RAPID COMMUNICATIONS

PHYSICAL REVIEW C VOLUME 48, NUMBER 5 NOVEMBER 1993

Light fragment production in the 3.65A GeV ^{12}C+^{208}Pb reaction

B. Grabež
Institute of Physics, P.O. Box 57, 11001 Beograd, Yugoslavia

(Received 24 February 1993)

We investigated the emission of light fragments from the ^{208}Pb target induced by 3.65A GeV ^{12}C projectiles. The events are classified according to the number of heavy fragments. Two mechanisms of the production of light fragments are observed.

PACS number(s): 25.75.+r

The main problem in the classification of the reaction channels in high-energy nuclear reactions was the fact that the measurements were mostly inclusive. This was caused by the lack of the classification parameters. However, certain regularities have been observed and it was adopted that the fragments in high energy nuclear collisions are produced by spallation (including deep spallation), fission, and multifragmentation. Hufner [1] using as classification parameters the mass of the fragments (A) and their multiplicity M defined the processes in the following way: Spallation is the process in which only one heavy fragment with mass close to the target mass A_T is formed (the special case of spallation is so-called deep spallation where M is also $M=1$ but $50<A<2A_T/3$); fission is the process which leads to two heavy fragments in the interval around $A=A_T/2$; and multifragmentation is the process whose result is the formation of several (more than two) fragments with $A<50$. However, Sangster *et al.* [2] and Porile *et al.* [3] observed that in the reaction 1–19 GeV p+Xe, fragments with $2\leq Z\leq 14$ (which corresponds to the mass region $A\leq 30$), except in multifragmentation, are also produced in the binary process of the light-fragment–heavy-residue type, similar to observations at intermediate energies [4]. The events with two light fragments $2<Z\leq 20$ accompanied by one heavy fragment have been observed in the experiment by Grabež and Gerc [5]. This indicated that the multiplicity of fragments $M>2$ does not mean multifragmentation and that various mechanisms contribute to the production of light fragments in high-energy nuclear interactions. Lewenkopf *et al.* [6] investigated the interaction of 200–980 MeV/nucleon Au with Ag and other elements in a CR-39 detector (H, C, and O). As the selection criterion they adopted the number of heavy fragments. In this way the interactions with $M_H=1$ are classified as spallation, with $M_H=2$ as fission, and $M_H=0$ as multifragmentation. In their experiment they also observed, similar to the previously cited experiment by Grabež *et al.* [5], the light fragments ($6<Z<15$) which are in coincidence with one heavy fragment. They called this process associated spallation; i.e., multifragmentation associated with spallation. With regard to this, our goal in this paper is to investigate the processes in which the light fragments are produced, and to try to make a clear separation between events which are produced by multifragmentation and some other processes.

In our experiment a CR-39 plastic track detector was used in the sandwich technique. The experimental method was similar to the one we used in our previous experiments [4,5]. In Fig. 1 we present the stacks used in our experiment. It can be seen that every stack consisted of two CR-39 foils and one Pb layer between them. The Pb target was vacuum evaporated on sheets of CR-39 detector. The free surface of the target was then covered with another CR-39 sheet. In this way the target was sandwiched between the two detector sheets, which enabled detection of reaction products in 4π geometry. The detector sheets were mounted on a plexiglass holder with six screws and as a result they could be returned to the same position after track etching. In this way the correlation between emitted fragments was preserved. The thicknesses of the Pb target varied from stack to stack between 0.7 and 0.8 mg/cm^2. The thicknesses of the CR-39 foils were 0.5 mm. Since the energy of emitted target products was not higher than 20 MeV/nucleon, they were stopped inside one foil. We had to deal with tracks which start and end inside one detector sheet. This means that for the measurement and identification of fragments we had to use a method suitable for such tracks.

The irradiation with 3.65A GeV ^{12}C ions was made at the Synchrophasotron of Dubna. After irradiation the target was removed by dissolution in 20% HNO$_3$ and the detector was etched for 3 h in 6.25N NaOH at 70 °C. The etching period was chosen to obtain fully developed (finished) tracks. Scanning and measurement have been performed by an optical microscope. As an identification method we used the measurement of the parameters of the finished tracks [7]. From the measured parameters of the finished tracks the range (R), mean etch rate ratio ($\bar{V}_T/V_B$), and emission angle with respect to the beam direction (θ) were determined for each target fragment. The mean etch rate ratio is the ratio of the mean etch rate ($\bar{V}_T$) along the track to the bulk etch rate (V_B; $V_B=1.35$ μm/h for our etch conditions). From the values of R and $\bar{V}_T/V_B$, the atomic number Z and energy

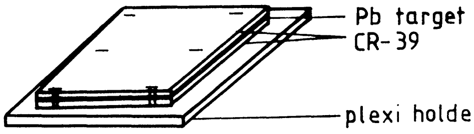

FIG. 1. Schematic diagram of the stack.

per nucleon (E/A) of products were determined as described in Ref. [7]. Essentially, the method is equivalent to the experiments using ΔE and E counters which allow determination of the Z and E of fragments. The available charge resolution is then determined by the errors in the R and $\bar{V}_T/V_B$ determination. In our experiment the maximum error in range determination was $\Delta R = 1$ μm. This range uncertainty together with possible error in determination of the tip radius implies an uncertainty in $\bar{V}_T/V_B$ of about 2%. This means that a fractional change in $\bar{V}_T/V_B$ with Z (charge sensitivity) higher than 2% can enable a charge resolution better than unit Z. According to the calibration results the charge resolution in our experiment was $\Delta Z \leq 1$ for fragments with $Z < 30$, $\Delta Z \leq 2$ for heavier fragments with energy $E/A > 0.5$ MeV and $\Delta Z \leq 4$ for heavy fragments with energy $E/A \leq 0.5$ MeV. The angular resolution was $\Delta\vartheta, \Delta\varphi \leq 5°$. Our experimental results are specially sensitive to the resolution between He and Li fragments. In Fig. 2 we present the $\bar{V}_T/V_B$ versus R calibration curve for He, Li, and Be ions. Taking into account previously mentioned errors in R and $\bar{V}_T/V_B$ determination it can be seen that charge resolution was better than $\Delta Z = 1$ for relevant ions.

Due to detection characteristics and conditions chosen in our experiment, the protons and ions with $Z = 2$ having an energy per nucleon of $E/A > 2.5$ MeV did not give observable tracks in CR-39. For other reaction products there was a decrease 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 strongest for low-energy ions. Taking into account the thicknesses of the targets used in our experiment and the ranges of ions in Pb it can be calculated that the detection efficiency at an angle of 85° (and 95° in the case of detection in 4π geometry) was about 37% for ions with $E/A = 0.1$ MeV. At the same angle the efficiency was 100% for products with an energy $E/A \geq 0.4$ MeV. Assuming isotropic emission the detection efficiency for the total yield of ions with an energy $E/A = 0.1$ MeV would be 88.5%. Taking into account the energy and angular distributions of the products observed in our experiment it can be shown that the influence of the target thickness on the measured multiplicity of fragments with $Z > 2$ is about a few percent and can be neglected.

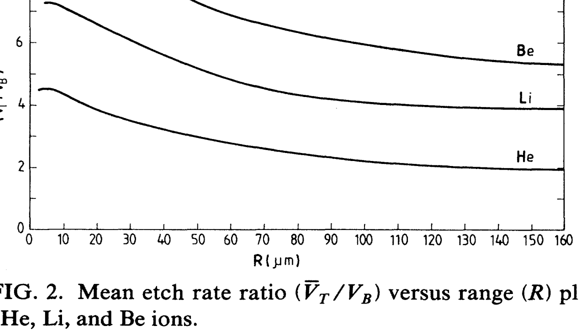

FIG. 2. Mean etch rate ratio ($\bar{V}_T/V_B$) versus range (R) plots for He, Li, and Be ions.

In our experiment we observed the events with multiplicity (M) of fragments with $Z > 2$ from $M = 1$ to $M = 4$. Our analysis included 1650 events with multiplicity $M \geq 2$. Among the observed events were the events in which one heavy fragment was accompanied by one or more light fragments (similar events in Ref. [6] were called associated spallation). The multiplicity of light fragments in such events varied from $M_{\mathrm{IMF}} = 1$ to $M_{\mathrm{IMF}} = 3$, i.e., the maximum total number of fragments with $Z > 2$ was $M = 4$. We used, as the observables useful for investigation of the events, similar to Ref. [8], $Z_{\max}$, the atomic number of the largest fragment produced per an event, and Z_{bound}, the sum of the atomic numbers of all fragments with $Z > 2$ emitted in one event. As was mentioned in Refs. [5] and [8] the difference between Z_{bound} and atomic number of the target (projectile) represents the number of light particles ($Z = 1,2$) which could be emitted during different phases of the interaction. As was shown in Ref. [8], the number of emitted light particles and Z_{bound} are anticorrelated and they seem to be equivalent measures of the impact parameter and of the degree of the violence of the collision.

Table I relates to events with multiplicity $M = 3$ of fragments with $Z > 2$ (ternary) events and presents the contribution of ternary events having the largest fragments with corresponding $Z_{\max}$ to the total number of ternary events. Besides our results, the results for the 8.8 GeV ^{4}He+Pb reaction [5] are also presented. It can be seen that in both interactions the ternary events are mostly produced in reactions where the largest fragment has $2 < Z_{\max} < 30$. This result resembles the result obtained in the study [9] of 1 GeV/nucleon Au-emulsion reaction data [10]. Namely, in Ref. [9] it was found that in events with at least one fragment with $3 \leq Z \leq 6$ the average charge of the largest fragment was $Z_{\max} < 30$. For the interaction investigated in our experiment there is no contribution of events with the largest fragment such that $30 < Z_{\max} < 60$, and this contribution is small for the 8.8 GeV ^{4}He+Pb interaction.

In Table II the contribution of ternary events with $Z_{\max} < 30$ to the corresponding interval of $Z_{\max}$ is presented. It can be seen that most of the ternary events have $2 < Z_{\max} < 10$ and that with an increase of $Z_{\max}$ this contribution decreases.

Tables I and II indicate that the boundary between light and heavy fragments is $Z \approx 30$, similar to the case for 600 MeV/nucleon Au+C(Al,Cu) interaction presented by Ogilvie *et al.* [11]. Therefore, as in Ref. [11] we define the light fragments as fragments with $2 < Z < 30$.

TABLE I. Contribution of ternary events having a largest fragment with corresponding $Z_{\max}$ to the total number of ternary events (%).

$Z_{\max}$	3.65A GeV ^{12}C+Pb	8.8 GeV ^{4}He+Pb
$Z_{\max} \geq 60$	16.3	18.3
$40 \leq Z_{\max} < 60$		3.8
$30 \leq Z_{\max} < 40$		6.3
$2 < Z_{\max} < 30$	83.7	71.6

TABLE II. Contribution of ternary events with $Z_{\max} < 30$ to the corresponding interval of $Z_{\max}$ (%).

$Z_{\max}$	3.65A GeV ^{12}C+Pb
$2 < Z_{\max} < 10$	64.5
$10 \leq Z_{\max} < 20$	25.8
$20 \leq Z_{\max} < 30$	9.7

In Figs. 3(a) and 3(b) we present the distribution of Z_{bound} for events with $M=2$ and $M=3$, respectively. As was previously mentioned Z_{bound} is the measure of the impact parameter and the degree of violence of the collision. According to this, from Figs. 3(a) and 3(b) it follows that $M=2$ events correspond to more violent collisions than ternary events. For $M=2$ and $M=3$ events there is an increase at large values of Z_{bound} which corresponds to the associated spallation events. In agreement with this the associated spallation events would correspond to the peripheral collisions. An opposite conclusion, reached by Lewenkopf *et al.* [6], was based on the fact that in their experiment the associated spallation was observed in asymmetric but not in symmetric heavy ion collisions. This would mean that, contrary to widely adopted statement, the number of light particles emitted is not a measure of the violence of the collision. Anyway, judging by Table I and Figs. 3(a) and 3(b) the transition between multifragmentation and associated spallation is not continuous and we probably have to deal with two different reaction mechanisms.

In Fig. 4(a) we present the distribution of the relative angles in the plane perpendicular to the beam for $M=2$ events. In Fig. 4(b) we present the distribution of the largest relative angle between the fragments in the plane perpendicular to the beam for $M=3$ events. From Fig. 4(a) it can be seen that the associated spallation events favor emission around $\varphi = 180°$, which is expected from momentum conservation. The broadening in distributions for events with $Z_{\max} < 60$ can be caused by the fact that in some of these events fragments with heavier charges did not get out of the Pb target and were not detected. But, as previously mentioned, the effect of the target on multiplicity of measured events is calculated to be only a few percent. More probably this broadening is due to the larger number of emitted but undetected light particles in events with $Z_{\max} < 60$. From Fig. 4(b) it also can be seen that, for $M=3$ events, emission of fragments around $\varphi_{\max} = 180°$ is more probable for associated spallation than for multifragmentation.

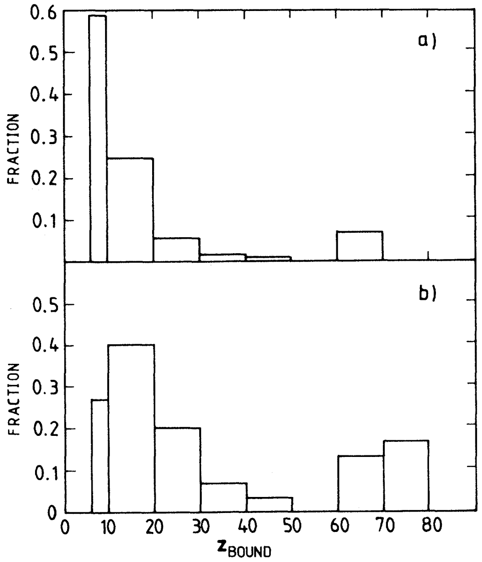

FIG. 3. The sum of the atomic numbers of all fragments with $Z>2$ emitted in one event for (a) $M=2$ and (b) $M=3$.

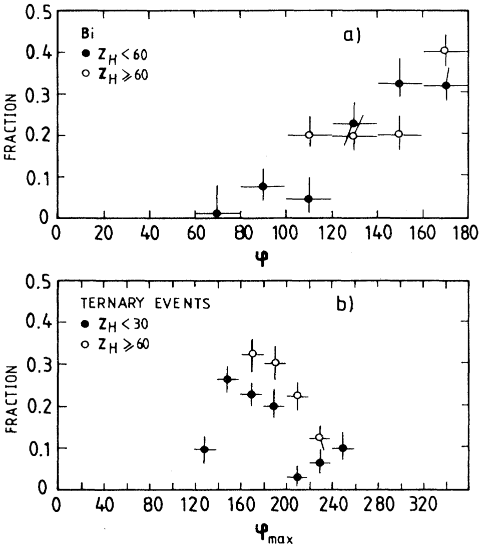

FIG. 4. (a) The distribution of the relative angles in the plane perpendicular to the beam for $M=2$ events. (b) The distribution of the largest relative angle between the fragments in the plane perpendicular to the beam for $M=3$ events.

We separated multifragmentation events using the criterion that in such events $Z_{\max} < 30$. In Fig. 5 we present the mean multiplicity of multifragmentation events at various ranges of Z_{bound}. It can be seen that multiplicity of light fragments first increases and then decreases with Z_{bound}; i.e., with the violence of the collisions. Similar behavior was obtained in Refs. [8,11] for 600

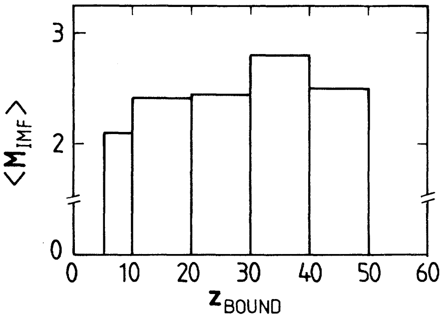

FIG. 5. The mean multiplicity of multifragmentation events at various ranges of Z_{bound}.

MeV/nucleon Au+C(Al and Cu) interaction. It is interesting to notice that, similar to ours, in their experiment the maximum multiplicity is reached near $Z_{\mathrm{bound}} \approx 40$. At first sight the $\langle M_{\mathrm{IMF}} \rangle$ in the interaction presented in Ref. [8] is much more dependent on Z_{bound} than in the interaction examined in our experiment. However, it should be noticed that the $\langle M_{\mathrm{IMF}} \rangle$ versus Z_{bound} dependence presented in Fig. 5 of this work is related only to multifragmentation events (i.e., to events with $Z_{\max} < 30$), and in Ref. [8] this dependence is shown for all detected events.

In our experiment the maximum measured multiplicity in multifragmentation events was $M_{\mathrm{IMF}} = 4$, the mean multiplicity was $M_{\mathrm{IMF}} = 2.25$, and the most probable multiplicity was $M_{\mathrm{IMF}} = 2$. For the 600 MeV/nucleon Au+^{12}C interaction the mean multiplicity of multifragmentation events was $M_{\mathrm{IMF}} = 3.5$ and the most probable multiplicity was $M_{\mathrm{IMF}} = 3$. For our interaction the energy in the c.m. system was $E_{\mathrm{c.m.}} = 41.4$ GeV, and for the 600 MeV/nucleon Au+^{12}C reaction it was $E_{\mathrm{c.m.}} = 6.8$ GeV. Taking into account the results from intermediate energies it seems that multiplicity of light fragments first increases and then decreases with the energy available to the system.

In conclusion, we investigated the light fragment production in the 3.65*A* GeV ^{12}C+^{208}Pb reaction. Our results support the existence of the associated spallation in asymmetric heavy ion collisions at high energies. Namely, we observed that the light fragments can be produced in the multifragmentation events and in the events in which one heavy fragment is accompanied by one or several light fragments (associated spallation). According to our results the transition between multifragmentation and associated spallation is not continuous and probably we have to deal with two different reaction mechanisms. The multiplicity of fragments in multifragmentation events first increases and then decreases with the violence of the collision and the energy available to the system.

---

[1] J. Hufner, Phys. Rep. **125**, 129 (1985).

[2] T. C. Sangster *et al.*, Phys. Lett. B **188**, 29 (1987).

[3] N. T. Porile *et al.*, Phys. Rev. C **39**, 1914 (1989).

[4] B. Grabež, R. Beckmann, P. Vater, and R. Brandt, Phys. Rev. C **34**, 170 (1986).

[5] B. Grabež and V. Gerc, Phys. Lett. B **207**, 27 (1988).

[6] C. Lewenkopf, J. Dreute, A. Abul-Magd, J. Aichelin, W. Heinrich, J. Hufner, G. Rusch, and B. Wiegel, Phys. Rev. C **44**, 1065 (1991).

[7] B. Grabež, R. Beckmann, P. Vater, and R. Brandt, Nucl. Instrum. Methods **211**, 209 (1983).

[8] J. Hubele *et al.*, Z. Phys. A **340**, 263 (1991).

[9] J. Aichelin and X. Campi, Phys. Rev. C **34**, 1643 (1986).

[10] C. J. Waddington and P. S. Freier, Phys. Rev. C **31**, 88 (1989).

[11] C. A. Ogilvie *et al.*, Phys. Rev. Lett. **67**, 1214 (1991).