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Multifragmentation through Exotic Shape Nuclei
in \( \alpha(5 \text{ GeV/u}) + \text{Au} \) Collisions

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We simulate the fragmentation processes in \( \alpha + \text{Au} \) collisions at a bombarding energy of 5 GeV/u using the QMD approach plus the statistical decay model. We find from the simulation that the angular-distribution of the intermediate mass fragments has a side peak when the intermediate nucleus formed by the dynamical process has an annular eclipse shape. This explains the experimental results qualitatively.

Multifragmentation has attracted attention as one of the most important aspects of light- and heavy-ion reactions in the intermediate and high energy region. It is speculated that the decay of a highly excited nuclear system contains information about the nuclear equation of state (EOS) and the liquid-gas phase transition of low density nuclear matter.

Very interesting results have been reported by the KEK experimental group for the angular-distribution of the intermediate mass fragments (IMF) in proton (12 GeV) and alpha (5 GeV/u) induced reactions. There are two components in the experimental data for the angular-distribution of IMF: one has a forward peak, and the other has a side peak at \( \theta_{\text{lab}} = 70^\circ \). In addition, the Coulomb barrier for the IMF emitted off-center is very much suppressed in this experiment. Recently this group has conducted new experiments of the proton induced reactions to choose only the central events using the two coincident IMFs with opposite azimuthal directions on the Au target. In these experiments, the component with the forward peak disappears, and the side peak is enhanced significantly and can be seen clearly even on a logarithmic scale.

For this reaction we can easily imagine that some high energy pions, protons and light fragments are emitted in the forward direction immediately after starting the collision. Afterwards IMFs are created through the thermal decay of a hot intermediate nucleus. If the hot intermediate nucleus decays isotropically, the angular-distribution of the IMF should have a forward peak. Hence the side peak might be explained by the hypothesis that the intermediate nucleus has an exotic shape and/or expands more strongly in the transverse direction than in the beam-direction.

In 1983 Hüffner and Sommermann suggested a trumpet-shaped hole to explain the enhanced backward emission of heavy fragments in high energy proton-induced reactions. In recent years, moreover, the decay from non-spherical nuclei has been suggested for multifragmentation in heavy-ion collisions.
In this paper we theoretically analyze the fragmentation processes of $\alpha(5 \text{ GeV/u}) + \text{Au}$ reactions and discuss the relation between the angular-distribution and the shape of the intermediate nucleus. We choose only the alpha-induced reaction here, since at the bombarding energy $E_{\text{lab}} = 12 \text{ GeV}$, the elementary processes of two-body collisions are too complicated for many open channels. Furthermore, our study is restricted only to central events, noting results of the recent experiments.

The purpose of this paper is to clarify the fragmentation mechanism qualitatively, particularly in view of the shape of the intermediate nucleus. For this purpose we use the Quantum Molecular Dynamics (QMD) approach which can automatically trace the nuclear phase-space distribution at the intermediate time stage, which must be assumed and put in by hand in statistical calculations.\textsuperscript{2),6),9) The QMD approach\textsuperscript{11)} is commonly used as a dynamical model for the theoretical study of fragmentation. In this approach, baryons are described as Gaussian wave packets which give the density distribution

$$\rho(r) = \sum_i \rho_i = \sum_i \frac{1}{(\pi L^2)^{3/2}} e^{-(r-r_i)^2/L^2},$$

where $L$ denotes the width parameter for the Gaussian wave packets. Then their motion is described by a mean-field plus two-body collisions. The experimental data of fragment multiplicities are reproduced well by using QMD together with the statistical decay model\textsuperscript{12)-14) in heavy-ion collisions around several 10 MeV/u\textsuperscript{15),16) and in proton-induced reactions from 100 MeV to 5 GeV.\textsuperscript{17) We now investigate the origin of the experimental results for the IMF angular-distribution by simulating the dynamical stage of $\alpha(5 \text{ GeV/u}) + \text{Au}$ collisions with QMD.

The actual calculations are performed in the following way. First, the initial distribution at rest is generated by the cooling method\textsuperscript{18) and boosted according to the bombarding energy. Second, we perform the QMD calculations and obtain the dynamical fragment distribution. Third, we boost each dynamical fragment to its rest frame and evaluate its excitation energy. Finally, we calculate the statistical decay\textsuperscript{12) from the dynamical fragments and obtain the final fragment distribution.

We use the zero-range symmetry force, the Coulomb force and a Skyrme-type interaction with the ‘hard’ EOS (the incompressibility $K = 380 \text{ MeV}$) parameterized in Refs. 11) and 19) for the effective interactions. Furthermore, we introduce a relativistic correction into the interaction term, as done in Ref. 20) to keep the stable Lorentz contracted phase-space distributions in all nuclei and fragments moving fast.\textsuperscript{21) For the cross-section of two baryon collisions we use Cugnon’s parameterization\textsuperscript{22) for an elastic channel and Wolf’s formulation\textsuperscript{23),24} for inelastic channels including three baryonic resonances: $\Delta, N^*(1440)$ and $N^*(1535)$. These resonances can decay into nucleons and mesons ($\pi$ and $\eta$).\textsuperscript{24) As for the parameters of the inelastic channels, we use the values used in Ref. 14), since the parameters in Refs. 23) and 24) give unphysically large cross sections above $E_{\text{lab}} = 1.5 \text{ GeV}$.\textsuperscript{14) Furthermore, we use Kodama’s prescription\textsuperscript{25) to maintain Lorentz covariance in the collisions within our time-fixation scheme around the several GeV/u energy region.\textsuperscript{23),25}

In the fragmentation process, the mean-field at low density is considered to play
an important role. In order to simulate the low density behavior, we use two kinds of the width parameters $L$ for the Gaussian wave packets (see Eq. (1)). The first (case I) is defined by $L = 1.301$ fm, and the second (case II) by $L = 0.884$ fm. The Gaussian width does not significantly affect the static properties of ground states made by the cooling method.\textsuperscript{18} In the dynamical process, however, the difference between these two cases leads to different instabilities in the low density region. The attractive force between nucleons is stronger in case I than in case II in the dilute medium.

In Fig. 1 we show the baryon and pion distributions in the coordinate space with every 12 fm/c time interval up to 40 fm/c, projecting on the $xz$-plane, restricted with positions $|y| < 1$ fm (upper columns), and the $xy$-plane, restricted with positions $|z| < 1$ fm (lower columns), in Figs. 1 (case I) and 2 (case II). There the $z$-axis and the $xy$-plane are defined as the beam-direction and the reaction plane, respectively. We overwrite the results of twenty simulations for the impact-parameter $b = 0$ fm in the same figure, and the black, grey, and white circles denote the nucleons, baryonic resonances and mesons, respectively.

Around the time step $t = 16$ fm/c, many resonances and pions are produced and propagate forward in both cases. After $t = 28$ fm/c, these high energy pions and nucleons are emitted forward. At this step, the shapes of the intermediate nuclei are different between the two cases. In Fig. 2 (case II), an empty region appears

Fig. 1. Time evolution of the baryon and meson distributions in the coordinate space at time steps 4, 16, 28 and 40 fm/c in $\alpha(5$ GeV/u) + Au collisions for the impact-parameter $b = 0$ fm in case I. The upper columns display the distributions in the $xz$-plane, restricted by $|y| < 1$ fm, while the lower columns in the $xy$-plane, restricted by $|z| < 1$ fm. The black, grey and white circles denote the nucleons, resonances and mesons, respectively.
in the center; an intermediate nucleus with an annular eclipse shape is constructed through the reaction. Next this exotic intermediate nucleus slowly expands side, and disintegrates into fragments in each event (not seen in Figs. 1 and 2, because twenty events are overwritten there). Apparently this fragmentation process is a type of the multifragmentation. On the other hand, in Fig. 1 (case I), the entire nucleus expands almost isotropically, emitting the nucleons, and finally the central part shrinks again, forming one large fragment with a small forward velocity. Note that a similar shape of the intermediate nucleus in case II was obtained using the BUU calculation in Nb + Nb. However, the two formation processes are quite different, and our process does not produce so a clear ring/doughnut shape.

Next we evaluate the angular-distribution of fragments in these two cases. Events are restricted to values of the impact-parameter $b < 3$ fm, because the main contribution to the side peak component comes from central collisions. In the actual calculation we perform six hundred QMD simulations up to $t = 100 \sim 200$ fm/c, when dynamical clusters no longer have exotic shapes, and one hundred cascade calculations of the statistical decay model for each QMD simulation. The numerical errors are given in the figure.

In Fig. 3, we show the angular-distribution of two kinds of fragments with the charge $Z = 1$ (open circles) and $3 \leq Z \leq 20$ (IMF) (full squares), for case I in Fig. 3 (a) and for case II in Fig. 3 (b). In these figures we do not give a comparison with experimental data, because the experimental group has produced data only for the fragments with $Z = 11$, and we do not have sufficient computer power to obtain sufficient statistics for individual fragments.
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Fig. 3. The angular-distributions of fragments for cases I (a) and II (b): $Z = 1$ (open circles) and $3 \leq Z \leq 20$ (full squares). The cross-section for the second fragment is multiplied by 10. Events are restricted to those satisfying $b < 3$ fm.

In case I, the angular-distributions of the two kinds of fragments both have forward peaks. In case II, however, the IMF angular-distribution has a side peak and this result agrees with experiment qualitatively. In addition, we can see that more IMFs are generated in case II than in case I. We have found in our simulations that this side peak of the IMF angular-distribution is strongly correlated with the shape of the intermediate nucleus, i.e., the annular eclipse shape.

The difference between the two processes (cases I and II) must be caused by the properties of the nucleon-nucleon effective interaction in the low density region. Immediately after the incident alpha drills a hole in the Au target, the baryon-baryon collision process exerts a side-directed force on the medium, and the surface along this hole must be very steep. The large Gaussian width in case I, however, creates a gentle surface, and causes the density to diffuse into the hole region. The nucleons along the hole, experiencing a rather strong attractive mean-field, gather in a group, and form a large compound nucleus. The IMFs are created through evaporation and binary fission.

In case II, on the other hand, the small width weakens the attractive mean-field in the low density region, and the transverse expansion becomes stronger than this attractive force. This expansion dilutes the medium and increases the instability. Then the medium must be vaporized, and multifragmentation occurs. From this consideration we can understand the reason for the larger cross-section of the IMF in case II (see Fig. 3), as well as the side peak.

Finally we make two comments on the contribution from non-central events.
With the increase of the impact parameter, the peak angle moves forward. In the middle impact-parameter region, the intermediate nucleus exhibits a partial eclipse and expands sideways. Such a process is also responsible for the side peak of the IMF angular-distribution, while the peak angle depends on the impact-parameter. However, it is difficult to believe that two IMFs generated through the partial eclipse shape would be observed in azimuthally opposite directions for the IMF-coincidence experiments.5)

In this paper, we have reported the results of a QMD simulation for the α + Au collision at 5 GeV/u. The dynamical instability in the dilute nuclear medium was simulated by changing the value of the Gaussian width parameters. We can strongly assert that this reaction constructs a hot nuclear system with an annular eclipse shape in the central collision. This exotic intermediate nucleus expands sideways and causes multifragmentation. As a result of this process the IMF angular-distribution has a side peak. This conclusion can also explain qualitatively the observed suppression of the Coulomb barrier for the IMF emitted sideways.

As for the Gaussian width, several people have used different values, based on considerations from their points of view,11), 14), 15), 26), 27) but a definite value has not been determined yet. Although our values of the Gaussian width in the present study are much smaller than those used in the above references, it is possible that the low density behavior is simulated well with the small Gaussian width of case II.

Of course we do not intend to assert that our calculation perfectly simulates all the time stages of the collision processes. In fact, the QMD simulation at present has not completely explained the experimental results on the IMF-multiplicity in the multifragmentation energy region.28) There are several ambiguities in the ingredients of the present QMD, i.e., in particular the details of the mean-field and the inelastic collision channels, which may also affect the fragmentation processes discussed above, as well as the change of the Gaussian width parameter. For example, the reason for the appearance of the side peak may become clear by introducing a repulsive momentum-dependent force, particularly the side-directed Lorentz force from the vector field.29)

The present results, however, suggest a relation between the fragmentation processes and nuclear properties in the low density region. From this point of view, the surface force in the effective interaction, which is not taken into account in the present study, may also affect these properties.

Though we cannot make a definite conclusion from this simulation alone, the authors do not have any other idea for candidates to explain the side peak and the large suppression of the Coulomb barrier for the IMF emitted sideways. In order to get more quantitative conclusions, we need more theoretical and experimental investigations for the dynamical instability of the collisions.

We hope experimentalists will obtain more information concerning the intermediate nucleus, such as its shape, size, temperature, and so on, because we would be able to extract information with regards to the hot nucleus from the sideways expansion of the intermediate nucleus, if its geometrical relations are identified experimentally.
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**Note added:** After the completion of the present work, the paper of G. Wang et al. appeared in Phys. Rev. C53. They showed a similar shape of the intermediate nucleus in the $^3$He (4.8 GeV/u)+Au collision. However, they used the BUU approach\textsuperscript{19}) and did not provide the IMF angular distribution.