot moving sources, etc.). This is just a matter of conservation laws. The concept of temperature means energy sharing between many nucleons until a certain equilibrium is reached. To produce a particle out of this state which carries away all the excitation energy one needs to collect this energy back on one particle as a result of collisions. Such an impossible anti-entropy process is never considered in thermodynamics.

To explain the transfer of all the incident energy and momentum to the emerging alpha one needs a special mechanism which can directly connect the entrance and exit channels without any intermediate stages causing the smearing of the initial energy and momentum over the additional degrees of freedom. Such a mechanism is well known as direct nuclear reactions, deuteron stripping (d,p) being the most vivid example. In this reaction deuteron slightly touches the extreme periphery of the target transferring the neutron to it. The proton is usually called as “spectator”, whose role is simply to fulfill the conservation laws by carrying away the excess energy released in reaction and to follow the initial projectile trajectory. This particular feature of stripping is used to place the transferred neutron into the ground or slightly excited states of the residual nucleus. Therefore, the first order Born approximation is used in theory to calculate the probability of the excess energy transfer from the neutron placed into the bound state to the outgoing proton.

No wonder that practically simultaneously with the first experimental results on the extremely fast alphas (Gierlik *et al.*, Z.Phys. **295A**, 295 (1980)) the theoretical explanation of these results appeared (Bunakov *et al.*, Izvestia ANSSSR (ser. fiz.) **44**, 2331 (1980)) in terms of the direct reactions theory. Initially the idea was to consider reaction of the heavy fragment t stripping from the initial ion I=T+t. Plane waves Born approximation and cut-off due to the strong absorption was used to obtain the analytical expressions for the qualitative description of the obtained results. The stripping cross-section was:

$$\frac{d^2\sigma}{d\Omega} \sim \sum_{\lambda} S_I S_f^{\lambda}(E^*)\,|\Phi_I(\mathbf{q})|^2 |\varphi_f^{\lambda}(r_{tT}=R)|^2 \exp\left\{-\frac{C_{\lambda}^2(\theta)}{\gamma R}\right\} \qquad (1)$$

Formfactor $$|\Phi_I(\mathbf{q})|^2 = const\cdot\exp\left\{-\frac{q^2}{2\sigma_\alpha^2}\right\} \quad \text{with } \mathbf{q}=\mathbf{k}_\alpha - \frac{m_\alpha}{m_I}\mathbf{k}_I$$

defines alpha-particle’s momentum distribution in the incident ion I. Spectral maximum when alpha velocity equals the velocity of incident ion – explains characteristic feature mentioned in lots of experimental papers on fast alphas.

$\varphi_f(r_{tT}=R)$ - wave function of the relative motion of the transferred fragment t in the final state of the residual nucleus B=T+t with the angular momentum λ.

$r_{tT}=R\geq R_T+R_I$ -cut-off radius due to strong absorption.

Quasi-classical description of the wave-function in the sub-barrier region of V_{tT} potential (Coulomb + centrifugal):

$$|\varphi_f^{\lambda}(r_{tT}=R)|^2 \sim \exp\left(-aE_\alpha\right) \tag{2}$$

$$a=\sqrt{\frac{\mu_{tT}}{2\hbar^2 V_{tT}(R)}}\cdot(R-R_0),$$ R_0 --internal turning point.

Explains the exponential decrease of the alpha spectrum.

The last factor
$$\exp\left\{-\frac{C_\lambda^2(\theta)}{\gamma R}\right\} \tag{3}$$

with $\gamma = {}^{a}\!/_{(R-R_0)}$ and $C_\lambda(\theta)=L_I-l_\alpha\cos\theta-\lambda$

reflects the angular momentum conservation in reaction.

Incident ion angular momentum L_I connected with k_I by $L_I=k_IR$ in the plane waves approximation or by $L_I=k_IR\{1-{}^{V_I(R)}\!/_{2E_I}\}$ in the eikonal approximation

Alpha angular momentum $l_\alpha=k_\alpha R$, λ - angular momentum of the residual nucleus B .

At zero angle θ the angular momentum conservation $\lambda=L_I-l_\alpha$

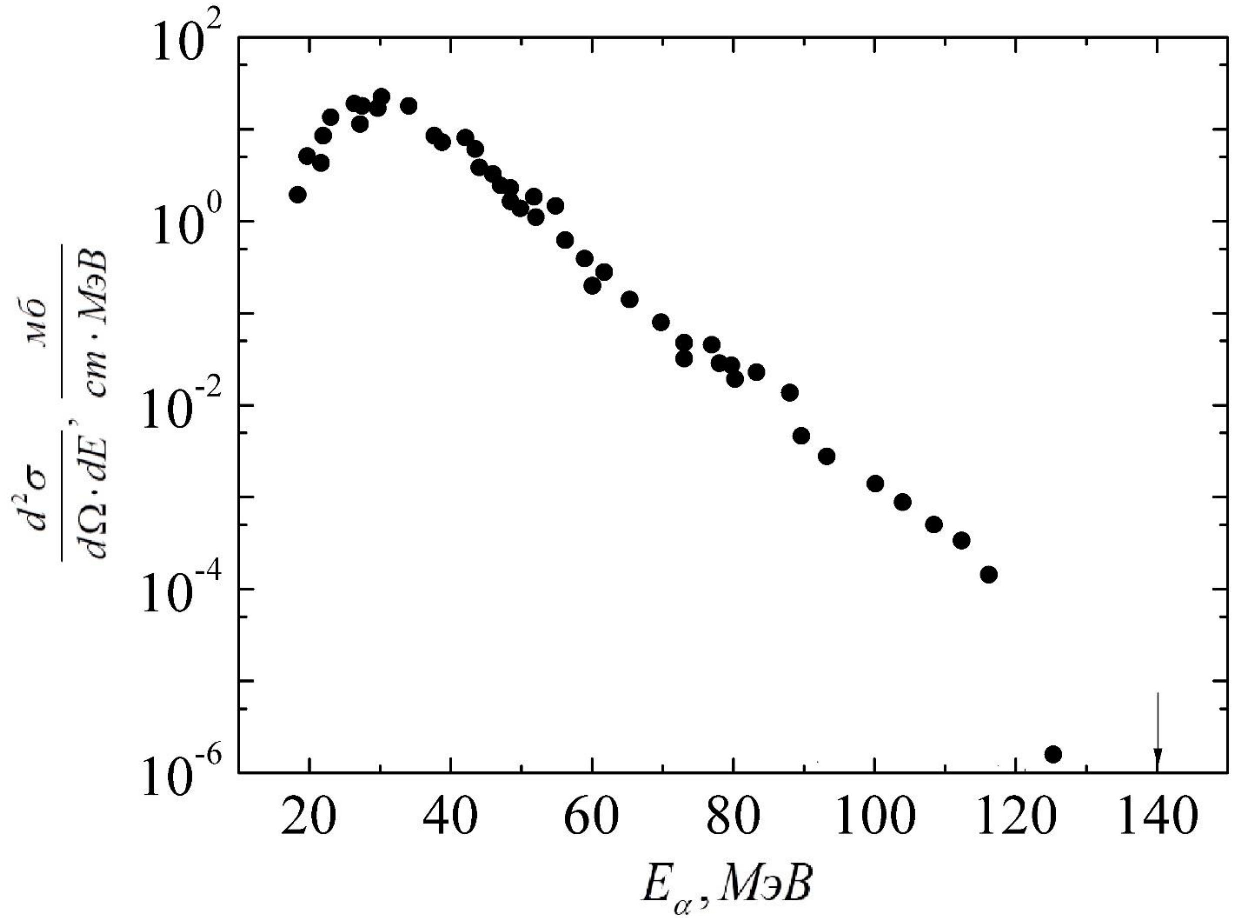
guarantees that the factor (3) equals to unity. For $\theta>0^o$ - exponential decrease.

Explains predominant emission of fast alphas in the beam direction.

Peripherical nature causes large angular moments λ of the residual nucleus. At small excitation energies E^* the nucleus cannot absorb more than $l_{\max}(E^*)$, defined by

$$E^* = \frac{\hbar^2}{2J} l_{\max}^2 \tag{4}$$

Therefore, even at $\theta = 0^o$ the factor (3) causes the additional exponential decrease of the spectrum.



Experimental example: alpha spectrum of $({}^{22}Ne + {}^{181}Ta)$ reaction at 178 MeV.

$E_\alpha^{(2)} = 140$ MeV, Sharp decrease at 125 MeV. Our DWBA estimates shows that near $E_\alpha^{(2)}$

$L_I - l_\alpha \approx 50\hbar$. Assuming the typical value $\hbar^2/2J \approx 6$ KeV for the residual nucleus ${}^{199}Tl$, one obtains the excitation energy

E^*=15 MeV in agreement with the experiment.

It was found later that the yields of the fast (with energies about 100 MeV) alphas depend strongly on the alpha separation energy in the target nuclei.

Then another type of direct reactions was considered, namely **direct knock-on reaction.**

(Bunakov, Zagrebaev, Z. Phys., **304 A**, 232 (1982)).

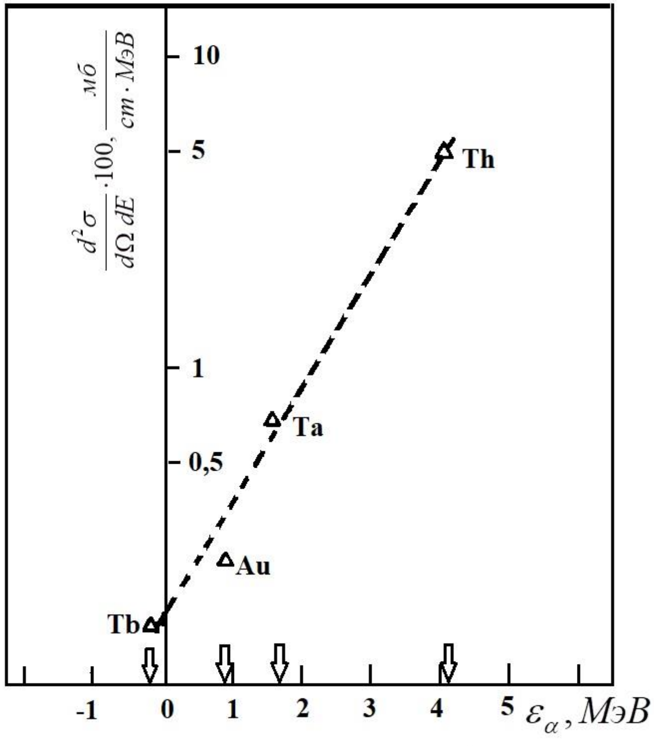
In this process the incident nucleus I substitutes the weakly bound alpha-particle in the periphery of the target and all the excess energy is carried away by this alpha. Mind that it is not the knock-out of alpha in elastic collision when the amount of the transferred energy is limited because of the strong mass inequality $m_I \gg m_\alpha$.

The cross-section of the direct knock-on is almost the same as that of stripping. Only the formfactor $\Phi_I(\mathbf{q})$ is substituted by the wave function $\varphi_i(r_{\alpha C}=R)$ of the alpha-particle at the periphery of the target nucleus in the sub-barrier region of the Coulomb potential V_α.

Therefore, a new factor appears in the cross-section expression:

$$|\varphi_i(r_{\alpha C}=R)|^2 \sim \exp\left(-b\varepsilon_\alpha\right)$$

where $b=\sqrt{\dfrac{2\mu_{\alpha C}}{\hbar^2 V_\alpha(R)}}\cdot(R-R_{\alpha 0})$, and $R_{\alpha 0}$ is the internal turning point.



Thus, the combination of the two direct processes describes all the experimentally observed characteristics of the fast alpha-particles: **the exponential decrease with increasing alpha energy, which becomes even more marked close to the limiting energy $E_{\alpha}^{(2)}$ and the peak of emission at $\theta = 0^{o}$.**

Recently new experimental studies were done at FNRL of the fast alpha-particles in heavy-ion collisions. The use of the new high resolution magnetic analyzer and detector system allows to measure light particles at the high-energy end of the spectrum whose yield is about $10^{-6} \div 10^{-8}$ of the yield at maximum. This allowed to observe alpha spectra in the vicinity of the two-body kinematic limit $E_{\alpha}^{(2)}$ for reactions $^{181}Ta(^{48}Ca,\alpha)^{225}Pa$, $^{197}Au(^{48}Ca,\alpha)^{241}Bk$, $^{181}Ta(^{56}Fe,\alpha)^{233}Bk$, $^{238}U(^{48}Ca,\alpha)^{282}Ds$, $^{238}U(^{56}Fe,\alpha)^{290}Lv$.

Most amazing in these experiments was that in the majority of reactions **alpha particles were observed with energies exceeding the kinematic limit $E_{\alpha}^{(2)}$.** In the previous experiments, especially in the accurately studied case of $^{181}Ta(^{22}Ne,\alpha)^{199}Tl$ reaction no particles were observed beyond the two-body limit. The same was true in the case of $^{181}Ta(^{48}Ca,\alpha)^{225}Pa$.

Observation of alphas beyond the two-body limit means that the residual nucleus B **decays in the course of the direct reaction.**

In attempts to find why Tl and Pa nuclei cannot decay during the reaction while the heavier ones Bk, Ds и Lv can, one might notice that their fissility parameters differ being 32.9 and 36.8 for the lightest pair and varying between 39.4 and 46.4 for the rest. It seems that fission barriers for Bk, Ds и Lv are so low that **the residual nuclei start to fission already during the direct reaction.**

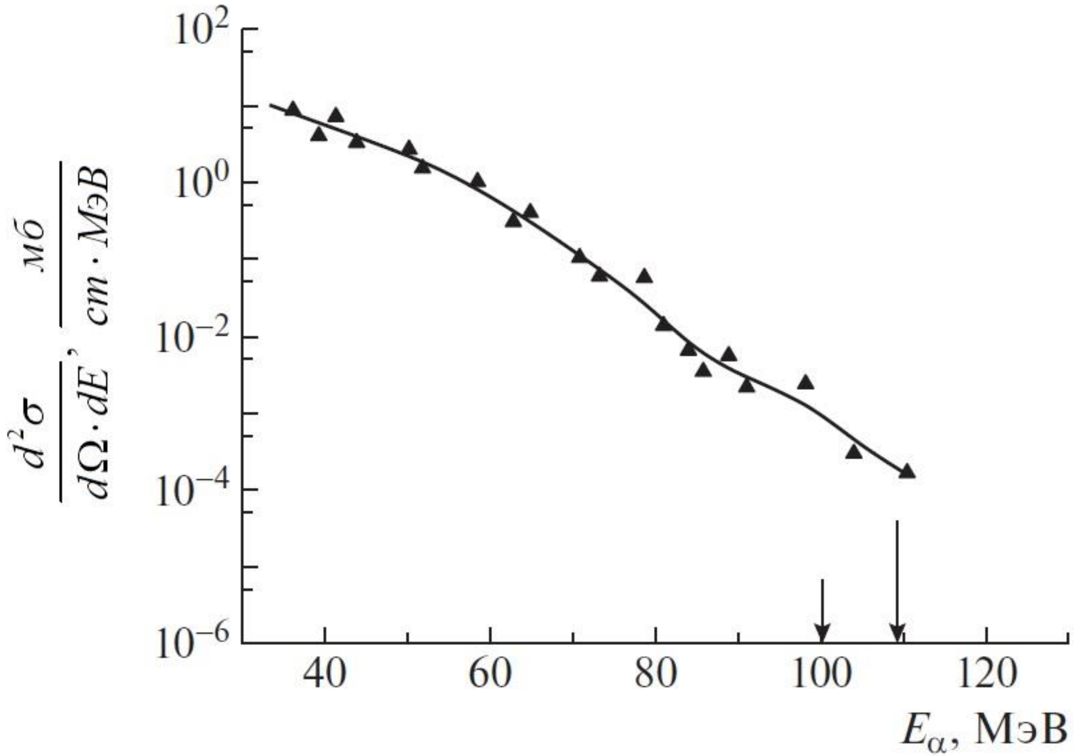
In the ex. (1) for the direct reaction cross-section the factor $S_f^{\lambda}(E^*) = |<\varphi_f^{\lambda}|\psi_B(E^*)>|^2$ measured the possibility to find the component φ_f^{λ}, describing the relative motion of the clusters T and t with angular momentum λ in the state $\psi_B(E^*)$ of the residual nucleus B. *But beyond the* $E_{\alpha}^{(2)}$ *limit this factor* $S_f^{\lambda}(E) = |<\varphi_f^{\lambda}|\psi_{fiss}(E)>|^2$ *measures the similarity of the function* φ_f^{λ} *to the state* $\psi_{fiss}(E)$ *of the already fissioning nucleus* B.

To understand how to reach the maximal value of this factor we shall consider the fission of two heavy nuclei in the microscopic dynamical model of Swiatecki (Swiatecki, Phys. Scripta **24**, 113 (1981). In this model the system passes three configurations and stages on its way to fission. At the energy equal to the Coulomb barrier, it passes the *contact configuration* when the surfaces of the nuclei come into contact and the neck appears. This is the “binuclear” configuration. If the system gets some additional energy E_x called “extra push”, the “*conditional equilibrium*” configuration is formed. This is already a configuration of the “mononucleus” where the intensive exchange of mass and charge only starts. Starting from his configuration the process called ***“fast fission” begins***. At this stage the system might go into the ***quasi-fission channel*** without forming the compound nucleus. It is obvious that **the factor** $S_f^{\lambda}(E)$ **would be**

maximal for the system in this fast quasi-fission stage if the quasi-fission fragments mass and charge distribution is close enough to the fragments T and t.

Of course, there is another mode of the residual nuclei disintegration, namely alpha decay. However then one should not see fast alphas beyond $E_{\alpha}^{(2)}$ limit because the fast alpha leaves the vicinity of the residual nucleus B in about 10^{-22} s. Therefore, even if the period of alpha decay is *mcs*, **fast alpha would be detected long before t**he decay of the nucleus B.

Moreover, Fig.3 shows the spectrum of the recently measured fast alphas in reaction $^{56}Fe + {}^{181}Ta$



The short arrow indicates $E_{\alpha}^{(2)}$ limit, while the long one shows the limit, corresponding to the zero energy of the secondary alpha. Of course, the probability for the zero-energy alpha to leave the nucleus B is also zero. Therefore, **the cross-section of the reaction including such an event should also be zero contrary to the experimental data.**

Therefore, secondary alpha-decay of residual nuclei cannot explain the existence of fast alphas beyond the $E_{\alpha}^{(2)}$ limit.

It is highly desirable to make measurements of the reaction products' masses in coincidence with the fast alphas around the $E_{\alpha}^{(2)}$ limit. Alphas with energy $E > E_{\alpha}^{(2)}$ should coincide with quasi-fission fragments' masses close to those in the initial reaction channel (namely, I and $T-\alpha$). For $E < E_{\alpha}^{(2)}$ we should see the decay products of the residual nuclei B. Unfortunately, however, there should also be an admixture of the quasi-fission channel (due to quasi-fission fragments with higher kinetic energy and to the inelastic interactions of the emerging fast alphas).

Finally, it is interesting to estimate the cross-section of the superheavy nuclei yields and yields of their direct quasi-fission products in the reactions with fast alpha emission. Taking into account existing data on the angular distribution of fast alphas one might get the following rough estimates: 1 MeV energy interval contains many levels of the resulting heavy (superheavy) nucleus with the sum cross-sections about 10 nb for $^{233,241}Bk$ and 0,1 μb for ^{282}Ds и ^{290}Lv.