Emission of Light Fragments from Heavy Nuclei in High Energy Nuclear Reactions

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Importance of the apparent reduction of the Coulomb barrier for emitted light fragments from heavy nuclei bombarded by high energy projectile is pointed out and a new model is presented. Some discussions are also given on the relation between emitted high energy particles and nucleonic clusters.

§1. An overall picture of high energy nuclear reactions

When a nucleus is bombarded by a high energy projectile, there occur so complicated phenomena that, at first sight, no simple and interesting picture of the processes seems to be possible. As experimental data have been slowly accumulated, however, interesting regularities have been discovered which were buried under the complexities, and we are now at a position to be able to say something intelligent about what are taking place.

Generally speaking, we know that very complicated phenomena are a treasure island where we shall be able to find many precious things if we know the way to find them. Theoretical considerations and experiments are equally important guides in this treasure island.

Serber's simple picture$^9$ continued for a long time as a basis for our understanding of high energy phenomena. This picture suggests to separate a high energy reaction into two phases — fast and slow processes. The fast process is the rapid development of a nucleonic cascade, and the slow process is the de-excitation of an excited nucleus by evaporation. Most of the long, thin prongs in stars in photographic emulsions are usually attributed to the fast process, and the short black prongs to the evaporation.

Recently, bombarding energies have been raised to the region from several hundred Mev to 28 Gev, and interesting new aspects have been revealed.$^{10,11}$ It is a purpose of this paper to discuss what alterations or
new ideas are necessitated by these new aspects.

§2. Small value of the Coulomb barrier

Experimental data on energy distribution of multicharged particles like $^9$Li show that majority of them have relatively low energies. The low energy part is usually considered mainly to consist of evaporated particles, and we are going to consider this part in this section. Discussion of the high energy part will be put off to next section.

Among experiments on fragmentation with the nuclear emulsion technique the case of $^9$Li emission is distinguished by its reliability because the so-called hammer track is very easily identifiable. Cüer$^9$ and Perfilov$^9$ summarized experiments on angular and energy distributions of $^9$Li from Ag and Br nuclei induced by high energy protons, $\pi$ and $K$ mesons. They showed that the experimental data are satisfactorily described in terms of the evaporation formula with the following values of the parameters:

a) the nuclear temperature, $T=8\sim15\text{Mev}$,

b) the nuclear velocity, $v=0.01c\sim0.02c$,

c) the Coulomb barrier for $^9$Li, $V=5\sim10\text{Mev}$.

Let us examine whether these values of the parameters are physically reasonable or not. a) The nuclear temperature is related to the nuclear excitation energy $E$. If we use the relation $E\approx(A/10)T^2$ suggested by the Fermi gas model, the value of $E$ is of the order of magnitude 1,000 Mev for the mass number $A\approx 100$. This is too big since the total binding energy is only about 800 Mev. The relation between $E$ and $T$ is, however, dependent on the model of nucleus. As another extreme case, let us assume that an excited state consists only of alpha particles and the temperature is above the critical temperature (which was estimated to be about 3 Mev$^9$), we have $E\approx(A/4)T$ which is about 250 Mev and is not too big. The Monte Carlo calculation$^9$ gave $E\approx 500$ Mev for the probable value of the excitation energy for a wide range of the incident nucleon energy. This shows that the value of the temperature is not inconsistent with the expected value of the excitation energy. b) The velocity $v$ of the nucleus after the fast process can be estimated from the magnitude of nuclear excitation. If the incident nucleon and secondary shower particles have relativistic velocities and move in the same direction, the total change in momenta is equal to the energy transfer divided by the light velocity $c$. Therefore, the nuclear velocity $v$ is estimated from the relation

$$v/c\sim0.5/A.$$
This gives several times too small value of $\nu$, but if some of the shower particles go to different directions from the incident direction, they carry less momenta away and a bigger momentum is transferred to the nucleus. The experimental value of $\nu$ is, therefore, not inconsistent with the theoretical expectation. c) The Coulomb barrier is about 30 Mev for Ag or Br. The experimental value 5-10 Mev is several times too small. In order to give the experimental value, the radius of the nucleus must be 3 or 6 times larger than the ordinary value. Such a tendency was suggested by Le Couteur. He estimated the thermal expansion of radius to be about 10\% at the temperature 7 Mev. Since the Coulomb barrier is a simple notion, it is not easy for us to understand the discrepancy mentioned above unless we suppose some drastic events to occur during the evaporation. Such an idea as local heating is useless in this case since it does not change the Coulomb barrier. In order that barrier is remarkably reduced, it is necessary that the fragment is brought without being accelerated to a place whose distance from the residual nucleus is several times of the nuclear radius. Bagge considered, surface waves of large amplitude are excited at the high temperature due to reduced surface tension, but, quantitatively, this does not seem enough to account for the reduction of the barrier.

True situation seems for us to be the following. The incident particle does not always hit the center of the target and the cascade shower within the target does not always give energy and momentum in a symmetrical way. The nucleus is thus locally heated, and this place of high temperature—fire spot—begins to expand and protrude into the nucleus like jets. At the beginning, the temperature is very high and, consequently, the expansion may be so rapid that the process is considered to be adiabatic. This high temperature jet rushes into the nuclear matter and extend it into the form of crust covering the jet. As the jet expands its temperature becomes lower and the expansion stops when the pressure balances with the pressure due to the surface tension of the crust. Suppose that the jet is of the cylindrical form of radius $R$, the condition of balance is $p \sim 2\sigma/R$ where $p$ is the final pressure and $\sigma$ is the surface tension. The value of $\sigma$ is estimated to be about 14 Mev for the area $4\pi r_0^2$, where $r_0$ is the nuclear radius parameter. The pressure $p$ is related to the initial pressure $p_0$ by the relation $p = p_0(\rho/\rho_0)^\gamma$ where $\rho$ and $\rho_0$ are the final and initial densities and $\gamma = 5/3$. $p_0$ is equal to $T_0\rho_0$. If we put $R \sim 5r_0$ and $\rho_0 \sim r_0^{-3}$, the condition of equilibrium is written as

$$T_0 \left( \frac{\rho}{\rho_0} \right)^\gamma \approx 28/(4\pi \times 5) \text{ Mev.}$$
For an initial temperature $T_1 \sim 10$ Mev, we have $\rho_0/\rho \sim (20)^{1/8} \sim 6$. This means that the length of the cylinder becomes about 6 times of the cross section and the distance of the end point from the center is three times of the initial diameter of the fire spot. If the fragment $^7$Li is emitted at this stage of expansion, the apparent Coulomb barrier may be low and the kinetic energy of the fragment can be small as required by the experiments. The nucleus becomes gradually uniform by repeating expansion and contraction and emitting nucleons and light fragments one after another, and gradually cools down. Low energy fragments are emitted only at a stage of low Coulomb barrier.

We have pointed out possibility of the above-mentioned mechanism. We need more quantitative dynamics of the expansion of the nuclear matter in order to see whether the fire spot actually continues to expand without stopping half-way due to, for instance, too rapid cooling. This kind of consideration is now in progress using gas dynamical method analogous to Landau's treatment of multiple meson production.

§3. Clusters

Let us now turn to the fast process. Energy and angular distributions of high energy $\alpha$ particles and fragments like $^7$Li seem to show fairly different tendencies from those of low energy fragments. As the probabilities of emission of high energy fragments are relatively small, statistics of the energy and angular distributions are not yet good, and it may be too early to draw any definite conclusions. Experiments on $\alpha$ particles are relatively abundant, and it is remarkable that the energy distribution of the $\alpha$ particles of energies above 30 Mev produced by protons of energies $140 \sim 660$ Mev is very well reproduced by a simple model of direct knock-on of $\alpha$ particles existing in the nucleus by the cascade nucleons if we take the preformation probability of $\alpha$ particles in the nuclear surface to be about 0.4. It is also noticed that the angular distribution of the high energy $\alpha$ particles is found to be quite similar to the angular distribution of cascade nucleons. These facts suggest that correlations of nucleons in the nuclear surface have some similarity with the correlations of nucleons in the $\alpha$ particles, at least concerning those components of correlation functions which are effective to the scattering by the incident particles. In this case, we do not have to distinguish strictly pick-up process from knock-on because a 3-particle cluster to be picked up by a high energy particle must have large momenta and this fact means this cluster is interacting strongly with surrounding nucleons.

The tendency of nucleon clustering in the nuclear surface seems to
be true also for larger number of nucleons. For instance, Nakagawa et al.,\textsuperscript{10} and Katcoff\textsuperscript{11} showed that angular distributions of energetic Li, Be, B fragments have the tendency of forward peaking.

The success of the direct knock-on model of $\alpha$ particles does not mean there is big probability of $\alpha$ particle formation in the nuclear surface, but means that the correlation is rather big when momenta of the 4 nucleons are big. Simultaneous study of emission of various fragments from the same nucleus will give us ample information about the many particle correlations of nucleons. For this purpose, high energy parts of the emitted fragment may be most important.

Although experiments on fragments have not been performed often, such experiments will be very interesting if special attention is paid to the high energy part.

References