Emission of intermediate mass fragments from neck zone in the ^{209}Bi+^{208}Pb reaction at 11.6 MeV/nucleon

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Intermediate mass fragments ($3 \leqslant Z \leqslant 25$) in correlation with projectilelike and targetlike fragments have been revealed among the ternary events produced in 11.6 MeV/nucleon ^{209}Bi+^{208}Pb reaction. Their characteristics (energy and angular distributions) are in agreement with the emission from the neck zone formed between projectile and target during partially damped collision. The analysis indicates that they can be produced by various mechanisms. Till now fragments with similar behavior were observed at incident energies above 20 MeV/nucleon.

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In recent years the studies of heavy ion collisions at intermediate energies have been mainly dedicated to the emission of intermediate mass fragments (IMF's) ($3 \leqslant Z \leqslant 25$) in these interactions. It was thought that the production of these fragments (multifragmentation) can be connected with the behavior of the highly compressed hot nuclear matter formed during the interaction, and various theoretical models regarding this process assumed that the production mechanism of IMF's mainly has a statistical character. But, recently in experiments at projectile energies in Fermi energy domain (20–50 MeV/nucleon) such IMF's have been observed [1–7] whose characteristics indicate that they are produced by a mechanism that is more of a dynamical origin than of the statistical origin. It has been found that such IMF's are produced in peripheral and midcentral collisions and that their angular distribution and energy distribution is consistent with their emission from the midrapidity (neck) zone formed between the two interacting ions. It seems that both the shape (dynamical) instabilities and excitation can play a role in the formation and emission of these fragments from the midrapidity zone. It should be noted that the neck emission of IMF's has been also observed [8,9] in ternary fission of the excited heavy nuclei produced in interaction of ^{232}Th with low energy light ions.

As already mentioned, till now the IMF emission from necklike structures has been experimentally observed in intermediate (Fermi) energy domain. In their theoretical study of the dissipation mechanisms in the overlap zone for semiperipheral heavy ion collisions Fabri *et al.* [10] concluded that the neck instabilities at beam energies just above 10 MeV/nucleon would lead to large variances in projectilelike and targetlike observables and that the larger effects (up to the cluster formation in the neck region) can be expected at higher energies. Also, Plagnol *et al.* [7] in their experimental study of Xe+Sn reaction at energies between 25 and 50 MeV/nucleon have found that the onset of the midvelocity emission is around 25 MeV/nucleon. In this Brief Report we report on the observation of the IMF's ($3 \leqslant Z \leqslant 25$) with the characteristics consistent with the emission from the necklike zone in the reaction ^{209}Bi+^{208}Pb at $E = 11.6$ MeV/nucleon. In our experiment these fragments have been detected and measured in coincidence with projectilelike and targetlike fragments. The mechanism responsible for their production at such low beam energy is still unclear.

Our experimental method enabled a 2π detection geometry in the laboratory system. For fragment detection we used a CR-39 plastic track detector. The layers of 0.5–0.7 mg/cm^2 of ^{208}Pb were evaporated on one surface of the sheets of CR-39. So prepared samples were irradiated by a normally incident 11.6 MeV/nucleon ^{209}Bi beam at UNILAC (GSI, Darmstadt). After irradiation the target layers were removed by dissolving in 20% HNO_3. Chemical development of the tracks of the emitted fragments was carried out in 6.25N NaOH at 70 °C in a mechanically stirred bath. The etching time was 1 h and this enabled us to get fully developed (finished) tracks of all fragments with $Z \geqslant 3$ produced in the interaction. Due to the detector characteristics and etch conditions used in our experiment, the protons and ions with $Z = 2$ having an energy per nucleon $E/A > 1$ MeV did not give observable tracks in CR-39. For other reaction products there was a decrease in the detection efficiency in the vicinity of the angle of 90° with respect to the beam direction due to thickness of the Pb target. The influence of the target on the efficiency of the detection is the strongest for low-energy ions (such as targetlike fragments after peripheral collisions). Taking into account the thicknesses of the targets used and the angular and energy distribution of the products investigated in our experiment it can be shown that the influence of the target thickness on the measured values is about a few percent and can be neglected.

Scanning and measurement have been done by one optical microscope. As an identification method we used the measurement of the parameters of the finished tracks [11]. Namely, from the measured parameters of the finished tracks the range R, the mean etch rate ratio ($\overline{V_T}/V_B$), and emission angle with respect to the beam direction θ were determined for each fragment. The azimuthal angle φ was measured directly. The atomic number Z and energy per nucleon E/A were determined from the values of R and $\overline{V_T}/V_B$ as described in [11]. According to the calibration results the charge resolution in our experiment was $\Delta Z \leqslant 1$ for $Z \leqslant 30$, $\Delta Z \leqslant 2$ for heavier fragments with energy $E/A \geqslant 0.5$ MeV and $\Delta Z \leqslant 4$ for heavy fragments with energy $E/A < 0.5$ MeV. The energy resolution for observed fragments

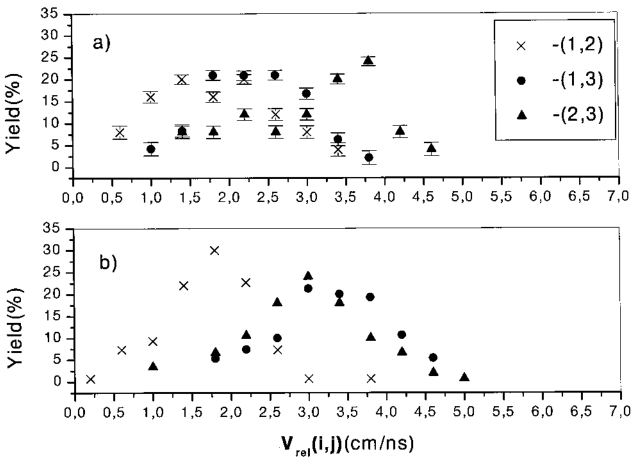

FIG. 1. The distribution of the relative velocities between the fragments taken two by two for (a) ternary events with one IMF fragment and (b) rest of the ternary events. The labels of the fragments are explained in the text.

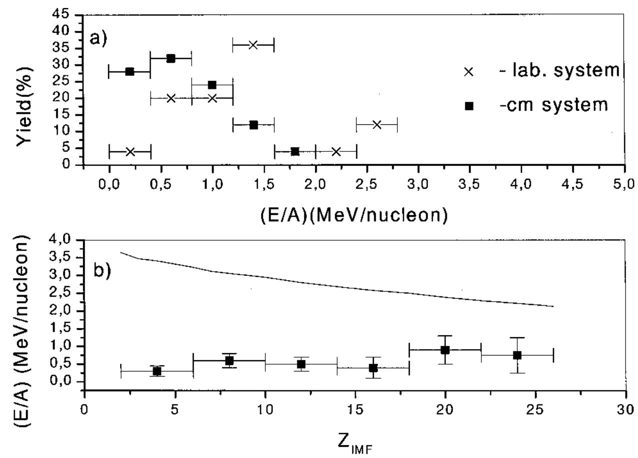

FIG. 2. (a) Distributions of the energy per nucleon of IMF's in the laboratory system $(E/A)_{lab}$ and projectilelike and targetlike c.m. system $(E/A)_{\rm c.m.}$, respectively. (b) Average $(E/A)_{\rm c.m.}$ as a function of Z_{IMF}. The solid line is explained in the text.

was $\Delta(E/A)\leqslant 0.05$ MeV. It should be noticed that a decrease in charge resolution for heavy slow fragments does not lead to an increase of the uncertainty in determining of their energy per nucleon. For these products the dependence of the range on the atomic number is small and, at the same time, R versus E/A plots are very steep. The angular resolution was $\Delta\theta,\Delta\varphi\leqslant 5°$.

From the detected events we separated and analyzed ternary events, i.e., the events that were characterized by the presence of three fragment tracks in correlation. Since in our experiment 2π geometry was available, such events can represent true ternary events, i.e., the events in which only three fragments were present in the exit channel and events with higher multiplicity of fragments in the exit channel but where one or more fragments are emitted backward and were not detected. We have found that about 10% of events with three tracks in correlation can be attributed to the events with four or more emitted fragments. They mostly correspond to the reactions in which after the initial collision both the targetlike and projectilelike fragments undergo fission and one of the four fission fragments was emitted backward in the laboratory system. Such events were omitted from our consideration. We have found that the ternary events that represent the events with three fragments in the exit channel can be, as it was expected, mostly identified as the projectilelike (or targetlike) fragment in correlation with two fission fragments originating from the decay of targetlike (or projectilelike) fragment. But about 10% of these events were characterized by the presence of one IMF in correlation with projectilelike and targetlike fragments. We have detected and analyzed 870 such events.

In Fig. 1 we present the distributions of the relative velocities V_{rel} between the fragments taken two by two for ternary events in which one IMF fragment is present and for the rest of the ternary events, respectively. In each event the lightest fragment was labeled 1 and the heaviest one 3. The points present the values averaged over V_{rel} intervals of 0.4 cm/ns. It can be seen from the figure that in events where IMF is present the distributions of V_{rel} between IMF and heavy fragments have a maximum at small values of V_{rel}. The distribution of V_{rel} between the two heavy fragments is moved towards larger values of V_{rel}. For system considered the V_{rel} between projectile and target was 4.8 cm/ns. This is in agreement with scenario, which supposed that after the collision the projectilelike and targetlike fragments move away at large relative velocities leaving behind them a small fragment emitted at rest in the c.m. system. For ternary events from the second group the distribution of V_{rel} between fragment 1 and fragment 2 has a well defined peak that corresponds to the fission of projectilelike (or targetlike) fragments as it was expected.

Distributions of the energy per nucleon of IMF's in the laboratory system $[(E/A)_{lab}]$ and in the center-of-mass system of projectilelike and targetlike fragments $[(E/A)_{\rm c.m.}]$ are presented in Fig. 2(a). In Fig. 2(b) the dependence of the average $(E/A)_{\rm c.m.}$ on the Z_{IMF} is shown. The points present the values averaged over Z_{IMF} intervals over four units. The solid line corresponds to the values obtained by calculations of the Coloumb barrier for touching spheres given by

$$E_c=\frac{1.44Z_{IMF}(Z_{source}-Z_{IMF})}{1.4[A_{IMF}^{1/3}+(A_{source}-A_{IMF})^{1/3}]+2}\ \text{MeV}, \qquad (1)$$

where for A_{source} and Z_{source} we have used the values 208 and 82 to approximate emission from projectilelike or targetlike source. To determine A_{IMF} we supposed that proton-to-neutron ratio of source is preserved in emitted IMF's. This approximation can influence the E_c values by not more than 10%. If the IMF's examined in this experiment were produced by statistical emission from projectilelike (or targetlike) excited fragments, after collision their energies per nucleon should roughly be near of the calculated values presented by solid line in Fig. 2(b). It can be seen from the Figure that the measured values of $(E/A)_{\rm c.m.}$ are a few times lower than the calculated.

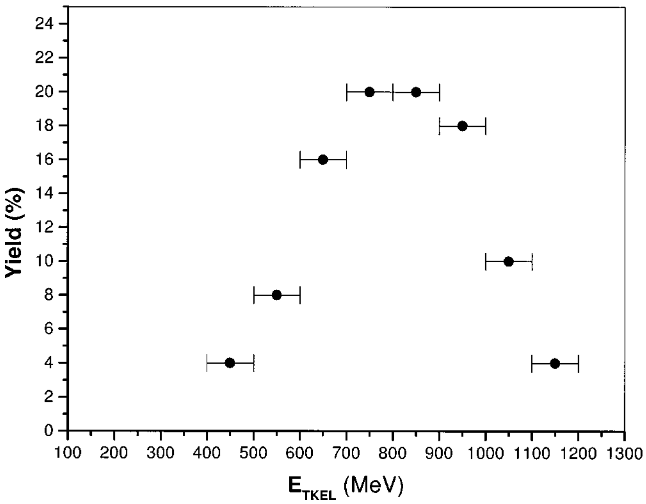

FIG. 3. Distribution of the total kinetic energy loss E_{TKEL} for ternary events with one IMF.

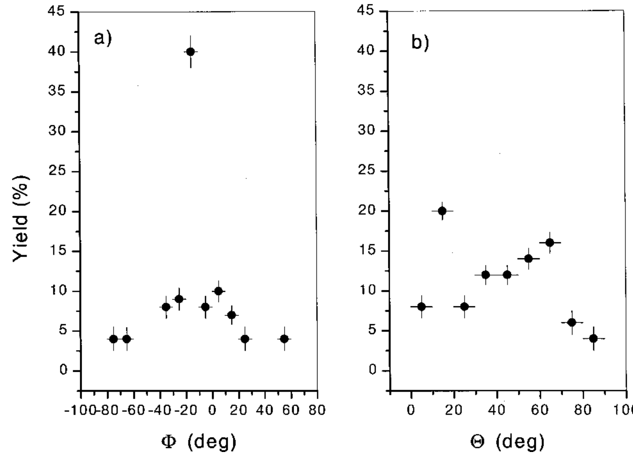

FIG. 4. (a) In-plane angular distribution of IMF's. (b) Distribution of angles between IMF's and the reaction plane.

The IMF originating from the neck zone should be practically at rest in the c.m. system of heavy fragments in the case of symmetric systems due to the near cancellation of the Coulomb fields of heavy fragments. This is in agreement with the small values of $(E/A)_{\mathrm{c.m.}}$ obtained in this experiment and presented in Figs. 2(a) and 2(b). Also, the mean values of the velocities of these fragments in the laboratory V_{IMFlab} should coincide with the velocity of the center-of-mass system of heavy fragments $V_{\mathrm{c.m.}}$. From our results we obtained the values $\overline{V}_{IMFlab}=(1.65\pm0.25)$ cm/ns and $\overline{V}_{\mathrm{c.m.}}=(1.75\pm0.25)$ cm/ns, respectively.

It can be seen in Fig. 2(b) that the values of $(E/A)_{\mathrm{c.m.}}$ are in the limit of experimental error independent on Z_{IMF}. This means that the energy of IMF's in the c.m. system of heavy fragments is roughly linearly dependent on Z_{IMF}. This trend is consistent with the emission of the neck fragments with a fixed initial velocity. It may be noted that a similar dependence is observed in experiments [8,9] in which the emission of IMF's from the neck zone during the fission process was examined.

In Fig. 3 we present the distribution of the total kinetic energy loss E_{TKEL} for ternary events having one IMF. E_{TKEL} is defined as the difference, in the center-of-mass reference frame, between the initial available kinetic energy (E_{inc}) and the total kinetic energy E_{TKE} of the projectilelike and targetlike fragment in the exit channel:

$$E_{\mathrm{TKEL}}=E_{inc}-E_{\mathrm{TKE}}, \tag{2}$$

where E_{TKE} was calculated from the relative velocity and the reduced mass of the dinuclear system. The fact that the energy of IMF's was not included in calculation of E_{TKE} does not have large influence on the distribution of E_{TKEL} because of their small energy. It can be seen from the figure that the relevant ternary events mainly originate from collisions with E_{TKEL} between 600 MeV and 1000 MeV. For the interaction studied in this experiment this interval of E_{TKEL} corresponds to the partially damped collisions. It should be mentioned that in experiments at energies above 20 MeV/nucleon [1,2,6,7] the emission from intermediate (neck) zone was observed in peripheral and semiperipheral collisions.

We defined the reaction plane as the plane specified by the beam axis and the separation axis of projectilelike and targetlike fragments in their center-of-mass system. The in-plane angle Φ of IMF was defined as the angle between the projection of the IMF velocity (in the corresponding c.m. system) onto the reaction plane and heavy fragments separation axis. The separation axis is taken to have positive direction towards the direction of the lighter heavy fragment and Φ could take the values between $-180°$ and $180°$. The out-of-plane angle Θ is defined as the angle between IMF velocity and the reaction plane. The distributions of Φ and Θ are presented in Figs. 4(a) and 4(b), respectively.

Figure 4(a) shows that IMF's have anisotropic angular distribution in the reaction plane. Namely, their velocities projected on to reaction plane are predominantly oriented along the separation axis of the projectilelike and the targetlike fragments, i.e., in the reaction plane the three fragments are almost collinear. Similar anisotropy in the in-plane angular distribution was observed in the case of the three-body exit channels in the reactions ^{84}Kr$+^{166}$Er and ^{129}Xe$+^{122}$Sn at 12.5A MeV ([12]), and in ^{100}Mo$+^{100}$Mo and ^{120}Sn $+^{120}$Sn at around 20A MeV ([13]). In these experiments such behavior was explained by the fast, nonequilibrium, asymmetric fission that follows the initial inelastic collision. The light fission fragment is supposed to be located between the two heavier fragments and is strongly peaked along the separation axis of the deep inelastic step. Since our analysis included IMF's with $3\leqslant Z\leqslant 25$ it seems logical to suppose that part of them could be produced by such mechanism. In any case the shape of the in-plane angular distribution of IMF's suggests that they are produced by a fast process, i.e., during or shortly after separation of heavy fragments.

The out-of-plane angular distribution of IMF's is shown in Fig. 4(b). It seems that this distribution has two peaks, i.e., it is the sum of at least two distributions: the first one of which is the contribution of the in-plane emission and the second one of which is the contribution of the out-of-plane emission. Therefore, it seems that IMF's in ternary events investigated in this experiment are produced by different scenarios. For example, above mentioned, fast, asymmetric fission would favor in-plane emission of fragments. On the other hand, simultaneous ternary breakup (neck instability) similar to the fission accompanied by IMF's [8,9] would favor out-of-plane emission of IMF's [14]. If only these two mechanisms would be responsible for production of fragments examined in this experiment this would mean that IMF's with lower Z values would be emitted preferentially out of plane and those with higher Z will be omitted in plane. But the analysis of our results did not show any dependence of angular distribution on Z of the fragments.

In conclusion, we have observed the production of intermediate mass fragments ($3 \leqslant Z \leqslant 25$) in correlation with projectilelike and targetlike fragments in 11.6 MeV/nucleon ^{209}Bi+^{208}Pb reaction. The energy and angular distributions of these fragments indicate that they originate from the intermediate (neck) zone formed between target and projectile during their collision. Till now such fragments were detected and studied in heavy ion collisions in Fermi energy domain (i.e. at energies above 20 MeV/nucleon). The analysis shows that in our experiment these fragments are predominantly emitted in partially damped collisions. They are characterized by the low kinetic energy that is linearly dependent on their atomic number. The shape of their in-plane angular distribution indicates that they are produced during or immediately after separation of projectilelike and targetlike fragments. The out-of-plane angular distribution of these fragments suggests that various processes, i.e., various types of instabilities whose mechanism is still unclear, can contribute to their formation.

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